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Utilization of Air Permeability In Predicting The Thermal Conductivity

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Abstract:

General linear regression models were used to determine the relationship between thermal conductivity and specific air permeability of 48 heterogeneous, needlepunched, nonwoven samples that were made from ceramic and glass webs. Parameters analyzed included number of needle barbs, fabric weight, thickness, and porosity. Other factors considered were fabric layering structure, temperature drop across the fabric and specific air permeability. Of the linear regression models examined, three models were found to be significant at greater than 95% confidence. These models had r^2 values of greater than 97%. Factors that proved to be greater than 95% significant in predicting the effective thermal conductivity of the samples tested were fabric thickness and weight, fabric porosity, fabric mean pore size, and specific air permeability.

Key words: Layered structures, Glass fibers, Ceramics, Textile composites, Thermal Properties, Needled nonwoven structures

Introduction

Determination of effective thermal conductivity of materials is both time consuming and expensive. However, since there is similarity between Darcy's permeability equation [2] and Fourier's Thermal conductivity equation [3, 7], an attempt is being made to predict the effective thermal conductivity of materials from experimental measurements of air permeability. Measurement of fabric air permeability is less time consuming as well as inexpensive. Devising a method to predict the effective thermal conductivity of a material from its air permeability will therefore reduce the time and expense associated with characterizing fabrics for thermal applications.

Consider Equations 1 and 2,

(1)

$$q_{fp} = k_{fp}\frac{\Delta P}{L} \qquad (1)$$

and

$$q_{tc} = k_{etc}\frac{\Delta T}{L} \qquad (2)$$

where k_{fp} is the air flow permeability, q_{fp} is the linear flow rate, ΔP is the pressure drop, L is the sample thickness, k_{etc} is the effective thermal conductivity, q_{tc} is the heat flux, and ΔT is the differential temperature. Using equations 1 and 2, then

$$k_{etc} = \frac{k_{fp}(\Delta P)q_{tc}}{(\Delta T)q_{fp}} \qquad (3)$$

Thus, it is conceivable, and therefore hypothesized, that the effective thermal conductivity can be predicted from the air permeability.

A thorough description of multilayered, glass/ceramic, nonwoven, needlepunched fabric samples used to test the above hypothesis is given in recent papers by the present authors [5, 6]. Methods used to evaluate the structural, physical and thermal properties of the samples are also presented in the literature [5, 6]. In the following methodology section,

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for the sake of reader clarity, a brief description on the experiment is presented.

Methodology

Synthetic glass and ceramic fibers were used in this research. Staple industrial glass fibers, having a density of 2.54 grams/cm^3 and diameter of 7.3 microns were provided by Owens Corning. Glass fibers were converted to webs having an average thickness of 0.46 cm with a 4.0% coefficient of variation (CV). Ceramic materials were provided in a web or blanket form by Kaowool Ceramic Fiber Products, Thermal Ceramics Department. Webs were produced from ceramic fibers having a density of 2.63 grams/cm^3 and diameter of 6 microns. The average thickness of the ceramic webs was found to be 1.04 cm with a 23.9% CV. The high variation in thickness is associated with the web construction method, i.e., melt blowing.

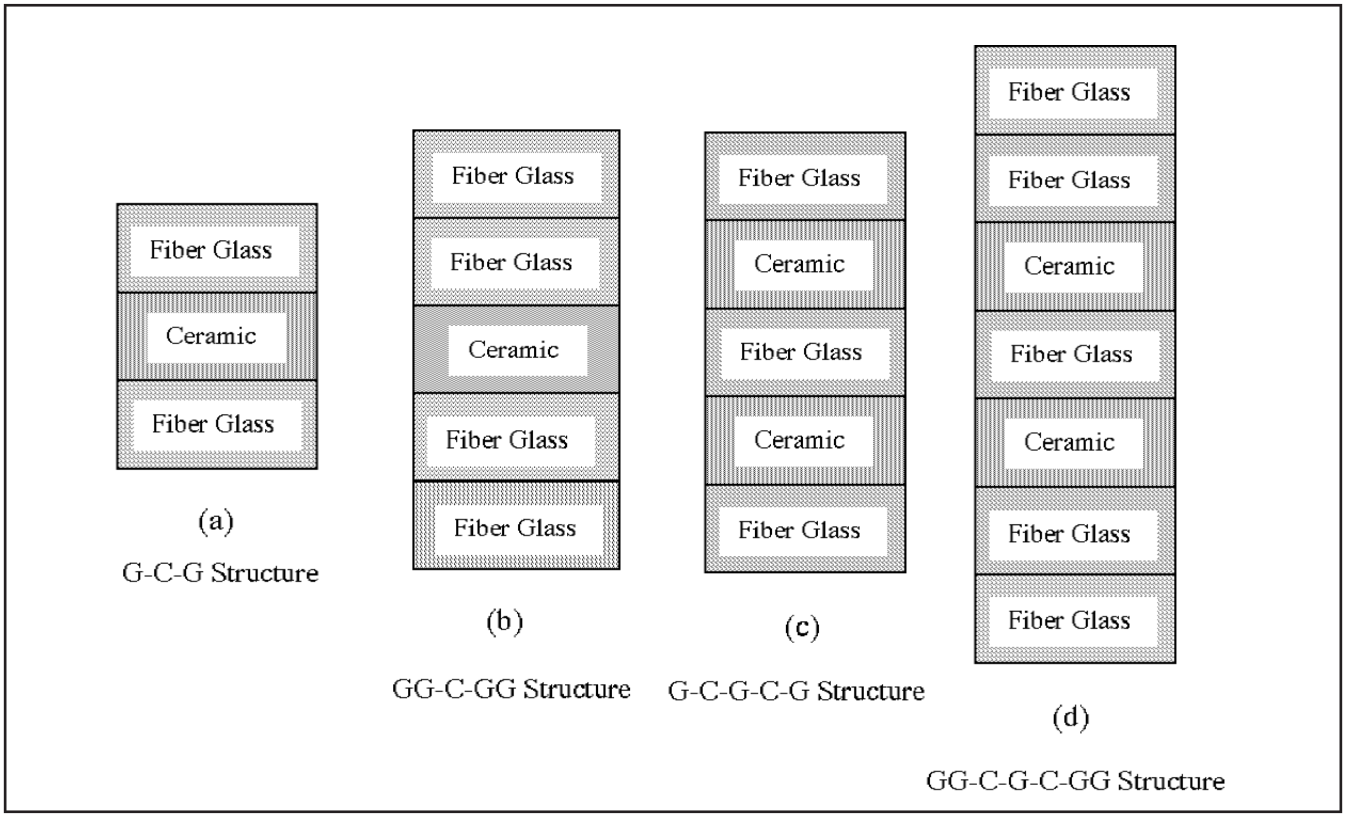
The webs were arranged as shown in *Figure 1*. Web arrangement was based on web thermal conductivity, ease of bonding and economics. The heat capacity of ceramic is higher than that of glass fibers. However, webs made from glass fibers and ceramic fiber webs with similar fiber diameters and densities, have equivalent thermal conductivities when tested at the same applied temperature [1, 4]. Also the glass fiber webs used in this research were more flexible than the ceramic webs. Thus, having glass webs on both surfaces of the sample made it easier to bond the webs together. Finally, adding glass webs to the structure decreases the cost of the insulation material since ceramic webs are more expensive than glass fiber webs.

The webs were bonded using a James Hunter needle-punching machine. A total of 575 needles were placed on the board, which has an area of 33 cm by 26 cm. The speed of the machine for all samples was 114 strokes per minute. Each side of the samples was needled twice. The needle penetration depth was set to within 2 mm of the sample thickness to assure that needles did not penetrate the entire thickness of the web. Needling in this fashion assured that channels supporting flow through the sample were created randomly. Along with varying the glass/ceramic layering structure, the number of barbs on the needles used for punching was also varied. Needles having 3, 6, or 9 barbs were used. Varying layer structure and number of barbs, twelve fabrics were produced. Four samples from each of the 12 fabrics were cut using an eight-inch diameter die.

Fabric Characterization

Physical characteristics measured for each sample included air permeability, thickness, weight, mean pore size and thermal conductivity. For all tests, average values using 4 samples per fabric were determined. The air permeability of each fabric was measured using the Frazier Permeability Tester. Specific details on the measurement of air permeability were presented in an earlier paper [5]. The thickness in centimeters of all samples was measured using an AMES 282 Gauge at zero pressure. Ten observations per sample were measured

Figure 1
SCHEMATIC DIAGRAM OF WEB ARRANGEMENT IN THE FABRIC INSULATION



and averaged to obtain the thickness of each fabric. The weight per area of the samples in grams/cm^2 was measured using a Lawson Precision Weighing Instrument. Four samples from each fabric were weighed and an average fabric weight was determined.

Temperature difference per unit thickness and thermal conductivity of the samples were determined using the Holometrix Guard Hot Plate (Model GHP-200). Forty-eight samples (4 fabric structures, 3 barbs, 4 repeats) were tested to measure change in temperature with time. The temperatures of the sample (cold and hot sides) were recorded every 30 minutes. This temperature difference was recorded until the fabric reached steady state. The sample was considered to be at steady state when the temperature difference between hot and cold side was constant for a 30-minute interval. Specific details of the determination of thermal conductivity were presented in an earlier paper [6].

Mean pore size for each fabric was determined by using an apparatus built at the North Carolina State University College of Textiles [9]. The test apparatus is shown in *Figure 2*. The fluid medium used in this research was distilled water. The surface tension used for water was 72.2. A two-inch diameter, circular sample was cut and weighed. The sample was presoaked in water for at least twenty-four hours prior to testing. It was weighed again to determine the weight of water and of the fabric sample, and then placed in the sample holding chamber. After establishing equilibrium, i.e., no change in fluid weight on the balance, the fluid weight and initial height of the chamber were recorded. The height of the chamber was moved in 1-millimeter increments, equilibrium was achieved, and the fluid weight and the chamber height were recorded again. If moving the chamber in 1-mm increments did not cause a change in the weight of the water, then the increment was slowly increased one mm at a time, up to a maximum of 1 centimeter, at which time there was a change in fluid weight. The fluid weight and chamber height were recorded at each change. This process was continued until the weight of the water in the bottle was approximately equal (within 0.02 milligrams) to the weight of water initially in the sample. The capillary pressure was determined by recording the difference in height of the meniscus and level of the bottle. This difference yielded a pressure in units of meters of water head. The capillary radius was calculated from equation 1. In equation 1, the capillary radius and capillary pressure are related by surface tension ∑, assuming the contact angle, ∑ is zero.

The mean pore size is determined by

$$\bar{x} = \frac{R_1\alpha_1 + R_2\alpha_2 + R_3\alpha_3 + \ldots + R_n\alpha_n}{\sum_{i=1}^{n}\alpha_i} \tag{4}$$

where $\bar{x}$ is the mean pore size of the sample, R_i is all pores of a given size and α_1 is the percentage the drainage from all pores of a given size. The sum of α_1 should be within 0.02 milligrams of the weight of water in the sample prior to testing. Three samples for each fabric were tested. The results of the experimental measurement of mean pore size are shown in *Table 1*.

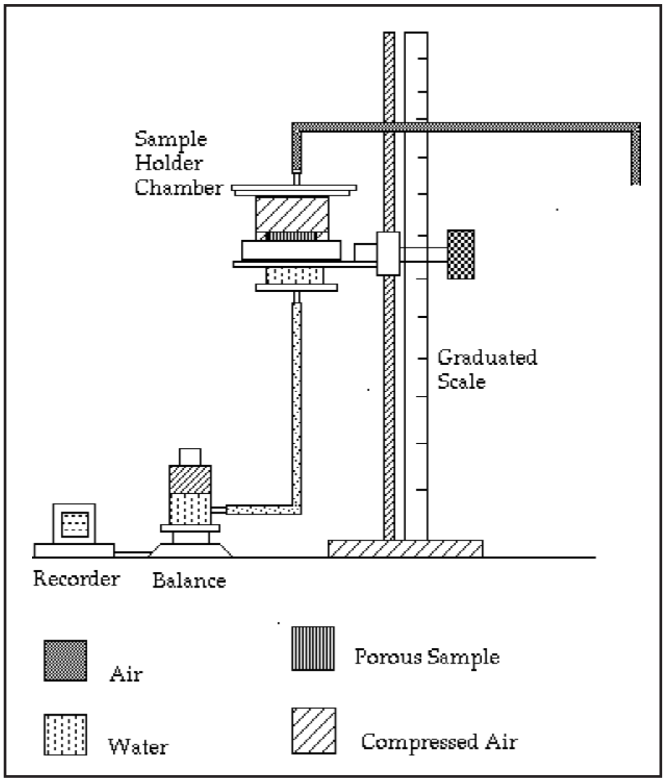


Figure 2
PORE SIZE DISTRIBUTION MEASUREMENT SYSTEM

Discussion of Results

Experimental measurements of air permeability and thermal conductivity of a multi-layered nonwoven fabric were presented in earlier papers [5, 6]. *Table 1* gives the material properties for the 12 fabric structures used in this research. *Table 2* gives the specific air permeability and the effective thermal conductivity coefficient for the 12 samples. The results reported in *Tables 1 and 2* are the averages of four samples for each structure. The specific air permeability, k^*_{fp}, given in *Table 2* is determined by

$$k^*_{fp} = \frac{(k_{fp})(L)}{\Delta P} \tag{5}$$

where ΔP in 0.5 inch water column is 124.5 Pa.

Using the SAS general linear model procedure [8], multiple regression analysis with backward elimination the feasibility of predicting the thermal conductivity from air permeability measurements was examined. A linear model was assumed. The regression analysis results are shown in *Table 3*.

Each of the three models given in *Table 3* shows the specific air permeability to be significant at greater than 99% confidence in predicting the effective thermal conductivity. The coefficient of determination (r^2) for each model was greater than 0.97 showing that each of these models would provide an accurate estimate of the effective thermal conductivity.

Considering the three models presented here and bearing in

Table 1
MATERIAL PROPERTIES OF NONWOVEN FABRICS SAMPLES

Number of Needle Barbs	**Fabric Structure**	**Weight** g/cm^2	**Thickness** cm	**Porosity**	**Mean Pore Size** microns	**Total Glass Thickness** cm
3 Barbs	G-C-G	0.129	1.69	0.9707	186.80	0.756
	GG-C-GG	0.181	2.37	0.9706	190.05	1.512
	G-C-G-C-G	0.221	2.50	0.9663	161.03	1.134
	GG-C-G-C-GG	0.252	2.98	0.9675	169.87	1.890
6 Barbs	G-C-G	0.131	1.58	0.9681	187.87	0.756
	GG-C-GG	0.170	2.06	0.9683	196.94	1.512
	G-C-G-C-G	0.218	2.40	0.9655	168.80	1.134
	GG-C-G-C-GG	0.263	2.98	0.9638	168.33	1.890
9 Barbs	G-C-G	0.143	1.84	0.9702	200.91	0.756
	GG-C-GG	0.175	2.07	0.9657	189.59	1.512
	G-C-G-C-G	0.231	2.27	0.9611	149.76	1.134
	GG-C-G-C-GG	0.270	2.66	0.9604	153.87	1.890

Note: All values are average of four samples. *Remaining thickness is due to ceramic content.

mind the goal of reducing the time required for determining the effective thermal conductivity of a sample, model 1 should be selected for use. Though model 1 has a slightly lower r^2 value, it requires the least amount of time, equipment and expertise to acquire data for all independent variables. The mean pore size measurement required in models 2 and 3 is very time consuming, requiring substantial sample preparation time and measurement time. The random nature of

Table 2
AIR PERMEABILITY AND THERMAL CONDUCTIVITY OF NONWOVEN SAMPLES

Number of Needle barbs	**Fabric Structure**	**Air Permeability** $cm^3/(cm^2s)$	**Specific Air Permeability** $cm^4/(dyn\ sec)$	ΔT °C	**Thermal Conducivity Coefficient** W/(m °C)
3 Barbs	G-C-G	17.54	0.02386	259.75	0.00096
	GG-C-GG	15.47	0.02939	267.92	0.00128
	G-C-G-C-G	11.82	0.02375	289.59	0.00119
	GG-C-G-C-GG	11.84	0.02832	293.76	0.00142
6 Barbs	G-C-G	16.17	0.02088	264.59	0.00088
	GG-C-GG	15.85	0.02624	266.62	0.00109
	G-C-G-C-G	11.68	0.02243	292.92	0.00116
	GG-C-G-C-GG	10.62	0.02242	301.26	0.00125
9 Barbs	G-C-G	16.38	0.02425	269.17	0.00099
	GG-C-GG	15.74	0.02614	269.59	0.00117
	G-C-G-C-G	11.12	0.02018	283.34	0.00114
	GG-C-G-C-GG	10.58	0.02266	302.09	0.00126

Table 3
STATISTICAL MODEL RESULTS FOR THERMAL CONDUCTIVITY

Model Number	Independent Variables	Estimate	Pr > _ t _	r^2
1	Fabric thickness	0.00023	0.0001	
	Fabric porosity	-0.01255	0.0362	0.9782
	Specific air permeability	0.02669	0.0011	
	Intercept	0.01211	0.0351	
2	Fabric weight	0.00204	0.0003	
	Fabric mean pore size	-0.02451	0.0446	0.9794
	Specific air permeability	0.03856	<0.0001	
	Intercept	0.00024	0.2760	
3	Thickness of glass	0.00022	0.0004	
	Thickness of ceramic	0.00018	0.0075	0.9836
	Fabric mean pore size	-0.02937	0.0200	
	Specific air permeability	0.02538	0.0009	
	Intercept	0.00060	0.0117	

needlepunched nonwoven samples and the sample thickness increase the time needed to accurately measure the mean pore size. The average time required for the samples in this study was 6 to 8 hours per sample. The porosity required in Model 1 can be easily calculated from measurements of the sample weight, thickness and cross-sectional area, and by knowing the fiber content and density of fibers in the sample [5]. Using Model 1, the relationship between effective thermal conductivity and air permeability is

$$\mathbf{k^*_{etc} = 0.02669\, k^*_{fp} + 0.00023\, L - 0.01255\, \varepsilon + 0.01211} \tag{6}$$

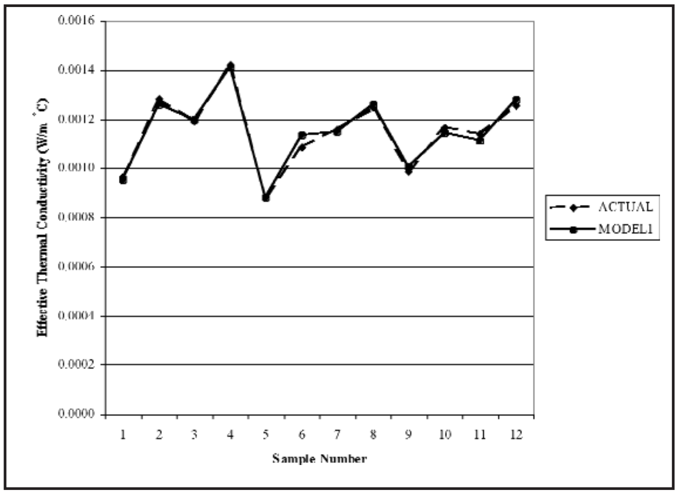
where k^*_{etc} is the predicted effective thermal conductivity, k^*_{fp} is the specific air permeability, L is the sample thickness, and ε is the sample porosity. *Figure 3* shows the comparison between the predicted k^*_{etc} and actual thermal conductivity coefficient, k_{etc}. There is very little deviation between the predicted and actual values.

Also it is important to note that the order in which the layers were arranged did not emerge as a significant factor in any of the acceptable models. The ceramic webs used in this research had very high packing density. It is believed that they were the dominant material influencing the effective thermal conductivity. Though the glass webs were not a major influence on the effective thermal conductivity of the samples, they were necessary for maintaining a stable fabric structure. The ceramic fibers were very short, making it impossible to hold the ceramic webs together by needling. The glass webs, having much longer fibers where used to help hold the ceramic webs together and stabilize the fabric structure.

Conclusions

In previous papers [5, 6] air permeability was experimentally measured and the effective thermal conductivity was calculated. In the present work, a design formula has been developed to predict the effective thermal conductivity coefficient from the specific air permeability. This equation was established using multiple regression analysis. Parameters studied for modeling purposes included fabric mean pore size, fabric weight, thickness of the glass and ceramic webs, number of needle barbs used in needle punching and fabric structure (layers). The predicted effective thermal conductivities, as a result of this design formula, were compared to the actual

Figure 3
COMPARISON OF ACTUAL AND PREDICTED EFFECTIVE THERMAL CONDUCTIVITY



thermal conductivities determined earlier [6].

Results show that the experimental specific air permeability does indeed accurately predict the thermal conductivity coefficient. Usage of the experimental specific air permeability yielded models with R-square values ranging from 0.9782 to 0.9836. In the most practical model, factors significant at 95% confidence included experimental air permeability, fabric thickness and fabric porosity.

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