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Effect of Phase Change Material Melting Points on Thermal Protection Behavior of Firefighters' Turnout Gear

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ABSTRACT

This study incorporated phase change material (PCM) in firefighters' turnout gear, aiming to harness the thermal protective properties of PCM to remarkably enhance the thermal protective performance (TPP) of turnout gear. It used an advanced 3D firefighters' turnout gear equipped human model for numerical simulations as a preliminary step toward designing and testing more advanced experimental models. The primary goal of this study is to determine the optimum melting temperature range and the corresponding location of PCM segments in turnout gear to maximize thermal protection. It was found that PCM melting temperature in the range of 50–80 °C could better protect the human body, and PCM location close to the clothing's inner surface could help further extend thermal protection time under high heat exposures. Utilizing PCM segments within firefighters' turnout gear could double the time required for the skin to reach second-degree burn injury compared to traditional gear lacking PCM technology. This research will provide valuable insights that can guide future experimental designs and contribute to the development of more effective protective gear for firefighters.

Keywords: 3D human thermal model, Firefighters' turnout gear, Phase change material, PCM melting point, Thermal protection enhancement

INTRODUCTION

Between 2018 and 2022, an average of 21,955 firefighter injuries occurred on the fireground annually in the United States, with thermal burns accounting for approximately 10% of these incidents (National Fire Protection Association, 2023). Firefighting remains one of the most dangerous occupations, and the risks firefighters face from thermal exposure highlight the urgent need for enhanced protective technologies. Turnout gear, the primary defense against fire hazards, plays a crucial role in safeguarding firefighters from thermal stress. The current firefighters' turnout gear thermal protective performance (TPP) rating must be no less than 35.0, equating to 17.5 seconds before second-degree burns occur in a flashover situation based on NFPA 1971 (Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting). However, it can take much longer time than a few seconds for firefighters to conduct rescue tasks in fire scenes. Hence, it is critical to enhance the thermal protection function of firefighter clothing for longer time protection under extreme heat conditions. One promising solution is the integration of phase change materials (PCMs) into firefighter turnout gear (Brundrett and Harmer, 2021).

PCMs are materials that can absorb substantial amounts of latent heat during their phase transition from solid to liquid, all while maintaining a constant temperature (Mondal, 2008). This unique thermal property makes PCMs an ideal candidate for improving the thermal protection of firefighter turnout gear. The integration of PCMs allows for the absorption of excess heat, providing a buffer that helps maintain safer body temperatures (below second-degree burn temperature, $\sim 60\,^{\circ}C$ (Coletta et al., 1976)) for the firefighter. When PCM melts, it absorbs heat from the environment, reducing the amount of heat transferred to the firefighter's skin. Once the PCM solidifies, it releases the stored heat, helping to regulate the temperature within the gear. This ability to stabilize temperature during extreme thermal events could significantly reduce the risk of thermal burns and improve overall safety for firefighters exposed to high-heat environments (Balaji et al., 2020).

The effectiveness of PCMs is dependent on their melting points, as different PCMs have different thermal properties. It is crucial to identify the optimal melting point for PCM integration into turnout gear to achieve the best thermal protection for firefighters. The ideal PCM should melt at a temperature that maximizes its protective capabilities. As such, understanding the relationship between the PCM's melting point and the heat exposure firefighters experience is essential for developing turnout gear that offers optimal thermal protection.

This study aims to explore and optimize the use of PCMs in firefighter turnout gear by determining the most effective PCM melting temperature range for turnout gear application. Numerical simulations will be employed to model the behavior of PCMs under fireground conditions, providing valuable insights into how different melting points affect the overall TPP of the gear. The TPP represents the time for the skin surface to reach second-degree burn under high heat exposures. The longer time the gear can hold skin below second-degree burn indicates better thermal protection. These simulations will serve as a foundation for the development of experimental designs and testing protocols, ultimately guiding the creation of more effective protective gear.

While existing numerical studies on fire protective clothing typically use one-dimensional (1D) models to assess heat transfer and protective capabilities (Fonseca et al., 2018; Fonseca et al., 2021; Hu et al., 2013; McCarthy and di Marzo, 2012; Zhang et al., 2021), there is a significant gap in the literature when it comes to the use of three-dimensional (3D) models for evaluating the full thermal performance of turnout gear. One-dimensional models often fail to account for the complex interactions between the gear and the human body in dynamic, real-world firefighting scenarios. In contrast, 3D models offer a more comprehensive approach by simulating heat transfer across the entire body and gear system, including the thermal effects on different body parts and how the gear performs during actual firefighting activities. These models are essential for accurately predicting the thermal protection provided by turnout gear and assessing the effectiveness of PCM integration.

Hence, this research will contribute to the development of more advanced 3D modeling techniques for evaluating fire protective clothing, which could improve the design and testing of future firefighter gear. The primary objective of this research is to identify the optimum melting temperature range and the corresponding location of PCM in firefighters' turnout gear to maximize thermal protection.

Ultimately, the findings from this study could lay the groundwork for the development of turnout gear with enhanced thermal protection. By optimizing PCM, this research has the potential to improve firefighter safety, reduce burn injuries, and provide more effective protective solutions for firefighters exposed to extreme heat on the fireground.

METHODS

A 3D human thermal body model was built in COMSOL Multiphysics (COMSOL, Inc., Burlington, MA 01803, USA). The Bioheat Transfer module in COMSOL was used for the heat transfer simulations.

3D Turnout Gear-Equipped Human Thermal Model

The human body model was built based on the anthropometric data of firefighters' bodies collected by NIOSH as explained in a previous publication by Xu and colleagues (2024). The firefighters' turnout gear model was built outside the human body. The overall thickness of the clothing was 6 mm (including the outer shell, moisture barrier, and thermal barrier), measured based on commercial firefighters' protective clothing (Globe GX-7 Firefighter JACKET Coat Size 36/32 Turnout Gear). Bio-based PCM (fatty acids) was used and embedded in the clothing material for thermal protection due to its nontoxic and thermally and chemically stable nature (PureTemp LLC). The PCM was broken into several segments to cover the body thermal zones – calf, thigh, abdomen, chest, back, and arms (ASTM F1291–16), but to avoid blocking joints to maintain firefighters' activities, as shown in Figure 1. The sizes of PCM segments were in the range of 4"–6.5", depending on the location they covered. The segments covering the limb areas were 4" × 11", while the segments covering the abdomen, chest, and back areas were 4.5" × 6" or 4.5" × 6.5" (Figure 1).

Based on the previous study, we found that 3-mm-thick PCM segments could achieve good thermal protection because it has sufficient thickness to provide enough thermal protection while not adding significant weight to firefighters' turnout gear (Xu et al., 2024). Hence, the 3-mm-thick PCM segments were applied to this study. Three different locations of PCM segments in turnout gear were explored, including 1-mm, 2-mm, and 3-mm below the outer surface of turnout gear, as shown in Figure 2. The PCM segment could replace part of the thermal barrier Hence, the overall thickness of the turnout gear clothing would not be increased. PCM melting points, using various PCMs in the range of 40–200 °C, were investigated to explore the optimum melting temperature range for turnout gear application.

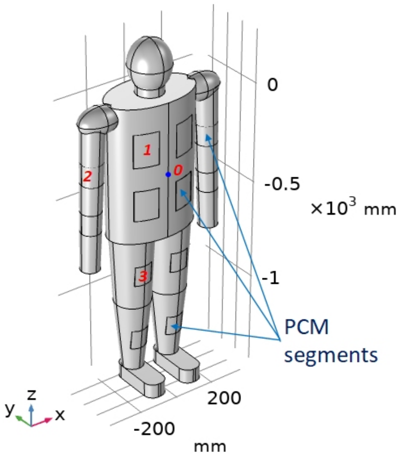

Figure 1: The 3D turnout gear-equipped human thermal model with PCM segments embedded in clothing. Probes 1–3 are at the locations directly protected by PCM segments.

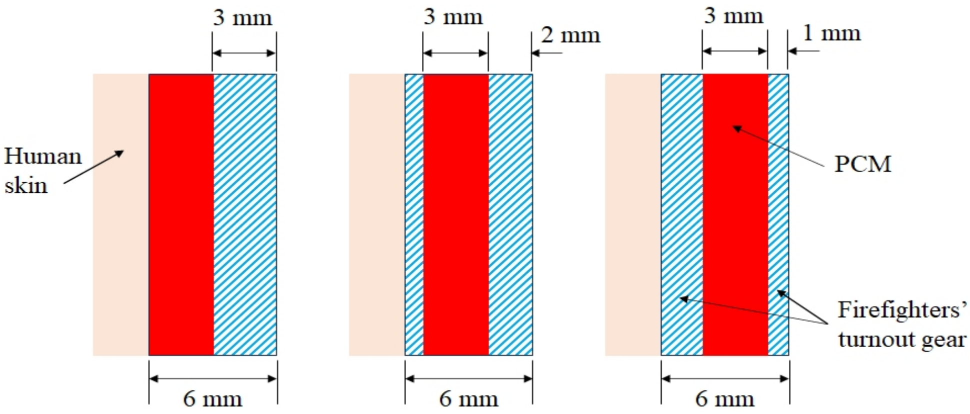

Figure 2: Locations of PCM segments in firefighters' turnout gear, located at 1-mm, 2-mm, and 3-mm (from right to left) below the outer surface of turnout gear. The PCM thickness is 3-mm (constant).

Three-dimensional (3D) heat transfer simulations were conducted for the firefighters' turnout gear-equipped human body. The transient heat diffusion equation was applied as the governing equation to simulate the thermal transport phenomena in turnout gear and PCM segments (Su et al., 2020; Xu et al., 2022). A bioheat source term was added to the heat diffusion equation for the human body to account for the effect of blood circulation on body heat transfer (Su et al., 2020; Xu et al., 2022). The equivalent heat capacity method was used to simulate the phase changing process of PCM segments (Xu et al., 2022; Xu et al., 2024). The thermophysical properties of human skin, firefighters' turnout gear, and PCM input into the model for numerical simulations are listed in Table 1.

Table 1: Thermophysical properties of human skin, firefighters' turnout gear, and PCM (ASTM F1930–18; Harris et al., 1982; Incropera and DeWitt, 2002; PureTemp LLC; Ventura and Martelli, 2009; Xu et al., 2022; Xu et al., 2024).

Layer of Protection	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (kJ/kg·K)	Latent Heat of Fusion (kJ/kg)
Human skin	0.36	1109	2.68	-----
Firefighters' turnout gear	0.30	500.0	1.30	
PCM	0.20 (avg.)	814.5	2.00	213.0

Boundary conditions: The turnout gear-equipped firefighter model was exposed to radiant/convective heat sources, mimicking the fire scenes. The heat fluxes of 83 kW/m^2 and 8.3 kW/m^2 were applied at the outer surface of the turnout gear in the simulation model as external heat sources, representing the flashover and hazardous conditions in the fire scene, respectively (Coletta et al., 1976).

Initial conditions: The initial temperature of firefighters' turnout gear was assumed to be 25 °C (typical room temperature). The initial human body temperature was maintained around 37 °C (the normal human core temperature). Governing equations can be found in our previous work (Xu et al., 2022; Xu et al., 2024).

Mesh for Modelling and Numerical Solution Reading Points

The finite element method was adopted for the numerical simulations. Free tetrahedral elements were used to establish the mesh structure for the 3D model (Xu et al., 2024). The mesh independent study indicated that the finer mesh size in COMSOL was sufficient for the human thermal model. Four (4) representative probes were built on the skin surface of the human model to record the skin surface temperature data during the heat exposures, as shown in Figure 1. Probe 0 is at the location where there is no PCM segment directly covering (protecting). It is used as the baseline for the comparison study. Probes 1–3 are at the locations directly protected by PCM segments. Probe 1 is located at the chest (human trunk area). Probes 2 and 3 are located at the arm and leg, respectively (the human limbs area).

HEAT TRANSFER ANALYSIS RESULTS

Figure 3 shows the times for skin surfaces at various locations (on the human trunk and limbs) to reach second-degree burn temperature (around 60 °C (Coletta et al., 1976)) when they were covered (protected) by different melting points of PCMs. Figures 3(c) and (d) give the correlations to predict the PCM thermal protection performances with respect to the melting points on the human body. The optimum melting temperature was observed in the range of 40–90 °C under flashover condition and 50–80 °C under hazardous condition.

In addition, the effect of PCM location in turnout gear on the temperature control performance was investigated. Figure 4 displays temperature profiles on the human body skin surfaces under flashover condition (heat flux of 83 kW/m^2). PCM melting point of 60 °C was selected in this study based on the optimum melting temperature range. It shows the temperatures on the chest (Probe 1) and arm (Probe 2) to represent the cases on the human trunk and limb, respectively.

DISCUSSION

This study investigated how the PCM melting points in firefighters' turnout gear affected the overall thermal protection capability. The PCM segment could enhance the thermal protection capability by 1–2 times when compared to the area not directly covered by PCM (Probe 0). The PCM melting points in the range of 40–90 °C and 50–80 °C provided the best thermal protection performance for the flashover and hazardous condition, respectively, as shown in Figure 3(a) and (b). Overall, the PCM melting temperature falling in the 50–80 °C interval could provide the best thermal protection for the firefighters' turnout gear application, and it showed similar optimum melting temperature intervals at different locations on the human body (Probes 1–3: chest, arm, leg). When the PCM melting point was too high (such as above 90 °C), it could not melt efficiently under heat exposures, losing the phase change function and, therefore, the thermal protection capability. Hence, the protection time decreased when the PCM melting point exceeded 90 °C. When the melting points were lower (around the skin's second-degree burn temperature), it showed better protection performance due to the effective phase change function and, therefore, the capability of maintaining skin temperature below the second-degree burn point. Under the flashover condition, the thermal protection time, defined as the duration for the skin surface temperature to reach 60 °C, remained within 45–55 seconds when the PCM had melting points between 40 °C and 90 °C. However, this duration decreased when the melting point exceeded 90 °C. Under hazardous conditions, the thermal protection time extended to 170–200 seconds when the PCM melting points ranged from 50 °C to 80 °C but declined when the melting point surpassed 80 °C.

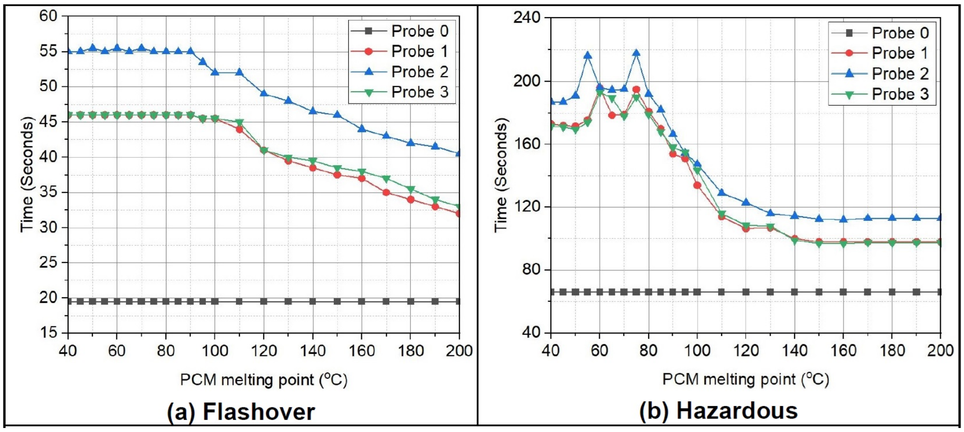

Figure 3: Time for the human body skin surface to reach second-degree burn temperature (60 °C) under (a) flashover and (b) hazardous conditions.

The PCM showed better thermal protection performance when it was located close to the inside of firefighters' turnout gear under high heat conditions, although the improvement in performance was not significant (Figure 4). This was because the PCM would melt faster and become a liquid state when it was located close to external heat sources, losing the phase change function early. When the PCM was close to the human body, it could slow down the melting process to extend the phase changing period and therefore the thermal protection time. In addition, the PCM segments could help double the thermal protection compared to conventional turnout gear without PCM (Figure 4).

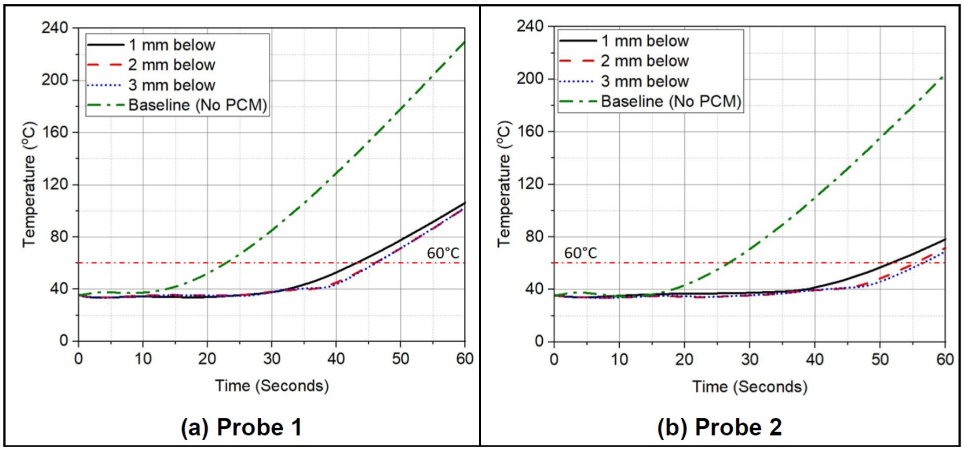

Figure 4: Temperatures on skin surfaces at the locations of (a) Probe 1 (chest – representing human trunk) and (b) Probe 2 (arm – representing limb) under flashover condition. (PCM melting point at 60 °C). The figures show a distinct pattern of slow temperature rise with PCM compared to no PCM condition.

Limitations and Future Directions

The human body in the simulation model was represented using various simple geometries, such as cylinders, cones, and ellipsoids (Figure 1), with dimensions based on the anthropometric data of firefighters. The primary objective of this study was to evaluate the thermal protection capabilities of PCM-integrated firefighters' turnout gear with respect to different PCM melting points. Despite the use of a simplified model, the observed trends in the results for the human body remained valid. To achieve more accurate simulation outcomes, a detailed human body model with realistic body curvatures will be developed and studied. Additionally, experimental studies using a human manikin will be conducted to validate the numerical model and assess the thermal protection performance of PCM-integrated turnout gear. In the experimental study, the PCM segments will cover the entire turnout gear to demonstrate that the use of a few representative PCM segments in the simulation model could show similar thermal transport phenomena at the PCM-covered areas as the fully covered turnout gear (helps to reduce computational costs).

CONCLUSION

This computational study investigated the impact of phase change material (PCM) melting points on the thermal protection performance of PCM-integrated firefighters' turnout gear. The findings indicated that the optimal melting temperature range for the best thermal insulation performance was between 50–80 °C. The study also developed correlations that describe the relationship between the time required for the human skin surface to reach second-degree burn injury and the PCM melting points under both flashover and hazardous conditions. Additionally, it was observed that the thermal protection time could be extended by approximately 5 seconds under high heat conditions when the PCM segments were positioned closer to the inner surface of the turnout gear, as opposed to near the outer surface.

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DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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