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Comfort and performance improvement through the use of cooling vests for construction workers

Use of cooling vests for construction workers

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Abstract

Purpose – The purpose of this study is to analyze the question “In what order of magnitude does the comfort and performance improvement lie with the use of a cooling vest for construction workers?”.

Design/methodology/approach – The use of personal cooling systems, in the form of cooling vests, is not only intended to reduce the heat load, in order to prevent disruption of the thermoregulation system of the body, but also to improve work performance. A calculation study was carried out on the basis of four validated mathematical models, namely a cooling vest model, a thermophysiological human model, a dynamic thermal sensation model and a performance loss model for construction workers.

Findings – The use of a cooling vest has a significant beneficial effect on the thermal sensation and the loss of performance, depending on the thermal load on the body.

Research limitations/implications – Each cooling vest can be characterized on the basis of the maximum cooling power (P_{max} ; in W/m^2), the cooling capacity (A_{uc} ; in Wh/m^2) and the time (t_c ; in minutes) after which the cooling power is negligible. In order to objectively compare cooling vests, a (preferably International and/or European) standard/guideline must be compiled to determine the cooling power and the cooling capacity of cooling vests.

Practical implications – It is recommended to implement the use of cooling vests in the construction process so that employees can use them if necessary or desired.

Social implications – Climate change, resulting in global warming, is one of the biggest problems of present times. Rising outdoor temperatures will continue in the 21st century, with a greater frequency and duration of heat waves. Some regions of the world are more affected than others. Europe is one of the regions of the world where rising global temperatures will adversely affect public health, especially that of the labor force, resulting in a decline in labor productivity. It will be clear that in many situations air conditioning is not an option because it does not provide sufficient cooling or it is a very expensive investment; for example, in the situation of construction work. In such a situation, personal cooling systems, such as cooling vests, can be an efficient and financially attractive solution to the problem of discomfort and heat stress.

Originality/value – The value of the study lies in the link between four validated mathematical models, namely a cooling vest model, a thermophysiological human model, a dynamic thermal sensation model and a performance loss model for construction workers.

Keywords Mathematical modelling, Cooling vest, Dynamic thermal sensation, Human performance, Thermal physiology

Paper type Technical paper

Introduction

Climate change, resulting in global warming, is one of the biggest problems of our time. Rising outdoor temperatures will continue in the 21st century, with a greater frequency and



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Conflict of interest: Paul Roelofsen and Kaspar Jansen declare that they have no conflict of interest.

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duration of heat waves. Some regions of the world are more affected than others. Europe is one of the regions of the world where rising global temperatures will adversely affect public health; especially that of the labor force, resulting in a decline in labor productivity. It will be clear that in many situations air conditioning is not an option because it does not provide sufficient cooling or it is a very expensive investment; for example, in the situation of construction work. In such a situation, personal cooling systems, such as cooling vests, can be an efficient and financially attractive solution to the problem of discomfort and heat stress. The use of personal cooling systems, in the form of cooling vests, is not only intended to reduce the heat load, in order to prevent disruption of the thermoregulation system of the body, but also to improve work performance. The question is “In what order of magnitude does the comfort and performance improvement lie with the use of a cooling vest for construction workers?”. To answer this question, a calculation study was carried out on the basis of four validated mathematical models, namely a cooling vest model linked to a thermophysiological human model, a dynamic thermal sensation model and a performance loss model for construction workers. The starting points, the calculation results as well as the findings are set out in this paper.

Cooling power and cooling capacity cooling vest

As yet there is no standard or guideline that states how the cooling power, the cooling capacity and the maximum cooling time of a cooling vest should be determined. In practice, it is therefore difficult to objectively compare cooling vests and to make an optimal choice for a specific type of work and working environment.

However, each cooling vest can be characterized on the basis of the maximum cooling power ($P_{\max}$; in W/m^2), the cooling capacity (A_{uc} ; in Wh/m^2) and the time (t_{c} ; in minutes) after which the cooling power is negligible, namely 20 W/m^2 . The cooling capacity of a cooling vest is then approximately 10% of the amount of heat produced per m^2 -body surface, with a metabolism of 58.2 W/m^2 (a sitting activity; the surface of the trunk is approximately 30% of the total body surface). Ergo, below this value it can be assumed that a cooling vest provides the body insufficient cooling (Figure 1) (Ciuha *et al.*, 2020).

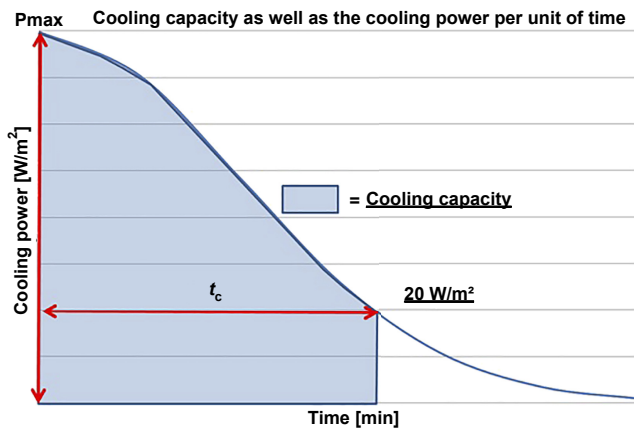
Cooling vests

In principle, cooling vests can be classified as follows (Ciuha *et al.*, 2020):

- (1) Active cooling vests ($P_{\max} = 44\text{--}60 \text{ W/m}^2$, $t_{\text{c}} = 151 - \infty \text{ min.}$, $A_{\text{uc}} = 118\text{--}331 \text{ Wh/m}^2$)
 - Air cooling vests (e.g. Teijin)
 - Liquid-perfused cooling vests (e.g. battery heated clothing)
- (2) Passive cooling vests ($P_{\max} = 6\text{--}92 \text{ W/m}^2$, $t_{\text{c}} = 21\text{--}210 \text{ min.}$, $A_{\text{uc}} = 7\text{--}164 \text{ Wh/m}^2$)
 - Evaporative cooling vests (e.g. Inuteq International B.V.)
 - Vests with phase change material (PCM) and gel inserts (e.g. StaCool Industries).
- (3) Hybrid cooling vests ($P_{\max} = 57\text{--}75 \text{ W/m}^2$, $t_{\text{c}} = 194\text{--}226 \text{ min.}$, $A_{\text{uc}} = 127\text{--}146 \text{ Wh/m}^2$) (e.g. Inuteq International B.V.)

Ad 1 a. Air cooling vests

Air-cooled vests provide a constant flow of (cooled) ambient air or (cooled) compressed air into the micro space between the torso and vest, promoting heat dissipation through evaporation of sweat and convection around the torso of the body. As a result, the cooling



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Figure 1.
Cooling vest model: cooling capacity and cooling power of a cooling vest

efficiency depends, among other things, on the moisture of the skin and the air that is drawn in. Actively cooled vests allow only limited freedom of movement when connected to a device that supplies air. There is no such limitation with fans in a cooling vest that are powered by a battery.

Ad 1 b. Liquid-perfused cooling vests

In a liquid-cooled vest, a cooled liquid, usually water, circulates through small tubes, close to the skin, through the fabric of the vest. The liquid is pumped from a container, which may or may not be contained in the vest.

Ad 2 a. Evaporative cooling vests

With this type of a cooling vest, the outside is moistened. The body is then cooled by natural evaporation. The cooling vests perform best in an environment with low humidity. The air flow around the body determines the degree of cooling. It is therefore important that no other clothing is worn over the cooling vest.

Ad 2 b. Vests with PCM and gel inserts

In this type of vest there is room for exchangeable cooling elements, consisting of a so-called PCM or a gel. The elements extract heat from the body through phase change (melting) and conduction. This type of vest is suitable in warm and humid environments and to be worn under protective clothing; for example, in melting, welding or extinguishing work.

Ad 3. Hybrid cooling vests

Hybrid cooling vests combine two or more of the cooling concepts described above.

Thermophysiological human model of Stolwijk

For the calculation study, use was made of the mathematical thermophysiological human model of Stolwijk, developed on behalf of National Aeronautics and Space Administration (NASA). The Stolwijk model consists of six segments (namely the head, the trunk, the arms, the hands, the legs and the feet), each with four layers (namely the core, the muscles, the fat

layer and the skin layer). The head is represented as a sphere. The other segments are represented as cylinders. Each cylinder consists of the aforementioned four layers. An extra element is the blood, which transfers the heat via convection from and to the layers and from and to the segments themselves. For the parts that are in contact with the environment, the mathematical relationships apply for heat loss via radiation, convection and evaporation as well as the influence of the clothing. For each component, dynamic energy balances are drawn up, the metabolism is calculated and the blood flow is determined. The cardiac output, heat production and heat losses through evaporation, etc. are obtained by summing them over the segments. The skin blood flow and average skin temperature are calculated by summing the skin blood flow and the skin temperature of each segment, weighted by skin area. Likewise, the average body temperature is obtained from the average of all segment temperatures with their specific heat capacity as a weighting factor. The total heat storage for the whole body is obtained by summing the individual storage per segment. The model can be used to simulate thermophysiology, thermal perception and performance loss under dynamic conditions. For detailed information about the model, please refer to the literature (Roelofsens, 2016). The cooling power of a cooling vest, as shown graphically in Figure 1, is built into the Stolwijk model.

ASHRAE 7-point scale

To quantify the thermal sensation, the 7-point psycho-physical ASHRAE scale is used:

Hot	3
Warm	2
Slightly warm	1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

In general, a thermal sensation of -0.5 to 0.5 is used for the comfort zone, in accordance with category II in NEN-EN-15251 (NEN-EN-15251, 2007). See the green-shaded area in the figures.

Dynamic thermal sensation (DTS)

In the Stolwijk model, an equation is included to predict the thermal sensation under dynamic conditions, the so-called dynamic thermal sensation (DTS), originally developed by Fiala (1998), based on the simulated core temperature and the mean skin temperature. The equation for predicting the thermal sensation is based on a large number of independent experiments. Using a multivariate analysis, it was found that the mean skin temperature, the core temperature and the rate at which the mean skin temperature changes are the parameters affecting the thermal sensation under dynamic conditions. The thermal sensation was assessed on the basis of the ASHRAE 7-point scale. The DTS is calculated as follows:

$$DTS = 3 * \tanh(f_{sk} + \varnothing + \Psi) \quad [-]$$

where

$f_{sk} = a_1 * \Delta T_{sk,m}$	$[-]$; for $\Delta T_{sk,m} > 0$
$f_{sk} = a_2 * \Delta T_{sk,m}$	$[-]$; for $\Delta T_{sk,m} < 0$
$\Delta T_{sk,m} = (T_{mean\ skin} - 34.4)$	$[K]$
$\varnothing = b_1 * \exp(b_2 / (\Delta T_{hy} + 0.4) + b_3 / (\Delta T_{sk,m} - 4))$	$[-]$; $\varnothing = 0$ when $\Delta T_{hy} + 0.4 \leq 0$ or $\Delta T_{sk,m} - 4 \geq 0$
$\Delta T_{hy} = (T_{hypothalamic} - 37.0)$	$[K]$
$\Psi = (\tau_- + \tau_+) / (1 + \varnothing)$	$[-]$
$\tau_- = c_1 * dT_{sk,m} / dt$	$[-]$; for $dT_{sk,m} / dt < 0$
$\tau_+ = c_2 * (dT_{sk,m} / dt)_{max} * \exp(-c_3 * \Delta t)$	$[-]$; for $dT_{sk,m} / dt > 0$
$\Delta t = t - t_0$	$[h]$
$t_0 = \text{time of occurrence of highest rate}$	$[h]$
$dT_{sk,m} / dt$	
$a1$ to $c3$	regression coefficients obtained through multivariate analysis, specific for the Stolwijk model

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Performance loss as a function of the thermal sensation

Mohamed and Korb (2002) found relationships for the performance loss of light, medium-heavy and heavy construction work as a function of the thermal sensation, based on 200 datasets of research conducted by several other scientists. The relationships derived by them were later tested in practice and slightly modified (Mohamed and Korb, 2003), namely,

$$P_{light} = 99.91 - 0.796 * PMV - 1.843 * PMV^2$$

$$P_{medium} = 99.81 - 1.3 * PMV - 2.27 * PMV^2$$

$$P_{heavy} = 83.952 + 15.09 * PMV - 4.76 * PMV^2$$

herein is,

P_{light} = the performance loss of light construction work (Metabolism < 130 W/m²) [%]

P_{medium} = the performance loss of medium-heavy work (130 ≤ Metabolism ≤ 190 W/m²) [%]

P_{heavy} = the performance loss of heavy work (190 < Metabolism ≤ 350 W/m²) [%]

PMV = predicted mean vote, according to (NEN)-EN-ISO-7730 [7] [-].

Experiments showed that the predicted DTS and the PMV were in agreement (Fiala, 1998), so in this study the DTS is used instead of the PMV.

Variant calculations

To get an impression of the comfort and performance improvement through the use of a cooling vest for construction workers, a few variant calculations were performed using the aforementioned human model. The following principles have been used for this:

Activity

Sedentary activity	70 W/m ²
Light activity	110 W/m ² (e.g. wallpapering and painting)
Medium-heavy activity	170 W/m ² (e.g. tiling and bricklaying)
Heavy activity	230 W/m ² (e.g. dig sand or use wheelbarrow)

Intrinsic clothing value	0.5 clo.
A cooling vest with PCM and gel inserts ($P_{\max} = 65 \text{ W/m}^2$, $t_c = 210 \text{ min}$, $A_{uc} = 164 \text{ Wh/m}^2$)	

Environmental condition

Air temperature	27 °C
Mean radiant temperature	27 °C
Relative humidity	50%
Air velocity	0.3 m/s

The scenario considered concerns an hour of sedentary activity, then an hour of light/medium-heavy or heavy activity, half an hour of sedentary activity, one hour of light/medium-heavy or heavy activity and finally another half hour of sedentary activity. The first situation concerns activities, varying from light, medium-heavy and heavy, without the use of a cooling vest (Figures 2, 4, and 6). In the second situation (Figures 3, 5, and 7), it is assumed that a cooling vest will be worn after 150 min at the start of the activity. It can clearly be seen to what extent the thermal sensation and the loss of performance, as a result of the thermal load, are influenced by the cooling with a cooling vest.

The calculation results are shown graphically in Figures 2–7.

The improvement of the thermal sensation (ΔTSV) as well as the reduction in performance loss ($\Delta Perf$), after 210 min, due to the use of a cooling vest, depending on the activity, are shown in Table 1.

In order to gain an impression of the influence of the cooling power curve on the thermal sensation and the loss of performance, two additional variant calculations were performed for light activity. The cooling capacity of the cooling vests are the same (i.e. 90 Wh/m^2), but the cooling power per time unit differs from each other (see Figure 8).

The calculation results are shown graphically in Figures 9 and 10.

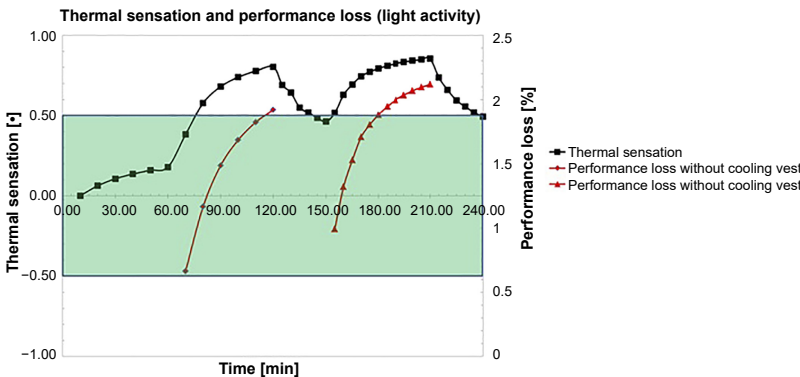


Figure 2.
Thermal sensation and
performance loss.
Without a cooling vest.
Light activity

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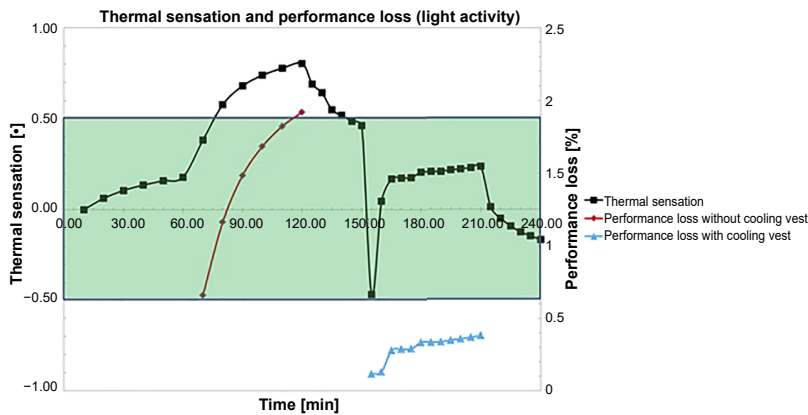


Figure 3. Thermal sensation and performance loss. Cooling vest donned after 150 min. Light activity

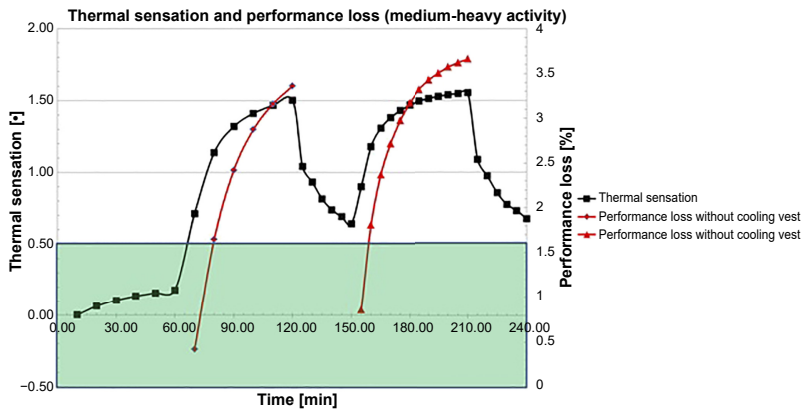


Figure 4. Thermal sensation and performance loss. Without a cooling vest. Medium-heavy activity

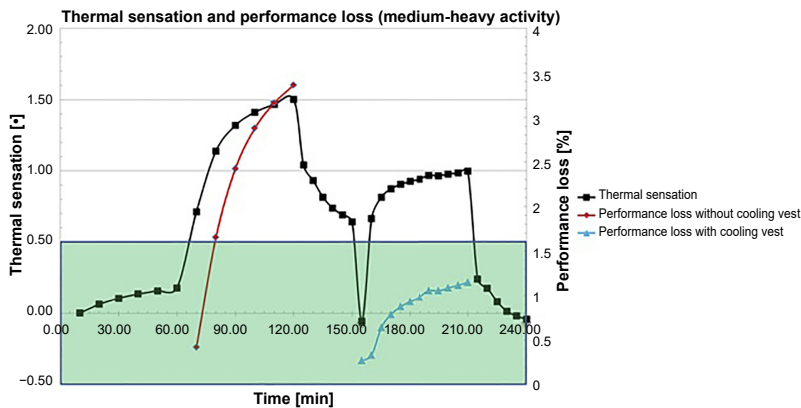


Figure 5. Thermal sensation and performance loss. Cooling vest donned after 150 min. Medium-heavy activity

Figure 6.
Thermal sensation and
performance loss.
Without a cooling vest.
Heavy activity

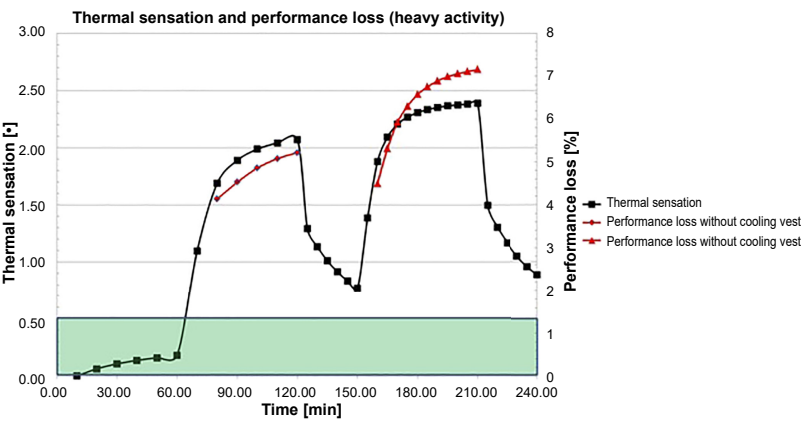


Figure 7.
Thermal sensation and
performance loss.
Cooling vest donned
after 150 min. Heavy
activity

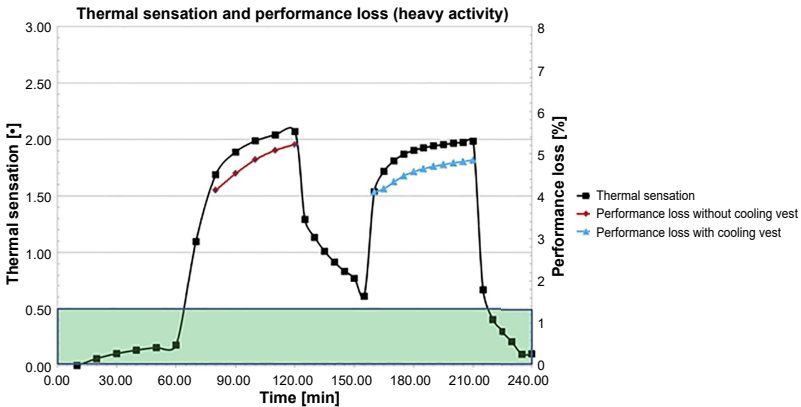


Table 1.
 Δ TSV and Δ Perf,
through the use of a
cooling vest

Activities	Δ TSV [°]	Δ Perf [%]
Light	0.61	1.7
Medium-heavy	0.56	2.5
Heavy	0.40	2.3

Conclusion and advice

Based on the foregoing consideration, the following are concluded and recommended:

- (1) Each cooling vest can be characterized on the basis of the maximum cooling power (P_{max} ; in W/m^2), the cooling capacity (A_{uc} ; in Wh/m^2) and the time (t_c ; in minutes) after which the cooling power is negligible
- (2) In order to objectively compare cooling vests, a (preferably International and/or European) standard/guideline must be compiled to determine the cooling power and the cooling capacity of cooling vests

- (3) The use of a cooling vest has a significant beneficial effect on the thermal sensation and the loss of performance, depending on the thermal load on the body
- (4) The performance improvement through the use of a cooling vest is partly dependent on the metabolism

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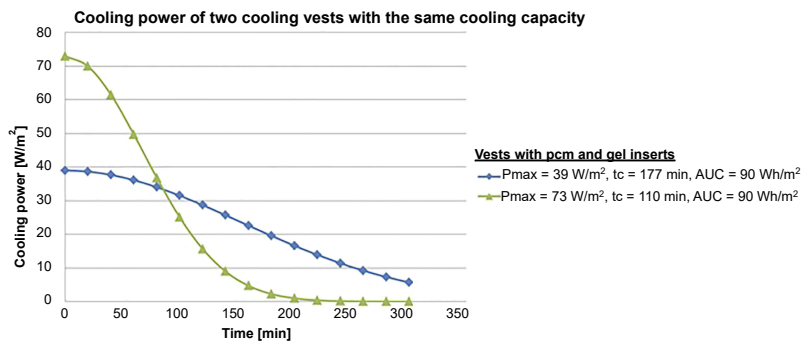


Figure 8.
The measured cooling power of two cooling vests with the same cooling capacity

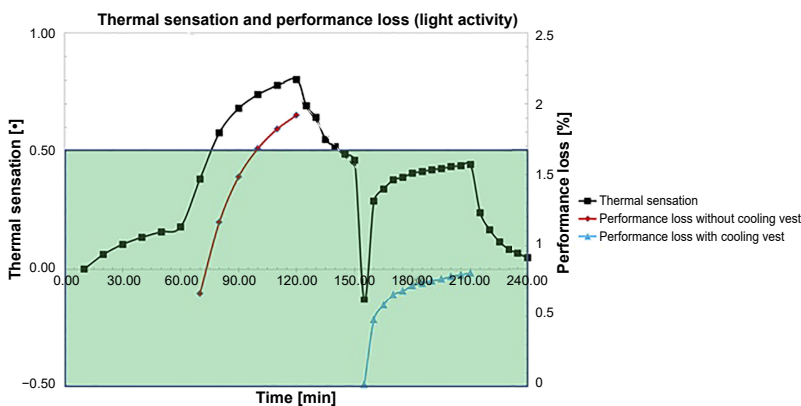


Figure 9.
Thermal sensation and performance loss. Cooling vest donned after 150 min; $P_{\max} = 39 \text{ W/m}^2$, $t_c = 177 \text{ min}$, $Auc = 90 \text{ Wh/m}^2$. Light activity

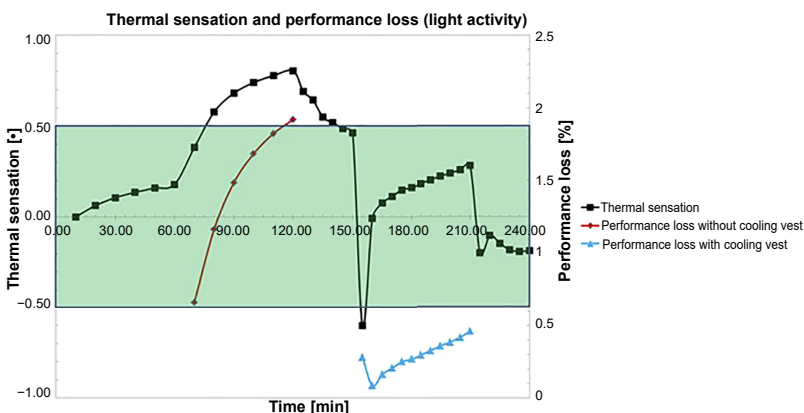


Figure 10.
Thermal sensation and performance loss. Cooling vest donned after 150 min; $P_{\max} = 73 \text{ W/m}^2$, $t_c = 110 \text{ min}$, $Auc = 90 \text{ Wh/m}^2$. Light activity

- (5) The performance improvement through the use of a cooling vest is relatively the greatest in medium-heavy activities
- (6) In situations where air conditioning is not an option, the use of cooling vests is an efficient and financially attractive solution to the heat stress of construction workers, as,
 - the investment is small
 - it increases the allowable exposure time under warm conditions
 - it improves physical and cognitive performance
 - it, after exertion and strain, promotes comfort and recovery and reduces fatigue
- (7) It is recommended to implement the use of cooling vests in the construction process so that employees can use them if necessary or desired.

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