Determination of Radiative Thermal Conductivity in Needlepunched Nonwovens

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ABSTRACT
Radiation heat transfer is found to be the dominant mode of heat transfer at temperatures higher than 400-500K [11]. Convection heat transfer being negligible in nonwovens, effective thermal conductivity is given by the sum of its conduction and radiation components. In this research two methods were identified to determine radiative thermal conductivity of needlepunched samples made from Nomex fibers. The first method involved the determination of radiative thermal conductivity using effective (total) thermal conductivity determined using a Guarded Hot Plate (GHP) instrument. In the second method radiative thermal conductivity was estimated using the extinction coefficient of samples. The extinction coefficient was determined by using direct transmission measurements made using a Fourier Transform InfraRed (FTIR) spectrometer. Results confirmed that radiation was the dominant mode of heat transfer at temperatures higher than 535 K. The conduction component of effective thermal conductivity did not change much in the range of densities tested. Empirical models for predicting the temperature difference across thickness of the fabric and the radiative thermal conductivity with R-square values of 0.94 and 0.88 respectively showed that fabric density, fabric thickness, fiber fineness, fiber length, mean pore size and applied temperature were found to have significant effect on the effective thermal conductivity and its radiation component. Though a high correlation between the results of Method 1 (Guarded Hot Plate) and Method 2 (FTIR) was not seen, the absorbance measurements made using the FTIR spectrometer were found to have significant effect on the radiative thermal conductivity.

INTRODUCTION
Heat flux passing through a participating medium may generally be represented by several mechanisms: free and forced convection, conduction and radiation. In fibrous materials however, convections has been reported to be negligible in several earlier studies [2, 12]. Woo et al. [12], conducted studies on melt blown and needle-punched nonwovens for apparel thermal insulation and found no evidence to indicate convective heat transfer even in low density nonwoven fabrics. Farnworth [2] also conducted test using low-density samples with fiber volume fractions of 0.2% and 0.4% and found that the convection mode of heat transfer was non-existent. The small size of the pores and the tortuous nature of air channels present prevent any heat transfer by convection. In the absence of any significant heat transfer by convection, effective (total) thermal conductivity (k_{eff}) can be written as the sum of its radiation (k_r) and conduction components (k_c).

$$k_{eff} = k_r + k_c \tag{1}$$

Radiation is found to be the dominant mode of heat transfer in fibrous insulation at temperatures higher then 400-500 K [6, 11]. Fibrous materials have been successfully used as thermal insulation in many engineering systems due to their ability to reduce the radiation heat transfer. This has lead to a considerable interest in determining the radiation component of effective thermal conductivity.

A model proposed by Strong et al. [9], predicted that the rate of radiative heat transfer through a bed of fibers was directly proportional to fiber diameter and inversely proportional to the volume fraction of the fibers in the fiber assembly. Lee and Cunnington [5] modeled the radiative thermal conductivity of an optically thick medium by a diffusion approximation in which the spectral extinction properties were calculated by a rigorous treatment of the fiber medium scattering phase function and the composition of the fiber material. Lee and Cunnington [5] modified the classic diffusion model, commonly used for optically thick, non-scattering media, to account for the effect of scattering by fibers and absorption by the matrix medium (air).

Mohammadi et al [6, 7] used thermal conductivity derived from Bhattacharya's model [1] and effective thermal conductivity determined from the Guarded

Hot Plate instrument to obtain the radiative thermal conductivity of glass and ceramic needlepunched nonwovens. Fricke et al. [3] determined the radiative thermal conductivity using the spectral hemispherical transmittance and reflectance in the wavelength range of 2.5 – 45 µm, using an integrating sphere attachment to an FTIR-spectrometer.

This research aims at developing empirical models for predicting the radiative thermal conductivity in needlepunched nonwoven materials at high temperatures. A comparison between two methods similar to those used by Mohammadi et al [6, 7] and Fricke et al. [3] is reported. The methods used to determine the radiative thermal conductivity are described in the next section. This research also reports the influence of various material and fabric construction parameters on the radiation and conduction components of effective thermal conductivity at high temperatures.

EXPERIMENTAL DESIGN AND SETUP

In this research Nomex fibers in two fiber finenesses, 1.67 dtex (1.5 denier) and 2.22 dtex (2 denier) and two cut lengths 5.08 cm (2 inches) and 7.62 (3 inches) were used to make needlepunched samples. Air-laid fiber webs with random fiber orientation and basis weights between 115-125 g/m^2 were prepared using a Rando Webber. Individual webs prepared using Rando Webber were needlepunched on one side with a single needling pass using a James Hunter Needle-Punching machine. The needle penetration depth was set to assure that needles penetrate through the entire thickness of the web. Two or three such needled webs were layered together and needlepunched once more. *Table I* describes different samples prepared for this research.

TABLE I. Sample Construction Parameters

Sample	Fiber Fineness dtex (denier)	Fiber Length cm (inches)	Number of Layers
N_{a2}	1.67 (1.5)	5.08 (2)	2
N_{a3}	1.67 (1.5)	5.08 (2)	3
N_{b2}	2.22 (2.0)	5.08 (2)	2
N_{b3}	2.22 (2.0)	5.08 (2)	3
N_{c2}	2.22 (2.0)	7.62 (3)	2
N_{c3}	2.22 (2.0)	7.62 (3)	3

Samples were prepared by cutting the needlepunched fabrics in a circular shape with a diameter of 20.32 cm (8 inches).

DETERMINATION OF EFFECTIVE THERMAL CONDUCTIVITY

Holometrix Guarded Hot Plate instrument (model GHP-200) [14], which conforms to ASTM C177 and ISO 2582 specifications, was used to determine effective thermal conductivity of samples. The test requires two identical samples to be placed on either side of the main/guard heater assembly of the GHP-200. In order to prevent the sample from being crushed due to the weight of the plates in the Guarded Hot Plate instrument, the samples were mounted on three high temperature resistant cylindrical spacers shown in *Figure 1*. The spacers prevent any pressure being applied on the sample due to the weight of the heater plates.

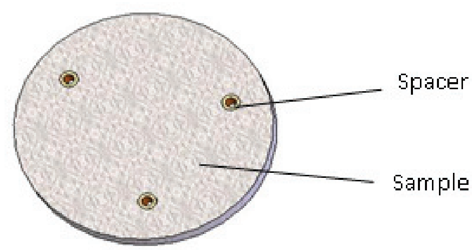

FIGURE 1. Fabric sample used for Guarded Hot Plate Test

The "hot side" and "cold side" temperatures were recorded every 1-hour until a state of thermal equilibrium was achieved. In testing these samples 10-11 hours was required to reach thermal equilibrium. The applied temperature (the temperature of the "hot side" at steady state condition) was in the range of 541–594 K. The effective thermal conductivity was determined from measurements of final surface temperatures, the power input to the main heater, and the geometry of the test samples as shown in *Eq. 2* [14].

$$k_{eff} = \frac{Q}{S}\left(\frac{1}{(\Delta T/d)_1 + (\Delta T/d)_2}\right) \tag{2}$$

where k_{eff} is the effective thermal conductivity (W/mK), Q is the heat generated by the electrical source (W), S is the main heater surface area (0.00835 m^2), d_1 and d_2 are the thickness of upper and lower samples being tested (m), ΔT_1 and ΔT_2 are the temperature gradient across the upper and lower samples (K).

DETERMINATION OF RADIATION COMPONENT OF EFFECTIVE THERMAL CONDUCTIVITY

Two methods were used to determine the radiation component of effective (total) thermal conductivity. In the first method the radiation component was determined by subtracting the conduction component from the effective thermal conductivity. This method assumes that the convection mode of heat transfer is negligible in nonwovens due to the small size and tortuous nature of the pore. The effective thermal conductivity was determined using the guarded hot plate instrument described in the previous section. To determine the conduction component *Eq. 3* generated by Fricke [3] was used.

$$k_c = k_s\left(1+\frac{C_r-1}{1+V_r(1+Z.(C_r-1)/(C_r+1))}\right) \tag{3}$$

where k_c is the combined solid and gaseous thermal conductivity (conduction component), k_s is the thermal conductivity of the solid material, V_r is ratio of the volume of fiber and gas, C_r is the ratio of thermal conductivity of gas to thermal conductivity of solid material and Z is the fractional part of all fibers which are oriented perpendicular to the microscopic heat flow. Results for this method are depicted in *Figure 3*.

In the second method absorbance was measured on Nicolet Nexus 470 Fourier Transform InfraRed Spectrophotometer (FTIR). The absorbance measurements were then used to determine the radiation thermal conductivity (radiation component). Due to the unavailability of an integrating sphere, measurements were made by testing the sample in transmission mode as shown in *Figure 2*.

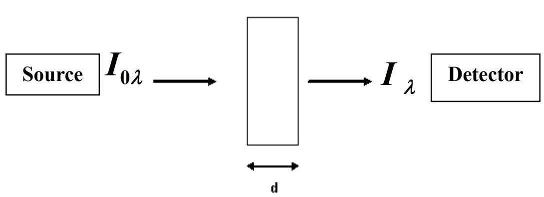

FIGURE 2. Schematic Diagram of Sample Being Tested on the FTIR Spectrometer

As shown in *Figure 2*, infrared radiations with intensity of $I_{0\lambda}$ are incident on a nonwoven sample with thickness of "d". The incident infrared radiations had a wavelength range from 2.5 – 20 µm. I_λ was the intensity of the infrared radiations transmitted through the sample. Absorbance values at 1868 intervals between 2.5 – 20 µm were extracted. The extinction coefficient was then calculated for each wavelength interval using Beer's Law [8] (*Eq. 4*),

$$I_{0\lambda} = I_\lambda e^{-E\,d} \tag{4}$$

where I_λ is the intensity of transmitted IR radiation, $I_{0\lambda}$ is the intensity of incident IR radiation, E is the extinction coefficient of the sample, and d is the path length (thickness of the sample). The extinction coefficient was then normalized over the density of the sample to give mass specific extinction coefficient as a function of wavelength, $e^*(\Lambda)$. Radiative thermal conductivity was calculated using *Eq. 5-8* [3].

$$\frac{1}{e^*(T)} = \int_0^\infty \frac{1}{e^*(\Lambda)} f_R(\Lambda,T)\,d\Delta \tag{5}$$

$$f_R(\Lambda,T) = \frac{15}{4\pi^4}\left[\frac{c_L h}{\Lambda k_B T}\right]^3 \frac{1}{\Lambda}\frac{\exp\{c_L h/(k_B \Lambda T)\}}{[\exp\{c_L h/(k_B \Lambda T)\}-1]^2} \tag{6}$$

$$T_r^{\,3} = \frac{1}{4}\left(T_h^{\,3} + T_c^{\,3}\right) \tag{7}$$

$$K_r = \frac{16 n^2 \sigma T_r^{\,3}}{3E(T)} \tag{8}$$

where $e^*(T)$ and $e^*(\Lambda)$ are mass specific extinction coefficients as a function of temperature and wavelength respectively. The Rosseland distribution function, $f_R(\Lambda,T)$, is defined by *Eq. 6*, where c_L is the velocity of light in a vacuum, h is Planck's constant, k_B is Boltzmann's constant, Λ is the wavelength, and T is the temperature. The radiative thermal conductivity was calculated using *Eq. 8*, which uses the mean radiative temperature T_r defined in *Eq. 7* as a function of the "hot side" temperature T_h and "cold side" temperature T_c, at the steady state condition while testing the samples on guarded hot Plate Instrument. *Eq. 8* also requires n, which is the refractive index of the fabric sample, σ, Stefan-Boltzmann constant, and E(T), the extinction coefficient at temperature T ($T=T_r$).

RESULTS AND DISCUSSION

Employing Method I, the conduction component (k_c) of effective thermal conductivity was calculated using Fricke's thermal conductivity (*Eq. 3*) outlined earlier. The values of k_c, calculated at three values of Z (0.67, 0.90 and, 0.95), were found to be nearly the same. Fricke [3] and Bhattacharya [1] in their work used Z=0.67 for random fiber orientation. Since preliminary computations showed negligible difference when using Z=0.67, 0.90 or 0.95, the value of Z used for all the remaining calculations in this work was 0.67.

Results showed that the conduction components (k_c) of effective thermal conductivities in all the samples were approximately equal, ranging from 0.02415 to 0.02424 W/mK with a CV% of 0.125 (*Figure 3*). An increase in the conduction component with an increase in the bulk density was not seen due to the limited range of densities studied in this research. Unlike the general close proximity of the calculated value of the conduction component, the radiative thermal conductivities (radiation component of effective thermal conductivity) were found to be varying with values ranging from 0.05560 to 0.06799 W/mK. It can also be seen in *Figure 3*, that radiation was the dominant mode of heat transfer, accounting for 69 to 75% of the total heat transfer. This is consistent with the fact stated in the literature earlier that radiation is the dominant mode of heat transfer at temperatures in excess of 400 – 500 K [11].

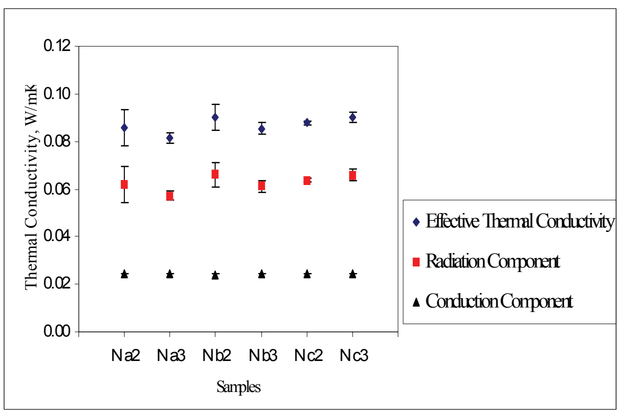

FIGURE 3. Radiation and Conduction Components of Effective Thermal Conductivity for samples N_{a2}, N_{a3}, N_{b2}, N_{c2}, and N_{c3}

Based on the results obtained by using Method I (GHP), statistical models was developed for predicting the radiative component of effective thermal conductivity, KR

KR = 0.0049 * SIZE + 0.0025 * THICK +0.0001 * AT – 0.0002 * DT – 0.0005 * DEN + 0.0169 (9)

The model had R-square value of 0.90, where KR is the predicted value of radiative thermal conductivity. All variables, fiber fineness in denier (SIZE), fabric thickness in mm (THICK), applied temperature in Kelvin (AT), temperature difference in Kelvin (DT) and fabric density in Kg/m^3 (DEN), were found to be significant with at least 98% confidence level. However, Model I requires observed value for temperature difference in order to predict radiative thermal conductivity, obtaining the temperature difference required testing the samples on the Guarded Hot Plate instrument, which is very time consuming. Therefore, Model 2 was developed in order to predict the temperature difference (DT) between the “hot side” and “cold side” of the sample.

DT = 13.45 * THICK + 1.88 * DEN + 0.25 * AT + 4.07 * LEN - 17.43 * LAY - 150.74 (10)

The model given in *Eq. 10* had R-square value of 0.94, with all the parameter significant with at least 99% confidence level. In order to predict radiative thermal conductivity without running any test on the Guarded Hot Plate instrument, Model1 described earlier was modified by replacing the observed values of temperature difference (DT) with the predicted values obtained from Model 2. The predicted values of temperature difference (DT) from *Eq. 10* were used to model the radiative component (KR) of the effective thermal conductivity. The model for KR using predicted DT values is given in *Eq. 11*.

KR = 0.0048 * SIZE + 0.0026 * THICK + 0.0001 * AT – 0.0005 * DEN – 0.0002 * DT2 + 0.0155 (11)

The model in *Eq. 11* had R-square value of 0.88. From the statistical analysis it can be suggested with at least 91 percent confidence that predicted temperature difference had a significant effect on the radiative thermal conductivity. All the other variables were found to be significant with at least 95 percent confidence level. Fabric density had the highest mean square value indicating that the largest proportion of variation in the radiative thermal conductivity is explained by the variations in fabric density.

Statistical analysis showed that density has a significant influence on the radiative thermal conductivity. As can be seen in *Figure 4*, radiation component of effective thermal conductivity decreases with increase in density. The decrease in the radiation component can be explained by the fact that, as the density of the nonwoven fabric increases, the packing density increases making the fibrous structure more packed. This causes the mean free path, which is defined as the distance traveled by a photon before hitting the surface of the surrounding fibers, to decrease thus causing a decrease in the heat transfer due to radiation mode [7].

One of the most important parameters influencing radiation heat transfer in nonwovens is mean pore size. From the test results it was found that as the size of the pores increased, the radiation component of effective thermal conductivity increased.

Figure 5 shows an overall increase in the radiation component with increase in mean pore size (applied temperature range between 556-572K).

Similar trends were also seen over applied temperature ranges between 541 – 546 K and 577 – 594 K.

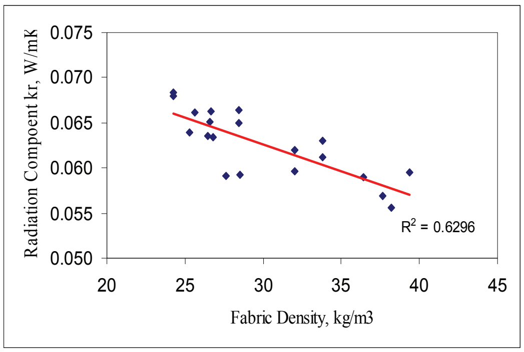

FIGURE 4. Effect of Fabric Density on the Radiative Thermal Conductivity k_r

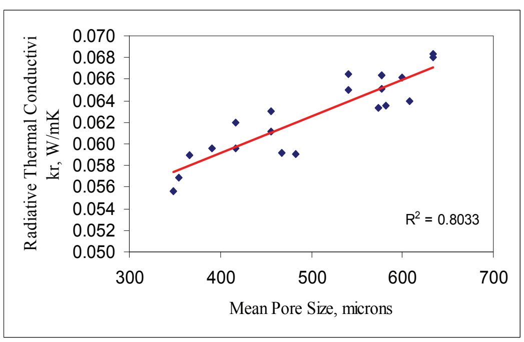

FIGURE 5. Effect of Mean Pore Size on Radiative Thermal Conductivity k_r (Applied Temperature Range 556 – 572 K)

The increase in the radiation component of effect thermal conductivity can be explained by the fact that as the mean pore size increase, more photons can pass through the open spaces between the fibers leading to increased heat transfer.

Effect of Fiber Fineness and Fiber Length

Though the mean radiative thermal conductivity for N_{a2}, made using finer fibers was lower than N_{b2}, the range of the value of radiative thermal conductivity was found to be overlapping (*Figure 3*). Same could be said about samples N_{a3} and N_{b3}. Therefore, a conclusive relationship between fiber fineness and radiative thermal conductivity could not be established based on the pair-wire comparison of samples. However a more complete statistical analysis of all the samples showed that fiber fineness was significant with at least 99% confidence level and the model in *Eq. 9* indicated that radiative thermal conductivity increases with increasing fiber denier. This was found to be consistent with other studies [4, 9]. Samples made using finer fibers have higher surface area as compared to nonwoven fabrics having the same density but made from higher denier fibers. This larger surface area leads to more scattering and absorption of thermal radiations causing a decrease in the radiative heat transfer. The mean pore size was also smaller in nonwoven samples made from lower denier fibers. Smaller mean pore size also leads to reduced heat transfer by radiation mode.

Radiative thermal conductivity was found to be apparently higher in sample N_{c3}, made with longer fibers, when compared with sample N_{b3}. However, higher radiative thermal conductivity in sample N_{c3} can also be attributed to lower density of sample N_{c3} when compared to that of sample N_{b3}. An opposite trend was seen on comparing sample N_{c2} and N_{b2}. N_{c2}, which was made from longer fibers, apparently had a lower radiative thermal conductivity when compared to sample N_{b2}. However due to the overlapping values of radiative thermal conductivity among the two samples, any conclusive relationship between fiber length and radiative thermal conductivity could not be made. Statistical analysis also indicated that fiber length did not have any direct effect on radiative thermal conductivity. The inconsistent results observed might be due to the non-uniformity of the samples tested.

Effect of Fabric Thickness

From statistical analysis, it can be suggested with at least 99% confidence, that fabric thickness had a significant effect on the radiation component of effective thermal conductivity. As evident from Model 2 (*Eq. 10*), which predicts temperature difference between the “hot side” and “cold side” of the sample at steady state, as the fabric thickness increased, the temperature difference increased. Since the predicted value of temperature difference was used in Model 3 (*Eq. 11*) to predict the radiation component, the overall effect was a decrease in the radiation component of effective thermal conductivity with an increase in fabric thickness. Statistical analysis showed that the radiation component of effective thermal conductivity decreased as the thickness of the fabric increased. The temperature profile departs from linearity as the exchange of infrared radiation between two elemental surfaces within the bed is reduced by shadowing [10], which arises from absorption and scattering by fibers in its path.

Comparison of Radiation Component Determined using Method I and II

As described earlier, Method I used effective thermal conductivity measurements made on guarded hot plate to determine the radiative thermal conductivity. In Method II the extinction coefficient of the sample, determined using a FTIR spectrometer, was used to calculate the radiative component of effective thermal conductivity. A comparison of the radiative thermal conductivity obtained using both methods is shown in *Figure 6*.

The difference between average values of k_r determined using the two methods was found to be approximately 6 percent. However, statistical analysis showed that this difference was significant and also that the correlation (R) between the two results was very low (0.24) as shown in *Figure 7.*

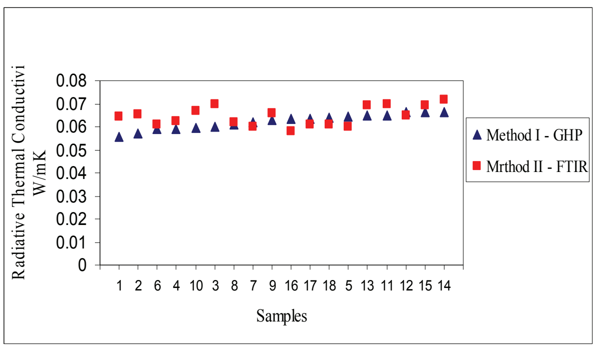

FIGURE 6. Comparison of Radiative Thermal Conductivity Values Determined using Method I and II

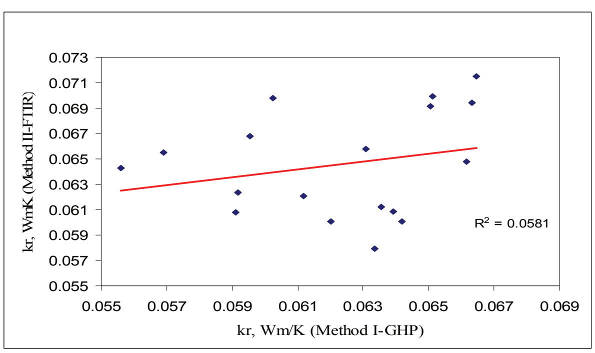

FIGURE 7. Scatter Plot of radiation thermal conductivity values obtained from Method I versus Method II

The difference and poor correlation between the results obtained from methods I and II can be attributed to the fact that direct transmission/absorbance measurements were made using the FTIR spectrometer without an integrating sphere attachment. Beer's Law used to determine the extinction coefficient is also based on direct transmission measurements. However, direct transmission measurements are only reliable for non-scattering samples. Owing to the tortuous nature of the pores and the random orientation of fibers in a nonwoven, a lot of scattering takes places as infrared radiations pass through a nonwoven sample [7]. Therefore for nonwovens, hemispherical transmission and reflectance measurements made using an integrating sphere [13] would have given more reliable results.

Although the results obtained from the two methods had poor correction, the absorbance measurements made on a FTIR spectrometer were valid readings. The average absorbance of the sample in the wavelength range of 2.5 to 20 μm (tested in a direct transmission mode) was found to have a significant effect on the radiative thermal conductivity as shown in the Model 4 given by *Eq. 12*.

$$KR = 0.0026 * THICK + 0.00007 * AT + 0.0035 * SIZE – 0.0002 * DEN – 0.0002 * DT – 0.0055 * ABSORB + 0.0496 \quad (12)$$

The above empirical model 4 with an R-square Value of 0.87 included absorbance as an independent variable. Statistical analysis showed that the absorbance value was significant with at least 99 percent confidence level.

CONCLUSIONS

In the range of fabric densities tested the conduction component was fairly constant in the samples tested. Since convection mode of heat transfer is negligible in the samples, the variations in the effective thermal conductivity can largely be explained by the variations in the radiative thermal conductivity. Radiation was found to be the dominant mode of heat transfer (almost 3 times that the conduction component of effective thermal conductivity).

Fabric density was found to be a significant factor influencing the radiation component of effective thermal conductivity. The radiative thermal conductivity was found to decrease with increase in the fabric density. Radiative thermal conductivity of a sample was also found to depend significantly on the size of the pores. Increase in the mean pore size was found to cause an increase in the radiation mode of heat transfer. Similar trends were seen over three different applied temperature ranges.

Statistical analysis showed that radiative thermal conductivity increases with an increase in fiber denier. Statistical analysis also showed that as fabric thickness increased the temperature difference between the "hot side" and "cold side" of the sample increased. However the length of fiber did not have any direct effect on radiative thermal conductivity.

Comparison of the radiative thermal conductivity obtained using Method I (GHP) and Method II (FTIR) showed the two averages to be only 6 percent different, but poor correlation was found between the radiative thermal conductivity values obtained from the two methods. However, absorbance values of the samples measured on the FTIR spectrometer were found to be highly significant in predicting the radiative thermal conductivity.

Predicted value of temperature difference used in Model 3 for predicting radiative thermal conductivity, eliminates the need to test the sample on the Guarded Hot Plate instrument to measure the temperature difference. Model 3 was found to have R-square value of 0.88. Fabric density, fabric thickness, fiber fineness, number of layer, applied temperature, temperature difference across fabric thickness and the predicted temperature difference were found to be at least 91 percent significant in predicting the radiative thermal conductivity.

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