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Aerogel Based Nanoporous Fibrous Materials for Thermal Insulation

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Abstract: In this research work, the thermo physiological properties of polyester/polyethylene nonwoven composite wraps of varying thicknesses impregnated with aerogel were studied and compared. The SEM images were also taken to compare the physical configuaration of the aerogel based fibrous composites. Specific thermal properties like thermal conductivity, thermal resistance, thermal diffusivity and thermal absorptivity were measured using alambeta instrument. The air permeability of the thermal wraps was measured in air permeability tester. The relative water vapor permeability and absolute water vapor permeability was measured in Permetest. These tests were conducted to understand thermal properties, air and water vapor permeability of flexible aerogel based composites with nanoporous structure. The results of the experiments were statistically analyzed and found to be within confidence intervals.

Keywords: Aerogel, Nanoporosity, Fibrous structure, Thermal insulation, Water vapor transmission

Introduction

Aerogel, with its nanoporous structure and mass, is a very suitable material to be used as super insulating composite material. Due to its enormous level of nanoporosity and specific surface, it has very very low density and thermal conductivity. In 1931, Kistler first measured the thermal conductivity of silica aerogel which was about 0.02 W/(m K) at normal atmospheric condition, and about 0.01 W/(m K) under vacuum condition [1]. Many other researchers have also investigated heat transfer behaviors inside aerogel based composite materials. Heat transfer phenomena in silica aerogel is closely associated with its complex nano-porous structure [2].

Thermal properties are among the most important features of fibrous structures and based composites. Most of the studies carried out until now are focussed at measurements of static thermal properties such as thermal conductivity, thermal resistance and thermal diffusion. Thermal insulation is an important factor for estimating physiological comfort for the application area. Thermal insulation properties are determined by the physical parameters of fibrous structures as well as the structural parameters [3]. Thermal properties are important in many flexible composite applications like protective clothing and sleeping bags. Thermal properties also affect performance in technical nonwoven composites which are used for building insulation, automobiles, aircraft, and industrial process equipment. Since the composite structure is essentially a mixture of fibers, resin, air and moisture, each having distinctively different thermal properties, the thermal behaviour of the system is the collective and interactive results of these constituents. Fibrous structures are important components for good thermal insulation in composites from the extreme conditions of the surroundings. The important constructive parameters are thickness, weight per unit area and packing fraction p.f., which is the ratio between the bulk density of fibrous structure samples (fibersþair) and of the same sample if it was made up wholly from the same polymer [4]. Fibrous materials are used as thermal insulating composite materials because of savings in both space and weight [5]. In extreme cold applications, the role of the middle layer is to protect the human body against chilling. Different kinds of fibrous materials are used as the middle thermal insulating layer of multilayer clothing, such as traditional nonwovens. Highly advanced thermal insulating materials like aerogel is used to treat nonwoven fibrous structures. These are characterised by excellent thermal insulation. However, such advanced thermal insulating composite materials are very expensive. Hence their usage is limited mostly limited to high- performance applications. In the trade, one can still observe the use of the traditional lining combined with the outer fibrous structure. The thermal characteristics of these standard thermal insulation materials are not commonly known.

The research reported here discusses the influence of aerogel on the thermal conductivity, thermal resistance and thermal diffusivity of nonwoven fibrous structure based composite materials. The relative water vapor permeability and evaporative resistance was also varied in order to study the effect of fibrous layer densities on heat transfer characteristics. Samples were also compressed in an effort to study the effect of pressure on thermal conductivity.

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Experimental

Materials

In this study, polyester/polyethylene (50/50) nonwoven thermal wraps treated with aerogel were used. The type of aerogel used was amorphous silica aerogel which is most suitable for application of textile material. The thermal wraps were chosen in three different thicknesses Sample 1 (3.4 mm), Sample 2 (6.2 mm), Sample 3 (6.6 mm).

Methods

Air Permeability Measuring Instrument

The principle of FX 3300 air permeability instrument depends on the measurement of air flow passing through the fabric at a certain pressure gradient Δp. In this instrument any part of the fabric can be placed between the sensing circular clamps (discs) without the garment destruction. As the fabric fixes firmly on its circumference (to prevent the air from escaping), the fabric dimensions doesn't play any role. Here is also enough space between the clamps and the instrument frame, which allows the measurement on large samples.

Water Vapour Permeability Measuring Instrument

The Permetest instrument enables the determination of relative WVP (%) and evaporation resistance Ret (m^2Pa/W) of dry and wet fabrics within 3-5 minutes.

SEM Micrographs

The nonwoven fabric sample of three different thickness treated with aerogel was characterised using SEM (VEGA TESCAN Inc., USA) at 30 kV. Measuring head of this small Skin Model is covered by a resistant semi-permeable foil, which avoids the liquid water transport from the measuring system into the sample. Cooling heat flow caused by water evaporation from the thin porous layer is quickly recorded by a special computer evaluated sensing system.

Thermal Properties Measuring Device

The Alambeta Instrument was used to measure the thermal properties like thermal conductivity, thermal resistance, thermal diffusivity, thermal absorptivity and peak heat flow density of the thermal wraps. The thickness of the samples was measured using UNI-Thickness meter. The fabrics were cut for 10×10 cm and the weight in gram per square meter was measured. Air permeability tester was used to test the air permeability of the thermal wraps with various pressure levels. SEM images were taken to compare the physical structures of the three fabrics on microscopic scale to determine if any difference were noticeable that could explain test results. All the experiments were carried out in standard atmospheric conditions of about 20 ^{o}±2 ^{o}C and 65±2 % relative humidity.

Results and Discussion

The thermo-physiological properties of PET/polyethylene nonwoven thermal wraps of varying thicknesses treated with aerogel were compared. The SEM images were also taken to compare the physical structure of the aerogel treated fabrics. Specific thermal properties like thermal conductivity, thermal resistance, thermal diffusivity and thermal absorptivity were measured using alambeta instrument and given in Table 1. The air permeability of the thermal wraps was measured in air permeability tester. The relative water vapor permeability and absolute water vapor permeability was measured in Permetest. These tests were conducted to understand thermal properties, air and water vapor permeability of aerogel treated nonwoven fabrics.

The results of the experiments were statistically analyzed and found to be significant. The results were evaluated and studied for air permeability, thermal resistance, thermal conductivity, thermal diffusivity and water vapor permeability. 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, thickness, fabric weight, water vapor permeability and air permeability properties for the three different thickness of fabrics treated with silica aerogel.

Air Permeability

Air permeability is the measure of airflow passed through a given area of a fabric. This parameter influences the thermal comfort properties of fabrics to a large extent. It is generally accepted that the air permeability of a fabric depends on its air porosity, which in turn influences its openness. With more porosity, more permeable fabric is obtained [6]. Statistical analysis results show that the there is a significance on the air permeability values of the aerogel treated nonwoven fabrics ($p=0.003$). Figure 1 shows the air permeability with respect to different pressure levels of the fabrics. The result indicates that air permeability is directly proportional to the pressure level. On comparison of three fabrics, the air

Table 1. Thermal properties of the fabrics

Sample no.	Thickness (mm)	Weight in g/m^2	Fabric density (kg/m^3)	Aerogel (%)	Thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$)	Thermal diffusivity (10^{-6} $m^2\cdot s^{-1}$)	Thermal absorptivity ($W\cdot m^{-2}\cdot s^{1/2}\cdot K^{-1}$)	Thermal resistance ($K\cdot m^2\cdot W^{-1}$)	Peak heat flow density ($W\cdot m^{-2}$)
1	3.4	272.6	79.6	1.5	0.0251	0.276	47.78	0.137	214.8
2	6.2	499.5	80.4	2.5	0.0276	0.420	42.56	0.225	181.0
3	6.6	440.7	66.7	2.0	0.0274	0.453	40.88	0.241	167.6

permeability is higher in the case of sample 1. It may be due to the fact that air permeability is related to porous structure of the fabric and is directly proportional to percentage of porosity of the fabric. It was also noticed that when the pressure level increased, the flow rate also increased. The air permeability was lower for samples with higher fabric thickness and may be attributed to the layered structure and high porosity.

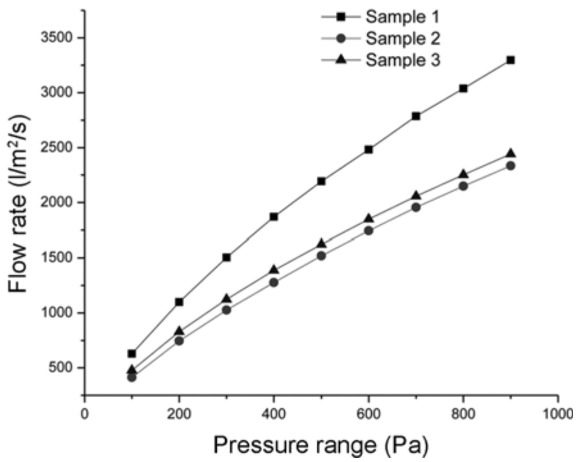

Figure 1. Flow rate dependence on pressure.

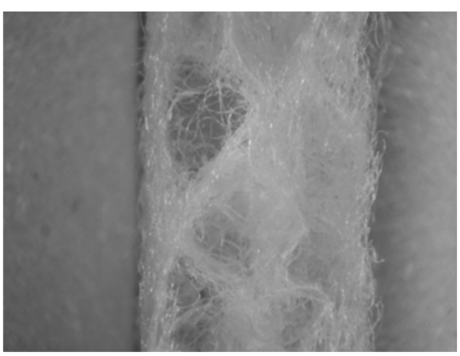

Figure 2. Structure of aerogel treated nonwoven fabrics.

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. The density difference of samples may be attributed to the fabric structure and also the percentage of aerogel particles present in the fiber.

Fabric density [kg/m^3] is calculated as ratio of areal mass (G [g/m^2]) and thickness (h [mm]). Approximate volume porosity of all samples are around 93 %. Fabric sample are created from multilayer nonwoven structures (shown in Figure 2) and it is complicated to calculate mean fiber density.

Particle Size Distribution

The particle size of aerogel is depicted in the Figure 3. The average particle size was 3520 nm. Ball milling was used for reduction of particle size. After regular interval of time the size was analyzed till a binomial distribution was obtained with 5 hrs of continuous milling.

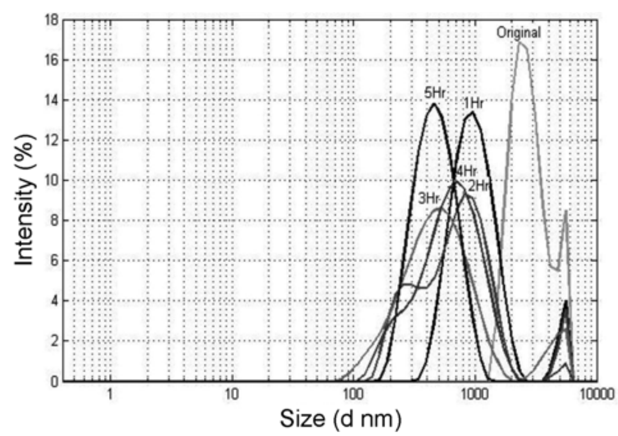

Figure 3. Particle size distribution after regular intervals of milling.

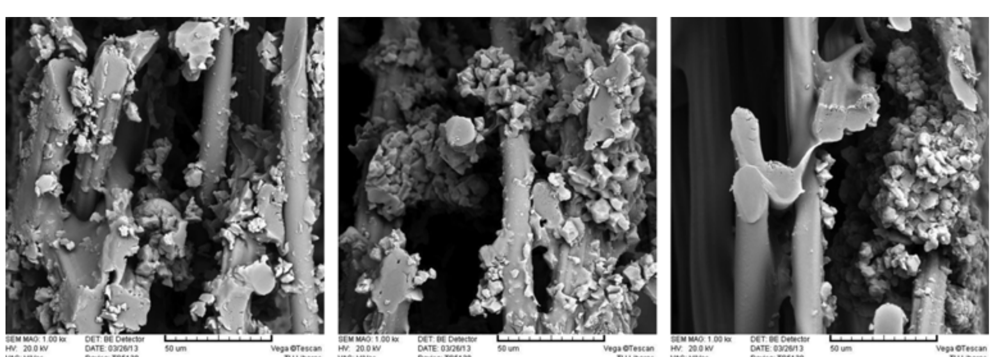

Figure 4. SEM images of nonwoven fabrics treated with aerogel.

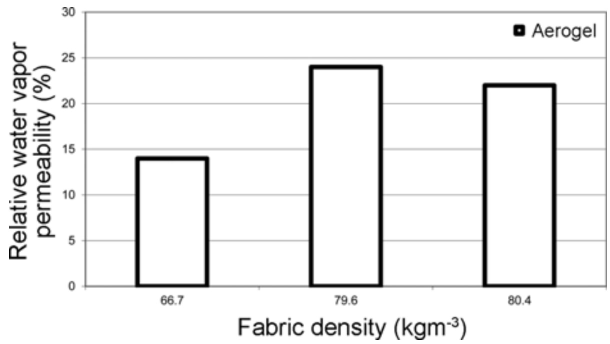

Figure 5. Relative water vapor permeability of aerogel treated nonwoven fabrics.

Scanning Electron Microscopy (SEM)

Scanning electron microscope SEM images were taken on microscopic scale for the cross section of the three fabrics with identical magnification. The physical structure confirmed to be different for three fabrics due to different thickness. It is shown in Figure 4. It was observed that sample 2 had higher fabric density as compared to other samples. The aerogel deposition on the fabric was also observed.

Relative Water Vapor Permeability

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 vapor present in a fabric should be optimum [7].

Figure 5 shows that water vapor permeability of the fabric has been decreased for sample 1 and increases for sample 2 & 3. Thus, the water vapor resistance of sample 2 was higher than sample 1 & 3. The decrease and increase in the water vapor permeability of the fabric may be attributed to the structure of the fabric and also the percentage of aerogel particles present in the fabric.

This behavior can be explained by the moisture vapor transmission mechanism. When vapor transmits through a textile layer two processes namely diffusion and sorption-desorption are involved. Water vapor diffuses through a textile structure in two ways, simple diffusion through the air spaces between the fibers and along the fiber itself [8].

Thermal Conductivity

Thermal conductivity, λ, is a measure of the rate at which heat is transferred through unit area of the fabric across unit thickness under a specified temperature gradient and thus is defined by the relation [6].

$$\lambda(W m^{-1} K^{-1}) = \frac{Q}{Ft\frac{\Delta T}{h}} \quad (1)$$

where, Q: amount of conducted heat, F: area through which heat is conducted, t: time of heat conducting, ΔT: drop of temperature, and h: fabric thickness. Thermal conductivity of air is 0.024 ($W \cdot m^{-1} \cdot K^{-1}$).

The analysis of variance (ANOVA) results shows that the fabric density affects the thermal conductivity values of the aerogel treated nonwoven fabric ($p=0.006$). The thermal conductivity of nonwoven fabrics depends on many factors including environmental temperature, thermal conductivity of the solid polymer materials and fabric dimensional and structural parameters such as fabric density, fabric porosity, and fiber arrangement. It is understood that the thermal conductivity of fibrous materials will increase with increasing environmental temperature due to the contribution of radiation, convection, and conduction [9]. Hence the thermal conductivity of a fabric increases significantly with increases in the heating temperature. The thermal conductivity of air is constant at a certain temperature; heat transfer in a fabric may be subject to some variations depending on the different thermal conductivities of the component fibers. Among the polymers, polyester (PET) has a low thermal conductivity (0.15-0.24 W m^{-1} K^{-1}) and polyethylene (PE) has a relative high value (0.34 W m^{-1} K^{-1}) and the thermal conductivity of silica aerogel is about 0.02 W/(m K) at normal atmospheric condition. The three different nonwoven fabrics with varying thickness considered in the study are composed of polyester and polyethylene fibers treated with silica aerogel. Since the difference in thermal conductivity of the two fibers is small, the conductivity of a low-density fabric of this type, corresponding to an air volume of about 90 %, is practically independent of the fiber composition. The volumetric proportion of fibers in a fabric is represented by the fabric density, which relates to the volumetric proportion of air trapped in the fabric (or fabric porosity). For nonwoven fabrics, the density is the primary factor contributing to the heat transfer through fabrics [10]. Figure 6 shows the comparison between thermal conductivity calculated for constituent fibrous material

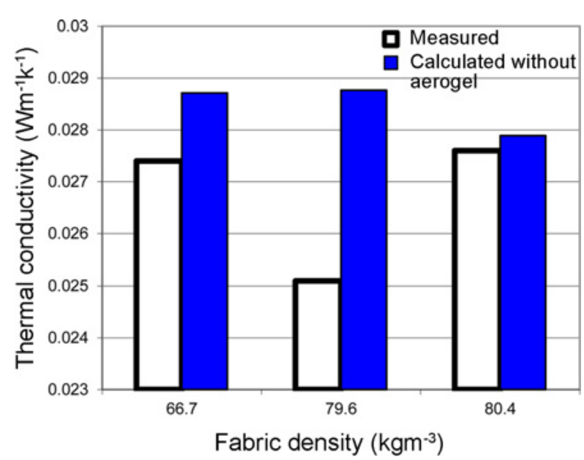

Figure 6. Thermal conductivity of aerogel treated nonwoven fabrics compared to calculated values without aerogel.

(i.e. polyester and polyethylene) without aerogel and the measured values from experimental samples with aerogel. The thermal conductivity of sample without aerogel treatment is calculated as;

$$\lambda_A = \lambda_a \cdot \lambda_M \tag{2}$$

Where, λ_a is the thermal conductivity of air, p is porosity and λ_M is the thermal conductivity of fibrous material i.e., polyester and polyethylene.

The combined thermal conductivity of fibrous material is calculated based on 50:50 fiber blend as;

$$\lambda_M = \frac{(\lambda_{PET} + \lambda_{PE})}{2} \tag{3}$$

Thermal Diffusivity

Thermal diffusivity describes the rate of temperature spread through a material. Thermal diffusivity of air at 300 K is 19×10^{-6} m^2/s. Thermal diffusivity, a, is calculated from the thermal conductivity and the heat thermal capacity as given below;

$$a = (m^2 s^{-1}) = \frac{\lambda}{\rho c} \tag{4}$$

where λ: thermal conductivity, ρ: fabric density, and c:specific heat capacity of fabrics.

The analysis of variance (ANOVA) results show that the effect of fabric density on the thermal diffusivity is significant (p=0.006). The comparisons of the average thermal diffusivity values show that the thermal diffusivity and fabric densities are inversely proportional. Figure 6 shows the results of thermal diffusivity and fabric density, where the sample 1 has the lowest value of the thermal diffusivity, whereas the sample 3 has the highest value of this parameter. Sample 3 shows the increase in thermal diffusivity with the decrease of fabric density. This may be attributed to the fabric structure shown in Figure 7, Fiber content and the aerogel particles present in the fiber.

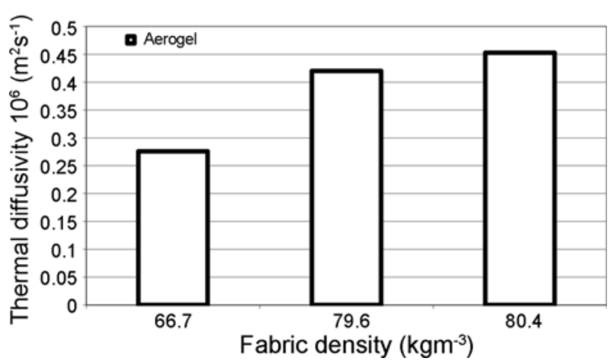

Figure 7. Thermal diffusivity of aerogel treated nonwoven fabrics.

Thermal Resistance

Thermal resistance is defined as the ratio of the temperature difference between the two faces of a material to the rate of heat flow per unit area. Thermal resistance determines the heat insulation property of a textile material. The higher the thermal resistance, the lower is the heat loss. The thermal resistance, R, is connected with the thermal conductivity, λ, and the fabric thickness, h, as follows [11].

$$R(m^2 K^{-1} W^{-1}) = \frac{h}{\lambda} \tag{5}$$

The statistical analysis shows that the fabric thickness has a highly significant influence on the thermal resistance (p= 0.006).

Thermal resistance is a function of the thickness and thermal conductivity of a fabric, and is a very important parameter from the view point of thermal insulation, and is proportional to the fabric structure also. The original thickness measurements for the three fabrics were under relaxed conditions. Figure 8 indicates that the thermal resistance of sample 1 is lower than the samples 2 and 3. If the thickness is higher like in sample 2 & 3, the thermal resistance is also higher. Due to increase in thickness, there is an increase in thermal insulation and the decrease of heat losses are due to the space insulated by the fabric. This may be attributed to aerogel particles in the fabric.

In the ideal case when all samples have same thermal conductivity, line in Figure 8 should have intercept equal to 0 and slope equal to 1/thermal conductivity. It is interesting that line calculated by least squares is following this assumption and approximately all tested samples have the same thermal conductivity equal to 0.0272.

Thermal Absorptivity

Thermal absorptivity is the quantity of heat penetrating a fabric during the time period when temperature is raised rapidly. The thermal absorptivity, b, is given by the following relation [6].

$$b(W s^{1/2} m^{-1} K^{-1}) = \sqrt{\lambda \rho c} \tag{6}$$

where, λ: thermal conductivity, ρ: fabric density and c: specific

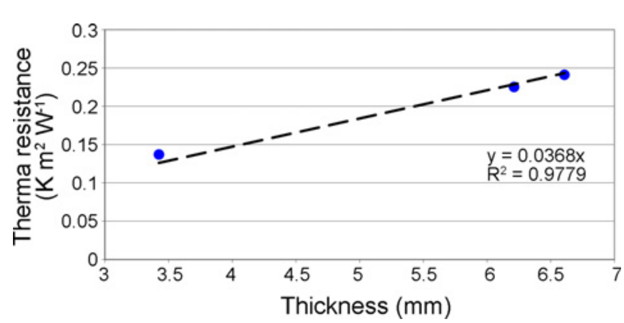

Figure 8. Thermal resistance vs thickness.

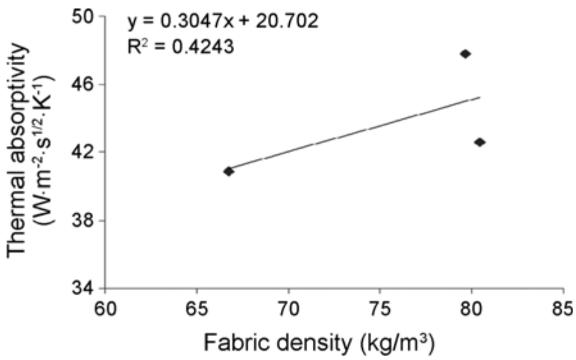

Figure 9. Dependence of thermal absorptivity of aerogel treated nonwoven fabrics density.

heat capacity of fabrics. Thermal absorptivity allows evaluating the transient contact properties of a textile material together with maximum heat flux, Qmax, and thermal diffusivity. Transient heat transfer occurs when a fabric initially contacts with the skin. The thermal absorptivity together with the maximum heat flux is accepted as the objective measure of warm-cool feeling of fabrics. The contact area between fabric and skin as well as heat capacity and fabric thermal conductivity determine the warm-cool feeling. Therefore, the surface property (roughness/smoothness) of a fabric has a great influence on this sensation. A smooth surface increases the thermal absorptivity and heat flux values due to a large area of contact with human skin. Conversely, a rough surface reduces the thermal absorptivity and the heat flux values. According to this, the high values of thermal absorptivity and maximum heat flux provide cool feeling, where as the low values provide the warm feeling.

The experimental values were statistically analyzed and found to be significant ($p=0.000$). The thermal absorptivity of sample 1 is higher than sample 2 & 3. This may be attributed to the surface roughness/smoothness of the fabrics. It shows that sample 1 had higher contact area with the measuring head of the instrument and comparatively sample had lower contact area with the measuring head. Thus, the sample 1 gives cooler feeling than sample 3. As explained above, a smooth surface increases the contact area of a fabric with a skin and therefore, the thermal absorptivity.

Dependence of thermal absorptivity of aerogel treated samples on fabric density is shown in Figure 9.

Conclusion

The polyester/polyethylene fiber based composites with silica aerogel impregnation having three different thicknesses were investigated. The thermal resistance of the composite structure is directly proportional to its thickness. This may be attributed to decrease in heat losses due to space insulated by fibrous structure and nanoporous aerogel architecture. Thermal conductivity and thermal diffusivity were found to be inversely proportional to the mass density which is attributed to the fiber volume fraction of the composite structure and mainly aerogel particles present in the composite. Thermal absorptivity showed the difference in warm/cool behavior of the composite structures with respect to surface roughness/smoothness. Relative water vapor permeability of the samples increased based on the fiber assembly and the aerogel structure present in the composite. Also, the air permeability was directly proportional to percentage of nanoporosity of the aerogel based composite structure. It was also noticed that, when the pressure level increases the flow rate also increases simultaneously. The fibrous structure density and the aerogel present in the composite have a significant effect on thermal properties of the overall structures.

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