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Study on Radiant Heat Flux Transfer Through Aluminised Multi-Layer Fabric at Low Level Thermal Radiation

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Abstract
This paper presents a method to measure the thermal radiant flux transfer through aluminised multi-layer protective clothing. The multilayer fabric consisted of a layer of aluminum foil, one of glass fabric, and a layer of cotton fabric. The temperature of the surface of the cotton fabric and the amount of the radiation heat flux transfer through multilayer fabric was measured. The results showed that by increasing the thickness of the glass fabric, the temperature of the cotton fabric surface as well as the amount of heat flux transfer through the multilayer fabric are decreased. There is a logarithmic relationship between the temperature of the cotton fabric surface and thickness of the glass fabric, which means that an increase in glass fabric has a significant effect on the reduction of thermal radiant flux transferring through clothing. However, the reduction of thermal radiant heat flux tends towards a constant value at higher values of glass fabric thickness. The value of radiant heat flux measured was also used to predict the temperature of the skin surface. The results showed that the aluminised multi-layer clothing decreases the temperature of the skin surface significantly during exposure to a low radiant heat source.

Key words: *thermal protection, thermal radiant flux, aluminised multi-layer clothing, glass fabric.*

Introduction

Many studied have been carried out on the protective performance of textiles against heat radiation and different methods have been proposed for measuring the thermal insulation properties of textiles against thermal energy [1, 2].

Sun et al. investigated the effects of thickness, weight and structural features on the radiation protection performance (RPP) and heat resistance of a single layer. They showed that the weight and thickness of the fabric has a direct impact on the RPP. Radiation protection of fabric can be improved with an increase in weight and thickness [3].

Torvi et al. [4] carried out experiments on samples of Kevlar/PBI fabrics. They investigated the effects of the fabric thickness and air gap on the time of second-and third-degree burns predicted. They presented a heat transfer model that could predict the temperatures of flame-resistant fabric and skin burn injuries when cooling. They showed that the energy stored within a fabric is important for the prediction of skin burns.

Zhu et al. examined heat transfer in a cylinder sheathed by flame-resistant fabrics exposed to convective and radiant heat flux [5]. Zhu et al. [6] used a new skin model to estimate of the thermal performance of flame resistant clothing fabrics sheathing a cylinder. Song et al. [87] analysed the energy stored in protective clothing while exposed to heat. The results of their work showed that in some cases, the amount of stored energy leads to a reduction in the clothes protection significantly. In another study, Song et al. [8] examined the thermal protection performance of protective clothing used for low radiant heat protection in the range 6.3 - 8.3 kW/m^2. They showed that with increasing layer thickness, there was an increase in the thickness of multilayered fabrics, a considerable increase in thermal protection performance , and protection against low radiant heat improved significantly. According to the research conducted by Abbott and Schulman [1], increasing the number of layers of fire retardant fabric leads to a decrease in body temperature. Lawson et al. [9] developed heat transfer for firefighters' protective clothing.

Hao and Yu [10] performed a study by comparison of the thermal protective performance of aluminised fabrics of basalt and glass fibres. Jin et al. [11] studied the effect of aluminised fabrics on the radiant protective performance of fire proximity suit materials. They used different aluminised films and base fabrics such as woven, knit and nonwovens. The results of the work showed that the RPP (radiant protective performance) of aluminised fabric is affected by the protective film as well as the structure of the base fabric. Cai et al. [12] studied the thermal insulation properties of aluminised aramid fabrics.

Boguslawska-Baczek and Hes [13] presented a method for the determination of heat transfer by radiation in textile fabrics based on known emissivity of the two plates of an Alambeta instrument. Hassan Mohammed Ali and Yu [14] investigated the thermal protection provided by firefighting fabric systems with different layers. They used phase change materials in different fabric systems to enhance the thermal protective performance of the clothing. They found that the clothing showed good thermal insulation and a high temperature drop in a flash-over environment. Cui et al. [15] conducted a research work to identify the effects of heat treatment on the mechanical and thermal performance of fabric used in firefighter protective clothing. They subjected X-fibre® fabric to heat treatment at 6.5 and 9.7 kW/m^2 for duration between 0 to 30 min. They found that the intensity of heat flux had a significant effect on the tensile strength, elongation at break and tear strength. Morrissey and Rosi [16] evaluated the effect of metallisation, porosity and thickness on the thermal resistance of two layer fabric assemblies. They concluded that the metallised mid- and shell-layer increased the thermal resistance of the fabric assemblies.

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The main aim of this study was to measure the radiant heat flux transfer through aluminised multi-layer protective clothing at low level thermal radiation. Glass fabrics of different thickness were used as the mid-layer. The fabric was exposed to a heat source. Measuring the radiant heat passing through the multilayer fabric allowed calculation of the radiant protective index. The temperature of the skin surface exposed to certain radiant heat flux was also predicted. Measuring the radiant heat flux reaching the skin surface and using an algorithm proposed by SFPE (Society of Fire Protection Engineers) allowed calculation of the skin surface versus the time of exposure.

Experimental

Materials

The multilayer fabric consisted of a layer of glass fabric in the middle, a layer of cotton fabric and one of aluminum foil. Aluminum foil was considered as the outermost surface layer exposed to heat. The thickness of the aluminum foil and mass per unit of area used in the experiments were equal to 7 µm and 18.9 g/m^2, respectively. Cotton fabric formed the innermost layer of the multilayer fabrics, which the same for all sample types. The thickness, warp density, weft density and area mass of cotton fabric were 0.42 mm, 30 cm^{-1}, 23 cm^{-1} and 130 g/m^2, respectively. Five different types of glass fabric were used in the middle layer, and thus five types of samples were prepared. The glass fabrics were coded as A to E, and their specifications are depicted in ***Table 1***.

Table 1. *Structural characteristics of the fabrics.*

Fabric code	Thickness, mm	Warp density, 1/cm	Weft density, 1/cm	Area mass, g/m^2
A	0.10	20.0	15.0	100
B	0.20	19.0	12.0	200
C	0.50	17.0	10.0	430
D	1.75	6.2	3.1	1500
E	3.50	4.4	2.2	3000

Testing apparatus and methods

In this study, a device was constructed to measure the radiation protection performance of the aluminised textiles. This device was constructed according to the ASTM F1939-08 "standard for evaluating the Radiant Protective Performance of Flame Resistant Clothing Materials" [17].

Figure 1 shows a schematic diagram of the apparatus. It consists of a series of radiant quart tubes considered as the heat source. The temperature of the heat source can be adjusted to the value desired. The sample is fixed vertically in specimen holders mounted in front of the heat source. The distance of the specimen from the heat source was adjusted to 25.4 mm. A radiant heat sensor (Captec® Radiant flux sensor 50 × 50 mm) is placed in thereverse side of the specimen and connected to a micro voltmeter. The sensor acts as a transducer and converts the heat radiant flux to electric current. The radiant heat flux in W/m^2 can be calculated from the micro voltmeter FLUKE 289 (FLUKE Corporation-USA) according to the calibration value of the sensor. The calibration multiple of the radiant flux sensor is 15.2 µV/(W/m^2). The resolution of the micro voltmeter is one microvolt, which means that the radiant heat flux can be measured to the nearest 1/15.2 = 0.07 of one unit of W/m^2.

To study the behaviour, the thermal resistance of multilayer fabrics against low thermal radiation, multilayer fabrics were prepared. These fabrics are composed of three layers: a surface layer of aluminum foil that is exposed to heat radiation, a middle layer made of glass fibre, a substrate layer of cotton fibres. Five different thicknesses of glass fabric were prepared and for each case five samples tested.

In the first stage, the radiant flux of the heat source is measured without any sample. The protective shutter between the heat source and specimen holder is closed. The lamps of the heat source are turned on for 60 seconds, and the protective shutter is then removed. After a minimum duration of 10 seconds, the response of the radiant flux sensor is recorded. According to the calibration value of the sensor, the amount of radiant heat flux is calculated. In the next step, the sample is placed inside the specimen holder. Since the sample is multi-layered, its outermost layer, i.e. the aluminised surface, is placed face-to-face with the heat source. The sensor is placed on the reverse side of the sample; the same position as it was in the no-sample test. The are lamps turned on for 60 seconds, and then the protective shutter is removed. The sample is exposed to heat radiation for 40 seconds. After a minimum duration of 10 seconds, the response of the radiant flux sensor is recorded. The heat flux is recorded using the micro-volt meter. Using sensor calibration coefficients, the radiant flux transfer through the sample is calculated.

Results and discussion

Thermal radiation protection index

To evaluate the performance of the samples, the thermal radiation protection index (*RPI*) is defined by ***Equation 1***. This

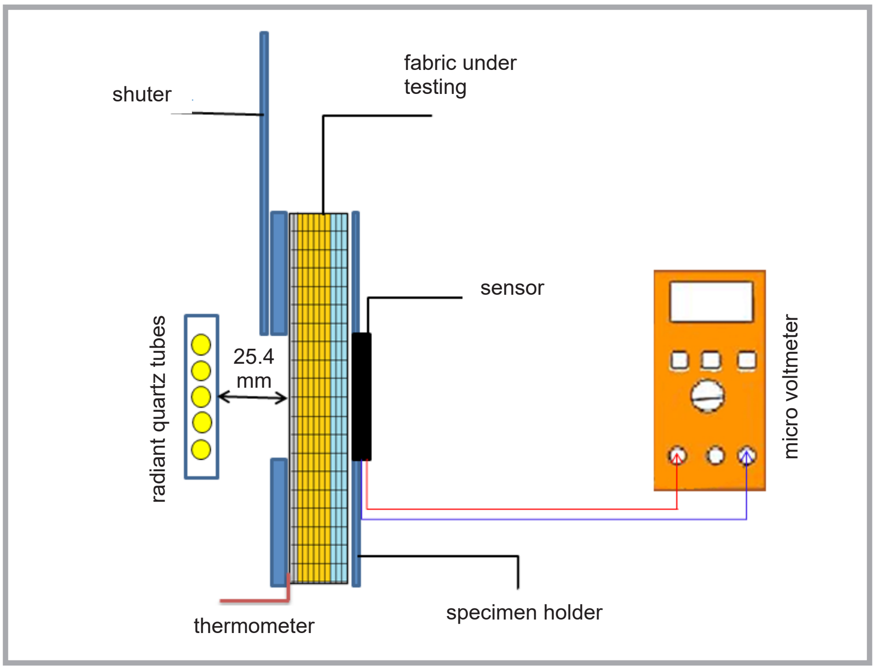

Figure 1. *Schematic diagram of the test apparatus.*

Table 2. *Heat radiation protection index for samples.*

Sample code	Radiant heat flux q''_r, W/m^2	CV of radiant heat flux, %	Heat radiant protection index, %
A	382.92 ± 0.07	17.32	93.50
B	292.71 ± 0.07	8.87	95.03
C	284.80 ± 0.07	19.12	95.16
D	171.34 ± 0.07	15.45	97.09
E	96.05 ± 0.07	18.05	98.37

Table 3. *Properties of skin [19].*

Property	Symbol	Value	Units
Thermal conductivity (heating)	K_h	0.5878	W/m-K
Thermal conductivity (cooling)	K_c	0.4518	W/m-K
Volumetric heat capacity	ρc	4.1868	J/cm^3-K
Basal layer depth	x	80	μm
Thermal diffusivity (heating)	α_h	1.40×10^{-7}	m^2/s
Thermal diffusivity (cooling)	α_c	1.08×10^{-7}	m^2/s

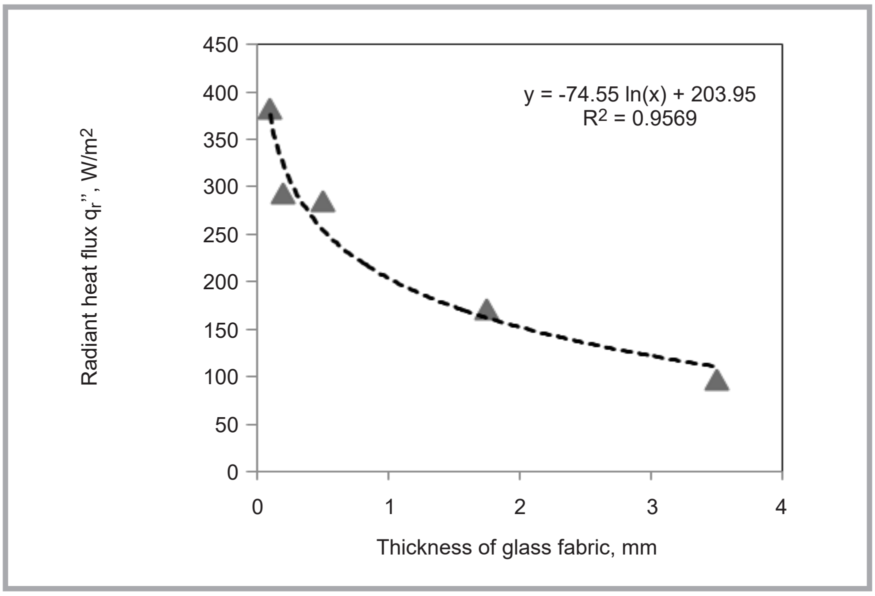

Figure 2. *Variation in the radiant heat flux transfer versus the thickness of glass fabric.*

dimensionless index represents the protection value of the sample against thermal radiation.

$$RPI = \left(1 - \frac{q''_r}{q''_s}\right) \times 100, \text{ in } \% \qquad (1)$$

where, q''_s is the radiant heat flux of the source (no sample), and q''_r is the heat flux transfer through the sample. Higher values of *RPI* represent better protection against thermal radiation. For each type, five samples were tested. Mean values of the thermal radiation flux as well as the coefficient of variations are given in ***Table 2***. The value of radiant heat flux of the source was found to be 5891.10 W/m^2. Values of the radiant protection index (*RPI*) were also calculated according to ***Equation 1*** and are shown in ***Table 2***.

As is apparent from ***Table 2***, thermal radiation flux transfer through the sample decreases as the sample thickness increases. It should be noted that the reflectivity of the aluminum foil also plays a major role in the reflection of the heat radiation flux. However, in the present study experiment the reflectivity of aluminum foil is the same for all samples measured. Due to this fact the reflectivity of the aluminum layer has no influence on the relationship between the radiation heat flux and material thickness analysed. The variation in radiant heat flux transfer through the sample versus the thickness of the glass fabric is depicted in ***Figure 2***. As can be seen, there is a logarithmic relationship between the radiant heat flux and sample thickness of glass fabric. The data points also showed a good regression correlation, with R-square equal to 0.96. With the increasing thickness of glass fabric, the variations show a steep slope initially and then tends towards the lower slope region at higher fabric thicknesses.

One applicable result of this is that as far as thermal radiant protection is concerned, the thickness of the fabric plays an effective role up to a certain value. The reduction of thermal radiant heat flux tends towards a constant value at higher values of glass fabric thickness.

Effect of time of exposure on the temperature of skin

One of the most important objectives of protective clothing is to prevent the skin from thermal damage. The degree of burning of skin depends on two factors i.e. the intensity of the radiation source and the exposure time [18]. There are different algorithms for predicting 1st and 2nd degree skin burns from the thermal radiation presented by SFPE. In this study we used the following algorithm to predict the temperature of the skin surface.

$$T = T_0 + \frac{q''_r}{k}\left[\frac{2\sqrt{\alpha t}}{\sqrt{\pi}}\exp\left(-\frac{x^2}{4\alpha t}\right) - x\,erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)\right] \qquad (2)$$

Equation 2.

The temperature *T* in °C of skin exposed to radiation flux at distance x from the skin surface is calculated from ***Equation 2*** [19] where, T_0 in °C is the initial temperature of the skin, q''_r radiant flux, α thermal diffusivity, and *k* thermal conductivity. On the skin surface, where $x = 0$ and considering that $\alpha = k/\rho c$, its temperature T_s in °C in time *t* is:

$$T_s = T_0 + \frac{2q''_r\sqrt{t}}{\sqrt{\pi k \rho c}} \qquad (3)$$

where, *ρ* is the density and *ρc* the volumetric hear capacity. Values of the properties of human skin are shown in ***Table 3***.

Considering an initial skin temperature of 33.3 °C and the values of skin properties from ***Table 3*** and inserting them into ***Equation 3***, the temperature of skin for

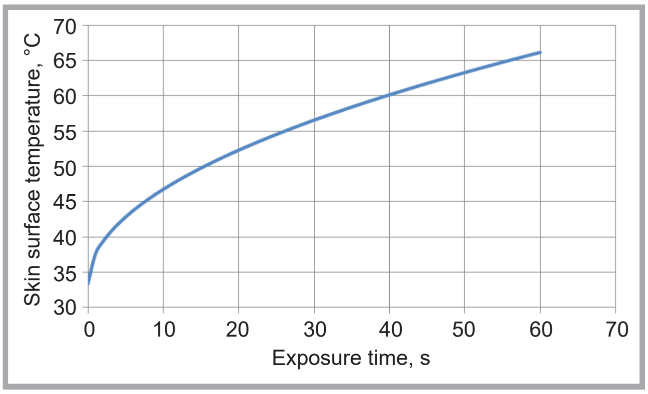

Figure 3. Skin surface temperature vs exposure time for bare skin.

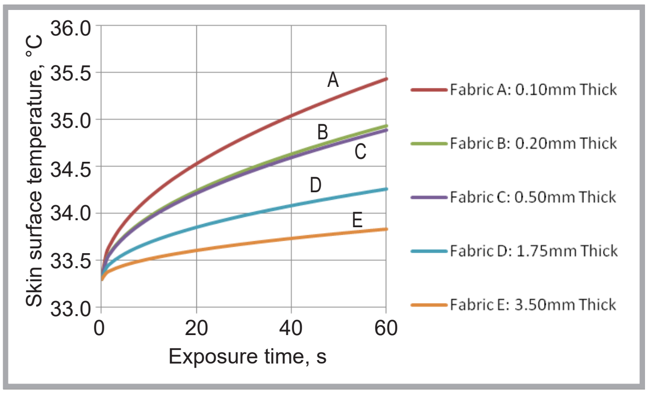

Figure 4. Skin surface temperature vs exposure time for covered skin.

different exposure times can be calculated as follows:

$$T_s = 33.3 + (7.1928 \times 10^{-4}).q"_r.\sqrt{t} \quad (4)$$

The value of radiant flux, q''_r, for all fabric types is obtained from ***Table 2***. The temperature of the skin surface predicted for all exposure cases was calculated according to ***Equation 4***. ***Figure 3*** shows the variation in temperature of the skin surface versus time of exposure in the case of bare skin. In this case there is no fabric in the sample holder, and the sensor measures the whole thermal radiant intensity of the heat source. As can be seen form ***Figure 3*** the temperature rise of the skin surface reaches around 70 °C after 60 seconds, which can cause severe damage to skin. Different fabrics were used as a barrier between the heat source and sensor. The radiant heat passing through the fabric was calculated. The temperature of the covered skin surface predicted was then calculated. ***Figure 4*** shows a comparison of different fabrics used in this study. The results show that the thickness of fabric has a significant effect on the reduction in skin temperature exposed to heat radiation.

Conclusions

The thermal radiation protective performance of multilayer fabrics was studied. The multilayer fabric consists of a layer of glass fabric in the middle, one cotton fabric and a layer of aluminum foil. The results showed that there is a logarithmic relationship between the thickness of the fabric glass fabric and temperature of the cotton fabric surface. With the increasing thickness of the glass fabric, the temperature decreases with a steep slope initially, then becomes less steep, and a slower reduction in the temperature of the cotton fabric surface occurs. The temperature of a skin surface exposed to thermal radiation was also calculated. The amount of thermal radiant flux transferring through the aluminised multilayer was used to calculate the temperature of the human skin the versus time of exposure. The results revealed that aluminised clothing plays an important and significant role in increasing the thermal protective performance of clothing.

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