The use of thermography to measure the cooling performance of personal cooling systems

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ABSTRACT – REZUMAT

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The thermoregulatory system is responsible for maintaining body temperature. When the body temperature is between 36.1ºC and 37.1ºC, our body is in a state of thermal well-being, and there is an exchange of body heat between our body and the ambience. When exposed to high temperatures, the body's heat exchange with the environment decreases, causing an increase in internal temperature. This requires a mechanism to assist the thermoregulatory system in maintaining the body's thermal well-being. Cooling garments help the body's thermoregulatory system reduce heat accumulation during stress. Cooling vests are the most used type of cooling garment because the trunk region is the area that has the most temperature receptors that regulate the body's internal temperature. The variation of cooling vests in the market differs depending on the cooling mechanism used. Thermography is a non-intrusive method of measuring surface temperature. It is an excellent choice for qualitative and quantitative analysis without disrupting an object's performance. This study used thermography to evaluate the performance of five cooling vests with different cooling mechanisms. The results showed that data obtained from thermography analysis can be compared to a standardised method for assessing the performance of personal cooling systems.

Keywords: *cooling devices, infrared thermography, personal cooling systems, thermal manikin, thermal imaging*

Utilizarea termografiei pentru măsurarea performanței de răcire a sistemelor personale de răcire

Sistemul de termoreglare este responsabil pentru menținerea temperaturii corpului. Atunci când temperatura corpului este cuprinsă între 36,1ºC și 37,1ºC, corpul nostru se află într-o stare de bunăstare termică și există un schimb de căldură corporală între corpul nostru și mediul înconjurător. Atunci când este expus la temperaturi ridicate, schimbul de căldură al organismului cu mediul înconjurător scade, provocând o creștere a temperaturii interne. Acest lucru necesită un mecanism care să asiste sistemul de termoreglare în menținerea bunăstării termice a organismului. Îmbrăcămintea cu efect de răcire ajută sistemul de termoreglare al organismului să reducă acumularea de căldură în timpul stresului. Vestele de răcire sunt cel mai utilizat tip de îmbrăcăminte cu efect de răcire, deoarece regiunea trunchiului este zona care are mai mulți receptori de temperatură care reglează temperatura internă a corpului. Varietatea de veste de răcire de pe piață diferă în funcție de mecanismul de răcire utilizat. Termografia este o metodă neintruzivă de măsurare a temperaturii suprafeței. Este o alegere excelentă pentru analiza calitativă și cantitativă, fără a perturba performanța unui obiect. Acest studiu a utilizat termografia pentru a evalua performanța a cinci veste de răcire cu diferite mecanisme de răcire. Rezultatele au arătat că datele obținute din analiza termografică pot fi comparate cu o metodă standardizată de evaluare a performanței sistemelor personale de răcire.

Cuvinte-cheie: *dispozitive de răcire, termografie cu infraroșu, sisteme personale de răcire, manechin termic, imagistică termică*

INTRODUCTION

Clothing plays a crucial role in regulating body temperature based on the environment and physical activity, according to ISO 11079:2007 [1]. In a moderate thermal environment, the body's thermoregulatory system maintains balance by regulating skin temperature, internal temperature, and the sweating system. The standard specifies two stress situations: stress due to cold and stress due to heat. To prevent heat stress, it is essential to wear appropriate clothing or use an external mechanism to help retain or dissipate body heat.

The clothes we wear impact our body's ability to regulate temperature. Clothes with thermoregulatory properties can help maintain a stable body temperature for the wearer. In cold weather situations, it's important for clothing to have good insulation to prevent heat loss from the body. In hot weather situations, the clothing should be breathable and able to transmit moisture to keep the wearer cool. Personal cooling systems can help regulate body temperature by dissipating body heat in stressful situations caused by excessive heat.

Cooling vests

Cooling garments are intelligent clothing designed to adapt to the environment using a thermal mechanism to cool when the user's body temperature increases. These garments are an excellent example of how technology can enhance comfort and well-being. Different types of personal cooling systems are available in the market, but vests are the most used due to their ergonomic design and ease of use [2–4]. Cooling vests differ in that the cooling mechanism dissipates heat [5]. The most used cooling vests are liquid cooling vests, air circulation cooling vests, phase change material (PCM's) cooling vests, and evaporation cooling vests.

The effectiveness of personal cooling systems is evaluated using the ASTM F2371:2016 [6] standard, which measures cooling performance and duration using a thermal manikin. Additionally, thermography can determine the heat dissipation of a thermal manikin wearing a cooling vest, which complements the standard.

Infrared thermography

The electromagnetic spectrum is divided into different areas, known as bands, with varying wavelengths. These bands are characterised by the methods used to emit and detect electromagnetic radiation. The infrared region spans from 0.8 μm to 1000 μm and is divided into four segments: near-infrared (NIR), short-wavelength infrared (SWIR), mid-wavelength infrared (MWIR), and long-wavelength infrared (LWIR) [7]. The surface temperature of an object can be determined with a thermographic camera that detects the radiation in the wavelength range between 0.8–14 μm when the object's temperature is above 0ºC [8]. Thermal imaging cameras use the heat emitted by an object to create a thermographic image, which displays the surface temperature distribution through colour differences. The intensity of the image or colour corresponds with the amount of infrared radiation received from the object [9]. The radiation in the thermogram reflects the energy emitted, transmitted, and reflected from the object and its surrounding environment [10].

Over the last two decades, the number of scientific publications related to infrared thermography in chemistry, engineering, and materials science has increased significantly. This measurement technique is highly advantageous as it enables the calculation of an object's surface temperature without any physical contact, making it a non-invasive and non-destructive process [11]. The amount of radiation received, as well as other parameters, determines the object's temperature.

MATERIALS AND METHODS

Method

This research involves using a thermal manikin and an infrared thermal camera to study the effectiveness of five different cooling vests. The manikin, which simulates the human body, is placed inside a climatic chamber under controlled environmental conditions and is outfitted with various cooling vests. The goal is to determine whether valuable data can be obtained through infrared analysis to assess the performance of different cooling vests and to compare this data with results obtained using a standardised method according to ASTM F2371-16 [12].

Equipment

Thermal manikin

The thermal manikin is a Newton's thermal manikin from Thermetrics LLC. Dimensions of the manikin correspond to an M size of a man. This manikin is made of plastic and simulates the body of an adult human of a height of 1.8 meters, with movable arms and legs. This manikin has 34 temperature sensors in the body, each with an independently controlled heating system capable of maintaining a constant temperature.

Climatic chamber

The thermal manikin is placed inside a climatic chamber model Walk-In that measures 9 meters in length, 2.8 meters in width, and 2.15 meters in height. This climatic chamber can be used at temperatures ranging from –30.0ºC to +60.0ºC, with a humidity range of up to 90% and an airspeed of 10 m/s.

Thermal Imaging Camera

With a thermographic camera, it is possible to measure the surface temperature of clothing. For this study, a Flir SC620 Western thermal infrared camera, a high-quality camera commonly used for research, has been used. Thermographic images will be treated with the software associated with the camera FLIR Tools, an easy program to analyse thermal images.

Characteristics of this camera are:

- Working temperature: –40ºC to +500ºC.
- Spectral response: 7.5–13.0 um
- Thermal sensitivity: 0.065ºC at 30ºC.
- IR Resolution: 640 × 480
- Accuracy: ± 2.0ºC.

Experimental design

Experimental conditions

Environmental conditions used are 35.0ºC ± 0.5ºC of temperature, 40 ± 5% humidity, and an airspeed of 0.4 ± 0.1 m/s. The manikin is standing and in a static position. The body temperature of the manikin is 35.0ºC ± 0.5ºC, and it wears, under the vests, a sweat suit to maintain 100% humidity throughout the body.

Testing samples

Testing samples are the most representative cooling vests on the market. Table 1 presents the testing samples, the cooling mechanism, and the accessories used with each vest.

According to the measurements of the thermal manikin used, the appropriate size for the vests is M.

Technical procedure

Before dressing the manikin, it is necessary to prepare each vest. Table 2 presents the preparation of each testing sample.

The manikin is placed inside the climatic chamber under environmental testing conditions. It is wearing the sweating system to simulate the perspiration system of a person in the body of the manikin, according

Table 1

MAIN CHARACTERISTICS OF THE TESTED COOLING VESTS		
Cooling vests	**Cooling mechanisms**	**Accessories**
#1	Liquid circulation	Pump, cooling system, battery
#2	Air ventilation	Battery
#3	Phase change material (36ºC)	PCM's packs
#4	Evaporation	-
#5	Vortex tube	Compressed air generator

Table 2

PROCEDURE FOLLOWED TO PREPARE THE SAMPLES TO BE TESTED	
Cooling vests	**Preparation**
#1	Fill the reservoir with water. To charge the battery
#2	To charge the battery
#3	Place in a fridge at a temperature lower than 21.0ºC
#4	To immerse in cold water and drain
#5	To use a compressed air generator

to the ASTM F2370:2022 [13]. The manikin's sweating system includes a water reservoir, a pump that supplies water, a second skin suit, and plastic tubes that conduct the water from the reservoir to the manikin. The second skin suit is wet, with 100% humidity. The body temperature of the manikin is programmed at 35.0ºC with the software associated with the manikin.

Effective power test

A preliminary test measures the heat removal rate (effective power) according to the ASTM F2371-16 standard. Environmental conditions used are 35.0ºC ± 0.5ºC of temperature, 40 ± 5% humidity, and an airspeed of 0.4 ± 0.1 m/s. The manikin is standing and in a static position. The body temperature of the manikin is 35.0ºC ± 0.5ºC, and it wears a sweat suit to maintain 100% humidity throughout the body. The standard test consists of two parts. In the first part, the PCS Baseline test is performed with the manikin wearing the vest but with the cooling mechanism working. During this test phase, we measure the energy needed for the sweating manikin to maintain a body temperature of 35.0ºC. Once the energy stabilises, we conduct the PCS Performance test to determine the energy required by the sweating manikin to maintain a body temperature of 35.0ºC while wearing the vest with the cooling system activated. The effective power is calculated as the difference in energy between the PCS Baseline test and the PCS Performance test.

Infrared analysis with a thermal camera

In this part of the study, the manikin is wearing a cooling vest for testing, but the cooling system of each vest is not working yet. Under stable testing conditions, the test reaches steady-state conditions with the following parameters: climatic chamber at 35.0ºC ± 0.5ºC, 40 ± 5% humidity, 0.4 ± 0.1 m/s wind speed, and the manikin's body temperature at 35.0ºC ± 0.1ºC. These conditions are maintained for 30 minutes. Afterwards, the cooling system is activated, and a thermal image is captured. Thermal images are taken from 0.5 m from the manikin while the cooling system is running. For the test of cooling vest #4, the manikin wears the dry cooling vest, and after reaching steady-state conditions, the vest is soaked in cold water, drained, and worn by the manikin before the thermal image is taken. For the cooling vest #5 test, the manikin wears the cooling vest without the PCM. After arriving at steady state conditions, the PCM packages are inserted into the vest before the thermal image is taken. Before the test of the cooling vests, a test is conducted under the same conditions with the manikin in a nude state.

The thermal images are analysed using the FLIR Tools software. The software requires input of the parameters outlined in table 3 to investigate the thermal picture.

Table 3

VALUES USED IN THE SOFTWARE FLIR TOOLS	
Parameters	**Input values**
Distance	0.5 meters
Environmental temperature	35.0ºC
Reflected temperature	30.0ºC
Emissivity	0.9
Temperature scale	34.0–40.0ºC

RESULTS

Results according to ASTM F2371-16 are shown in table 4.

Table 4

EFFECTIVE POWER OF THE DIFFERENT COOLING VESTS TESTED	
Cooling vests	**Effective power (W/m^2)**
#1	175
#2	230
#3	171
#4	15
#5	8

Figures 1–6 present the thermal images captured during the second part of the study.

Table 5 presents the average surface temperature of the different cooling vests tested and taken from the software.

Fig. 1. Nude manikin

Fig. 2. Manikin with vest #1

Fig. 3. Manikin with vest #2

Fig. 4. Manikin with vest #3

Fig. 5. Manikin with vest #4

Fig. 6. Manikin with vest #5

Table 5

SURFACE TEMPERATURE OF THE COOLING VESTS AFTER THE TEST

Cooling vests	Surface temperature (ºC)
Nude manikin	41
#1	33
#2	31
#3	33
#4	31 (upper part) / 36 (lower part) / 34 (complete vest)
#5	38

DISCUSSION OF RESULTS

When the effective power ranges from 165 to 540 W/m^2, only vests #1, #2, and #3 can provide cooling, as indicated in Table 4. When arranging the data based on effective cooling power from highest to lowest, the air ventilation vest (cooling vest #2) exhibits the highest cooling capacity, followed closely by the liquid cooling vest (cooling vest #1) and the PCM vest (cooling vest #3) with similar cooling power. The vortex tube vest (cooling vest #5) demonstrates the lowest effective cooling power.

A thermal camera captures and converts the temperature of an object into a thermal image, allowing us to obtain qualitative and quantitative information about its surface temperature. In a thermographic image, the darker the blue-black colour, the lower the surface temperature of the vest, which indicates that more cooling is being provided to the manikin. Our study's temperature scale indicates that white-yellow in the picture denotes a temperature close to 40ºC, and blue-black colour denotes the lowest temperature, close to 34ºC. Figure 1 represents the manikin without any kind of cooling vest. In this figure, the manikin is white-yellow, which means that it is the image of the manikin with the highest temperature, with an average surface temperature of 41ºC, according to table 4. Upon comparing the thermal images of the manikin wearing different cooling vests from figure 2 to figure 6, it is observed that the thermal image of the manikin wearing vest #5, in figure 6, displays colours of the vest that closely resemble the picture of the nude manikin with an average surface temperature of 38ºC. This implies that vest #5 has the lowest cooling performance among all tested cooling vests, as confirmed by both the standard test and the thermographic analysis. When analysing figure 5, it is evident that cooling vest #4 exhibits different colours in its upper and lower parts. The upper part appears in blue-black with a surface temperature of 31ºC, while the lower part is in red-orange colours, with a surface temperature of 36ºC. This indicates that the average surface temperature of this cooling vest is 34 ºC. The disparity in colour between the upper and lower parts of the vest suggests that the upper part provides more excellent cooling to the manikin than the lower part. This is because the cooling mechanism of vest #4 involves pre-treating the upper part with water, which it then absorbs and retains to provide greater cooling power. The effective power results are low at 15 W/m^2, as this is an average of the areas of the manikin covered by the vests. This includes both wet and dry regions of the vests. Upon examining figures 2, 3, and 4, it's evident

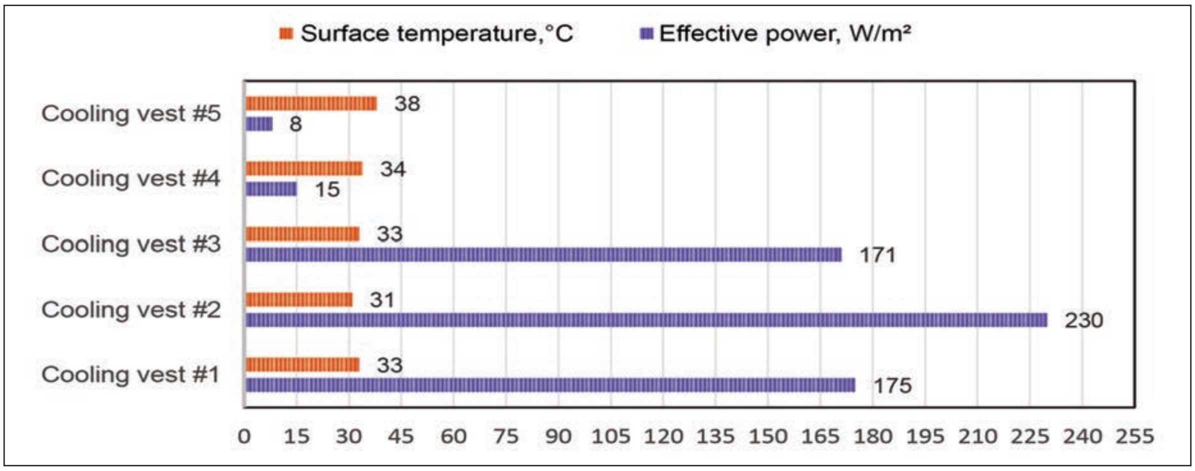

Fig. 7. Graphical comparison between the effective power and the surface temperature of the cooling vests tested

that the colour distribution is similar among all three vests. Vest #1 has a surface temperature of 33ºC, vest #2 has a temperature of 31ºC, and vest #3 has a temperature of 33ºC. When using a thermal camera, it is possible to measure the surface temperature of materials with an accuracy of 2°C, according to the camera's specifications.

Figure 7 compares the cooling power and surface temperature of the various tested cooling vests. Looking at figure 7, when arranging the data based on surface temperature, from lowest to highest, the air ventilation vest (cooling vest #2) exhibits the lowest temperature, followed closely by the liquid cooling vest (cooling vest #1) and the PCM vest (cooling vest #3) with the same surface temperature. The vortex tube vest (cooling vest #5) presents the lowest effective power. This finding aligns with the cooling power of each vest, which can be seen in figure 7, that the air-cooling vest has the highest cooling power, followed by the liquid cooling vest and PCM cooling vest with a similar effective power. Again, the vortex tube cooling vest, cooling vest #5, presents the worst performance, with the highest surface temperature.

CONCLUSIONS

The study aimed to use a thermal infrared camera to compare the cooling capabilities of five different cooling vests. To achieve this, a testing protocol using a thermal manikin with a thermographic camera was performed, and the results were compared with a standard testing method according to ASTM F2371 to verify that both testing methods can be complementary. In this study, the thermal infrared analysis and the standard test demonstrated that the air vest provided the highest cooling performance, and the vest that used the cooling mechanism of a vortex tube tested demonstrated the lowest cooling performance. PCM's cooling vest and the liquid circulation cooling vest exhibited similar behaviour in the thermal infrared analysis and the standard test. If we only consider the wet area, the evaporation vest has demonstrated good cooling performance with the thermal infrared analysis. However, with the standard test, the effective power is deficient because this test finds all the segments of the manikin covered by the vest, not only the wet areas.

The comparison results suggest that a thermal imaging camera can be an effective and straightforward method to evaluate the cooling performance of personal cooling systems. This approach can complement the standard ASTM method F2371. However, it's important to note that this study has limitations that should be considered in the future. The results and conclusions about cooling performance are based on comparing five cooling vests with different materials and designs. Therefore, future studies should aim to include an extended range of cooling vests available in the market.

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