ADVANCES IN FOREST FIRE RESEARCH

2022

Edited by
DOMINGOS XAVIER VIEGAS
LUÍS MÁRIO RIBEIRO

Usage of pouches with phase change materials (PCMs) to increase the thermal performance of a firefighter jacket - development and thermal behaviour evaluation of the multilayer system

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

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

**Corresponding author*

Keywords

Multilayer system; Phase change materials; Transient behaviour; Thermal performance

Abstract

In recent years, the growth in size and duration of wildland fires and the increasing demand for high-performance protective clothing have led Thermal Protective Clothing (TPC) research and development to seek solutions to minimise firefighter thermal load and skin burns. In this context, the present work was developed under the framework of the DIF-Jacket project (https://difjacketproject.fe.up.pt), where the main goal is to develop a new multilayer system with phase change materials (PCMs) to be used in a jacket of wildland firefighters and the subsequent development of an experimental procedure to evaluate its transient behaviour. For that purpose, a small-scale multilayer system was developed, which consisted of three layers: an outer textile layer, a pouch with PCMs (intermediate layer) and an inner textile layer. The pouch with PCMs was incorporated into the multilayer system to absorb the incoming heat from the environment, increasing the time a firefighter can be exposed to it. Subsequently, an experimental set-up was developed to evaluate the transient behaviour of the solution with PCMs, simulating the different phases to which a firefighter is exposed to (i.e., direct exposure to a radiative heat flux followed by a post-fire period). Therefore, the effect of some pouch-related parameters on the multilayer system thermal behaviour was studied, namely different geometries of the pouches (square and rectangular) and two types of PCMs. As main conclusions, similar tendencies were obtained with the square and rectangular pouches. The best temperature homogeneity of the PCM pouches was obtained with the macro encapsulated PCM. The incorporation of PCMs in the multilayer system significantly delays its heating. Further research must be conducted to delay even more the increase of temperature during the exposure time. Nevertheless, the described set-up can be used to analyse several opposing requirements of a multilayer system with PCM pouches integrated, allowing the correlation of geometrical features and properties of the system components (either textiles or PCM pouches) with the system transient temperature behaviour.

1. Introduction

The intense demands of Thermal Protective Clothing (TPC) market and the technological development in the textile industry encourage the development of protective clothing with high thermal protection while maintaining high comfort performance (G. Song and F. Wang, 2019; R. Paul, 2019). Emerging technologies have come into sight to minimize the heat stress felt by users exposed to a hot environment, such as cooling vests either with water perfused tubes (L.P.J. Teunissen *et al*., 2014) or incorporating Phase Change Materials (PCMs) (C. Gao *et al*., 2012). Recently, A. Fonseca et al. (2020) obtained promising numerical results showing the potential of phase change materials (PCMs) to increase the thermal protection of firefighters' bodies.

Phase change materials (PCMs) are materials that can be used to absorb/release energy in the form of latent heat through a phase transition (L. F. Cabeza *et al*., 2015; A. Fonseca *et al*., 2018). The incorporation of PCMs into firefighter's protective clothing can target absorption of metabolic heat produced by the human body (enhancing comfort) or absorption of heat from the environment (enhancing protection). R. Paul, (2019) stated that when PCMs are incorporated into the firefighter's protective clothing, they can absorb the heat metabolically produced by the human body during its melting process, giving the wearer a cooling effect. However, A. Fonseca *et al*. (2018) found that the optimum position for the PCM layer is the closest to the external heat source, since it favours a higher use of the PCM storage capacity and takes advantage of its high thermal inertia in a more efficient way. As this work targets protection enhancement, PCMs were incorporated into the firefighter's protective jacket to absorb the heat from the fire, thus increasing the time that the firefighter can be safely exposed to it. However, it is also crucial to release the energy accumulated during fire exposure, as excessive heat accumulation promotes the occurrence of third-degree burns, limiting the time the firefighter has to remove the garment. For that reason, the next step is to develop an innovative solution following the multilayer system of a convectional jacket structure with the addition of PCMs incorporated through pouches. Additionally, it is necessary to consider the transient behaviour of PCMs and, consequently, a new methodology for evaluating the protective clothing under transient conditions was developed.

2. Materials and methods

2.1. PCMs and its incorporation in the multilayer system

To incorporate the multilayer system of the firefighter jacket, two different PCMs were studied and their main thermophysical properties are presented in Table 1.

Table 1 - PCMs and their thermophysical properties; T_m, ΔH_m, C_p, k, and T_{max} stand for melting temperature, latent heat of fusion, specific heat, thermal conductivity and maximum operation temperature, respectively.

PCM	Form (at 25 ºC)	T_m / ºC	ΔH_m / kJ·kg^{-1}	c_p / kJ·kg^{-1}·ºC^{-1}	k / W·m^{-1}·ºC^{-1}	T_{max} / ºC
A	Solid (pure state)	69-73	120	2	0.6	90
B	Solid (powder)	77-85	75	2	0.1	110

In the PCMs pouches construction, a low thickness polymeric film was chosen due to its high thermal resistance and ability to maintain its excellent mechanical properties under hot severe environmental conditions. Square 7 cm x 7 cm pouches and rectangular 7.0 cm x 3.5 cm pouches were constructed in order to evaluate the effect of the pouch geometry. PCM A was melted before being incorporated into the pouches to have a more homogeneous distribution across the pouch. It was not necessary to melt PCM B since it was already a uniform powder (macro encapsulated in silica).

2.2. Experimental set-up for the evaluation of transient behaviour

The experimental procedure developed to evaluate the transient behaviour consisted of two different phases:

1) Heating phase – the sample is placed between the installation table and the IR lamp and therefore exposed to a constant radiant heat flux;
2) Cooling phase – the sample is removed from the installation (i.e., not exposed to a heat flux) and is left to cool down to room temperature.

The installation shown in Figure 1 was used to evaluate the sample transient behaviour. It consisted of a table and an IR lamp at the height of 30 cm from the table top, corresponding to a heat flux of 3.07 kW·m^{-2}. Additionally, a thermal camera was used to monitor the surface temperature of the sample and three data loggers to monitor the temperature on the sample's inner layer. The samples were placed in the laboratory 24 hours before testing to ensure they were in equilibrium with ambient conditions at the start of the test. As test stopping criteria of the heating phase, the maximum operating temperature of the PCM was used, i.e., 90 °C and 110 °C, respectively, for the tests with PCM A and PCM B (maximum obtained in, at least, one of the data loggers).

Figure 1 – Installation for the evaluation of samples transient behavior.

The tests were performed with the PCMs pouches and the assembly (outer layer + PCM pouch + inner layer), both insulated with extruded polystyrene (XPS) to maximize a unidirectional heat transfer. Also, XPS surface reflectivity was increased by applying a white coating to reduce temperature increase and prevent it from melting. The PCM pouches' mass to surface area ratio was also considered since the mass influences the amount of energy that the PCM will accumulate. Thus, a mass to surface area ratio of 0.38 $g \cdot cm^{-2}$ (maximum achievable ratio) was used to make a comparative analysis of the efficiency of the PCMs. The experimental set-up for the transient behaviour evaluation tests is shown in Figure 2.

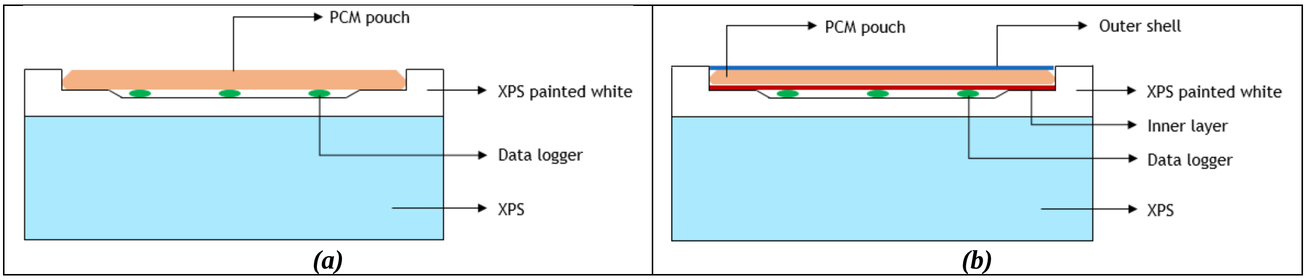

Figure 2 - Schematic representation of the experimental set-up for the transient behavior evaluation tests considering: (a) only the PCM pouch and (b) the assembly outer layer + PCM pouch + inner layer.

3. Results

This work focused mainly on evaluating the effects of the pouch geometry and the type of PCM introduced into it and, in addition, the influence of the incorporation of PCMs pouches into a firefighter jacket. Thus, the test described in section 2.2 was performed on square and rectangular pouches to study the transient behaviour of PCM pouches. Similar tendencies were obtained, so only the results obtained with the square pouches were included in this article. The comparison of the temperature profiles obtained during heating/cooling test of PCM pouches with PCM A or PCM B is shown in Figure 3. This figure contains the mean value (solid lines) of the temperatures of the three data loggers of three tests and the respective standard deviations (areas around the solid lines with the same colour).

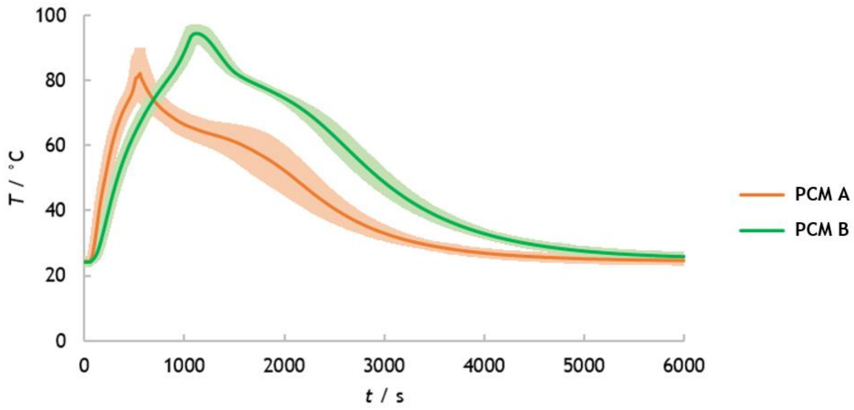

Figure 3 - Temperature profiles obtained in the PCM pouch during the heating/cooling test, considering PCM A and PCM B (three independent measurements per sample; standard deviation).

In Figure 3, it is shown that PCM B exhibits slower heating and cooling than PCM A, which can be explained by the fact that PCM B has a thermal conductivity six times lower than PCM A and equal specific heat (Table 1). The density of PCMs can also influence their heating and cooling rates. However, the supplier did not provide this information and, therefore, the density effect on the heating and cooling rates of the PCMs could not be analysed. In addition, PCM B is more homogeneous in the way it spreads across the pouch and it is easier to incorporate into pouches as it is already a uniform powder. As it is necessary to melt the PCM A before introducing it into the pouches, this PCM has the drawback of the appearance of air bubbles during the construction of the pouch. This air bubble is visible in the thermal camera image shown in Figure 4 and leads to a higher standard deviation in the results.

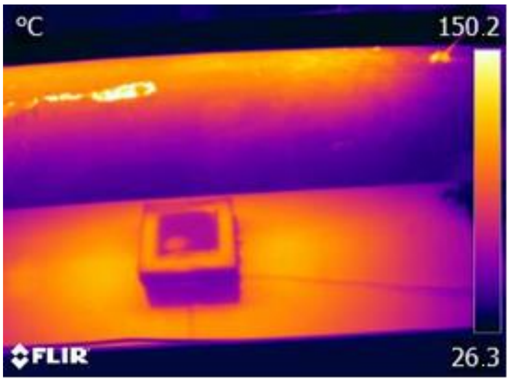

Figure 4 - Thermal camera image of the square pouch with PCM A after 4 min of exposure to IR radiation.

Lastly, the impact of the incorporation of PCM pouches on the thermal performance of the multilayer system was studied. PCM B was chosen for this study since it showed greater homogeneity (without bubbles) and was easier to incorporate into the pouches. The effect of the incorporation of PCM B on the sample's inner layer measured by the data loggers is presented in Figure 5, where the solid line is the mean value of the temperatures of the three data loggers of three tests and the area around the solid line with the same colour is the respective standard deviation.

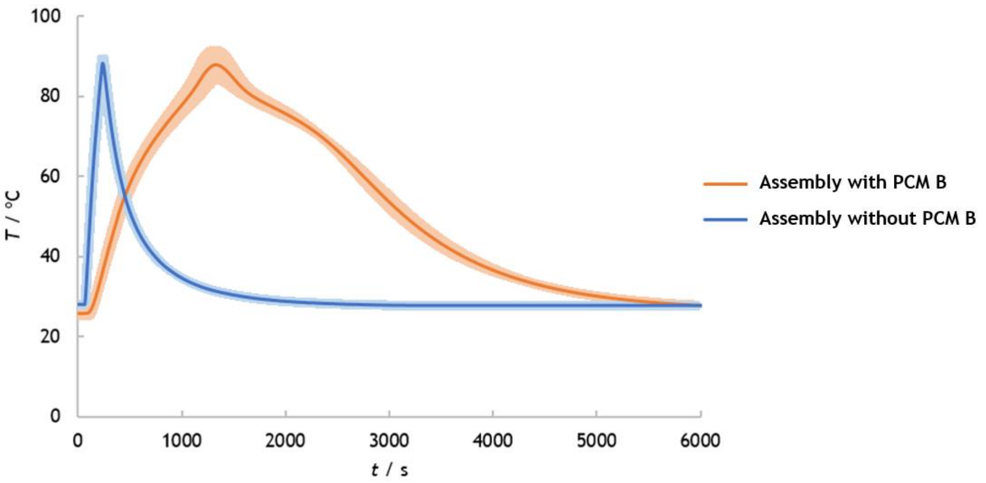

Figure 5 - Effect of the incorporation of PCM B on the multilayer system temperature (three independent measurements per sample; standard deviation).

Figure 5 shows that the assembly's behaviour without PCMs is different from the assembly with PCMs. During the exposure to the radiant heat flux, the assembly without PCM pouch (i.e., consists only of an outer shell and an inner layer) shows an increase in heating rate significantly sharper than the increase rate obtained for the assembly with PCM pouch, with an initial heating rate of 0.44 ± 0.01 $°C \cdot s^{-1}$. As the initial heating rate of the assembly with the incorporated PCMs is 0.09 ± 0.01 $°C \cdot s^{-1}$, it corresponds to a decrease of 79.5 %. This decrease is due to the fact that the assembly with PCM pouch has an additional layer, which provides higher thermal insulation (due to the addition of PCM and pouch material). Nevertheless, the effect of PCM latent heat on the pouch temperature is slightly evident at approximately 1600 s (beginning of the cooling phase); it is observed a slight change in the decline of the temperature profile. Further studies considering a large amount of PCM should be interesting to study. Although the incorporation of PCMs is beneficial since it decreases the heating rate of the assembly, it also dramatically delays its cooling by almost 4500 seconds.

As future considerations, to avoid the increase in the cooling time, further research must be conducted to delay even more the increase of temperature during the exposure time. Furthermore, it is important to study the impact of incorporating PCMs on the weight and on the evaporative resistance in the firefighter jacket. Also, since one of the most important considerations to be taken in the development of protective clothing is mass transfer, it is still necessary to optimise the performance of the developed multilayer system, considering relevant aspects related to mass transfer (e.g., the effect of the distribution/quantity of water inside the jacket on the occurrence of burns).

4. Conclusions

A multilayer system with integrated PCMs was studied at a small scale. The developed multilayer system consists of three layers: an outer shell, a PCM pouch, and an inner layer. An experimental procedure was also developed to evaluate the transient behaviour of PCMs pouches and the multilayer system, simulating different phases that a firefighter is exposed to in firefighting. As a result, the following conclusions were obtained:

- The pouch geometry does not significantly influence the thermal performance of the multilayer system;
- Powder rather than pure state PCMs must be selected to fill in the pouches to avoid operational problems. For instance, the macro encapsulated PCM showed the most promising results since it presented a greater homogeneity in its spread across the pouch and a more straightforward incorporation method into the pouches;
- The incorporation of PCMs is beneficial since it decreases the initial heating rate of the assembly, but it also dramatically delays its cooling.

Furthermore, the developed set-up can be used to analyse several opposing requirements of a multilayer system with PCM pouches integrated, allowing the correlation of geometrical features and properties of the system components (either textiles or PCM pouches) with the system transient temperature behaviour.

5. Acknowledgements

This work was financially supported by LA/P/0045/2020 (ALiCE), UIDB/00532/2020 and UIDP/00532/2020 (CEFT), and by PCIF/SSO/0106/2018 - Project for "Development of an innovative firefighter's jacket", funded by national funds through FCT/MCTES (PIDDAC).

6. References

G. Song and F. Wang, Firefighters' Clothing and Equipment, 1st Edition. New York, United States: CRC Press, 2019.

R. Paul, High Performance Technical Textiles, First Edit. Leeds, United Kingdom: John Wiley & Sons Ltd, 2019.

L.P.J. Teunissen, L.C. Wang, S.N. Chou, C. hsien Huang, G.T. Jou, H.A.M. Daanen, Evaluation of two cooling systems under a firefighter coverall, Appl. Ergon. 45 (2014) 1433–1438. https://doi.org/10.1016/j.apergo.2014.04.008.

C. Gao, K. Kuklane, F. Wang, I. Holmér, Personal cooling with phase change materials to improve thermal comfort from a heat wave perspective, Indoor Air. 22 (2012) 523–530. https://doi.org/10.1111/j.1600-0668.2012.00778.x.

A. Fonseca, S. F. Neves, and J. B. L. M. Campos, "Thermal performance of a PCM firefighting suit considering transient periods of fire exposure, post – fire exposure and resting phases," Appl. Therm. Eng., vol. 182, no. February 2020, p. 115769, 2021, doi: 10.1016/j.applthermaleng.2020.115769.

L. F. Cabeza, I. Martorell, L. Miró, A. I. Fernández, and C. Barreneche, Introduction to thermal energy storage (TES) systems. Woodhead Publishing Limited, 2015.

A. Fonseca, T. S. Mayor, and J. B. L. M. Campos, "Guidelines for the specification of a PCM layer in Firefighting Protective Clothing Ensembles," Appl. Therm. Eng., 2018, doi: 10.1016/j.applthermaleng.2018.01.028.