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Smart Firefighters PPE: Impact of Phase Change Materials

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Abstract: Considering the high level of heat and flame exposure firefighters encounter while performing their work activities, personal protective equipment (PPE) is of the utmost importance to enhance their safety. Phase change materials (PCMs) are known as advanced materials able to absorb high amounts of thermal energy, with the potential to increase the thermal performance of protective clothing. In this work, a PCM-vest was developed for the first time, and its thermal performance was evaluated. A three-stage approach was followed: (1) at a small scale in the laboratory, the effect of different encapsulated PCMs on a multilayer assembly performance was evaluated; (2) in the laboratory, the essential requirements of heat and flame tests were assessed; and (3) in a simulated urban fire, the thermal performance of three different PCM-vests (different textiles and designs) was studied. As the main conclusions, the PCMs significantly affected the heating rate of the multilayer assembly, particularly when a PCM with higher latent heat was used. In some cases, the heat transfer index (HTI) doubled by comparison with the sample without PCMs. As a drawback and as expected, the cooling time was increased. The PCM-vest sample ensured the requirements of the heat and flame tests. Through this study, the positive impact of using PCMs to enhance the heat protection of conventional PPE can be highlighted.

Keywords: phase change materials; thermal protection; firefighters; smart personal protective equipment; smart protection; advanced materials

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1. Introduction

Firefighters are emergency response professionals specialized in extinguishing fires and handling various types of emergencies (e.g., rescue operations and medical services [1]). During the firefighting, the hazardous environment conditions and the high-intensity activities require clothing that simultaneously ensures the body's physical integrity and minimizes the incoming heat flux.

Clothing is the first protection against the heat wave coming from the outside. However, its thermal efficiency is time-limited due to its intrinsic properties (e.g., thermal and evaporative resistance), and it has the disadvantage of impairing metabolic heat and sweat evaporation, jeopardizing the body's thermal homeostasis. Therefore, episodes of harsh burns or heat stress can occur. The need for clothing solutions that address overheating and provide automatic body cooling is crucial.

Several ergonomic aspects of the firefighter's protective clothing and its properties have been optimized to respond to the demanded tasks (e.g., during structural firefighting) while wearing task-specific equipment (e.g., a helmet and a self-contained breathing apparatus). However, current personal protective equipment (PPE) poses a significant burden, hindering heat transfer and evaporation of sweat during physical exertion [2]. In critical conditions, the body fails to regulate the temperature, leading to diminished operational capacity, potential accidents, and even heat-related illnesses (e.g., heat exhaustion and heat stroke; [3]). Thermal strain and discomfort among firefighters are prevalent issues, as revealed by surveys [3].

Typical firefighter protective clothing consists of multiple layers to ensure non-flammability, including a vapor-permeable membrane, heat insulation, and a non-flammable lining. According to firefighter surveys, enhancing clothing design and incorporating active thermal underwear are desired improvements [2,3]. Furthermore, several approaches to improving the thermal protection of firefighter clothing have been adopted to monitor parameters in real time (e.g., wearable electronics [4]) or to react to the heat source, such as phase change materials (PCMs) [5,6]. PCMs are materials capable of storing and releasing thermal energy during phase transitions in the form of latent heat [7–9]. Despite being commonly used for thermoregulation [10–13], incorporating PCMs with higher melting points and storage capacities into firefighting clothing makes it possible to improve the overall thermal protection offered to firefighters. In practice, adding a PCM instead of a textile layer with the exact thermal properties (e.g., thermal resistance, heat capacity, etc.) has the advantage of accumulating thermal energy in its latent form, reducing the rate at which heat reaches the wearer's skin. This addition can significantly extend the time available for firefighters to operate in high-temperature environments before experiencing burns or heat-related injuries [6].

Besides the latent heat and melting temperature, the mass of PCM compromises the clothing's thermal efficiency [14]. To integrate high amounts of PCMs in firefighter protective clothing, Santos et al. [6] proposed using pouches filled with microencapsulated PCMs. Using microencapsulated PCMs provides several benefits in various applications, including firefighting clothing [5,15]. Firstly, it enhances the stability and durability of PCMs by protecting them from leakage or degradation. Further, the encapsulation shell acts as a barrier, preventing the PCM from directly contacting the environment.

In our previous work [5], a new PCM-vest comprised individual PCM pouches. The vest design followed the SUCAM procedures [16] and eco-design, but its thermal protective efficiency and performance were not assessed. The smart vest was developed to be the first layer of protection (outer layer) against the incoming heat flux. This specification entails that the vest performance should accomplish the heat and flame requirements [17,18] as demanded in firefighters' protective clothing International and European standards EN 469:2020 and EN ISO 15384:2020. These standards require both the tests of flame spread (EN 15025:2016) and of heat transfer—radiation (ISO 6942:2002), while EN 469:2020 requires the additional test of heat transfer—flame (ISO 9151:2016) [17,19–21].

Therefore, the main goal of this study is to evaluate the impact of incorporating phase change materials in a smart firefighter vest, both in laboratory and simulated conditions. For that purpose, this study envisaged tests in a laboratory and simulated conditions; on the one hand, considering the International, European, and National standards; on the other hand, considering real ambient conditions of a simulated firefighting scene, performed in straight collaboration with the Portuguese National School of Firefighters (ENB).

2. Materials and Methods

This study evaluated the impact of the incorporation of PCMs in a smart PPE for firefighters. For that purpose, the investigation proceeded according to a three-stage approach. The first stage consisted of preliminary tests to evaluate the thermal performance of different phase change materials. Subsequently, the most promising PCM was submitted to heat and flame performance tests stipulated in firefighters PPE standards. The final stage encompassed the proof-of-concept validation in a simulated environment.

2.1. Evaluation of PCM Thermal Performance—Preliminary Tests

This study analyzed three different encapsulated phase change materials with varying intrinsic properties, such as melting point and heat storage capacities, Table 1. Within the under-study phase change materials, PCM 1 and PCM 2 possess similar heat-storage capacities but different melting points, and both are in powder form. Regarding PCM 3, it presents a lower melting point and heat storage capacity and is encapsulated as a granulate.

Table 1. Properties and characteristics of the PCMs.

PCM	Commercial Name	Melting/Freezing Temperature Range, °C	Heat Storage Capacity, kJ/kg	Form	Composition
PCM 1	RUBITHERM® PX82	77-85/85-77	105	Microencapsulated (powder)	~60% organic material (PCM) 40% inorganic material (hydrophilic silica)
PCM 2	RUBITHERM® PX52	49-53/52-48	100	Microencapsulated (powder)	~60% organic material (PCM) 40% inorganic material (hydrophilic silica)
PCM 3	RUBITHERM® GR42	38-43/43-37	55	Encapsulated (granulate)	~30% organic material (PCM) 70% inorganic material (natural porous mineral particle)

Six grams of these materials were integrated into a membrane pouch (7 × 7 cm) made from a membrane of expanded polytetrafluoroethylene laminated with an aramid non-woven thermal barrier to evaluate the PCM thermal performance. This pouch was placed in a multilayer system composed of an outer shell fabric, a 3D knit fabric, an outer shell/cork matrix (to insert the pouch), and an outer shell layer, which simulates the architecture of the developed vest. Subsequently, these ensembles were tested in an experimental set-up built for simulating convective heat exposure, Figure 1e (procedure adapted from ISO 6942:2002 [20]). The sample was placed in a frame (i.e., 6 × 6 cm; Figure 1b) and exposed for 60 min to a heat source (i.e., 1500 W heat gun, Esco tornado 1500; Figure 1a). The cooling process was then studied by turning the heat source off. A thermocouple was placed at the center of the sample, on the surface not exposed to the heat source (Figure 1c), to monitor the temperature evolution during heating and cooling periods.

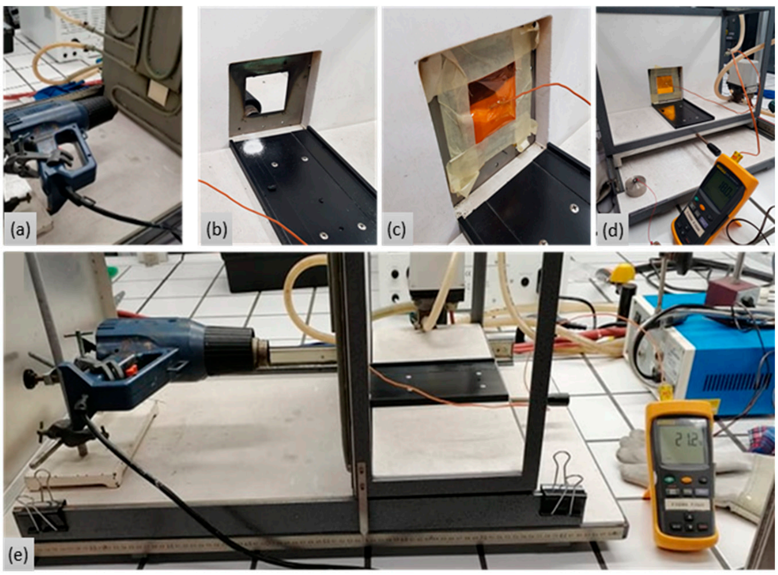


Figure 1. Experimental set-up used for the thermal performance assessment of PCM pouches: (**a**) heat source (at 15 cm from the sample); (**b**) sample frame (6 × 6cm metal frame); (**c**) thermocouple (type K) location; (**d**) temperature acquisition device (Fluke 51 II); (**e**) entire set-up.

2.2. Evaluation of PCM Integration According to Firefighters' PPE Performance Tests

The most promising phase change material was submitted to heat and flame performance tests, Table 2, required by EN 469:2020 [19]; i.e., EN ISO 15025:2016 [19], ISO 6942:2002 [20], and ISO 9151:2016 [21].

Table 2. Heat and flame performance requirements according to EN 469:2020.

Standard	Description	Minimum Compliance Values	
EN ISO 15025:2016	Flame spread test	A1 or A2	
ISO 6942:2002	Heat transfer (radiation)	Level 1: RHTI 24 $\geq$ 10.0 s RHTI 24-RHTI 12 $\geq$ 3.0 s	Level 2: RHTI 24 $\geq$ 18.0 s RHTI 24-RHTI 12 $\geq$ 4.0 s
ISO 9151:2016	Heat transfer (flame)	Level 1: HTI 24 $\geq$ 9.0 s HTI 24-HTI 12 $\geq$ 3.0 s	Level 2: HTI 24 $\geq$ 13.0 s HTI 24-HTI 12 $\geq$ 4.0 s

For that purpose, the PCM pouches were integrated into the same multilayer assembly used in the first stage of this study. The same tests were performed in an assembly without the pouch with the PCM to analyse the effect of the incorporation of the PCM.

2.3. Proof-of-Concept Simulated Environment Validation

Three different vests were developed, and their thermal performance was evaluated considering real ambient conditions of a simulated urban fire. Two of the vests have the same design but different fabrics in the construction (vests 1 and 2, Table 3). Vests 2 and 3 differ in design, maintaining the same fabrics (Table 3).

Table 3. Developed vests.

Vest	Design	Assembly
1	Strap vest	Fabric 1 (external layer) Fabric 3 Cork matrix Fabric 1 (internal layer)
2	Strap vest	Fabric 2 (external layer) Fabric 3 Cork matrix Fabric 2 (internal layer)
3	Vest with shoulder protection	Fabric 2 (external layer) Fabric 3 Cork matrix Fabric 2 (internal layer)

Vests are composed of a structure with a removable matrix of individual PCM pouches. The main structure is made of one type of fabric (e.g., fabric 1, in vest 1; Table 3), while the removable matrix comprises a fabric (main structure fabric) and a cork layer with the PCM pouches integrated. The sequence of vest components listed in Table 3 started from the external to the internal layer of the vest. The main properties of the fabrics used are shown in Table 4; note that the cork layers had ~1 mm of thickness and had micro holes to be permeable to water vapor.

For real urban fire scenario simulations, the vests were submitted to fire exposure in a 20-foot container, measuring 5.90 m in length, 2.35 m in width and 2.39 m in height. To simulate an urban fire scenario, the vests were worn over conventional PPE by a firefighter exposed to fire 5 m from the fire front, Figure 2. The firefighter was equipped with a conventional urban PPE, regulated according to EN 469:2020, complemented with gloves, a balaclava, a helmet, and a self-contained breathing apparatus (SCBA). A dual-channel data logger (EasyLog EL-GFX-DTC, Lascar electronics, Whiteparish, UK) was used for monitoring the temperature. In this regard, one of the thermocouples was placed in the interface between the vest and the conventional PPE to monitor the temperature transmission over time, and the other in the vest's outer shell in the side exposure to fire to monitor the temperature the vest is exposed to.

Table 4. Properties of the fabrics.

Layer	Composition	Position in the Vest	Thickness, mm	Emissivity	Thermal Resistance, $m^2 \cdot K \cdot W^{-1}$	Evaporative Resistance, $m^2 \cdot Pa \cdot W^{-1}$
Fabric 1	Nomex® special blend	Outer and inner layer	0.42	0.70	0.026	1.520
Fabric 2	98% aramid, 2% others	Outer and inner layer	0.35	0.76	0.033	4.841
Fabric 3	100% Polyester	Middle layer	3.50	-	0.092	7.987

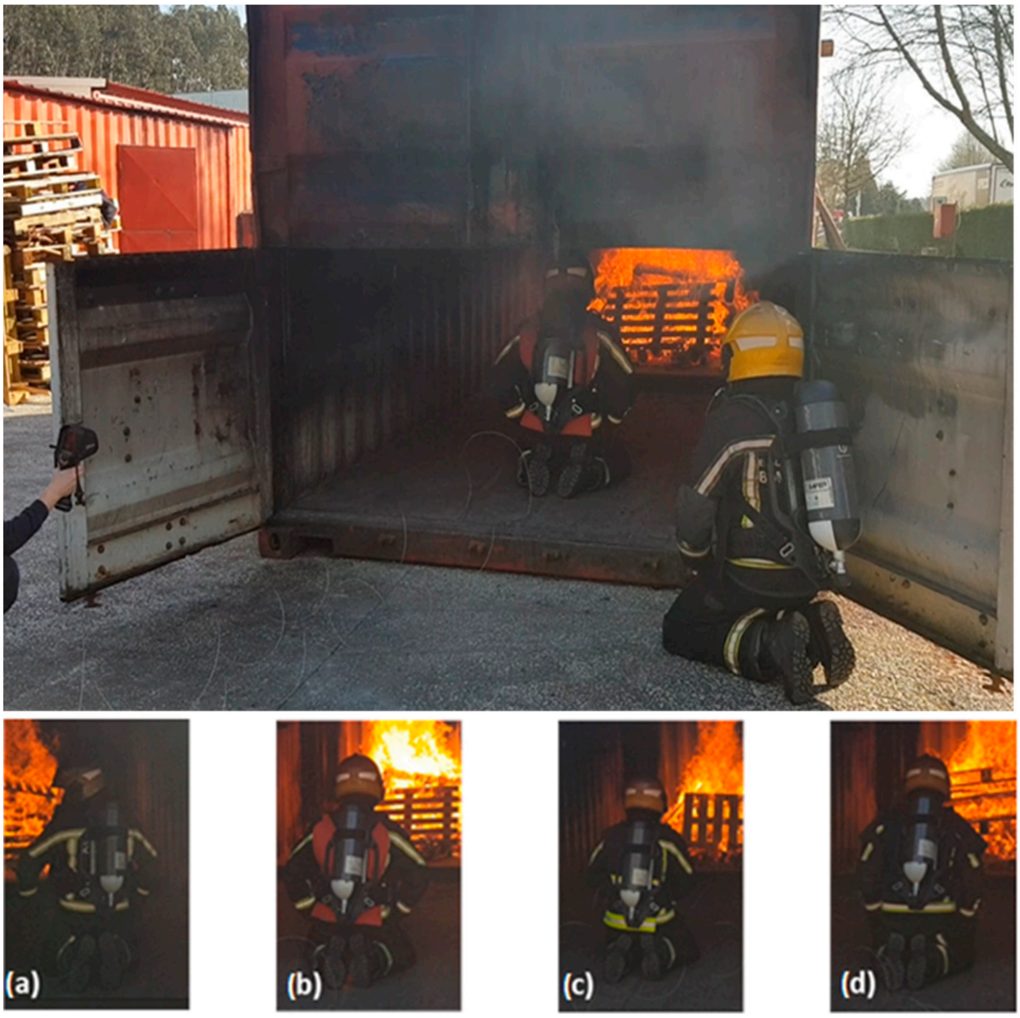


Figure 2. Simulated environment tests in the container used to simulate urban fire scenarios: (**a**) control test with conventional PPE; (**b**) test with vest 1 over conventional PPE; (**c**) test with vest 2 over conventional PPE; (**d**) test with vest 3 over conventional PPE.

Figure 2 illustrates the simulated environmental test where the firefighter is kneeling facing the fire. Furthermore, it also displays the wood pallets (100% pine Euro pallet) used as fire loads. Four pallets were placed in the fire ignition, two horizontally and two on the sides. During the trials, the wood pallets were added to the ignition font to maintain the container temperature constant during each test. Between tests, the fireman rested and hydrated for about 20 min. During the test, firefighting ventilation tactical maneuvers were carried out to fuel combustion and simultaneously to make gases escape from above, avoiding the sudden entry of oxygen, which can lead to a gas explosion. The test stopped according to the firefighter (thermal) sensation of heat.

This methodology was also used for monitoring the temperature using a thermal camera FLIR E76 (Teledyne FLIR; Wilsonville, OR, USA). Three measuring points were explored: above the firefighter's head, on the firefighter's shoulder, and back, Figure 3.

Figure 3. Simulated environment tests in the container used to simulate urban fire scenarios: temperature monitoring with a thermal camera.

Temperature monitoring was done 5 m from the measuring object (firefighter) in the three target zones. A default emissivity of 0.98 was considered in the camera settings.

3. Results

3.1. Preliminary Tests of PCM Thermal Performance

In the first stage of this study, the PCM-assembly thermal performance was evaluated by exposing the samples to a heat source followed by a cooling period, as described in Section 2.1. The temperature evolution over time was obtained for four samples: three with different PCMs and another without PCMs (Figure 4).

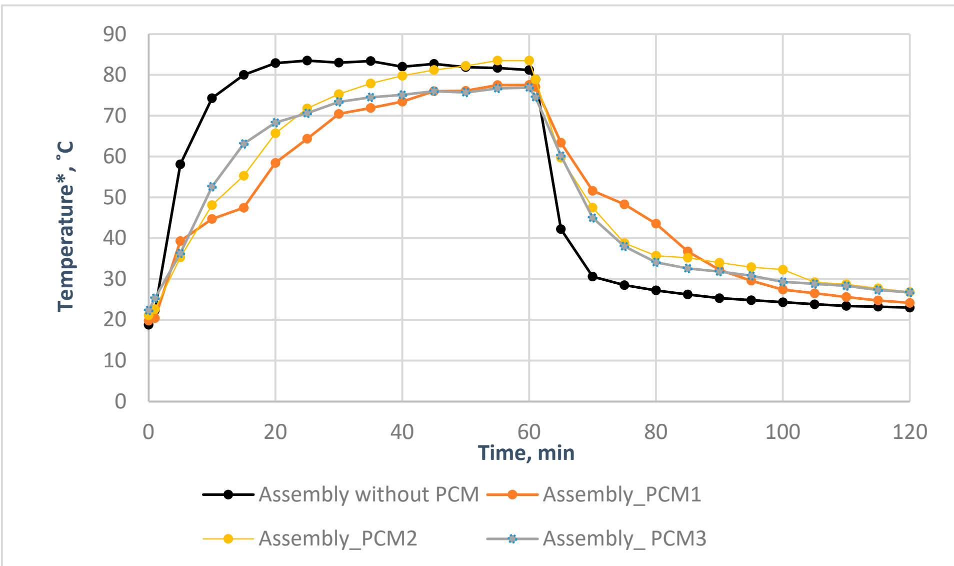


Figure 4. Thermal performance evaluation of assembly without and with different PCMs (* temperature measured on the opposite side to heat exposure).

The figure above shows the positive effect of integrating the PCM into the assembly regarding thermal protection because the temperature increase was delayed compared to the results obtained in the ensemble without the PCM. Furthermore, PCM 1 has better results in terms of thermal protection (higher delay in the heating stage), as expected, since this PCM presents a higher melting point and storage capacity. However, the duration of the cooling phase is increased due to the presence of the PCM material. For instance, at minute 65 (i.e., 5 min of the cooling phase start), a temperature drop of ~14 °C is obtained with the assembly with PCM 1, while a drop of ~37 °C is obtained with the same assembly without the PCM. The same tendency is observed with the remaining PCMs.

3.2. Evaluation of PCM Integration According to Firefighters' PPE Performance Requirements

Regarding using phase change materials in an assembly for firefighters' PPE, it is essential to guarantee that incorporating these non-textile materials does not negatively impact the heat and flame performances of protective clothing. Therefore, the main heat- and flame-required tests, according to EN 469:2020, were performed on the assembly with and without PCM pouches. Concerning flame spread, the samples were tested according to ISO 15025:2016 [19], procedure A, and the main results are described in Table 5 [17,19].

Table 5. Flame spread test results for the assembly with and without PCMs according to ISO 15025:2016.

Required Parameters	Assembly without PCM Pouch	Assembly with PCM Pouch
Flame reached the top or the hedge of the specimen	No	No
Flame propagation time (s)	0	0
The residual glow spreads beyond the burnt area to the undamaged area	No	No
Occurrence of fusion	No	No
Residual glow time (s)	0	0
Occurrence of flaming debris	No	No
Flaming debris burns or perforates the filter paper	No	No
Hole formation	No	No

The results presented in the table above show that PCM incorporation does not compromise the flame spread requirements.

Regarding the heat transfer on exposure to flame, the results described in Table 6 show the impact of phase change materials as a thermal barrier because the heat transfer index (HTI) doubled in the sample containing these smart materials.

Table 6. Heat transfer on exposure to flame test results for the assembly with and without PCMs according to ISO 9151:2016.

Sample	HTI 24 (s)	HTI 12 (s)	HTI 24–HTI 12 (s)
Assembly 1 without PCM pouch	47	33	14
Assembly 1 with PCM pouch	104	78	26

The same tendency was verified when the assemblies were exposed to a radiant heat source, as shown in Table 7, for assembly 1.

Table 7. Heat transfer on exposure to radiation test results for different assemblies, with and without PCMs according to ISO 6942:2002.

Sample	RHTI 24 (s)	RHTI 12 (s)	RHTI 24–RHTI 12 (s)
Assembly 1 without PCM pouch	60.6	43.5	17.1
Assembly 1 with PCM pouch	124.1	88.6	35.6
Assembly 2 with PCM pouch	145.5	105.6	39.9
Assembly 2 with PCM pouch empty	78.2	55.7	22.5

In Table 7, the heat transfer index for another assembly (assembly 2) is shown, where the insulator layer (cork) was substituted with a layer of the outer shell to increase the assembly's breathability. This change resulted in an increase of 11.4 and 17.0 s, in the RHTI 24 and RHTI 12, respectively. Furthermore, the exclusion of the PCM from assembly 2 implies a significant decrease in the RHTI (e.g., a decrease of 67.3 s in the RHTI 24).

3.3. Proof-of-Concept Simulated Environment Validation

Three developed vests were submitted to simulated environment tests to understand the impact of the developed vest with the incorporation of phase change materials as a thermal barrier. To set a term of comparison, a control test was performed by measuring the temperature outside and inside the conventional urban PPE. The results obtained are presented in Figure 5.

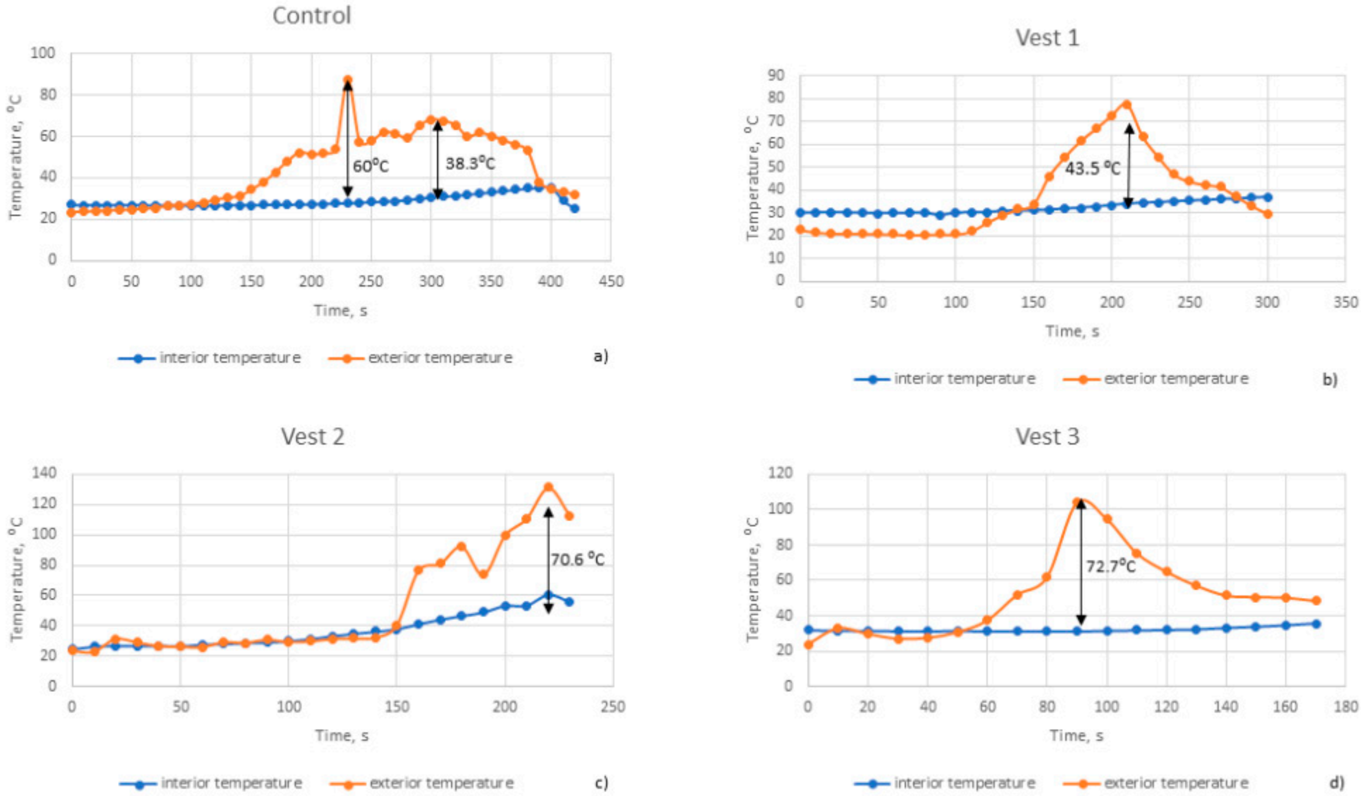


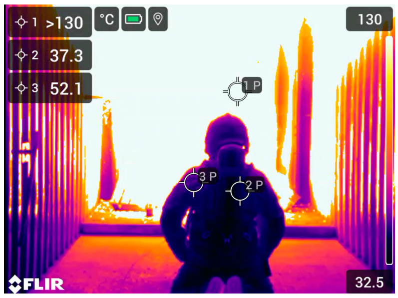
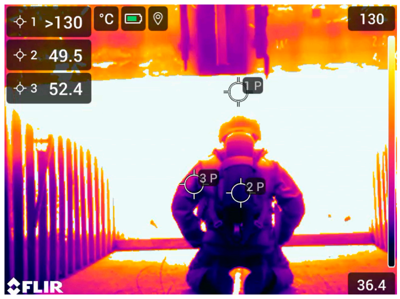
Figure 5. Temperature over time in real environment simulation when the firefighter wears a conventional PPE covered with: (**a**) no vest (control test); (**b**) vest 1; (**c**) vest 2; and (**d**) vest 3.

In Figure 5a, referring to the control test, it is possible to observe two temperature peaks instead of one, which happened in the remaining tests. This fact was due to the change of the firefighter position in the chamber from kneeling (first peak) to sitting (second peak).

By comparing the results obtained for the control test (Figure 5a) with the ones obtained for vest 1 (Figure 5b), it is possible to observe that in the test with vest 1, for the same firefighter position, the maximum temperature difference between the interior and the exterior increased slightly since in the test related to vest 1 (Figure 5b), the maximum temperature reached by the vest did not exceed the melting temperature of the PCM used (i.e., 82 °C). Concerning the tests with vest 2 (Figure 5c) and vest 3 (Figure 5d), the temperature of the exterior surface of the vests was higher than the PCM melting temperature, exceeding 100 °C. A very similar difference between the internal and external temperature of vests 2 and 3 was obtained (70.6 and 72.7 °C, respectively).

During the real environment simulation, a thermal camera was used to measure the temperature on the surface of the protective clothing (shoulder and back) and the ambient temperature above the firefighter's head. The results obtained are displayed in Table 8.

Table 8. Thermal camera results after 1 min 30s of fire exposure for the different target areas of measurement.

Test	Measuring Area	Temperature (°C)	Thermal Photograph
Control (Urban PPE)	Above head	>130	
	Shoulder	52.1	
	Back (above SCBA)	37.3	
Vest 1	Above head	>130	
	Shoulder	52.4	
	Back (above SCBA)	49.5	
Vest 2	Above head	>130	
	Shoulder	90.4	
	Back (above SCBA)	50.3	
Vest 3	Above head	>130	
	Shoulder	70.0	
	Back (above SCBA)	59.3	

In each of the trials (control, vest 1, vest 2, and vest 3), the values recorded in the shoulder area were consistently higher than those measured in the back area. The variations observed between the trials can be attributed to differences in the thermal charge within the container, rather than variations in the protective clothing. It is important to note that these measurements were taken on the outer layer's surface. Unfortunately, due to the thermal camera's limitations, it was impossible to accurately determine the temperature directly above the firefighter's head, as the camera could not provide precise values above 130 degrees.

4. Discussion

Laboratory tests and a simulated firefighting scene were used to study the effectiveness of phase change materials (PCMs) in enhancing the thermal performance of smart personal protective equipment (PPE). Three different PCMs were analyzed in terms of their thermal characteristics.

The findings indicate that including PCMs in the assembly enhances the reduction in heat transfer during the heating phase, showcasing the thermal barrier effect facilitated by these innovative materials.

Although the samples with PCMs exhibited a positive effect during the heating phase, it was observed that introducing these materials in the assembly resulted in a delayed temperature decrease during the cooling phase. This delay was expected, as PCMs release heat after the removal of the heat source when the reverse phase transition occurs. This indicates that the vest must be optimized to delay the heat wave considerably and, after the utilization of the vest must be put to cool down, preferentially in a ventilated place [14].

Among the PCMs tested, PCM 1 displayed the most promising results, demonstrating a delayed temperature increase compared to the other PCMs during the heating phase, while exhibiting similar behavior during the cooling phase.

In the flame tests, the addition of PCMs in the assembly did not adversely affect flame spread results. Regarding heat transfer indexes when the assemblies were exposed to a radiant heat source or flame, the samples containing PCMs exhibited a higher heat transfer index compared to those without these materials; the time required for the temperature to increase by 24 °C nearly doubled in the samples with PCMs. However, this occurs due to the increase in the sample thermal resistance, because the PCM is solid at the experimental temperature (i.e., of ~40 °C).

Furthermore, the developed vests underwent environment simulation tests. During the entire test of vest 1, the temperature inside the vest was lower than the PCM melting temperature. For that reason, the difference in the internal and external temperature is due to the vest's thermal properties (sensible heat) instead of the latent heat of the PCM. For the remaining vests (2 and 3), the temperature on the vest's surface significantly exceeds the melting point of the PCM. Therefore, in both tests, the temperature difference between the internal and external vest surface is significantly greater than the result obtained with the control test (no vest). This finding underscores the favorable effect of incorporating these materials into smart firefighter PPE; furthermore, the effect of the PCM latent heat cannot be quantified. As future considerations, more locations inside the vest must be studied, such as the surface temperature of the PCM pouches as well as the spaces between the pouches, in order to study the temperature distribution along the vest.

5. Conclusions

One of the main challenges in firefighting is the protective garment's ability to keep firefighters safe. To achieve this goal, this work focused on enhancing the protective garment's thermal performance using phase change materials with higher melting points and storage capacities. The research concluded that using a PCM improves the thermal protection of the smart PPE assembly during the heating phase. However, as a drawback, the cooling phase is extended. PCM 1 exhibited the most promising results, and the incorporation of PCMs did not negatively affect flame spread results. Moreover, using PCMs increased the heat transfer index and effectively enhanced temperature differentials in the environment simulation tests, supporting their positive impact on smart firefighting PPE.

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