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Thermal behavior of nonwoven basalt and glass fabrics under flashover environment

Akram H M Ali[1] & Weidong Yu[2,a]

[1]Key Laboratory of Textile Science & Technology, Ministry of Education, Donghua University, Shanghai, P R China 201620
[2]Textile Materials and Technology Laboratory, Donghua University, Shanghai 201620, P R China

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The thermal properties of nonwoven basalt and glass fabrics have been evaluated and compared. The thermal stability of the both fabrics has been analyzed using thermogravimetry analysis (TGA). In order to assess the thermal radiation protective performance when exposed to the fire environment, the spectral reflectance of nonwoven fabrics with different thicknesses is evaluated by the ultraviolet–visible–near infrared (UV–Vis–NIR) spectrophotometer. The thermal protective performance of the nonwoven fabrics is analyzed and characterized using thermal protective performance (TPP) testing apparatus. The TGA, UV-Vis-NIR spectrophotometer and TPP tests reveal that the basalt and glass fabrics exhibit good thermal stability, and the nonwoven fabrics present excellent thermal protective performance and thermal insulation properties for real exposure time applications.

Keywords: Basalt fabric, Glass fabric, Nonwoven fabric, Thermal property, Thermal stability

1 Introduction

Thermal protective clothing is primarily designed to provide protection against thermal hazards. The thermal hazards include exposure to low level thermal radiation in the range of 5–20 kW/m^2, and to high temperature radiant sources showing that the temperature can reach up to 800^{o}C (refs 1, 2), or even higher, and that the heat fluxes can be very high (up to 80 kW/m^2) or more. The thermal performance requirements of the firefighting fabrics depend on the sources to which they were exposed to. Although the heat energy is generally transferred by conduction, convection and radiation, during fire, the bulk energy causing injuries in fire fighter is due to the radiation heat[3]. The radiation-dominated heat flux (under normal conditions less than 20% of the total flux) are due to convection. Heat flux levels may be as high as 5-6 cal/cm^2/s in a wavelength range 1-6 microns with a peak at about 2 microns[4]. Thus, thermal protective clothing, with excellent thermal radiation reflective performance when exposed to intense heat flux environments, has been of great interest.

The thermal performance of fire fighters' protective clothing has been a point of interest and discussion for several decades. A great effort still needs to be done in terms of detailed scientific analysis for predicting the thermal performance of protective clothing throughout the range of fire environments normally faced by a firefighter. Some of the basic analyses and comparing varieties of existing fire protective materials and firefighting protective clothings are the reflective properties and thermal storage properties of materials[5]. The development of fire protective clothing with long term durability has always been a matter of public attention.

Glass and basalt are being used, with the greatest practical significance, in the area of firefighting fabrics[6, 7]. In the 1700s, Réaumur recognized that glass could be finely spun into that can be sufficiently pliable to be woven into textiles. At the Columbia Exhibition of 1893, Edward Libbey of Toledo exhibited dresses, ties and lamp-shades woven from glass. Glass are used in a number of applications which can be divided into four basic categories, namely (i) insulations, (ii) filtration media, (iii) reinforcements, and (iv) optical[8]. Basalt rock is an environment-friendly natural material; it is used for basalt production. 1/3 of the Earth's crust consists of basalts and eruptive rock, so this material is easily found worldwide. It has good heat insulation qualities and absolutely nonflammable with high thermo durability. Temperature for long application is up to

[a]Corresponding author.
E-mail: wdyu@dhu.edu.cn

700ºC; temperature of short term application is up to 1000ºC (ref. 9).

The high-temperature behavior of nonwoven fabrics has been the subject of numerous investigations. Thermal insulation performance is a function of many parameters such as the thermal conductivity and the density of the material. Lower thermal conductivity is an indicator of the better insulation property. The glass and basalt fabrics for protective clothing have not been reported earlier, Hao and Yu[10] studied the structure and thermal property of basalt fabric, by presenting a comparative analysis with glass fabric, using CH-2 projection microscope, scanning electron microscope (SEM), and thermogravimetry (TG). Novitskii and Sudakov studied nonwoven basalt encasing of fibrous insulation alternative to glass cloth[11].

The aim of present investigation is to study and compare the thermal behavior of nonwoven basalt and glass fabrics. These two kinds of fabrics have a high application in the field of firefighting due to their high resistance towards high temperature exposure, high thermo durability and non-flammable behaviour. Thermal behavior of these fabrics under flashover environment is studied.

2 Materials and Methods

Nonwoven basalt fabric was purchased from Zhejiang GBF Basalt Fiber Co., LTD, and nonwoven glass fabric was purchased from Deqing Guotai Fireproof & Insulation Materials Factory. The basic specifications of nonwoven basalt and glass fabrics are given in Table 1.

2.1 Sample Preparation

Nonwoven Basalt and glass fabrics of seven different thickness were used. Fabric samples were purchased from companies and manually laminated with layers to get different thickness. Different samples of nonwoven glass fabric are designated by character G and the number indicates to the thickness of sample, for example G2 is a glass fabric sample of 2mm thickness. Similarly character B is used for nonwoven basalt fabric and different thicknesses are shown by the numbers, e.g B2 for basalt fabric of 2mm thickness and B3 for basalt fabric of 3mm thickness and so on. These characters were given for all samples in reflectance and transmittance test. The digital fabric thickness gauge No YG141N test method was employed for determining the thickness of nonwoven fabrics (Table 2).

Table 1—Specifications of basalt and glass fabrics

Property	Basalt	Glass
Diameter, µm	13	10
Density, g/cm^3	2.65	2.60
Softening temperature, ^{o}C	840	960

2.2 Characterization Methods

To evaluate fire fighter's fabric performance, the thermal radiation performance of the nonwoven basalt and glass fabrics is necessary to know. The optical reflectance and transmittance spectra of nonwoven basalt and glass fabrics were characterized using UV–Vis–NIR spectrophotometer (Hitachi, U-4100) over the wavelengths range 250 - 2600 nm. Spectral reflectance and transmittance over a wide range of wavelengths is suitable to evaluate fire fighter's fabric performance. The experiment was performed with a scan speed of 10 nm s^{-1}.

The thermogravimetry analysis (TGA) and differential thermogravimetry (DTG) of nonwoven basalt and glass fabrics were performed with a TG NETZSCH STA 409 PC/PG which allows simultaneous detection of mass changes and heat effect of decomposition for samples during raising the temperature regime up to 1000°C.

Thermal protective performance (TPP) rating of clothing materials has been successfully used for clothing for the fire service, military and general industry. The amount of heat transferred depends upon both the exposure and the insulative or protective performance of the materials from which the garment is made[12]. The TPP rating of a fabric is the amount of energy in cal cm^{-2} applied to the fabric until it is estimated for second-degree burns of the skin behind the fabric, using the Stoll criterion. The Stoll criteria are used in American Society for Testing and Materials (ASTM) F 1060 to test the thermal protective performance of protective in heat flux of 2 cal cm^{-2} s^{-1} (84kW m^{-2})[13].

Table 2— Physical properties of nonwoven basalt and glass fabrics

Sample		Thickness mm	Mass per unit area, g m^{-2}	
Basalt	Glass		Basalt	Glass
B 2	G 2	2	162.8	216
B 3	G 3	3	214	260.7
B 4	G 4	4	263.7	342
B 5	G 5	5	382.3	406
B 6	G 6	6	509	591.3
B 7	G 7	7	593.5	758.7
B 8	G 8	8	675	931.2

In order to observe the practical performance of the nonwoven basalt and glass fabrics, the fire exposure experiment was performed using TPP apparatus equipped with a number of thermal sensors. During the experiment, the fabrics were exposed to flash fire generated by burning liquefied gas for 5 min, and then natural cooling down was performed for 10 min. The thermal sensors were used to measure the temperature of different locations of the fire scene, such as the flame center, the front surface and the back surface of the fabrics. Thermocouples have become the industry-standard method for measurement of a wide range of temperatures with reasonable accuracy, and they are used in a variety of applications. The applied sensor is used for temperatures up to approximately 1500°C. A computerized data acquisition system scans and records the temperature in every one second.

3 Results and Discussion

3.1 Thermal Radiation Performance Analysis

The spectral reflectance depends on the direction and wavelength of incident radiation. They are also affected by thin-film coatings and surface roughness[14, 15]. Spectral reflectance results of seven nonwoven fabrics with different thickness are obtained using UV–Vis–NIR spectrophotometer measurement. The reflectance curves of different fabrics throughout the full range of wavelengths from 250nm to 2600nm are presented in Fig. 1.

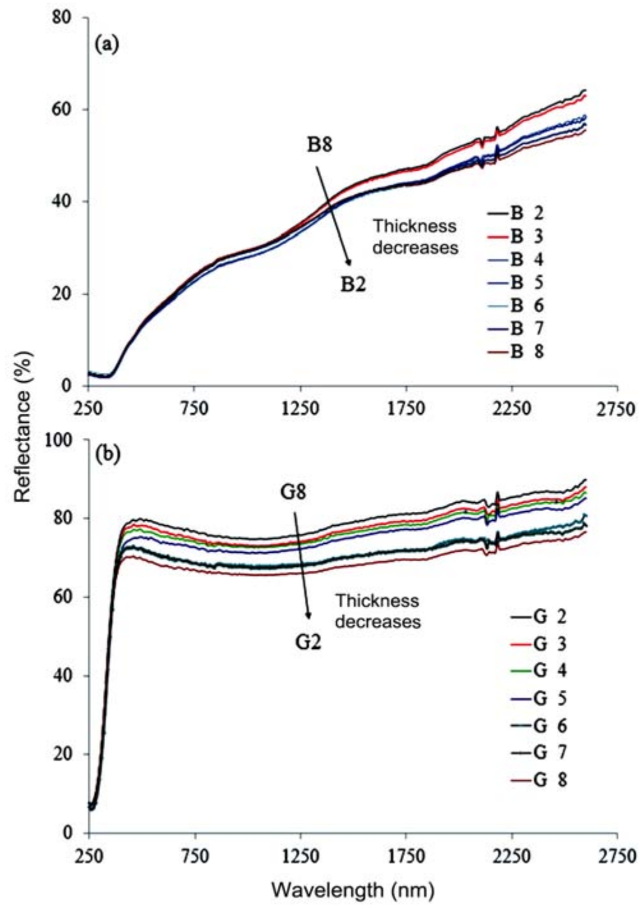

Fig. 1—Spectral reflectance for nonwoven (a) basalt and (b) glass fabrics

Spectral reflectance results of the nonwoven basalt and glass fabrics indicate that samples have substantially high reflectance The reflectance result curves exhibit a gradual increase in fabrics reflectance corresponding to the fabric thickness, and there is obvious increase in reflectance when thickness increases from 6mm to 7mm. Nonwoven glass fabrics have high reflectance of about 70% or more in NIR and Vis wavebands, This can be due to the smooth surface and the morphological structure which might be attributed to the spinning process. However, nonwoven basalt fabrics have a reflectance of about 25% and more on NIR wavelength.

The reflectance and transmittance through full wavelength for different thicknesses of nonwoven basalt and nonwoven glass fabrics are represented in Tables 3 and 4.

UV–Vis–NIR spectrophotometer has a wide range of wavelengths The ultraviolet (UV) wavelengths are in the range of 10 - 380 nm, the visible (Vis) wavelength range is from 380 nm to 780 nm and near infrared (NIR) is from 780 nm to 2600 nm. There is no significant difference in the results of B2 - B8 and G2 - G8 as illustrated in Fig. 1, because the thickness has no significant effect on the optical properties.

The radiative properties, such as reflectance, transmittance, and emittance of 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[16].

An important function of thermal protective fabric is the thermal protection of fire fighters during exposure to flash fires. Measurements have indicated that the heat flux from flash fire is primarily due to radiation, being less than 30 per cent convective heat even for a body immersed in it[4], so the main thermal protection for firefighters is radiant heat. From the UV–Vis–NIR spectrophotometer results, it can be concluded that the nonwoven fabrics have good thermal radiation protective performance.

Table 3—Average properties of nonwoven basalt fabrics through different wave

Sample	NIR reflectance %	Vis reflectance %	UV reflectance %	NIR transmittance %
B2	41.7	16.6	3.3	23.8
B3	42.0	17.4	2.8	18.1
B4	42.2	17.1	3.0	11.1
B5	42.3	16.4	2.7	3.0
B6	42.5	16.5	2.8	2.9
B7	44.9	17.1	2.9	1.7
B8	45.5	17.0	2.7	0.9

Table 4—Average properties of nonwoven glass fabrics through different wave

Sample	NIR reflectance %	Vis reflectance %	UV reflectance %	NIR transmittance %
G2	69.6	68.3	35.9	19.3
G3	71.7	70.4	34.0	18.2
G4	72.2	70.4	36.9	15.1
G5	77.0	73.9	35.9	7.3
G6	78.2	75.5	36.8	4.0
G7	79.0	76.5	36.4	2.5
G8	80.8	78.1	37.7	2.2

3.2 Transmittance Characteristics

Spectral transmittance results for eight different thicknesses of nonwoven basalt and glass fabrics are shown in Fig.2. All of the spectral transmittance curves show an increase in fabric transmittance according to fabric thickness and fabric weight per square mass.

3.3 Thermogravimetry

Thermogravimetric analyzer (TGA) is an essential laboratory tool used for material characterization. It is based on the measurement of mass loss of material as a function of temperature in a controlled atmosphere[17]. To evaluate the thermal stability of basalt and glass fabrics, the thermogravimetry analysis was applied and pursued by presenting a comparative analysis between two kinds of fabric. Figure 3 shows the TG curves for nonwoven basalt and glass fabrics.

TG curves indicate that there is no significant mass loss when the temperature range is below 250°C, and the mass loss of nonwoven glass fabric increases rapidly. However, a significant mass loss is observed when the temperature is increased form 250°C to 400°C. On the other hand, better thermal stability is observed for nonwoven basalt fabric. The characteristic parameters of thermal decomposition of nonwoven basalt and glass fabrics obtained from TG curves are shown in Table 5.

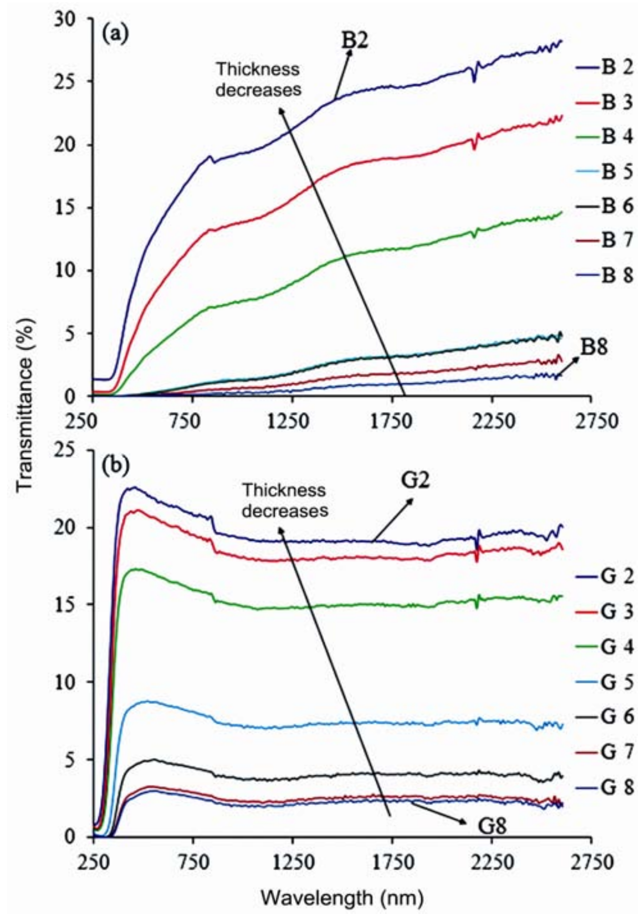

Fig. 2—Spectral transmittance for nonwoven (a) basalt and (b) glass fabrics

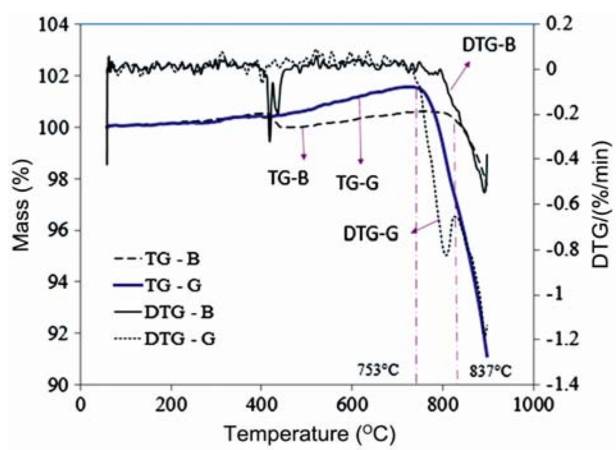

Fig. 3—TG and DTG curves for nonwoven basalt and glass fabrics

From characteristic parameter of thermal decomposition obtained from TG curves, it is shown

Table 5—Characteristic parameters of thermal decomposition of nonwoven basalt and glass fabrics obtained from TG curves

Sample	T_o, °C	T_i, °C	Mass loss, %
Basalt fabric	276.0	540.1	0.74
Glass fabric	268.1	469.6	1.33

T_o = Starting decomposition temperature.
T_i = Maximum mass loss temperature.

that both the basalt and glass fabrics have good thermal stability during the TG process. The mass loss at low temperatures in the samples is not significantly observed in the initial stage, when the temperature range is below 200°C. The maximum mass loss is obtained during the temperature range 250 – 400°C and with increasing temperature the mass loss continues increasing but with a low gradient. It is clearly observed that the fabrics resemble in the thermal behavior, but basalt fabric has better thermal stability than glass fabric and the mass loss values of the basalt and glass fabrics are 0.74% and 1.33% respectively. For basalt fabric the starting decomposition temperature is 276.0°C, compared to 268.1°C for glass fabric. The final decomposition temperature for basalt and glass fabrics are 540.1°C and 469.6°C respectively, which is also related to the good thermal stability of chemical composition, the crystalline degree and the orientation.

3.4 Thermal Protective Performance Test

The curves of the tested temperature versus time are compared and analyzed to evaluate the thermal protective performance and thermal durability of the fabrics.

The samples were exposed to flame and kept at high temperature. The area of the air is large and the air temperature is maintained at a constant temperature which simulates the hot plate effect, while the measurement is exactly on the surface of samples. The experimental curves show the registration of temperatures on the two sides caused by the heat power passing through the sample. During the experiment, the fabrics are exposed to the fire for 5 min, and then natural cooling is performed for 5min. The thermal sensors measure the temperature at different locations in the fire scene, such as the flame center and the front and back surfaces of the fabrics. The computerized data acquisition system scanned and recorded the real-time temperatures in every 1 s. The curves of the measured temperature versus time are also compared and analyzed to evaluate the thermal protective performance and thermal durability of the fabrics. The temperature of the flame generated was maintained always at approximately 1000°C in each experiment.

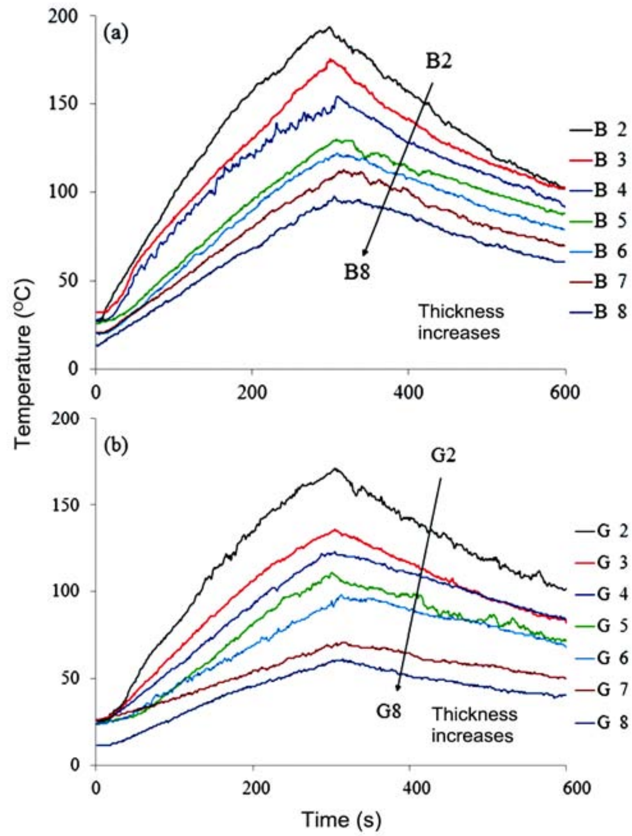

Fig. 4—TPP test for nonwoven (a) basalt and (b) glass fabrics

Figure 4 shows the back surface temperature of protective fabrics. The temperatures recorded by thermal sensors increased rapidly from room temperature to high temperature and become nearly steady in the initial few seconds. In the natural cool down stage, the temperatures reduce quickly with some discrepancies and gradually become steady. The temperatures always increase because the heat transfer is increased as a function of time, and the thickness has a principal effect on the TPP for single layer fabrics. The thermal insulating performance of the fabrics can be evaluated by comparing the insulating temperature per unit thickness. It may be noted that the thicker fabric exhibits better thermal insulation characteristic of substrate fabrics with identical structures. The temperature drop across the fabric can obviously be observed and viewed as a function of the measured thickness of the fabric.

The thermal resistance is a very important parameter from the point of view of thermal insulation, and is proportional to the fabric structure. Due to increase in thickness, we can observe the increase of thermal insulation, and in the same way the decrease in heat losses. The thermal resistance of fabrics is a function of the actual thickness of the material and the thermal conductivity K. This function is given by the following relationship:

$$\boldsymbol{R} = \boldsymbol{L} / \boldsymbol{K}$$

where $\boldsymbol{R}$ is the thermal resistance ($m^2 KW^{-1}$); and $\boldsymbol{L}$, the actual thickness (mm) of the sample.

The thermal protective performance test shows that basalt and glass fabrics possess good thermal insulation properties, and the insulation properties are increased with thickness. Nonwoven glass fabrics show more insulation ability as compared to basalt fabric, more than 30 °C for same fabric thickness.

4 Conclusion

The nonwoven basalt and glass fabrics appear to have good thermal radiation protective performance throughout full range of the wavelength (250 - 2600nm) using ultraviolet-visible-near infrared spectrophotometer analysis. Through full wavelength the glass fabric has a higher spectral reflectance than basalt fabric. However, the average of glass fabric spectral reflectance in NIR waveband is 32% higher, in Vis 56% higher and in UV 33% higher than basalt fabric. There is no significant different between two fabrics in NIR transmittance.

The thermogravimetric analysis indicates that the nonwoven basalt and glass fabrics have extremely same thermal behavior with starting decomposition temperature mode and very small mass loss. Besides, basalt fabric presents a higher thermal stability than glass fabric. This behavior could be related to the crystalline degree as well as the orientation of the fabric.

Thermal protective performance test shows that high fire resistance for nonwoven basalt and glass fabrics have a good thermal insulation performance during flash over fire exposure at about 1000°C, with the advantage of using glass fabric having high insulation properties (more than 30°C) as compared to nonwoven basalt fabrics.

References

1 Song G, Paskaluk S, Sati R, Crown E, Dale J & Ackerman M, ***Text Res J***, 81 (2011) 311.

2 Juricic D, Musizza B, Gasperin M, Mekjavic I, Vrhovec M & Dolanc G, ***Mediterranean Conference on Control Automation*** (IEEE, New York), 2007, 920.

3 Barry V H & Barry N H, ***Do test methods yield meaningful performance specification, performance of protective clothing, ASTM STP 900*** (Amiriacen Society of Testing and Mareial, Philadelphia), 1986, 327.

4 Abbott N J & Schulman S, ***Industrial Text,*** 6 (1976) 48.

5 Fernandez M J, Plaza C, Polo A & Plante A F, ***Waste Management***, 32 (2012) 158.

6 Abdolkarim A & Paul J H, ***Composites B***, 36 (2005) 394.

7 Pyshnova V V, Skobelkina T N, Yurchenko V G, Knot'ko A V & Putlyaev V I, ***Fiber Atomic Energy***, 101 (2006) 455.

8 Hearle J W S, ***High-performance Fibers*** (Woodhead Publishing), 2001, 187.

9 Xian Q H, ***Hi-tech Fiber Applicat***ion, 30 (2005) 7.

10 Hao L C & Yu W, ***Therm Anal Calorim***, 100 (2010) 55.

11 Novitski A G & Sudakov V V, ***Refractories Industrial Ceramics***, 45 (2004) 239.

12 Benhnke W P, ***Fire Technology***, 13 (1977) 6.

13 Bengi K & Aysun C, ***Fibers Text Eastern Eur***, 13 (2005) 51.

14 Z ZM, F CJ & Z QZ, ***Advances in Heat Transfer***, 37 (2003) 179.

15 Oloomi S A A, Saboonchi A and Sedaghat A, ***Middle East J Sci R,*** 5 (2010) 210.

16 Zhang Z M, Fu C J & Zhu Q Z, ***Advances Heat Transfer***, 37 (2003) 179.

17 McNaught A D & Wilkinson A, ***Compendium of Chemical Terminology***, 2nd edn (International Union of Pure and Applied Chemistry, USA), 1997.