THE HEAT TRANSFER IN THE FIREFIGHTING FABRICS CONTAINING PHASE CHANGE MATERIALS

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ABSTRACT

The theoretical heat transfer of flexible multilayer firefighting composite fabric including two stages of phase change materials (PCM) has been analyzed, and the designing method has been discussed in systematically. It is necessary to have simpler methods to evaluate the heat transfer through multilayer thermal insulation. A mathematical model has been developed to describe the heat flux through the multilayer firefighting fabric, where the heat transfer consists of thermal radiation, solid spacer and (PCM). This study discusses heat transfer mechanism of firefighting insulation material in specific high temperature and severe heat environment based on the testing results and their analysis.

Keywords: heat transfer, phase change materials, insulation materials,Flash over temperature.

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Introduction

From the structural point view, the fabric is solid material exists in the form of fibers and phase change material. Therefore, in the environment of high temperature and severe heat, fabric inside is not only the presence of gas phase and a solid phase thermal conductivity, but also there is thermal radiation and convection. The heat transfer characteristics of the composite fabric in its multi-layered composite structure and monolayer structure can be equivalent to a general flat multi-wall heat transfer.Before entering to formulate the present problem of heat and transfer, when the outer layer of firefighting clothing is exposed by high intensity thermal radiation, several important assumptions can be made to simplify the formulation

- Fibers volume changes due to the moisture content changing are neglected.
- Heat transfer is one-dimensional and is along the fabric thickness layers. There is no lateral transport.

Many factors impact on the thermal protective performance of the fire insulation composite fabric, such as the composite laminated structures, heat transfer properties, and thermal stability of the composition layer. The high performance material plays a key role in many parameter such as the structural properties of the composite fabric, achieving the optimization of the laminate structure, the performance of the overall structure, and composite mode. The high performance material has a great influence on the protective properties especially the research was adopted the high temperature environment and severe heat. Therefore, this study focuses on the raw materials as well as different combinations of composite fabric structure, and fire insulation performance of the multi-layer fabric, studying the preparation of flexible composite fabric with the optimal fire insulation effect.

2. Background

Thousands of fire fighters sustain burn injuries every year, to minimize this number in the past few years, researchers have developed fire protective and thermal insulating garment with excellent thermal protective performances based on the application of new technologies [1, 2]. Thermal protective clothing has been designed to prevent or minimize firefighter's skin burn damage due to high heat exposure. Textile fabrics with multilayer fire protective garments have some insufficiency in order to protect fire fighters against burn injuries. The protective performances were depend on the thermal properties of the fabrics, the insulating air between layers and in the fabrics stricter to resist heat flux from flash fire exposures [2, 4]. Emergency conditions may be encountered during flashover of a large building.

2.1 Design Concepts and Principles

The actual use of fire insulation protective clothing not only requires good flame retardant properties, should also have a good thermal insulation protection performance, to ensure the firefighter safety at the scene of the fire during the operation against high temperature burns. The traditional fire insulation fabrics were based on a simple multi-layer superimposed structure, relying solely on the thermal isolation of the material itself and the heat resistance of fire insulation effect. For flash over, high-performance insulation flexible fabric, relying on the material itself, thermal isolation and heat resistance cannot be completed withstand with the protection of personal protective equipment. The reason is to meet the resistance of flash over generated by the high heat radiation and high temperature and the durability of the thermal protection of the fibrous, material used to have the following properties:

- Flame retardancy: The fabric is exposed to flame difficult to burn or difficult to spread flame.
- Isolation: a dampening effect of the barrier is formed between the open flame heat source and the human body.
- Thermal insulation: isolation and absorption to heat to reduce the heat damage to the human body.
- Durability: as a daily working heat protective clothing, the thermal protection, and other physical, chemical resistance must be stable. If you meet these, will definitely lead to only rely on the simple superposition of the multilayer rigid and heavy fabric, limited adiabatic durability.

In the past few years, the human protective material put forward higher requirements using new materials, and high-tech advances especially in lightweight, flexible, intelligent high-performance fabrics. Firefighting fabric should have a chemical stability and thermal fatigue resistance beside the fabric lightweight, soft, smart, safe, reliable and efficient thermal insulation. These properties set to achieve a reasonable match between the multi-layer structure of the functional design and special finishing.

2.2 Composite Fabric Structure and Performance Design

The high temperature environment and flash over source and environment are extremely complex and there is a dynamic change in the environment. Severe thermal problems and life threatening injuries are associated with these conditions. These conditions have a typical temperature range of 300°C to 1200°C and radiant fluxes of 12.56 to 209.34kW/m^2. During these situations the skin temperature of the firefighter must be lower than 44°C, because when the temperature reached 55°C it is likely to cause a second degree burn on human tissue, and at the 72°C is the human tissue temperature at which an instantaneous burn injury is likely to occur [5].

Many scientists have done a lot of research on the fire environment, on the basis of the size of the fire, heat flux and temperature. Generally fire divided into three typical state: conventional state, dangerous state and critical state, according to Abbott criteria [6] as shown in Table 1

Table 1: Firefighter thermal environments

Status	Air temperature (°C)	Radiant heat flow (Cal/cm^2·sec)	Tolerance time
Conventional	20-70	$<$ 0.04	10-20 min
Danger	70-300	0.04-0.30	1-5 min
Critical	300-1200	0.30-0.5	15-20 Sec

Under conditions of no wind, A. Tewarson studied the fraction of fire radiation of the different types of fuel. Usually, the convection heat from the total release of heat is more than the 60% to 70%, and the thermal radiation energy of the total release of energy is by 30% to 40%. Thermal radiation is the most important ways to heat exchange with neighboring objects. The wavelength range of the electromagnetic wave is from zero to infinity, but wavelength absorbed by the object and converted to heat radiation is the visible light (from 0.4 ~ 0.8μm) and infrared (from 0.8 ~ 20 μm), i.e. The wavelength in the 0.4 ~ 20μm, collectively referred to as a hot ray [7, 8].

The innovative design of composite firefighting fabric for high-temperature fire environment is to use of the hierarchical functional decomposition, sharing isolated from the principle of the layer-by-layer protection, focusing on the introduction of a phase change the endothermic energy storage mechanisms and materials to implement step by step the high energy consumption and cooling.

During firefighting operation the temperature in the environment is typically around 100°C to 300°C and the heat flux between1 to10 kW/m^2. In flash over cases the temperature could be up to 1000°C and heat flux of 80kW/m^2 or more [9] The firefighting composite fabric designed to use in scenes of the high temperature environment about 1000°C.

2.3 Radiation heat transfer (Qrad):

To obtain the temperature distribution throughout the firefighting fabric both the energy equation and the radiative heat transfer equation should be solved. The thermal radiation model was described, it is an extension of the model developed by Mell and Lawson for fire fighter protective clothing [10]. We assume that for material layer, the contribution to radiative flux self-emission is much smaller than that due to the absorption of the externally incident flux. The major radiative flux incident on the boundaries of a material layer are assumed to be

- The external incident heat flux on the outer garment layer. This occurs to forward incident fluxes and the backward incident fluxes on the inner boundaries.
- Interlayer radiative flux and its reflection. This occurs when the material surfaces bounding and the air layers have different temperatures and contributes to both the forward and backward incident flux.

According to the first assumption the backward reflection of radiation due to the external flux is calculated. Under these assumptions, the net radiative flux $q_{x,l}$ at a distance *x* measured from the left boundary, within material layer *l* can be obtained from the Beer-Lambert law, and can be expressed as

$$q_{x,l} = q_l^{i+} e^{-k_l x} + q_l^{i-} e^{-k_l (d_l - x)} \tag{1}$$

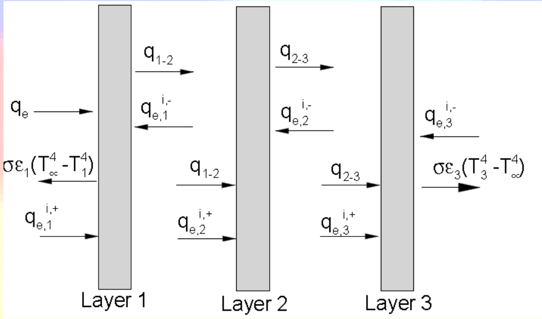

Figure 1: cross-section of a three layered firefighting protective clothing ensemble.

Corresponding radiative heat transfer diagram was drawn to calculate the radiation heat transfer. When the reflective screens are N layers, the total radiative resistance (Rrad) is expressed as follows

$$R_{rad} = \frac{1}{A}\left[\frac{1}{\varepsilon_c} + \frac{A_c}{A_h}\left(\frac{1}{\varepsilon_h} - 1\right) + \sum_{i=1}^{N} \frac{A_c}{A_i}\left(\frac{2}{\varepsilon_r} - 1\right)\right] \tag{2}$$

The total radiation heat transfer (Qrad) can be obtained

$$R_{rad} = \frac{\sigma A\left(T_{1000}^4 - T_{40}^4\right)}{\frac{1}{A}\left[\frac{1}{\varepsilon_c} + \frac{A_c}{A_h}\left(\frac{1}{\varepsilon_h} - 1\right) + \sum_{i=1}^{N} \frac{A_c}{A_i}\left(\frac{2}{\varepsilon_r} - 1\right)\right]} \tag{3}$$

where, σ is the Stefan-Boltzmann constant ($5.67\times10^{-12}\,W/cm^2K^4$) .

3. Materials:

The firefighting multilayer flexible composite fabric system was functionally designed to provide protection against high heat flux environment. The layer structure consists of: the outer layer (heat reflective layer), phase change the endothermic composite layer, inner layer (isolated comfort layer). The outer layer (heat-reflective layer) is a metal aluminum foil fabric, formed directly on the reflective insulation layer, and the main thermal radiation reflection; intermediate endothermic layer using a refractory fiber felt, a high temperature resistant fiber such as basalt fiber and glass fiber fabric were used as the thermal storage layer containing phase change material (PCMs). Two stages of the phase change materials (PCMs) uniformly dispersed in the interstices of the fibrous mat or applied between the two layers of fabric, (48%) NaCl+ (52%) MgC_{l2} were used as first stage PCM. Galactitol ($C_6H_{14}O_6$) was used as second stage thermal storage PCM. The first stage (PCM) molten liquid phase temperature at about 450°C, this is the phase change endothermic composite layer; the second stage (PCM) is molten liquid phase temperature at 192°C. First stage phase change material is contained into the nonwoven basalt fabric and second stage phase change material is contained into the nonwoven glass fabric. Entire composite fabric structure as shown in Figure 1.

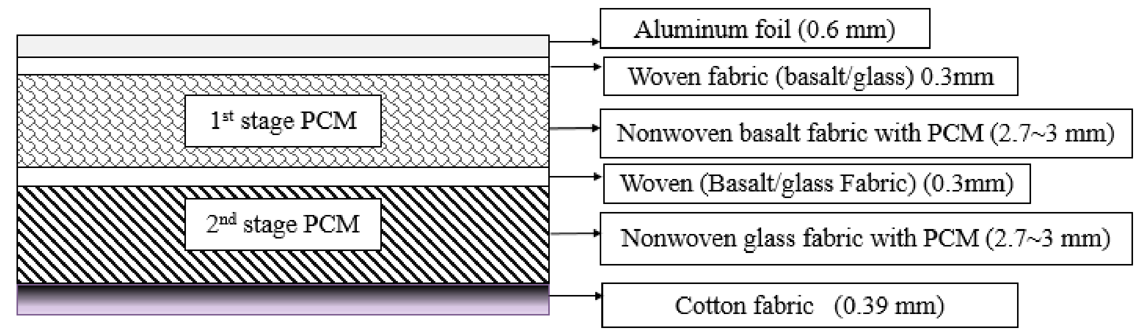

Figure **Error! No text of specified style in document.**: The structure of the fire protective composite fabric

4. Fabric Heat Transfer Model

Fabric heat transfer analysis shows that the front of the textile and clothing insulation material there are two heat transfer mechanism, one is the thermal conductivity of the gas phase and solid phase; another is thermal radiation. Convection plays a very small role and it can be neglected [11, 12]. Therefore, the energy balance equations of the textile and garment materials available (1).

$$\rho C_p \frac{\partial T}{\partial t} = \left(\lambda \frac{\partial T}{\partial t}\right) - \frac{\partial q_r}{\partial x} \tag{4}$$

where, T is the temperature, ρ is the density, c_p is the specific heat at constant pressure, λ is the thermal conductivity for the inner radiation heat flux, t is time, χ is the spatial coordinates of the specimen thickness direction.

Fiber interstices of the gas conduction in the textile and clothing insulation material, the thermal conductivity of a solid heat transfer of the fiber and its contact point is very difficult to obtain, so many researchers use different models to characterize the solids in the fabric of thermal conductivity and the thermal conductivity of gas coupling the comprehensive thermal conductivity, the easiest and used two models is the parallel model and series model.

Radiative calculations of thermal insulating fabric or fiber insulation material mainly used optical thin approximation method. Optical thin approximation method considers the insulation fabric material as the material of the optical thickness. In this case, the radiation flux density for optical thin limit can be represented by the formula:

$$q_r = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \tag{5}$$

where σ glassy Boltzmann constant, 5.67 × 10^{-8} ($W/(m^2 \cdot K^4)$); T_1 and T_2 are fabric surface and the counter surface temperature (K) respectively; ε_1 and ε_2 are the fabric surface boundary and the counter surface boundary cricket total transmit rate respectively.

4.1The Heat Transfer of the Composite Fabric incorporated Phase Change Material

For the phase change material applied to the composite fabric, taking into account the phase change material heat transfer of the latent heat change of the composite fabric, the energy conservation equation can be expressed as follows:

$$\rho_f C_{p,f}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(k_f\frac{\partial T}{\partial x})+\gamma q_{rad}e^{-\gamma x}+\rho_f Q\frac{\partial Z}{\partial t} \quad (6)$$

where $\rho_f, C_{p,f}$ and k_f are the density of the fabric, the specific heat, and thermal conductivity coefficient, respectively; Q is the heat of melting of the phase change material; Z is a fabric, the phase change layer in the solid phase material mass fraction (as a solid when Z = 1, all the liquid is Z = 0); extinction coefficient of the fabric ; q_{rad} fabric outer layer, cannot deep continue into the other layers of the incident radiant heat flow to the surface of the fabric.

4.2The heat transfer process in the phase change material

Composition of heat transfer in in the phase change material

Boiling

In general, means heating thus increasing the temperature of the substance to its boiling temperature and above. The heat required to change a mass m of a pure substance from a liquid to a vapor is generally given in terms of a latent heat of vaporization as:

$$Q = m\Delta H_{vap} \quad (7)$$

Latent heats are in general functions of pressure; they are usually given at 1 standard atmosphere (or 1 bar) in standard texts. For many applications the pressure dependence of latent heats is neglected.

Condensation

The heat released when one condenses a liquid is the same magnitude as the amount required to vaporize the same mass of the liquid. It will just have a negative sign rather than a positive one (because when something condenses, it releases heat.

Freezing and melting

The heat required to melt or solidify a pure substance is calculated in the same manner as that required to vaporize or condense that substance, except a different latent heat called the latent heat of fusion is used. It is used to freeze things.

Sublimation

At a certain range of pressures, rather than melting, a solid will be transformed directly into a gas, and vice versa. The latent heat of sublimation is the sum of the heats of vaporization and fusion, assuming the effect of pressure changes is negligible:

$$\Delta H_{sub} = \Delta H_{Vap} + \Delta H_{Fus} \quad (8)$$

The right side of the formula (4-41) in consideration of the phase change material phase change latent heat, when the melting of the solid PCM absorbs heat, corresponding to the Z value changes from 1 to 0. Z can be expressed by the following function:

$$Z = \frac{1}{2} erfc\left(\frac{T - T_m}{T_0}\right) \qquad (9)$$

where $erfc$ is the fill error function, and its expression, such as the formula (5) below; T_m the fluctuation value of the melting transition temperature, T_0 whichever is ± 2 ° C for the melting temperature of the phase change material;

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-\eta^2} d\eta \qquad (10)$$

When the density of the fabric, the specific heat, and thermal conductivity coefficient, and the fabric thickness were constant the decreasing of heat transfer is due to PCM work.

During the last half of the twentieth century, significant advances have been made in developing an understanding of phase change heat transfer (e.g., boiling and condensation). Further advances in phase change heat transfer will continue to take place motivated by new technologies such as microelectronics, thermal management in space, advanced terrestrial and space power systems and processing of designed materials. In the past, because of the complexity of the processes, very often we have "oversimplified", maybe out of necessity, the modeling of the processes.

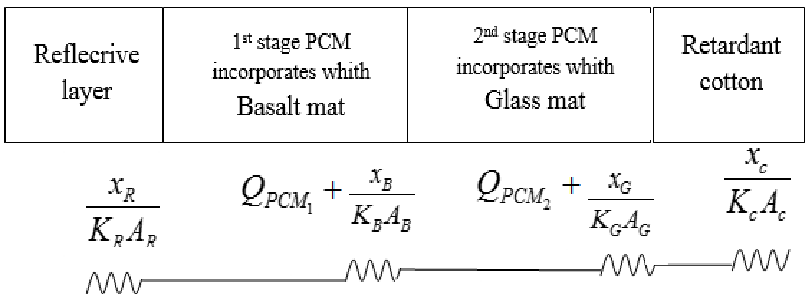

Figure 3: The mechanism of heat transfer through the firefighting fabric

The firefighting fabric exposed to temperatures of about 1000°C this Figure illustrated how each layer behave under flash over environment. The outer layer which consists of glass with aluminum foil reflect heat radiation and decrease the heat exposure to about 700°C or more due to the metal material has a low emissivity and a high reflectance properties.

The first stage phase change material absorbs this heat during phase change and maintain the temperature at about 450°C its melting point temperature. The phase change gives the temperature cutoff effect. The basalt nonwoven containing the first stage phase change material is decreasing the temperature to about 300°C.

The second stage phase change material absorb the remaining heat and maintain at 192°C its melting temperature and the nonwoven glass fabric containing the PCM the comfort layer the retardant cotton fabric decrease the temperature to about 40°C, this temperature avoids the second degree burns. Figure 4-6 shows the model structure of the firefighting fabric.

The impedance of the heat transfer in each layer is given in equation

$$\frac{x}{KA} \tag{11}$$

where x is the fabric thickness, K is the thermal conductivity and A is the surface area.

The heat absorbed by the PCMs

$$Q = m\Delta H_{vap} \tag{12}$$

Where m is the CPM mass, ΔH_{vap} is the latent heat of vaporization.

5. Result and Discussions

5.1 Theoretical and practical results

The main characteristics of heat conductivity are as follows:

$$\lambda = QL / At(T_1 - T_2) \tag{13}$$

where λ is Thermal conductivity [W/(mºC)] , Q expresses the heat flow [W] passing in 1 h through area (A) of $1m^2$ of the fabric thickness (L) at a temperature difference $(T_1 – T_2)$ of 1ºC.

The assumption is the fabric is solid material exists in the form of fibers and phase change material. Heat transfer by conduction can be used to model heat loss through the fabric. For a barrier of constant thickness, the rate of heat loss is given by:

$$Q = \frac{kAt(T_1 - T_2)}{x} \tag{14}$$

where Q is the heat conduction, A is thearea, t is time, k is the thermal conductivity, (T_1–T_2) is the temperature deference, x is the thickness.

The theoretical result of the heat transfer through the basalt fabric

$$Q_{b\,\text{theoretical}} = \frac{0.33\times 0.2\times 5(450-300)}{0.3} = 165W \tag{15}$$

thethermal conductivity is 0.33, the surface area 0.2m, the time is 5min, (T_1–T_2) is the temperature deference,0.3 is the thickness.

From the TPP test results, the 3mm thicknesses basalt fabric decrease temperature of about 160ºC.

The heat transfer through glass fabric

$$Q_{b\,\text{practical}} = \frac{0.33\times 0.2\times 5(160)}{0.3} = 176W \tag{16}$$

The theoretical result of the heat transfer through the glass fabric is given in the following equation

$$Q_{g\,\text{theoretical}} = \frac{0.3\times 0.2\times 5(192-44)}{0.3} = 148 \tag{17}$$

While the practical result is obtained from the TPP testing results, the 3mm thicknesses glass fabric decrease temperature of about 140ºC. The heat transfer through glass fabric is given in the following equation.

$$Q_{g\,\text{practical}} = \frac{0.33\times 0.2\times 5(140)}{0.3} = 140W \tag{18}$$

The actual testing results show that there exists a high degree of agreement to those results with the predicting results.

Latent heat storage (LHS): is the amount of energy stored in the material with phase change, the amount of energy storage in the LHS depends upon the mass and latent heat of the material. The thermal energy storage (THS) can be defined as the temporary thermal energy storage at high or low temperatures. Innovative methods for providing sustainable heating and cooling through thermal energy storage (TES) have gained increasing attention as heating and cooling demands in the built environment continue to climb. As energy prices continue to soar and systems reach their maximal capacity, there is an urgent need for alternatives to alleviate peak energy use. TES systems allow decoupling of energy production from energy utilization, both in location and in time. The length of time is one of the important characteristics of a storage system during this time energy can be kept stored with acceptable losses. The volumetric energy capacity, or the amount of energy stored per unit volume is another important characteristic of a storage system. The smaller volume with high heat capacity are the indicator to the better storage system. Therefore, a good system should have a long storage time and a small volume per unit of stored energy. The first law efficiency of thermal energy storage systems can be defined as the ratio of the energy extracted from the storage of the energy stored in it, the CPM efficiency is given as follow.

$$\eta = \frac{m_c (T - T_0)}{m_c (T_\infty - T_0)} \quad (19)$$

where m_c is the total heat capacity of the storage medium, $T - T_0$ are the maximum and minimum temperature of the storage during discharging respectively, and T_∞ is the maximum temperature at the end of charging period. The losses to environment between the end of discharging and the beginning of the charging periods, as well as during these processes are neglected. The first law efficiency can have only values less than one

The amount of energy stored (E) depend upon the mass (m) and latent heat of fusion (λ) of the material. Thus,

$$E = m\lambda \quad (20)$$

The storage operates isothermally at the melting point of the material; the system operates over a range of temperatures T_1 to T_2 that includes the melting point. The sensible heat contributions have to be considered and the amount of energy stored is given by

$$E = m\left[\left\{\int_{T_1}^{T^+} C_{ps}\, dT\right\} + \lambda + \left\{\int_{T^*}^{T_2} C_{p1}\, dT\right\}\right] \quad (21)$$

where C_{ps} and C_{p1} represent the specific hears of the solid and liquid phases and T^* is the melting point

5.2 The absolute effectiveness for the thickness and PCM

5.2 1The thickness effect

To calculate the absolute value of the thickness effectiveness first the actual temperature drop through the fabric were obtained. Thermal protective performance test were applied, and steady-state heat transfer in the open flame fire were obtained for the composite fabric; and the surface temperature versus time curve were extracted, the same procedure to measure the fire insulation properties of the firefighting. Thermal protective performance test was applied to measure the front surface temperature and back surface temperature. Δ_{Tn} is the actual temperature drop = the front surface temperature – the back surface temperature

$$\Delta_{Tn} = T_1 - T_2 \tag{22}$$

Then the absolute temperature is the actual temperature drop divided by the back surface temperature (curve 3 in thermal protective performance test Figure 3-20)

$$\delta_T = \frac{\Delta_{Tn}}{curve3} \tag{23}$$

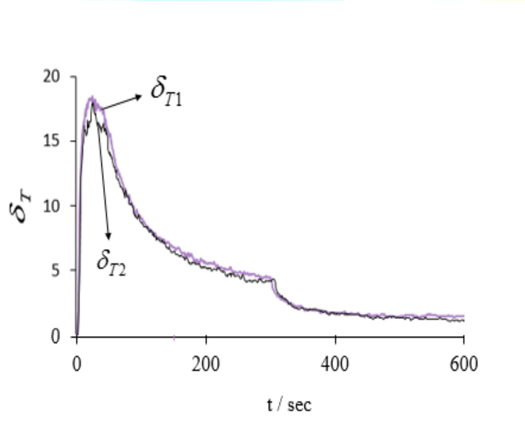

Figure 5:The absolute temperature for two samples have different thickness

Figure 5 shows the absolute drub temperature of two samples, sample1 is 1.5mm thicker than sample 2, δ_{T1} is the absolute temperature drop through the first sample (thicker sample), δ_{T2} is the absolute temperature drop through the second sample (thinner sample). The Figure shows there is no significant between the two samples, and the fabric thickness efficient in the fire insulation is relatively small.

5.2.2 The phase change material effect

To calculate the absolute temperature drub value of the PCMs, and the effectiveness of the phase change material, the actual temperature drop through the fabric were obtained, Thermal protective performance test were applied, and steady-state heat transfer in the open flame fire were obtained for the composite fabric; and the surface temperature versus time curve were extracted, the same procedure to measure the fire insulation properties of the firefighting.

Thermal protective performance test was performed to measure the front surface temperature and back surface temperature. Two samples were investigated the first sample is thin fabric incorporated with the PCMs, the other sample without PCM is 2mm thicker. Δ_{Tn} is the actual temperature drop by the fabric = the front surface temperature – the back surface temperature

$$\Delta_{Tn} = T_1 - T_2 \tag{24}$$

Then the absolute temperature were calculated. The absolute temperature is the actual temperature drop divided by the back surface temperature (curve 3 in thermal protective performance test Figure 6.

$$\delta_T = \frac{\Delta_{Tn}}{curve3} \tag{25}$$

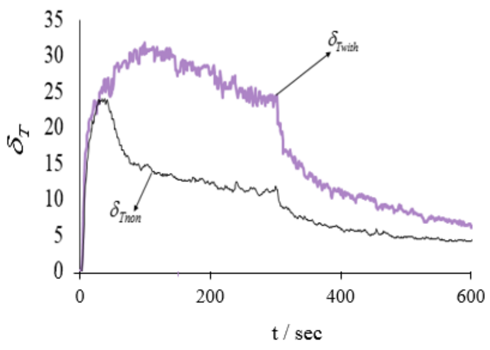

Figure 6: The absolute temperature for two samples with and without phase change materials

Figure 6 shows the absolute drub temperature of two samples, sample1 incorporated with PCMs and 2mm thinner than sample 2, δ_{Twith} is the absolute temperature drop through the first sample (with PCMs), δ_{Tnon} is the absolute temperature drop through the second sample (no PCMS). The Figure shows the absolute drop temperature when using phase change material relatively high compare to the thicker sample without PCMs. sample with PCMs there is no significant between the two samples.

Conclusion

The thermal insulation properties of the firefighting fabric design structures depend on; the establishment of open flame fire - fabric - air layer - heat transfer model of human skin, and accurate heat transfer model of the system by hear transfer calculation and model simulation.However, there are large differences in the fabric warming stage. Nevertheless, the heat transfer model of the fire - fabric - air layer created by the present subject - human skin system is effective, can prevent the analysis of the heat transfer mechanism of the open flame adiabatic fabric, also guiding the functional structure of the fire insulation fabric design and forming .

The analysis of the heat transfer and the fireproof insulation properties measured show that the firefighting fabric have good thermal insulation propertied for short period of time, but for the processed fabric it is difficult to achieve firefighters safety for long time during severe heat environment of the body's efficient, long time protection still need to conduct in-depth, and therefore in a prolonged fire insulation fabric research. Due to the physical contracture and surface permeability of the textile fabric, the thickness increase have no significant effect in flashover environment compare to the PCMs.

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