

PAPER • OPEN ACCESS

Thermal performance deterrence caused by PCM inclusion in firefighting garments: The other side of the story

To cite this article: A Fonseca *et al* 2021 *J. Phys.: Conf. Ser.* **2116** 012018

View the [article online](#) for updates and enhancements.

You may also like

- [Exploratory breath analyses for assessing toxic dermal exposures of firefighters during suppression of structural burns](#)
Joachim D Pleil, Matthew A Stiegel and Kenneth W Fent
- [Smart personal protective equipment \(PPE\): current PPE needs, opportunities for nanotechnology and e-textiles](#)
Rayan A M Basodan, Byoungyoul Park and Hyun-Joong Chung
- [Enhancing performance and reducing wearing variability for wearable technology system-body interfaces using shape memory materials](#)
Rachael Granberry, Crystal Compton, Heidi Woelfle et al.



The Electrochemical Society
Advancing solid state & electrochemical science & technology

242nd ECS Meeting

Oct 9 – 13, 2022 • Atlanta, GA, US

Early hotel & registration pricing
ends September 12

Presenting more than 2,400
technical abstracts in 50 symposia

The meeting for industry & researchers in

BATTERIES
ENERGY TECHNOLOGY
SENSORS AND MORE!



Register now!



**ECS Plenary Lecture featuring
M. Stanley Whittingham,**
Binghamton University
Nobel Laureate –
2019 Nobel Prize in Chemistry



Thermal performance deterrence caused by PCM inclusion in firefighting garments: The other side of the story

A Fonseca¹, S F Neves¹ and J B L M Campos¹

¹CEFT Transport Phenomena Research Center, Department of Chemical Engineering, Faculty of Engineering, University of Porto, s/n Rua Dr. Roberto Frias 4200-465 Porto, Portugal

E-mail: eq10026@fe.up.pt

Abstract. Firefighters usually encounter high heat flux exposures, which can cause severe burns. The addition of a phase change material (PCM) layer into a firefighting garment assembly has proven to be beneficial as it lowers the garments temperature during the fire exposure. However, after the fire exposure, accumulated heat in the PCM garment is discharged towards skin and environment which can have a negative influence on thermal performance. In this study, a one dimensional numerical approach was used to study the effect of environment parameters (ambient convective heat flux) as well as PCM parameters (latent heat, melting temperature) on the thermal performance of the firefighting garment, after the fire exposure. It was concluded that the amount and phase change temperature at which latent heat is discharged had a significant effect on thermal performance, depending on the heat exposure scenario. For high – intensity exposures, skin damage is promoted by an increase in both properties whilst for low intensity exposures, a decrease in melting temperature would promote greater skin damage. The results outlined in this paper could aid in the manufacture of PCM firefighting garments, as skin damage due to PCM resolidification might be an important parameter to take into account when maximizing thermal performance.

1. Introduction

Firefighters are known to face thermal stressful situations which may cause severe burns or even death [1]. Therefore, works in improving firefighting suits have been significant in the literature. A practical way to completely alter the fabric properties would be, for example, the addition of a phase change material. There are several studies reporting the benefits in incorporating a PCM in a firefighting garment suit. Recently, the current authors performed such a study where the different variables associated with the PCM which influence thermal performance were identified and studied [2].

Typically, the thermal performance of a firefighting suit is measured by taking into consideration only the heat exposure time until a burnout is registered. However, more recently, there has been recognition that thermal performance should also take the post fire exposure phase into account, as the accumulated heat in the garment can originate a skin burnout [3].

In this work, the influences of ambient parameters as well as PCM parameters on thermal performance are studied in detail for post fire exposures. A one-dimensional numerical study is carried out where the ambient convective heat coefficient as well as the PCM melting temperature and latent heat are subject to independent parametric studies in an effort to see their influence in the discharge of



the stored energy present in a PCM firefighting garment. The conclusions will allow for more informed decisions regarding the choice of PCM as well as aid in the design of PCM firefighting garments.

2. Methodology

2.1. Problem description

In order to analyze the effect of PCMs in enhancing the garment thermal protection, a typical firefighting protective clothing (FFPC)-skin system was used (Figure 1), consisting of a series of garment, skin layers, and air gap. The outer shell and thermal inner layers were considered to be a Kevlar®/PBI fire resistant fabric and an Aralite® fabric, respectively. The external surface of the garment (boundary 1 in Figure 1) was initially subject to a sudden heat flux during a certain amount of time. Three fluxes were chosen to reflect the different scenarios that firefighters can encounter: 84, 12 and 5 kW/m² [4]. After, the system was exposed to a chilled environment with defined ambient temperature and convective heat flux. Ambient convective heat flux, PCM melting temperature and latent heat, were subject to independent studies, to observe their influence on thermal performance. PCM mass was considered to be constant in each of the heat exposure scenarios

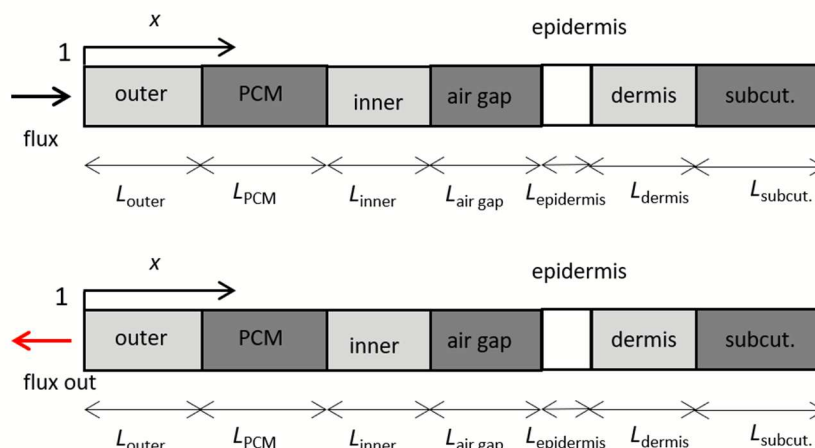


Figure 1. Geometry and boundaries of garment - skin system for heat exposure and cooling period

2.2. Geometries and boundary conditions

The firefighting garment is essentially composed of an outer layer, a thermal inner, and a PCM layer. An air gap between the thermal inner and the skin is also present (Figure 1). In this work, three heat exposure scenarios were considered. They include a low - and medium-intensity exposures (5 and 12 kW/m² for 5 min) corresponding to pre-flashover conditions, and a high intensity exposure (84 kW/m² for 8 s) representing flash fire conditions [4].

After the heat exposure scenario, the firefighter is likely to be exposed to a chilled environment. Windy conditions might be present as well as a reduced ambient temperature. In this work a constant ambient temperature is defined. Different ambient convective heat fluxes are considered (0-90 W/m²K) to simulate the presence of natural convection and strong winds caused e.g. by a blower fan or a helicopter nearby.

2.3. Mathematical model

The apparent heat capacity method was used to simulate the phase change (eq. 1) in the PCM layer.

$$\rho C_{app} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \cdot \left(k \frac{\partial T}{\partial x} \right) \quad (1)$$

where ρ , C_{app} , T , t and k , represent, respectively, density, apparent specific heat, temperature, time and thermal conductivity. The index app stands for apparent. Fourier heat transport was assumed in the remaining layers. In the air gap, radiative heat transport was also assumed according to eq. 2.

$$q_{rad}^{air} = \sigma \varepsilon_{eq} (T_{inne}^4 - T_{ski}^4) \quad (2)$$

$$\varepsilon_{eq} = \frac{1}{\frac{1 - \varepsilon_{shell}}{\varepsilon_{shell}} + \frac{1}{F_{inner-skin}} + \frac{1 - \varepsilon_{skin}}{\varepsilon_{skin}}} \quad (2b)$$

where, ε_{eq} , ε_{skin} , ε_{fab} , T_{inner} , T_{skin} , $F_{inner-skin}$ and q_{rad} represent, respectively, the equivalent, skin, and outer shell emissivity, the thermal inner and skin surface temperatures, the view factor between the thermal inner and skin, and the total radiative heat flux.

Numerical solutions were obtained on a FEM platform. Grid convergence tests were performed. A spatial mesh of 900 elements was used (200 for PCM layer). A varying order BDF solver was used to control the time step taken using relative tolerances of 10^{-5} and 10^{-3} for the exposure and post exposure phases respectively. The maximum time step allowed was 0.1 s. Validation of the model has been performed in other works [2,5].

2.4. Burn Criterion

The Henriques burn criterion was utilized to estimate the time to second degree burn (t_{2nd}). Essentially the damage (Ω) is equal to 1 when t_{2nd} occurs (eq.3). The PCM re-solidification damage (Ω_λ) was calculated according to eq. 4 where the indices “R” and “NR” refer to re-solidification and no re-solidification considered, respectively. This gives an idea of the skin damage done just by the latent heat released by the PCM in the post-exposure phase.

$$\Omega = \int_0^t P e^{-E_a/RT} dt \quad (3)$$

$$\Omega_\lambda = \frac{\int_0^{t_{2nd}^R} P e^{\frac{-E_a}{R T_R}} dt - \int_0^{t_{2nd}^{NR}} P e^{\frac{-E_a}{R T_{NR}}} dt}{\int_0^{t_{2nd}^R} P e^{\frac{-E_a}{R T_R}} dt} \quad (4)$$

3. Findings

PCM re-solidification mainly affects skin damage in low and high – intensity scenarios. Skin damage due to PCM re-solidification increases with an increase in melting temperature and latent heat (i.e. λ). This can have consequences in the PCM choice. For example, if considering PCM candidates with melting temperatures close to 100 °C, the one with the highest latent heat should be chosen (Figure 2a). However, if the PCM materials available have higher melting temperatures (i.e. 300 °C), not only is the t_{2nd} obtained much less, but it also doesn't rise with a higher latent heat (i.e. Figure 2a, 300 °C “R”). This happens due to the increase in PCM re-solidification skin damage with latent heat, which can almost account for 80 % of the total skin damage done (Figure 2b). In contrast, for the low-intensity heat exposure, PCMs with lower melting temperatures originate higher PCM skin damage (i.e. Figure 2d, 120 °C). The t_{2nd} rises with latent heat, but on the other hand, the PCM – resolidification becomes more influential on the burns obtained (Figure 2d).

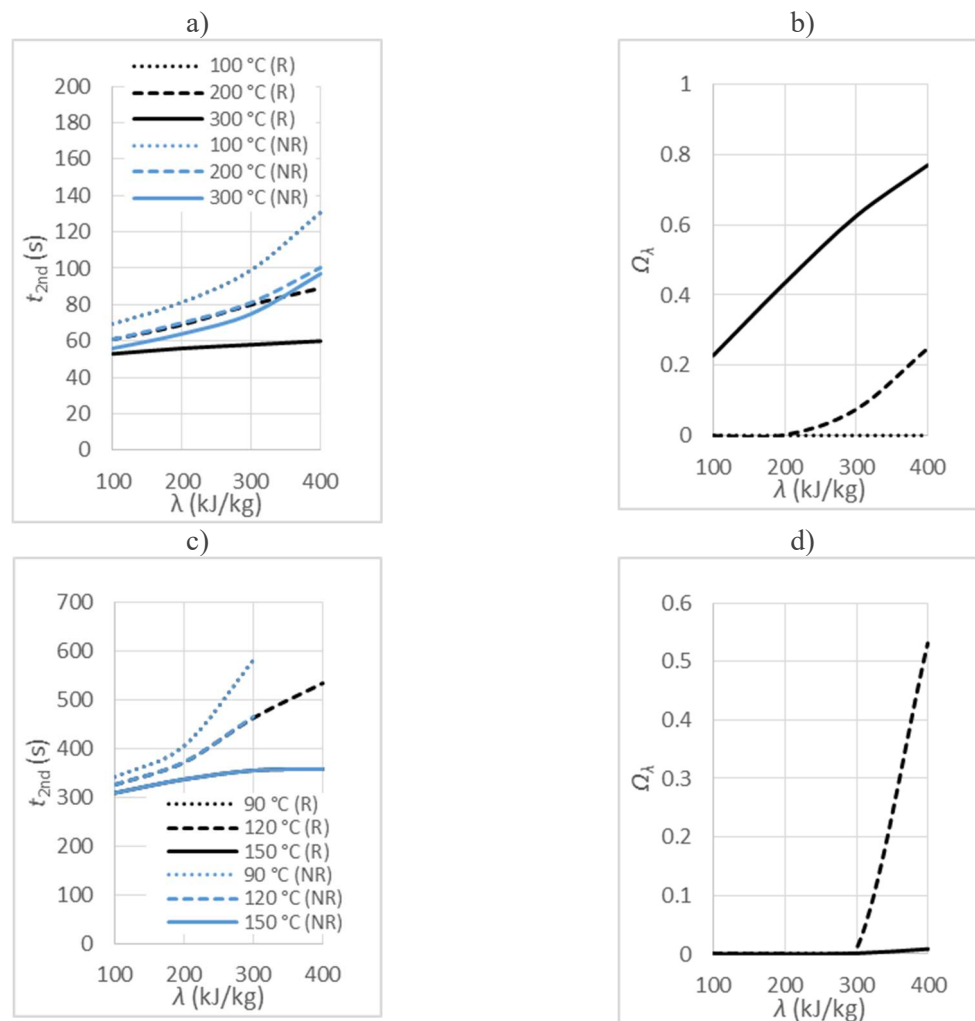


Figure 2. Time to second degree burns (t_{2nd}) and PCM skin damage (Ω_A) for the high- (a,b) and low- (c,d) intensity heat exposure scenarios.

4. Conclusions

A one – dimensional numerical model of a PCM firefighting garment has been considered where heat transfer was described by the Fourier equation and the phase change was modeled according to the apparent heat capacity method. Parametric studies were conducted involving ambient parameters (i.e. ambient convective heat transfer) to define various possible post - fire heat exposure scenarios, as well as PCM parameters (melting temperature and latent heat), for high-, medium- and low- intensity heat exposure scenarios. It has been shown that PCM re-solidification in post-fire exposure phases is responsible for significant skin damage. Solutions should focus on managing this latent heat rejection. Possible ones include removing the PCM from the suit after the fire exposure for example so that it can also regenerate faster.

References

- [1] Raimundo A M and Figueiredo A R 2009 *Fire Saf. J.* **44** 514-21
- [2] Fonseca A, Mayor T S and Campos J B L M 2018 *Appl. Therm. Eng.* **133** 81-96
- [3] He J and Li J 2016 *Text. Res. J.* **86** 235-44
- [4] Phelps H and Sidhu H 2015 *Fire Saf. J.* **74** 43-7
- [5] Torvi D A and Threlfall T G 2006 *Fire Technol.* **42** 27-48