Thermal Comfort Conditions by Wearing a Cooling Vest

Naoe NISHIHARA, Shin-ichi TANABE,* Hirofumi HAYAMA** and Masayoshi KOMATSU***

Department of Human Environmental Engineering, Graduate Course, Ochanomizu University, Bunkyo-ku, Tokyo 112–8610, Japan

* Department of Architecture, Waseda University, Shinjuku-ku, Tokyo 169–8555, Japan
** Graduate School of Engineering, Hokkaido University, Sapporo 060–8628, Japan
*** NTT FACILITIES, Toshima-ku, Tokyo 170–0004, Japan

To evaluate the effect of a cooling vest, subjective experiments were conducted in a climatic chamber. The chamber was controlled at an operative temperature of 33.0°C, relative humidity of 37%, and still air. The proposed cooling vest has ice bags inside. The skin temperature at cooling parts was kept about 33°C. There was no significant difference in the total sweat rate, evaporative heat loss from the skin, and skin wettedness of the subjects between when the cooling vest was worn and when it was not. Sweating sensations were significantly lower when the cooling vest was worn. Thermal and comfort sensations were closer to the neutral conditions when the cooling vest was worn. This effect was estimated to be equal to a 3°C decrease of operative temperature. The whole body comfort sensation was greatly affected by the whole body thermal sensation. Excess cooling caused local thermal discomfort. When designing of comfortable cooling garments, it is important to decrease the whole body thermal sensation effectively and to prevent the body from cooling down excessively.

(Received April 4, 2001; Accepted in revised form September 26, 2001)

Keywords: thermal sensation, comfortability, artificial climatic chamber, subjective experiment, cooling garment.

INTRODUCTION

To evaluate the effect of a cooling vest and the local discomfort caused by wearing it, subjective experiments were conducted in a climatic chamber. The cooling vest is a garment that has a cooling function, which alleviates thermal discomfort under moderate heat stress. It is able to cool down the human body directly, so it might be effective for saving energy compared with conventional cooling systems.

Previous studies of cooling garments pointed out that they were useful for alleviating thermal physiological stress (Bishop et al., Duncan and Konz, Pimental et al., Hayashi and Tokura). They reported on the effect of cooling garments. However, there were few surveys on the local discomfort associated with it. The purpose of this study is to evaluate not only the effect of a cooling vest but also the local discomfort caused by wearing it.

To alleviate thermal discomfort under moderate heat stress, a new cooling vest was designed and proposed in this paper. From a literature survey, even if the mean skin temperature is similar, the sensations differ depending on body segments. Since the density of cold spots on the trunk is greater than that of other parts, its sensitivity is also higher. Cold stimuli applied to the trunk affect thermal sensation more than that of the extremities. Shvartz et al. reported that cooling of the chest or back had the advantage of effective cooling, because it allowed cool blood to be circulated directly into the circulatory system and the relatively large surface area to be cooled. Based on these literature surveys, we designed a cooling vest that cooled down the trunk. Cooling methods include water-cooled, air-cooled, ice bag, and fan systems. Epstein et al. described that the ice-bag vest had the highest cooling capacity among them based on physiological results. The ice bag system does not require mechanical devices, so it might minimize work disturbance. A cooling vest for this study was designed and named “Comfort Vest II” as shown in Fig. 1. Sixteen small ice bags were used for the present vest. The distribution of ice bags is illustrated in Fig. 2. The melting point of the ice bag was −1°C and the latent heat of phase change was 335 kJ/kg, which is indicated by the manufacturer’s specification. Six ice bags (120 g/each) at the chest
and ten ice bags (100 g/each) at the back were distributed. The cooling area was about $5.7 \times 10^{-2} \text{ m}^2$ at the chest and $7.7 \times 10^{-2} \text{ m}^2$ at the back. The total weight of this cooling vest was 2,295 g. The cooling packs were insulated with one layer each of aluminum, styrene sheet, vinyl sheet, and water absorptive flannel. The outermost layer of flannel was used to absorb condensation formed on the side of human body effectively.

The cooling vest was put on a thermal manikin wearing a work uniform. The surface temperatures of the cooling vest were measured with Copper-Constantan thermocouples, after the thermal manikin reached the thermal steady state at the operative temperature of 32.8°C. This method took no account of latent heat transfer. The average surface temperature of the cooling vest (1-120 min) was about 16.8°C and it kept under 20°C for 5 h. Properties of the fabric of the cooling vest are shown in Table 1. The cooling power of the present cooling vest at the chest and back, measured using the thermal manikin, was 33 W/m².12

**METHODS**

Subjective experiments were conducted to evaluate the effect of the cooling vest in a climatic chamber at Ochanomizu University in July, 1998. The plan of the chamber and experimental set up are shown in Fig. 3. Six college-age male subjects participated in the wearing trial test. All subjects were volunteers who were paid for participating in the experiments. Photographs of the subjective experiment are shown in Fig. 4. Anthropometric data for the subjects are listed in Table 2.

Experimental conditions are shown in Table 3. Experiments were performed with and without cooling vests in the chamber which was conditioned at an operative temperature of 33°C, relative humidity of 37%, and still air. Each condition was thumbnailed as [Cooling vest] and [Control], respectively. In addition, an experiment without a cooling vest at operative temperature of 28.5°C ([to=28°C]) was carried out. The subjects wore work clothes, which were consisted of a long sleeve shirt, a cotton T-shirt, trousers, socks, and their own undershorts. This clothing ensemble was estimated 0.88 clo by measurement with thermal manikin. The cooling vest was worn over work clothes as shown in Fig. 4.

The experimental procedure is shown in Fig. 5. Each subject stayed in the anteroom for 10 min (sedentary activity) before entering the chamber. The chamber was conditioned at an operative temperature of 33°C, relative humidity of 37% RH, and still air. Each subject was asked to go up and down 25 steps every 10 min during the experimental session. During the intermittent period, subjects remained sedentary.

![Fig. 1. The cooling vest (Comfort Vest II)](image1)

![Fig. 2. Distribution of the ice packs](image2)

### Table 1. Properties of the fabric of the cooling vest

<table>
<thead>
<tr>
<th>Water absorption *1 (mm)</th>
<th>Air permeability *2 (cm²/cm-s)</th>
<th>Dryness *3 (min)</th>
<th>Water vapor resistance *4 (g/m²/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction of warp</td>
<td>Direction of weft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>126</td>
<td>96</td>
<td>173.9</td>
<td>120</td>
</tr>
</tbody>
</table>

*1 JIS L 1096 6.26.1 B. *2 JIS L 1096 6.27.1 A. *3 It was measured in accordance with JIS L 1096 6.25.1 A. Because of a fabric size limit, a 20×20 cm sample was used instead of a 40×40 cm sample. *4 JIS L 1099 A-1.
Thermal Comfort Conditions by Wearing a Cooling Vest

This activity was estimated at 1.4 met. They were allowed to drink as much water as they wanted. However, consumption of water by each subject was precisely recorded. No food was permitted to consume during the experimental session.

Skin temperatures at 8 points on the body, namely the forehead, upper arm, hand, chest, back, thigh, leg, and foot, were measured. The mean skin temperature was calculated by Equation (1). The temperature and relative humidity under the clothing at the chest and back were also measured. These were recorded every 1 min during the experimental period. The total body sweat rate was calculated from pre- and post-test weights, and it was adjusted for water intake. Subjects evaluated their thermal sensation, comfort sensation, thermal acceptability, sweating sensation, and body parts that were desired to be cooled every 10-min during the experimental period. The evaluation scale is shown in Fig. 6. Subjects were also asked to evaluate their overall feeling for the cooling vest.

\[
\bar{T}_s = 0.07 \ T_{\text{forehead}} + 0.15 \ T_{\text{upper arm}} + 0.05 \ T_{\text{hand}} + 0.18 \ T_{\text{chest}} + 0.17 \ T_{\text{back}} + 0.18 \ T_{\text{thigh}} + 0.13 \ T_{\text{foot}} + 0.07 \ T_{\text{foot}}
\]  

(1)

The total body sweat rate, evaporative heat loss and skin wettedness were calculated from pre- and post-test weights. To estimate these values, it is necessary to consider sweating that doesn’t account for heat loss, and pre- and post-test weights of the work clothes and the cooling vest were measured in this study. However, because 1) the subjects weren’t dripping with perspiration and 2) it was difficult to distinguish the sweating that doesn’t account for heat loss from the condensation caused by the low temperature of the cooling vest, only pre- and post-test weights of subjects were used for calculations. ASHRAE Fundamentals Handbook 1997 was referred to. The method of calculation was shown as follows:

\[ E_{\text{total}} \] was defined as the total evaporative heat loss.

Fig. 3. Plan and experimental setup in a climatic chamber

Fig. 4. Scene of subjective experiment (standing and under step activity)

Table 2. Anthropometric data for subjects

<table>
<thead>
<tr>
<th>Number</th>
<th>Sex</th>
<th>Age [year]</th>
<th>Height [cm]</th>
<th>Weight [kg]</th>
<th>Body surface area* [m²]</th>
<th>Rohrer Index** [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Male</td>
<td>22.5</td>
<td>170.0</td>
<td>60.3</td>
<td>1.71</td>
<td>122.6</td>
</tr>
</tbody>
</table>

* Calculated by Takahira’s Equation: \[ A = 72.46 \ W^0.425 \times H^{0.725} \].  ** Rohrer Index = \( W/L' \times 10^3 \). ( ) standard deviation.
where

$$AD = \text{Du Bois' body surface area}$$

$$\text{AD} = 0.202 \cdot m^{0.425} \cdot h^{0.725}$$

$$m: \text{weight [kg]}$$

$$h: \text{height [m]}$$

$$E_{\text{res}}: \text{evaporative heat loss due to respiration}$$

$$E_{\text{es}}: \text{evaporative heat loss from the skin}$$

$$h_{fg}: \text{latent heat of vaporization of water}$$

$$= 2,430 \text{kJ/kg (at 30°C)}$$

$$m: \text{weight [kg]}$$

$$\theta: \text{time [s]}$$

Evaporative heat loss due to respiration $E_{\text{res}}$ and from skin $E_{\text{es}}$ were,

$$E_{\text{res}} = 0.0173 \cdot M \cdot (5.87 - P_a)$$

$$E_{\text{es}} = h' \cdot w_{\text{lin}} \cdot LR \cdot (P_{a, s} - P_a)$$

where

Table 3. Experimental conditions

<table>
<thead>
<tr>
<th>Experimental condition</th>
<th>Environmental condition</th>
<th>Clothing condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Operative temperature (°C)</td>
<td>Relative humidity (%)</td>
</tr>
<tr>
<td>Control</td>
<td>32.8 (0.19)</td>
<td>37 (1.2)</td>
</tr>
<tr>
<td>Cooling vest</td>
<td>33.1 (0.25)</td>
<td>37 (1.5)</td>
</tr>
<tr>
<td>to=28°C</td>
<td>28.5 (0.16)</td>
<td>35 (1.9)</td>
</tr>
</tbody>
</table>

( ) standard deviation. ○: wearing, ×: not wearing.

Fig. 5. Experimental procedure

from the human body.

$$E_{\text{total}} = E_{\text{es}} + E_{\text{res}} = \frac{h_{fg} \cdot dm}{A_D \cdot d\theta}$$

where

$$A_D: \text{Adipose tissue surface area}$$

$$A_D = 0.202 \cdot m^{0.425} \cdot h^{0.725}$$

$$m: \text{weight [kg]}$$

$$h: \text{height [m]}$$

$$E_{\text{es}}: \text{evaporative heat loss from the skin}$$

$$h_{fg}: \text{latent heat of vaporization of water}$$

$$= 2,430 \text{kJ/kg (at 30°C)}$$

$$m: \text{weight [kg]}$$

$$\theta: \text{time [s]}$$

Evaporative heat loss due to respiration $E_{\text{res}}$ and from skin $E_{\text{es}}$ were,

$$E_{\text{res}} = 0.0173 \cdot M \cdot (5.87 - P_a)$$

$$E_{\text{es}} = h' \cdot w_{\text{lin}} \cdot LR \cdot (P_{a, s} - P_a)$$

where

Fig. 6. Voting scale

$$LR: \text{Lewis ratio}$$

$$LR = \frac{h}{h' \cdot c} \cdot 1.65 \text{[°C/kPa]}$$

$$M: \text{metabolic rate [met]}$$

$$P_a: \text{water vapor pressure in ambient air [kPa]}$$

$$P_{a, s}: \text{saturated water vapor pressure at skin temperature [kPa]}$$

$$h': \text{sensible heat transfer coefficient overall including clothing}$$

$$R_t: \text{total thermal insulation}$$

$$= \text{total thermal insulation of work clothes}$$

$$0.23 \text{m}^2 \cdot \text{°C/W}$$

$$l_m: \text{moisture permeability index = 0.4}$$
Thermal Comfort Conditions by Wearing a Cooling Vest

The maximum possible evaporative heat loss $E_{\text{max}}$ was the value of $E_{\text{sk}}$ when skin wettedness $w$ was 1.0.

$$E_{\text{sk}} = w \cdot E_{\text{max}}$$  \hspace{1cm} (5)

Mean differences in the results among the experimental condition were tested for significance using the Fisher PLSD test. The data collected 20–100 min after entering the climate room were used for analysis of correlation.

RESULTS

Thermal sensation vote

The results of the whole body thermal sensation vote are shown in Fig. 7. There was significant difference between [Control] and [to =28°C] for the 20–100 min period ($p < 0.01$). By wearing the cooling vest, the thermal sensation vote was significantly closer to the neutral conditions * than [Control]. The average for [Cooling vest] for the 20–90 min period was 0.70, which was significantly closer to the thermal neutrality than that of [Cooling vest].

To estimate the cooling performance of the cooling vest, the PMV index was used in this study because 1) the thermal sensation vote with the cooling vest was closer to the neutral conditions than that without it and 2) it is an index that predicts the mean value of the thermal sensation votes of a large group of persons on the 7-point thermal sensation scale and it makes it easier to compare the predicted value with the actual subjective evaluations.

From the thermal sensation votes, cooling performance was estimated to be equal to a 5.3°C decrease with [Cooling vest] and a 7.7°C decrease with [to =28°C] of operative temperature, which were compared with [Control] (calculated by using PMV in condition of 0.88 clo and 1.4 met). Given that there was a difference of operative temperature in the chamber of 4.3°C between [Control] and [to =28°C], the cooling performance of cooling vest was estimated to be equal to a 3°C decrease of operative temperature.

As for the local thermal sensation vote at the chest that was cooled by the cooling vest, the average for the 20–90 min period was −0.99, which was significantly lower than that of [Control] of 1.44 and [to =28°C] of 0.18 ($p < 0.01$).

Comfort sensation vote

The results of the comfort sensation vote are shown in Fig. 8. The average for the 20–90 min period was −1.53 in [Control], −0.76 in [Cooling vest] and −0.14 in [to =28°C]. There was significant difference between [Control] and [to =28°C] for the 20–100 min period ($p < 0.01$). By wearing the cooling vest, the comfort sensation vote was significantly closer to comfortable state than [Control]. From comfort sensation votes, cooling performance was estimated in the same way as the thermal sensation vote and was found to be equal to a 3°C decrease of operative temperature (calculated by using DISC in condition of 0.88 clo and 1.4 met).

Regarding the local comfort sensation vote at the chest that was cooled by the cooling vest, the average for the 20–90 min period was −0.37, which was significantly more comfortable than that of [Cooling vest] ($p < 0.05$).

Sweating sensation vote

The results of the sweating sensation vote are shown in Fig. 9. The average for the 20–90 min period was 1.35 in [Control], 0.56 in [Cooling vest] and 0.13 in [to =28°C]. There was significant difference between [Control] and [to =28°C] for the 20–100 min period ($p < 0.01$). The sweating sensation vote of

*1: Thermal neutrality is defined as the condition in which the subject would prefer neither warmer nor cooler surroundings (P.O. Fanger: Thermal Comfort, McGraw-Hill Book Company, New York, 1972). In this paper, the neutral condition means the condition where the value of the thermal and comfort sensation vote is 0.
[Cooling vest] was significantly lower than [Control]. Wearing the cooling vest was useful to decrease the sweating sensation.

The thermal discomfort by wearing the cooling vest

The relationship between the thermal sensation vote at the chest that was cooled by the cooling vest and whole body comfort sensation vote is shown in Fig. 10. By wearing the cooling vest, the data of the whole body comfort sensation vote were widely distributed. Most of them were more uncomfortable side than the value that had been obtained by theoretical calculation (calculated by using PMV and DISC in condition of 0.88 clo and 1.4 met).

The relationship between the local thermal sensation and local comfort sensation at the chest is shown in Fig. 12. If the thermal sensation vote at the chest that was less than −1, the local comfort sensation was distributed on the more uncomfortable side than the value that had been obtained by theoretical calculation (calculated by using PMV and DISC in condition of 0.88 clo and 1.4 met).

Skin temperature

The results of skin temperature (the average value for the 20–90 min period) are shown in Fig. 13. By wearing the cooling vest, the skin temperature at the chest and back decreased by about 3°C.

Sweat rate, evaporative heat loss, skin wettedness

Results of the mass loss, \( E_{\text{total}} \), \( E_{\text{sak}} \), and \( w \) are shown in Table 4. The values of [Control] and [Cooling vest] were significantly higher than \([t_0=28°C]\) (\( p<0.01 \)). However, there was no significant difference between [Control] and [Cooling vest].

DISCUSSION

By wearing the cooling vest, the thermal and comfort sensation vote was significantly closer to the neutral conditions than the condition without the cooling vests. From the subjective votes, the effect of this cooling vest was estimated to be equal to a 3°C decrease of operative temperature. Regarding the relationship between the whole body thermal sensation vote and the whole body comfort sensation vote,
Thermal Comfort Conditions by Wearing a Cooling Vest

Experimental data agreed well with the value that had been obtained by theoretical calculation using PMV and DISC in condition of 0.88 clo and 1.4 met. These results mean that the whole body comfort sensation was greatly affected by whole body thermal sensation regardless of the cooling vest. Even if the local thermal sensation at the cooling parts was low, there were some cases where the whole body thermal sensation was higher. In these cases, subjects felt warm discomfort caused mainly by the whole body thermal sensation vote being deviated from thermal neutrality.

As for the thermal sensation vote at the cooling part of less than −1, the local comfort sensations were distributed on the more uncomfortable side than the value that had been obtained by theoretical calculation. It means that excess cooling might cause local thermal discomfort. It is important to prevent over-cooling down of the body when designing of comfortable cooling garment.

Total body sweat rate, evaporative heat loss and skin wettedness were calculated from pre- and post-test weights. There was no significant difference between when the cooling vest was worn and when it was not. However, in our previous study that was conducted by using the old type of cooling vest, we concluded the total sweat rate, $E_{sk}$ and skin wettedness with the cooling vest were lower than without it. Benzinger reported that sweating was regulated by the central temperature and that if skin temperature is under 33°C, the threshold of the central temperature for sweating becomes higher. The old type of cooling vest decreased the skin temperature at the chest to about 31°C. Because the old type of cooling vest lowered the local skin temperature, sweating might be depressed. On the other hand, the proposed new cooling vest in this study kept the temperature about 33°C, so there was no significant difference between when the cooling vest was worn and when it was not in the total sweat rate, $E_{sk}$ and skin wettedness. Sweating sensations were significantly closer to neutral conditions when the cooling vest was worn. This means that the cooling vest is useful to minimize the sweating sensation.

CONCLUSIONS

To evaluate the effect of a cooling garment and the local discomfort associated by wearing it, subjective experiments were conducted in a climatic chamber. A cooling vest was proposed in this paper with ice bags...
Experiments were performed under both wearing and non-wearing conditions of cooling vests in the chamber which was controlled at an operative temperature of 33°C, relative humidity of 37%, and still air. The results of the thermal comfort by wearing the cooling vest were as follows:

1) Thermal and comfort sensations were closer to the neutral conditions and this effect was estimated to be equal to a 3°C decrease of operative temperature.

2) The whole body comfort sensation was greatly affected by the whole body thermal sensation regardless of whether the cooling vest was worn or not.

3) For thermal sensation vote at cooling parts of less than −1, the local comfort sensations were distributed on the uncomfortable side. This means that excess of cooling might cause local thermal discomfort.

4) Skin temperature at cooling parts was kept about 33°C.

5) There was no significant difference in the total sweat rate, evaporative heat loss from the skin and skin wettedness between when the cooling vest was worn and when it was not.

6) Sweating sensations were significantly lower when the cooling vest was worn than it was not.

This study was supported in part by grants from the Descente and Ishimoto Memorial Foundation for the Promotion of Sports Science. The authors wish to express their appreciation to Ms. R. Takaki and Ms. Y. Yamamoto for their assistance during the experiments.

REFERENCES


7) Lee, U., and Tamura, T.: Distribution of Cold...
冷却ベスト着用時の熱的快適性

西原直枝、田邉新一*、羽山広文**、小松正佳***
　(お茶の水女子大学大学院人間文化研究科，*早稲田大学理工学部，
　**北海道大学大学院工学研究科，***NTT ファシリティーズ)

原稿受理平成 13 年 4 月 4 日；原稿受理平成 13 年 9 月 26 日

冷却衣服着用時の熱的快適性を評価するために被験者実験を行った。人工気候室は、作用温度 33.0℃、相対湿度 37%、静穏気流に制御した。本研究で開発した冷却衣服は水冷式で体幹部を冷却する構造であり、冷却部位の皮膚温を約 33℃に冷却した。全身発汗量、皮膚表面における潜熱損失量および皮膚ぬれ率については、冷却ベストの有無による有意な差が認められなかった。発汗感覚は冷却ベストの着用により有意に低下した。冷却ベストの着用により、温冷感および快不快感は非着用時に比べて有意に熱的中立状態に近づき、その冷却効果は作用温度約 3℃分であった。冷却ベスト着用時の全身快不快感は、非着用時の PMV および DISC による予測值と一致し、全身温冷感による影響が大きかった。また、局所温冷感が低くなりすぎると、局所不快感が生じた。これらの結果より、快適な冷却衣服の設計には、全身温冷感を効率よく下げて熱的中立状態に近づけるとともに、適度な冷却を行わないようにすることが重要であることが明らかとなった。

キーワード：温冷感，快適性，人工気候室，被験者実験，冷却衣服。