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RESEARCH ARTICLE

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Modeling and Analyzing for Thermal Protection of Firefighters' Glove by Phase Change Material

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ABSTRACT

Firefighter injures caused by burns and thermal stress occupies around 5%-10% of the total injuries annually. Glove is the thinnest/weakest components among the firefighter turnout gear, which can put firefighters, are at risk of severe wrist and hand burns during fire calls. Burns can occur quickly and enhancing the thermal protective performance of firefighters' gloves will prevent these burns. One-dimensional (1D) heat transfer modeling and simulations were performed through the COMSOL Multiphysics software to investigate the improvement of thermal protective performance when integrating a Phase Change Material (PCM) layer into a conventional structural firefighting glove. Parametric studies were conducted to explore the effects of PCM thermal properties, layer thickness, and location in glove structure on hand protection. It was found that a PCM with a higher density, specific heat, and latent heat of fusion had a larger heat capacity and thermal inertia, resulting in better thermal protective performance. The optimum melting point of PCM was found to be in the range of 80°C–140°C. A PCM layer with a thickness of 0.5 mm–1.0 mm showed sufficient thermal protection. The location of the PCM layer should be close to the inner glove surface for high-heat situations. Overall, modeling suggests that the addition of a PCM layer could significantly enhance the thermal protective performance of firefighters' gloves, with results showing increased time (2–4 times as long) for skin to reach second-degree burn temperature when compared to the conventional glove without PCM.

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Structural firefighting gloves; Thermal protective performance; 1D heat transfer modeling and simulations; Novel material

Introduction

Firefighter injures caused by burns and thermal stress occupies around 5%-10% of the total injuries annually (NFPA statistics–Firefighter fire ground injuries by nature of injury). Firefighters could be at risk for severe and life-threatening burns during fire calls. They depend on Personal Protective Equipment (PPE) and protective clothing to maintain their safety. Firefighters' protective ensembles provide barrier protection from the dermal contact of hazardous materials such as heat, flame, and combusted product and include multi-layer garments, boots, and gloves. Minimal thickness and weight are necessary for protective gloves to ensure protection while not negatively impacting hand performance and function.

To comply with NFPA 1971 (Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting), the current structural firefighting gloves must meet the minimum requirement of a Thermal Protective Performance (TPP) rating of 35. This rating equates to 17.5 seconds until heat from flashover flames passes through the glove layers and causes second-degree burns on the hand i.e., until a temperature of 60°C is reached [1]. Neverless, the exposure to a high-temperature environment could be much longer than the few-seconds when firefighters are conducting the rescue tasks at fire scene to maintain protection for much longer exposures to extreme heat without causing burn injuries, it is critical to enhance the thermal protection function of these gloves. Hence, a thin layer of Phase Change Material (PCM) will be integrated into glove. The additional PCM layer can help achieve more efficient thermal protection without adding significant bulk. This would increase the protection from burn injuries while maintaining hand dexterity. When a material undergoes the phase changing process (e.g., *via* melting), it absorbs a large amount of heat (latent heat) while maintaining a

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constant temperature. Applying this PCM phenomenon to gloves may allow gloves to achieve efficient temperature control and therefore, significantly delay the time to cause second-degree burn injuries, under extreme heat conditions.

Microencapsulated PCMs (either micro-size diameter encapsulated PCM particles or micro-size thickness of laminated PCM films) have been studied for thermo-regulation in textiles. It was found that incorporating microencapsulated PCMs with melting points in the range of 15°C–35°C in garments could help improve human thermal comfort in both hot and cold environments [2,3]. In a hot environment, the PCM melts, absorbing large amounts of heat to mitigate the temperature increase for the human body. In a cold environment, the PCM solidifies, thereby releasing the heat to keep the human body warm. Furthermore, several researchers have also investigated thermal protection by microencapsulated PCMs in firefighters' protective clothing [4-8]. However, it was found that unlike in thermo-normal environmental conditions (e.g., 15°C–35°C), mixing a micro-size particle or film of microencapsulated PCM within firefighters' protective fabrics does not provide a large enough heat capacity for significant temperature control under extremely high temperatures [4-7]. A few researchers studied the application of a bulk PCM layer (i.e., 0.5 mm–10 mm thickness of PCM) in firefighters' protective clothing and found that (i) the clothing temperature could be reduced by 8.5°C through adding a 3 mm PCM layer in clothes and (ii) the PCM layer could extend the time to reach second-degree burn by up to two times for clothes [9-11]. Nevertheless, current work undertook limited parametric studies on gloves.

The criteria to determine the thermal protective performance of structural firefighting gloves is the duration of time before reaching the second-degree skin burn temperature (~60°C) after exposure to a flashover flame [1]. Therefore, the purpose of this research was to determine how adding a layer of PCM to firefighters' gloves can increase the time before skin temperature reaches 60°C. This study numerically simulated the thermal protection afforded by firefighters' gloves with an integrated bulk PCM layer. Parametric studies were conducted on heat transfer models to systematically explore the effects of PCM thermal properties (i.e., PCM melting point, latent heat, density, and specific heat), PCM layer location and thickness, environmental heat sources (convective, radiant, and conductive heat sources), and blood circulation under the skin on the thermal performance of PCM-integrated firefighters' gloves. These parametric studies were explored under different conditions that firefighters may face in fire scene, i.e., explosive/flashover; hazardous conditions as well as direct conductive contact to hot object conditions. The current NFPA 1971 standard only gives the minimum time requirement for a flashover condition. This work expanded beyond that to explore thermal protective performance of glove under all the conditions.

Materials and Methods

One-dimensional heat transfer simulations were conducted through the COMSOL Multiphysics software heat transfer module. The numerical modeling geometry is shown in Figure 1. A typical structural firefighting glove includes four layers: inner thermal lining (base layer), thermal barrier, moisture barrier, and outer shell. This provides three potential locations for integration of a PCM layer as indicated in Figure 1 (i.e., L3, L4, and L5).

The numerical model also included the skin on the hand which was assumed to be 2.5 mm thick based on the average skin thickness around the human body (Skin functions and Layers) (Figure 1(a) model). To investigate how blood circulation under the skin affects the hand skin temperature control, the skin bioheat transfer model (ASTM F1930-18) (Figure 1(b) model) was included in the numerical simulations. According to the ASTM F1930-18, human skin can be further detailed into three layers: epidermis, dermis, and subcutaneous.

The heat diffusion (energy) equation, as expressed in Equation (1), was applied to simulate the conduction heat transfer between the glove structure and hand skin [12]:

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + Q_{bio} \quad (1)$$

Here, ρ is density, c_p is specific heat, k is thermal conductivity, T is temperature, t is time, and Q_{bio} is the bioheat source term indicating heat transfer by blood circulation, which only occurs in the dermis and subcutaneous layers of the skin. There is no blood circulation in the epidermis layer. The bioheat source term is expressed by Equation (2) per [13]:

$$Q_{bio} = \rho_b c_{p,b} \omega_b \left(T_b - T\right) + Q_{met} \quad (2)$$

Where ρ_b is density of blood (1060 kg/m^3), $c_{p,b}$ is specific heat of blood (3.93 J/g.K), ω_b is the rate of blood perfusion in skin (0.00125/s), T_b is blood temperature (37°C), and Q_{met} is metabolic heat source (assumed zero in skin) [14,15].

For PCM, the equivalent heat capacity method was adopted for the phase change simulations in COMSOL. The latent heat of fusion of PCM is integrated into the specific heat, as expressed in Equation (3), for the phase changing process [15]. The natural convection in molten PCM is negligible in this study.

$$c_p = \frac{1}{\rho}\left[\rho_s c_{p,s} + \left(\rho_l c_{p,l} - \rho_s c_{p,s}\right) B\left(T\right)\right] + L\frac{\partial \alpha}{\partial T} \quad (3)$$

Here, $c_{p,s}$ and $c_{p,l}$ are the specific heats of solid and liquid state PCM, respectively; ρ_s and ρ_l are the densities of solid and liquid state PCM, respectively; L is the latent heat of fusion of PCM; $\frac{\partial \alpha}{\partial T}$ is the Gaussian function used to account for the latent heat during phase change; B(T) is the liquid fraction (ranging from 0 to 1) used to determine the change between solid (0) and liquid (1) phases of PCM, where values between 0 and 1 represent the melting mushy zone (B(T)) as detailed in Equation 4.

$$B(T) = \frac{T - T_m + \Delta T}{2\Delta T} \quad (4)$$

Here, T_m is the peak melting point of PCM and 2ΔT is the melting temperature range of PCM [15].

Boundary conditions

The temperature at the human skin base (the left-most point in Figure 1) was assumed to be maintained at normal internal body temperature, 37°C [14]. The surface of the outer shell of the glove was assumed to have either heat flux (representing convective and radiant heat flux) or constant temperature (representing direct thermal contact) boundary conditions [1]. The detailed heat flux or temperature data were indicated in Section 2. Moreover, there are air gaps between each of the glove layers as well as between the hand skin and glove. These air gaps were assumed to be 0.1 mm thick for perfectly fitting gloves based on the surface roughness of textile fabrics.

Initial conditions

The initial glove temperature was assumed to be room temperature at 25°C. For the model shown in Figure 1(a), the initial surface temperature of the skin was assumed to be 34°C (typical average skin temperature). For the model shown in Figure 1(b), the initial temperature distributions from the base of the subcutaneous layer to the surface of the epidermis were assumed to be 37°C, 35°C, and 34°C in the subcutaneous, dermis, and epidermis layers, respectively, thereby, representing a linear distribution [14].

Model characteristics

The extremely fine mesh size was selected for the modeling. The maximum element size was 0.115 mm. Around 105 mesh elements were established in the entire finite volume domain, which was sufficient to achieve a consistent convergence for this 1D heat transfer simulation.

The properties of each layer of structural firefighter glove are shown in Table 1. The properties are based on the materials of each layer. Commercially available bio-based PCMs were used in this study. Bio-based PCMs will be non-toxic and thermally and chemically stable. PCMs with different melting points commercially available from PureTemp® LLC were integrated into the structural firefighter glove for numerical investigation. The thermal properties for these PCMs are displayed in Table 2. The properties of the hand skin, including subcutaneous, dermis, and epidermis layers, are shown in Table 3.

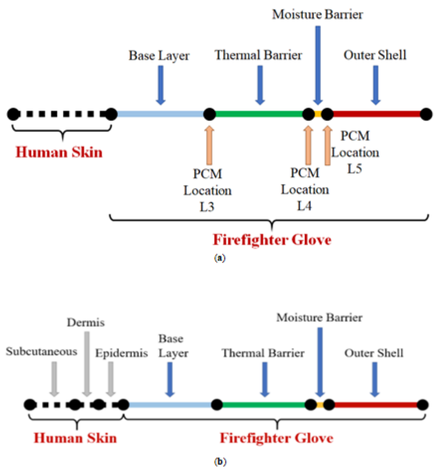

Figure 1. 1D numerical modeling geometry for a typical structural firefighter glove: (a) considering average skin thickness (no bioheat transfer) – no blood circulation; (b) considering bioheat transfer in human skin (epidermis, dermis, and subcutaneous layers) – considering blood circulation.

Table 1. Typical firefighter glove material properties [16-20].

	Materials	Thickness (mm)	Density (g/ml)	Thermal Conductivity (W/m.K)	Specific Heat (J/g.K)
Inner thermal lining (base layer)	Insulated cotton lining	1	0.134	0.05	1.865
Thermal barrier	Fire retardant cotton	1	0.520	0.1	1.3

Moisture barrier	PTFE, Teflon	0.1	2.285	0.25	1.03
Outer shell	Reinforced double layer Kevlar padding	1.5	0.567	0.8	1.3

Table 2. Thermal properties of bio-based PCMs from PureTemp company (PureTemp LLC).

Products	**PCM 44**	**PCM 53**	**PCM 60**	**PCM 68**	**PCM 151**
Melting Point (˚C)	44	53	61	68	151
Latent Heat (J/g)	180	225	220	213	217
Thermal Conductivity, Liquid (W/m.K)	0.15	0.15	0.15	0.15	0.15
Thermal Conductivity, Solid (W/m.K)	0.25	0.25	0.25	0.25	0.25
Density, Liquid (g/ml)	0.87	0.84	0.87	0.87	1.36
Density, Solid (g/ml)	0.97	0.92	0.96	0.96	1.49
Specific Heat, Liquid (J/g.K)	2.15	2.60	2.38	1.91	2.17
Specific Heat, Solid (J/g.K)	2.01	2.36	2.04	1.85	2.06

Table 3. Properties of human skin layers (ASTM F1930-18).

	Epidermis	**Dermis**	**Subcutaneous**
Thickness (mm)	0.075	1.125	3.885
Thermal Conductivity (W/m.K)	0.6280	0.5820	0.2930
Density (g/ml)	1.109	1.109	1.109
Specific Heat (J/g.K)	3.968	3.773	0.234

Model optimization

To determine the PCMs with the most potential for successful incorporation into firefighters' protective gloves, parametric studies were conducted to explore the effects of PCM thermal properties on glove thermal insulation performance. The melting point (T_m), latent heat of fusion (L), specific heat (c_p), and density (ρ) are the four major PCM properties that were optimized in this model. The variations of these thermal properties were based on the data of current commercial bio-based PCMs (see Table 2). Because the thermal conductivity values of bio-based PCMs are quite consistent, the data in Table 2 were used directly in the simulations. The location and thickness of the PCM layer were also optimized. Three different PCM thicknesses were examined, including 0.5 mm, 0.75 mm, and 1 mm. It is not expected to have the PCM layer greater than 1 mm in thickness when considering the dexterity of firefighters' hands during their work activities, because the average thickness of each glove layer is only around 1 mm as illustrated in Table 1. A PCM reference was created with T_m at 100°C, L at 200 J/g, c_p at 2.0 J/g.K, and ρ at 1.00 g/ml. The data of reference PCM are based on the average properties of bio-based PCMs on the market. The reference PCM layer was placed between the base layer and thermal barrier (location L3 in Figure. 1), whose thickness was set at 1 mm in this study. A firefighting glove no-PCM reference (baseline control) was also included in this study.

Convective and radiant heat flux model

When firefighters are working in fire scene, they are exposed to convective and radiant heat fluxes from fire flames. The total heat flux (including both convection and radiation) at the outer glove surface was 83 kW/m^2 for explosive/flashover conditions and 8.3 kW/m^2 for typical hazardous conditions according to Standard [1].

A firefighting glove without a PCM layer (baseline control) was also included in this study. Before the study, it was found through the simulations that it took about 17.5 seconds and 74.5 seconds for the baseline control glove to reach second-degree burn temperature under explosive/flashover and hazardous conditions, respectively. The result for flashover condition is consistent with that provided by the NFPA 1971 Standard which verifies the simulation model.

Conductive contact model

At fire scenes, conductive contact occurs when they must lift or grab hot objects. Heat energy is rapidly transferred from the outer surfaces of firefighter's gloves to their hands because of the pressure provided by hands while working and direct contact with hot objects [1]. Therefore, it is important to examine how thermal contact affects PCM performance in firefighters' gloves. The typical burning temperature that can cause hazards to firefighters through thermal contact is between 300°C and 1000°C [1]. To examine multiple temperatures within this typical range, hot object temperatures of 1000°C, 800°C, 600°C, and 400°C were applied at the outer surface of the glove as the boundary conditions in this study.

Initial conditions

The initial glove temperature was assumed

Results and Discussion

Effects of PCM thermal properties

With fixed values of L at 200 J/g, c_p at 2.0 J/g.K, and ρ at 1.0 g/ml, the glove's thermal protective performances under various T_m of PCMs were explored, as shown in Figure 2. From the simulation results, it can be concluded that the PCM layer with T_m ranging from 90°C to 140°C would provide the longest time (39 seconds) to reach the second-degree skin burn temperature under explosive/flashover situations (heat flux at 83 kW/m^2). Even the worst case showed twice as much time when compared to the baseline control (conventional glove without PCM). With the lower T_m of PCM (T_m below 90°C), the variations in T_m did not show significant effects on the glove's thermal protective performance. However, when the T_m was above 140°C, the glove's thermal protective performance dropped significantly with the increase of T_m because the skin tolerance temperature limit is only 60°C. When T_m is too high, the inner surface temperature of the glove is already beyond the skin second-degree burn temperature during the phase change process of the PCM.

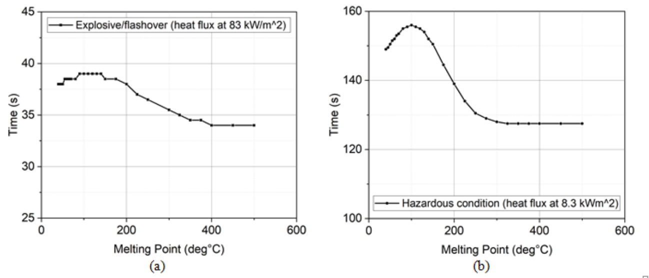

Figure 2. Time to second-degree skin burn temperature (60°C) under different T_m of PCM for (a) explosive/flashover situation (heat flux at 83 kW/m^2) and (b) hazardous condition (heat flux at 8.3 kW/m^2).

A similar trend was observed under hazardous conditions (heat flux at 8.3 kW/m^2). The PCMs with T_m in the range of 80°C to 130°C gave the best thermal protective performance, similar to the results obtained from the explosive/flashover situations. All times to second-degree skin burn temperature increased around four times (reached above two minutes) compared to the flashover situations.

Moreover, the effects of the PCM's L, c_p, and ρ on the glove thermal protective performance were investigated. The T_m of PCM was set at 100°C for the parametric studies. The results under explosive/flashover and hazardous situations are shown in Figures 3(a) and (b), respectively. All three factors (L, c_p, and ρ) showed their own linear patterns. Higher values of these factors resulted in better thermal protection because these factors directly contribute to the heat capacity of the material. The higher heat capacity resulted in larger thermal inertia of material, and therefore, longer times to reach second-degree skin burn temperature. Based on this optimization, the PCM from PureTemp® with a melting point of 151°C (see Table 2) was determined to be the optimal PCM for firefighters' gloves due to the appropriate melting point and high heat capacity values. Therefore, this PCM was used for all subsequent analyses.

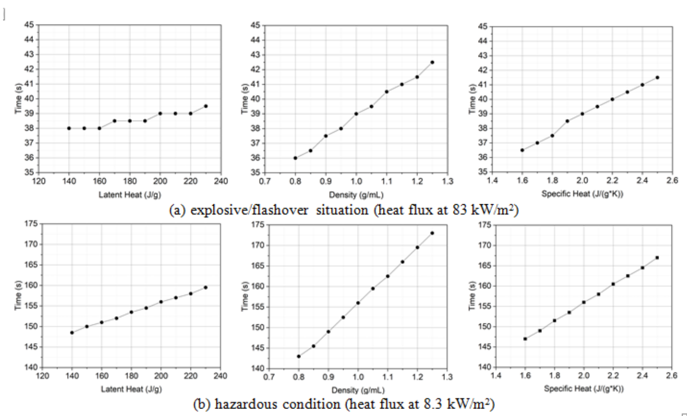

Figure 3. Times to second-degree skin burn temperature (60°C) – Effects of latent heat, density, and specific heat variations on glove thermal insulation performances for (a) explosive/flashover situation (heat flux at 83 kW/m^2) and (b) hazardous condition (heat flux at 8.3 kW/m^2).

Effects of PCM layer location and thickness

The location and thickness of the PCM layer in firefighters' gloves were investigated to improve thermal protection. Figures 4 and 5 show the PCM location and thickness studies under explosive/flashover and hazardous conditions. For the thickness study, the PCM location was set at L3 in the glove. The results showed that the greater thickness could provide longer times to the second-degree skin burn temperature, which leads to better thermal protective performance. Thicker layers mean more PCM encapsulated into the gloves, leading to higher heat capacity and thermal inertia to absorb more heat while melting.

For the PCM location study, the PCM thickness was set at 1 mm. The results under the two situations showed two opposite patterns. Under the explosive/flashover condition (heat flux at 83 kW/m^2), the PCM layer at location L3 provided the best thermal protection performance, while L5 exhibited the worst performance among the three locations. Under the hazardous condition (heat flux at 8.3 kW/m^2), the PCM layer at L5 showed the best thermal protection performance, and the PCM layer at L3 became the worst.

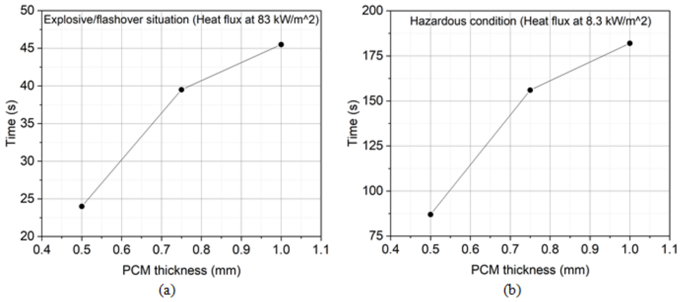

Figure 4. Effects of PCM thickness variations on glove thermal protection performance (times to second-degree skin burn temperature (60°C)) for (a) explosive/flashover situation (heat flux at 83 kW/m^2) and (b) hazardous condition (heat flux at 8.3 kW/m^2) (PCM at location L3).

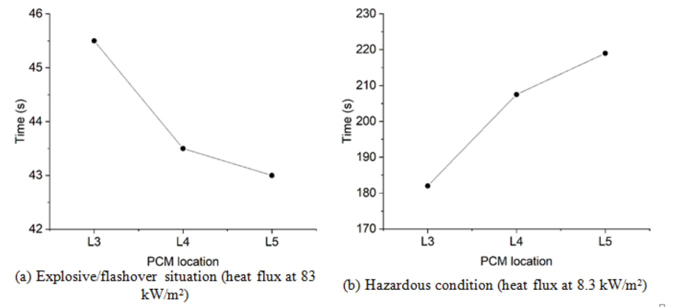

Figure 5. Effects of PCM layer location variations on glove thermal protection performance (times to second-degree skin burn temperature (60°C)) for (a) explosive/flashover situation (heat flux at 83 kW/m^2) and (b) hazardous condition (heat flux at 8.3 kW/m^2) (PCM thickness of 1 mm).

Under high heat flux conditions, the PCM located at L5 (closest to the outer environment) melted rapidly and stayed in liquid phase, losing its phase change function. Hence, the time to protect skin from second-degree burn injury was relatively shorter. When the PCM was placed at L3 (toward the inner surface of glove, close to hand), the thermal barrier layer, moisture barrier layer, and outer shell could effectively protect the PCM layer and help reduce its melting speed. Thus, the PCM layer could hold the temperature for a longer time, providing better hand protection compared to location L5. Therefore, under the explosive/flashover condition, a glove with a PCM layer at L3 showed the best thermal protective performance.

Under low heat flux conditions, it could take a longer time for the PCM layer at L5 to melt (undergo the phase change process). Hence, the longer melting time could help mitigate the rate of temperature rise in the glove, resulting in an increase in protection time for the hand. When the PCM layer was located at L3 (close to hand), it would take an even longer time to melt, resulting in the hand skin reaching second-degree burn temperature before the PCM melted. Thus, the phase change function was not effective in low heat flux conditions. The PCM located closest to the outer environment (L5) had better thermal protection due to its more efficient phase change under hazardous situations.

All the numerical modeling results for PCM-integrated structural firefighters' gloves show improved thermal protective performance compared to the baseline control glove without PCM. As previously stated, it took about 17.5 seconds and 74.5 seconds for the firefighters' glove without PCM to reach second-degree burn temperature under explosive/flashover and hazardous conditions, respectively. The incorporation of a 0.5 mm thickness layer of PCM showed 24.0 seconds and 87.0 seconds to reach second-degree burn (6.5 second and 12.5 second improvements) for explosive/flashover and hazardous conditions, respectively. When the thickness of PCM increased to 1 mm, the times could be significantly improved, up to 2–3 times longer compared to the baseline control (glove without PCM). The time extension, even by a few minutes or seconds, will be critical for firefighters to conduct rescues without compromising the safety of their hands.

Conductive heat sources (direct contact on hot surfaces)

The simulation results for 1000°C, 800°C, 600°C, and 400°C direct contact are shown in Figures 6(a), (b), (c) and (d), respectively. The parametric studies on the PCM layer thicknesses and locations were conducted for these heat sources. For the studies on PCM thickness effect, the PCM layer location was set at L3, while for the studies on PCM location effect, the PCM thickness was set at 1 mm.

All four groups of conduction simulations showed the same pattern, with the PCM layer at L3 providing the best thermal protective performance under conductive contacts. The direct contact accelerated the heat transfer from outside toward the hand in the glove structure. The PCM located closest to the outer environment (L5) melted very fast, losing the function of phase change. The times to second-degree burn injury were shorter than those under convective and radiant heat flux.

It took 10.5 seconds, 12 seconds, 15 seconds, and 22 seconds to reach second-degree burn injury for the baseline control glove without PCM under 1000°C, 800°C, 600°C, and 400°C thermal contact temperature, respectively. Therefore, all the results showed that PCM can improve the thermal protective performance of gloves under direct thermal contact conditions (even with the thinnest PCM layer at 0.5 mm). The greater thickness of PCM layer (0.75 mm or above) could significantly increase the thermal protection times by 3 to 4 times.

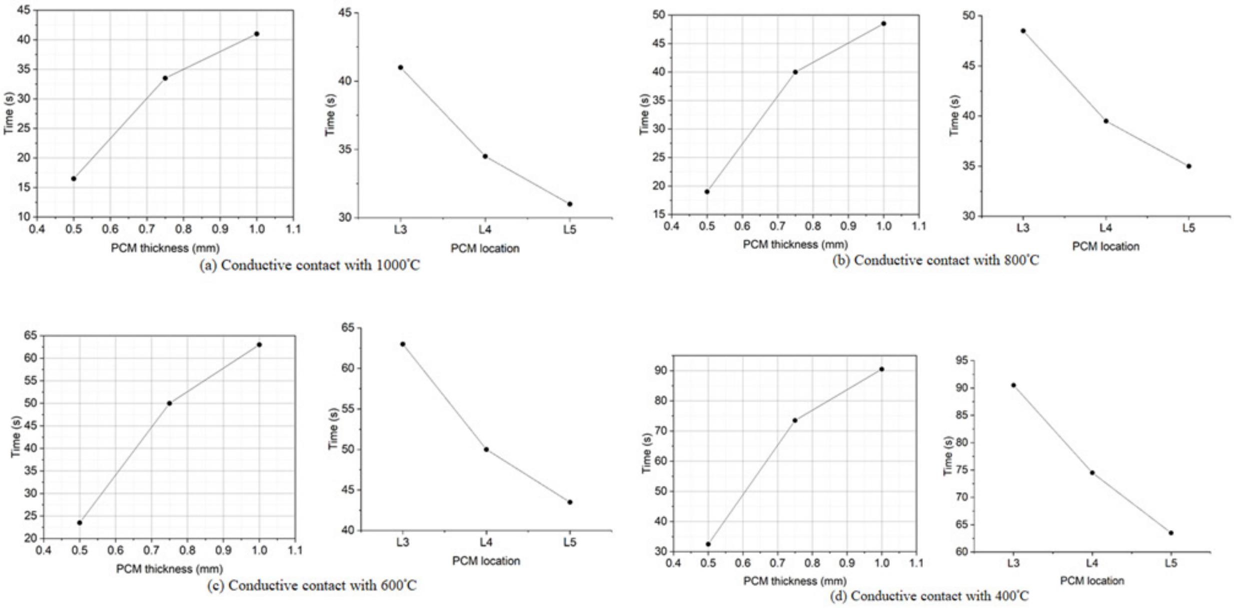

Figure 6. Effects of PCM layer thickness and location variations on glove thermal protection performance (times to second-degree skin burn temperature (60°C)) under (a) conductive contact at 1000°C, (b) conductive contact at 800°C, (c) conductive contact at 600°C, and (d) conductive contact at 400°C. (For the studies on PCM thickness effect, the PCM layer location was set at L3; for the studies on PCM location effect, the PCM thickness was set at 1 mm.)

Effect of blood circulation in skin

To discover if blood circulation in the skin has a significant effect on the hand skin temperature control in the fire scene, a skin bio heat transfer model (Figure 1(b)) was applied in this study. Figure 7 displays the comparison between the models with and without blood circulation under explosive/flashover and hazardous conditions. It was found that the blood circulation could remarkably affect the heat transfer in hand skin, and therefore, the thermal protective performance of gloves. The flow of blood could help enhance the heat transfer and increase the time to second-degree burn temperature on the hand skin. It was noticed that the blood circulation effect was more profound for the thinner layer of PCM (i.e., 0.5 mm thickness). While the thickness of the PCM layer increased, the effect of bioheat decreased but it was still considerable especially under the low heat flux condition (see Figure 7).

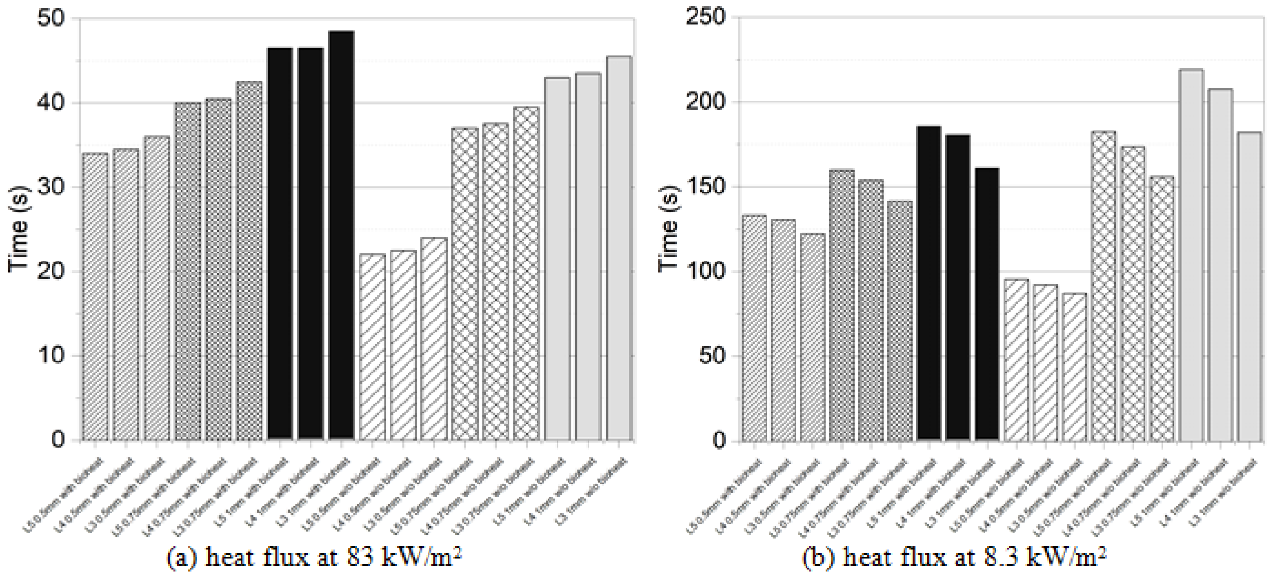

Figure 7. Times to second-degree skin burn temperature (60°C), considering the effect of skin bioheat transfer (blood circulation), under (a) explosive/flashover situation (heat flux at 83 kW/m^2) and (b) hazardous condition (heat flux at 8.3 kW/m^2). The x-axis shows the location and thickness of PCM layer in firefighters' glove.

When considering the effect of blood circulation, the times to second-degree skin burn temperature for the baseline control glove without PCM were 20 seconds and 76 seconds under explosive/flashover and hazardous conditions, respectively. Therefore, it was found that gloves integrated with PCMs of 0.75 mm or 1 mm thickness showed significantly greater improvements in thermal protective performances compared to the one with a 0.5 mm thick PCM layer.

Study limitations and future studies

This study was based on 1D heat transfer numerical models and did not consider moisture transfer in the glove and hand. A future NIOSH study will create three-dimensional (3D) models to simulate heat transfer in firefighters' gloves with PCM. The moisture transfer in the glove due to the hand sweating and external hose spray will also be evaluated in the 3D simulation model. The 3D model will help fine-tune the PCM distribution in gloves to achieve the (theoretical) best thermal protective performance for the hand. The dynamic humidity conditions at the exterior glove surface and inner hand sweating condition will be applied to the boundary conditions for the moisture transfer simulations. Moreover, experimental measurements for the PCM-integrated glove samples will be conducted to further demonstrate the simulation model and feasibility of incorporating PCM layer in firefighters' gloves.

Conclusion

Based on the 1D heat transfer numerical studies, it was found that adding one layer of PCM could significantly improve the thermal protective performance of firefighters' gloves in thermal conditions typical of fire scenes compared to the conventional gloves that do not include PCM. To achieve the optimum design of PCM-integrated gloves, the following parameters need to be taken into consideration:

• PCMs with higher density, specific heat, and latent heat of fusion should be used to provide larger heat capacity for better thermal protective performance.

• The ideal melting temperature of PCM is expected to be within the range of 80°C–140°C to achieve the best performance.

• The thicker the PCM layer, the better thermal protective performance can be achieved. However, the potential deleterious effects of increased glove thickness such as reduced dexterity should be considered. For thermal protection purposes, the PCM layer should be greater than 0.5 mm thickness. For hand dexterity purpose, the PCM thickness is not recommended to exceed 1 mm.

• The location of the PCM layer depends on the conditions expected at the fire scene. Under flashover (heat flux at 83 kW/m^2) and thermal contact conditions (400°C–1000°C direct contact), it is highly recommended to place the PCM close to the hand; under typical hazardous conditions (heat flux at 8.3 kW/m^2), it is better to locate the PCM closer to the outer environment.

All parameters should be collectively considered for the design of PCM-integrated firefighters' gloves. It was also found that the circulation of blood had a remarkable influence on heat transfer in the hand skin. Therefore, blood circulation should be considered in the thermal modeling of the hand.

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Disclaimer

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