# A Comparative Study of Firefighters' Clothing using Organic and Inorganic Phase Change Material

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ABSTRACT

*Firefighters are often exposed to high temperature environments which can lead to dehydration and high body temperatures. Consequently, a reduction in mental concentration and an increase in fatigue levels will occur. The aim of this study is to investigate the implementation of Phase Change Material (PCM) into firefighter internal clothing to improve thermal protection. Both organic and inorganic types of PCM have high heat absorbing capacity and therefore can be used as thermal energy storage to enhance firefighter's body cooling and thermal protection. Experimental prototypes were constructed using cotton drill shirts, cotton mesh pockets and PCM packaged into aluminium pouches. The selected type of PCM studied was of paraffin wax as organic PCM and Glauber's salt as inorganic PCM which were used to create samples to be tested under simulated conditions. To increase the thermal conductivity of PCMs, the addition of copper metal foam to the paraffin wax was also analysed. The results indicated that the copper foam was able to reduce the melting time whilst evenly distributing the heat. This paper will provide detailed thermal analysis of different category of PCM and comparison of their respective heat absorbing performance, to achieve maximum thermal protection for firefighters via fully passive cooling approach. This implementation of PCM based firefighting clothing will lead to an improvement in firefighter's cooling sensations, potentially increase their operation time, better mental concentration.*

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2017-05-10
Accepted for publication: 2017-07-02
Published: 2017-12-31

**Keywords:** *Thermal management; firefighting; phase change material; passive cooling; paraffin wax*

## Introduction

Firefighting is considered to be a hazardous and dangerous profession in which firefighters perform intensive physical labour in high temperature environments. Among the several types of conditions faced are the initial stages of fire, known as flashovers, with temperatures ranging from 500 to 600˚C and radiations of up to 20 to 40kW/m$^2$ [1-4], and also the growth stage of fire, the pre-flashovers, having temperatures from 100 to 300˚C with heat fluxes between 5 to 12kW/m$^2$ [3]. Such extreme working conditions can lead to compromised physical and cognitive capacity affecting operational capability, endurance and safety [5]. It is crucial for them to be clothed in an appropriate and high quality Personal Protective Clothing (PPC) with fire resistance and thermal properties [6]. The current standard of PPC´s consists of a waterproof, flame-resistant outer shell and an inner liner which is generally made up of a moisture barrier and a thermal liner [6-8]. This whole ensemble is heavy, bulky and has thermoregulation issues due to its insulation properties and the low water vapour permissibility [9].

Most research has been performed aiming to improve the thermal protection of PPC´s for firefighters. One of the most prominent approaches is the use of Phase Change Material (PCM), which has thermal regulating properties through the absorption of latent heat. During the phase change of such material, they are able absorb or release energy depending on the process, being able to have cooling effects on the system in which it is embedded [6, 10, 11]. One of the most well-known PCMs is the use of ice, in the form of ice packs. Studies show that ice vests have quick and strong cooling effects [12]. However, current researches also pointed out that ice have extremely low melting temperatures which may lead to abnormal redness of skin and excessive reduction in local skin temperatures, consequently causing discomfort for the wearer [13]. Besides ice, another extensively investigated PCM are the hydrated inorganic salts, which are salts mixtures, such as sodium sulfate with additives and water, with its thermo-physical properties, including melting temperature and latent heat, being altered based on the amount and type of additive utilised [13]. House, et al. (2013) states that salt PCM are more advantageous compared to ice due to the salt PCM being able to solidify without the use of a freezer [14].

Several studies investigated the advantages and disadvantages associated with the use of inorganic salts in protective clothing, pointing out characteristics such as phase segregation, lack of thermal stability and corrosion [13, 15], while also having good thermal conductivity and energy storage density [13, 16]. An alternative also explored in numerous works, is the use of organic hydrocarbons such as paraffin wax as PCM, some of these studies showed that due to its low melting point, the paraffin should not be utilized in textiles [17], while others argued that the melting point was proportional to the amount of carbon in the wax, which allows it to be increased, making the organic PCM´s more suitable for fabric applications, despite some issues like supercooling and low thermal conductivity. A more direct study by Bühler et al. compared the performance of organic and inorganic PCM and concluded that salt hydrates had a higher heat buffering capacity per volume compared to paraffin, and therefore are more suited to be used for heat protection in fibres and fabrics [18].

A factor of vital importance to maximize the cooling effects of the PCM in protective vests is the location of the material in the body, impacting the transfer capability of water vapour through the material and clothing layers [19]. It is known that when external temperatures are higher than skin temperature, the human body will reduce the excessive heat through the process of evaporation of sweat on the skin [4]. To maximize heat transfer, the PCM should be located as close as possible to the skin, and in contact with the larger skin area as possible [20, 21]. The optimum location to place the PCM would be against the abdomen, back and chest, thus providing the best transfer capability.

The objective of this research is to investigate and compare the implementation of organic and inorganic PCM into firefighter´s protective clothing for better thermal protection. Paraffin wax and Glauber´s salts were proposed and tested, to assess their thermal performance. It is noted that organic PCMs have poorer thermal properties such as latent heat capacities and thermal conductivities as compared to inorganic PCMs. However, by improving its heat transfer characteristics will be an option to be comparable to inorganic PCMs as heat absorbing materials and yet maintain its positive chemical characteristics. The thermal enhancement of PCM is purposed to increase the heat transfer rate for improve the body cooling performance of the firefighters during fire recuse missions.

## Method and Material

The proposed thermal design for the Personal Protective Clothing (PPC) were chosen based on its suitability to be used for fire protection and body cooling for firefighters. The encapsulation method chosen was the macro-encapsulation through the use of aluminium foil pouches, given that due to the thinness of the foil, aluminium can have relatively good heat transfer between the PCM and the skin [22].

During the standby for emergencies, firefighters are clothed with their station wear, which consists generally of a shirt and either pants or shorts; such vestment will also be used as internal clothing beneath the PPC. Given that the PCM´s will be located mostly on the upper limbs, the focus will be on the shirt, which is usually fire retardant or made out of 100% cotton. Based on the research found regarding cooling systems with PCM and their implementation methods [20, 21], the final proposed design was developed to have the packaged PCM placed within mesh pockets, such as described in Figure 1. Instead of having two cotton drill fabric layers to create the pocket, one layer of the pocket will be constructed using cotton mesh instead, with the objective of allowing a larger area of the packaged PCM to be in direct contact with the skin, hence improving the cooling sensation for firefighters.

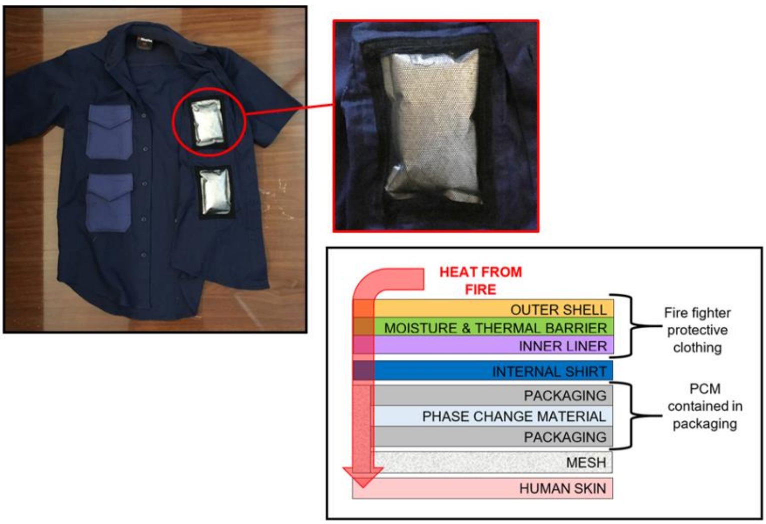


**Figure 1**. Prototype of internal clothing of PPC (left) and schematic diagram of the heat transfer from the external fire through to the skin (right).

Since the back and torso are the most thermosensitive areas of the human body, it would be advantageous to have the packaged PCM on the back of the shirt. However, such design may lead to difficulty of assembly and increased preparation time. Furthermore, firefighters also wear a breathing apparatus (BA) positioned on their back, which may compress the package, causing a possible leakage. As a result, to attest the advantages and disadvantages, both designs were implemented and tested for performance evaluation.

The first design involves having four pockets at the front of the shirt. The pockets will be located directly in front of the chest and abdomen as seen in Figure 2. This design has the main advantage of evenly covering the chest and abdomen areas, with the main disadvantage of having the same location as the straps for the breathing apparatus, which may cause potential problems. To avoid compression by the straps of the BA, an alternative design has also been considered and shown in Figure 3. This design has the same mesh pockets as seen in Design 1, it also has four pockets at the front of shirt but the top two pockets will be located more inwards whilst the bottom two pockets will be located further down on the shirt. Such modification in the pockets positions aims to avoid the obstruction of the breathing apparatus straps and consequent compression of the PCM packages. As a result of these changed pocket locations, the packaged PCM will not be covering as much thermosensitive areas. To compensate for such fact, two additional pockets were added to the back of the shirt. However, by including two additional pockets, the preparation time and weight carried by the firefighters will consequently increase.

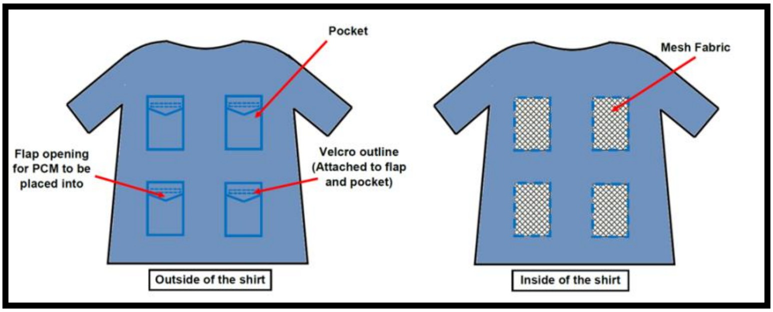


**Figure 2**. Design 1: Four pockets evenly distributed amongst the thermosensitive areas of the human body: chest and abdomen areas.

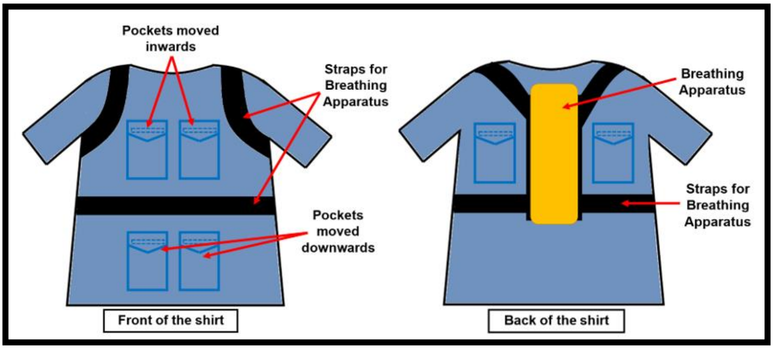


**Figure 3**. Four pockets placed at the front of the shirt and two pockets placed at the back of the shirt avoiding the BA.

Table 1 presents the thermos-physical properties of the selected PCMs to being used for internal clothing as well as to be tested in this experimental analysis. The selected PCM for testing and comparison are the Glauber´s salts and the paraffin wax. Given that the paraffin wax is flammable, its use in protective clothing is questionable; however it was included on the tests due to the fact that it is readily available and also has a similar latent heat to the Glauber´s salts, thus absorbing roughly the same amount of heat. Regarding ice as aforementioned, although it has a higher latent heat and thermal conductivity when compared to other types of PCM, it requires refrigeration before use also causing redness on the skin, causing discomfort for the wearer. Therefore, due to its practical disadvantages, ice was considered not suitable for protective clothing applications and was not included in the experimental procedure.

**Table 1**. Properties of selected PCM.

| | **Melting Temperature (˚C)** | **Specific Latent Heat (J/kg)** | **Specific Heat (Solid/Liquid) (J/kgK)** | **Density (Solid/ Liquid) (kg/m$^3$)** |
|---|---|---|---|---|
| Paraffin Wax | 28 [23] | 240000 [23] | 2150/2180 [23] | 880/770 [23] |
| Glauber's Salt | 32 [24] | 252500 [24] | 1740/3300 [24] | 1460/1330 [24] |

**Figure 4.** Copper foam used for experimental testing.

There are several methods to enhance the thermal conductivity of PCM for increasing the body cooling performance. The method explored was using Copper as metallic inclusions into PCM due to its high thermal conductivity of 398 W/m.K [25]. A copper foam was used for such purpose such as can be seen in Figure 4.

## Experimental Setup

In this preliminary experiment, the entire shirt prototype with the packaged PCM was not included for testing. Only one package of PCM was tested and the results were examined accordingly. Samples that were tested included pure paraffin wax, pure Glauber's salt and paraffin wax with the inclusion of copper. Each packaged sample for testing included three k-type thermocouples which were used to record the change in temperature over time. The locations of these thermocouples were placed in the sample as demonstrated in Figure 6 and the test rig is shown in Figure 5.

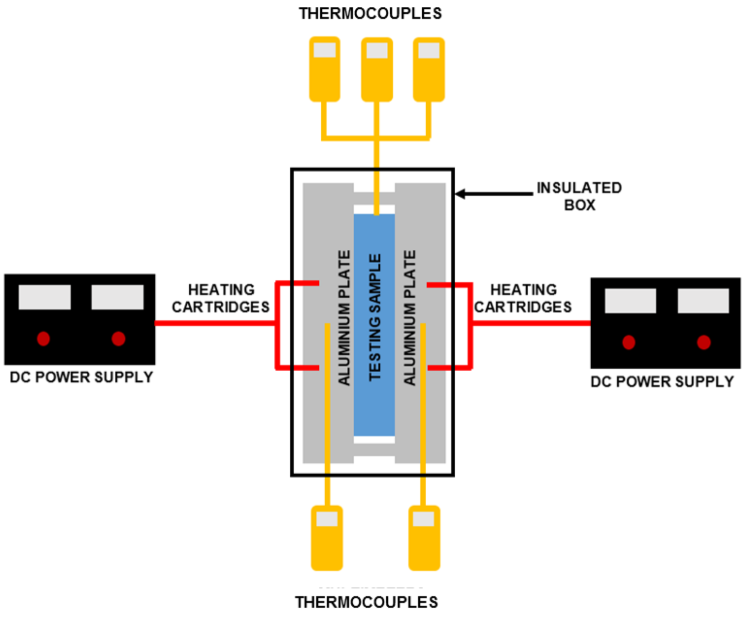


**Figure 5**. Schematic diagram of experimental set up.

The experimental test rig shows in Figure 5 consists of two aluminium heating plates enclosing the sample to be tested. One heating plate is used to replicate the incoming radiative heat flux from the fire whilst the other heating plate is used to replicate the heat flux produced from the human body. Each heating plate has two heating cartridges connected to a DC power supply and two K-type thermocouples connected to data logger for measuring the temperatures of the heating plates. The entire test rig was placed in an insulated box filled with cotton wool to minimise any heat losses to the surrounding environment. As mentioned previously, there are three thermocouples situated in the samples to be tested. These thermocouples are purposed to measure the change in temperatures of the PCM over time at different heights show in Figure 6.

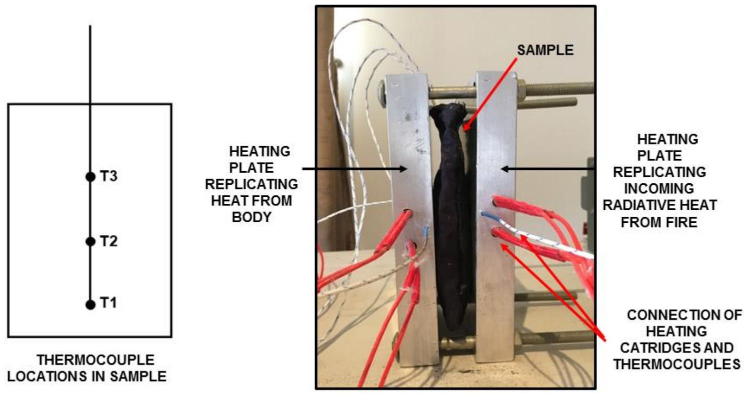


**Figure 6.** Test rig setup and thermocouple locations.

To simulate the microclimate conditions of the firefighter PPC under bearable scenario, the assumptions and experiment settings are listed in the following.

1) A person wearing PPC whilst carrying a compressed air cylinder and walking in a relatively hot environment can produce a metabolic rate of approximately 270W/m$^2$ [26].
2) The maximum radiative heat flux that a human can tolerate without any pain or burns is around 1250W/m$^2$ [27].
3) The dimensions of the selected aluminium foil packaging are 0.08m by 0.12m when empty and flat but when filled with the PCM, it is assumed that the contacting dimensions on the skin will be 0.06m by 0.10m, resulting in an area of 0.006m$^2$.
4) The total amount of time is 50 minutes, including arrival time of 5 minutes and operation time of 45.
5) The skin temperature whilst wearing PPC in a hot environment for around 40 minutes reaches around 38-39˚C [12].
6) The initial temperature of the PCM is assumed to be at room temperature of 20 ˚C

The material composition and heat transfer of the firefighting PPC are shown in Figure 7.

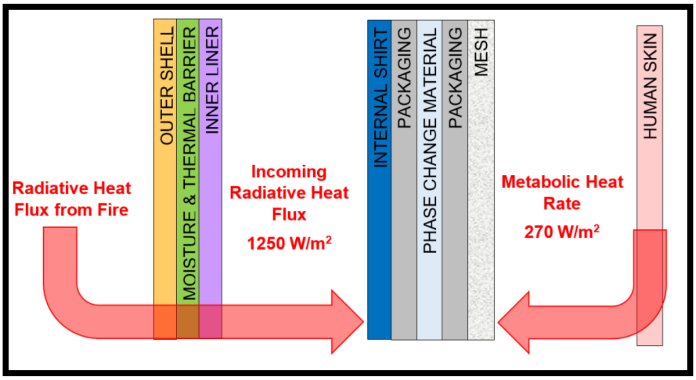


**Figure 7**. Experimental testing condition simulating fire rescue activity.

## Results and Discussion

As presented previously, the experiments were conducted on one PCM package (both organic and inorganic) as passive heat absorbing device using hot plates for replicating microclimate conditions of the firefighting PPC.

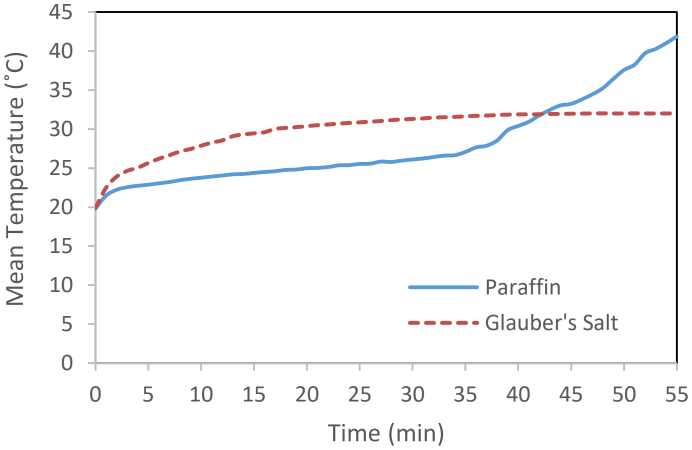


**Figure 8**. Temperature profiles of pure paraffin wax and Glauber's salt samples.

Figure 8 illustrates the temperature variations over time for the pure paraffin wax and pure Glauber's salt samples that were tested. The heat being supplied from the heating plates were transferred to the samples which caused them to rise from their initial temperatures. Based on the experimental results, the Glauber's salt rose to a higher temperature compared to the paraffin wax before maintaining a constant temperature. The Glauber's salt rose to a temperature of approximately 30-31˚C before reaching a constant temperature range. This is due to the Glauber's salt having a higher thermal conductivity compared to the paraffin wax. As previously mentioned, Glauber's salt has a thermal conductivity value of 0.544W/m.K whilst the paraffin wax is 0.15W/m.K. Approximately after 30 minutes of heating, the temperature of the Glauber's salt ranges between 31-32˚C. Compared to the paraffin wax, the Glauber's salt appears to have a longer latent phase stage. This is caused by the Glauber's salt having a larger specific latent heat of material of 252 kJ/kg compared to the paraffin wax of a latent heat value of 240 kJ/kg. From the results obtained and by comparing the paraffin wax with the Glauber's salt, it concludes that the Glauber's salt will be more suitable to be used in the firefighter internal clothing due to more heat transfer being transferred to the PCM, resulting a lower packaging temperature. Consequently, the wearers will have a cooler feel internally which results better body cooling performance using Glauber's salt as inorganic PCM.

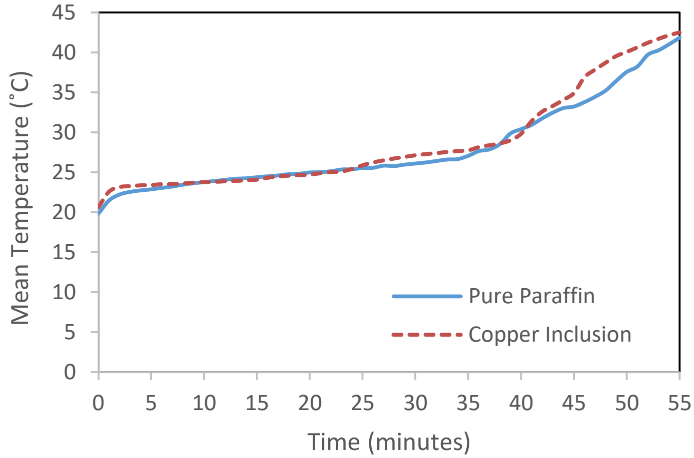


**Figure 9**. Temperature profiles of pure paraffin wax and copper inclusion samples.

Figure 9 compares the temperature profiles for the pure paraffin wax and paraffin wax with the copper foam sample. From the temperature profiles, it shows that the sample with the copper metal foam requires less time to increase the initial temperature of the sample. Hence, the sample with the copper foam was able to reduce the melting time of the paraffin wax. Overall, the addition of the copper foam to paraffin wax does not appear to have significance on heat absorption rate (melting process) due to averaging the temperatures instead of accessing individual temperature at respective thermocouple location. Hence the mean temperature profiles for both samples are generally quite similar. In order to see more distinctive difference in melting behaviour, increasing the porosity of the copper foam in the Copper-Paraffin wax mixture will produce a more noticeable change between the temperature profiles. However, this approach will reduce the mass of the heat storing PCM and consequently result a shorter body cooling time.

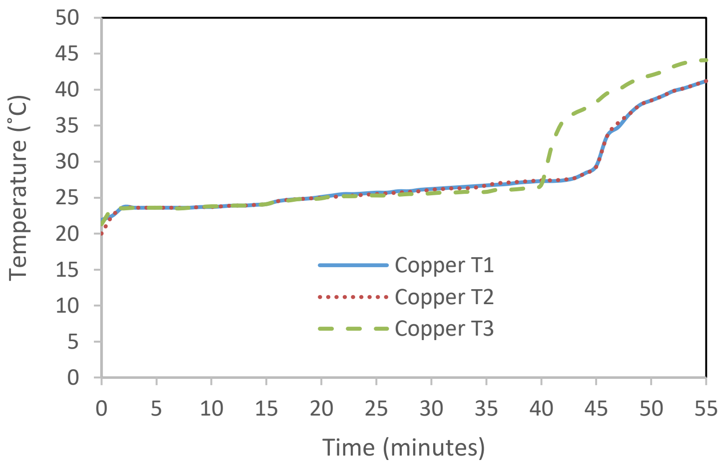


**Figure 10**. Temperature profile of copper inclusion sample for each of the three thermocouples.

The present of copper foam material was able to enhance the heat transfer of the paraffin wax and also act as a heat spreader. By having the copper metal foam, there was a more uniform distribution of the temperature within the paraffin wax. This can be seen by comparing the temperature profiles in Figure 10 and 11. In Figure 10, the temperatures at each of the thermocouple locations throughout the whole sample remained fairly similar. However, as illustrated in Figure 11, the temperatures varied at each of the thermocouple locations. This indicates that the sample with the copper foam has more effective diffusion of heat into the larger mass of the paraffin wax compared to the pure paraffin wax sample. This also suggests that the liquid layer closest to the heating aluminium plates have avoided potential superheating issues by reducing the temperature gradient between the surface and the inner core regions inside the PCM package.

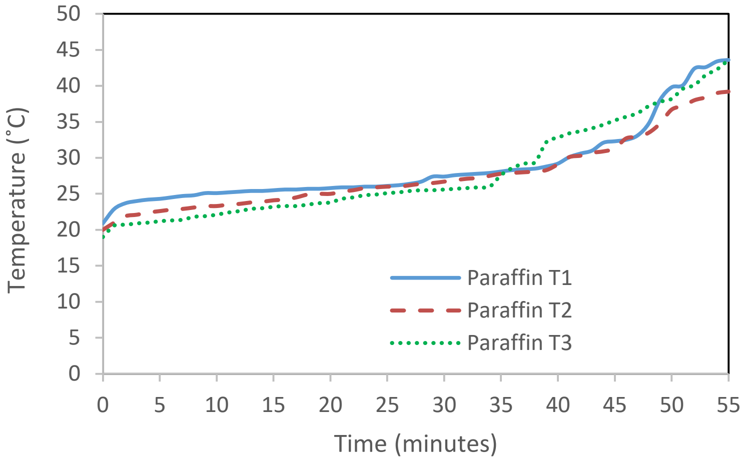


**Figure 11**. Temperature profiles of pure paraffin sample for each of the three thermocouples.

## Conclusion

The implementation of PCM based cooling packages into firefighter internal clothing was preliminarily investigated. Two different types of PCMs were tested under similar simulated conditions. Based on the experimental results, Glauber's salt is more ideal to be used in regard to fire rescue mission due to being more light weight and less thick compared to paraffin wax. Experimental tests were also developed to examine the thermal performance between the paraffin wax and Glauber's salt when under simulated conditions. From the results obtained, it shows that the Glauber's salt has better thermal performance compared to the paraffin wax due to having a longer latent phase and higher thermal conduction which allowed more heat absorption into the PCM and hence achieve better body cooling effect. The inclusion of metal copper foam to the paraffin wax was also analysed. The results indicated that the copper foam sample was able reduce the melting time of the paraffin wax and also enable even distribution of heat.

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