Thermal Protective Performance of Aerogel Embedded Firefighter's Protective Clothing

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ABSTRACT

Firefighters' protective clothing (FPC) is a four-component ensemble that protects the human body against the following properties: a. radiation; b. flashover conditions; c. puncture and abrasion hazards; while still maintaining an adequate level of dexterity and comfort. Therefore, the thermal protective performance (TPP) of FPC is very important. Generally, FPC with higher TPP will result in fewer injuries. In this study, aerogel is proposed to be used in FPC to improve its TPP, and the feasibility is examined. The results show that the temperature on the back surface of the FPC samples that were filled with aerogel was 100 °C lower than that of those unfilled FPC samples under the same heat exposure. However, a short temperature jump occurred during the tests due to the penetration of infrared radiation (IR) light. In addition, the weight of the FPC sample in which the aerogel was embedded was lessened about 24.3%. It is concluded that filling aerogel in FPC can effectively improve its TPP and lessen its weight, while some additives must be used to absorb or scatter the IR light that causes the temperature jump.

Keywords: aerogel; firefighter's protective clothing; thermal protective performance

INTRODUCTION

The statistics in China show that there were 43 deaths and 330 injuries of firefighters from 2000 to 2005 because of firefighting or rescue activities [1]. As the most important protective equipment for firefighters, the thermal protective performance (TPP) of the firefighter's protective clothing (FPC) directly affects firefighter's personal safety and the efficiency of the rescue activities. It is known that 20% of the accidents of the workers in thermal protective clothing are caused by physical stress and 16% by flame [2]. Therefore, high heat-resistance and flame-resistance are important to FPC.

According to the public safety industry standard of China [3], FPC in China consists of four layers: outer shell, moisture barrier layer, thermal barrier layer, and comfort layer. The outer shell layer could protect the body against heat and physical shock; the moisture barrier layer is to prevent water penetration into the thermal barrier layer and to transfer the moisture vapor outside; the thermal barrier layer protects the human body from heat; the comfort layer improves the wearing comfort. Generally, the thicker the thermal barrier layers in FPC, the better the TPP of FPC. However, a thick thermal barrier layer usually results in poor mobility. The total weight of a firefighter's equipment, which includes heavy self-contained breathing apparatus and FPC in actual firefighting activities, reaches as much as 25 to 35 kg and the burden caused by the weight is remarkable[4]. This motivates the present paper which is to improve the TPP of FPC by introducing aerogel while reducing the total weight.

Aerogel is an advanced material known for its unique properties such as low density, low thermal conductivity, high specific surface area, and excellent thermal insulative [5]. The thermal conductivity of aerogel is usually from 0.004 to 0.03 W/m·K [6]. Nowadays, aerogel has been employed in many applications such as construction, aerospace, and defense [7]. It has also been used in protective clothing. NASA used aerogel to produce space suits in 2002 [8]. The US Navy evaluated aerogel undergarments as passive thermal protection for divers [9]. Corpo Nove and Hugo Boss have designed and produced an 'Antarctic Jacket' using aerogel as insulation materials in extreme conditions down to minus 50 °C [10]. In addition, McFarlane Enterprises has produced a cold weather garment that is insulated with encapsulated aerogel [11].

From those applications it is seen that aerogel was mainly used to keep warmth in low temperature situations. However, little information has been studied with respect to its application in clothing in high temperature scenarios such as FPC in fires. Therefore, the purpose of this research was to embed aerogel into the thermal barrier layer of FPC and determine its TPP. In addition, an analytical balance was used to measure the mass of the FPC samples with aerogel, and that mass was compared to the mass of the common FPCs. The research will help to develop FPC with higher TPP and better dexterity.

METHODS AND MATERIALS

Methods

The experimental equipment consists of two parallel parts: the radiation heater and the sample holder. The radiation heater was made of six U-shaped carbon rods arranged vertically within firebricks held by a steel framework. The heater was powered by a three-phase alternating current power supply that was controlled by KZG-3KP SCR temperature control cabinet. Details of the heater could be found in [12].

The sample holder was largely composed of thermal insulation board with the size of 760 mm × 760 mm × 50 mm. The exposed surface of the holder was covered with aluminum foil to protect the insulation board from being heated. There was a 200 mm × 200 mm square opening located in the center of the insulation board where the FPC sample was placed. A water-cooled heat flux meter was installed near the opening. The exposed surface of the sample holder is shown in *Figure 1*.

Four K-Type thermocouples, A1, A2, B1 and B2 in *Figure 2*, were closely attached on the back of the FPC sample, readings of which are denoted as TA1, TA2, TB1, and TB2, respectively, in the following part. An IR thermal imaging camera (product number: Research N1) was laid behind the sample holder, so the temperature field of the back surface of the FPC sample can be recorded. The sample rate of the IR camera was 25 times per second.

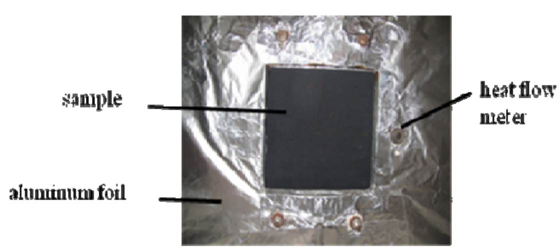

FIGURE 1. The heat exposed surface of the sample holder.

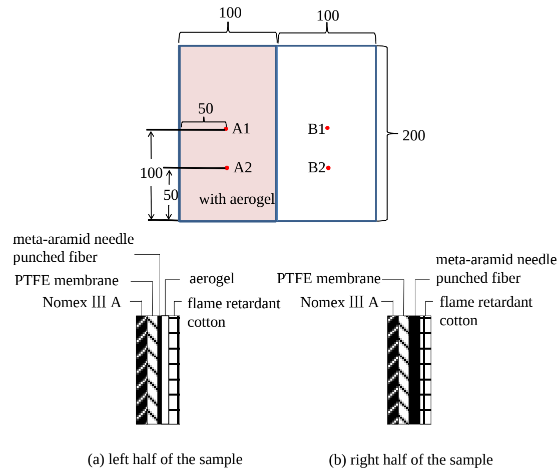

FIGURE 2. Constitutions of the sample (A1, A2, B1 and B2 are the locations of the thermocouples, and the unit of the length is millimeter).

Materials

The sample was composed of materials which are widely used in FPC in China. The materials of each layer are shown in *Table I* all of the materials were cut to 230 mm × 230 mm square and sequentially placed. *Figure 2* shows the constitutions of the FPC sample. The thermal barrier layer of the right half of the FPC sample in *Figure 2* is 3 mm meta-aramid needle punched fabric, while that of the left half is 2.5 mm silica aerogel plus 0.5 mm meta-aramid needle punched fabric. Therefore, both halves of the sample's thermal barrier layer had the same thickness. The physical parameters of the aerogel used here are shown in *Table Ⅱ*.

The mass of all the layers was measured by an analytical balance for the left and right half of the FPC sample, respectively. The surface densities for each layer were calculated and are shown in *Table I* As aerogel is very light, the surface density of the thermal barrier layer that is filled with aerogel is 374 g/m^2, and it is 264 g/m^2 lighter than the one without aerogel. Thus, the whole weight of FPC could be reduced by 24.3% if aerogel is used in the thermal barrier layer.

TABLE I. Masses of all the layers.

Layer	Material	Surface Density, g/m^2
Out shell	Nomex III A	218
Moisture barrier layer	PTFE Membrane	107
Thermal barrier layer with aerogel	0.5 mm Meta-aramid Needle Punched Fiber + 2.5 mm aerogel	374
Thermal barrier layer without aerogel	3 mm Meta-aramid Needle Punched Fiber	638
Comfort layer	Flame Retardant Cotton	124

TABLE II. The Physical Parameters of Silica Aerogel in this paper.

Porosity	Specific Surface Area	Density	Thermal conductivity
96%	550 m^2/g	15 kg/m^3	0.014 W/m·K

RESULTS

Incident Heat Flux

Figure 3 depicts the incident heat flux versus time on the exposed surface of the FPC sample. The incident heat flux increases very fast from 0 to 400 s, while the increasing rate slows down from 400 to 860 s. The maximum incident heat flux is 17.6 kW/m^2 at 860 s. The power was turned off at 860 s, and after that the incident heat flux decreases rapidly.

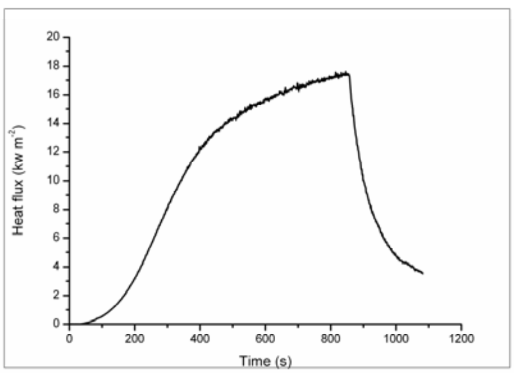

FIGURE 3. Incident heat flux versus time on the exposed surface of the sample.

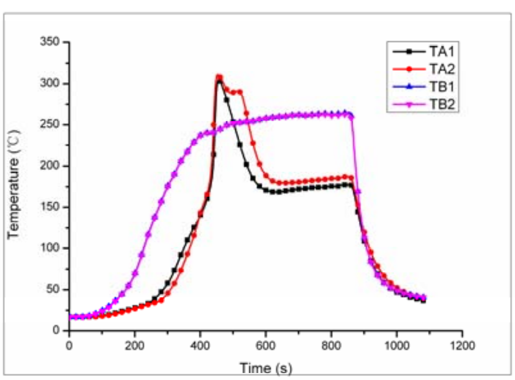

FIGURE 4. Temperature versus time of the four test points.

Temperatures

The temperature of the four test points on the back surface of the FPC sample are shown in *Figure 4*. TB1 and TB2 of the right half are almost the same and the change trends correspond to that of the incident heat flux. However, the temperature on the left half seems more complicated. The curve of TA1 is divided into 5 stages according to the temperature trends before the power is turned off and the details of the 5 stages are shown in *Table III*.

TABLE III. The Slope Of The TA1 at Each Stage.

Stage	Time(s)	Slope	Interpretation
1	0-260	0.08	Rose Very Slowly
2	260-420	0.78	Increased Faster Than Before
3	420-460	4.95	Increased Sharply
4	460-610	-1.19	Decreased Rapidly
5	610-860	0.04	A Steady And Very Slow Rising Period

As shown in *Figure 4*, at the end of the first stage, TA1 reached 38.5 °C while TB1 and TB2 were as high as 136.8 °C. The temperature difference between the left and right half was about 98.3 °C. At Stage 2, the temperature difference between the two halves kept at about 100 °C. However, this situation changed at Stage 3, where TA1 increased rapidly to a level higher than TB1 or TB2. The trend of TA2 was almost the same as TA1 in the first 3 stages, while it had a short steady state during 490 s to 520 s in Stage 4 instead of decreasing at a certain slope as TA1. At Stage 5, both of TA1 and TA2 came to a very slow rising period and TA2 is a little higher than TA1. At this stage, TA2 was about 80 °C lower than TB1 or TB2. All of the four temperatures decreased rapidly after the power was turned off at 860 s.

IR Images

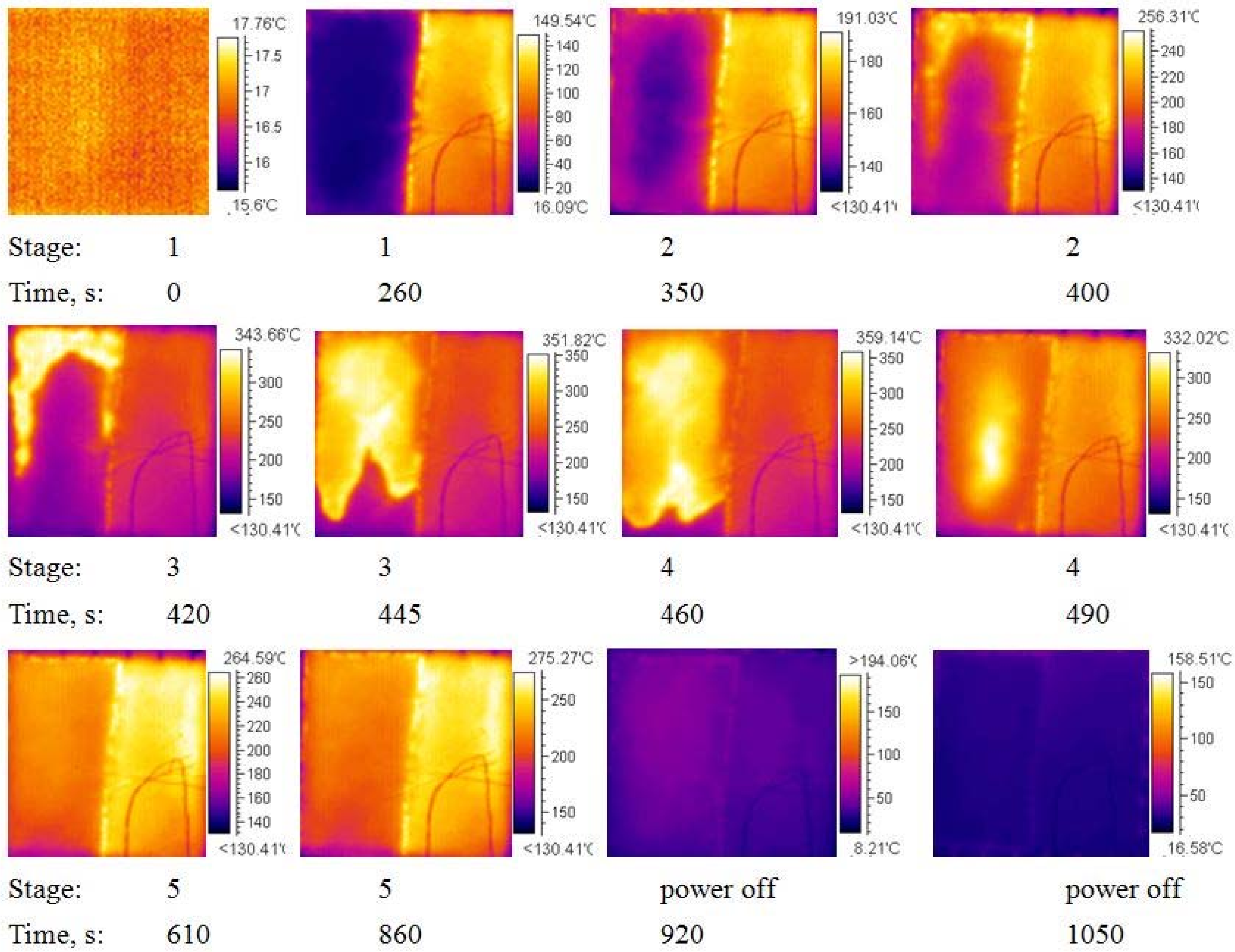

FIGURE 5. Temperature history of the back surface of the tested FPC sample.

The temperature field on the back surface of the sample was recorded by an IR camera. The representative series of the IR images are shown in *Figure 5*, with brighter color indicating higher temperature. This figure shows clearly the temperature history of the tested sample. For example, the temperature of the left half was lower than that of the right half for Stages 1 and 5 as discussed above.

Subfigures from Stage 2 showed that the temperature of the left half rose gruadually from the edge to the center at this stage. At 400 s, the upper part of the left side became nearly as bright as the right half. At Stage 3, this bright area expanded quickly from top to bottom. The process of this sharp temperature rise was shown clearly in the figure. It is anticipated that the total thermal conductivity of the left half experienced a mutation during this process which was possibly caused by the temperature rise. This will be discussed later.

Gradually, the left half was surrounded with a red halo at Stage 4 as shown by the image at 460 s, which means that the temperature of the left half started to decrease. The halo became larger towards the center bottom part of the left half where thermocouple A2 was positioned. This phenomenon accounts for TA2 having a short steady state during 490 s to 520 s in *Figure 4.*

DISCUSSION

The above results show that the TPP of the FPC materials that used aerogel in the thermal barrier layer is excellent most of the time, except during the sharp rise from 420 s to 610 s. The reason for the sharp rise will be discussed here.

The heat transfers mainly through three ways: conduction, convection and thermal radiation. As a high porosity material, the solid volume ratio of the aerogel is extremely low. Also, the aerogel's solid-state thermal conductivity is only about 0.002 W/m·K. For the air convection inside the aerogels, it is usually very small as the pore size of the aerogel is smaller than the mean free path of air (about 70 nm). Thus, with the increase of temperature, thermal radiation becomes the main form of heat transfer in aerogels [13].

The radiative heat transfer in aerogel strongly depends on the wavelength of the incident radiation, λ, as the absorption coefficient is a function of λ [14]. As shown in *Figure 6*, the absorption coefficient reaches its maximum value when $\lambda = 9.5\ \mu m$, and gets its minmum value when λ locates between 3 and 5 μm. At room temperature (e.g. 290 K), the peak wavelength is calculated by Wien's displacement law as:

$$\lambda_m = 2.898 \times 10^3\ K\cdot\mu m / 290\ K = 9.99\ \mu m \quad (1)$$

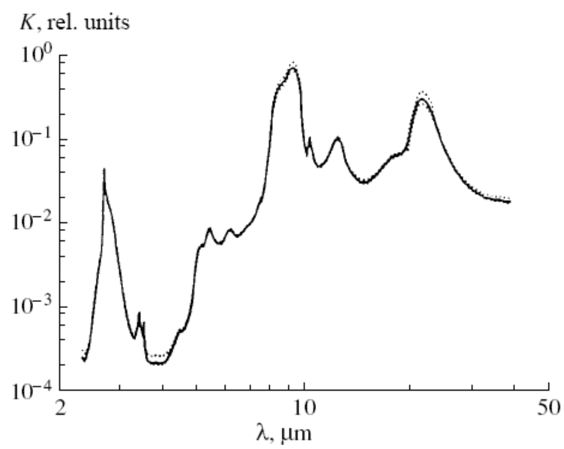

FIGURE 6 The IR absorption coefficient of aerogel as a function of wavelength [15]

Accordingly, at this wavelength the incident radiation is effectively absorbed by the aerogel so that the radiative transmission through aerogel is weak [15]. Thus, at Stage 1, the temperature of the left half rose very slowly where the increasing slope in *Figure 4* was 0.08. The max temperature difference was 125 °C between the two halves.

With the increase of temperature, the incident IR wavelength became smaller. When it was samller than 8 μm, the absorption coefficient decreased apparently. This resulted in the fast temperature rise at Stage 2, where the increasing slope was 0.78, bigger than that at Stage 1.

With the continuous increase of temperature, the IR wavelength decreased quickly. When the wavelength decreased to 3 ~ 5 μm, the absorption coefficient reduced to the minimum. At this stage, the transmitted part of the incident radiation achieved its maximum value which induced the sharp rise of TA1 and TA2 in *Figure 4* between 420 s and 460 s. The increasing slope reached 4.95.

However, the sharp rise did not last for a long time. This is because the increased temperature resulted in a rapid decrease of wavelength within the aerogel. When the wavelength was samller than 3 μm, the absorption coefficient rose (see *Figure 6*) and the remarkable thermal insulative properties of aerogel were again apparent.

n summary, using aerogel in FPC could obviously reduce the weight and improve the TPP in most of the experiment time except the time period where a sharp temperature rise occurred because of the lowest absorption coefficient. However, this problem could be solved if some additives were added to absorb the IR radiation when the absorption coefficient of aerogel becomes low. Zeng et al. [16] considered that doping about 8% carbon in silica aerogel can lower the total energy transfer by about 1/3 at room temperature. However, carbon is easily oxidized at high temperature, so this method can only be used when the temperature is below 300 °C. Kwon et al. [17] added 5 wt% TiO_2 powder in silica aerogel, and obtained a thermal conductivity of 0.0136 W/m·K at room temperature and 0.0284 W/m·K at 400 °C. However, the preparative cost is high. Finding an appropriate additive in silica aerogel for application in FPC to increase its TPP while reducing cost is still an unsolved problem that needs further study.

CONCLUSION

As aerogel has the characteristics of low density and low thermal conductivity, it was embedded in the thermal barrier layer of FPC, and the thermal response was tested in comparison with common FPCs. It was found that the FPC with aerogel had the advantages of lighter garment and better thermal protection. The main findings are as follows:

(1) When exposed to radiant heat, the backside temperature of the FPC samples with aerogel was about 100 °C lower than that of the samples without aerogel, except for a sharp temperature rise between 420 s and 610 s in the test.
(2) This sharp temperature rise was found to be induced by the small absorption coefficient of aerogel when the incident wavelength is about 3 ~ 5μm. Therefore, to use aerogel in FPC, additives should be added to absorb or scatter the incident radiation with the wavelength of 3 ~ 5μm.
(3) The total density was reduced by 24.3% when aerogel was embedded in the thermal barrier layer of FPC sample.

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