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Experimental investigation on the thermal protective performance of nonwoven fabrics made of high-performance fibers

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Abstract In this study, the thermal protective performance of nonwoven fabrics made of Nomex (polyisophthaloyl metaphenylene diamine), PPS (polyphenylene sulfide), P84 (polyimide), and basalt fibers was investigated. The objective was to determine the influence of fiber type, thickness of fabric, and wet on the thermal protective performance of nonwoven fabric. The thermal resistances of different nonwoven fabrics were measured using a dry hot plate instrument, the basalt nonwoven fabrics had a highest thermal resistance in all fabric, and the thermal resistance of nonwoven fabric increased with the increase in thickness. The six nonwoven fabrics were exposed to a hot environment for a few minutes by using a self-designed apparatus. The test results showed that the nonwoven fabrics made with basalt fiber exhibited the best thermal protective performance, and the thermal protective abilities of nonwoven fabrics increased with fabric thickness. Interestingly, nonwoven fabrics with added water were found to be able to keep the fabric surface lower temperature compared to dry fabrics when exposed to a hot environment, indicating the excellent thermal protective performance of wet nonwoven fabrics.

Keywords Thermal protective performance · High-performance fibers · Nonwoven fabric · Wetted fabric

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Introduction

Firefighters are generally subjected to a variety of hazard conditions, such as flash fire and intense heat flux. The most common exposure is to low-level radiant heat flux over prolonged periods of time. So the development of long-term durability thermal protective and thermal insulating clothing has been a matter of public attention. A basic requirement for the fabrics used in the high-temperature environment is that the fabrics should have good thermal insulation properties. Thermal insulation properties of textile fabrics are actually influenced by the gamut of fiber and fabric properties. Fiber type, fabric thickness, weight, fabric cover factor, fabric porosity are major factors of thermal protective properties of fabrics [1, 2].

Nonwoven is a kind of fibrous fabric material formed by fibers with orientation or random arrangement that compose into schistous matters or fiber web, which is one of the most important components for good thermal insulation of a body from the surrounding [3–5]. Nomex, PPS, P84, and basalt fibers have great high-temperature resistance and thermal stability, which were widely used in the fields of thermal insulation [3, 6, 7]. In the past few years, many studies have discussed about the thermal protective performance of Nomex, basalt woven fabric, and the thermal stability of PPS and P84 fibers [4, 8–11]. However, less work was concerned about the thermal protective properties of nonwoven fabric when exposed to environments of intense heat, especially when comparing the thermal protective performance of these nonwoven fabrics. In addition, this is normally assessed by the thermal protective performance test which is conducted on dry fabrics. However, a few recent studies have suggested that the performance of the fabrics when wetted could be very important, because of the pattern of use by firefighters [12, 13]. It is therefore important to understand what the effect is of wet on the thermal transmission of protective fabrics.

This paper focuses on the thermal protective performance of high-performance fiber nonwoven fabrics made of Nomex, PPS, P84 and basalt fiber by using the self-designed test apparatus. During the thermal durability experiment, Nomex, PPS, and P84 nonwoven fabrics were exposed to thermal environment generated for a few minutes. The main objective was to investigate the heat-insulating properties of different nonwoven fabrics and the effects of fiber type, thickness, and wet on thermal protective performance of nonwoven fabrics.

Experimental

Materials

The characteristics of the five types of nonwoven fabric used for thermal protective materials are provided in Table 1. The nonwoven fabrics were purchased from Shanghai An Delu textile Co. Ltd. The basic structure and properties of nonwoven fabrics are presented in Table 1.

Methods

Measuring thermal resistance of nonwoven fabrics

The thermal insulation of different nonwoven fabrics made of high-performance fibers 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. The relative humidity was controlled at 65 %. The air speed was 1 ms^{-1}. After the system reached steady state, the thermal resistance of the sample was obtained.

Evaluation of thermal protection of nonwoven fabrics

The thermal protection performance of fabrics was evaluated with a self-designed apparatus. As shown schematically in Fig. 1, the apparatus consisted of a heating control system, a thermal protective plate, a specimen holder, the two temperature sensors, and a data acquisition system. The thermal protective plate was of nested structure with a cylindrical internal layer and a rectangular outer layer. The intermediate space was filled with heat-insulating fibers in order to minimize the 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 on a thin stainless steel tube with heat-resistant puddle, was embedded in the surface of fabrics. 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 in 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.

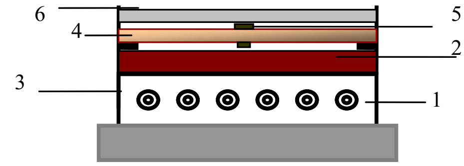

Fig. 1 Schematic diagram of the test apparatus. *1* Heating control system; *2* copper heat plate; *3* thermal protective plate; *4* fabric sample; *5* temperature sensor; *6* cold plate

Table 1 Structural characteristics of the nonwoven fabrics

Sample no.	Materials	Thickness/mm	Area mass/g m^{-2}
*A*1	Nomex fiber	2.5	300
*A*2	Nomex fiber	2.7	350
*A*3	Nomex fiber	3.2	400
*B*1	PPS fiber	3.2	400
*C*1	P84 fiber	3.2	400
*D*1	Basalt fiber	3.2	400

Testing procedures

Prior to testing, all dry fabrics are conditioned for at least 24 h in a standard atmosphere of 65 ± 2 % RH and 20 ± 2 °C.

For the wet fabrics, fabrics were immersed in distilled water for certain minutes and dehydrated by centrifugal method to remove the residual water on the surface of the fabric, so as to reach a totally wet condition. The fabric was then placed in atmosphere to liberate gradually to a prescribed moisture regain before testing. Moisture regain was calculated according to the following formula:

$$W = \frac{G - G_0}{G_0} \times 100\,\%$$

where W is moisture regain, G and G_0 are the wet and dry weight of sample, respectively.

Experimental results and discussion

Thermal resistance of different nonwoven fabrics

Figure 2 gives the average thermal resistance of different nonwoven fabrics. The thermal resistance of *A*1 was 0.1123 $m^2\ KW^{-1}$, and the thermal resistance of *A*3 was

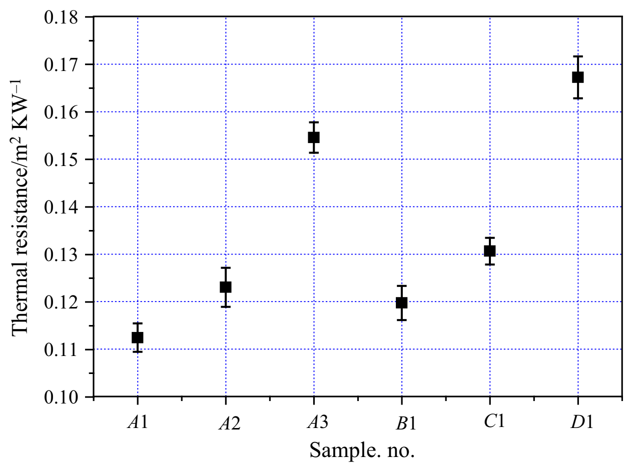

Fig. 2 Thermal resistance of different nonwoven fabrics

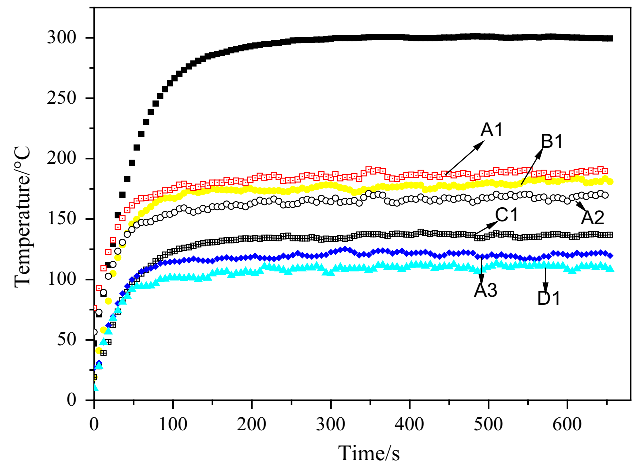

Fig. 3 Thermal protective performance of different high-performance nonwoven fabrics

0.1547 $m^2 KW^{-1}$. This was due to the fact that the thermal resistance increased with the increase in thickness of nonwoven fabric. Thus, we can improve thermal insulation properties of nonwoven fabric by increasing the thickness of fabric. As can be seen, the thermal resistance of *D*1 was the largest in all nonwoven fabric, which reached to 0.1671 $m^2 KW^{-1}$. The thermal resistance of six nonwoven fabrics was in the order $D1 > A3 > C1 > A2 > B1 > A1$. This implies that the basalt fiber has the best thermal insulation performance.

Thermal protective performance of different high-performance nonwoven fabrics

During the thermal protective performance experiment, two thermal sensors, positioned at different locations, were used to measure the upper surface temperature and the lower surface temperature of fabrics, respectively. The temperature of the heat source can be controlled easily in each experiment. We can obtain the insulation temperature according to the upper surface and lower surface temperature of fabric. The temperature versus time of six kinds of nonwoven fabrics is shown in Fig. 3. As indicated in the figures, the temperatures recorded by thermal sensors increased rapidly from room temperature (20 °C) to different stable higher temperature (*A*1:185 °C; *A*2:165 °C; *A*3:120 °C; *B*1:175 °C; *C*1:135 °C; *D*1:110 °C). When the thickness and area mass of fabrics were the same, basalt nonwoven fabric had the best thermal insulation performance of all the fabrics, the insulating temperature drop across the fabric approach to 200 °C. The basalt nonwoven fabric has best heat-insulating properties, perhaps related to the excellent thermal property of the fiber and the lower thermal conductivity. The basalt fiber has been widely used in the fields of thermal protection and heat insulation due to its excellent thermal stability performance. It is reported that basalt fiber has a softening temperature of 960 °C. The basalt fiber can be used for a long period at 800 °C [3, 15]. The insulating temperature of Nomex, PPS, and P84 nonwoven fabrics was 180,120, and 160 °C, respectively. The order of insulating temperature of four different nonwoven fabric materials was basalt > Nomex > P84 > PPS.

The most important structure parameters of nonwoven are thickness and mass per unit area. From Fig. 3, it could be found that the temperature drop across the fabrics can be obviously observed and viewed as a function of the measured thickness of the fabric. When the thickness was 2.5 mm, the insulation temperature of Nomex nonwoven was 125 °C. When the thickness was 3.2 mm, the insulation temperature was 180 °C. So the thermal insulation performance of the nonwoven fabric could be evaluated by comparing the insulating temperature per unit thickness. It might be noted that the thicker fabric exhibits better thermal insulation characteristic for the same structure and material fabric. This indicated that, as expected, thermal protection of fabrics improves as their thickness or weight increases. In other words, the thermal insulation performance of the nonwoven fabric largely depends on the thickness for single-layer fabrics. The main reason had two aspects, one aspect was that the thermal resistance of fabric was greater with the increase in thickness of fabric, and the insulation thermal properties of fabric were the better. Secondly, with increase in the thickness of the fabric, the radiation heat transfer coefficient of fabric decreased, and the thermal insulation performance of fabric was the better.

Effect of wet on the thermal protective performance of different high-performance nonwoven fabric

One serious potential concern for thermal protective clothing is the temperature transmission through the fabric.

This is normally assessed by the thermal protective performance test which is conducted on dry fabrics. However, a few recent studies have suggested that the performance of the fabrics when wetted could be very important, because of the pattern of use by firefighters. This study is an investigation, conducted to evaluate the influence of wet on the thermal protective performance of four kinds of nonwoven fabrics by comparing their temperature transmission. From all the curves in Fig. 4a–d, it was evident that all the curves showed a similar trend as shown in Fig. 5, and the variation in surface temperature of fabrics in all test process could be divided into two stages as follows:

Stage one (A–B): from the beginning of the curve to the first transition point of the curve. At this stage, the surface temperature of fabric was raised to a stable temperature swiftly, and this temperature was 70 °C. The heat absorbed by the evaporation of water equaled to the heat transfers from heat source to the fabric, so the surface temperature of

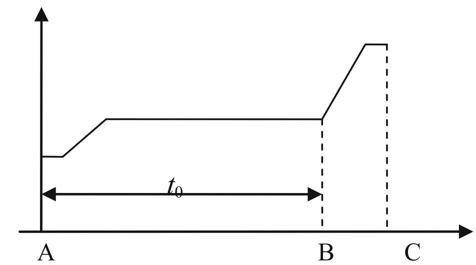

Fig. 5 Schematic diagram of the surface temperature of fabric

the fabric was kept constant. Thus, a dynamic thermal balance had been set up between the fabric and the environment at this stage.

Stage two (B–C): from the stable temperature of stage one to the other stable temperature. At this stage, the water and moisture of fabric had fully evaporated from the surface of fabrics to the environment, and the moisture regains of fabrics

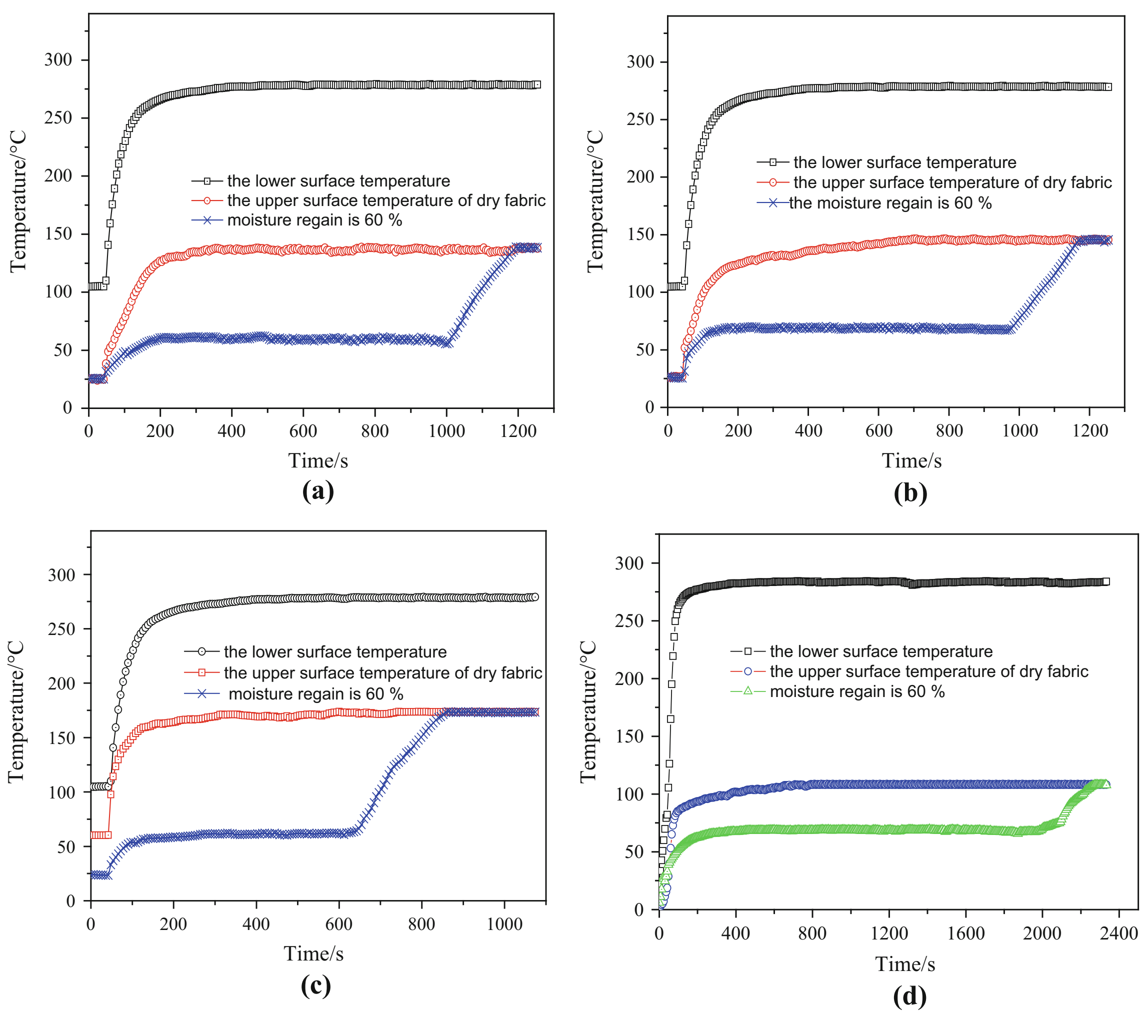

Fig. 4 Effect of wet on the thermal protective performance of different high-performance nonwoven fabric **a** Nomex; **b** P84; **c** PPS; **d** basalt

were almost zero. So the fabrics absorbed a lot of heat from heat source, and the temperature of fabric increased obviously.

In stage one, the upper surface temperature of nonwoven fabric was lower, which showed the thermal insulation performance of nonwoven fabric was better. In addition, we can determined the thermal protective performance of fabrics by comparing the time (t_0) of stage one. Table 2 showed the duration of different nonwoven fabrics in stage one, and it could be seen that the duration of basalt nonwoven was longest, i.e., 2000 s (33.3 min), for the P84 and Nomex nonwoven fabric 1000 s (16.6 min), and for PPS nonwoven only 680 s (11.3 min). Since the theories of water retention by different textile materials are quite different, the duration of stage one may be different. The duration of stage one for basalt, P84, and Nomex nonwoven fabrics was longer than PPS, which due to the three nonwoven may have the higher water absorbing capacity than PPS nonwoven fabrics. High-performance fibers have compact nonpolar molecular chains with extremely high crystalline and orientation which shows an awkward ability of water absorbing, so the water mainly existed in the pores between fibers and the surface of nonwoven fabrics. The basalt nonwoven fabrics were made of fibers with small linear density. There existed more pores in basalt nonwoven fabric than others nonwoven fabrics, so the basalt nonwoven had great water retention ability. These results

Table 2 Duration of different nonwoven fabrics

Fabric	Nomex	P84	PPS	Basalt
Time/s	1008	990	680	2000

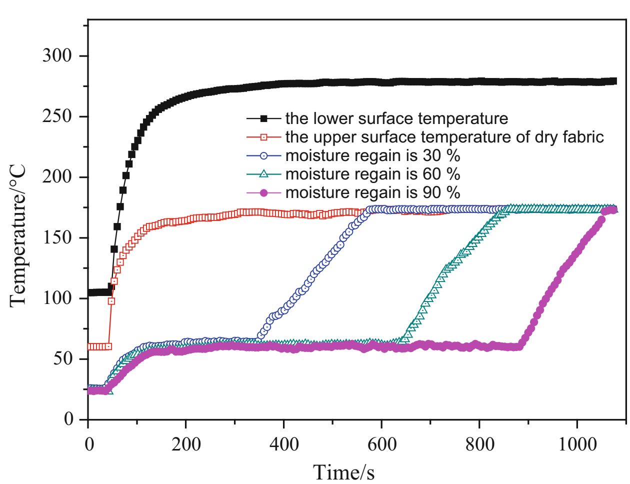

Fig. 6 Effect of the mass of wet on heat insulation performance of nonwoven fabric

Table 3 Duration of PPS nonwoven fabric at different moisture regain

The moisture regain/%	30	60	90
Time/s	350	680	900

suggest that the insulating effectiveness of the high-performance nonwoven fabric is obviously affected by the presence of wet. So we can improve the thermal protective performance of nonwoven fabric by adding wet.

In order to discuss the influence of the mass of wet on thermal protective performance of nonwoven fabric, we chose different moisture regain of PPS nonwoven fabric, and the moisture regain was 30, 60, and 90 %, respectively. Figure 6 shows the temperature versus time of the PPS nonwoven with different moisture regain. It was evident that the duration of stage one was much longer with the increase in moisture regain of nonwoven fabric. Table 3 also presents the duration of stage one in the same tests conducted. It can be found that the duration of stage one was 400 s when moisture regain is 30 %, and the time was 900 s when moisture regain is 90 %. It is easy to understand that the water mass is more, and it took longer time for the water to be evaporated sufficiently. So we can further improve the thermal protective of fabric by adding the mass of water into fabric.

Conclusions

From above experimental results, we draw some conclusions. (1) The basalt fabrics had a highest thermal resistance in all fabric, and the thermal resistance of nonwoven fabric increased with the increase in thickness. (2) When exposed to thermal environments, the basalt nonwoven fabric exhibits best thermal insulating performance than P84, PPS, and Nomex nonwoven fabric, and the insulating temperature reached up to 200 °C. (3) The effect of thickness on the thermal insulating performance of nonwoven is obviously, for the same materials and structure nonwoven, the insulating temperature of nonwoven fabrics increased with the increase of thickness. (4) The insulating effectiveness of the high-performance nonwoven fabric is obviously affected by the presence of wet. The wet fabric showed the better thermal protective performance than dry fabric.

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