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Use of Aluminum-Coated Interlayers to Develop a Cold-Protective Fibrous Assembly

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ABSTRACT: In this article, we report on an experimental investigation of the thermal insulation and moisture vapor resistance of a thermal insulation assembly consisting of polyester battings and metal-coated thin nonwoven interlayers. Because of the blocking of radiation by the coated metal nanoparticles, the thermal radiative conductivity of the interlayer decreased from 0.0249 to 0.0194 W/m K after coating. We found that the thermal insulation of the fibrous assembly could be greatly improved without any significant effect on the moisture transfer through the incorporation of metal-coated interlayers between the fibrous battings in appropriate patterns. The thermal resistance of the assembly increased gradually with increasing number of incorporated interlayers until it reached a plateau. The presence of more metal-coated interlayers closer to the hot (heat-source) side was beneficial to higher thermal insulation. The moisture vapor resistance of the assembly showed no significant changes with increasing number of interlayers. The incorporation of three interlayers showed the best thermal insulation properties with little effect on the moisture transmission. This kind of thermal insulation assembly will have significant advantages in cold-protective clothing because of its high insulation properties and breathability. © 2013 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40205.

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INTRODUCTION

Fibrous insulation materials have been used in many applications, including in functional protective clothing, sleeping bags, and building envelopes.[1,2] A high thermal insulation within the constraint of mass and thickness is desirable to protect the wearer of clothing from a hot or cold environment or for energy savings in buildings.[3–6] To make the wearer comfortable, it is quite important to enhance the thermal insulation of cold-protective clothing without increasing its weight or affecting the moisture permeability. For this purpose, inflatable fabric,[7] low-density and high-porosity nonwoven materials,[8] and multiple layers[9] have been applied to make cold-protective outfits so that static air can be captured within fibrous materials.

Heat can be transferred through fibrous insulation materials through conduction, radiation, and convection. Even though porous fibrous materials exhibit high thermal conduction resistance, heat transfer by radiation through clothing systems[10] has usually been neglected. Heat transfer by radiation becomes a significant component when the temperature difference across the boundaries of the fibrous insulation is high.[11–13] The radiative heat flux (HF) through fibrous insulations can be reduced by a decrease in the fiber fractional volume, an increase in the fiber emissivity, and a reduction in the fiber radius.[3] Therefore, the development of superfine fibers has been found to be one of the most efficient ways of reducing the radiative HF within fibrous insulations and thereby improving the thermal insulating performance. The coating of TiO_2 nanoparticles has been reported to reduce the thermal radiative conductivity by changing the reflective properties of the fibers.[11] It has been suggested and shown[14–18] that the incorporation of a thin reflective interlayer within the fibrous insulation can block the radiative heat transfer and hence significantly improve the total thermal insulation.

For cold-protective clothing applications, it is highly desirable to have a high thermal resistance but a low moisture vapor resistance. The moisture-transfer ability of the fibrous assembly is vital to the comfort sensation of clothing systems as it determines the diffusion of sweat from human skin to keep the body warm and comfortable. Inflatable fabric has little applicability as it is not permeable to moisture transmission.[7] It is, therefore, important to optimize the construction of clothing assemblies to maximize moisture transmission through clothing and minimize the moisture absorption and condensation within clothing.[15]

Although it has been shown that the number of reflective interlayers in the fibrous assembly is important im maximizing improvements in thermal insulation,[16] the effect of the positions of the interlayers has not been investigated experimentally. Therefore, it was the objective of this study to experimentally investigate the effect of the number of reflective layers and their specific positions in the fibrous assembly on the total thermal insulation. Furthermore, the effect of the interlayers on the total moisture vapor resistance of the fibrous assembly was also investigated.

EXPERIMENTAL

Materials

Polyester batting and superfine melt-blown polyester nonwoven fabric were purchased from a local market and had the specifications shown in Table I. The superfine melt-blown polyester nonwoven fabric was coated with aluminum (Al) via physical vapor deposition (PVD). The PVD was conducted on a vacuum-sputtering machine (Hong Kong Productivity Council, Hong Kong). The dimensions and physical characteristics of the polyester batting and Al-coated interlayer are also listed in Table I. Figure 1(a) is a picture of the polyester batting, and Figure 1(b) is the Al-coated interlayer.

Sample Preparation

The polyester batting and interlayer were cut into a round shape with a diameter of 23.6 cm, as shown in Figure 1(a,b), respectively. Polyester battings, together with the Al-coated polyester interlayer, were stacked up layer by layer into a fibrous assembly, as shown in Figure 1(c). Six thin battings with a total thickness of 30 mm and a weight of 12.05 g (the most applicable thickness of assembly in cold-protective clothing design[18]) were used as a fibrous assembly to perform the thermal insulation resistance test. Different numbers of interlayers were sandwiched into the battings during the test to show the effect of the interlayers on the thermal insulation properties of the fibrous assembly. As shown in Figure 1(d), the interlayers were incorporated into polyester batting at different gaps in between battings to form a set fibrous assembly. For each sample, five tests were performed, and the results were averaged.

Table I. Characteristics of the Polyester Batting and the Interlayer

Characteristic	Polyester batting	Al-coated nonwoven interlayer
Thickness (mm)	5.0	0.236
Mass (g/m^2)	46.0	33.7
Fiber diameter (μm)	36.7	2.15
Fiber volume (%)	0.7	9.5
Fiber emissivity	0.62	0.02
Fiber density (kg/m^3)	1350	1500
Fiber thermal conductivity (W m^{-1} K^{-1})	0.14	1.3

Field Emission Scanning Electron Microscopy (SEM) Analysis

A field emission scanning electron microscope (FEI Sirion 200) was used to examine the morphology of the interlayer before and after coating. During testing, a sample with a size of 50 mm × 50 mm^2 was stuck to the sample holder and sputtered with gold. SEM images were taken with a magnification of 10,000× under an accelerating voltage of 20 kV.

Fourier Transform Infrared (FTIR) Analysis

The FTIR spectra were obtained on a Nicolet Magna 760 FTIR spectrometer to obtain the transmittance spectra for each sample. The Rosseland mean extinction coefficient, as an average value of the extinction coefficient weighted by the local spectral energy flux, was obtained to provide a measurement of the effectiveness of the thin layers in blocking thermal radiation. The thermal radiative conductivity was then calculated from the FTIR spectra according to Wan et al.[13]

Determination of the Thermal Resistance and Moisture Vapor Resistance

A sweat-guarded hotplate[6,19] was used to measure the thermal resistance and moisture vapor resistance of the fibrous assembly, as shown in Figure 2.[6] The device contained a water container, which was covered by a manmade skin. The edge of the skin was sealed well within the container so that no water leaked out during the test. Water was provided by the water tank through an insulated pipe, and the water level in the tank was always higher than that of the container to ensure full contact between the water and manmade skin in the container. The water container was surrounded with a guard in which a heating element was inserted. The upper surface of the hotplate was controlled at a temperature of 35°C to simulate skin temperature. The temperature of the bottom guide plate and side ring was also controlled at 35°C so that the heat supplied to the hotplate could only be transmitted upward through the fibrous assembly. The HF supplied to the hotplate to maintain its temperature at 35°C was measured at the same time.

All of the temperatures were measured with resistance temperature detector (RTD) sensors (conforming to BS 1904 and DIN43760 standards, 100 Ω at 100°C), and the heating elements were made of thermally resistant wires. Temperature controls were achieved by the regulation of the heat supply through computer digital-to-analog (D/A) outputs according to a proportional-integral-derivative (PID) algorithm. To ensure the accuracy in the measurement of the heat supply and stability of the system, the power supply was direct current and was stabilized with a voltage stabilizer.[6]

The total thermal resistance (I_t) of the fibrous assembly (including the surface air layer) was calculated by the following equation:[19]

$$I_t = \frac{A(T_s - T_a)}{\text{HF}} \tag{1}$$

where A is the area of the hotplate (m^2), T_s is the surface temperature of the hotplate (°C), T_a is the temperature of the ambient air (°C), and HF is the heat flux (W) when there is no water in the hotplate (no moisture transfer).

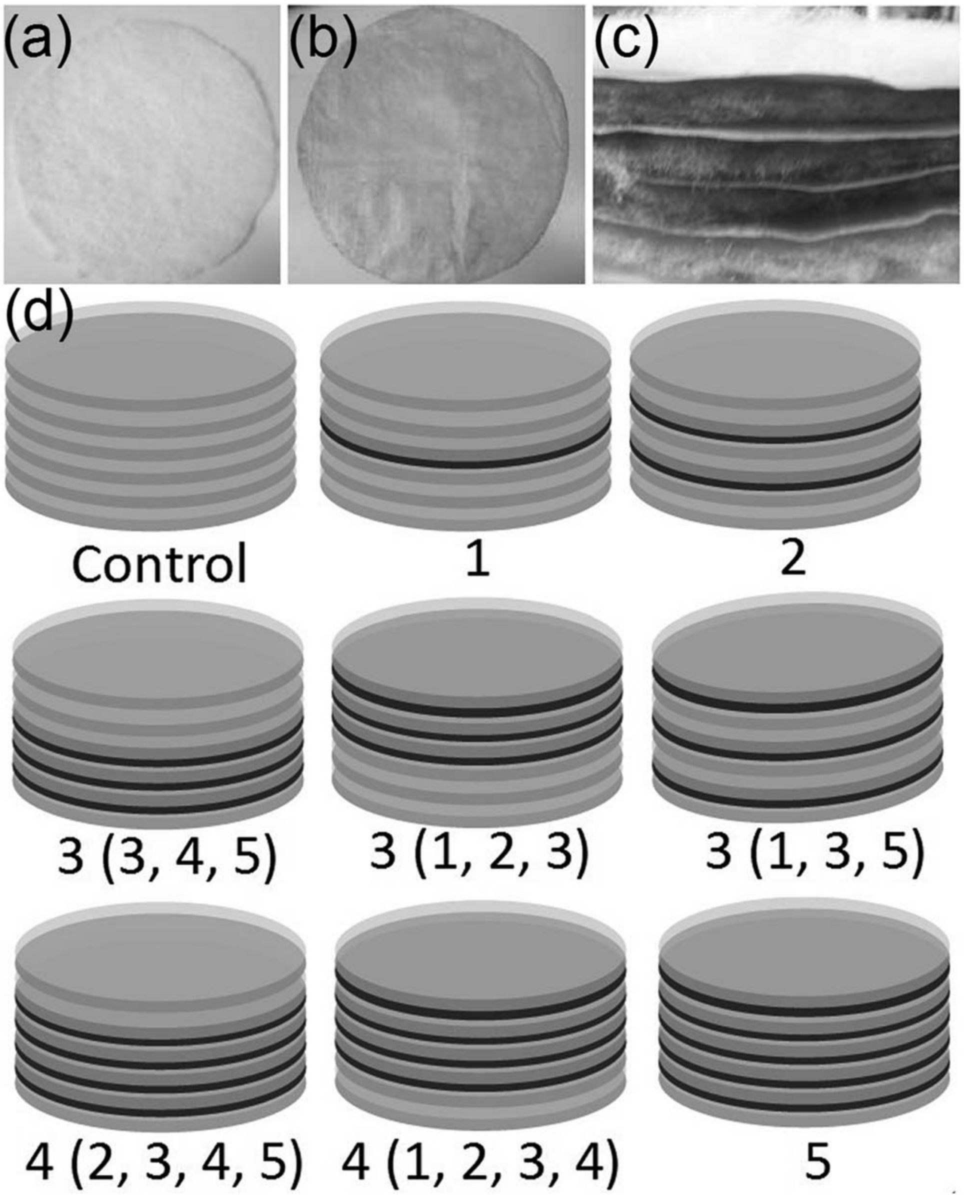

Figure 1. (a) Polyester batting, (b) Al-coated interlayer, (c) multilayer fibrous assembly, and (d) schematics of the fibrous assembly with different numbers of sandwiched interlayers.

In the measurement of the moisture vapor resistance, warm water was supplied to the water container underneath the upper surface of the hotplate. The hotplate was covered with a water impermeable but moisture permeable fabric to prevent the overflow of water. The total moisture vapor resistance of the fibrous assembly (including the surface air layer) was calculated as follows:[19]

$$R_e=\frac{A(P_{ss}-P_a)}{H_e}-R_{es} \tag{2}$$

where A is the area of the hotplate (m^2), P_{ss} is the saturated water vapor pressure at the inner side of the skin (made of a Goretex breathable fabric) on the surface of the hotplate (kPa), P_a is the water vapor pressure of the ambient air (kPa), H_e is the evaporative heat loss [W; $H_e=\lambda Q$, where λ is the heat of evaporation (J/g) and Q is the evaporative water loss (g/s)], and R_{es} is the evaporative resistance of the skin, which was precalibrated ($R_{es}=8.6$ m^2 KPa/W).

RESULTS AND DISCUSSION

SEM Photographs

Figure 3 shows the surface morphology of the interlayer before and after coating. The Al nanoparticles were well dispersed and coated onto the fibers of the interlayers. The diameter of the particles could be estimated as less than 200 nm. In the coating process, the fabric was sputtered with Al vapor; this resulted in the deposition of Al nanoparticles onto the surface of the fibers. The particles were distributed on most regions of the stem of the fibers, and the fibers were jacketed with metal particles as a

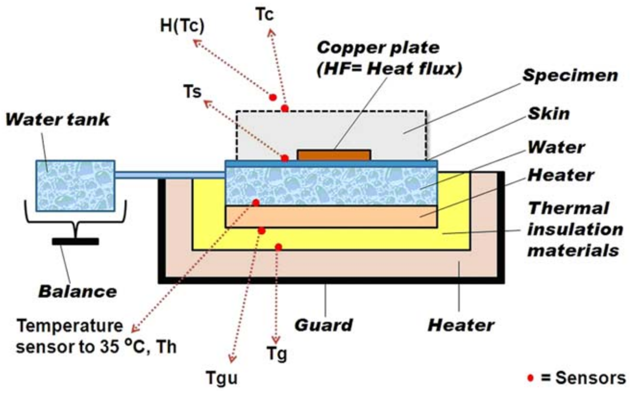

Figure 2. Schematic of the sweating guarded hotplate. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

whole. Because of the reflection and scattering effect to radiation, metal particles on the fiber surface could be expected to exhibit a high blocking ability to thermal radiation.

Thermal Radiative Conductivity

The thermal radiative conductivity of fibrous materials is greatly affected by the addition of particles such as titanium dioxide.[11] Thermal radiative conductivity of fibrous materials has been characterized by measuring the spectral transmittance percentage of the FTIR spectra.[11,13] It provides an indirect but accurate method for measuring the thermal radiative conductivity of fibrous materials. FTIR analysis showed that the spectral transmission decreased evidently after coating, as shown in Figure 4. After calculation, the Rosseland mean extinction coefficients of these two samples were 328 cm^{-1} for the uncoated sample and 420 cm^{-1} for the coated sample, respectively. The radiative thermal conductivities were then calculated as 0.0249 and 0.0194 W/m K for the uncoated and coated samples, respectively. It was obvious that the thermal resistance greatly increased after the PVD treatment. Previous work[11,18] has proven that the coating of the TiO_2 nanoparticles and Al nanoparticles granted the fabric with thermal insulation properties due to the blocking of thermal radiation. A cold-protective clothing prototype was also developed on the basis of thermal reflective interlayers.[18] According to the thermal radiative conductivity of the Al-coated nonwoven fabric in this study, this prototype will benefit the design of cold-protective clothing once it is correctly inserted in polymer battings.

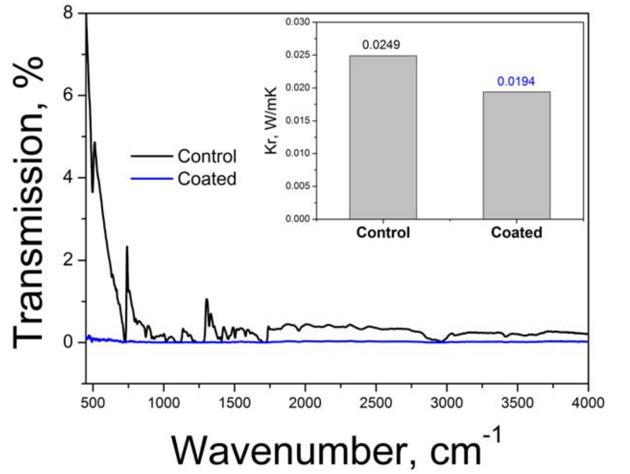

Figure 4. FTIR spectra of the control and coated nonwovens. The inset shows the calculated radiative thermal conductivity of the control and coated samples. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Thermal Resistance

Fibrous assemblies incorporate different number of interlayers [Figure 1(d)] were tested on a sweat-guarded hotplate, and Figure 5 shows the thermal resistance. The thermal resistance of the fibrous assembly without interlayers was around 0.33 m^2 K/W, and it increased sharply when the interlayers were incorporated into the assembly. This was easy to understand as the thermal radiative conductivity of the assembly was greatly reduced by when the interlayers were sandwiched. Because of the thermal radiation reflective properties of the interlayer, the whole fibrous assembly exhibited the ability to block thermal radiative conduction in cold-protective clothing.

The blocking effect to thermal radiation could be strengthened simply by the addition of more interlayers. With increasing number of the incorporated interlayers from none to three, the thermal resistance of the assembly increased almost linearly to 0.46 m^2 K/W. However, the thermal resistance slightly increased further when more than three interlayers were incorporated, as shown in Figure 5. As a whole, the thermal resistance increased with increasing number of interlayers. The thermal resistance

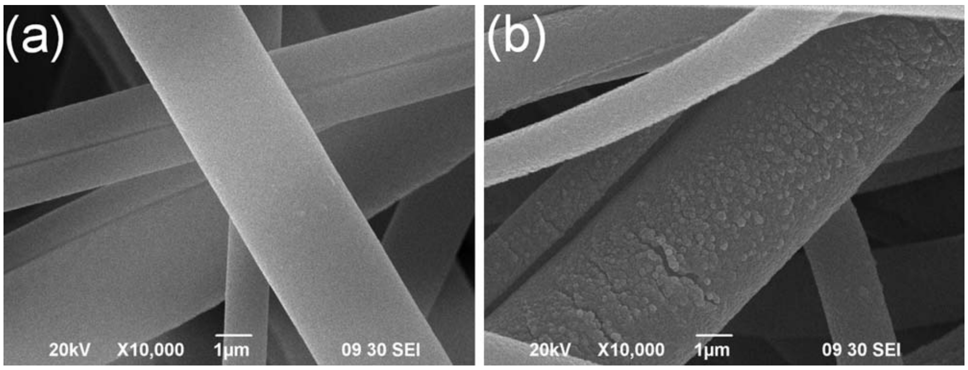

Figure 3. SEM photographs of nonwoven interlayers (a) before and (b) after coating.

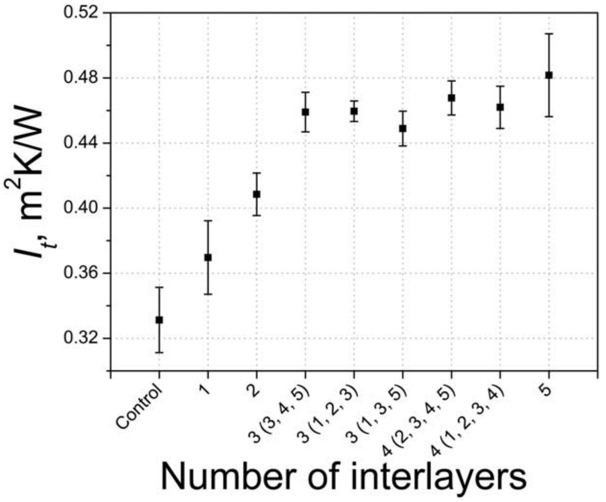

Figure 5. Thermal resistance of the fibrous assembly with multiple interlayers.

could be enhanced almost 30% by the incorporation of five interlayers. This is very important for cold-protective clothing design because the incorporation of interlayers can achieve higher thermal insulation properties without the addition of much weight to the assembly. At the same time, a thinner assembly may achieve the same thermal insulation properties as a thick assembly does under the same situation by the incorporation of interlayers. This will not only save materials in the clothing system but will also make the apparel lighter and more flexible.

When three or four interlayers are to be incorporated into the fibrous assembly, they can be located either close to or far from the skin. It is shown in Figure 5 that the thermal resistance is slightly higher when the interlayers are located close to the skin (close to the hotplate in experimental). It seems that interlayers closer to the skin in clothing can block more thermal radiation from the heating source. This suggests that the interlayers are better when they are located close to the human body in the design of cold-protective clothing.

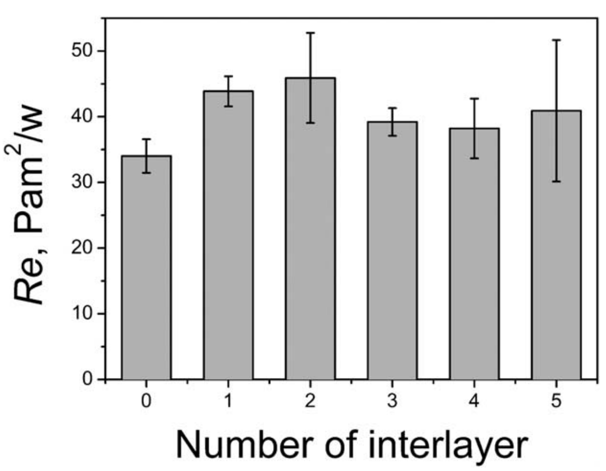

Figure 6. Water vapor resistance of the assembly with multiple interlayers.

Water Vapor Resistance

The moisture-transfer properties of the fibrous assembly is vital to the comfort sensation of clothing systems. In the thermal insulation assembly, not only should the assembly protect heat transfer from the human body to the environment, but it should also diffuse sweat from human skin to keep the body warm and comfortable.

The water vapor resistance showed a slight increase when multiple interlayers were incorporated into the fibrous assembly, as shown in Figure 6. The assembly without an interlayer incorporated showed a water vapor resistance of 35 Pa m^2/W. After the incorporation of one interlayer (either uncoated or coated), the water vapor resistance increased to around 40 Pa m^2/W. The increase in the water vapor resistance was due to the incorporation of the interlayer but not the coating of the Al nanoparticles as there was no evident difference when the incorporated interlayer was coated. It was evident that the incorporation of interlayers slightly increased the moisture resistance of the assembly by 5 Pa m^2/W. The water vapor resistance remained in the range 38–46 Pa m^2/W when more interlayers were incorporated; this suggested that the incorporation of interlayers only affected the moisture transfer to some extent.

To develop a thermal insulation fibrous assembly, it is ideal if the thermal insulation is improved while the moisture transportation of the clothing is not severely affected. The incorporation of metal-coated nonwoven interlayers has shown great potential for this purpose.

CONCLUSIONS

PVD was successfully applied to coat Al nanoparticles onto the surface of polyester nonwovens to develop a thermal insulation interlayer. SEM photographs suggested that the Al particles were distributed on a wide area of the surface of the fibers. The thermal radiative conductivity of the interlayer was decreased from 0.0249 to 0.0194 W/m K after coating. The thermal insulation of the fibrous assembly of the polyester battings was greatly improved by the incorporation of multiple reflective interlayers. The thermal resistance of the assembly increased greatly almost linearly when the number of incorporated interlayers increased from one to three, and the thermal resistance was enhanced by 30%. However, a further increase in the thermal resistance was not observed when more interlayers were sandwiched into the assembly. The moisture vapor resistance increased slightly after the incorporation of one interlayer, but no further increase was observed when more than one interlayer was incorporated. The thermal insulation assembly consisting of thermal reflective interlayers had significant advantages in cold-protective clothing as a higher thermal insulation was achieved, and the moisture transmission properties were not evidently affected.

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