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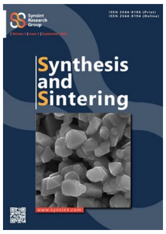

Research article

Investigating the synthesis and application of phase change material composites in firefighting clothing

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ABSTRACT

Firefighters respond to emergencies and tackle accidents and fires. Currently, efforts are being made to enhance the protection provided by firefighting clothing. Embedding phase change materials (PCMs) in firefighting clothing can lead to the absorption of external heat flow and flame heat, thereby preventing burns by offering enhanced thermal protection. Considering the importance of maintaining occupational safety and health for firefighters, this systematic review aims to investigate the use of PCMs in firefighting clothing and evaluate their effectiveness in providing thermal protection. The research draws on studies obtained from a systematic search of the Web of Science and Scopus databases. The following keywords were utilized: "phase change materials", "firefighting clothing", "firefighting vest", and "firefighting garment". Out of 225 articles identified, 13 numerical and experimental studies met our eligibility criteria. The melting temperature of PCM used in the reviewed studies ranged from 25 to 450 °C, with enthalpy values between 55 and 430 kJ/kg. The results highlighted the potential impact of PCM on enhancing the thermal resistance of firefighting clothing, as well as extending the time it takes for second-degree burns to occur. Additionally, it was concluded that the effectiveness of PCM is influenced by its type, melting temperature, enthalpy, and mass. Environmental conditions, fire scenarios, and exposure time also play significant roles in this context.

KEYWORDS

Firefighting clothing
Phase change materials
Thermal protection
Thermal resistance

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1. Introduction

Firefighting is one of the most challenging professions, and its employees are responsible for taking emergency action against accidents and fires [1]. Firefighters have intense physical activity during work and face intense heat flow and high temperatures [2]. Among the stages of fire, pre-flashover has a temperature of 100–300 °C with radiation of 5–12 kW/m^2, and flashover has a temperature of 500–600 °C and radiation of 20–40 kW/m^2 [3, 4]. Working in such conditions, in addition to causing injuries, burns, and complications caused by thermal stress in firefighters [5], can decrease the physical and cognitive capacity of people and affect their workability and safety [6]. In 2022, 3500 burns and heat stress injuries among firefighters during fire-ground operations were reported in the United States [7]. Therefore, firefighters wear personal protective equipment (PPE), including firefighting clothing and breathing apparatus, to prevent these injuries.

Firefighting clothing usually consists of different protective layers, including a waterproof and flame-resistant outer layer and an inner layer that protects against moisture and heat [8]. Some features of firefighting clothing, such as weight, bulk, ease of movement, moisture transferability, and materials used to resist fire and heat, are important [9]. The outer layer is usually made of durable fabric such as Nomex, and the inner layers are made of different materials. There may also be

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an air gap between the clothing layers to improve the insulating properties of the clothing, which, according to Lu et al.'s study [10], can be 9–12 mm [11].

In the past, some traditional methods have been tried to reduce thermal stress in firefighters, such as blowing cold, dry air inside firefighters' clothes, putting hands and forearms into cold water periodically, and using ice-cooling vests. However, these methods limit the performance of firefighters and interrupt their vital firefighting work. Ice vests also make their clothes heavier and have many limitations [12–14]. Nowadays, it is trying to improve the protection level of firefighting clothing. So, on the one hand, skin burns and thermal strain can be prevented, and on the other hand, the measures taken do not create an obstacle to firefighting operations or the ease of movement of firefighters. According to skin burn models, the skin is assumed to have three layers: epidermis, dermis, and subcutaneous. Considering the medical definition, first-degree burns involve the epidermis, and second-degree burns involve the epidermis and part of the dermis. Third-degree burns also damage deep tissues. If the tissue temperature reaches more than 44 °C, the skin will be burned and damaged [15, 16]. To improve thermal protection and reduce burn damage, the embedding of phase change materials (PCMs) in the layers of firefighting clothing has been investigated in many studies [17–20].

Phase change materials can store a large amount of thermal energy in the form of latent heat while changing the phase at a constant temperature. The phase change is usually from solid to liquid and vice versa. By absorbing and releasing thermal energy, these materials can be referred to as heat or cold storage according to their melting and freezing points [18]. The properties of energy storage by PCMs are used in different fields and sciences, such as astronautics, maintaining thermal comfort in buildings, heat recovery, thermal management of batteries, photovoltaic thermal applications, smart textiles, and cooling vests [21–23]. These materials can be of organic, inorganic, or eutectic origin [24]. Organic PCMs include paraffin and fatty acids. Paraffin is widely used in cooling clothing, but it is not ideal for firefighting clothing due to its flammability. Inorganic PCMs are also hydrates of salts and metals. Some salt hydrates with suitable characteristics can be used in firefighting clothing [18].

PCM is usually used in clothing for temperature regulation and cooling with a melting temperature of less than 30 °C. Still, in the case of firefighting clothing, its purpose is to absorb external heat flow and flame heat to prevent burning by providing thermal protection [25].

The important point in the use of phase change materials in firefighting clothing as thermal protection is that these materials must have a melting point of 50–90 °C, high enthalpy, and low thermal conductivity. Phase change materials can be packaged and placed inside clothing. Also, these materials can be used as electrospun fibers or inserted into textiles as microcapsules or nanocapsules, which, in this case, does not increase the weight and bulk of firefighting clothing [26]. Microencapsulated PCM in diverse clothing increases the thermal protection of the clothing and makes it possible for divers to work in harsh temperature conditions [27]. In their study, Zhu et al. [28] tested the composite fabric with a layer of PCM with a melting temperature of 47–53 °C against the flame. They concluded that the PCM layer increases the protection time against heat and emphasized the importance of PCM layers in firefighting clothing in reducing the heat load on the human body [28]. Therefore, considering the importance of maintaining occupational safety and health in firefighters and preventing accidents and occupational injuries, the purpose of this systematic review is to investigate the use of PCMs in firefighting clothing and their effectiveness in creating thermal protection.

2. Materials and methods

This research was conducted using papers from a systematic search on June 25, 2024, on the Web of Science and Scopus databases. The following keywords, "phase change materials", "firefighting clothing", "firefighting vest", and "firefighting garment" were used. After entering the records into EndNote X8 and removing duplicate studies, the author screened the titles and abstracts of the retrieved publications. Accordingly, studies that did not use PCM in firefighting clothing or that did not check the thermal resistance performance of the firefighter clothing were excluded. In addition, book chapters, reviews, review articles, conference papers, articles written in languages other than English, and articles where the full text was unavailable were excluded. Overall, 13 studies were included after quality assessment, which is presented in Fig. 1 as a flowchart of the study process.

3. Results and discussion

A total of 225 articles were added to EndNote. After removing duplicates, 209 records remained. Upon reviewing the title and abstract, 186 articles were excluded. Out of 23 selected titles, one article was excluded due to its non-English language. 5 articles were removed due to limited access to the full text. 1 article was removed because it was not relevant. 3 articles were removed because they were conference articles. The full text of 13 articles was reviewed. Out of 13 reviewed articles, 7 (53.84%) were mathematical modeling studies and 6 (46.15%) were experimental studies. In most articles, PCM was added as a coating to the fabric of the layers of firefighting clothing. The melting temperature of PCM used in the reviewed studies, to improve the thermal performance of clothing, was at least 25 °C and at most 450 °C, and the enthalpy was at least 55 kJ/kg and at most 430 kJ/kg. The results of all studies indicated the potential effect of PCM on increasing the thermal resistance of firefighting clothing. The most effective PCMs were those with a high melting temperature and enthalpy. In some studies, the effect of the air gap between the clothes and the body, as well as between the layers of the clothes, was considered, but in others, this effect was ignored. Moreover, in only one study, the effect of moisture in the skin and layers of clothing on the thermal performance of PCM in firefighting clothing was investigated, and the effect of moisture was ignored in the majority of articles. In Table 1, a summary of the important points of the reviewed studies is presented. These studies are discussed in more detail below.

Mercer and Sidhu [26] conducted a mathematical modeling study in 2007 on firefighter clothing. They examined the model in two parts: clothing layers (waterproof and flame-resistant outer layer, micro PCM layer, and thermal insulation layer) and skin layers (epidermis, dermis, and subcutaneous). An air gap of 0.5 mm was considered between the skin and the clothes. The selected PCM had a melting temperature of 78 °C and a latent heat of 267 kJ/kg. PCM with a thickness of 1 mm was used, which added 2 kg to the weight of the firefighter's clothing. They defined two scenarios. First, they considered the flash fire scenario with a heat flow of 83.2 kW/m^2 for 3 seconds. The output of the model showed that without the PCM layer, second-degree burns occur after 29 seconds, but with the presence of the PCM layer, this time increased to 300 seconds. The second one was the scenario of exposure to a heat flow of 1.2 kW/m^2 for 5 minutes. In this case, the

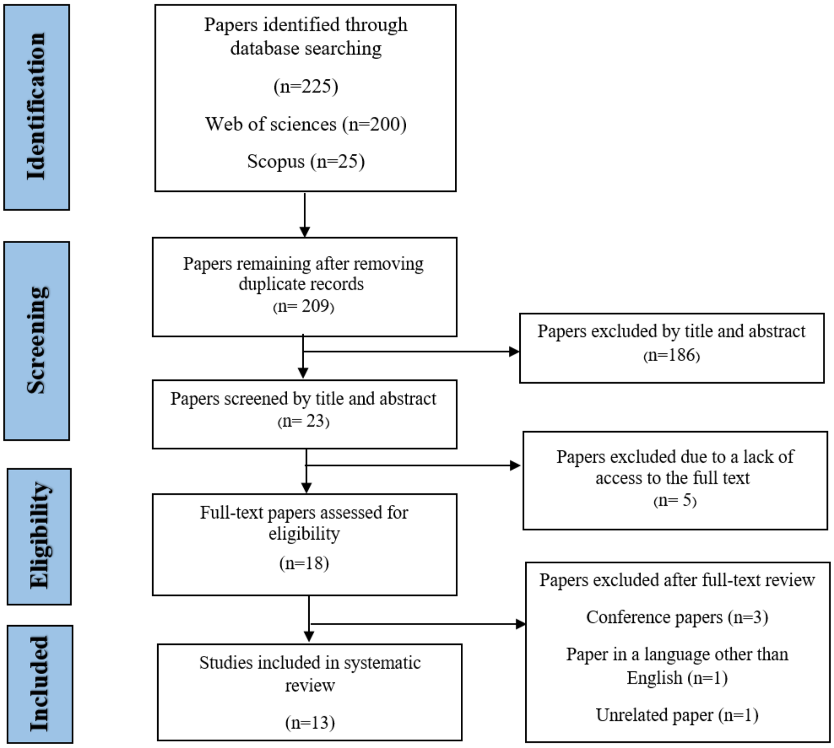

Fig. 1. Flowchart of the systematic review process.

results showed that without the PCM layer, second-degree burns occur after 240 seconds, but with the presence of the PCM layer, this time increased to 440 seconds [26]. In another study, these authors considered the same model in the face of a heat flow of 1.2 kW/m^2 for 5 minutes and investigated the effect of PCM melting temperature and air gap in clothing. The best scenario was an air gap of 5 mm and a melting temperature of 60 °C. In the worst-case scenario, an air gap of 0.1 mm and a melting temperature of 90 °C were considered. According to the mathematical model output, the optimal melting temperature of PCM was determined to be 65–70 °C. The melting temperature of PCM should be considered as low as possible, but only to the extent that it is solid in the temperature conditions encountered by firefighters. For a given melting temperature of PCM, increasing the air gap in the garment increases the duration of thermal protection [29].

In 2013, Hu et al. [30] studied the mathematical modeling of firefighting clothing with outer, waterproof, PCM, and inner layers. The PCM layer was assumed to have four thicknesses (1, 2, 5, and 10 mm) and two positional conditions. The positions include A (positioning of PCM between two outer and waterproof layers) and B (positioning of PCM between two waterproof and inner layers). The melting temperature of PCM was 77.85 °C, and the latent heat was 267 kJ/kg. The results showed that, assuming the same thickness, placing the PCM in position B compared to position A makes the duration of the phase change longer, and with the increase in thickness, this time difference increases. This means that the feeling of heat in the body is lower, and there is high thermal protection. The optimal thickness of the PCM layer in firefighting clothing should be chosen based on the firefighter's exposure to specific heat flux and the physical activity of the firefighter to extinguish the fire, so that the clothing is not too heavy [30]. In 2014, during a study, Mohammed Ali et al. [17] designed firefighting clothing containing layers of glass with aluminum foil, non-woven basalt + NaCl-MgCl$_2$, non-woven glass fabric + galactitol, and cotton fabric. Two types of PCM (NaCl-MgCl$_2$ with a melting temperature of 450 °C and a latent heat of 430 kJ/kg, and galactitol with a melting temperature of 192 °C and a latent heat of 413 kJ/kg) were used and sprayed on non-woven fabrics. To check the thermal resistance of clothes in flashover conditions, laboratory thermal protective performance tests were conducted considering the ambient temperature of 800–1000 °C for 5 minutes. A UV-Vis-NIR spectrophotometer was also used to check the thermal radiation performance of the fabric. Spectrophotometer results showed that non-woven fabrics have satisfactory thermal radiation protection performance. According to the results of the tests, the composite fabric in this clothing had good thermal resistance and a high-temperature drop to prevent second-degree burns during flashover [17].

In a study in 2014, Farag designed a 3-layer firefighter clothing, including the outer, moisture barrier, and thermal layers. The inner thermal layer consisted of woven and knit Spentex fabric (carbon-based flame-resistant fiber) coated with hydrated salt. Four types of hydrated salt PCM, including magnesium chloride hexahydrate (MCH), barium hydroxide octahydrate (BHO), sodium phosphate dibasic heptahydrate (SPDH), and polyethylene glycol (PEG), with different weights (236 and 472 g/m^2), were coated in fabric samples. Performance tests of thermal protection under a heat flow of 8.3 W/cm^2 showed that the amount and duration of heat protection increased with the introduction of PCM into clothing. PEG showed the best protection, and BHO had more protection than SPDH. MCH was not approved because it absorbed atmospheric moisture [18]. Shaid et al. [19]

designed firefighting clothing with an outer layer, moisture barrier, and thermal layer in 2016. The thermal layer on the body side was coated with aerogel/n-eicosane composite powder, and on the other side with nanoporous aerogel particles. FT-IR, DSC, SEM, infrared thermal imaging, and hotplate tests were used to check the chemical and thermal properties. The fabric sample was exposed to heat at 250 °C for 10 minutes. In the obtained composite, the amount of PCM loading was 550% of the weight of the aerogel, and the amount of loading of the composite powder on the fabric was 12% of the weight of the fabric. The results showed an increase in the strength of the clothing against the threats of damage and burns, giving firefighters more time to prevent burns. The use of PCM/aerogel composites increases the thermal resistance [19]. In another study in 2018, this author investigated the flammability effect of the thermal layer in firefighting clothing when treating the fabric with aerogel, PCM, and aerogel/PCM. The results showed that the fabric treated with PCM/aerogel has the best resistance to ignition, radiant heat transfer, and time to pain and burns. At the same time, this fabric has less weight and better protection than other samples [31].

Table 1. A summary of the reviewed studies.

Type of study	PCM	T_m of PCM (°C)	PCM enthalpy (kJ/kg)	PCM packaging	Clothing design	Results	Ref.
Mathematical modeling	-	78	267	Micro PCM	The layers of the clothing model, from outside to inside, include the outer, PCM, and thermal insulating layer.	With the presence of the PCM layer, the time required for the occurrence of second-degree burns increased.	[26]
Mathematical modeling	-	60–90	200	Micro PCM	The layers of the clothing model, from outside to inside, include the outer, PCM, and thermal insulating layer.	The optimal melting temperature of PCM was determined to be 65–70 °C.	[29]
Mathematical modeling	-	77.85	267	-	The layers of the clothing model, from outside to inside, include the outer, waterproof layer, PCM, and inner layer.	The more the PCM layer is embedded in the inner layers of the clothing and closer to the body, the more protection it has.	[30]
Experimental	NaCl (48%) + $MgCl_2$ (52%)	450	430	Coated to fabric	The layers of the clothing model, from outside to inside, include the glass with aluminum foil, non-woven basalt + NaCl-$MgCl_2$, non-woven glass fabric + galactitol, and cotton fabric.	The composite fabric in this clothing had good thermal resistance and a high-temperature drop to prevent second-degree burns during flashover.	[17]
	Galactitol ($C_6H_{14}O_6$)	192	413				
Experimental	Magnesium chloride hexahydrate (MCH)	118	170	Coated to fabric	The layers of the clothing model, from outside to inside, include the outer, moisture barrier, and thermal layer + hydrated salt.	The amount and duration of heat protection increased, and PEG showed the best protection.	[18]
	Barium hydroxide octahydrate (BHO)	78	280				
	Sodium phosphate dibasic, heptahydrate (SPDH)	48	280				
	Polyethylene glycol (PEG)	58	180				
Experimental	n-eicosane/ aerogel composite	41.77	177	Coated to fabric	The layers of the clothing model from outside to inside include the outer, moisture barrier, and thermal layer + n-eicosane/aerogel composite.	The use of PCM/aerogel composites increases the thermal resistance.	[19]

Table 1. Continued.

Type of study	PCM	T_m of PCM (°C)	PCM enthalpy (kJ/kg)	PCM packaging	Clothing design	Results	Ref.
Experimental	-	-	-	Coated to fabric	The layers of the clothing model, from outside to inside, include the outer, moisture barrier, and thermal layer + PCM/aerogel composite.	The results showed that the fabric treated with PCM/aerogel has the best resistance to ignition.	[31]
Mathematical modeling	-	50.6	199.8	-	The layers of the clothing model from outside to inside include the outer, PCM, and thermal inner layers.	The role of mass, melting temperature, latent heat, and position of PCM in clothing is significant.	[32]
Mathematical modeling	Stearic acid	54	157	-	The layers of the clothing model, from outside to inside, include the outer, PCM, and thermal inner layers.	In short-term exposure to medium and high heat fluxes, magnesium nitrate hexahydrate requires less mass than other PCMs.	[33]
	$CH_3COOH.3H_2O$	58	266				
	Barium hydroxide octahydrate	78	280				
	Rubitherm® PX82	82	105				
	Magnesium nitrate hexahydrate	89	140				
Mathematical modeling	Rubitherm® RT42	42.5	220	Coated to fabric	The layers of the clothing model from outside to inside include the outer, moisture barrier, and thermal layer + Rubitherm® RT42.	Condensation of steam in the skin, compared to the dry state, decreased the PCM liquid fraction in second-degree burns.	[34]
Mathematical modeling	Generic	78	267	-	The layers of the clothing model, from outside to inside, include the outer, PCM, and inner layers.	The PCM and air gaps reduced the possibility of skin burns. Also, it is better to place the PCM layer close to the outer layers of the clothing.	[11]
	H_2O	0	333				
	$CaCl_2.6H_2O$	29.7	171				
	$Na_2SO_4.10H_2O$	32.4	254				
	$Zn(NO_3).6H_2O$	36.4	147				
	$Ba(OH)_2.8H_2O$	78	267				
	$MgCl_2.6H_2O$	116	165				
Experimental	Paraffin	25	135	Coated to fabric	The layers of the clothing model from outside to inside include the outer, moisture barrier, thermal layer, PCM, and inner layer.	PCM with a melting temperature of 35 °C and a coverage of 45% on the fabric showed the best performance during the tests.	[35]
		30	180				
		35	180				
		42	120				
Experimental	Rubitherm® PX82	77–85	105	Micro PCM	The layers of the clothing model, from outside to inside, include the outer, cork matrix + PCM, and inner layers.	Rubitherm® PX82 has better thermal performance than other PCMs.	[36]
	Rubitherm® PX52	49–53	100				
	Rubitherm® GR42	38–43	55				

Fonseca et al. [32], during a 2018 mathematical modeling study on the effect of PCM application in firefighting clothing, provided guidelines on PCM properties. In this study, the clothing was considered in three outer layers, PCM, and thermal inner layers, without an air gap between the layers and the body. Three heat fluxes that a firefighter can encounter, including 84 kW/m^2 for 8 seconds (high intensity) and 5 and

12 kW/m^2 for 5 minutes (low and medium intensity), were investigated. The PCM weight of the clothing was assumed to be 200 grams. The results showed that in the case of firefighting clothing, the melting temperature of PCM should be chosen in such a way that it melts under the influence of an external heat source, not body heat. Increasing the melting temperature reduces the time to second-degree burns. Also, the time to second-degree burns is related to the mass of PCM and its latent heat. This study suggested the placement of PCM in the outer layers of clothing and away from the skin to prevent temperature increases in the skin-clothing system [32]. In another study in 2021, this researcher studied the mathematical modeling of the effect of PCM in firefighting clothing in three phases: fire exposure, post-fire exposure, and resting phase. As in the previous study, the heat fluxes were considered 5, 12, and 84 kW/m^2. The use of 5 types of PCM in firefighting clothing, including Stearic acid, $CH_3COOH.3H_2O$, Barium hydroxide octahydrate, Rubitherm® PX82, and Magnesium nitrate hexahydrate, was considered. For the exposure phase, the optimal masses of PCM were obtained for exposure to different heat fluxes and durations, which also depend on the properties of PCM. For example, in short-term exposure to medium and high heat fluxes, magnesium nitrate hexahydrate requires less mass than other PCMs. Rubitherm® PX82 is the material that requires the most mass because it has the lowest specific heat. For the post-fire exposure, the alarming time, and for the rest phase, the PCM cooling time was calculated. The alarming time for all PCMs was 18–24 seconds. The presence of PCM in clothing increases the duration of exposure. PCMs cool faster, with higher melting temperatures and lower latent heat. Magnesium nitrate hexahydrate had the lowest cooling time [33]. Another study by this researcher in 2023 addressed the effect of free water on 3-layer firefighting clothing. In this mathematical modeling, it was assumed that the clothing has an outer layer, a moisture barrier, and a thermal inner layer along with the PCM coating, and these layers contain moisture. This moisture may not evaporate due to the heat, but the steam condenses on the skin surface and causes a skin temperature increase and discomfort. The heat flux was considered 5, 12, and 84 kW/m^2. To evaluate thermal performance, skin temperature, skin heat flux, and PCM liquid fraction profiles were obtained along with time-to-second-degree burns. The results showed that the condensation of steam in the skin, compared to the dry state, decreased the PCM liquid fraction in second-degree burns. Part of the latent heat of PCM is used to absorb the condensation heat. In firefighting clothing, the role of PCM should be protection against incoming dry heat, but the presence of steam reduces the effectiveness of PCM. Therefore, moisture management in firefighting clothing is serious [34].

A mathematical modeling study by Phelps et al. [11] was conducted in 2019 on designing firefighter clothing with outer, PCM, and inner layers and considering air gaps. They investigated the use of different PCMs, such as generic, H_2O, $CaCl_2.6H_2O$, $Na_2SO_4.10H_2O$, $Zn(NO_3).6H_2O$, $Ba(OH)_2.8H_2O$, and $MgCl_2.6H_2O$, in the model of firefighting clothing, and $MgCl_2.6H_2O$ with a thickness of 0.17 mm was introduced as the best PCM to deal with body damage in fire. In their model, they considered exposure to heat fluxes 5–84 kW/m^2 in the form of different firefighting scenarios. The results showed that the PCM and air gaps reduced the possibility of skin burns. Also, it is better to place the PCM layer close to the outer layers of the clothing [11]. During a study in 2021, Wang et al. [35] designed firefighting clothing with an outer layer, a moisture barrier, a thermal layer, PCM, and an inner layer. They used paraffin with melting temperatures of 25, 30, 35, and 42 °C. The thermal performance of the fabric was analyzed with low-level thermal radiation (heat flux of 8.5 kW/m^2 for 300 seconds) and fire exposure (heat flux of 84 kW/m^2 for 60 seconds). The results showed that PCM improves the thermal performance of firefighting clothing. In this regard, the type of PCM, its phase change temperature, mass, and thermophysical properties play a decisive role. In this study, PCM with a melting temperature of 35 °C and a coverage of 45% on the fabric showed the best performance during the tests. With the increase in PCM content, the time to second-degree burns increased [35]. In 2023, Santos et al. [36] conducted their study in three stages to design a personal protective vest for firefighters. First, the performance of encapsulated PCMs was evaluated in a small-scale laboratory setting. Second, heat and flame tests were performed in the laboratory in accordance with EN 469:2020. Third, the thermal performance of 3 vests with different designs or fabrics was simulated in urban fire conditions. The wooden pallets were set on fire, and the firefighters put on their vests and firefighting clothing to put out the fire. Between the tests, a 20-minute rest was considered. The results showed that Rubitherm® PX82 has better thermal performance than other PCMs because it has a higher melting temperature and enthalpy. Also, the temperature difference between the inner and outer surfaces of the vest with PCM was higher than without PCM, which indicates the great effect of PCM [36].

This study was accompanied by some limitations, including the lack of access to some articles due to the payment of fees and the study of articles only in English.

4. Conclusions

Since firefighting is considered a dangerous job, its employees are engaged in carrying out their mission in all accidents, disasters, and fires, eliminating danger and extinguishing fire. Maintaining the safety and health of these people is very important, and trying to improve the resistance of firefighting clothes against heat is a vital issue. This systematic review study tried to investigate the impact of PCM application on firefighting clothing and its characteristics, and in this regard, the following results were obtained:

- The embedding of PCM in firefighting clothing improves thermal performance, increases the clothing's resistance to heat, and then increases the time before second-degree burns occur.
- Increasing the air gap in firefighting clothing increases the duration of thermal protection.
- The position of the PCM in the firefighter clothing is decisive. Some studies have suggested this position is close to the body, and others suggest it is close to the outer layers and external heat source. Therefore, it is suggested to conduct more studies on this matter.
- The greater the amount of PCM used, the greater the thermal insulation power of the clothing increases, but the clothing becomes heavier. Therefore, the optimal thickness of PCM should be determined according to the heat flux, exposure status, physical activity, and the amount of added weight to the clothing, which can be different for each firefighting work situation. So more studies should be done.
- The PCM used in firefighting clothing should have a suitable melting temperature and latent heat because the effect of PCM depends on its type, melting temperature, enthalpy, and mass. In

this regard, environmental conditions, fire scenarios, and exposure time also play an important role.

- Using PCM composite with other materials, such as aerogel, can strengthen the thermal insulation properties of clothing. Also, the use of PCM composite layers with different melting temperatures and latent heat in firefighting clothing can increase the strength and duration of thermal protection.
- The presence of moisture in the firefighting clothing should be controlled because the latent heat of PCM is used for steam condensation heat instead of incoming dry heat, and the effectiveness of PCM is reduced. Therefore, the effect of humidity should be investigated in the studies.
- It is recommended to upgrade the studies from modeling and simulation to human field studies in real-world conditions.

CRediT authorship contribution statement

Elnaz Rahimi: Writing – original draft, Conceptualization, Investigation, Writing – review & editing.
Aziz Babapoor: Conceptualization, Investigation, review & editing.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Declaration of competing interest

The authors declare no competing interests.

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References

[1] M. Desmond, Becoming a firefighter, Ethnography. 7(2006) 387–421. https://doi.org/10.1177/1466138106073142.
[2] D. Barr, W. Gregson, T. Reilly, The thermal ergonomics of firefighting reviewed, Appl. Ergon. 41(2010)161–72. https://doi.org/10.1016/j.apergo.2009.07.001.
[3] N.N. Daeid, An introduction to fires and fire investigation, Fire investigation, CRC Press. (2004). 13–24.
[4] R. Rossi, Fire fighting and its influence on the body, Ergonomics. 46 (2003) 1017–1033. https://doi.org/10.1080/0014013031000121968.
[5] A.M. Raimundo, A.R. Figueiredo, Personal protective clothing and safety of firefighters near a high intensity fire front, Fire Saf. J. 44 (2009) 514–521. https://doi.org/10.1016/j.firesaf.2008.10.007.
[6] L. Nybo, Exercise and heat stress: cerebral challenges and consequences, Prog. Brain Res.162 (2007) 29–43. https://doi.org/10.1016/S0079-6123(06)62003-7.
[7] R. Campbell, S. Hall, United States Firefighter Injuries in 2022, National Fire Protection Association. (2023).
[8] R, Nayak, S. Houshyar, R. Padhye, Recent trends and future scope in the protection and comfort of fire-fighters' personal protective clothing, Fire Sci. Rev. 3 (2014) 1–19. https://doi.org/10.1186/s40038-014-0004-0.
[9] P. Chitrphiromsri, A.V. Kuznetsov, Modeling heat and moisture transport in firefighter protective clothing during flash fire exposure, Heat Mass Trans.41 (2005) 206–215. https://doi.org/10.1007/s00231-004-0504-x.
[10] Y. Lu, J. Li, X. Li, G. Song, The effect of air gaps in moist protective clothing on protection from heat and flame, J. Fire Sci. 31 (2013) 99–111. https://doi.org/10.1177/0734904112457342.
[11] H. Phelps, S. Watt, H. Sidhu, L. Sidhu, Using phase change materials and air gaps in designing fire fighting suits: a mathematical investigation, Fire Technol. 55 (2019) 363–381. https://doi.org/10.1007/s10694-018-0794-z.
[12] B.L. Bennett, R.D. Hagan, K. Huey, C. Minson, D. Cain, Comparison of two cool vests on heat-strain reduction while wearing a firefighting ensemble, Eur. J. Appl. Physiol. Occup. Physiol. 70 (1995) 322–328. https://doi.org/10.1007/BF00865029.
[13] J. Carter, M. Rayson, D. Wilkinson, V. Richmond, S. Blacker, Strategies to combat heat strain during and after firefighting, J. Therm. Biol. 32 (2007) 109–116. https://doi.org/10.1016/j.jtherbio.2006.12.001.
[14] J. House, H. Lunt, A. Magness, J. Lyons, Testing the effectiveness of techniques for reducing heat strain in Royal Navy nuclear, biological and chemical cleansing stations' teams, J. Roy. Nav. Med. Serv. 89 (2003) 27–34. http://dx.doi.org/10.1136/jrnms-89-27.
[15] D. Torvi, J. Dale, A finite element model of skin subjected to a flash fire, ASME J. Biomech. Eng. 116 (1994) 250–255. https://doi.org/10.1115/1.2895727.
[16] G. Mercer, H. Sidhu, A heat transfer model describing burns to the skin from automotive airbags, ANZIAM J. 47 (2005) C339–C354. http://dx.doi.org/10.21914/anziamj.v47i0.1048.
[17] A. Hassan Mohammed Ali, W. Yu, Thermal protective performance of multilayer fire fighting fabric, Int. J. Cloth. Sci. Technol. 26 (2014) 235–246. https://doi.org/10.1108/IJCST-03-2013-0032.
[18] R. Farag, Enhancing the Protection Performance of Flame Resistant Fabrics Using Phase Change Materials, AATCC J. Res. 1 (2014) 5–10. https://doi.org/10.14504/ajr.1.4.2.
[19] A. Shaid, L. Wang, R. Padhye, The thermal protection and comfort properties of aerogel and PCM-coated fabric for firefighter garment, J. Ind. Text. 45 (2016) 611–25. https://doi.org/10.1177/1528083715610296.
[20] T. Lippong, S. Houshyar, B. Singh, C.D. Lai, Z. Bingjie, A Comparative Study of Firefighters' Clothing using Organic and Inorganic Phase Change Material, J. Mech. Eng. (JMechE). 4 (2017) 84–97.
[21] Z. Zheng, Z. Chang, G.-K. Xu, F. McBride, A. Ho, et al., Microencapsulated phase change materials in solar-thermal conversion systems: understanding geometry-dependent heating efficiency and system reliability, ACS Nano. 11 (2017) 721–729. https://doi.org/10.1021/acsnano.6b07126.
[22] B. Peng, G. Huang, P. Wang, W. Li, W. Chang, et al., Effects of thermal conductivity and density on phase change materials-based thermal energy storage systems, Energy. 172 (2019) 580–591. https://doi.org/10.1016/j.energy.2019.01.147.
[23] E. Rahimi, A. Babapoor, G. Moradi, S. Kalantary, M.M. Esmaeelpour, Personal cooling garments and phase change materials: A review, Renew. Sustain. Energy Rev. 190 (2024) 114063. https://doi.org/10.1016/j.rser.2023.114063.
[24] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2009) 318–345. https://doi.org/10.1016/j.rser.2007.10.005.
[25] F. Shakeriaski, M. Ghodrat, M. Rashidi, B. Samali, Smart coating in protective clothing for firefighters: An overview and recent improvements, J. Ind. Text. 51 (2022) 7428S–7454S. https://doi.org/10.1177/15280837221101213.
[26] G. Mercer, H. Sidhu, Mathematical modelling of the effect of fire exposure on a new type of protective clothing, ANZIAM J. 49 (2007) C289–C305. http://dx.doi.org/10.21914/anziamj.v49i0.346.
[27] J.A. Gear, M.J. Lachut, Y. Ding, Enhanced thermal performance of garments embedded with encapsulated phase change material, ANZIAM J. 47 (2005) C137–C51. http://dx.doi.org/10.21914/anziamj.v47i0.1035.

[28] F. Zhu, Q. Feng, R. Liu, B. Yu, Y. Zhou, Enhancing the thermal protective performance of firefighters' protective fabrics by incorporating phase change materials, Fibres Text. East. Eur. 23 (2015) 68–73.

[29] G.N. Mercer, H.S. Sidhu, A theoretical investigation into phase change clothing benefits for firefighters under extreme conditions, Chem. Prod. Process Model. 4 (2009). https://doi.org/10.2202/1934-2659.1349.

[30] Y. Hu, D. Huang, Z. Qi, S. He, H. Yang, H. Zhang, Modeling thermal insulation of firefighting protective clothing embedded with phase change material, Heat Mass Trans. 49 (2013) 567–573. https://doi.org/10.1007/s00231-012-1103-x.

[31] A. Shaid, L. Wang, S.M. Fergusson, R. Padhye, Effect of aerogel incorporation in PCM-containing thermal liner of firefighting garment, Cloth. Text. Res. J. 36 (2018) 151–164. https://doi.org/10.1177/0887302X18755464.

[32] A. Fonseca, T. Mayor, J. Campos, Guidelines for the specification of a PCM layer in firefighting protective clothing ensembles, Appl. Therm. Eng. 133 (2018) 81–96. https://doi.org/10.1016/j.applthermaleng.2018.01.028.

[33] A. Fonseca, S.F. Neves, J. Campos, Thermal performance of a PCM firefighting suit considering transient periods of fire exposure, post–fire exposure and resting phases, Appl. Therm. Eng. 182 (2021) 115769. https://doi.org/10.1016/j.applthermaleng.2020.115769.

[34] A.F. Malaquias, S. Neves, J. Campos, Incorporation of phase change materials in fire protective clothing considering the presence of water, Int. J. Therm. Sci.183 (2023) 107870. https://doi.org/10.1016/j.ijthermalsci.2022.107870.

[35] Y. Wang, Y. Ma, R. Chen, Y. Su, Thermal protective performance of firefighting protective clothing incorporated with phase change material in fire environments, Fire Mater. 45 (2021) 250–260. https://doi.org/10.1002/fam.2928.

[36] G. Santos, S.F. Neves, M. Silva, J.M. Miranda, J.B. Campos, et al., Smart firefighters PPE: impact of phase change materials, Appl. Sci. 13 (2023) 10318. https://doi.org/10.3390/app131810318.