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Study on Thermal Insulation Properties of Aluminised Aramid Fabrics

DOI: 10.5604/12303666.1152723

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Abstract

In order to prevent or minimise skin burn damage resulting from high temperature, a kind of thermal insulation composite fabric, the surface of which is aluminised, was developed. In this study, the thermal insulation properties of aluminised aramid fabrics were investigated. The reflectance of aramid fabrics and aluminised aramid fabrics were measured using a UV–Vis–NIR spectrophotometer. The reflectance of aramid fabric increased from 63.6% to 92.3% as a result of aluminising. The thermal insulation of aluminised fabrics and non-aluminised fabrics was measured using a dry hot plate instrument, where the aluminised fabrics had a higher thermal resistance than those non-aluminised , and the thermal resistance of aramid fabric could be enhanced by almost 45% when aluminised. The aluminised and non-aluminised fabrics were exposed to a hot environment for a few minutes using self-designed apparatus. The results showed that the aluminised aramid fabrics had better thermal insulation performance than the non-aluminised aramid ones. Therefore aluminised aramid fabric exhibits great thermal insulation properties and can be used in the field of thermal protection.

Key words: *thermal insulation, aramid fabric, aluminised fabric, reflectance, thermal protection.*

Introduction

Fire fighters are generally subjected to a variety of hazardous conditions, such as flash fire and intense heat flux, and can be burned by radiant energy that is produced by a fire and localized flame contact exposure. The most common exposure is to low level radiant heat flux over prolonged periods of time. Thus the development of thermal protective and thermal insulating clothing of long term durability has been a matter of public attention. Structural firefighter protective clothing is designed to shield the firefighter from environmental hazards, such as heat, abrasive surfaces, and some chemicals. Firefighter clothing is typically a three layer system consisting of an outer shell (OS), moisture barrier (MB), and thermal liner (TL) [1, 2]. Aramid materials have great thermal stability and are widely used as outer shell materials of firefighter clothing, such as Kevlar and Nomex fibre materials made by Dupont [3, 4]. A basic requirement for fabrics used in thermal protective fields is that the fabrics should have good thermal stability and thermal insulation. Many researchers have focused on the effects of fabric structure, thickness, weight and fabric type on the thermal properties of fabrics and found that the thickness, weight and fabric structure had great effects on the thermal insulation properties of fabrics [5 - 9].

Heat can be transferred through fibrous insulation materials via conduction, radiation, and convection. Previous work has proven that radiation heat transfer is found to be the dominant mode of heat transfer at temperatures higher than 400 - 500 K [10]. As is known, reflective surface is effective in providing radiation heat protection. The radiation heat flux (HF) through fabrics can be reduced by the use of an aluminised surface with 90% reflectivity [11]. Therefore the development of aluminised fabric has been found to be one of the most efficient ways of reducing the radiation heat flux and improving the thermal insulation performance. Two researchers noted that aluminised basalt fibre fabric had better thermal protective performance than non-aluminised fabrics [12, 13]. However, there has been little reported on aluminised aramid fabric and its thermal insulation properties when exposed to hot environments.

This study focused on the thermal radiation reflectance, thermal resistance and thermal protective performance of aluminised fabrics made of Nomex and Kevlar fibre by using a UV–Vis–NIR spectrophotometer, dry hot plate instrument and a self-designed apparatus, respectively. During the thermal protective experiment, aluminised and non-aluminised fabrics were exposed to a high temperature environment for a few minutes. The main objective of this study was to

Table 1. *Properties of aluminum foil.*

Sample	Thickness, μm	Area mass, g/m^2
Aluminum foil	6	18.5
Aluminum foil	10	24.6

investigate and compare the thermal insulation properties of aluminised and non-aluminised aramid fabrics.

Experimental

Materials

Aluminum foil has excellent reflective performance and has been widely used in the field of thermal insulation. In order to improve the thermal insulation properties and obtain prolonged durability of fabrics, aluminum foil, acting as an outer thermal protective layer, was glued onto the surface of fabrics. In this study, aramid fabrics were purchased from Henan Xinxing textile Co., Ltd (China) and aluminum foil - from Shanghai Shenhuo aluminum foil Co., Ltd (China). The properties of the aluminum foils are listed in ***Table 1***.

Sample preparation

The aluminised aramid fabrics were prepared in a lab, in which the aluminum foils were glued onto the surface of aramid fabric using a high temperature resistance inorganic adhesive (Ruyi NGWG-1600, provided by Nengxu High Temperature Products Sales Company, Zibo, China). Characteristics of the aramid fabrics and aluminised aramid fabrics used for their heat-insulating properties are provided in ***Table 2***. B1 and B3 are fabrics of A1 and A3 aluminised using 6 μm aluminum foil and B2 is fabric of A1 aluminised using 10 μm aluminum foil, respectively. The basic structure and properties of all fabrics are presented in ***Table 2***. ***Figure 1*** provides photos of the test sample.

Methods

Measuring the reflectance of the fabrics

In order to analyse the reflective performance of different fabrics, it is necessary to know the spectral reflectance over a wide range of wavelengths. Thus the reflective performance of the aramid fabrics and aluminised aramid fabrics prepared were characterized by using a U-4100 UV–Vis–NIR spectrophotometer (Hitachi, Japan) over wavelengths ranging from 380 to 2500 nm, with an accuracy of 0.1 nm. The average reflectance of fabrics in different wavebands was obtained to provide an evaluation of the effectiveness of aluminised fabric in blocking thermal radiation.

Table 2. *Structural characteristics of the different fabrics.*

Item	Pattern	Materials	Warp-weft density, threads per 10 cm	Thickness, mm	Area mass, $g\ m^{-2}$
A1	Plain	Nomex fibre	205 × 192	0.44	162.5
A2		Nomex fibre		0.58	215.5
A3		Kevlar 49 fibre		0.44	168.3
B1		Nomex fibre /aluminised		0.45	196.3
B2		Nomex fibre/aluminised		0.46	206.5
B3		Kevlar 49 fibre /aluminised		0.45	199.6

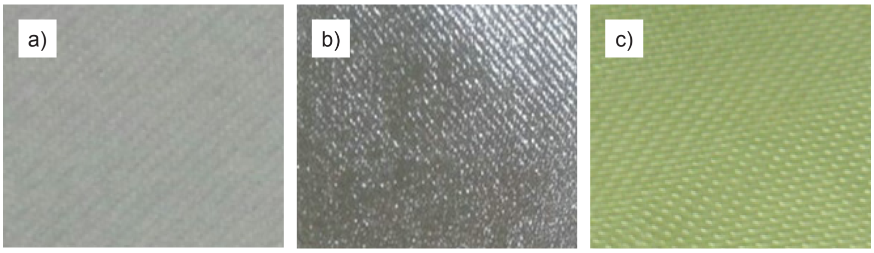

Figure 1. *Photos of test sample: a) Nomex fabric, b) Kevlar fabric, c) aluminised Nomex fabric.*

Measuring the thermal resistance of the fabrics

The thermal insulation of aluminised and non-aluminised fabrics was measured using a guarded hot plate [14]. To measure the thermal resistance of the fabrics, the sample to be tested was mounted on a dry hot plate that was heated to a constant temperature (35 °C). The air temperature in the chamber was set to 20 °C, and the relative humidity was controlled at 65%. The air speed was 1 m/s. After the system reached a steady state, the thermal resistance of the sample was obtainable. The accuracy of the thermal resistance is 0.001 m^2KW^{-1}.

Evaluation of the thermal protection of the fabrics

The thermal protection performance of the fabrics was evaluated with a self-designed apparatus. As shown schematically in ***Figure 2***, the apparatus consisted of a heating control system, thermal protective plate, specimen holder, two temperature sensors, and a data acquisition system. The thermal protective plate was of a nested structure with a cylindrical internal layer and rectangular outer layer. The intermediate space was filled with heat-insulating fibres in order to minimise heat dissipation to the external environment during the experiment. The fabric was fixed on the specimen holder. The heating control system could accurately control the temperature of the copper heat plate. The temperature of the heat source was always the same in each experiment. The temperature sensor, mounted in a thin stainless steel tube with a heat resistant puddle was embedded in the surface of the fabrics. The temperature sensors had a rapid response time, with a tolerance of ± 0.01 °C. The sensors were individually calibrated to ensure the accurate reading of temperatures and were connected to the data acquisition system, which provided a continuous record of the rate of temperature rise of the sensors. The specimens were 20 cm in diameter. Prior to testing, all fabrics were conditioned for at least 24 h in a standard atmosphere of 65 ± 2% RH and 20 ± 2 °C.

During the experiment, the fabrics were exposed to a hot environment for 10 min. The temperature sensors measured the temperatures at different locations, such as the upper and lower surfaces of the fabrics. The computerised data acquisition system scanned and recorded the real-time temperatures. Curves of the temperature measured versus the time were compared and ana-

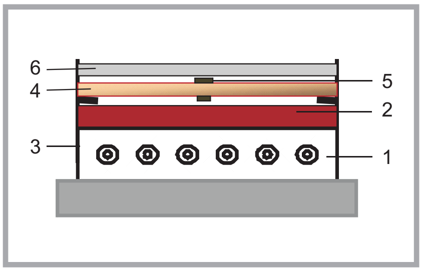

Figure 2. *Schematic diagram of the test apparatus; 1) heating control system, 2) copper heat plate, 3) thermal protective plate, 4) fabric sample, 5) temperature sensor, 6) cold plate.*

***Table 3.** Average reflection properties of fabrics in different wavebands.*

Sample	Vis reflectance, %	NIR reflectance, %	Full wave range reflectance, %
Aluminum foil (10 μm)	95.2	96.9	95.7
Aluminum foil (6 μm)	92.1	93.6	92.8
A1	60.1	65.0	63.6
A2	68.4	65.5	64.4
A3	58.4	61.4	60.4
B1	89.7	92.7	92.3
B2	89.9	93.5	93.1
B3	83.3	88.3	87.5

lysed to evaluate the thermal insulation performance.

Results and discussion

Reflective performance of aluminum foil

Figure 3 gives spectral reflectance results of the aluminum foil. It can be found the samples have high reflectance throughout the full range of wavelengths from 380 to 2500 nm. The reflectance of the aluminum foils throughout the infrared wavelength range is well above 85%, as illustrated in ***Table 3***, which is due to the smooth surface of the aluminum foil. As is known, the radiation properties, such as reflectance, transmittance, and emittance of a single layer structure and multilayer structures, largely depend on the direction and wavelength of incident radiation. They are also affected by thin-film coatings and surface roughness [7]. Generally the smooth surface has a better reflectance performance. It is also significant that the effect of surface roughness seems to have a great effect on the radiation reflective performance of the aluminum foil.

Reflective performance of aramid fabrics and aluminised aramid fabrics

A requirement for fabric with good thermal protective performance is that its absorption rate and transmission rate should be as small as possible, while the reflectance is as large as possible. It is significant that the effect of surface roughness seems to have a great effect on the radiation reflective performance of the fabrics. The results of spectral reflectance for different aramid fabrics are presented in ***Figure 4*** and ***Table 3***. It is obvious that the reflectance curves of different fabrics are slightly different throughout the wavelengths from 380 to 2500 nm. The reflectance slightly increased with the increasing of fabric thickness. The Nomex fabrics had higher reflectance than the Kevlar fabric in all wavelength range, which can be explained by the fact that Nomex fibre is white and Kevlar fibre - yellow. As white colour has good reflectance, this results in the great reflection property of Nomex fabric.

Figure 5 and ***Table 3***, respectively, provide spectral reflectance characteristics and the average reflectance of aluminised fabrics in different wavebands. The results revealed that there were obvious differences between the aluminised and non-aluminise fabrics e.g. the reflectance of aluminised fabrics was higher than the non-aluminised ones. The reflectance of samples A1 and A2 increased from 63.6% to 92.3% and from 64.4% to 93.1% when aluminised, respectively. The reflectance of the three aluminised fabrics were obviously different. Aluminised fabric B2 had the best reflective performance, which reached up to 90% for the majority of the wavelength. Aluminised fabric B3 presents the worst reflective performance. However, the average reflectance throughout the full range of wavelengths exceeded 85%. When the reflectance increased, the transmission and absorption rate decreased, which implies that aluminised fabrics exhibit excellent thermal radiation protective performance. Based on the reflective performance of different aluminised fabrics, the thickness of aluminum foil and construction of the fabrics have significant effects on the reflectance. The surface of aluminised Kevlar fabric made of yarns with a large linear density is not as smooth as Nomex fabrics made of yarns with a small linear density. Consequently the rough surface results in its lower reflectance. The little reflectance difference between the two kinds of aluminised Nomex fabrics may be due to the similar surface conditions. Although large differences exist between the aluminised fabrics, all of them present high reflectance, close to 90% or even more in NIR wavebands. Previous work has proven that the peak heat flux level lies in the range from 16.7 to 22.6 $\text{Jcm}^{-2}\text{sec}^{-1}$ and that it is concentrated over the wavelength range 1 – 6 μm, with a peak at about 2 μm [7]. Thus the main thermal protection for firefighters is the protection against radiant heat. From the

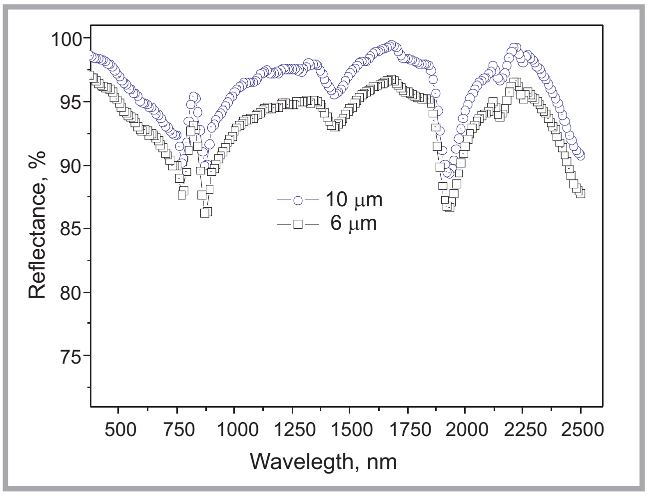

***Figure 3.** Spectral reflectance of aluminum foil.*

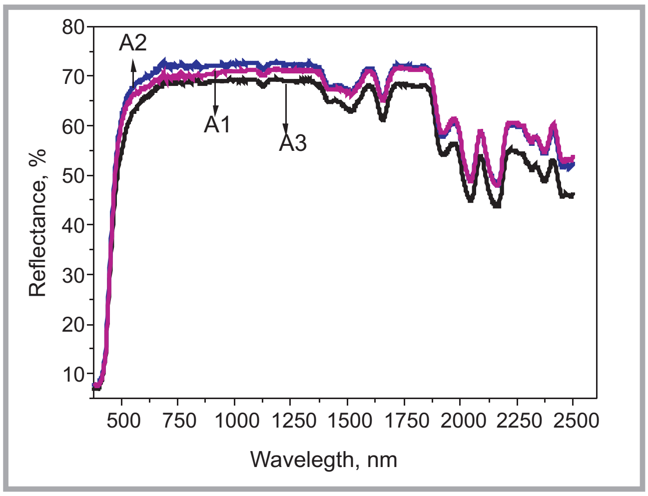

***Figure 4.** Spectral reflectance of non-aluminised aramid fabrics.*

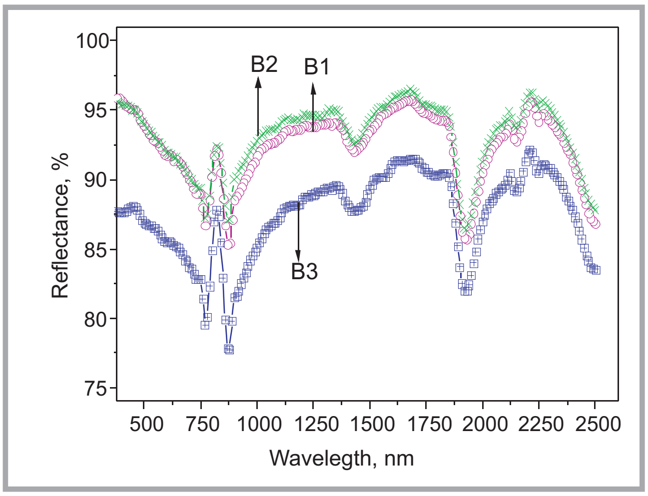

Figure 5. *Spectral reflectance of the aluminised fabrics.*

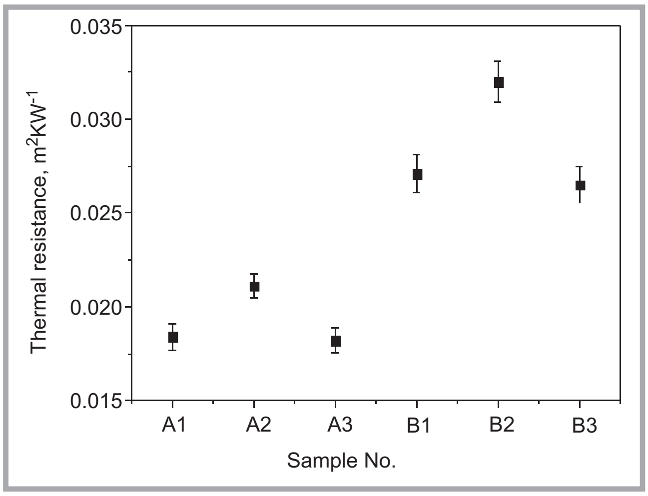

Figure 6. *thermal resistance of different fabrics.*

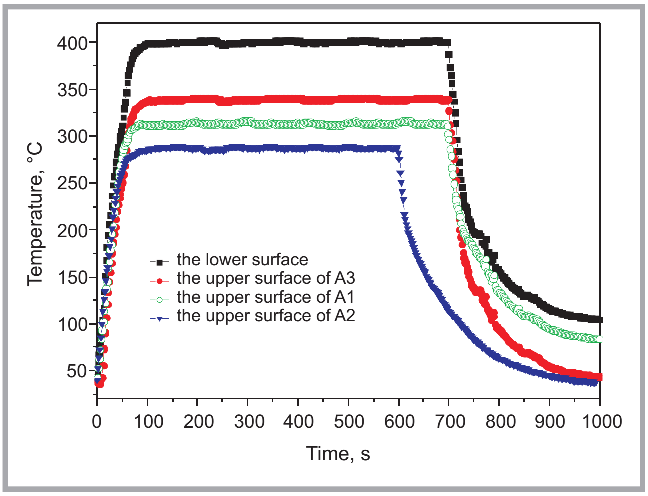

Figure 7. *Surface temperature of different aramid fabrics.*

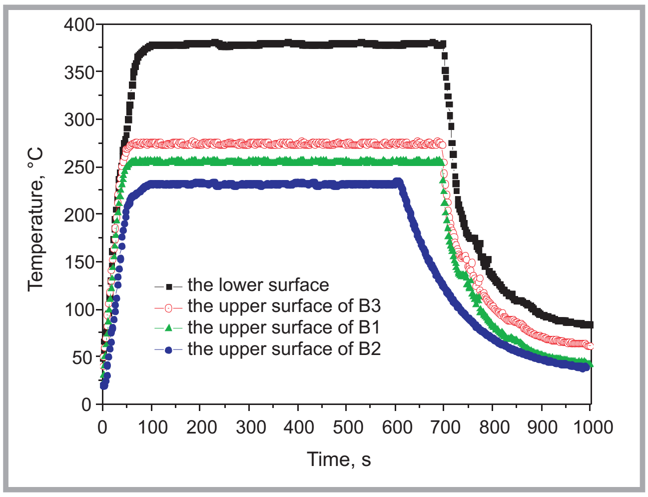

Figure 8. *Surface temperature of different aluminised fabrics.*

reflectance results, it can be safely concluded that aluminised fabrics have good thermal protective performance and exhibit great potential in the fields of thermal protection and thermal insulation.

Thermal resistance of different fabrics

Figure 6 gives the average thermal resistance of aluminised and non-aluminised aramid fabics. The thermal resistance of samples A1 and A3 are around 0.017 m^2KW^{-1} and that of A2 is 0.021 m^2KW^{-1}, which is due to the fact that the thermal resistance increases with an increase in the thickness of the fabric. As can be seen, the thermal resistance increased sharply when the fabrics were aluminised. The thermal resistance of fabric A1 increased from 0.017 m^2KW^{-1} to 0.027 m^2KW^{-1} when aluminised. The thermal resistance could be enhanced by almost 60% with aluminisation. The thermal resistance of B2 is the highest, reaching 0.033 m^2KW^{-1}. Thus we can improve the thermal insulation properties of aluminised fabric by increasing the thickness of aluminum foil, suggesting that aluminising is a good method to increase the thermal resistance of fabrics. Because aluminum foil has good thermal radiation reflective performance, the whole aluminised fabric exhibits the ability to block thermal radiation conduction. It was easy to understand why the thermal radiation conductivity of the fabric was greatly reduced when aluminised. Therefore the thermal insulation properties of fabrics can be improved by the aluminising method.

Thermal protective performance of aramid fabrics and aluminised fabrics

The temperature of aramid fabrics and aluminised fabrics versus time, respectively, are shown in ***Figures*** *7* and ***8***, respectively. The temperatures recorded by temperature sensors increased rapidly from room temperature to high temperature and became nearly steady, and in the natural cool down stage, the temperatures decreased quickly.

As shown in ***Figure*** *7*, the lower surface temperature of aramid fabrics was approximately 400 °C, while the upper surface temperature of different aramid fabrics was different. The results revealed that there are significant differences in thermal protective performance among the fabrics. The average temperature of the upper surface and lower surfac, as well as the temperature difference of fabrics, are shown in ***Figure 9***. The upper surface temperature of A1 was higher than for A2, from which we can conclude that thicker fabric exhibits a better thermal insulation characteristic for fabrics with the same structure. Therefore the thermal protective performance of fabrics can be improved by increasing the fabric thickness. In addition, A1 had a higher insulting temperature than A3 for the same thickness, which implies that

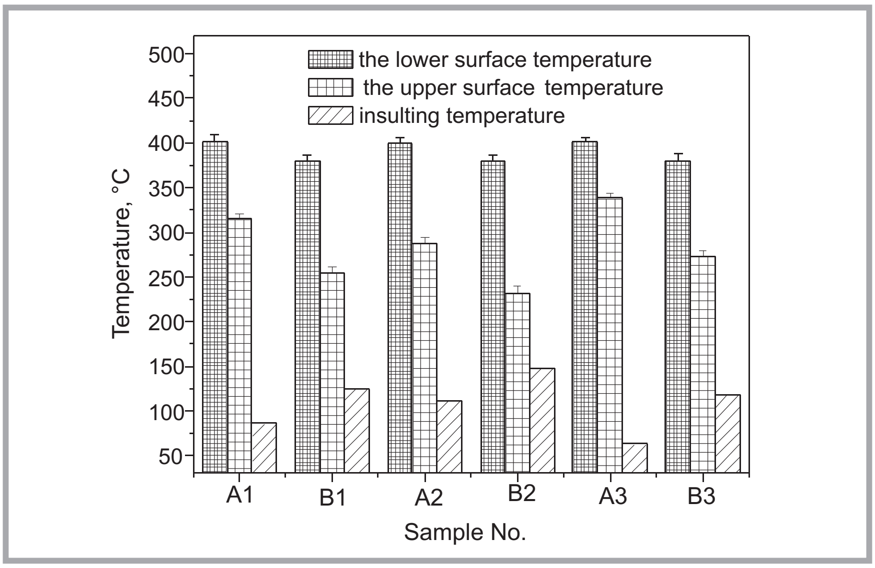

Figure 9. *Surface temperature of the aramid fabrics and aluminised fabrics (**Note**: the insulating temperature is the difference between the upper surface temperature and lower surface temperature of the fabric).*

the thermal protective performance of Nomex fabric is better.

As can be seen from ***Figure 9***, B2 has the best thermal protective performance of all aluminised fabrics, with the insulating temperature of sample B2 reaching up to 148 °C, higher than that of sample A1 (non-aluminised fabric), which was 86 °C. The insulating temperature of sample A3 increased from 63 °C to 118 °C when aluminised. It also can be noted that the lower surface temperature of the non-aluminised fabrics was higher than that of aluminised fabric in the same thermal environment, which is ascribed to the fact that aluminum foil has great reflection to heat flux, thereby reducing the radiation heat. When faced with the same heat source, the lower surface temperature of aluminised fabric was lower, implying that aluminised fabric is more effective for thermal protection and heat insulation. Based on the insulating temperature of samples B1 and B2 , we can state that B2 has better heat-insulating performance than B1. The thermal insulation performance of aluminised fabric can also be improved by increasing the thickness of the aluminum foil. The initial degradation temperature of Nomex fibre is only 420 °C and the melting point of aluminum 660 °C. Aluminised Nomex fabric has greater thermal stability and protective performance, and is suitable to protect people from higher temperature.

Since there has been much emphasis on the outer shell material of thermal protective clothing, we can state that the outer layer fabric is the most apparent component, playing the chief role in the overall performance of thermal protective clothing. Aluminised aramid fabric can be used as the reflective layer of outer shell material for thermal protective clothing.

Conclusion

The thermal insulation properties of three kinds of aramid fabrics and three kinds of aluminised aramid fabrics were evaluated using three methods. UV–Vis–NIR spectrophotometer tests indicated that aluminised aramid fabrics had good reflective performance and presented high reflectance, close to 90% throughout wavelengths from 380 to 2500 nm. The aluminised fabrics had higher thermal resistance than the non-aluminised fabrics, and the thermal resistance of aramid fabric could be enhanced by almost 45% when aluminised. When exposed to a high temperature environment, the insulating temperature of aluminised aramid fabric (B2) reached up to 148 °C, which was much higher than that of non- aluminised aramid fabric. These results showed that aluminised fabrics exhibit great potential applications in the field of thermal protection because of their high thermal insulation properties.

Acknowledgements

We wish to thank the Hubei Provincial Department of Education through project (144011) for their financial support. This project is supported by the Funding of the Innovative Team of Hubei Collaborative Center for Textile Key Technology (No. 52300100316).

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Received 13.05.2014 Reviewed 25.07.2014