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# An innovative thermal protective clothing system for firefighters

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## ABSTRACT

*Nowadays, despite the evolution of personal protective equipment (PPE), the number of firefighters injured and burned during fire extinguishing operations is still very high, leading in some cases to loss of life. Therefore, the research and development of new solutions to minimize firefighters' heat load and skin burns, with consecutive improvements of commercial firefighters' suits, is of extreme importance. The integration of phase change materials (PCMs) in a protective clothing system has been used to significantly reduce the incoming heat flux from the fire environment. This study consists in the development of a protective clothing system composed by a vest, specially designed to protect the torso (back, chest and abdomen) with a layer of PCM pouches, to be worn over a fire-resistant jacket – selection and design based on numerical models' predictions. Therefore, several mockups were made, varying the number of PCM pouches and their distribution in the vest, allowing the creation of air ducts to increase the breathability of the vest. The most promising solutions are being evaluated in a real controlled environment, at a Portuguese National School of Firefighters (ENB) simulation site, using a fire manikin and thermocouples to monitor vest temperature during heat and flame exposure, and consequently to verify PCMs influence in heat protection. Results regarding the development of a PCM vest will be presented, focusing on the integration of PCM pouches and the thermal performance of the most promising solutions.*

**Keywords**
thermal protective clothing,
firefighters,
phase change materials,
heat protection

## 1 Introduction

During fire extinguishing activities, firefighters are exposed to high temperatures and high intensity of thermal radiation, making the use of personal protective equipment (PPE) imperative. Firefighters' protective clothing must keep firefighters protected against several hazards, such as heat and flames, without compromising their mobility and consequently allowing them to escape from dangerous situations [1]. Despite the evolution of firefighting personal protective clothing and the significant training given to firefighters, there are still many injuries and fatalities during firefighting activities due to the unpredictable nature of their job. A recent study, conducted regarding the analysis of fire fatalities in Southern Europe from 1945 to 2016, concluded that burns and suffocation were the main cause of death among firefighter forest-fire fatalities [2].

The best approach to prevent burn injuries and reduce risk of death from unpredictable hazards is to apply high-performance personal protective equipment [3]. Current firefighters' protective clothing is engineered specifically to prevent burn injury when working in direct contact with flames [2]. However, this personal protective equipment is heavy, stiff and with reduced vapor permeability, which increases the physiological strain. In addition, during firefighting activities, the current PPE tends to store high amounts of thermal energy which can be discharged to the skin, leading to skin burns, specifically compression burns. Furthermore, firefighters' protective clothing becomes wet during fire extinguishing activities, from external and internal sources, namely by the wearer perspiration resulting from the exposure at high-temperature and strenuous activities. This phenomenon, combined with the reduced vapor permeability of the garments, can cause steam burns since water vapor is transferred to the human skin and condenses [3].

Therefore, the main challenge for firefighting protective clothing is the development of innovative PPE with high-level of protection with minimum physiological burdens, which can be achieved by using and developing advanced materials.

With this purpose, recent studies have been conducted regarding the integration of phase change materials (PCMs) in firefighting protective clothing since these advanced materials can absorb and release energy in the form of latent heat when phase transition occurs [4]. A wide spectrum of PCMs for textile applications is available and depending on their properties, namely heat storage capacities and melting point, they can be used for different purposes [5]. Commonly PCM with melting points close to body temperature is used to improve thermal comfort. However, in firefighters' thermal protective clothing, PCMs can be used to improve heat protection, using PCMs with higher melting points due to their high thermal storage capacities [5].

Several studies have shown that the integration of a layer of PCM in the structure of firefighting protective clothing increases the insulation of the suit and reduces the occurrence of thermal injuries. Once PCM absorbs heat, the transfer of external heat through the garment to the skin slows down, reducing the occurrence of skin burns on firefighters [6].

This study emerges to develop an innovative thermal protective clothing system for firefighters, with outstanding performance, by following a procedure based on numerical models to optimize the design. This innovative clothing system will incorporate advanced materials, namely PCMs, to minimize firefighters' heat-load and skin burns.

Since currently there is still a gap in smart PPE standardization, the performance requirements that should be accomplished by the developed vest are defined in the standards for structural and wildland firefighters' protective clothing (EN 469 and EN ISO 15384), namely heat and flame, mechanical and comfort requirements. Regarding heat and flame performance requirements, both standards require the following tests: flame spread (EN 15025), heat transfer – radiation (ISO 6942) and heat resistance (ISO 17493). The mechanical performance tests required by the two standards are as follows: main seam strength (ISO 13935-2), tear strength (ISO13937-2) and residual tensile strength (ISO 13934-1). Concerning comfort parameters, both standards require water-vapor resistance test.

To integrate PCM pouches in the thermal protective vest, different approaches were analyzed to achieve the best compromise between heat protection and comfort parameters, such as thermal and water-vapor resistances. The major challenge is to integrate the PCM pouches without compromising protective clothing system ergonomics and, simultaneously, accomplishing the requirements of the International, European and National standards.

## 2 Methods

Regarding the development of a protective clothing system, this study focuses on the integration of a phase change material (PCM), achieving a compromise between efficiency, comfort and wearability. The integration of phase change materials in thermal protective clothing leads to an increase in heat protection. Nevertheless, this efficiency is associated with the use of a high amount of material [7], which increases the weight of the garment. Besides, PCM incorporation methods can decrease garments flexibility when compared to conventional ones. Therefore, the restriction of PCM protection to an optimal body zone can increase heat protection, while limiting the additional weight.

Restricting the application of the new solution to the torso area, the percentage of covered body area is high, which has a significant and direct impact on heat transfer between the fire environment and the firefighter. In addition, critical burns with severe consequences tend to occur on the torso region. For instance, circumferential burns on the chest decrease skin elasticity and limit the thoracic expansion, which imposes mechanical restrictions to breathing [8].

Therefore, in this study, the development of a thermal protective clothing system with PCM consists in the integration of these smart materials in a vest specially designed to protect the torso with a layer of PCM pouches, to be worn over the firefighter dolman.

### 2.1 PCM integration

The integration of PCM in firefighters' protective clothing considered several variables: the amount of PCM on each pouch, pouch size and quantity, and the distribution of the pouches in the vest. The best combination of these variables was studied using numerical tools to maximize heat protection without compromising breathability.

This study comprised two types of PCM with the main characteristics summarized in Table 1.

*Table 1. Phase change materials properties and characteristics.*

| PCM | Melting / Congealing Area (°C) | Heat Storage Capacity (kJ/kg) | Form |
|---|---|---|---|
| **PCM 1** | 56-59 / 56-54 | 250 | Pure |
| **PCM 2** | 77-85 / 85-77 | 105 | Microencapsulated |

To minimize firefighters' heat load, in addition to PCM integration, the thermal protective vest was designed as a multilayer system. The composition and the architecture of the multilayer system were also targets of this study. The first proposal consists of introducing PCM pouches between two layers of a heat and flame resistance fabric accomplishing the requirements stablished for the outer layer of firefighters' suit. The second approach introduces insulant materials in the multilayer vest, being studied two different materials: a microperforated material composed of biologically degradable insulating cellulose cells (Fig. 1, ensemble 1) and a 3D knit fabric (Fig. 1, ensemble 2), that contributes to the introduction of an air layer.

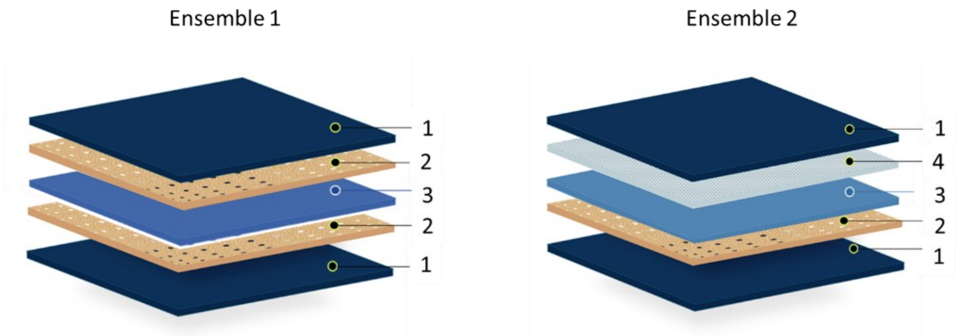


*Fig. 1 Proposed ensembles for vest architecture: 1) outer shell fabric; 2) microperforated material composed by biologically degradable insulating cellulose cells; 3) PCM pouches layer; 4) 3D knitted fabric.*

Accordingly, with the guidelines for selection, use, care and maintenance (SUCAM) of smart garments protecting against heat and flame, particularly with PCM packages, it is important to ensure that PCM pouches can be removed for cleaning and inspection purposes. Therefore, concerning the integration process, the best way to make the PCM pouches removable was analyzed. This study used several innovative manufacturing technologies and processes, namely tailoring, lamination, laser cutting, and adhesive bonding.

## 2.2 PCM pouches development

The main requirements concerning materials for PCM pouches construction are: i) resistance to high temperatures, to protect from the extreme environmental conditions in firefighting activities; ii) waterproofness, to prevent the material outflow and iii) breathability to promote vapor transfer between the body and the environment. Considering these requirements, a selection of potential materials for pouch development was done, resulting in two promising solutions. The first option is a waterproof film that withstand extreme temperatures but does not accomplish the breathability requirement. The second option consists of a membrane that accomplishes all the established requirements since it can withstand high temperatures being waterproof and breathable.

To assemble the pouches, several manufacturing technologies were studied, namely ultrasounds, high frequency and bonding. The latter proved to be the most promising. Therefore, two different bonding processes were used on PCM pouches development using two different types of tape (Fig. 2).

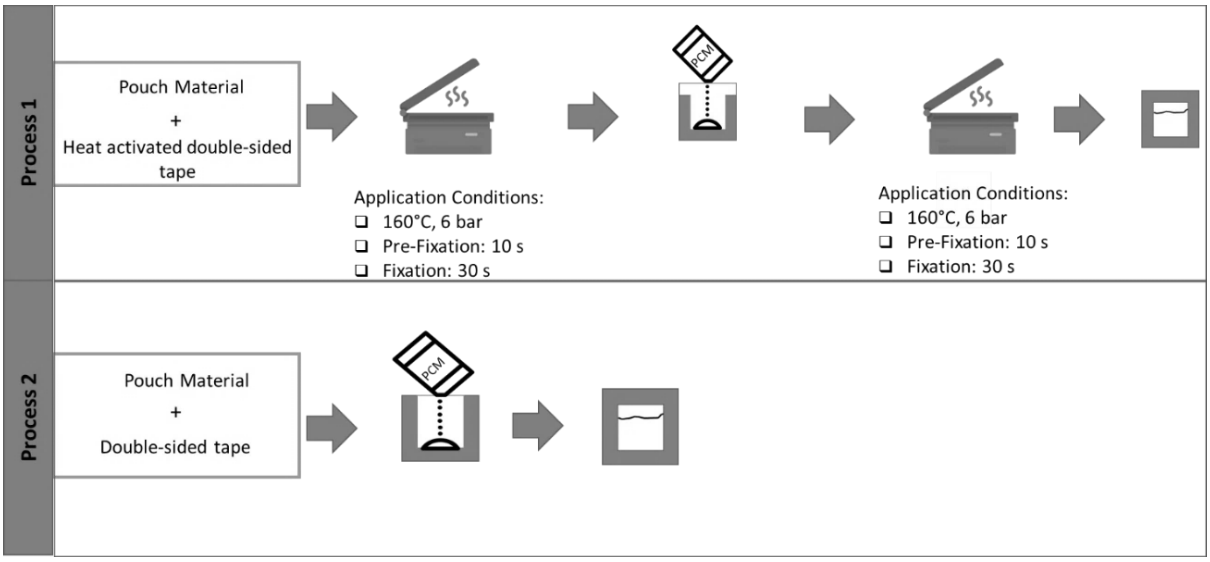


*Fig. 2 Different processes used for PCM pouches development using bonding technology.*

The processes used in this study are represented in Fig. 2. Regarding the first process, the double-sided tape is activated applying heat on a thermal press under the conditions described in Fig. 2. On the other hand, the tape used does not need heat for activation, being applied manually in the second process.

### 2.3 Evaluation of PCM pouches performance

After the integration and development of the PCM pouches, these components were evaluated regarding their performance when exposed to heat. For that purpose, since currently there is no standard to evaluate firefighters' clothing with phase change materials, an experimental set-up was built for preliminary tests (Fig. 3). This set-up consists of a 6 cm x 6 cm frame to support the sample, heated using a 1500 W heat-gun. A thermocouple was placed at the center of the sample to monitor the temperature over exposure time.

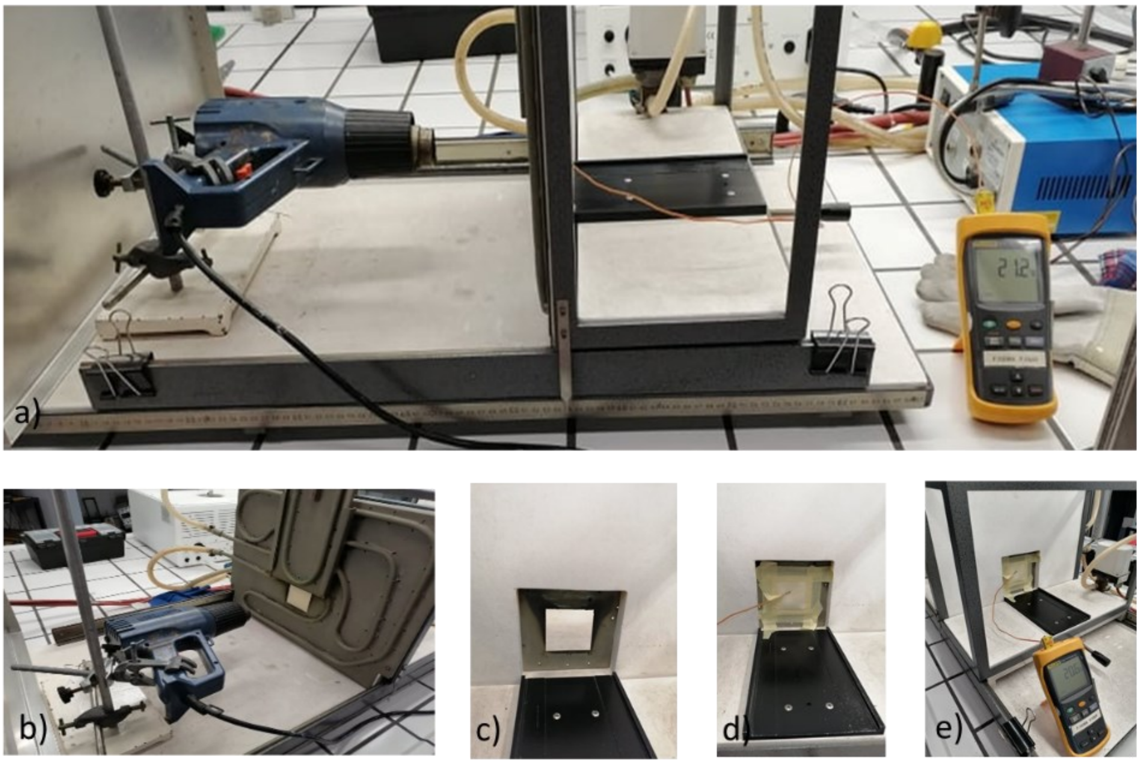


*Fig. 3 Experimental set-up for preliminary evaluation of PCM pouches: a) global view; b) heat source; c) sample frame; d) sample placed in the frame connected to a thermocouple; e) temperature acquisition device.*

This experiment made it possible to evaluate the heat resistance of the aforementioned joining processes, specifically the resistance of the used tapes when exposed to heat. Additionally, this test was used to evaluate the thermal performance of the PCM pouches.

Afterwards, considering the results obtained from the preliminary tests, the most promising solutions will be tested according to the standards for structural and wildland firefighters' protective clothing (EN 469 and EN ISO 15384).

## 3 Results

### 3.1 Proposal of PCM integration

The integration of PCM on the developed thermal protective vest took in consideration the guidelines described in the SUCAM of smart garments protecting against heat and flame, namely the fact that PCM must be removable from the vest for inspection and maintenance purposes. Therefore, this study was conducted to integrate these innovative materials in removable pouches integrated in a PCM matrix which can be removed from the main structure of the vest. The proposed integration form allows, additionally, the recyclability of the components individually (Fig. 4).

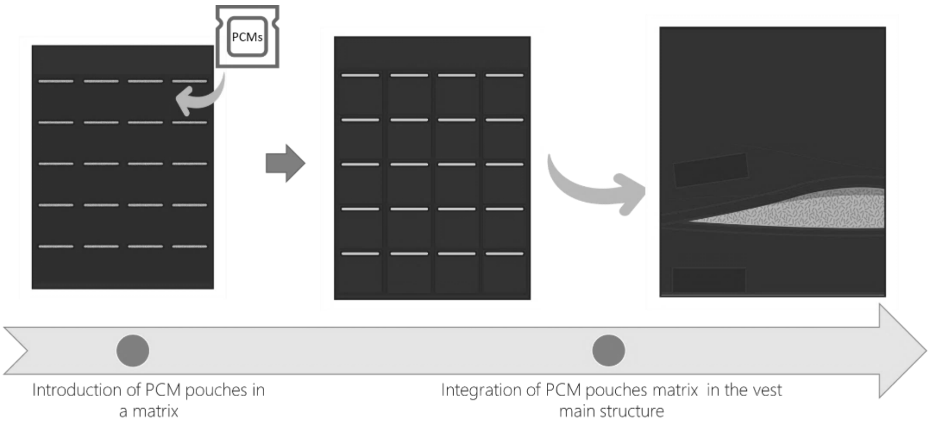


*Fig. 4  Integration of the PCM pouches in a thermal protective vest.*

### 3.2 Evaluation of PCM pouches joining

Initially, the PCM pouches were assembled through bonding technology using the heat-activated double-sided tape following the first process described in Fig. 2 (section 2.2). In this stage, to evaluate the effect of the different PCMs regarding the integration and their influence on the joining heat resistance, two PCM packages, constructed with film and filled to their maximum capacity, were submitted to heat exposure for 5 minutes, according to the experimental set-up described in Fig. 3. The experiments showed that the tape used is not suitable for the manufacture of PCM packages, since heat affects its behavior allowing PCM to leaks from the pouches, as shown in Fig. 5.

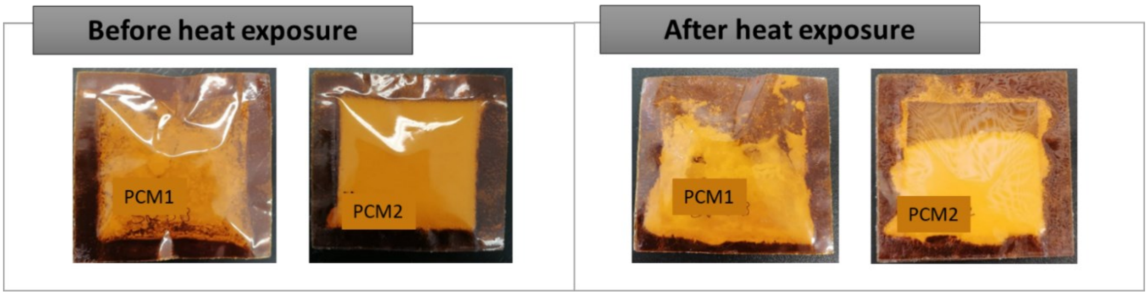


*Fig. 5  Film PCM packages before and after heat exposure.*

The pouches with PCM1 required more complex procedures and showed more disadvantages than the pouches with PCM2. Firstly, since PCM1 is in rock solid state at ambient temperature, it is necessary to melt the PCM to fill the pouch. Furthermore, when exposed to heat, after the melting point is reached, the liquid form of the PCM interacts with the tape leading to the opening of the pouch and consequently leaking of the PCM. Due to the described difficulties, the PCM1 was discarded from the subsequent experiments.

Afterwards, to evaluate the performance of the double-sided tape, without heat activation, following the second process described in Fig. 2 (section 2.2), two PCM packages filled to their maximum capacity were submitted to heat exposure for 5 minutes, according to the experimental set-up described in Fig. 3 (section 2.3). The heat resistance joining performance of PCM packages constructed with membrane was also evaluated in this stage. The results presented in Fig. 6 show that the double-sided tape used, without heat activation, has a higher heat resistance, keeping PCM confined for both membrane and film pouches.

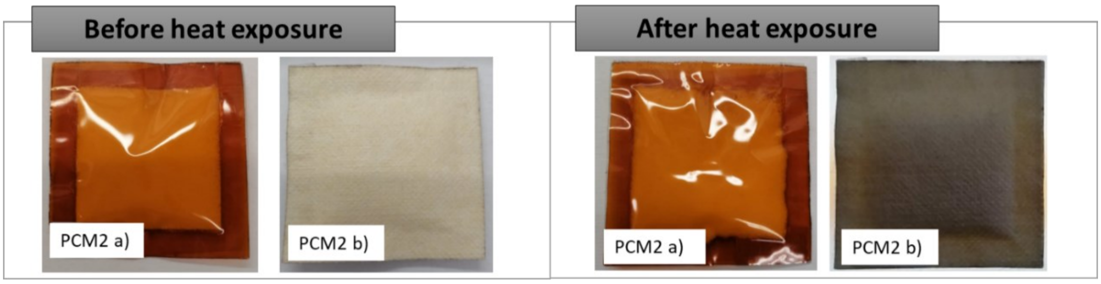


*Fig. 6 PCM packages before and after heat exposure: a) film and b) membrane.*

Considering the results concerning the two bonding processes and correspondent tapes under study regarding heat resistance difference, it is possible to conclude that the second process has proven to be more promising and was selected for the PCM pouches construction regarding the evaluation of thermal performance.

### 3.3 Evaluation of PCM thermal performance

After assessing the best bonding process for the PCM pouches development, the PCM pouches' thermal performance was tested. The evaluation of the PCM thermal performance was made by exposing the samples in the experimental set-up described in section 2.3, registering the temperature after 1, 5, 10, 15, 20, 25 and 30 minutes of exposure. After 30 minutes, the heat source was turned off and the temperature was registered every 5 minutes for 30 more minutes. To set a term of comparison that allows analyzing the improvement of thermal performance with the integration of the PCM, samples of the outer shell fabric as well as the film and the membrane empty pouches were exposed to heat according to the process mentioned above.

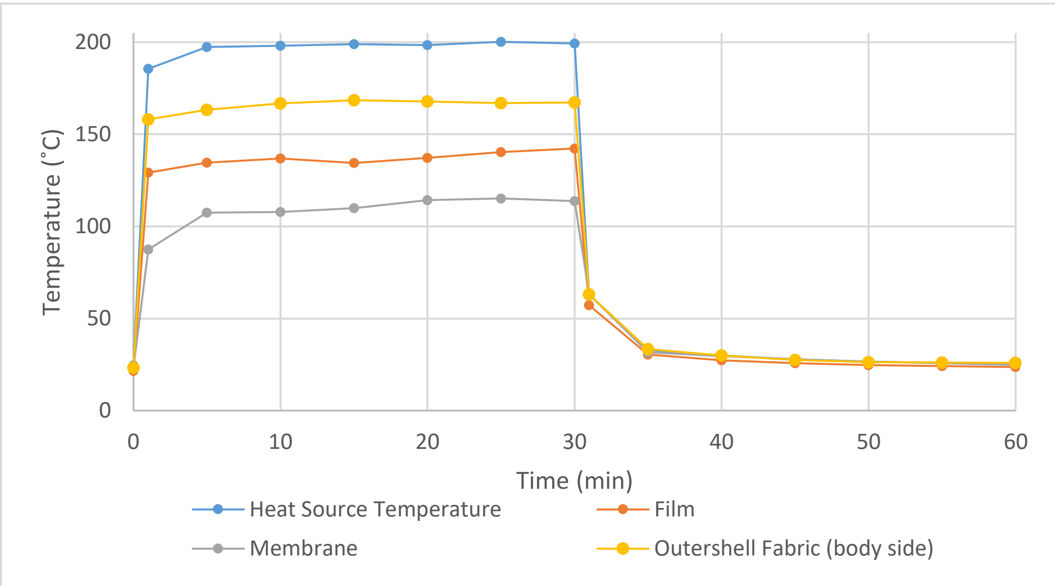


*Fig. 7 Thermal performance of the materials used in the vest without PCM integration.*

As expected, all samples act as a thermal barrier since the temperature measured at the samples surface, on the opposite side of the exposure, is lower than the heat source temperature, measured in the outer shell sample surface closer to the heat source, over time (Fig. 7). Nevertheless, the membrane presents better results achieving a lower temperature.

The following figure demonstrates that the incorporation of PCM in the ensemble reduces the temperature reached after 30 minutes of heat exposure and increases the time necessary to reach 43 °C, the threshold temperature for an edema formation in the skin.

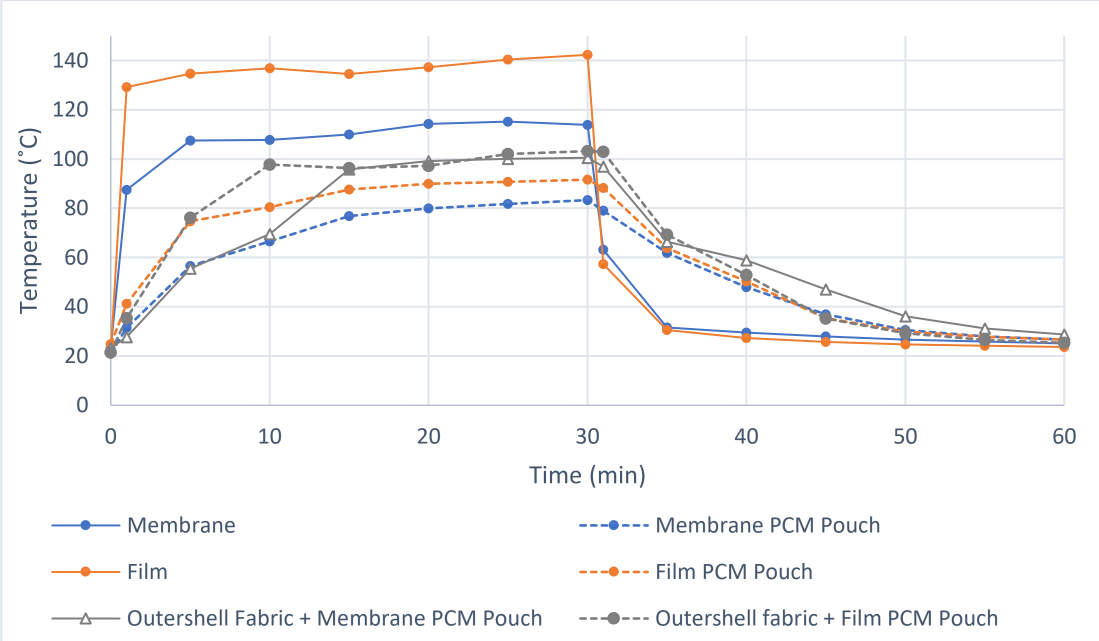


*Fig. 8 Thermal performance of the materials used in the vest with PCM integration.*

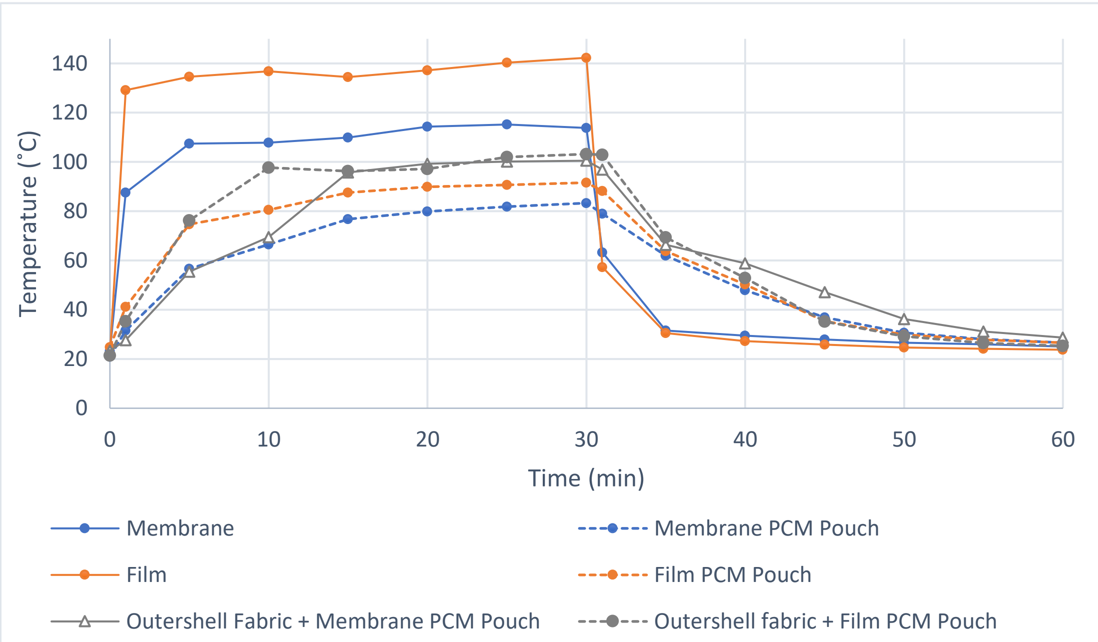


Fig. shows for the first 5 minutes of exposure that when the outer shell fabric is added to the membrane PCM pouch, the temperature is higher than without the outer shell fabric (only membrane PCM pouch). This phenomenon is because the outer shell fabric reaches higher temperature compared to the membrane, as demonstrated in Fig. 7. Concerning film PCM pouches, a similar behavior was verified. Comparing membrane and film pouches regarding the heating stage, the isolated membrane obtained better results, achieving lower temperatures over time. Nevertheless, concerning the results of PCM pouches with the outer shell fabric after 15 minutes of exposure, the membrane and the film pouches have shown similar results.

On the other hand, the results presented in Fig. 8 show the introduction of PCM delays the decrease of temperature during the cooling stage, while the samples without PCM cool instantly to 60 °C. Meanwhile, the samples with PCM have presented similar cooling behavior.

With the purpose of reducing the heat transfer between the heat source and the body, reducing simultaneously the effect of the temperature of the outer shell on the PCM pouch, an insulation layer between the outer shell and the PCM pouch was added. Two different ensembles were submitted to heat exposure in the same conditions as the previously tested samples. Since there was no significant difference regarding the cooling stage in the previous experiment, considering that the membrane presented better results for the heating stage, reaching a lower temperature, the following tests only incorporate the membrane PCM pouches.

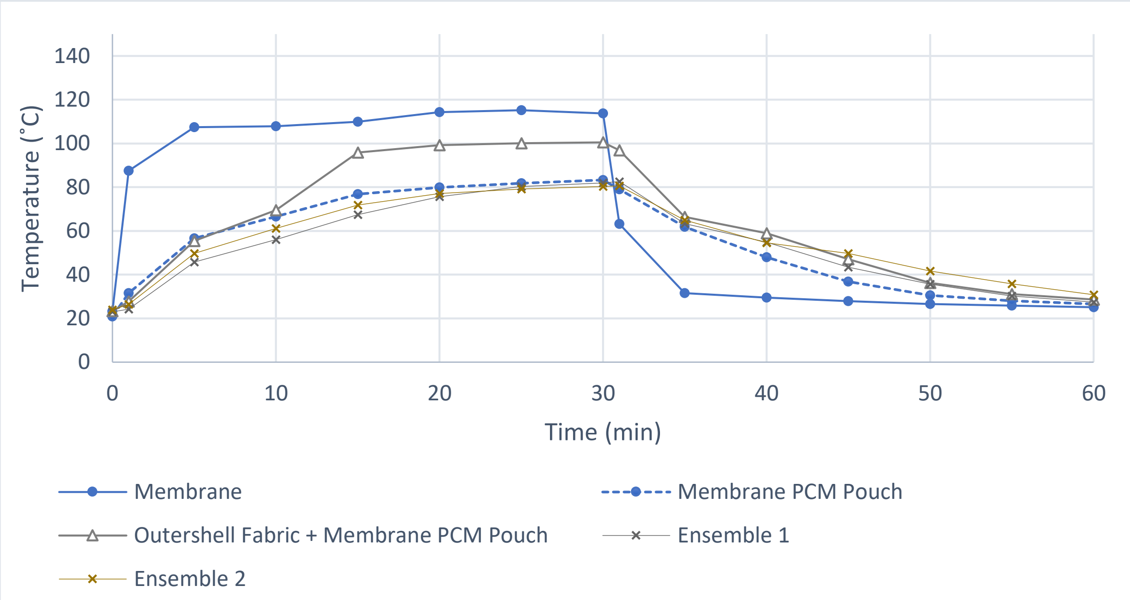


*Fig. 9 Thermal performance evaluation of the two ensembles proposed.*

The results regarding the evaluation of thermal performance of the two ensembles proposed (Figure 9) show that the introduction of the insulation layers between the PCM pouch and the outer shell leads to a significant reduction of the heat transfer from the heat source to the surface close to the body. In addition, the developed ensembles achieved better results compared to the isolated membrane PCM pouch concerning the heating stage. However, the introduction of an insulation layer delays cooling, with a behavior closest to the sample composed by the membrane PCM pouch and the outer shell fabric.

To compensate for the fact that the introduction of the PCM leads to an increase in the cooling time, the vest under development will have a quick-release system that makes it possible to be quickly and easily removed so that in the cooling phase, the vest will no longer be in contact with the body.

## 4 Conclusions

Despite the firefighters' personal protective clothing evolution, the current equipment presents limitations regarding the compromise between heat transfer and comfort parameters, leading to the occurrence of burns during firefighting activities. In the present study, PCM pouches were integrated on an innovative thermal protective clothing system for firefighters to minimize firefighters' heat load. Taking into consideration the SUCAM guidelines and eco-design principles, the protective clothing was designed to enable a quick removal of the PCM pouches from the vest.

This study approached the development of PCM pouches by using two double-sided adhesive tapes, with different application processes, filled with two different PCM: PCM1 in pure form and PCM2 microencapsulated. The results obtained in this study have shown that the integration of PCM1, in pure form, is much more complex than the integration of microencapsulated PCM2. In addition, the double-sided adhesive tape, without heat activation, showed better results regarding heat resistance. Additionally, the study of a suitable material for the pouch's development was done using two different materials, a film and a membrane, with the latter achieving lower temperatures over time.

The integration process of the PCM pouches made of membrane into the innovative vest was studied using and testing two different multilayer proposals acting as insulating layers and having as objective the heat transfer reduction from the heat source to the surface close to the body. Both ensembles significantly improve the heat transfer reduction during the heating phase when compared to the isolated membrane PCM pouch. Regarding the cooling phase, the use of the insulating layers leads to a temperature decrease delay. To avoid and/or minimize this undesirable situation, the innovative vest will present a quick and easily removable system enabling the user to remove it when the cooling phase starts.

Further studies are envisaged not only in laboratory conditions, according to International, European and National standards, but also in simulated real conditions to be performed in straight collaboration with ENB – the Portuguese National School of Firefighters.

## Author Contributions

G. Santos: conceptualization, investigation, methodology, writing – review and editing, supervision, funding acquisition; R. Marques: conceptualization, investigation, writing – original draft preparation, visualization; F. Marques: conceptualization, investigation; J. Ribeiro: conceptualization, investigation, writing – review and editing; A. Fonseca: conceptualization, software, investigation; J. M. Miranda: conceptualization, investigation, funding acquisition; J. B. L. M. Campos: conceptualization, investigation, funding acquisition; S. F. Neves: conceptualization, software, investigation, writing - review and editing, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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## Conflicts of Interest

The authors declare no conflict of interest.

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