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DOMINGOS XAVIER VIEGAS
LUÍS MÁRIO RIBEIRO

Firefighting: Challenges of Smart PPE

Gilda Santos*[1]; Rita Marques[1]; J. Ribeiro[2]; A. Moreira [2]; P. Fernandes[2]; Margarida Silva[3,4]; André Fonseca[3,4]; João M. Miranda[3,4]; João B. L. M. Campos[3,4]; Soraia F. Neves[3,4]

[1]CITEVE - Technological Centre for the Textile and Clothing Industries of Portugal, V. N. Famalicão, Portugal, {gsantos, rmarques}@citeve.pt
[2]CeNTI - Centre for Nanotechnology and Smart Materials, V. N. Famalicão, Portugal, {jpribeiro, amoreira, pfernandes}@centi.pt
[3] CEFT - Transport Phenomena Research Center, Department of Chemical Engineering, Faculty of Engineering, University of Porto, s/n Rua Dr. Roberto Frias 4200-465 Porto, Portugal, {up201909589@up.pt}, {eq10026, jmiranda, jmc, sfneves}@fe.up.pt
[4]ALiCE - Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

**Corresponding author*

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Abstract

The continuous research and development regarding firefighters' personal protective equipment (PPE) has led to significant improvements in recent decades. The findings that contributed the most to the firefighters' protective clothing evolution, increasing the protection, were the use of high-performance fibers, flame-retardant polymer fibers and the changes on clothing structure namely the incorporation of a multi-layer system. Despite the evolution of firefighters PPE, every year an undesirable number of firefighters are seriously burned during firefighting operations with some of them eventually losing their life. Therefore, the need to proceed the research and development regarding thermal protective clothing arises, to increase firefighters' protection and consequently minimize firefighters' heat load and skin burn. Firefighters' protection can be further increased with the incorporation of smart textiles in the personal protective equipment, such as integrated sensors to monitor parameters such as heart rate, oxygen saturation, carbon dioxide detector and setting real-time communication with a command post. In addition to the wearable electronics, regarding smart textiles alternatives for firefighters PPE, several studies have been conducted to incorporate phase change materials (PCM) in firefighters thermal protective clothing with satisfactory results. These advanced materials will absorb the heat from the fire leading to a reduction of the amount of heat to which firefighters are exposed to and an increase of the time that firefighters can be exposed to heat. The evolution of firefighters PPE has been followed by an evolution and update of the international and national standards that specify performance requirements for firefighters' protective clothing for structural and wildland firefighting as well as technical rescue. In respect to structural firefighting, the applicable European standard is EN 469:2020: Protective clothing for firefighters – Performance requirements for protective clothing for firefighters' activities and regarding the wildland firefighting, the international standard prevailing is EN ISO 15384:2020: Protective clothing for firefighters – Laboratory test methods and performance requirements for wildland firefighting clothing. For technical rescue the applicable European standard is EN 16689: 2017: Protective clothing for firefighters – Performance requirements for protective clothing for technical rescue. Given the growing trend towards the incorporation of smart materials in firefighters PPE is important to study and develop new standards to certify these innovative protective clothing for firefighters, regardless the efforts being done within CEN / TC 248/WG 31 - Smart Textiles. To preserve the protection of firefighters protective clothing there are some actions that must be taken during the protective garments' life cycle. Therefore, recently was developed a technical report, a CEN/ TR1760:2021 that describes the guidelines for selection use, care and maintenance of smart garments protecting against heat and flame. This study will focus on the analysis of firefighters protective clothing evolution regarding the use and integration of advanced smart materials, namely phase change materials, taking in consideration the evolution and requirements of international and European standards as well as national legislation for firefighters' protective clothing.

1. Introduction

Firefighters are often exposed to high temperatures and heat-fluxes due to high radiation produced by fire during fire extinguish operations. Therefore, personal protective equipment is of extreme importance for firefighters to ensure their protection during firefighting activities. Due to the importance of firefighters' protective clothing, over time several research and development studies were taken leading to a continuous evolution of firefighters PPE. Currently, the emergence of smart textiles opened a wide range of opportunities to increase the level of protection of firefighters' protective clothing.

1.1. Firefighters PPE evolution

The scientific developments that led to the introduction of high-performance fibers have been the first major contribution for the increase of the firefighters' personal protective equipment level of protection, however, the biggest revolution regarding firefighters' protection was the use of flame-retardant polymer fibers, namely aromatic polyamides (aramids) and polybenzimidazole (PBI). Nowadays meta-aramids and para-aramids are widely used in firefighters' PPE due to their good thermal tolerance and long-time stability at high temperatures (Hertleer et al., 2013). Alongside the research and development of innovative fibers for firefighters' PPE, the major finding that contributed to increasing firefighters' PPE level of protection, resulting from studies regarding the clothing structure, was the introduction of a multi-layer system, used currently for structural firefighting. Three layers compose this multilayer system: outer shell (flame retardant fabric), vapor barrier, and thermal barrier. The design of the multilayer system allows the wearer to be firstly protected from heat and flame but also against moisture.

1.2. Smart firefighters PPE

The research and development carried out in the field of firefighters' PPE increasingly encompasses advanced materials and/or electronic components. From the combination of these smart materials with conventional PPE appears a new typology of PPE for firefighters. Regarding the development of garments with wearable electronic technologies, many include the integration of sensors for vital function and location monitoring in textiles, communication interface and energy supply with the purpose of increase functionality and protection of firefighters clothing (Mäkinen, 2008). On the other hand, the evolution in the field of advanced materials led to the emergence of new materials which can improve firefighter' clothing functionality. Currently, the development of new materials with adaptive function, such as phase change materials (PCM) has been the subject of interest to the researchers.

1.2.1. Phase change materials

Phase change materials are substances that can absorb and release energy in form of latent heat during a phase transition (Fonseca et al., 2018). These materials are commonly used to improve thermal comfort, however, when applied in smart firefighters' PPE they can be additionally used to improve the heat protection due to its high thermal storage capacities. An extensive spectrum of PCM for textile application is available with different heat storage capacities and melting points. Since PCM becomes liquid when exposed to heat, when integrated into textiles they should be confined to a container. To avoid this problem, PCM can be encapsulated in a polymeric structure(Zhu et al., 2015). Several recent studies have shown that the addiction of PCM layer into a conventional firefighter suit can be used to mitigate severe burns, increasing the time to second burns (Zhang et al., 2021).

1.3. Standardization and Certification

Due to the nature of their job, firefighters require the use of the most suitable PPE available, to be protected from the risks inherent to their activities. Therefore, is of most importance to ensure a high quality of PPE that is assessed through compliance with standards. International and European standards specify the performance requirements for firefighters' protective clothing. Regarding wildland firefighting prevails the international standard EN ISO 15384:2020: Protective clothing for firefighters – Laboratory test methods and performance requirements for wildland firefighting clothing. On the other hand, the requirements for structural firefighting protective clothing are defined in the European standard EN 469:2020: Protective clothing for firefighters – Performance requirements for protective clothing for firefighters' activities. As for technical rescue the applicable European standard is EN 16689: 2017: Protective clothing for firefighters – Performance requirements for protective clothing for technical rescue. Although PPE sector benefits from an abundance of standards, regarding smart PPE there is still a gap in the standardization. Currently an important study is being conducted concerning the requirements and testing procedures for innovative smart protective garments within CEN / TC 248/WG 31 - Smart Textiles. In fact, a new European standard named FprEN 17673 Protective clothing - Protection against heat and flame - Requirements and test methods for garments with integrated smart textiles and non-textile elements is now at a final stage of approval. At the same time, there have been an evolution regarding the guidelines for selection, use, care, and maintenance (SUCAM) of garments protecting against heat and flame. In this field, a new technical report (CEN/ TR1760:2021) was developed that includes guidelines regarding smart personal protective clothing.

2. Methods

The purpose of this study involves the analysis of the major differences between the structural and wildfire firefighting protective clothing as well as a comparison of the prevailing standards for both firefighting protective clothing and further examination of the alterations done to the previous standards. This study is important to define and understand the prevailing performance requirements for each type of firefighting protective clothing, being the starting point for the development of innovative smart firefighters' PPE.

In addition, the study concerning possible ways to integrate phase change materials into a firefighter protective clothing, to enhance heat protection, was approached, creating a smart PPE. The integration methods study has considered the technical report (CEN/ TR1760:2021) which presents a section dedicated to smart garments with PCM. Besides the best practices mentioned by SUCAM the integration study took in consideration also circular economy and sustainable principles using techniques as eco-design.

3. Results

The purpose of the phase change materials integration is to improve heat protection. Thus, this study will focus on protective clothing for structural and wildland firefighting and will not analyse the protective clothing for technical rescue that is only applied for protection against limited heat and flame.

According to Portuguese firefighters' legislation (dispatch 7316/2016) and accomplishing the respective standards the following figure presents the current personal protective clothing for structural and wildland firefighting.

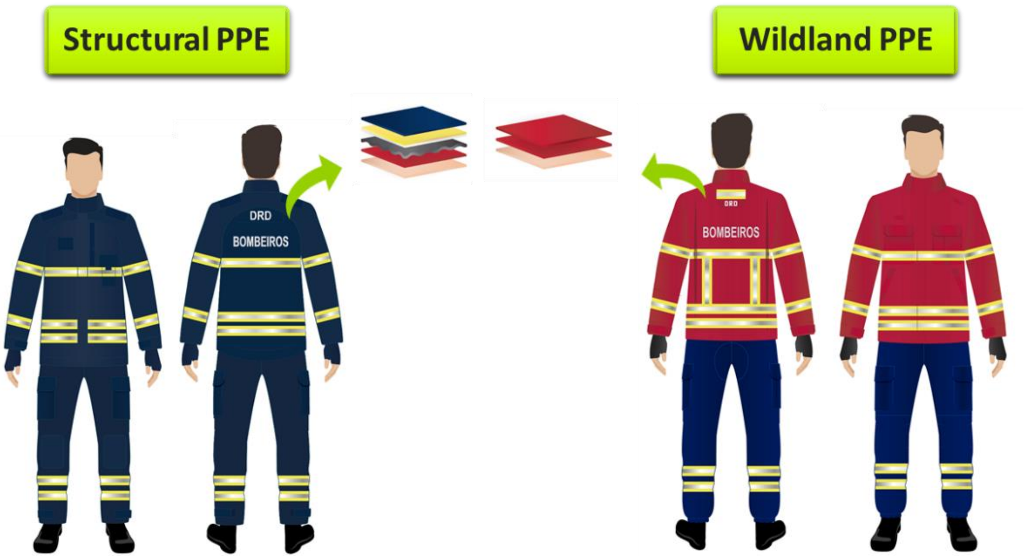

Figure 1. Structural and wildland PPE according to dispatch 7316/2016

The protective clothing suit for structural firefighting consists in a multilayer system composed by three layers with different functions as described in section 1, to be worn over the undergarment. In contrast, the wildland firefighting protective clothing suit has only one layer, outer shell, to provide protection against heat and flame, and must be worn over a long sleeve shirt.

The standards for structural and wildland firefighters' protective clothing (EN 469 and EN ISO 15384) define the performance requirements that must be accomplished. The focus of this study will be in thermal, mechanical and comfort performance requirements. The following table comprises a comparison regarding minimum compliance values for test methods used both in structural and wildland firefighting protective clothing standards.

Table 1. Comparison between the minimum compliance values for wildland and structural firefighting protective clothing for the same test methods

Protective Clothing Standard	Standard	Description	Minimum compliance values	
EN 469:2020	EN ISO 15025	Flame spread test	A1 or A2	
EN ISO 15384:2020			A1 and A2	
EN 469:2020	ISO 6942	Heat transfer (radiation)	Level 1: $RHTI_{24} \geq 10,0s$ $RHTI_{24}-RHTI_{12} \geq 3,0s$	Level 2: $RHTI_{24} \geq 18,0s$ $RHTI_{24}-RHTI_{12} \geq 4,0s$
EN ISO 15384:2020			$RHTI_{24} \geq 11,0s$ $RHTI_{24}-RHTI_{12} \geq 4,0s$	
EN 469:2020	ISO 13935-2	Main seam strength	≥ 300 N	
EN ISO 15384:2020				
EN 469:2020	ISO 13937-2	Tear strength	≥ 30 N	
EN ISO 15384::2020			≥ 25 N	
EN 469:2020	ISO 13934-1	Residual tensile strength	≥ 450 N	
EN ISO 15384:2020			≥ 600 N	
EN 469:2020	EN 31092	Water vapor resistance (Ret) / Thermal resistance (Rct)	Level 1: Ret>30 m^2Pa/W	Level 2: Ret≤30 m^2Pa/W
EN ISO 15384:2020			Ret ≤ 10 m^2Pa/W Rct ≤ 0,055 m^2K/W	
EN 469:2020	ISO 17493	Heat resistance	180°C	
EN ISO 15384:2020			260°C	
EN 469:2020	ISO 5077	Dimensional change	≤3% woven fabrics ≤5% non-woven and knitted fabrics	
EN ISO 15384:2020				

The comparison presented in table 1 allows to conclude that despite both standards use the same test methods, the minimum compliance values change for several tests. In addition to the test methods described in table 1, structural protective clothing has some specific required tests, presented in table 2.

Table 2. Specific required tests and minimum compliance values for structural firefighting protective clothing

Standard	Description	Minimum compliance values	
ISO 9151	Heat transfer (flame)	Level 1: $HTI_{24} \geq 9,0s$ $HTI_{24}-HTI_{12} \geq 3,0s$	Level 2: $HTI_{24} \geq 13,0s$ $HTI_{24}-HTI_{12} \geq 4,0s$
EN 20811	Water penetration	Level 1: >20kPa	Level 2: ≥20 kPa
EN 6530	Resistance to chemical penetration	No penetration to innermost surface; Index of repellence ≥80%	
EN ISO 12127-1	Contact heat test	Level 1: -	Level 2: 250 °C (10s)

Regarding test methods to evaluate performance requirements, the update of the standard for structural firefighting protective clothing in 2020, introduced the contact heat test and reduced the number of chemicals that are used in resistance to chemical penetration test. In addition, flame testing of hardware like labels (≥10 cm^2), badge and retroreflective materials as well as the moisture barrier shall be tested as part of the assembly. For the wildland firefighting, EN 15614 was superseded by EN ISO 15384 demanding now slightly higher values for the mechanical parameters and a higher temperature (260 °C) for the heat resistance of the materials.

The PCM integration in firefighters' protective clothing have considered the guidelines present in CEN/ TR1760:2021. This technical report defines guidelines regarding selection, use care and maintenance of smart garments protecting against heat and flame. The following figure presents the main topics within each step of PPE life cycle.

Figure 2. Main topics approached in SUCAM guideline

In addition to the generic guidelines concerning protective clothing on use, care and maintenance up to and including the disposal of the protective gear, this document provides examples of the scenarios and SUCAM procedures, being garments with PCM packages one of the given examples.

PCM packages must be selected considering the melting temperature more suitable for the exposure needs that vary with different parameters: activity level (heat produced by the body), climatic conditions, exposure length and logistical opportunities or limitations, for instance the possibility to replace the PCM packages during the mission.

Regarding cleaning and decontamination of garments with PCM, the PCM packages must be withdraw from the garment, and be cleaned according to manufacturer's instructions, and wiped with a soap solution. Garments with PCM packages must be stored horizontally during the solidification process to avoid material accumulation at the lower end of the package, and consequently, uneven cooling effect, reduced protection and potential tactile discomfort during next use. If noticing any problems during care and maintenance procedures such as PCM substance leaking or if any package has not melted even if being above the melting temperature, the situation must be reported.

Concerning the inspection of PCM packages on regular basis the user must inspect the packages according to the figure 3 and at least once a year verify if PCM will melt at their melting point. The disposal of broken packages must be according to manufacturer's instructions.

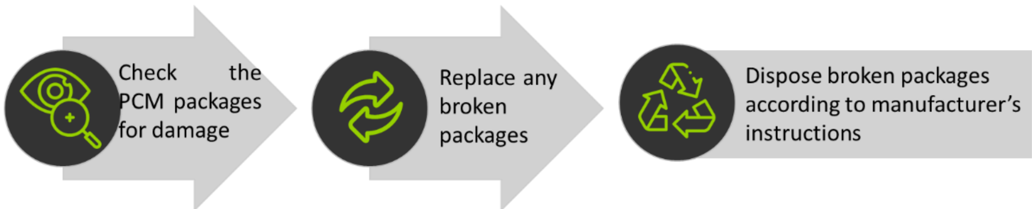

Figure 3. Inspection and disposable procedure for PCM packages

Considering that recent studies in which was found that the optimum position for the PCM layer is the closest to the external heat, PCM packages are being integrated into a vest to be worn over a conventional firefighter PPE, creating a smart protective clothing system. The design of the vest was studied to protect mainly the torso of the firefighter preserving ergonomics. However, after some firefighters feedback a second version was developed to enhance the protection of the upper limbs, Figure 4.

Figure 4. Study of PCM vest design: ergonomic (left) and enhanced protection (right)

The distribution of PCM packages in the vest took in consideration different variables namely the amount of PCM in each package, and the size and the amount of the PCM packages to achieve a commitment between heat management and breathability.

Considering SUCAM guidelines for garments with PCM packages and the different parameters concerning PCM packages distribution in the vest, the integration of PCM packages is described schematically on Figure 5.

Figure 5. Study of the integration of PCM packages in the vest

As evidenced in Figure 5, PCM packages were integrated in a matrix composed by two layers, an insulation material and a flame retardance fabric. The introduction of the PCM packages through laser cut openings makes routine inspections and cleaning procedures described in SUCAM easy and allows the replacement of broken packages. Afterwards, this matrix was inserted into the vest main structure creating a PCM vest. In addition to making SUCAM procedure easier, the design of the vest considered also circular economy principles, since this removable system allows the separation of all the components of the vest making possible to recycle them.

4. Conclusions

The use of smart textiles, and in this specific case textiles with PCM integrated, combined with conventional PPE can play an important role towards the increase of firefighter's heat protection.

Having in mind a modular approach that could fit both, wildland and structural firefighters, the analysis of the major differences between the respective protective clothing as well as a comparison of the prevailing standards and legislation was performed.

A first architecture of a PCM vest to be worn over the conventional protective clothing was designed based on the integration study done aiming at protecting mainly the torso to preserve ergonomics. Protective standards requirements, best practices mentioned by SUCAM and also circular economy and sustainable principles using techniques as eco-design were taken into account.

The study will proceed with testing and simulation measurements in straight collaboration with ENB (Portuguese national firefighters' school), towards the solution improvement.

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