Aerogel Based High Performance Thermal Insulation Materials

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Abstract. In this paper, the thermal properties of polyester/polyethylene nonwoven thermal wraps of varying thicknesses treated with aerogel were analyzed and compared. The microscopic images were taken by confocal microscope and image analysis to compare the physical structure of the aerogel treated nonwoven fabrics. Thermal conductivity and thermal resistance were measured using FOX heat flow meter instrument. The water vapor resistance and thermal resistance were measured using sweating guarded hot plate (SGHP). These tests were conducted to understand and to compare the thermal properties and water vapor resistance of aerogel treated nonwoven fabrics. The results of the experiments were statistically analyzed and showed that the fabric density and the aerogel present in the fabric have a significant effect on thermal properties and water vapor resistance of the aerogel treated nonwoven fabrics.

Keywords: Aerogel, Thermal Insulation, Thermal Conductivity, Nonwoven

1. Introduction
Silica aerogels consist of more than 96 percent air and remaining is a matrix of silicon dioxide. It is popular due to its properties such as low thermal conductivity (0.01 W/m.K), high porosity (99%), high optical transmission (99%) in the visible region, high specific surface area (1000 m²/g), low dielectric constant (1.0–2.0), low refractive index (1.05), and low sound velocity (100 m/s) [1]. Due to these features, they are used in super thermal insulation, acoustic insulation, radiation detectors, low dielectric constant aerogel films in ultra-large-scale integrated circuits, super hydrophobic aerogels for oil spill cleanup, window applications, catalysts, Internal Confinement Fusion (ICF) targets in thermonuclear fusion reactions, cosmic dust capture and waste management (gas absorption, radioactive waste confinement) etc.,[2]. In Textiles and clothing, it is used to preserve body heat loss in the cold weather where thermal transmittance properties of fabric are important. Thermal transmittance is the rate of unidirectional heat transfer per unit area in the steady state, between parallel planes, per unit difference of temperature of the plates (W/m²K). Factors affecting the thermal properties are thermal conductivity of the fibre, air contained within the fabric, thickness of the fabric, bulk density of the fabric (includes the number, size and distribution of the air spaces within the fabric), heat loss by conduction/convection/radiation from skin to fabric, heat loss by evaporation of water.
from skin or fabric, heat gain due to water absorption by fabric, external environment likes temperature, relative humidity and movement of surrounding air. Clothing comfort includes three main considerations like thermo-physiological, sensorial and psychological comfort [3, 4]. Thermo-physiological comfort is an important parameter of clothes. The factors affect that thermophysiological comfort are heat exchange within clothing, air permeability, transfer and evaporation of moisture. Due to metabolic processes, human body produces heat continuously. Heat generated by body is directly proportion to greater physical exertion. Because of sweat, the body begins to feel cool through the evaporation of the sweat on the skin [5]. Hence, the clothing should ensure high moisture transmission to facilitate cooling due to evaporation of sweat. Water vapour permeability is the ability to transmit vapour from the body. The sweat should be removed from the skin surface to the surface of fabric of the next-to-skin clothing for greater comfort. After the body has stopped sweating, the textile fabric should release the vapour held to the atmosphere in order to reduce the humidity on the surface of the skin [6]. The literature review reveals a lacunae in study of aerogel’s application to thermal clothing. This study discusses the influence of aerogel on the thermal conductivity, thermal resistance and thermal transmittance depending on varying fabric densities of nonwoven fabrics treated with aerogel. The water vapour resistance and thermal resistance were also measured to study the effect of nonwoven layer densities on heat transfer characteristics.

2. Experimental method

2.1 Materials
In this study, polyester and polyethylene nonwoven thermal wraps, treated with amorphous silica aerogel, were used. The thermal wraps were chosen in three different thicknesses shown in Table 1. The properties of amorphous silica aerogel is shown in Table 2.

| Table 1. Sample description |
|-----------------------------|
| Sample Description | Thickness (mm) | Weight (g/m²) | Density (kg/m³) |
|------------------------|----------------|---------------|-----------------|
| Silica aerogel treated nonwoven fabrics (Polyester + Polyethylene) | 3.424 | 272.56 | 79.66 |
| nonwoven fabrics | 6.212 | 499.46 | 80.42 |
| (Polyester + Polyethylene) | 6.608 | 440.7 | 66.73 |

| Table 2. Properties of Silica Aerogel [7] |
|-----------------------------|
| Properties | Value range |
|------------------------|---------------|
| Particle size range | 0.1–0.7mm |
| Pore diameter | 2–20 nm |
| Particle density | 120–140 kg/m³ |
| Surface chemistry | Fully hydrophobic |
| Thermal conductivity | 0.012W/mK at 25°C |

2.2 Methods
The thickness of the samples was measured using UNI-Thickness meter. Sweating guarded Hot Plate (SGHP) and Permetest was used to measure the water vapor resistance and thermal resistance of the samples. The fabrics were cut to dimensions of 10x10cm and the weight of the fabric was measured. All experiments were carried out in standard atmospheric conditions of about 20°±2°C and 65±2% relative humidity.

2.2.1 Microscopic analysis. The nonwoven fabric samples of three different thickness treated with aerogel were characterised using Image analysis ((with macro zoom objective and CCD camera) and confocal microscope (OLYMUPUS Confocal Scanning IR Laser Microscope, LEXT LS3000-IR).
Image analysis was done to compare the physical structures of the fabrics on microscopic scale to determine if any difference were noticeable that could explain test results.

2.2.2 Thermal transmittance measuring device. FOX heat flow meter instruments were designed for accurate thermal conductivity and thermal resistance measurements of thermal insulation materials according to the ASTM C518 and ISO 8301 standards. The FOX heat flow meter instruments also can be successfully used for testing, thermal transmittance of textile materials at conditions very much the same as in design suggested in the ASTM D1518 – “Standard test method for thermal transmittance of textile materials” – except sizes of the chamber and plate, and type of the heat flow source. After turning on the FOX instrument and re-zeroing its plates a 12”-wide (~304 mm) piece of the textile material was placed on the lower plate. Temperature of the set point was set at 10°C for upper plate and 35°C (~ human skin temperature) for the lower plate. Thermal equilibrium criteria was set as 12 and 3 blocks of all tests.

2.2.3 Water Vapour and Thermal Resistance measuring instrument. Thermal resistance Rct (m² K/W) is a quantity specific to textile materials or composites, which determines the dry heat flux across a given area in response to a steady applied temperature gradient, while water vapour resistance Ret (m² K/W) is a quantity specific for textile materials or composites, which determines the ‘latent’ evaporative heat flux across a given area in response to a steady applied water vapor gradient [8]. These features were measured by SDL M259B Sweating guarded hot plate apparatus following standard ISO 11092 [9], consisting of a measuring unit with temperature and water supply control, thermal guard with temperature control and the test cabinet into which is built the measuring unit that is thermal guarded, and in which the ambient air temperature and humidity are controlled according to ISO 11092. Besides, a humidity control device automatically controls the relative humidity within the cabinet and a cooling device automatically cooled the air temperature when needed [9]. The specimen to be tested was placed on an electrically heated plate with conditioned air ducted to flow across and parallel to its upper surface [9,10]. For determination of thermal resistance Rct, the heat flux through the test specimen was measured after steady-state conditions have been reached. Rct for a material was determined by subtracting the thermal resistance of the once the apparatus reached the steady condition, test time was 30 minutes.

Water vapor permeability of materials was measured with a guarded hot plate by saturating the plate surface with water. The power required to maintain the surface at a given temperature was related to the rate at which water evaporates from the surface of the plate and diffuses through the material. The thermal resistance of the material to convective heat transfer must be known before it was possible to extract the vapor permeability coefficient. Woodcock [11] developed a moisture vapor permeability index, known as \( i_m \), which serves as a very convenient relative measure of the moisture vapor permeability of materials.

\[
\frac{i_m}{\text{(Q)} \frac{R_{\text{total}}}{A} - (T_{\text{plate}} - T_{\text{air}})} = \frac{S(p_s - \phi p_a)}{p_s}
\]

(1)

Where \( i_m \) = Moisture vapor permeability index; \( R_{\text{total}} \) = Thermal resistivity of the fabric plus the boundary air layer, clo; \( A \) = Surface area of guarded plate measurement area, m²; \( T_{\text{plate}} \) = Temperature of the saturated plate surface, °C; \( T_{\text{air}} \) = Temperature of the ambient air, °C; \( Q \) = Power required to maintain a constant saturated plate surface temperature, watts; \( S \) = Lewis relation between evaporative mass transfer coefficient and convective heat transfer coefficient, 2.2 °C/mmHg; \( p_s \) = Saturated water vapor pressure at the plate surface, mmHg; \( p_a \) = Saturated water vapor pressure of the ambient air, mmHg and \( \phi \) = Relative humidity of ambient air, fractional relative humidity (not %).

The \( i_m \) value is a relative measure of the permeability of the material to the passage of water vapor. The \( i_m \) index should vary between 0 (for completely impermeable materials), and 1 (for completely
permeable materials). In practice, the value of 1 as an upper limit is not approached until the wind speed over the plate becomes great enough to minimize the contribution of radiative heat transfer [12]. The moisture vapor permeability index, \( i_m \), may be combined with the total dry thermal resistance, \( R_{total} \), to yield a quantity which takes into account both convective and evaporative heat transfer. In this report \( R_{total} \) is given in clo units, so the term becomes \( i_m / \text{clo} \). The term \( i_m / \text{clo} \) provides a good ranking measure between materials if one is interested in materials which minimize the potential for heat stress [12].

3. Results and discussion

The results were evaluated and studied for thermal resistance, thermal conductivity, thermal effusivity, water vapor resistance and dry thermal resistance of the aerogel treated nonwoven fabrics. It was examined by one-way analysis of variance (ANOVA) with 95% confidence level. A significant difference (\( p<0.05 \)) has been observed in the thermal resistance, thermal conductivity, thermal effusivity, water vapour permeability and dry thermal resistance properties for the three different thickness of fabrics treated with silica aerogel. It was found that there was an insignificant difference between the temperatures on thermal properties and between the instruments (SGHP & permetest) for water vapour resistance.

3.1 Microscopic analysis

![Microscopic images taken using (a) Image analysis and (b) confocal microscope for aerogel treated nonwoven fabric.](image)

Figure 1. Microscopic images taken using (a) Image analysis and (b) confocal microscope for aerogel treated nonwoven fabric.

Image analysis was done on microscopic scale for the cross-section area of the three fabrics with different magnifications. The physical structure confirmed to be different for three fabrics due to different thickness shown in Figure 1. It was observed that sample 2 has higher fabric density of 80.4 kg/m\(^3\) as compared to other samples. The aerogel deposition in the fabric between the fibers was also observed.
3.2 Fabric density
Fabric density is the factor of weight and thickness. To obtain an indication of the effect of fabric density on thermal properties, nonwoven fabrics with comparable densities in different thicknesses and their corresponding weights were measured for aerogel treated nonwoven fabrics shown in Table 1 (a, b and c). The density difference of samples may be attributed to the fabric structure, thickness and also the percentage of aerogel particles present in the fiber.

3.3 Influence of Water Vapour Resistance
The Water Vapor Permeability (WVP) depends on the water vapor resistance which indicates the amount of resistance against the transport of water through the fabric structure. To maintain the degree of comfort of the user, the amount of water present in a fabric must be minimum. The analysis of variance (ANOVA) results show that the effect of fabric density on the water vapor resistance measured using SGHP had significant difference ($p=0.001$). Figure 2 shows that the water vapor resistance, measured using Sweating guarded hot plate, and it can be seen that the fabric which has the densities 80.4 and 79.6 kg/m$^3$ is higher than the 66.7 kg/m$^3$ density. The water vapor permeability of the fabric may be attributed to the structure (open or closed cell structure) of the fabric and also the percentage of aerogel particles present in the fiber. This behavior can be explained by the moisture vapor transmission mechanism where vapor transmits through a textile layer by two processes, namely, diffusion and sorption-desorption. Water vapor diffuses through a textile structure in two ways, simple diffusion through the air spaces between the fibers and along the fiber itself.

![Figure 2. Water vapor resistance measured in Sweating guarded hotplate (SGHP)](image)

3.4 Thermal Resistance ($R_c$) measured from SGHP
Thermal resistance depends on the thickness and thermal conductivity of the fabrics. The analysis of variance (ANOVA) of dry resistance show that the effect of fabric density on the thermal resistance is significant ($p=0.001$). The aerogel treated nonwoven fabrics have different $R_c$ values depending on the fabric densities (Figure 3). The difference in $R_c$ values was due to the thermal conductivity of the fiber substance, which was about 0.14 (Wm$^{-1}$K$^{-1}$) for polyester and 0.34(Wm$^{-1}$K$^{-1}$) for polyethylene [16]. The thermal conductivity of aerogel particles present in the fibers was about 0.02 (Wm$^{-1}$K$^{-1}$). In any case, as the presence of fibers in these kinds of materials is very small compared to the air entrapped in the nonwoven fabrics, the fiber substance and aerogel particles used has influence on $R_c$ and $R_{et}$.
Dry thermal resistance is calculated by measuring the temperature difference between the surface of the heated measurement area of the guarded hot plate and the temperature of the "ambient air away from the plate. It is this temperature difference which drives heat transfer through the fabric. The equation used for calculating the thermal resistance [12]:

\[ R_{\text{total}} = \frac{A(T_{\text{plate}} - T_{\text{air}})}{Q} \]  

Where \( R_{\text{total}} \) = Thermal resistivity of material plus the boundary air layer, clo (clo is a unit of thermal resistance and is equal to 0.155 °C-m2/watt); \( A \) = Surface area of guarded plate measurement area, m2; \( T_{\text{plate}} \) = Temperature of the plate surface, °C; \( T_{\text{air}} \) = Temperature of the ambient air, °C and \( Q \) = Power required to maintain a constant plate surface temperature, watts.

Figure 4 shows the direct proportionality between thickness and thermal resistance. As the thickness of the fabric increases the thermal resistance also increases. The correlation of thermal resistance and thickness also shows higher value of about \( R^2 = 0.99 \). Even the slight difference in
thickness changes the thermal resistance value. The analysis of variance (ANOVA) results show that effect of thickness on the thermal resistance is significant (p=0.005).

3.5 Comparative Analysis of Sweating Guarded Hot Plate (SGHP) and Permetest
The water vapour resistance and permetest for the aerogel treated nonwoven fabrics for three different densities are shown in Figure 5. The water vapour resistance were measured using two devices and the mean value of five separate measurements was used. The water vapour resistance measured using SGHP showed an increase for the fabric densities 80.4 and 79.6 kg/m$^3$ and shows a decrease for the fabric density 66.7 kg/m$^3$ and in the water vapor resistance measured using permetest shows that the fabric densities have the same trend for the fabric densities from 66.7 to 80.4 kg/m$^3$. The statistical analysis shows that the Sweating guarded hot plate and Permetest has an insignificant difference on water vapor resistance (p=0.22). The correlation ($R^2=0.83$) between the two test methods for materials are good. This is due to the difference in the water vapor resistance of the fabric densities 79.4 and 80.4 kg/m$^3$. This may be attributed to properties which depend on water vapor diffusion through air passages in the structure.

![Correlation between SGHP and Permetest for water vapor resistance](image)

**Figure 5.** Correlation between SGHP and Permetest for water vapor resistance

3.6 Thermal transmittance of aerogel embedded nonwoven fabrics
Thermal transmittance (U-value) is the rate of transfer of heat (in watts) through one square meter of a structure divided by the difference in temperature across the structure. It is expressed in watts per meters squared Kelvin, or W/m$^2$K. Insulation is inversely proportional to thermal transmittance.

| Thickness (mm) | Fabric density (kg/m$^3$) | U1 (W/m$^2$K) | U2 (W/m$^2$K) | $\lambda$ (W/mK) | $R$ (m$^2$K/W) | $R'$ (mK/W) | Intrinsic clo | Specific Clo |
|---------------|--------------------------|---------------|---------------|----------------|----------------|-------------|--------------|--------------|
| 3.424         | 79.66                    | 2.898         | 5.126         | 0.018          | 0.195          | 55.743      | 0.222        | 63.380       |
| 6.212         | 80.42                    | 2.119         | 3.106         | 0.019          | 0.322          | 51.923      | 0.366        | 59.036       |
| 6.608         | 66.73                    | 2.151         | 3.174         | 0.021          | 0.312          | 47.734      | 0.358        | 54.274       |

*U1 – Combined thermal transmittance, U2- Intrinsic thermal transmittance, $\lambda$ – Thermal conductivity, R – Intrinsic thermal resistance, R’ – Intrinsic thermal resititivity

The combined thermal transmittance or combined thermal conductance of the specimen plus the air (Eq. 3 of the ASTM D1518) can be calculated from the lower plates result (lower plate thermal conductivity) multiplied by 10.
\[ U_1 = \lambda_L \times 10 \ [\text{W/(m}^2\text{K})] \]  

(3)

i.e. divided by the 0.1m (100mm) thickness. It equals the heat flux [W/m²] through the specimen, measured by the lower heat flow meter, divided by the temperature difference \( \Delta T \) of 25°C. The bare plate transmittance \( U_{bp} \) was calculated the same way after running the test without sample. Example for FOX 314 \( U_{bp} \approx 6.67 \ [\text{W/(m}^2\text{K})] \). The intrinsic transmittance \( U_2 \) of the fabric alone can be calculated using Eq.4 of the ASTM D1518:

\[ U_2 = \frac{U_{bp} \times U_i}{U_{bp} - U_i} \ [\text{W/(m}^2\text{K})] \]  

(4)

The thermal transmittance of a fabric or batting is of considerable importance in determining its suitability for use in fabricating cold weather protective gear and clothing. The thermal interchange between man and his environment is, however, an extremely complicated subject which involves many factors in addition to the equilibrium insulation values of fabrics and battings. Therefore, measured thermal transmittance coefficients can only indicate relative merit of a material. In order to calculate U-Values it is important to first find thermal conductivity, thermal resistance and thermal transmittance which is shown in Table 3. Thermal transmittance, commonly known as the U-value, is a measure of the rate of heat loss of a component. It is expressed as watts per square metre, per degree Kelvin, W/m²K. With the increase in thickness, the combined thermal resistance decreases. The U-value is calculated from the reciprocal of the combined thermal resistances of the materials which is attributed to the element, air spaces and surfaces, which also considered as the effect of thermal bridges and air gaps of the aerogel embedded nonwoven structure. The combined thermal transmittance is shown in Figure 6 (a) and (b).

4. Conclusion

The Polyester/Polyethylene nonwoven thermal wraps treated with silica aerogel of three different thickness were measured. The thermal conductivity, resistance and transmittance of the fabric was directly proportional to fabric density. This may be attributed to decrease in heat losses due to space insulated and the structure of the fabric. Water vapor permeability is influenced by fabric structure, number of gaps and their orientation within the fabric. Water vapor resistance showed the influence of thermal resistance (\( R_{ct} \)) of the fabric which depends on fabric boundary air layer which in turn increased with the increase in fabric thickness. Also, the thermal resistance (\( R_{ct} \)) of the fabric showed a different trend when plotted with the fabric densities which was due to the weight and thickness of the fabric. The comparative analysis showed a significant difference on the thermal properties. Also, the comparative analysis was done for the SGHP and permetest instruments which showed an insignificant difference. There was a good correlation between the values of water vapor resistance from both the instruments. So, it can be concluded that the fabric density and the aerogel present in the fabric have a

Figure 6. (a) Combined thermal transmittance and (b) Intrinsic thermal transmittance
significant effect on thermal properties and water vapor resistance of the aerogel treated nonwoven fabrics.

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