

PREDICTIVE MODELS TO ASSESS THERMAL AND EVAPORATIVE RESISTANCES OF INNOVATIVE THERMAL PROTECTIVE CLOTHING

Abstract: Protection and comfort are critical considerations in the development of thermal protective clothing (TPC), however, achieving optimal performance while maintaining worker comfort remains a significant challenge. For TPC, thermal and evaporative resistance are key properties closely linked to comfort perception and typically assessed using specialized and expensive equipment, such as thermal manikins. Straightforward method to quantify comfort is still needed. In this study, predictive models of varying complexity were developed to address this gap. These models range from simple applications of electrical circuit theorems to numerical analyses employing bi- and tri-dimensional approaches. A case study featuring an original firefighting vest will be presented, highlighting the effect of different properties, dimensions, and configurations of the integrated materials on the overall properties. The circuit theorem provided reasonably accurate estimations of the vest's properties when heat and mass transfer were predominantly unidirectional. More advanced numerical analyses are required to account for bi- and tri-dimensional effects.

Keywords: thermal protective clothing, predictive models, thermal resistance, evaporative resistance.

1. INTRODUCTION

Over the years, numerous innovative solutions have been explored for integration into thermal protective clothing to enhance body protection. These include wearable sensors and active heating/cooling systems, presenting significant challenges for manufacturers and developers to achieve optimal performance while maintaining wearer comfort. In laboratory settings, even basic tests, such as evaluating the impact of different fibre types in a prototype, require a series of resource-intensive and laborious steps: sourcing or producing fibres, textile manufacturing, and assembling the new prototype. While numerical analysis offers an alternative, it is often time-consuming and demands substantial computational resources. Moreover, despite the widespread use of experimental and numerical approaches to assess the thermal performance of protective clothing, a simple and efficient method for quantifying comfort indicators remains lacking. For Thermal Protective Clothing (TPC), the thermal and evaporative resistances of the product are two properties closely related with the comfort sensation, and they are usually evaluated through specialized and costly equipment found in textile/clothing laboratories (e.g., thermal manikins and sweating guarded-hotplate). In this work, predictive models were developed, considering different levels of complexity, relying from simple electrical circuit theorems to numerical analysis (bi- and tri-dimensional approaches). The developed approaches were used to study and optimize the performance of a firefighting vest when subjected to standard tests.

2. MATERIALS AND METHODS

2.1. PCM FIREFIGHTER VEST

The vest consists on a group of pouches with PCMs (phase change materials) alternated with layers of textiles (Santos et al. 2023). The effect of various parameters on the vest properties (thermal and evaporative resistances) was studied, including different dimensions of the pouches (width and thickness), two types of PCMs, different materials (e.g., textiles, cork, impermeable materials used in PCMs pouches), and various configurations of the vest. In all the studies, the goal was to determine the distribution of pouches on the vest (i.e., fraction of area covered by pouches) that would guarantee the standard requirements.

2.2. CONSIDERED STANDARD REQUIREMENTS FOR TPC

According to ISO 15384, the TPC must meet maximum thermal and evaporative resistance thresholds of $0.055 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ and $10 \text{ m}^2 \cdot \text{Pa} \cdot \text{W}^{-1}$, respectively. For that reason, these parameters were established as relevant requirements for the new vest design.

2.3. MATHEMATICAL MODELS FORMULATION

To evaluate the vest's thermal and evaporative resistances, heat and mass transport through vest samples were model based on the procedures outlined in ISO 11092, i.e., samples evaluated in sweating guarded hotplate apparatus. For thermal resistance determination, the sample is exposed to dry conditions ($RH=0\%$) and a temperature difference (of $15\text{ }^{\circ}\text{C}$). For evaporative resistance determination, a humidity gradient was imposed ($\Delta RH = 60\%$) at isothermal conditions (at $35\text{ }^{\circ}\text{C}$). The surface facing the apparatus plate is labelled as 1 in Figure 1 and the surface exposed to a constant air flow ($1\text{ m}\cdot\text{s}^{-1}$) is identified as 2, for the three models studied. The models independently account for heat conduction and water vapour diffusion through the different sample elements. They enable the prediction of heat and mass flux under steady-state conditions, replicating the conditions of the standard test and to calculate the thermal (or evaporative) resistance of the sample.

To illustrate the main mathematical assumptions, a vest configuration was chosen consisting of three layers of generic materials, with a PCM pouch placed between the inner and middle layers, as described in Figure 1.

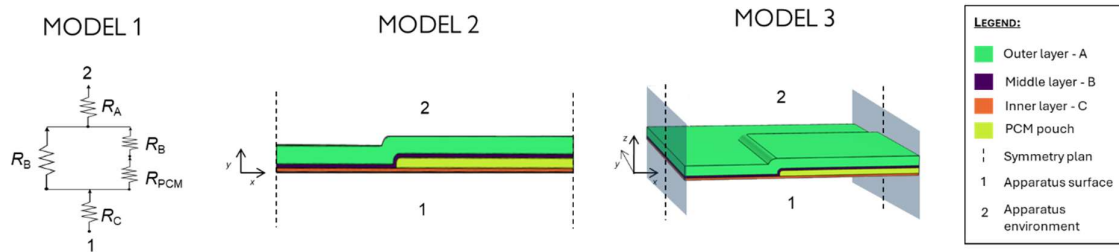


Figure 1. Schematic diagrams of a vest sample with three layers (A, B, and C) and a PCM pouch integrated for the three models developed (model 1, 2 and 3) to predict the (thermal/evaporative) resistance of the vest (R)

Model 1

The temperature/concentration gradients between sample surfaces were treated as unidirectional, from surface 1 to 2, and in series. For partially covering materials (e.g., PCM pouch, Figure 1), a parallel heat/mass transfer arrangement was applied to the specific integrated layer (e.g., Layer B in Figure 1).

Model 2

Heat and mass transfer in the PCM vest's components (air gaps, textiles, insulation, and PCM pouches) was numerically analysed using FEM (Finite Element Method). Due to the vest's matrix structure, consisting of repeating units, the simulation domain focuses on a cross-section of a single unit (Model 2, Figure 1), considering a bi-dimensional approach.

Model 3

Building on Model 2's assumptions, Model 3 predicted phenomena in the vest using a 3D geometry. Simplification was achieved by modelling only $\frac{1}{4}$ of a single unit due to the vest's repetitive structure (Model 3, Figure 1).

Heterogeneous distribution of proprieties

Previous models calculated vests with a uniform pouch distribution. For non-uniform distributions (areas with and without pouches), the total thermal/evaporative resistance was determined using a parallel arrangement of pouch-covered and uncovered areas.

3. RESULTS AND DISCUSSION

Model 1 provided accurate estimates of vest properties when PCM pouches covered less than 8% of the surface area (Table 1). For higher coverage or scenarios with impermeable materials and spatially dependent water diffusion (Figure 2), Model 1 was inadequate.

For larger pouch-covered areas, the two-dimensional approach (Model 2) predicted thermal and evaporative resistances with reasonable accuracy but tended to overestimate compared to the three-dimensional model (Model 3). Nevertheless, computational time is considerably less when Model 2 is used instead of Model 3 (from seconds to hours).

A configuration satisfying both thermal and evaporative resistance standards was achievable only with a heterogeneous pouch distribution on the vest.

Table 1. Comparison between the vest thermal resistance obtained with Model 1 and Model 2 for different configurations of the vest (8 % of PCM coverage area; PCM pouch with a width equal to ~0.06 m)

Case	Observations	Thermal resistance Model 1 / $\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$	Thermal resistance Model 2 / $\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$	ΔR %
32	3 layers + 1 pouch PCM A; 8% coverage	0.0351	0.0355	-1.1
59	2 layers + 1 pouch PCM A; 8% coverage	0.0271	0.0275	-1.5
74	3 layers + 1 pouch PCM B; 8% coverage	0.0454	0.0473	-4.2
96	2 layers + 1 pouch PCM B; 8% coverage	0.0275	0.0293	-6.5

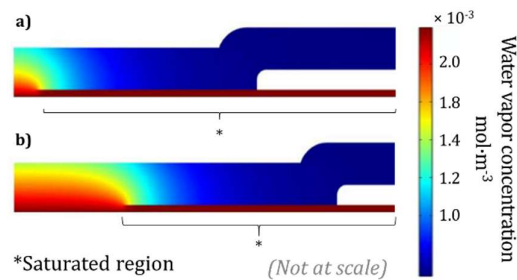


Figure 2. Water vapour concentration maps along the layers of two configurations of the vest (a and b) with impermeable materials integrated with different dimensions, using Model 2.

4. CONCLUSION

The thermal and evaporative resistances of a PCM vest were numerically analysed using three predictive models across various configurations. The most simplified model provided accurate predictions for unidirectional transfer scenarios (e.g., low impermeable material content) but is unsuitable for complex cases. For such scenarios, bi- and tri-dimensional models are recommended. This study highlights the value of simplified models in early TPC development to quickly identify bottlenecks and minimize variables.

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