

# Design of Phase Change Material Integrated Firefighters' Turnout Gear Considering Moisture Content Effects in Heat and Post-Heat Exposure

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## ABSTRACT

Phase change materials (PCMs) are widely used for thermal management due to their ability to absorb, store, and release heat during phase transitions, typically between solid and liquid states. This study explores the enhanced thermal protection of turnout gear with integrated PCMs in various moisture conditions. A unique thermal model three-dimensional (3D) manikin was developed. The manikin was equipped with turnout gear and heat, and moisture transfer simulations were conducted under both heat and post-heat exposure scenarios. The effects of varying moisture concentration (MC), ranging from 0% to 100% added water, were simulated in turnout gear fabrics. Results showed that MC impacted thermal protection during heat exposure, with the shortest protection times for PCM-integrated gear occurring at MCs between 30% and 60%, compared to MC across the 0% to 100% range. However, MC had minimal impact on thermal performance during post-heat exposure. Based on a 3D human thermal model, a 2-mm-thick PCM segment was found to be the optimal choice, balancing both thermal protection during heat exposure and efficient cooling during post-heat exposure.

**Keywords:** 3D human thermal model, Firefighters' turnout gear, Moisture concentrations, Phase change material, Optimum PCM thickness, Heat and post-heat exposures

## INTRODUCTION

Firefighters can be exposed to a wide range of thermal conditions. In a recent report from the National Fire Protection Association (NFPA), more than 10% of injuries incurred in fire fields were caused by thermal stress and burns (Campbell and Hall, 2024). Hence, new research is needed to explore novel materials that can better protect firefighters from burn injuries and thermal stress at a fire scene. Phase change material (PCM) can absorb large amounts of heat while maintaining a constant melting temperature. In this study, we use this phenomenon of PCM to significantly enhance the thermal protection of current commercial firefighters' turnout gear. A 3D human thermal model equipped with turnout gear is vital for exploring the feasibility of integrating PCM into turnout gear and evaluating the resulting improvements in thermal

protection. This is the first study to simulate, and numerically explore, the heat and moisture transport phenomenon in PCM-integrated turnout gear on a human body, under heat and post-heat exposure, by using a 3D human model equipped with turnout gear.

In addition to heat exposure, turnout gear can be easily wetted by external water hose spray as well as the wearer's sweat. The effect of various moisture concentrations (MCs) on thermal behavior of PCM-integrated firefighter turnout gear is still unknown. Hence, this study explored the thermal transport phenomenon in the PCM-integrated turnout gear when there was moisture present in the fabrics. The optimum design of PCM segment thickness was determined by considering the thermal performance of turnout gear under both heat and post-heat exposures. This research aims to contribute to firefighter protection efforts as well as aid manufacturers who are developing and manufacturing advanced PCM-integrated firefighter turnout gear. The results from this study can be used to guide future experimental design and testing.

## METHODS

A 3D human thermal body model was built by COMSOL Multiphysics (COMSOL, Inc., Burlington, MA 01803, USA). The coupled Heat Transfer in Porous Media and Transport of Diluted Species in Porous Media modules in COMSOL were used for the heat and moisture transfer simulations (Xu et al., 2025).

### 3D Turnout Gear-Equipped Human Thermal Model

The human thermal model was built based on the 50 percentile anthropometric data of male firefighters' bodies collected by NIOSH (Hsiao et al., 2014). The firefighters' turnout gear model was built outside the human thermal body. The overall thickness of the clothing was 6 mm, which included the outer shell, moisture barrier, and thermal barrier, measured based on commercial firefighters' protective clothing (GLOBE GX-7 44 × 32 Firefighter Turnout Bunker Gear COAT JACKET RESCUE TOW).

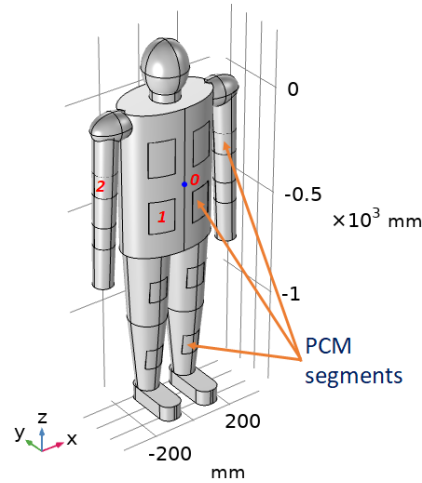
The 3D heat and moisture transfer simulations (Xu et al., 2025) were performed to investigate the thermal and moisture transport behaviors in PCM-integrated turnout gear during heat and post-heat exposures. The hazardous condition of an external heat flux of 8.3 kW/m<sup>2</sup> (Coletta et al., 1976) was applied at the outer surface of turnout gear in heat exposure. Natural convection from the surrounding environment (air temperature at 25°C, standard ambient temperature) was used as the boundary condition at the outer surface in post-heat exposure to mimic firefighters leaving the fire scene (Xu et al., 2025). Figure 1 shows the 3D human thermal model equipped with turnout gear. A bio-based PCM from PureTemp LLC, with a 60°C melting point (PureTemp LLC), was applied in turnout gear. To maintain firefighter movements and activities in fire scenes, PCM segments were used in the clothing instead of a whole layer of PCM. The PCM segments covered the important body thermal zones (ASTM F1291 – 16). The sizes of PCM segments were in the range of 4"-6.5", depending on the locations they covered (Xu et al., 2024). We investigated the temperature control performance of

turnout gear for the human trunk (e.g., abdomen) and limbs (e.g., arms), including the skin areas covered by PCM segments and those with no PCM covering. Three different thicknesses of PCM segments were studied under post-heat exposure, i.e., 1-mm, 2-mm, and 3-mm thick PCM (Figure 2). In addition, the effects of moisture concentrations (MCs) in the turnout gear were explored. The MC was determined by Equation (1) (Xu et al., 2025):

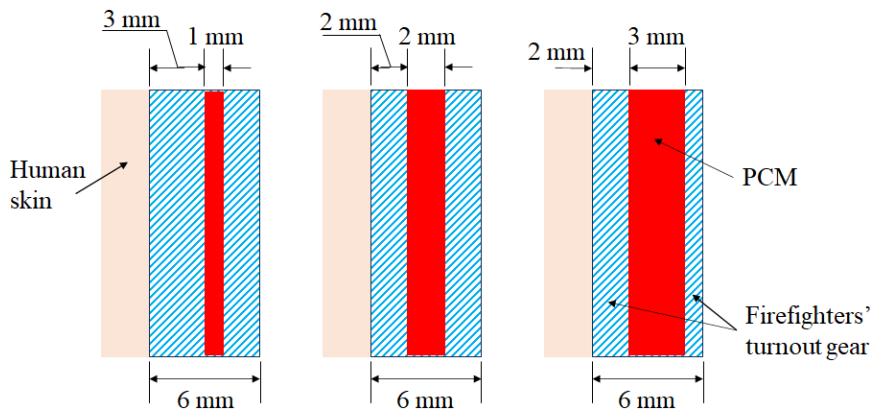
$$MC = \left[ (M_{wet} - M_{dry}) / M_{dry} \right] \times 100\% \quad (1)$$

where  $M_{wet}$  is the total mass of wet turnout gear;  $M_{dry}$  is the total mass of dry firefighters' turnout gear. The MC is the weight percentage of water added to the turnout gear fabrics (Xu et al., 2025).

Various MCs in firefighters' turnout gear (0-100 wt% of water added in clothing fabrics) were investigated to evaluate their effects on the thermal performance.



**Figure 1:** The 3D turnout gear-equipped human thermal model with PCM segments embedded in clothing (Numbers 0, 1 and 2 are the locations of probes to detect temperatures on the skin surface at those places).



**Figure 2:** Thickness distribution of PCM segments in firefighters' turnout gear (showing 1-mm, 2-mm, and 3-mm thickness PCM segments).

The material properties of PCM, human skin, and firefighters' turnout gear as well as the properties of water moisture are listed in Table 1, which were used for numerical simulations.

**Table 1:** Thermophysical properties of human skin, firefighters' turnout gear, PCM, and water moisture (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).

	Density (kg/m <sup>3</sup> )	Thermal Conductivity (W/m·K)	Specific Heat (kJ/kg·K)	Latent Heat (kJ/kg)
Human skin	1109	0.36	2.68	-----
Firefighters' turnout gear	500.0	0.30	1.30	
PCM	814.5	0.20 (avg.)	2.00	213.0 (fusion)
Water moisture	997.0	0.61	4.18	2442 (vaporization)

### 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 finer element size in COMSOL was chosen based on mesh independent study (Xu et al., 2024). Three (3) representative probes were built on the skin surface of the human model to record the skin surface temperature data during the heat and post-heat exposures, as shown in Figure 1. Probe 0 was at the location where there was no PCM segment directly covering (protecting). It was used as the baseline for the comparison study. Probes 1 and 2 were at the locations directly protected by PCM segments. Probe 1 was located at the abdomen (human trunk area). Probe 2 was located at the arm (human limbs area).

### HEAT AND MOISTURE TRANSFER ANALYSIS RESULTS

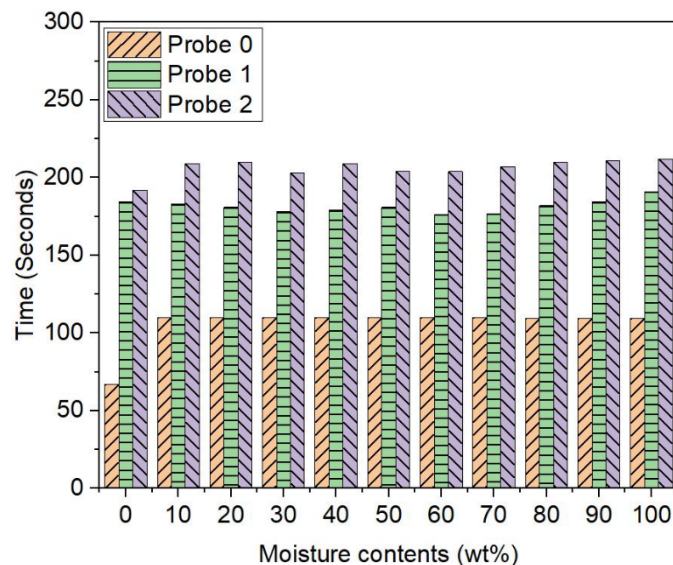
Figure 3 displays the times for the skin surface to reach second degree burn injury (~60°C (Coletta et al., 1976)) under hazardous condition (heat flux of 8.3 kW/m<sup>2</sup> (Coletta et al., 1976)). The thermal protection times for the PCM-covered skin areas (e.g., Probes 1 and 2) were the shortest when the MCs were in the range of 30-60 wt% in wetted turnout gear. Figure 4 shows moisture concentrations on skin surface during the heat exposure under hazardous condition.

In addition, the effect of MC and PCM thickness on the thermal dissipation of skin surface during post-heat exposure was investigated. Figures 5 and 6 display the skin temperature changes under different initial MCs and thicknesses of PCM segments under post-heat exposure, respectively.

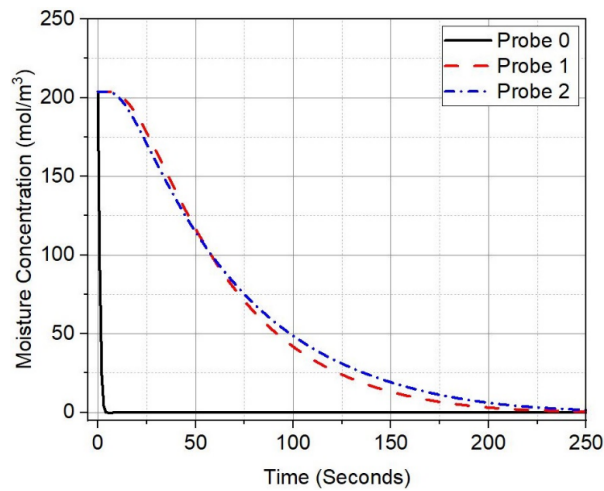
## DISCUSSION

The 3.0-mm PCM segments could significantly extend the thermal protection time on skin (Figure 3). The skin areas protected by PCM segments could double the protection time. The moisture contents would also affect the thermal performance in turnout gear. The MC increases the overall thermal conductivity ( $k$ ) and heat capacity ( $c$ ) of fabrics (see Table 1 material properties). Thus, the thermal protective performance of wet gear was the combined results from the increased  $k$  and  $c$ . The increased heat capacity value of wet gear played a major role in the area not covered by PCM segment. Hence, the thermal protection time at the uncovered area in turnout gear (Probe 0) extended when adding MC and MCs had a minor effect in wet gear. Both increased  $k$  and  $c$  affected the thermal protective performance at the areas covered by PCM segments (Probes 1 and 2) in turnout gear. The increased  $k$  value could increase the heat transfer rate (reduce the protection time), while the increased  $c$  value could decrease the heat transfer rate (extend the protection time) in turnout gear. Thus, the thermal protection times of the PCM-covered areas varied with MCs. They were the shortest when the MC was in the range of 30-60wt%. It is likely that the increased  $k$  dominated the heat transfer in this MC range. The protection time increased when the MC was beyond this range potentially due to the increased  $c$ .

For the area with no PCM coverage (Probe 0), the moisture transported (MC dropped) rapidly through the porous medium of the turnout gear, as shown in Figure 4. For the PCM-covered areas in turnout gear (Probes 1 and 2), the moisture transfer rate was slower potentially due to being blocked by the PCM segments (Figure 4). This moisture could still be dissipated (shown in Figure 4) through the areas not covered by PCM segments.

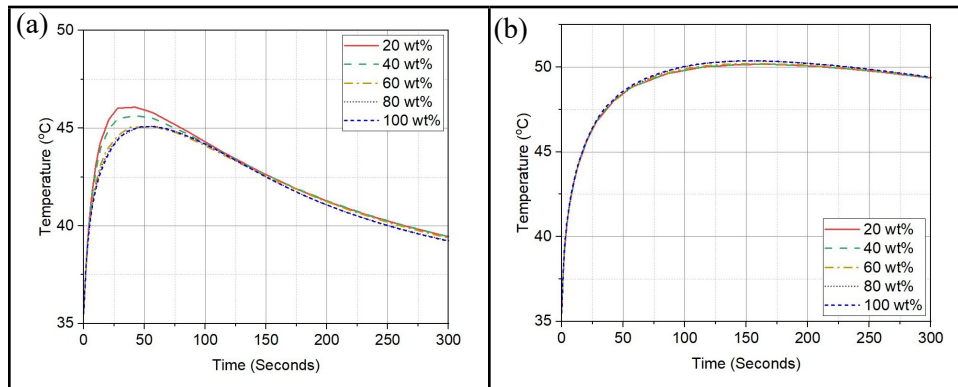


**Figure 3:** Times for skin surface to reach 60°C (second degree burn temperature) at various moisture concentrations under hazardous condition (external heat flux at 8.3 kW/m<sup>2</sup> (Coletta et al., 1976)). Note: Probe 0 detects the area not covered by PCM; Probes 1 and 2 detect the areas covered by PCM segments at human trunk and limb, respectively (see Figure 1). The 3-mm thick PCM segments were applied.

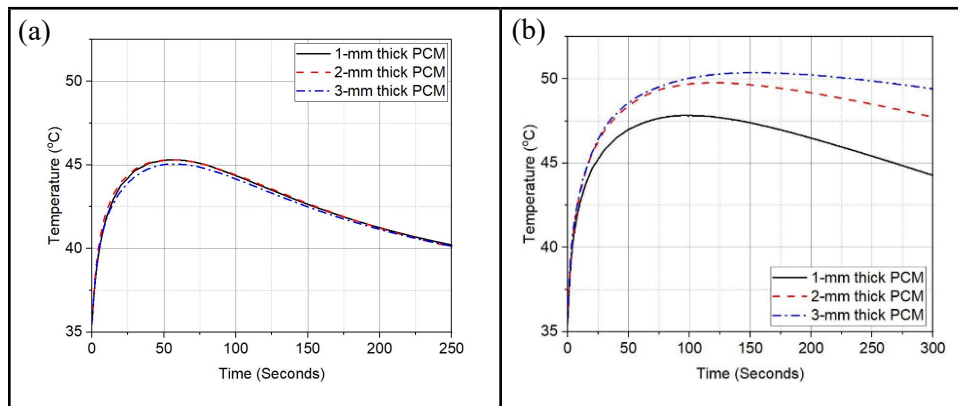


**Figure 4:** Moisture concentration on skin surface during heat exposure (hazardous condition: external heat flux at  $8.3 \text{ kW/m}^2$  (Campbell and Hall, 2024)). The 3-mm thick PCM segments were applied with 100 wt% initial MC in turnout gear.

Moisture could help reduce the skin temperature rise in the area not covered by PCM (Probe 0) due to the efficient water evaporation during post-heat exposure (Figure 5(a)). The effect of different MCs in the area covered by PCM segment (Probe 1) was minor under post-heat exposure (Figure 5(b)), potentially because the PCM segment was able to block the efficient moisture transport (Figure 4) and therefore led to inefficient water evaporation. The PCM segments reduced the cooling rate in turnout gear during post-heat exposure because they needed to release large amount of latent heat of fusion for solidification process. Hence, the skin area with no PCM coverage (Probe 0) cooled down faster, compared to that covered by PCM (Probe 1), as shown in Figures 6(a) and (b). The cooling rate at Probe 0 was not affected by the thickness of PCM, while that at Probe 1 changed with respect to the thicknesses of PCM segment. The thinner PCM segment resulted in a faster cooling rate on skin surface than the thicker PCM in post-heat exposure (Figure 6(b)), although the thicker PCM segment could provide better thermal protection under heat exposure (Xu et al., 2024). Therefore, the PCM thickness selection was based on the combined consideration between heat and post-heat exposures. The previous study by our team found that the 2-mm and 3-mm thick PCM segments showed good thermal protection performance in heat exposure (Xu et al., 2024). The 2-mm thick PCM also showed an efficient cooling rate (skin surface temperature did not exceed  $50^\circ\text{C}$ ) in post-heat exposure in this study.



**Figure 5:** Skin temperatures at various MCs under post-heat exposure. (a) Temperature 0 (area with no PCM coverage); (b) Temperatures at Probe 1 (PCM covered area); (The 3-mm thick PCM segments were embedded in turnout gear.



**Figure 6:** Skin temperatures for various thick PCM segments under post-heat exposure. (a) Temperatures at Probe 0 (area with no PCM coverage); (b) Temperatures at Probe 1 (PCM covered area). The case of 100 wt% initial MC was applied in turnout gear.

## LIMITATIONS

The 3D numerical model used regular geometries, such as cylinders, cones, and ellipsoids, to build a human body (Figure 1). It was not an exact human body configuration due to the limitation of geometry building in COMSOL Multiphysics. This might affect the simulation results, but the influence is expected to be minor and not impact the trends identified. The cylinders, cones, and ellipsoid geometries used to build the human body were very close to the configurations of real human body parts. The sizes and ratio of the cylinders and ellipsoids were based on the anthropometric data from real firefighter's calf, thigh, waist, chest, arm, shoulder and neck (Hsiao et al., 2014). Therefore, the model configuration was comparable to a real firefighter to achieve accurate simulations. In addition, although one piece of clothing with the average properties' values of fabrics was applied instead of separate layers of turnout gear, the simulation results may still well represent

the overall heat and moisture transfer behaviors in turnout gear. However, the limited environmental condition, PCM thicknesses and conditions, and turnout gear designs studied limit the generalizability of the findings. In the future, a more accurate model with separate layers will be studied to explore more detailed transport phenomena inside turnout gear.

## CONCLUSION

The 2-mm thick PCM segment in turnout gear seems to provide a good balance between thermal protection and decent heat dissipation rate when considering heat and post-heat exposures, respectively. Moisture concentration affects the thermal protection time during heat exposure but has only a minor effect during post-heat exposure in PCM-integrated turnout gear.

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## DISCLAIMER

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