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A mathematical model for heat transfer in fire fighting suits containing phase change materials

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ABSTRACT

Fire fighting is a hazardous occupation and the use of good quality thermal protective clothing is vital in the prevention of heat related injuries. Protective fire fighting clothing is generally chosen for its thermal and fire resistant properties, while also considering the weight, bulk and ease of movement of the suit. This research proposes incorporating a phase change material (PCM) into the fabric of the fire fighting suit in conjunction with air gaps to increase the thermal protection. A mathematical model of heat transport through a suit that contains PCMs and air gaps is presented. We investigate the distribution of temperature within the fabric during exposure to different fire situations. To assess the protective nature of the clothing, we model the skin as three layers with differing thermal properties (the epidermis, dermis and the subcutaneous layer) and examine the temperatures within the skin. The model can then be used to determine if the inclusion of a PCM layer would provide increased thermal protection to the fire fighter. Our earlier research has indicated that the most effective position for a PCM layer is near the outside of the suit. This paper will focus on the effect of the PCM layer in combination with air layers in the suit. Our results clearly show that an additional air layer increases the protection provided by the suit. This benefit comes without significantly increasing the overall weight of the suit.

1. Introduction

Fire fighting is an extremely dangerous occupation where the fire fighter is exposed to high temperatures and heat fluxes, often while completing high intensity physical labour. Fire fighting suits must be designed to protect the wearer from these extreme conditions, but cannot be so bulky or heavy that they restrict movement or cause additional strain on the fire fighter. To reduce the physiological strain on the fire fighter a number of different methods have been trialled. For example, ice vests worn under the fire fighting suit have been shown to effectively reduce heat strain on the fire fighter [1,2], as has periodic immersion of hands and forearms into cool water [1,3]. While these methods are useful, they have obvious limitations. The storage of ice vests is impractical in scenarios such as fire fighting on ships, or fighting bush or wildland fires in remote locations. Also, frequent rest periods that are required for cool water immersion techniques to be effective are unlikely to be feasible in emergency situations.

To reduce the physiological strain on fire fighters and prevent skin burns, a number of authors have proposed incorporating a PCM layer into the structure of the fire fighting suit [4–6]. A PCM is a latent heat storage material [7], which is able to absorb a comparatively large amount of heat as it undergoes a phase change. In the context of fire fighting suits, the ideal PCM has a melting temperature between 40 and 90 °C [6]. At room temperature the PCM is a solid; then, when the fire fighter enters a heated area, the PCM starts to melt, absorbing heat while maintaining a constant temperature, thus decreasing the quantity of heat that travels through the suit [4]. Once all of the PCM has melted it does not exhibit any special thermal properties, however it can still act as an insulating layer. When the suit is removed from the heated area, the PCM will solidify, releasing the heat that it had previously absorbed. The suit is consequently easily portable, and requires no special storage conditions, unlike ice vests. The added advantage is that it can be reused, since the PCM can be incorporated into a fabric in a number of ways to ensure that once it has melted it does not escape from the suit. One such method used in textiles is microencapsulation of the PCM. Small capsules of the PCM are then spread across the surface of a fabric, creating a layer within the fabric that has the same thermal properties as the PCM [8].

There are a variety of PCMs available, with a large range of thermal properties. Depending on the material chosen, a PCM can have a melting temperature from −30 °C to over 800 °C [8]. They are currently used in many different textile applications, however

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they have mostly been used to retain body heat under cold conditions. For example, they are used in diving suits, snow clothing and astronauts space suits to protect the wearer from the freezing external environment [9,10]. In these scenarios, the PCM has a much lower melting point, and is a liquid at room temperature. When the suit is placed in a cold environment, the PCM solidifies and releases the latent heat it has stored, heating the body of the wearer. This is the reverse process that is used to protect fire fighters from extreme heat when wearing a fire fighting suit with a PCM layer.

It is important to note that the fire fighting suits currently being used do not contain a PCM layer. The current structure of a standard fire fighting suit consists of a waterproof outer shell and a fabric wadding to provide insulation. Since PCMs have not been included in protective fire fighting clothing to date, the aim of our investigation is to develop a mathematical model that allows us to investigate the effectiveness of the use of PCM technology in the development of protective clothing for fire fighters. Similar work has been completed by McCarthy and di Marzo [4], where they have both mathematically modelled and physically tested a suit composed of a face cloth, moisture barrier, a PCM and a thermal liner. These authors found that when a PCM was included in the suit the resulting temperatures behind the face cloth layer of the suit were up to 7 °C lower than in a suit without a PCM, when exposed to a low heat flux of 2.5 kW m^{-2}.

In our model, we include the process of phase change, which absorbs heat. Furthermore, since our aim is to investigate the effectiveness of the suit, the heat transfer through the skin is also modelled, which includes the heat loss in the skin due to blood perfusion. These processes have not been considered by other authors in their investigations of using PCMs in protective fire fighting clothing. Our previous work has shown that the inclusion of a PCM layer significantly reduces the temperatures of the layers of the suit and extends the amount of time a fire fighter can spend in dangerous environments without suffering serious burns, and that the best location for the PCM layer is directly under the waterproof outer shell [11]. In this work, we are interested in the effect of an additional air layer within the suit in combination with the PCM, as air layers have been shown to have an insulating effect [12].

2. Method

The mathematical model used to investigate the system is a one dimensional heat transfer model. A one dimensional model is a reasonable approximation of heat transfer through the fire fighting suit and skin, as the surface area of the suit is large compared to its thickness. The model is similar to the one used by McCarthy and di Marzo [4], in that it only considers conductive heat transfer (as the convective effects through the suit have been shown to be an unnecessary inclusion in the heat transfer model [4]) and does not consider the effects of degradation of the materials in the fire fighting suit. Unlike McCarthy and di Marzo, this work uses a heat flux as the boundary condition, as they use temperature data recorded experimentally, which is not possible for us to achieve [4]. Since the model is one dimensional, only heat transfer normal to the clothing and skin surface is considered. Moisture transfer is not considered in this model, as it has a negligible effect compared to the effect of the PCM, and the extra complexity is not warranted [13]. An air gap naturally occurs between the suit and the fire fighters skin as the suits are not skin tight. The structure of the four fire fighting suit configurations being investigated in this paper is shown in Fig. 1.

Configurations A and B are used as benchmarks, as they have no PCM layer in the suit. Configurations C and D have a PCM layer incorporated, which is placed directly beneath the outer layer in both configurations, as previous work has indicated that this is where it has the largest effect [11]. In Configurations B and D, there is an additional air gap with a width of 1 mm placed beneath the second layer of the suit. To examine the effectiveness of all suit configurations on preventing the fire fighter from suffering burns, the heat transfer through the skin is also considered in the model. The skin is assumed to be composed of three layers, all with differing thermal properties. These layers are the epidermis, the dermis and the subcutaneous layer [13,14].

From conservation of energy, the governing equations for the one dimensional model used is given by

$$\rho C\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - G\rho_b C_b (T - T_c) - \rho Q\frac{\partial}{\partial t}(Z) \tag{1}$$

$$Z = 0.5 \times \mathbf{erfc}\left(\frac{T - T_{melt}}{T_{range}}\right) \tag{2}$$

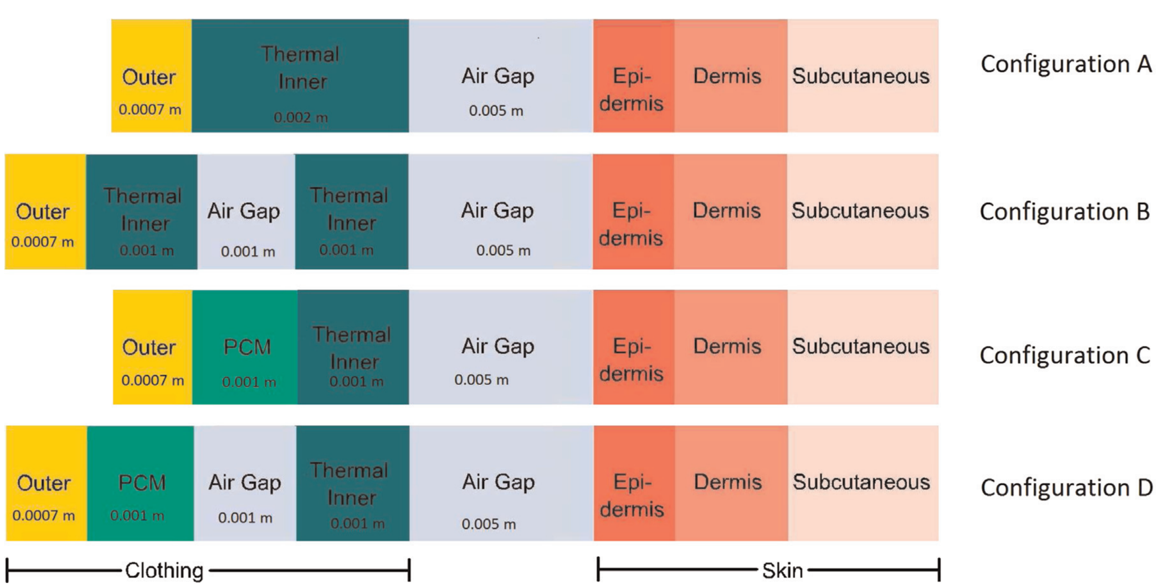

Fig. 1. Schematic diagram of the four different arrangements of the layers of the suit and skin simulated by the model.