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Transport Properties of Aerogel-based Nanofibrous Nonwoven Fabrics

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Abstract: In this study, nanofiber web was laminated onto nonwoven fabric and silica aerogels were applied between these two layers during laminating process. The transport properties of the obtained fabrics were examined in terms of air permeability, water vapor permeability as well as thermal performance. Especially, the effect of aerogel areal density and thermal adhesive on thermal insulation properties of layered fabrics were investigated and analyzed. It was observed that air permeability and water vapor permeability of these layered fabrics were determined by nanofiber web and nonwoven substrate respectively, aerogels present in this layered structure showed limited influence on air permeability and insignificant effect on water vapor permeability. Results also indicated that thermal resistance of layered fabrics was directly proportional to areal density of aerogel with a correlation coefficient 0.91. The use of adhesive in textile structure would significantly reduce the thermal insulation performance. A series model was considered for thermal resistance of layered fabrics, and the results showed a good agreement between theoretical model and experimental values.

Keywords: Aerogel granule, Layered fabric, Air permeability, Water vapor permeability, Thermal insulation

Introduction

Electrospun nanofiber web is an ultrathin fibrous membrane-like web of extremely fine fibers with the diameters ranging from nano scale to micro scale, which possess several amazing characteristics such as very large surface area to volume ratio, high density of pores, flexibility in surface functionalities, and superior filtration performance [1,2]. However, this ultrafine nanofiber web has very limited mechanical properties and cannot be used without other substrate such as nonwoven as a support to provide strength and durability [3]. It is widely used as a component of multilayered fabric for functional textile.

Nonwoven fabric is a manufactured sheet or web structures bonded together by entangling fibers or filaments, by various mechanical, thermal, and/or chemical processes [4]. With this unique structure, nonwoven fabrics possess plenty of functional properties such as high bulkiness and resilience, great compressional resistance, good filling properties and excellent thermal-insulating properties [5]. Thus, unlike traditional woven or knitted fabric they are more widely used in technical applications especially as thermal insulators. Their impact on thermal insulation properties is determined by the physical parameters of fibrous structures as well as the structural parameters. In order to satisfy extreme cold applications, highly advanced thermal insulating materials like silica aerogel is usually used to treat nonwoven fibrous structures to enhance thermal insulation performance. Silica aerogel exhibits superior thermal insulation performance with extremely low thermal conductivity as well as low bulk density and high specific surface area [6-8]. Nowadays, it has well been acknowledged as one of the most attracting thermal insulating materials for applications in air crafts, building constructions, and so forth. For textile use, aerogel granules are usually applied into nonwoven structure by thermal bonding or impregnation, acting as a medium to fill the interstitial space among fibers [9]. Although a lot of studies confirmed that the present aerogel in nonwoven structure would improve the thermal performance, the transport properties of aerogel based nanofibrous nonwoven fabric is not well investigated. Some researchers also stated that the application of aerogel in textile structure may cause some adverse effect on thermal insulation enhancement since the porosity of textile fabric is reduced by the adhesive, but this was not experimentally studied in existing literature.

In this paper, nanofiber web was laminated on to nonwoven fabric using thermal adhesive and silica aerogels were applied between these two layers during laminating process. The present of nanofiber web could further protect the layered fabrics against losses of silica aerogel. The layered fabrics were examined in terms of air permeability, water vapor permeability as well as thermal performance. Especially, the effect of aerogel areal density and thermal adhesive on thermal insulation properties of layered fabrics were investigated and analyzed. Moreover, a series model was considered for the thermal resistance of this layered system.

Experimental

Materials

PAN nanofiber web with areal density of 1.17 g/m^2 from CXI lab (nanocenter, TUL, Czech Republic) was used as top layer, which was produced in a vertical electrospinning setup as illustrated in Figure 1. Nonwoven substrate made by

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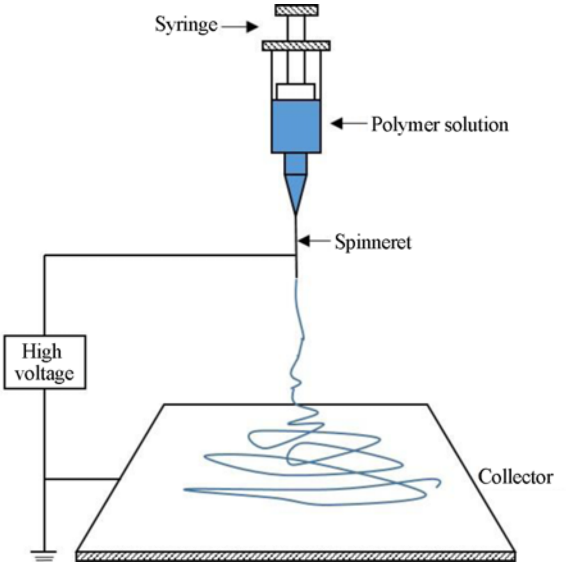

Figure 1. Schematic diagram of set up of electrospinning apparatus.

Table 1. Specifications of aerogel granules

Properties	Value range
Particle size (mm)	0.1-0.7
Pore diameter (nm)	~20
Particle density (kg/m^3)	About 120
Surface chemistry	Fully hydrophobic
Thermal conductivity (W/m·K)	0.012 (at 25 °C)

nonwoven department (TUL, Czech Republic) was used as bottom layer. The nonwoven was 100 % polyester, lightweight and highly porous needle punched. The thickness of nonwoven substrate was 1.22 mm, weight 87.02 g/m^2. Silica aerogel granules were purchased from Cabot aerogel Corp., the specifications of the aerogel granule are listed in Table 1.

Fabrication of Layered Fabrics

The layered nanofiber web/nonwoven fabrics were prepared by laminating technique, using low melting powder as thermal adhesive to provide proper bond strength. Aerogel granules were uniformly applied on nonwoven substrate during the spraying of low melting powder onto nonwoven surface, followed by the placement of nanofiber web on the top (Figure 2). The low melting powder used here was 10 g/m^2, which was determined by previous studies. The layered system was subsequently held together on a heated plate at 110 °C at a given pre-tension and continuous pressure, and the layered fabric was obtained as it cooled down.

In order to investigate the effect of aerogel areal density on thermo physiological properties, layered fabrics containing varying areal density of aerogel were developed. A layered fabric without aerogel granules was also prepared as control sample.

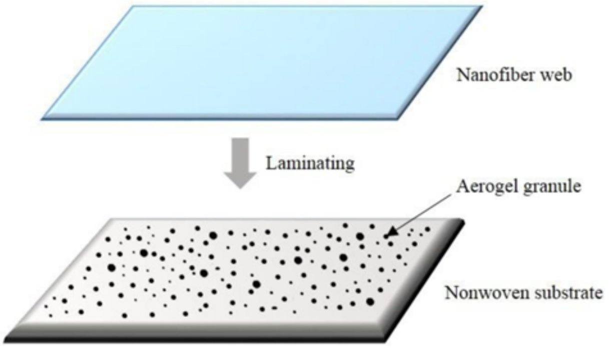

Figure 2. Structure of layered fabric.

Testing Methods

Morphology

Cross sectional morphology of layered fabrics were examined using a Dino-lite digital microscope.

Air Permeability

Air permeability is described as the rate of air flow passing perpendicularly through a known area, under a prescribed air pressure differential between the two surfaces of a material. Tests were performed according to ISO 9237, Determination of the Permeability of Fabrics to Air, using a Tex test FX-3300 air permeability tester. Two pressure drops 100 Pa and 200 Pa were chosen for the measurement of air permeability to investigate the effect of pressure gradient on air permeability.

Water Vapor Permeability

The Permetest instrument was used for the determination of relative WVP (%) and evaporation resistance Ret (m^{2}Pa/W).

Thermal Insulation Performance

Alambeta Instrument was used to measure thermal conductivity and thermal resistance, according to EN 31092 Standard. The measuring head of the Alambeta contains a copper block which is electrically heated to approximately 32 °C to simulate human skin temperature, this temperature is maintained by a thermometer connected to the regulator. The lower part of the heated block is equipped with a direct heat flow sensor which measures the thermal drop between the surfaces of a very thin, non-metallic plate using a multiple differential micro-thermocouple.

Results and Discussion

Cross Sectional Morphology

Cross sectional images of layered fabrics were taken with identical magnification. In order to observe the entire structure of the cross section, the magnification was chosen to be 50. The images are shown in Figure 3. Sample codes show the arrangement of layered fabrics. For example, code

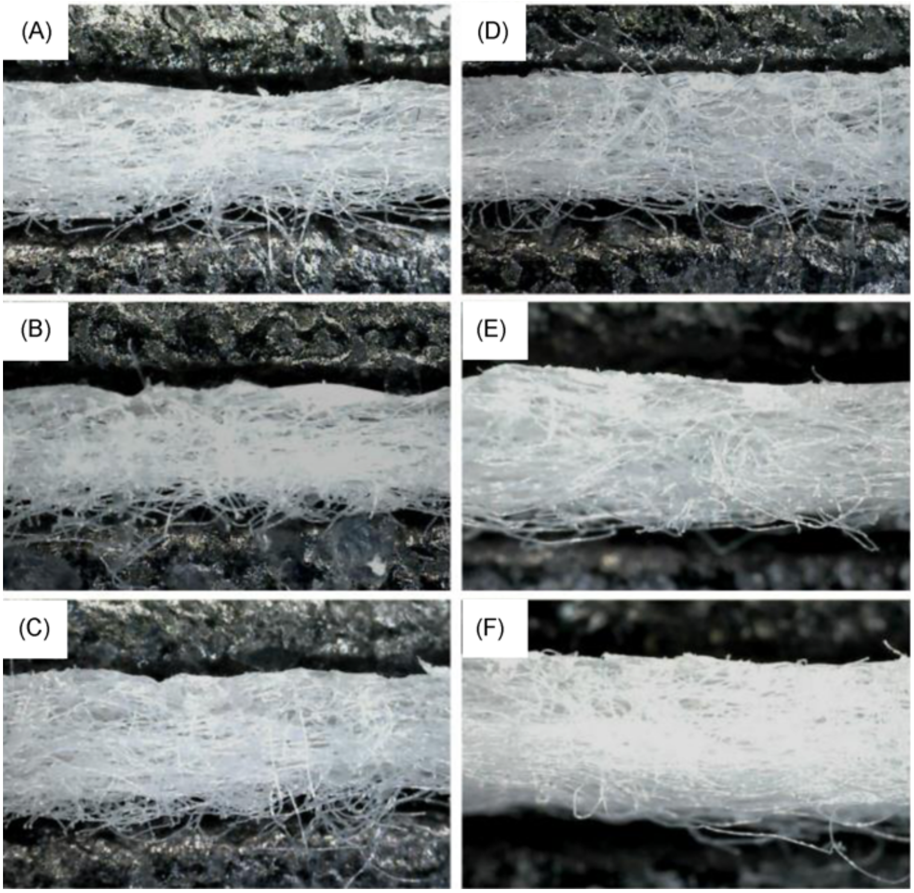

Figure 3. Cross sectional images of different layered fabrics (50×); (A) NTS, (B) NA_1S, (C) NA_2S, (D) NA_3S, (E) NA_4S, and (F) NA_5S.

NTS refers to layered fabric composed of nonwoven substrate (S) and nanofiber web (N) laminated by thermal adhesive. For codes NA_1S, NA_2S, NA_3S, NA_4S and NA_5S, A_1, A_2, A_3, A_4 and A_5 refer to aerogel granules of varying areal density, 1.25 g/m^2, 2.50 g/m^2, 3.75 g/m^2, 5.00 g/m^2 and 6.25 g/m^2 respectively.

It was observed that nanofiber web was well laminated onto the upper surface of nonwoven substrate and granules were deposited on the nonwoven substrate under the nanofiber web. Remarkably, significant increase in thickness was observed for sample NA_4S and NA_5S in comparison with other samples.

Air Permeability of Layered Fabrics

The results of air permeability of different fabric systems under different pressure gradients are given in Table 2. Air permeability of nonwoven substrate was found to sharply decrease when a nanofiber web was laminated onto its surface. This is mainly because nanofiber web has a large number of microscopic pores and very low porosity, which

Table 2. Air permeability of samples under different pressure gradients

Samples code	Thickness (mm)	100 Pa (mm/s)	Slope (mm/Pa·s)	200 Pa (mm/s)	Slope (mm/Pa·s)
S	1.22	2160±54.57	21.60	3743±189.15	18.71
N	0.04	32.22±0.88	0.32	73.48±1.09	0.37
NTS	1.25	32.59±3.01	0.33	61.01±5.93	0.31
NA_1S	1.39	39.55±2.02	0.40	84.52±3.25	0.43
NA_2S	1.41	33.08±2.73	0.33	67.28±4.73	0.34
NA_3S	1.42	30.58±2.10	0.31	54.97±5.12	0.27
NA_4S	1.48	36.71±2.46	0.37	74.77±3.73	0.37
NA_5S	1.53	41.28±1.13	0.41	84.21±1.90	0.42

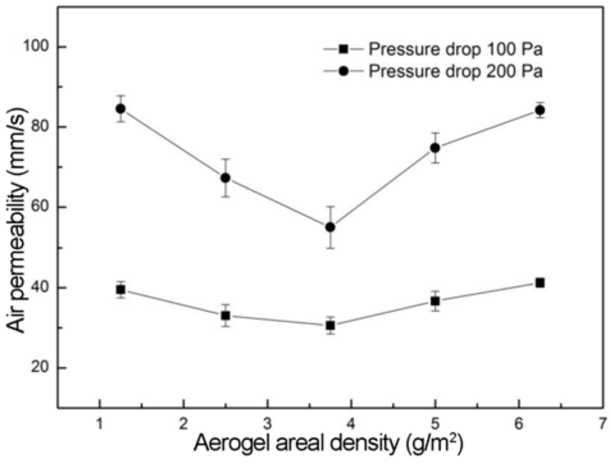

Figure 4. Effect of aerogel areal density on air permeability.

covers the open pores of nonwoven substrate and prevents the air flow go through [10]. Moreover, the thermal adhesive would reduce the pores of nonwoven substrate in some degree, this may also account for the decrease in air permeability. Aerogel showed limited influence on air permeability of layered fabrics. For a specified fabric, air permeability had a strong correlation with air pressure gradient, and very small difference can be observed between two slopes under different pressure gradients. This indicated that the rate of air flow was directly proportional to the pressure gradient, which consisted well with Darcy's law.

The effect of aerogel areal density on air permeability of layered fabrics under different pressure gradients are illustrated in Figure 4. Air permeability directly depends on pore size and porosity, since the aerogel granule can be approximately considered as air-proof material due to its nano scale pores, the air permeability of layered fabrics tended to decrease as the increase of aerogel. It was also found that there was a critical value in aerogel areal density, 3.75 g/m^2 in this study, above which the air permeability showed an increasing trend with the increasing of aerogel. The reason could be that there may appear more air gap between nanofiber web and nonwoven substrate due to the much bigger size of aerogel granules compared to the thickness of nanofiber web, the enlarged air gap in this layered system will allow more air to flow through. This was also indicated by the significant increase in fabric thickness (sample NA$_4$S and NA$_5$S).

Water Vapor Transmission of Layered Fabrics

Water Vapor Permeability is a measure of the passage of water vapor through the material. It depends on the water vapor resistance Ret which indicates the amount of resistance against the transport of water through the fabric structure. The higher the relative water vapor permeability (RWVP), the lower the Ret, and the better the thermal comfort of a fabric. The water vapor transmission of samples are shown in Table 3. Although the nanofiber web exhibited superior water vapor transmission properties, the water vapor permeability of layered fabrics were determined by nonwoven substrate. Aerogel showed insignificant effect on water vapor permeability of this layered fabrics.

Table 3. Water vapor transmission of samples

Samples code	Relative water vapor permeability (%)	Water vapor resistance (Pa m^2/W)
S	66.30±0.21	4.53±0.16
N	96.43±2.96	0.50±0.24
NTS	69.05±0.60	4.57±0.14
NA$_1$S	65.32±1.30	4.48±0.27
NA$_2$S	65.20±1.19	4.33±0.15
NA$_3$S	67.55±1.78	4.29±0.29
NA$_4$S	62.77±1.25	4.48±0.24
NA$_5$S	63.93±1.27	4.38±0.21

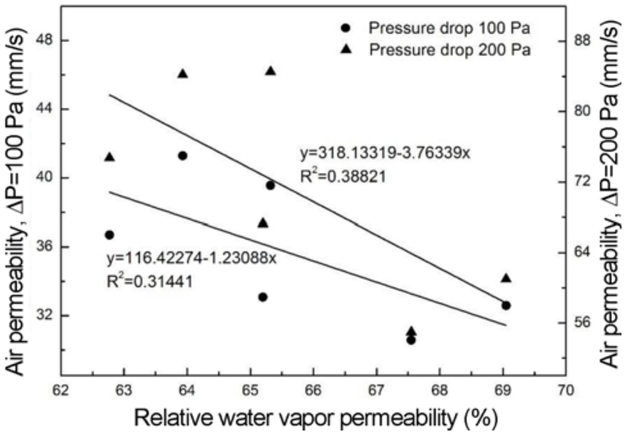

Figure 5. Correlation between relative water vapor permeability and air permeability.

Air permeability and water vapor transmission rate are dependent mainly on the fabric geometrical parameters, namely, thickness and porosity [11,12]. In this study, the correlation between water vapor permeability and air permeability of layered fabrics were investigated as shown in Figure 5. Results showed insignificant proportional correlation between air permeability and relative water vapor permeability, with correlation coefficient 0.31 and 0.39 respectively for pressure drop 100 Pa and 200 Pa.

Thermal Performance of Layered Fabrics

Thermal conductivity, k (W/m·K), measures the rate at which heat is transferred through unit area of the fabric across unit thickness under a specified temperature gradient. Thermal resistance, R (m^2·K/W), expresses the ability of material to prevent heat flow through the thickness over unit surface area. Thermal resistance is related to thermal conductivity and the fabric thickness *L* (m):

Table 4. Thermal performance of samples without aerogel

Samples	Thermal conductivity 10^{-3} W/m·K	Thermal resistance 10^{-3} m^2·K/W
Nanofiber web (N)	-	0.90±0.04
Nonwoven substrate (S)	34.63±0.32	35.40±1.61
Layered fabric (NTS)	36.98±0.97	31.94±0.80

$$R = \frac{L}{k}$$

Amount of stagnant air within the fabric and fabric density are the most important factors governing thermal insulation of textiles. The higher the thermal resistance, the lower in the heat loss [4].

The measured thermal properties of nonwoven substrate, nanofiber web and the integrated fabric of these two materials are given in Table 4. An obvious difference was observed in thermal resistance of samples NTS and S, this is attributed to the thermal adhesive which may block the open pores throughout the nonwoven substrate and reduce the trapped air in this layered fabric. Since the thermal performance of high porous textile is determined by the stagnant air present in textile structure, more heat flowed through the layered fabric NTS due to its decreased air volume fraction.

For multilayered fabric systems, the layers are considered to set as a series of thermal resistance, according to electrical analogy with conduction heat transfer, the following equation can be used for calculating the total thermal resistance [13]

$$R_t = \Sigma R_i$$

However, the use of thermal adhesive in this layered structure will improve thermal conductivity as mentioned above, this will cause some loss in total thermal resistance since the fabric thickness is not proportionally decreased. This loss in thermal resistance, ΔR, can be obtained by

$$\Delta R = R_S + R_N - R_{NTS}$$

In this study, the loss in thermal resistance is 4.36×10^{-3} m^2·K/W, which accounts for 13.65 % of the total thermal resistance. This indicated that the use of adhesive in textile structure has significant effect on the final thermal insulation performance, which is noteworthy for the development of textile composites as thermal insulators.

The effect of aerogel areal density on thermal conductivity and thermal resistance of layered fabric are presented in Figure 6. The aerogel-based fabrics showed lower thermal conductivity and much higher thermal resistance in comparison with sample NTS, indicating that the present of aerogel had significant effect on improving thermal insulation performance. For silica aerogel granules, more than 93 % of their volume is occupied by air, so the layered fabrics would get more trapped air as the aerogel granules were applied between these two layers. It was observed that the thermal resistance of layered fabrics was directly proportional to the areal density of aerogel since the increment of trapped air in this layered fabric was determined by the amount of aerogel, the correlation coefficient between thermal resistance and aerogel areal density was about 0.91. However, this value was only 0.75 for thermal conductivity.

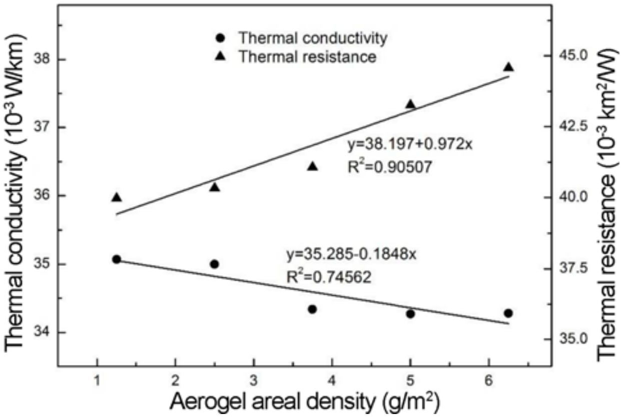

Figure 6. Effect of aerogel areal density on thermal insulation performance.

Series Model for Thermal Resistance

The decrease of thermal resistance induced by adhesive is believed to strongly depend on the amount of adhesive and its distribution. In this study, the amount of thermal adhesive in each layered fabric is totally identical, if the adhesive is assumed to uniformly spread only in the very thin middle layer consisted by aerogel granules and air, then the loss of total thermal resistance in each layered system can be approximately considered to be the same. Therefore, the total thermal resistance of layered fabric with aerogel can be calculated by

$$R_t \approx R_S + R_M + R_N - \Delta R$$

where R_M is thermal resistance of the middle layer.

The thermal performance of this middle layer is determined by aerogel granules and the air space in this structure. Assuming it is a homogeneous layer without aerogel loss from this layer, then the effective thermal conductivity of this layer can be obtained by using

$$\frac{k_{eff}}{k_0} = (1-\phi) + \phi\left(\frac{k_a}{k_0}\right)$$

$$\phi = \frac{\rho_s}{\rho_V \cdot L}$$

where k_0 is the thermal conductivity of stagnant air (0.024 W/K·m at 25 °C), k_a is the thermal conductivity of aerogel granules, ϕ is the volume fraction of aerogel granules, ρ_s is

Table 5. Comparison of theoretical and experimental values of thermal resistance

Samples code	From experiment (R) 10^{-3} m^2·K/W	From series model (R') 10^{-3} m^2·K/W	Error (%) $\frac{\lvert R-R'\rvert}{R}\times 100$
NA_1S	39.97	38.00	4.93
NA_2S	40.33	39.07	3.12
NA_3S	41.07	39.74	3.23
NA_4S	43.26	42.48	1.80
NA_5S	44.58	44.80	0.50

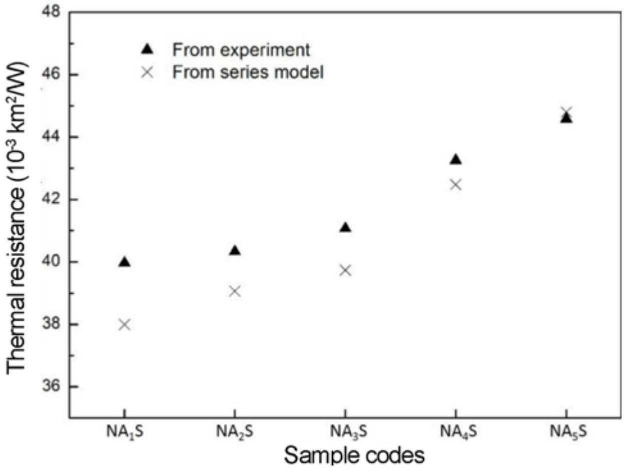

Figure 7. Theoretical and experimental values of thermal resistance.

the areal density of aerogel in layered fabric (kg/m^2), ρ_V is the bulk density of aerogel (kg/m^3) and L is the thickness of the middle layer.

Thus, the total thermal resistance of layered fabrics can be expressed as

$$R_t = R_S + R_N + \frac{\rho_V L^2}{k_0(\rho_V L - \rho_S) + k_a \rho_s} - \Delta R$$

Thermal resistance values obtained from experiment and series model are shown in Table 5 and Figure 7. Results showed a good agreement between thermal resistance from experiment and those of series model for the layered fabrics. Average error was about 2.07 %. The error showed a decreasing trend with the increasing of aerogel, the reason could be that the series model is based on the assumption that the thin middle layer between nanofiber web and nonwoven substrate is an uniformly continuous layer, so if aerogel is too less to form a continuous layer, the thermal resistance will be underestimated by theoretical model since the thickness of the middle layer is decreased.

Conclusion

Nanofiber web was laminated on to nonwoven fabric and silica aerogels were applied between these two layers during laminating process. Transport properties of the resultant fabrics were investigated. It was found that air permeability of these layered fabrics was determined by nanofiber web, aerogels present in layered structure had limited influence on air permeability. A critical value of 3.75 g/m^2 in aerogel areal density was determined, above which the air permeability showed an increasing trend with aerogel due to the enlarged air gap between nanofiber web and nonwoven substrate. It was observed that the water vapor permeability of layered fabric was determined by nonwoven substrate, aerogel had insignificant effect on water vapor permeability. Results also showed that thermal resistance of layered fabrics was directly proportional to the areal density of aerogel, the correlation coefficient was about 0.91. Remarkably, the loss in thermal resistance induced by adhesive was 4.36×10^{-3} m^2·K/W, accounting for 13.65 % of the total thermal resistance. This indicated that the use of adhesive in textile structure could have significant effect on thermal insulation enhancement. The measured thermal resistance values of layered fabrics showed a good agreement with those calculated from theoretical model.

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