Fire Safety Journal 156 (2025) 104444

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Effects of moisture contents on temperature control performance of structural firefighters' gloves with the incorporation of phase change material

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ARTICLE INFO

Keywords:
Structural firefighting gloves
Phase change material
Temperature control performance
Moisture content effect
Glove thermal protection improvement

ABSTRACT

Phase change materials (PCMs) are extensively utilized in thermal management applications. We examined thermal protection enhancement in structural firefighting gloves through the incorporation of PCMs, particularly under conditions influenced by moisture from hand sweating or external water sources. We conducted experiments to assess the impact of varying moisture content (MC) levels within glove fabrics on the temperature regulation performance of PCM-integrated firefighters' gloves. Three scenarios in fire settings were considered in the study, including contact with hot surfaces (conductive heat) and exposure to hazardous environments and flashovers (radiant/convective heat sources). Our findings indicate that under intense heat, the time before reaching a second-degree burn threshold (60 °C) on hand skin surface was minimized at lower MC levels. However, when the MC level exceeded specific values, the duration of thermal protection increased with higher moisture levels. The PCM integration extended thermal protection by between 1.4 and 2.1 times during direct contact tests and by between 1.2 and 1.5 times under radiant/convective heat exposures, compared to non-PCM gloves under similar wet conditions. Additionally, PCM layer's release of latent heat during solidification led to a prolonged temperature rise on skin surface at post-exposure, while moisture assisted in enhancing the thermal dissipation rate following heat exposure due to effective water evaporation.

1. Introduction

Firefighters often work in fire scenes under dangerous and harmful conditions, which can lead to unexpected accidents, injuries, and deaths [1]. Around 19,200 injuries occurred at firegrounds in the United States in 2021, with 6 % of these injuries caused by burns (including fire and chemical) and 5 % caused by thermal stress [1]. Personal protective equipment (PPE) can help reduce the risk of firefighter injuries when conducting rescue tasks in fire scenes. Firefighters' gloves are designed to protect firefighters' hands to avoid burn injuries in fire scenes. A typical structural firefighting glove has an outer shell, thermal barrier, moisture barrier, and inner thermal lining (base layer) from outside to inside [2].

The current commercial firefighters' gloves must meet the minimum requirement of a thermal protective performance (TPP) rating of 35 under flashover condition based on NFPA 1971 (Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting). The minimum TPP rating is equivalent to a 17.5-s protection time before skin temperature reaches second-degree burn injury (the skin temperature of second-degree burn injury is defined as occurring at 60 °C) [3,4].

1.1. PCM-integrated firefighter turnout gear

Firefighters always need sufficient time to stay in fire scenes and conduct rescue tasks without being injured [4]. Hence, the improvement of firefighters' PPE is very important. Increasing the TPP of firefighters' PPE is helpful in reducing the risk of injuries caused by burn and thermal stress. Phase change material (PCM) can absorb large amounts of latent heat of fusion during the phase changing (melting) process. Hence, the use of PCM in firefighters' gloves could enhance their TPP without

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https://doi.org/10.1016/j.firesaf.2025.104444
Received 9 December 2024; Received in revised form 6 May 2025; Accepted 2 June 2025
Available online 3 June 2025

significantly increasing the glove thickness due to the need for hand dexterity.

The most popular type of PCM used in thermal management applications is solid-liquid PCM due to the high latent heat of fusion and small volume change during phase transition (compared to solid-gas or liquid-gas phase changing process). Solid-solid PCMs could also have small volume change and fair amount of latent heat during the phase transition. However, organic and polymeric solid-solid PCMs show the slower phase transition rate, and organometallic and inorganic solid-solid PCMs have higher production costs [5]. While phase changing (melting or solidifying), the PCMs maintain a temperature around their melting points. Using this phenomenon, PCM technology can help to substantially enhance thermal protection without significantly increasing the thickness of firefighters' gloves (thus, not compromising the hand dexterity of firefighters).

In the early 1980s, integrating PCM into fabrics to increase thermal insulation performance was initially developed by the NASA research program [6]. More recently, researchers began to apply PCM to firefighters' turnout gear for thermal protection enhancement [6–12]. For instance, Su et al. [10] completed an experimental study on TPP of flame-retardant PCM firefighting protective clothing. Two types of PCMs, one with a melting point of 25 °C and the other with a melting point of 42 °C, were selected in this study. The PCM was coated on the fabric and exposed to a high heat flux of 84 ± 2 kW/m^2 for 45 s (flashover condition; combined radiant and convective heat source), which is the standard TPP testing condition based on NFPA 1971. The results indicated that the shortest second-degree burn time occurred while the PCM-coated fabric was placed in the mid-layer, and the PCM with a melting point of 42 °C provided a longer time of sample ignition since the PCM with a melting point of 25 °C partially melted before testing.

In a 2022 study, Xu et al. [7] developed a 1-D numerical model for firefighters' gloves to systematically explore the optimum parameters and properties of PCM. The model could also predict the second-degree burn time of the PCM-integrated structural firefighting gloves. The PCM with a melting point between 80 °C and 140 °C showed the best performance for firefighters' gloves in this model. The thickness of between 0.5 and 1.0 mm of the PCM layer could provide sufficient thermal protection. Considering the location of the PCM layer in the firefighters' glove structure, closest to the external environment while under the hazardous condition (8.3 kW/m^2) and closest to hand skin while under the flashover condition (83 kW/m^2) could provide better thermal protection than other locations under the same condition. Compared with conventional firefighters' gloves, the second-degree burn time of PCM-integrated firefighters' gloves could be increased between 2 and 4 times [7].

In addition, in a 2024 study, Wang et al. [9] conducted experimental tests to investigate the thermal protection improvements of firefighters' gloves by three bio-based PCMs with melting points of 68 °C, 108 °C, and 151 °C to verify the 1-D numerical model [7]. The results showed that the thermal protection time of samples with a PCM layer could be extended by between 2 and 5 times under a hot object direct contact test (200 °C conductive heat source), and it could be extended about 1.5 times under the condition of radiant/convective heat sources (furnace heating elements to provide 200 °C and 300 °C furnace environmental temperatures). PCMs with melting points of 68 °C and 108 °C provided better thermal protection performance than the PCM with a 151 °C melting point [9]. The experimental results showed consistent trends with the previous numerical studies, including the optimum PCM melting points identification and thermal protection time enhancement range by using PCM [7,9].

1.2. Effect of moisture contents on firefighter turnout gear performance

Water has been widely used during firefighting not only to put out the fire but also to reduce the temperature of structures in fire scenes to avoid collapsing. During firefighting, water could be easily poured or splashed on the firefighters' gloves. In addition, firefighters' hands would sweat while staying close to the fire scene. These two water/moisture sources could soak the firefighters' glove fabrics and affect their thermal properties.

Researchers have investigated moisture transport phenomena and effects in thermal protective clothing [13–20]. For instance, Barker et al. [14] conducted numerical and experimental studies to explore the effects of absorbed moisture on the TPP rating of firefighting clothing. A low-heat flux condition of 6.3 kW/m^2 was used in their heat transfer model and experimental setup. A total of seven moisture content (MC) levels of 0 % (dry), 5 %, 10 %, 15 %, 20 %, 50 %, and 100 % were explored in their study. The test results showed that with a relatively lower MC level (weight of water content <15 wt% of dry sample weight), the added moisture provided a negative effect, reducing the thermal protection time by around 10 %–20 % compared to the dry sample due to the increased thermal conductivity of wetted clothing. When the MC was above 20 wt%, the time to reach second-degree burn extended and reached the result of a dry sample, which matched their numerical predictions [14].

He et al. [18] conducted experimental research regarding the effect of air gap and moisture in thermal protective clothing under the condition of radiant heat flux 21 kW/m^2 (lower level of flashover condition). The test results also showed that 20 wt% MC was the key point for the TPP of moist thermal protective clothing. While the MC increased from dry conditions, the TPP rating decreased and reached the lowest value at 20 wt% MC. Beyond this key point, the time of skin temperature to reach a second-degree burn was extended with increased MC level due to the effect of increased specific heat of wetted clothing [18]. The phenomena were consistent with the previous studies at low heat flux conditions [14].

Sweating could also affect the TPP of firefighting clothing and lead to either improved thermal protection or burning injury, because different MC levels will affect the thermal conductivity and heat capacity values. Yang et al. [15] considered the sweating rate, the evaporation of sweat, change of blood flow, and metabolism in their bio-heat transfer model to investigate heat stress and skin burn under conditions of low-level thermal radiation (heat flux of 8.5 kW/m^2). By comparing their model to the old bio-heat transfer model (Pennes model [21]) without considering these factors, they found that the times to first-degree burn (44 °C) and second-degree burn (60 °C) were extended by between 28.3 and 37.8 s and between 31.9 and 70 s for the studied clothing samples, respectively [15].

Zhang et al. [20] conducted an experimental study to discover the effect of moisture management performance (MMP) on TPP of fire protective clothing under 8.5 kW/m^2 radiative heat source with four different continuous sweat rates (SR) of 0, 3, 10, and 19 μL/min cm^2. It was concluded that under continuously sweating conditions, the effect of MMP on firefighting clothing materials was more important than their thickness or weight. The fabric layer near the skin with good MMP could provide a better TPP rating and less absorbed heat, and therefore, the heat flux exchange at the skin was also decreased [20].

1.3. Current research gap and objectives of this study

There are limited studies on the influences of moisture content on the performance of PCM-integrated firefighters' turnout gear. Malaquias et al. [8] proposed a new mathematical model to investigate the thermal protective performance of PCM embedded fire protective clothing considering the presence of water. A three-layer (outer shell, moisture barrier, and thermal inner) structure was used in their study as the conventional firefighting clothing, and PCM was infiltrated in the thermal inner fabrics. The results showed the importance of considering moisture management in PCM embedded fire protective clothing for maximizing the PCM efficiency. Nevertheless, most of the current research on the effect of moisture contents on PCM-integrated firefighters' clothing was numerical simulation work. There are limited experimental studies. This research will experimentally investigate the thermal performance of PCM-integrated firefighters' gloves under different wet conditions.

In addition, most current research has been related to thermal protection clothing but not structural firefighting gloves [7,8,10,12–20]. Firefighters' gloves are usually thinner than clothing because of the need for dexterity [2]. While maintaining the dexterity of the hand, improving the thermal protective performance of gloves is necessary and essential [7,9]. Moreover, the investigations of the MC level effects on the PCM-embedded firefighting protective equipment, especially gloves, are very limited.

This is the first experimental study that holistically investigated the effects of different MC levels on PCM-integrated firefighters' gloves by conducting temperature control performance tests. In addition, the residual heat in the glove fabrics, the stored heat by PCM, and water vapor could also cause thermal burn injuries on firefighters' hands at post-heat exposure. There are limited studies on the heat and moisture transport behaviors of PCM-integrated firefighters' gloves at post-heat exposure [9,12]. This work is also the first experimental study that systematically investigated the effects of moisture evaporation and condensation in the post-heat exposure stage.

Therefore, the objectives of this research were to explore (1) the effects of different MC levels (0 %, 10 %, 20 %, 50 %, and 70 %) in firefighters' gloves, (2) the effect of PCM in glove fabrics under wet conditions, and (3) the influence of MC levels in PCM-integrated firefighters' gloves during the post-heat exposure period on the glove thermal protection performance through temperature control

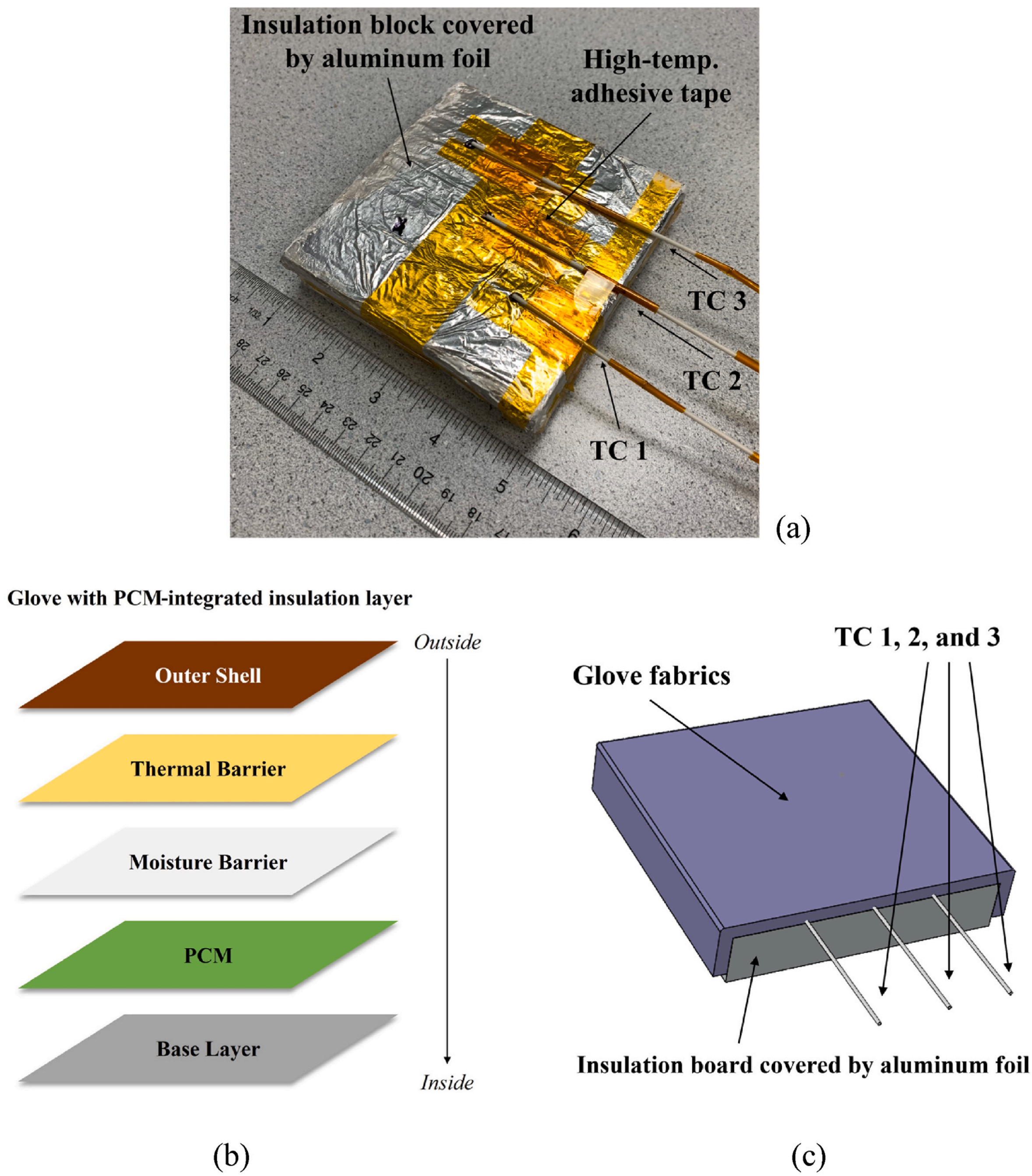


Fig. 1. (a) High-temperature insulation block covered by aluminum foil to prevent water penetration; thermocouples (TCs) were attached on the surface to measure hand skin temperature during the tests; (b) glove layers with PCM embedded; (c) demonstration of a completely fabricated test sample.

performance tests.

2. Materials and methods

2.1. Materials and equipment

A commercial structural firefighting glove certified to meet the requirements of NFPA 1971 Standard was used in this study. A bio-based PCM with a melting point of 68 °C from PureTemp LLC [22] was selected and studied in the tests due to its good thermal protection performance [7,9]. A high-temperature insulation board (Fiberfrax® Duraboard® MD) [23] was cut into 4" × 4" pieces to form an insulation block, mimicking the human hand and supporting firefighters' glove fabrics [9]. Aluminum foil [24] was used to cover the insulation boards to avoid moisture penetration fully.

The temperature was sensed by fine-gage wire type K thermocouples (TCs) [25] and converted (analog to digital conversion) by a data acquisition system (DAS) [26] to record and store the temperature data in the computer. Firefighters' glove fabrics were adhered on insulation boards by high-temperature ceramic adhesive (Aremco Pyro-Paint 634-AS) [27], and TCs were taped on samples with high-temperature adhesive tape (polyimide film with silicone adhesive, up to 260 °C) [28]. An IKA C-MAG HS hot plate [29] was applied as the conductive heat source. A high temperature versatile box furnace (model STV-1600-101,012) [30] was used to provide radiant and convective heat sources.

2.2. Sample preparation

The test sample fabrication procedure was established based on the previous work on dry structural firefighting gloves testing with no additional moisture content [9]. Additional aluminum foil was used to cover the high-temperature insulation block completely (used to mimic the human hand [9]) to prevent any moisture from fabrics from getting absorbed and the added water from being penetrated, as shown in Fig. 1 (a).

The PCM was encapsulated by the moisture barrier material from a commercial glove to prevent leakage based on the procedure established in our previous work [9]. Different thicknesses of encapsulated PCM (called PCM layer) were investigated in our previous work [9]. The 1-mm thick PCM layer showed the best performance when considering both thermal protection times and hand dexterity [9]. Hence, this work was focusing on the 1-mm thick PCM layer for the moisture effect studies. The PCM layer was in the footprint of 4" × 4". The total mass of PCM in encapsulation was 6.44 g. The PCM layer was placed between the base layer and the moisture barrier (Fig. 1(b)). Our previous work [9] also investigated the thermal performance of firefighters' glove with an additional thermal barrier (ATB) inserted that had the same thickness and location as the PCM layer. The results showed that in both direct contact and furnace tests, the gloves with PCM layer could provide better thermal protection compared to the conventional glove (control group) and the control group with an ATB [9]. The PCM could extend the thermal protection time by up to 30–55 s and 240 s compared to the glove with an ATB in the furnace and direct contact tests, respectively [9]. Considering this study was to compare the novel PCM gloves and commercial conventional gloves, the control groups were the same with the commercial conventional gloves which could be found in the market.

The raw material cut from firefighters' gloves was weighed before the PCM layer was inserted. The mass of glove fabrics was used to calculate the amount of water added to the test sample. Five different MC levels—i.e., 0 % (dry glove fabrics), 10 wt% (M10), 20 wt% (M20), 50 wt% (M50), and 70 wt% (M70)—were investigated in this study. The MC level was determined by using equation (1) [17]:

$$Moisture\ Content\ (MC) = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100\% \tag{1}$$

where M_{wet} is the total mass of wet glove fabric; M_{dry} is the total mass of dry fabric cut from the firefighters' gloves. The MC is the weight percentage of water added to the glove fabrics.

After the sample fabrication, the total weight of the sample, including glove fabrics, insulation block, and thermocouples (Fig. 1(c)) was measured and recorded as the reference for the repeat tests. Each sample test was repeated three times in a series, if possible, to obtain consistent test data (see Section 3 Experimental methods). Therefore, additional water needed to be added to compensate for the amount of evaporated moisture during the previous heating test.

3. Experimental methods

Two types of temperature control performance tests were performed under three test conditions. One was a direct contact (DC) test using a hot plate (Fig. 2(a) and (b)), which simulated firefighters grabbing, holding, or lifting hot objects in fire scenes. In the DC test, the sample contacted the hot surface, and conductive heat transfer dominated this process. The other type was the furnace test, which simulated combined radiant and convective heat sources (Fig. 2(c) and (d)).

Two test conditions were involved in the furnace test, i.e., one was the hazardous condition and the other was the lower bound of flashover condition. The DC and furnace tests simulated the conditions that firefighters could be exposed to in fire scenes. The temperatures of the glove sample surface, PCM layer surfaces (both sides), and hand skin (insulation block) surface were monitored by TCs. There were three TCs (TC 1, TC 2, and TC 3) attached to the insulation block surface (Fig. 1(a)). The ambient temperature and furnace temperature were also sensed by the TCs. The time of central hand skin temperature (TC 2) to reach second-degree burn was recorded. The level of second-degree burn was set at 60 °C in this study [4].

All samples were placed in the testing area for 24 h to balance the potential moisture content difference between the glove fabrics and the room environment after they were fabricated. The room temperature and humidity were controlled by the lab air conditioning. Before starting the tests, water was evenly added to the firefighters' glove fabric layers to adjust the target MC level. The amount of added water was based on the calculation from equation (1) above. For the 0 % MC level samples (dry samples), no water was added to the samples. After the water was added to the sample, the total mass of the wetted sample was measured and recorded as a reference. After that, the wetted sample was placed on the table for 5 min to let the fabrics get completely soaked before the test.

During the tests, the PCM would absorb or release latent heat of fusion for the phase changing process. In the heating process, the large amounts of latent heat absorption could reduce the thermal transport rate in the glove samples. Moreover, the MC in the glove fabrics would evaporate or condense in the test, leading to the absorption or release of latent heat of vaporization from water vapor to the glove sample.

The MC would increase the effective specific heat (C_p) and thermal conductivity (k) of glove fabrics due to the higher specific heat and thermal conductivity values of water compared to dry fabrics. The increased C_p can slow down the temperature rise rate, while the increased k can speed up the conductive heat transfer in the glove sample. Therefore, the temperature change rate in the glove and the hand skin is affected by the two combined factors.

3.1. Direct contact test procedure

In the DC test, the temperature at the hot plate surface was controlled at 200 °C. A thermocouple was attached at the center of the hot plate surface to monitor the surface temperature during testing. Heat loss occurred from the hot plate surface to the surroundings, but it could be compensated for by the power level of the hot plate to maintain the surface temperature reading from the TC at 200 °C. When the surface

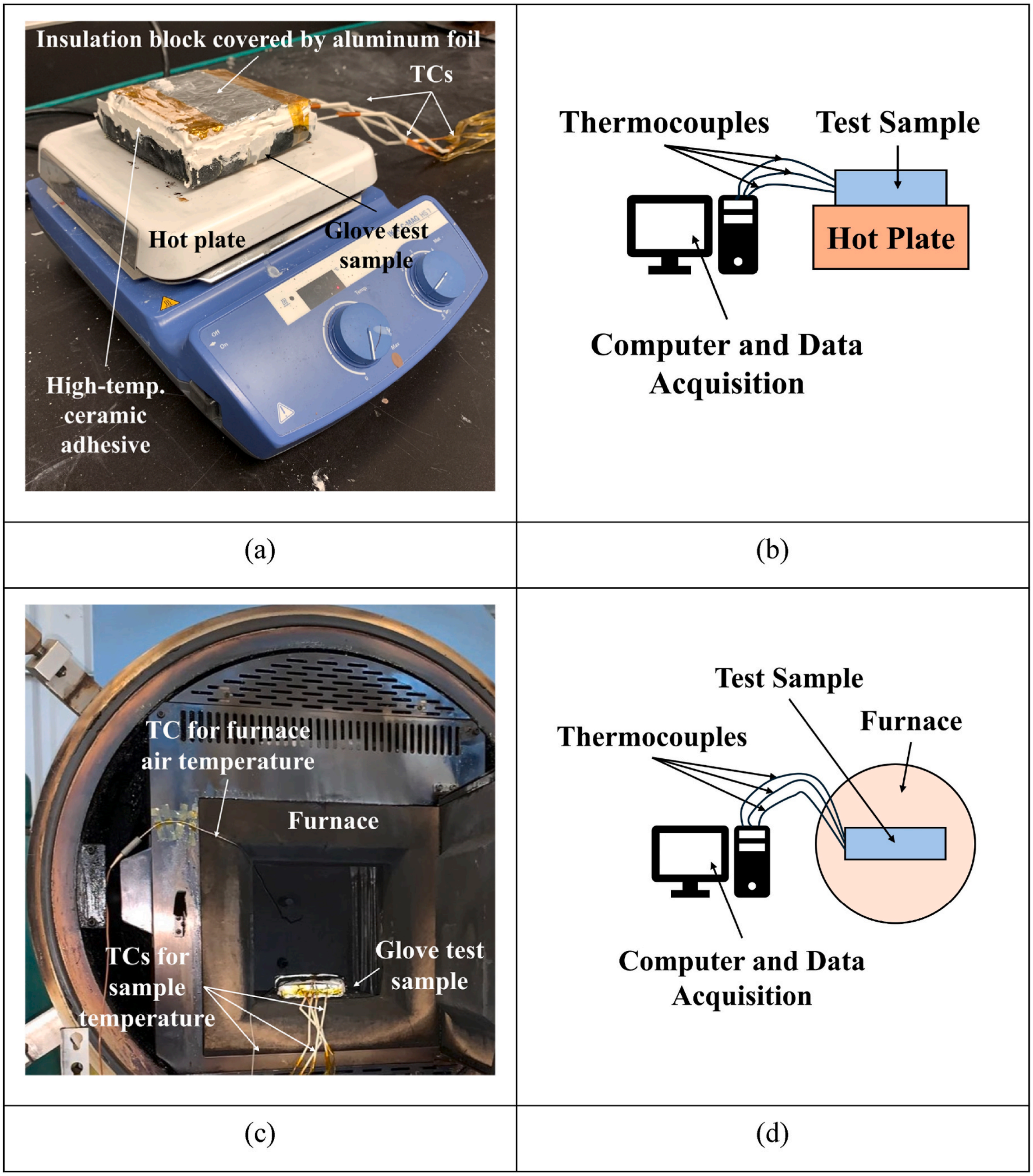


Fig. 2. Experimental set-up for (a) & (b) the DC test (photo & schematic diagram) and (c) & (d) the furnace test (photo & schematic diagram).

temperature of the hot plate reached 200 °C, the dry or wetted glove sample was placed on the hot plate (with the glove outer shell surface directly touching the hot plate) for the heating process (Fig. 2(a)). When the reading of TC 2 reached 60 °C, the sample was removed from the hot plate and placed under a room environment for the cooling process as post-heat exposure. When the reading of TC 2 decreased from the elevated temperature to below 60 °C, the test was completed. Each sample test was repeated at least three times to obtain consistent data.

3.2. *Furnace test procedure*

A furnace test simulates hazardous or flashover conditions in a fire scene. The major/primary heat source in the furnace is heating elements that provide a radiant heat source, while the hot air in the furnace can also generate some degree of natural convection. The combined radiant and convective heat transfer occurred on the glove outer surface in the furnace.

Two test conditions were included in the furnace test. The first test condition was setting the furnace temperature at 200 °C (F200) with an average heat flux of 10 kW/m^2 from heating elements to mimic hazardous conditions [4]. The furnace was pre-heated to the setting temperature at the heating rate of 10 °C/min before the test. When the furnace temperature reached 200 °C, the dry or wet glove sample was placed into the furnace for heating. When the temperature reading of TC 2 reached 60 °C, the glove sample was removed from the furnace and placed under the room environment for the cooling process as post-heat exposure. The test was completed after the TC 2 reading decreased below 60 °C. The temperature data was continuously recorded during the test. Each glove sample was repeated for the F200 test three times to gain consistent data.

The second test condition was setting the furnace temperature at 300 °C (F300) with an average heat flux of 15 kW/m2 from heating elements to mimic the lower bound of the flashover condition [4]. The test procedure was the same as for the F200 test described above. However, the F300 test could not be repeated since the sample was burned and damaged under the flashover condition in the furnace.

4. Results and discussion

4.1. Temperature measurements

Fig. 3 shows the temperature profile of the commercial firefighters' gloves and PCM-integrated glove samples during the DC, F200, and F300 tests under an MC level of 50 wt (M50) condition. The furnace was automatically controlled by its sensor according to the setting temperature, which caused the fluctuations of the furnace temperature profile in Fig. 3(c)–(f). The solid vertical lines in the figures indicate the time that TC 2 (the center of insulation block surface—representing the hand skin surface at the center of hand palm or dorsal side)—reached 60 °C (second-degree burn), which was also the time that the glove sample was moved away from the test heat sources.

From the temperature profiles, it was discovered that under wet (such as the M50) condition, the PCM layer could significantly extend the thermal protection time (when TC 2 reached 60 °C). In the DC test, the glove sample with a PCM layer provided a thermal protection time of 328 s, which was 1.78 times the baseline (184 s for glove with no PCM). In the F200 test (the hazardous condition), the thermal protection time of the PCM-integrated sample was extended 1.88 times compared with the baseline. In the F300 test (the lower bound of the flashover condition), the thermal protection time could be extended by about 1.35 times by the PCM layer.

4.2. Thermal transport phenomena from PCM to hand surface in the heating process

Fig. 4 displays the temperature profiles from the PCM layer surface and hand surface (insulation block surface) in DC, F200, and F300 tests under dry and wet (such as M10 and M70) conditions. The thermal transport phenomena from the PCM layer in the glove sample to the hand surface during the heating processes could be discovered from the temperature profiles in Fig. 4. The PCM and hand surfaces showed a relatively higher temperature increase rate under the M10 condition and a lower temperature increase rate under the M70 condition compared to the dry condition case. Since the glove fabrics were porous media, the porosity of the fabrics was reduced when water was added to the glove materials, which could increase the effective thermal conductivity of the fabrics. Hence, the temperatures on the PCM and hand surfaces in the M10 condition increased relatively faster than those in the dry test condition due to the significant effect of the increased thermal conductivity.

When a larger amount of water was added to the glove sample (e.g., M70 condition), the high specific heat of water and water evaporation began to dominate the heat transfer process. The added water needed to absorb a large amount of heat for temperature increase and vaporization, which, on the other hand, slowed down the heat diffusion rate. Hence, the PCM and hand surfaces under high moisture content (such as M70) showed a lower temperature rise rate.

4.3. Time for hand surface to reach second-degree burn

Fig. 5 shows the times for the hand skin (the surface of the insulation block) to reach second-degree burn injury (60 °C) in the DC, F200, and F300 tests. The thermal protection performances of gloves under various MC levels (dry, M10, M20, M50, and M70) were investigated, including commercial firefighters' glove (control group, no PCM integrated) and PCM-integrated glove samples. For the DC and F200 tests, each test was repeated for three times. The standard deviations of the repeated tests were evaluated to demonstrate the reliability of the experimental results. For DC testing, the average thermal protection times of all cases were between 150 and 430 s with standard deviations between 2.31 and 57.80 s, as shown in Fig. 5(a). For furnace testing, the average thermal protection times of all cases were between 200 and 350 s with standard deviations between 4.00 and 46.88 s, as shown in Fig. 5(b). The standard deviations were relatively small in all of the tests, which confirmed the reliable experiments were performed.

When a small amount of MC (such as below 20 wt%) was added to the glove sample, the time for the hand skin to reach 60 °C was shortened compared to the dry glove sample because of the increased thermal conductivity in wetted glove fabrics. When the MC level in the glove further increased (such as beyond 20 wt%), the thermal protection time would be extended because the high heat capacity of water began to dominate the heat transfer process, reducing the heat diffusion rate in the glove materials.

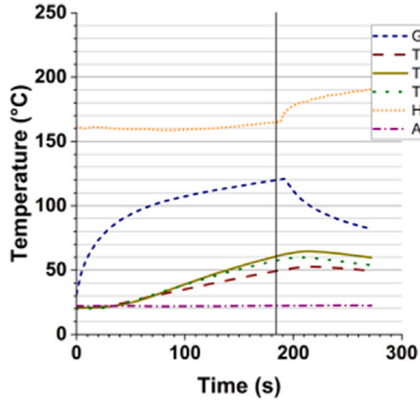
The shortest thermal protection time of PCM-integrated glove occurred at M20 under high-heat conditions. When the MC level exceeded 20 wt%, the protection time of the PCM-integrated glove increased with the increase of the MC in glove fabrics. The longest protection time was at M70 in the furnace tests—longer than that of the dry glove sample as shown in Fig. 5(b) and (c). The shortest thermal protection time of glove with no PCM (control group) occurred at M10 in the furnace tests (Fig. 5(b) and (c)). The protection time of the control group glove increased with the increase of the MC level in glove material in the DC tests (Fig. 5(a)).

With the PCM layer integrated into the firefighters' glove sample, the thermal protection time could be significantly extended compared to the control group (conventional firefighters' gloves) under wet conditions. The thermal protection time could be extended between 1.4 and 2.1 times under the DC test and between 1.2 and 1.5 times under the F200 and F300 tests for wetted glove samples. It was discovered that dry glove samples could provide the longest thermal protection time when directly contacting hot objects in fire scenes. The thermal conductivity of material plays an important role in conductive heat transfer. The thermal conductivity of dry glove fabrics was lower than that of wet fabrics. Gloves with an MC level of 70 % could protect firefighters from second-degree burn injury for longer times under thermal radiation conditions (furnace tests). The high heat capacity of water (moisture) had a major effect on radiation and convective heat transfer, which reduced the heat diffusion rate in the glove for longer thermal protection on the hand skin.

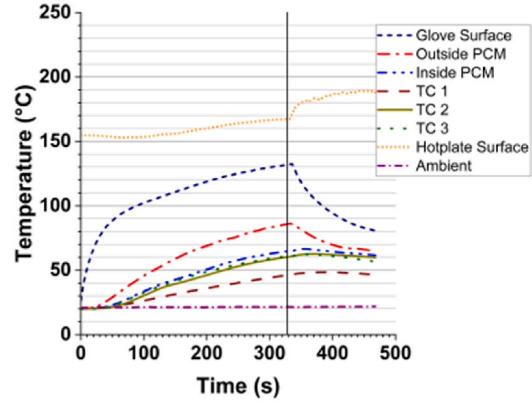
4.4. Post heat exposure

Fig. 6 shows the temperature profiles on the hand skin surface equipped with dry and wet glove samples in the DC and F200 tests for both heating and cooling (post-heat exposure) processes. Both the control group (conventional firefighters' gloves) and PCM-integrated firefighters' glove would release the stored thermal energy toward the environment and hand in the post-heat exposure. Hence, the temperature readings on the hand skin surface (TC 1, TC 2, and TC 3) would continuously increase for a while before dropping after the sample was moved away from heat sources. The melted PCM from the heating process would release a large amount of latent heat of fusion to the environment and hand for solidification in the post-heat exposure, which further slowed down the temperature decrease rate on the hand surface compared to the glove with no PCM.

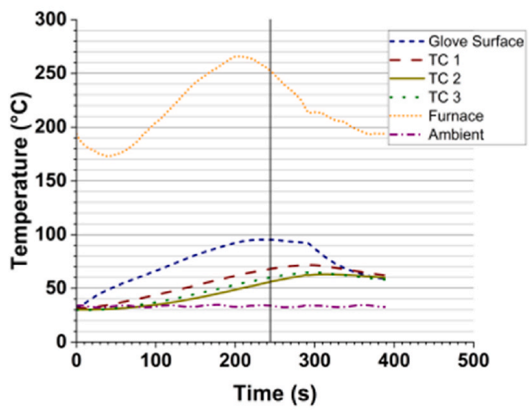
The results of the DC and F200 tests showed different temperature increasing and dropping trends in the post-heat exposure process. The DC test was designed to mimic contacting hot objectives, which was primarily conductive heat transfer. Also, while conducting the DC test, the sample was placed upside down (i.e., glove sample touching hot plate surface with insulation block facing up as shown in Fig. 2(a)) during the heating and post-heat exposure processes. In the F200 and



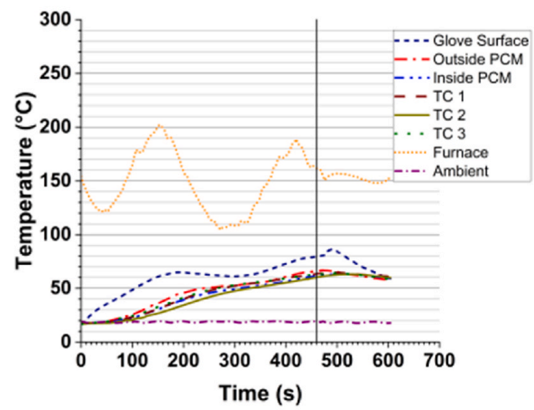
(a) DC test (no PCM, baseline), TC 2 reached 60°C at 184 s.



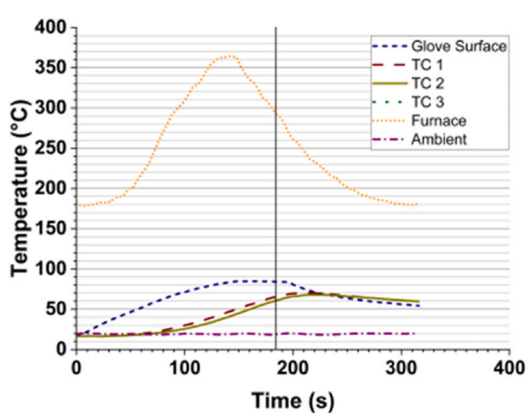
(b) DC test (with PCM integrated), TC 2 reached 60°C at 328 s.



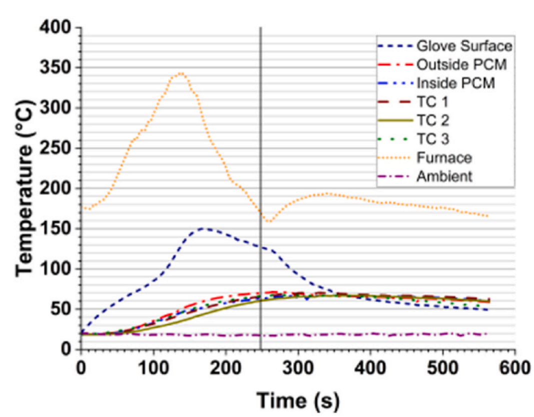
(c) F200 test (no PCM, baseline), TC 2 reached 60°C at 244 s.



(d) F200 test (with PCM integrated), TC 2 reached 60°C at 460 s.



(e) F300 test (no PCM, baseline), TC 2 reached 60°C at 184 s.



(f) F300 test (with PCM integrated), TC 2 reached 60°C at 248 s.

Fig. 3. Temperature profiles of DC, F200, and F300 tests for firefighters' glove samples (with/without PCM layer) under the MC level of 50 wt%: (a) and (b) the DC tests; (c) and (d) the F200 test; (e) and (f) the F300 tests for commercial (baseline) and PCM-integrated commercial glove samples, respectively. Note that "Outside PCM" indicates the temperature at the outer surface of the PCM layer (towards the environment). In contrast, "Inside PCM" indicates temperature at the inner surface of the PCM layer (towards the hand). The solid vertical lines indicate when the glove sample was moved away from heat sources.

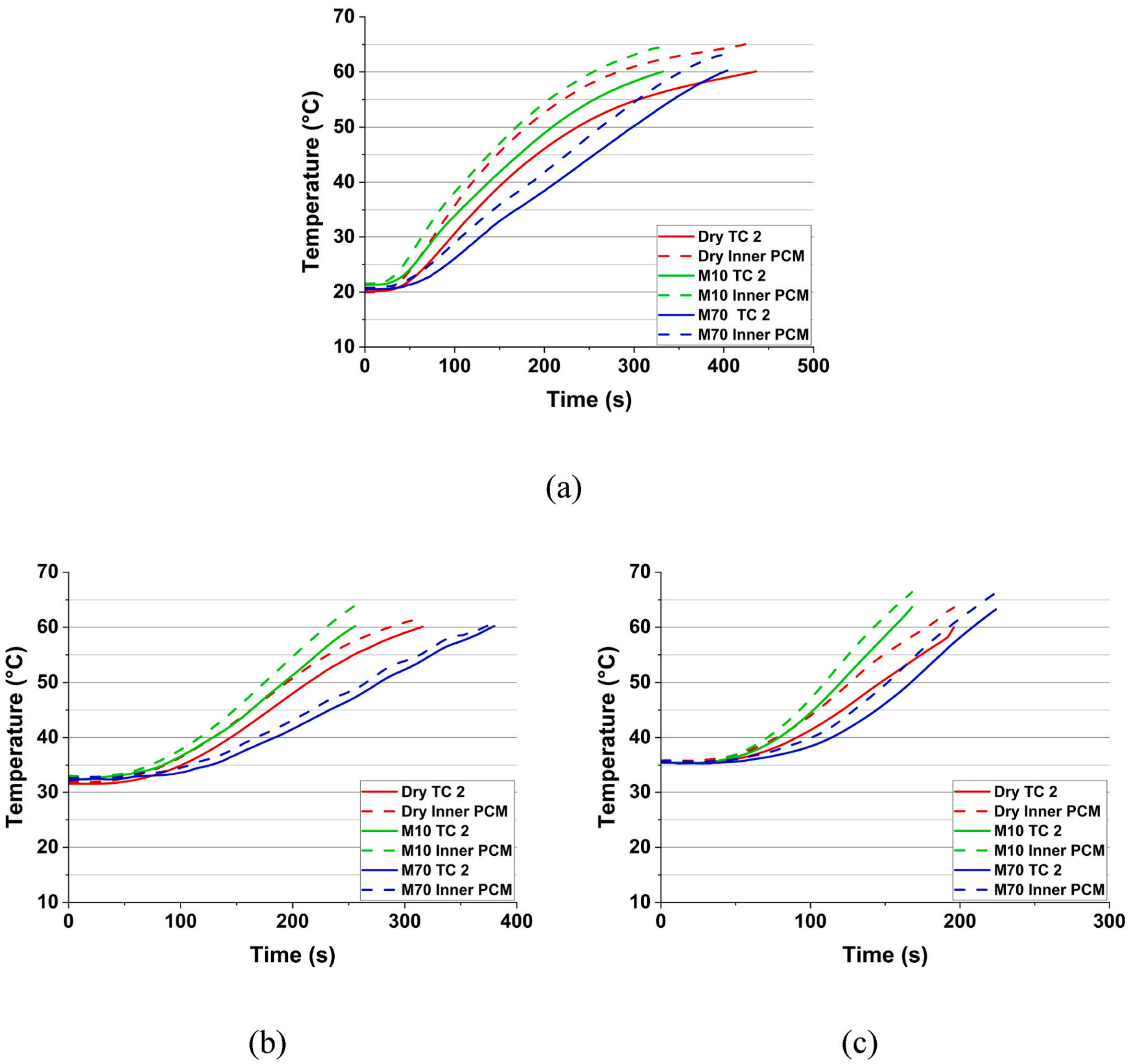


Fig. 4. Temperature profiles at the inner surface of the PCM layer and hand skin surface (TC 2) in (a) DC test, (b) F200 test, and (c) F300 test.

F300 tests, the sample was placed upward (i.e, glove sample facing up with insulation block facing down) during heating and post-heat exposure processes. The upside-down position could block moisture evaporation. Also, the insulation panels pressed the glove fabrics due to their weight, which could affect the thermal conductivity of glove fabrics. Therefore, the temperature trends of the DC and F200 tests in the post-heat exposure process were not comparable because of the differences in sample configuration during the tests.

In the DC test of the control group (Fig. 6 (a)), the results showed that the glove sample with M50 provided a longer cooling process than the dry sample because the thermal energy stored in the moisture content was released to the surrounding and hand after the heating process. In the DC test of the PCM-integrated sample (Fig. 6(b)), dry PCM-integrated samples provided a longer time for cooling down. With PCM integrated, the heat capacity of moisture content (water) had a minor influence compared to the large latent heat from PCM, and the increased thermal conductivity due to the wetted fabrics helped the PCM layer efficiently dissipate the stored thermal energy. Therefore, in the DC tests, the moisture content in PCM-integrated glove sample could significantly increase the heat dissipation rate after leaving heat sources.

In the furnace tests, the wet glove showed a faster temperature decrease rate (steeper decrease slope) in the post-heat exposure compared to the dry one, even when the wet glove provided a longer time for the hand skin surface to reach 60 °C than the dry glove did (Fig. 6(c) and (d)). This is because the evaporation of water could absorb a large amount of heat from the glove sample to efficiently cool down the glove and hand skin.

4.5. *Limitations of the experimental study*

In this study, the F300 test was not able to be repeated for the same glove sample since the glove samples were burned and damaged after testing due to the high temperature. This limitation can be overcome by preparing more samples for the repeated F300 test. In addition, the experimental study was conducted on glove fabric sample instead of an entire glove on a three-dimensional hand model. Although it did not test the actual overall performance of entire glove, this study used adhesive to fix the glove sample on an insulation block to well mimic the glove equipped hand situation for thermal testing.

5. Conclusions

This study examined the impact of various MC levels on the thermal management capabilities of PCM-integrated firefighters' gloves. In the DC tests, it was observed that adding a PCM layer to the gloves initially decreased thermal protection time as the MC increased from 0 % to 20

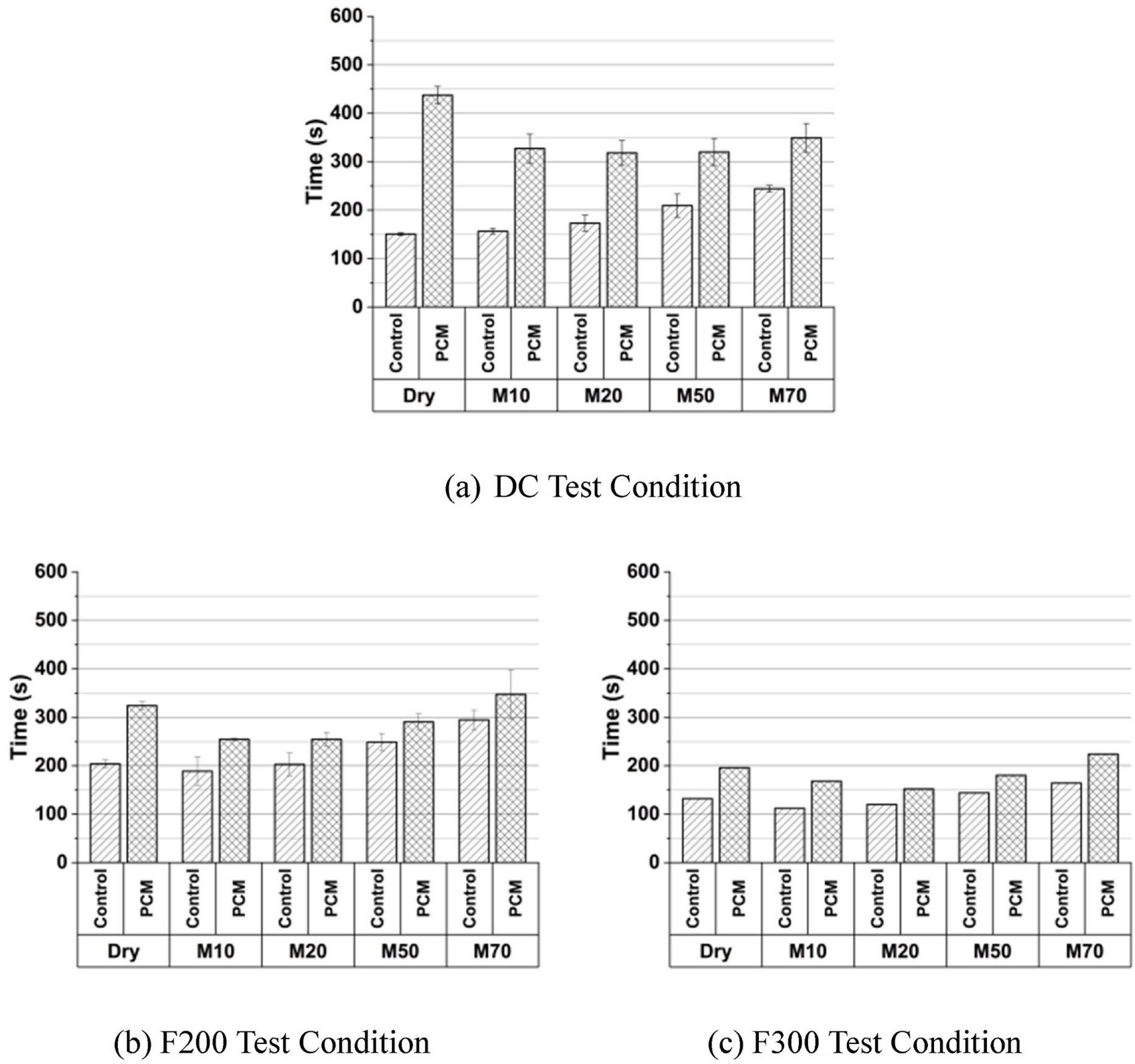


Fig. 5. Time for hand skin surface to reach second-degree burn injury (60 °C) under (a) DC test condition, (b) F200 test condition, and (c) F300 test condition.

%. Beyond 20 % MC, thermal protection time began to increase. In contrast, conventional gloves (control group) demonstrated a continuous increase in thermal protection time as MC levels increased. Specifically, in DC tests, incorporating a 1-mm PCM layer into the glove enhanced thermal protection by between 1.4 and 2.1 times compared to the traditional firefighters' glove under wet conditions.

In the F200 and F300 tests, a decrease in thermal protection time was noted with slight increases in MC. Once the MC surpassed a certain threshold—10 % for the control group and 20 % for the PCM-integrated gloves—thermal protection time increased with higher MC levels. At low MC levels, the increased thermal conductivity of the wetted fabrics facilitated faster heat transfer, reducing thermal protection time under intense heat. However, beyond the threshold MC levels, the greater heat capacity of water prevailed, enhancing the glove's thermal protection time. Integrating a 1-mm PCM layer extended the thermal protection time by between 1.2 and 1.5 times compared to the traditional firefighters' glove in furnace tests (radiant/convective heat sources) under wet conditions.

Further analysis revealed that the PCM's absorption and storage of significant latent heat during heating led to a prolonged cooling period for the hand surface under PCM protection compared to conventional gloves. Moreover, efficient moisture evaporation during the post-heat exposure phase significantly enhanced thermal dissipation rates in PCM-integrated gloves and on the hand surface, providing further thermal management benefits.

The study demonstrated that integrating a PCM layer significantly improved the thermal protection of firefighters' gloves compared to conventional gloves under wet conditions, regardless of the moisture content in the glove samples.

In the future research, we will study a full PCM-integrated glove on a three-dimensional human mannequin hand to evaluate the enhancement in thermal protection with different hand postures or gestures to mimic firefighters operating the equipment and tools in fire scenes. It will investigate the glove overall thermal performance on a hand. Additionally, the approach could be extended to other PPE items, such as firefighters' clothing, helmets, and boots with focusing on dexterity of joints (shoulder, elbow, hip, knee, and ankle).

CRediT authorship contribution statement

Xun Wang: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Weihuan Zhao:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Susan S. Xu:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding

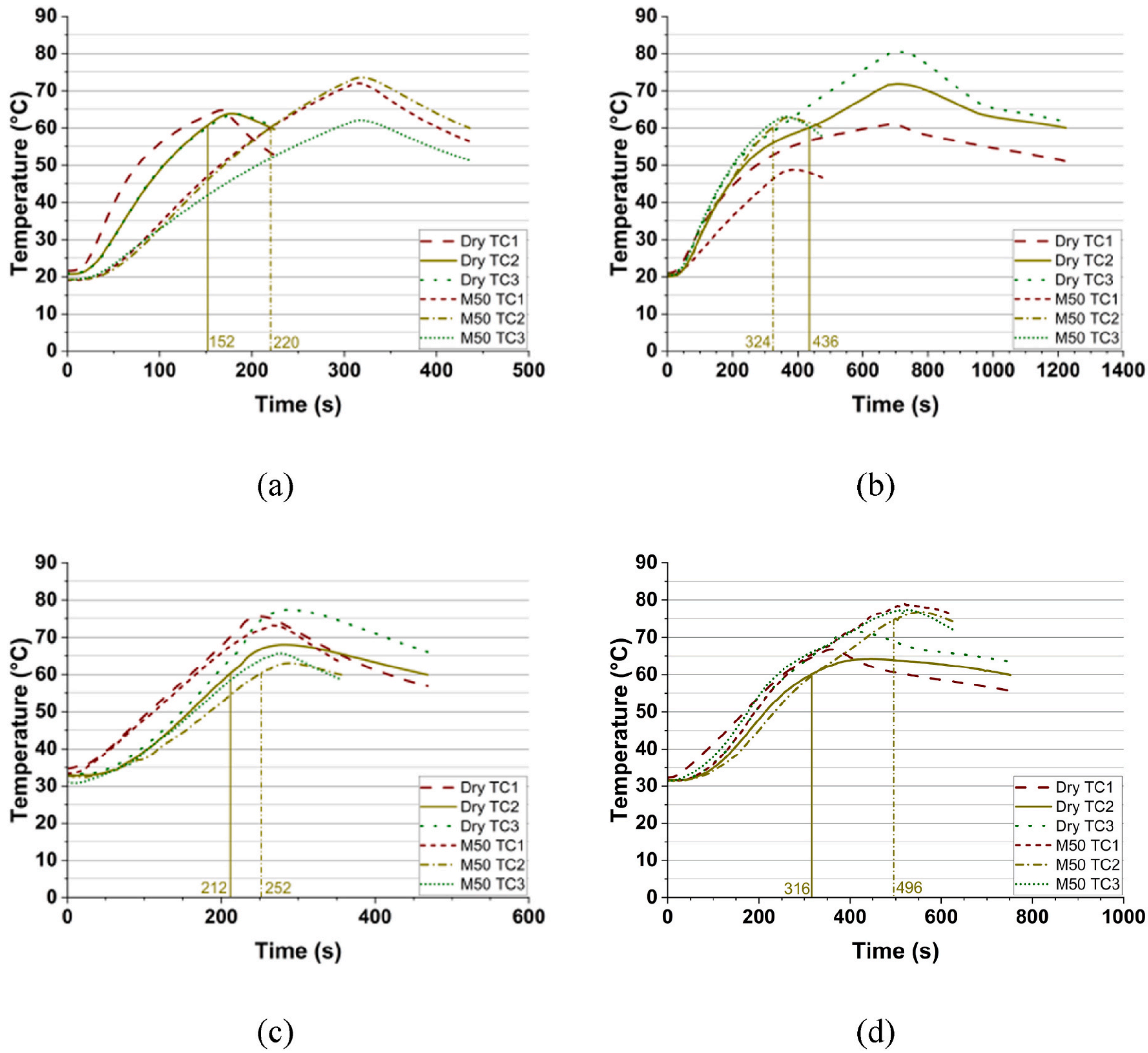


Fig. 6. Temperature profiles on the hand skin surface (TC 1, TC 2, and TC 3) in the heating and cooling (post-heat exposure) processes. (a) Control group in DC test under dry and M50 conditions; (b) PCM-integrated sample in DC test under dry and M50 conditions; (c) Control group in F200 test under dry and M50 conditions; and (d) PCM-integrated sample in F200 test under dry and M50 conditions. We note that vertical solid and dash-dot lines indicate the times when glove samples were moved away from heat sources (beginning for post-heat exposure). The vertical solid and dash-dot lines represent the dry and the wet (M50) glove, respectively.

acquisition, Conceptualization. **Jonisha Pollard:** Writing – review & editing, Visualization.

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 (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute an endorsement by NIOSH, CDC.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the CDC NIOSH Nanotechnology Research Center (NTRC) for its financial support of this research. The authors also thank Jay Tarley, and Jeff Powell for their thoughtful review of this manuscript.

Data availability

Data will be made available on request.

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