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Comparing Dynamic and Static Methods for Measuring Thermal Conductive Properties of Textiles

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ABSTRACT

Dynamic and a static methods for measuring thermal conductivity of textiles have been developed, and the measuring processes and results are described in detail in this paper. Three different textile materials are used for the actual test, and the data are analyzed, illustrated, and compared. Moreover, a theoretical model is used to obtain the temperature-time curves as predictions corresponding to the dynamic method, and comparisons of the theoretical predictions and experimental results are provided. The static and dynamic methods are also compared, and their applicability to porous media like textiles is discussed.

The importance of the thermal properties of textiles is indisputable, and extensive research work has been done in this area. Hager [12] investigated, both experimentally and theoretically, the effects of radiant heat transfer on the thermal insulation of textiles. In a series of papers, Rees and colleagues [6, 22, 23] developed a thermal transmission apparatus for measuring the thermal properties of textiles, and analyzed the effects of various factors on the warmth or comfort of clothing from the viewpoint of thermal equilibrium between a human body and the clothing. Farnworth [11] proposed a theoretical model to predict the combined conductive and radiative heat flow through textiles. Stuart and Holcombe [26] studied the heat transfer through fiber beds by means of radiation and conduction. They reported that a portion of the radiated heat is absorbed by fibers in its path, resulting in a shadowing effect along the projected path. They then derived the heat transfer equations that take this shadowing effect into account.

Many of these studies involved the development of instruments for measuring textile thermal properties. Although recently several new techniques have emerged for thermal property measurement, including the heat pulse [3, 19], heat balance [16], heat wave [2], photothermal [7], and photoacoustic [17] methods, the approach that uses a hot plate and a thermocouple remains an effective technique for textile materials. After reviewing previous research and existing experimental devices for measuring fabric thermal properties, Martin and Lamb [18] developed a dynamic measurement apparatus. Two layers of measured material are heated up to 125°C and then placed between two metal plates at room temperature. The temperature decrease at the center line of the sample is recorded and thermal diffusivity is thus calculated, but the method has some problems. First, the material being measured is heated to a rather high temperature, which may significantly change its composition as well as its thermal properties. The high temperature also induces intense radiant heat transfer, which is difficult to take into account. Further, it is hard to determine exactly the time and temperature of the beginning of the cooling process because of the time required to mount the sample, during which irregular cooling occurs. In addition, heat transport between the sample and the metal plates generally depends on the pressure between them, and the exact pressure is difficult to determine because of the unknown compressional behavior of the measured material.

A textile structure is essentially a mixture of fibers, air, and moisture, each having distinctively different thermal properties, so the thermal behavior of the system is the collective and interactive results of these three constituents. Furthermore, textile materials are

porous with a very easily distortable structure and ill-defined boundary surfaces. As a result, several critical measuring conditions have to be strictly observed to obtain reliable and meaningful test results.

First, once a textile surface is heated, a temperature gradient develops along the thickness of the fabric, and as a result, forced convection caused by the air in the pores of the textile occurs. This forced convection will greatly alter the thermal response of the textile, and adds some uncertainty to the measurement process and the results.

Also, unless a noncontact measuring technique is used, the testing result will probably vary, depending on the contact pressure applied to the textile, because of the potential connection between its thermal conductivity and its thickness, *i.e.*, the proportion of air in the fabric. Consequently, a mechanism maintaining a stable and constant pressure during measurement becomes crucial. Next, besides a highly stable heat source, the surrounding temperature and relative humidity have to be either controlled or closely monitored, since the heat transfer rate is known to be proportional to the temperature difference between the heat source and the sample, which at equilibrium retains the surrounding temperature. The ambient relative humidity will determine the concentration of the moisture in the sample and hence its thermal properties. In addition, the dynamic response of the material during the transient period of the thermal measurement process is, by definition, a function of time. Therefore, the timing of every step during the whole testing procedure is another very important variable. It is also not easy to eliminate the influences of boundary conditions and other factors occurring during the time of measurement. We will further elucidate these issues in the section on measurement procedures.

We have developed and tested a new dynamic measurement method for thermo-insulating properties of textiles, and we consider the feasibility of testing the thermal behavior of textiles using this approach. We also test the same samples using a static method. The dynamic method measures the transient process during heating of a specimen, whereas the static method offers a result after the heating process is stabilized. The experimental devices and testing procedures are designed to minimize the influence of the boundary conditions on the results. Sample compression during measurement is easily and exactly controlled, and the measuring devices are easy to assemble in a laboratory at low cost, compared with the devices used in either the standard test method [1] or the previous studies.

Moreover, we apply a theoretical model to predict the heating process of the measurements corresponding to the dynamic method. We compare and discuss theoretical and experimental temperature values in the samples during the heating process, as well as the results obtained from both methods. We also examine their applicability to porous media.

Determining Thermal Conductivity

Thermal conductivity is the most important parameter describing the thermal behavior of a material. However, with different methods, there are different ways to determine this property.

STATIC METHOD

In the case of a static method, which is very similar to ASTM C518, Standard Test Method for Steady-State Heat Flux Measurements, the thermal conductivity of a material is calculated from [21]

$$\lambda = \frac{CLU}{\Delta T} \quad , \tag{1}$$

where λ is the thermal conductivity ($Wm^{-1}K^{-1}$), C is the constant of the sensor ($Wm^{-2}\mu V^{-1}$), L is the thickness of the sample (m), U is the input voltage to the sensor (V), and ΔT is the temperature difference between the two surfaces of the specimen (°C). Since we know all the other parameters, once we obtain U and ΔT, we can calculate the thermal conductivity of the specimen from Equation 1.

DYNAMIC METHOD

It is less direct to determine λ in a dynamic method. First, we have to find another parameter, thermal diffusivity α, which can be derived from a temperature-time curve describing the heating process of the specimen. The temperature curve can be obtained through experiment using a dynamic method or through theoretical prediction.

There are several theories for predicting the heating process of materials, including those for heat conduction in a finite slab [5] and those for a semi-infinite body [10]. For simplicity, we have adopted the theory for a semi-infinite slab, *i.e.*,

$$\frac{\partial T}{\partial \tau} = \alpha \frac{\partial^2 T}{\partial^2 x} \quad , \tag{2}$$

where T is the temperature (°C), τ is the time (s), x is the distance from the heat source (m), and α is the thermal diffusivity (m^2s^{-1}).

The initial conditions for this equation include T_H, the constant temperature of the heat source (°C), and T_o, the temperature of the samples at $\tau = 0$ (°C, the

ambient temperature). The solution of the equation can be expressed as

$$T(x, \tau) = T_H + \frac{2(T_o - T_H)}{\sqrt{\pi}} \int_0^{\xi} e^{-\xi^2} d\xi \quad , \quad (3)$$

where $\xi = \frac{x}{2\sqrt{\alpha\tau}}$. We then use the Taylor series to obtain the specific solution of the temperature distribution $T(x, \tau)$ at position x and time τ:

$$T(x, \tau) = T_H + \frac{2(T_o - T_H)}{\sqrt{\pi}} \times \sum_{n=0}^{\infty} \left[(-1)^n \frac{\xi^{2n+1}}{(2n+1)n!} \right] \quad . \quad (4)$$

Thus, we can obtain the value of α from this result using experimental data. In Equation 4, T_o and T_H are both given values. From an experimental curve measured at a given position x and time τ, we can find the specific value for $T(x, \tau)$. By assuming different values for α and bringing them into Equation 4, we can calculate a theoretical value for $T(x, \tau)$. The thermal diffusivity of the material is then determined as the α value, which yields a difference smaller than a given error allowance between the experimental and theoretical values for $T(x, \tau)$. We have developed a computer program for this α value calculation, where $n = 30$ is set in evaluating the Taylor series.

The validity of Equation 2 or 4 to a particular material can be tested using the well-known criterion

$$\frac{2L}{\sqrt{4\alpha\tau}} \leq 0.50 \text{ or } \tau \geq \frac{4L^2}{\alpha} \quad , \quad (5)$$

where L is the thickness of the material. Using the data in Tables III and IV, we have found that for materials 1 and 2, the observation time of $\tau > 400$ seconds, and for material 3, $\tau > 7$ seconds, are required in order to satisfy the criterion.

Once the thermal diffusivity is available, the thermal conductivity can be readily calculated using the relation from [14]

$$\lambda = \alpha c \rho \quad , \quad (6)$$

where λ is the thermal conductivity ($Wm^{-1}K^{-1}$), c is the specific heat of the measured material ($JKg^{-1}K^{-1}$), and ρ is the specific weight of measured material (Kgm^{-3}).

Experimental

Measuring Devices

Dynamic Method

The measuring device (Figure 1) consists of a metal vessel (2) heated by constantly circulating water at a flow speed of 5 l/min from a thermostat (1) so that a constant temperature is maintained at the bottom of the vessel, which serves as a heat source. The distance L is pre-selected to maintain an accurate given pressure on the sample (3) to be tested. A thermocouple (4) is placed at position x. The signal generated from the thermocouple is fed into a recorder (5) where it is processed and a time-temperature curve is generated. To achieve accurate timing, a contact switch is placed at point a in Figure 1 to synchronize the heating and measurement processes.

Static Method

The device for the static method is shown in Figure 2 and has two metal vessels. The upper vessel (3) is heated exactly as for the dynamic method, but the lower vessel (4) is connected to circulating water at room temperature, also at a flow speed of 5 l/min, from another thermostat (2). The distance L is precisely set by means of an adjustable support (7) placed under the lower vessel to assure a given pressure on the sample (5). A 50 × 50 mm heat flux sensor (6) is mounted on the surface of the lower vessel, coinciding with the center of the sample. Again, a time-temperature curve is generated from the recorder (10) so as to insure that the heating process has stabilized before taking a measurement.

In order to determine the exact temperature difference ΔT between the upper and lower surfaces of the sample, two differential thermocouples (8) are placed such that one is on the surface of the heat flux sensor at the lower vessel and the other is on the upper surface of the sample tested, both aligned vertically. The signal generated by the differential thermocouples is fed into a recorder (9), and the exact ΔT can be read using a voltage-ΔT calibration graph.

Calibration of Methods

To assure the accuracy of the testing results, we first used a homogeneous nonporous material to check the testing methods, in this case, a poly(ethylene terephtalate) film, 0.2 mm thick with various numbers of layers, tested by both static and dynamic methods for thermal conductivity. The results are listed in Table I, and each value is the average of five measurements with a maximum CV of 12%.

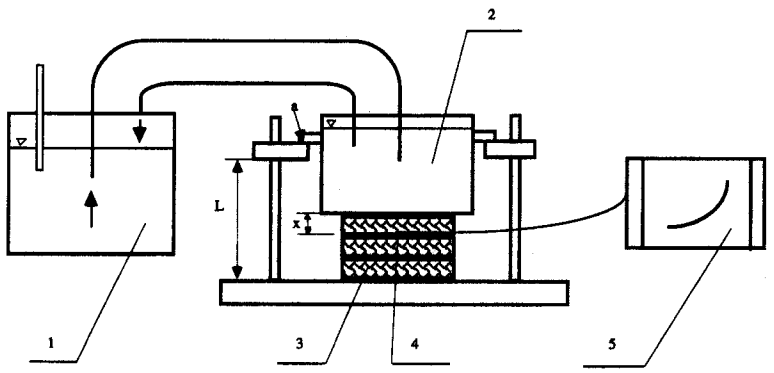

FIGURE 1. Device for the dynamic method: (1) thermostat, (2) vessel with circulating water, (3) textile sample, (4) thermal couple, (5) recorder, (a) contact switch, (x) thickness of measured sample (distance between sensor and hot plate).

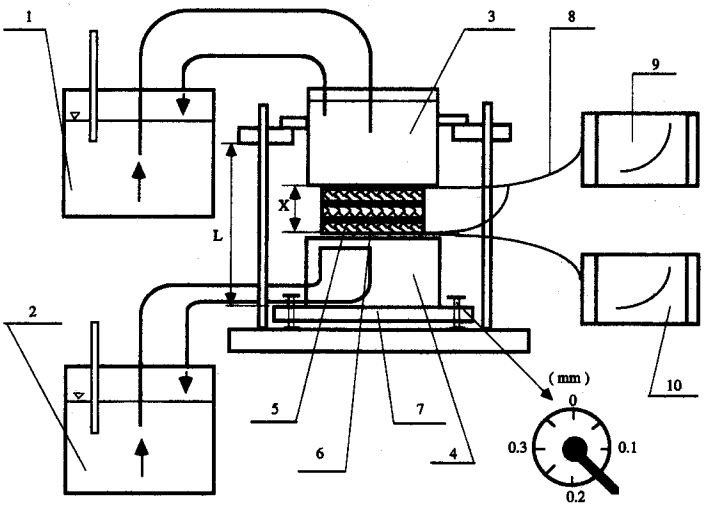

FIGURE 2. Device for the static method: (1) thermostat for the upper vessel, (2) thermostat for the lower vessel, (3) heated upper vessel with hot circulating water, (4) lower vessel with circulating water at ambient temperature, (5) textile sample, (6) heat flux sensor, (7) adjustable support, (8) differential thermocouple, (9) recorder, (10) recorder.

Several things can be said about the results. First, the thermal conductivities tested by both methods agree with the typical value for the material provided in the handbook [13, 15]. This demonstrates the reliability of both testing devices. Also, the results corresponding to both test methods are consistent with each other, indicating that for such a homogeneous nonporous material, the thermal conduction process is stabilized after an extremely short transient process in both testing methods. There is no temperature and time-dependent convection, which would lead to a very complicated thermal interaction process in a porous material, as we will discuss later. Furthermore, in both tests, the apparent independence of the test results with the number of layers again reveals the intrinsic nature of the thermal conductivity of a solid, homogeneous, nonporous material.

TABLE I. Thermal conductivity of a PET film tested by both static and dynamic methods.

Number of layers	Static method, $W\ m^{-1}\ K^{-1}$	Dynamic method, $W\ m^{-1}\ K^{-1}$
1	0.182	0.187
2	0.186	0.197
3	0.182	0.175
4	0.182	0.182
5	0.179	0.188
6	0.184	0.182
7	0.184	0.182
8	0.184	0.189
10	0.182	0.188
12	0.188	0.180
14	0.187	0.191
16	0.184	0.183

Finally, we used the static method to test the thermal conductivity of the air between the heated and cold plates of the device. The sides of the measured space were carefully insulated to prevent outside thermal convection. The results in Table II are in excellent agreement with the established theories [20]: when the distance is very small, the air confined in the test area does

TABLE II. Air thermal conductivity and its dependence on distance, tested by the static method.

Distance between plates, mm	Air conductivity, $W\ m^{-1}\ K^{-1}$
1.5	0.0268
2.0	0.0264
2.5	0.0261
3.0	0.0255
4.0	0.0277
5.0	0.0275
6.0	0.0281
7.0	0.0293
8.0	0.0304
9.0	0.0318
10.0	0.0353
11.0	0.0375
12.0	0.0394
13.0	0.0442

not move. Thus, the thermal conductivity is very close to the theoretical value of still air, confirming the accuracy of the testing device. When the distance grows beyond 8 mm, however, thermal conductivity increases significantly with increasing distance, revealing the occurrence of a thermal convection.

Materials Tested

We selected three different textiles for testing: first, nonwoven fabric 1, 75% polyester (PET), 11 dtex, 25% biocomponent of polyester/co-polyester (PET/co-PET), perpendicularly laid and thermobonded; second, nonwoven fabric 2, 75% recycled PET, 25% polypropylene (PP), perpendicularly laid and thermobonded; and third, a knitted jersey of 100% polyamide (nylon).

The area weight was measured according to EDANA 40.3-90 [8] and the thickness measured according to EDANA 30.4-89 [9] under a pressure of 100 Pa. Table III lists the specific weight under a pressure of 100 Pa and the specific heat of each fabric estimated by mass fractions of the different proportions of the fibers in the samples, using data from reference 13.

Measurement Conditions

For the dynamic method, the samples were circles with a 0.14 m diameter, the thermocouple was Cr/CrNi with a 0.1 mm diameter wires, the temperature of the heated plate was 40 ± 0.1°C, the original temperature of the samples (ambient temperature) was 19–21°C, the measurement time was 5–120 seconds, and the position of the thermocouple was under various numbers of sample layers.

For the static method, the samples were circles of the same diameter, the heat flux sensor was an Omega HFS, the differential thermocouples were Cr/CrNi with 0.1 mm diameter wires, the temperature of the heated plate (upper vessel) was 40 ± 0.1°C, the temperature of the bottom plate (lower vessel) was 19–21 ± 0.1°C, the original temperature of the samples (ambient temperature) was 19–21°C, and the time of measurement was 5–20 minutes, depending on the thermal conductivity of the sample.

Because of the limit of our facilities, all the testing was done in a room where temperature and humidity were not controlled. In order to minimize the effect of the ambient environmental condition, we quickly completed all the measurements at one time so that environmental changes during this relatively short time would not generate any significant error. Besides, all the samples were hydrophobic with properties that were much less susceptible to humidity variations.

Measurement Procedures

For the dynamic method, the number of layers of material to be tested was determined based mainly on the thickness of the sample. Before testing, a fixed weight representing a given pressure was placed on top of the layered sample, and the thickness of the sample was measured so that the distance L on the device could be adjusted accordingly. The sample was then placed on the measurement device and the vessel was placed on the sample, as shown in Figure 1. The two holders supporting the partial weight of the vessel, depending on the chosen distance L, assured exactly identical pressure on the sample. After the vessel was positioned, the heating and recording processes started simultaneously owing to the control of the contact switch.

For the static method, the first two steps were the same as in the dynamic method. The lower temperature part of the differential thermocouple was placed on the heat flux sensor at the bottom vessel. The sample to be tested was placed on the measurement device, and the higher temperature part of the differential thermocouple was placed on the sample surface. The heated vessel was put on the sample with the two holders so that the chosen pressure could be applied. The output signals of the heat flux sensor and the differential thermocouple were stabilized, and the voltage of the output U and the temperature difference ΔT were then recorded.

Results and Discussion

From Figure 1 for the dynamic method, we used the vertical position of the thermocouple in the specimens as a representation of the total thickness of the material. For the static method in Figure 2, we used the number of layers of the specimens between the differential thermocouples.

TABLE III. Fabrics and their parameters under 100 Pa pressure.

Material	Area weight, K gm^{-2}	Thickness, m	Specific heat c, J kg^{-1} K^{-1}	Specific weight ρ, K gm^{-3}
1	0.34	0.0120	1380	28.3
2	0.40	0.0068	1390	58.8
3	0.091	0.0003	1890	303.3

The materials under investigation are listed in Table III with their specifications. The values of thermal diffusivity α and thermal conductivity λ obtained through the dynamic method are listed in Table IV. We measured a number of fabric layers (six layers for materials 1 and 2 and twenty layers for material 3), and placed the thermocouple under various numbers of layers in each specific experiment. The position of the thermocouple was expressed as the distance x from the heated plate. Each data value was the mean of five tests. The *CV* values were between 1.5–11.2% in various experiments.

TABLE IV. Thermal properties of materials tested with the dynamic method.

Material	Position of thermocouple, m	α, m^2 s^{-1}	λ, W m^{-1} K^{-1}
1	.0120	1.45 10^{-6}	.057
	.0240	1.53 10^{-6}	.060
	.0360	1.45 10^{-6}	.057
2	.0068	4.65 10^{-7}	.038
	.0136	6.85 10^{-7}	.056
	.0204	5.99 10^{-7}	.049
3	.0006	5.23 10^{-8}	.030
	.0009	7.50 10^{-8}	.043
	.0012	8.02 10^{-8}	.046
	.0015	8.19 10^{-8}	.047
	.0018	9.42 10^{-8}	.054
	.0021	1.08 10^{-7}	.062
	.0024	1.15 10^{-7}	.066
	.0027	1.32 10^{-7}	.076

EFFECT OF PRESSURE

We tested the influence of pressure or specimen compression. The pressure influence on the thermal conductivity values as a function of sample thickness for material 3, for instance, are shown in Figure 3. The results did not differ considerably at three pressure levels of 100, 500, and 1,000 Pa, so we chose 100 Pa as the standard pressure for all the tests. At this range, pressure had no significant effect on all sample types. This conclusion is consistent with that reported in reference 4, and has been found to be the case for both dynamic and static methods.

EFFECT OF SPECIMEN THICKNESS

From Table IV and Figure 4, we see that for the dynamic method, the effect of the position of the ther-

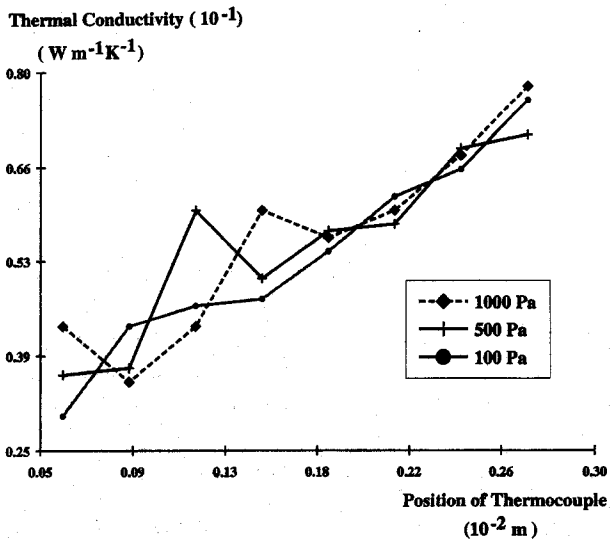

FIGURE 3. Thermal conductivity λ measured by the dynamic method as a function of the position of the thermocouple at various levels of pressure for material 3.

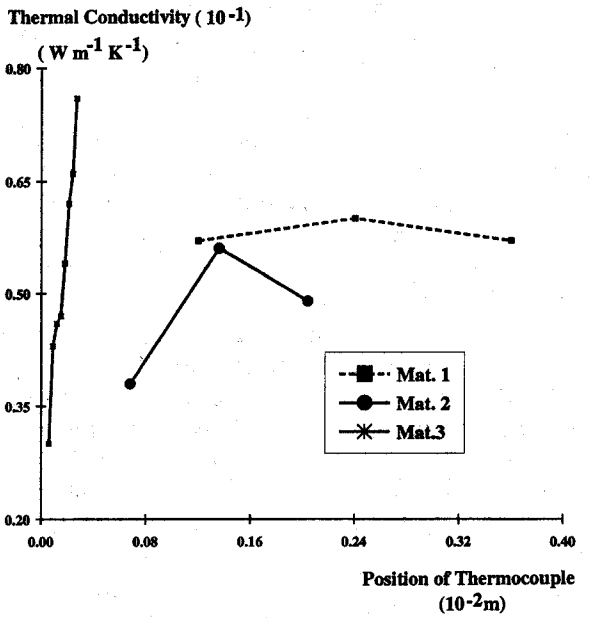

FIGURE 4. Thermal conductivity λ measured by the dynamic method as a function of the position of the thermocouple for the three materials.

mocouple on the testing results varies depending on the specimen type; it has the most dramatic effect on material 3, less so on material 2, and barely any on material 1, corresponding exactly to their density ranks. The higher the density or specific weight, the greater the influence of specimen thickness.

For the static method, on the other hand, the effect of numbers of layers is less significant than in the dynamic case, as shown in Table V and Figure 5. For materials 1 and 2, an increased number of layers leads to a slight reduction in thermal conductivity. The effect on material 3 fluctuates, but the average value seems to remain constant, meaning there is no net influence from the thickness change. The *CV* values are between 0.7 and 7.8% in various tests.

TABLE V. Thermal conductivity of materials tested with the static method.

Material	Number of layers	λ, W m^{-1} K^{-1}
1	1	.048
	2	.045
	3	.044
2	1	.035
	2	.034
	3	.033
3	2	.049
	3	.049
	4	.051
	5	.052
	6	.047
	7	.049
	8	.049
	9	.047

The unique behavior of material 3 is likely due to the change in heat transport mechanism. In fibrous media at the relatively low density $\left(<100\ \frac{kg}{m^3}\right)$ to which the materials 1 and 2 belong (as shown in Table III), heat transport is mainly through air and thermal radiation. At higher densities, such as the case of material 3, conduction by fibers becomes significant.

COMPARISON OF DYNAMIC AND STATIC METHODS

As opposed to the previous case of polymer film, for fibrous media there is a significant difference between the results obtained with the dynamic and static methods, as shown in Tables IV and V. When all conditions are the same, the thermal conductivity λ measured by the dynamic method is generally higher. As mentioned above, λ values from the dynamic method depend on specimen thickness; it is less so in the case of the static method. Additional

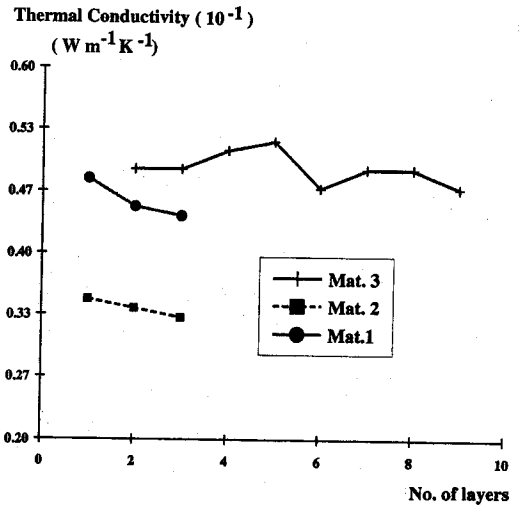

FIGURE 5. Thermal conductivity λ measured by the static method as a function of the number of layers for the three materials.

thermal resistance due to residual air layers between specimens and between specimen and heated plate, as suggested by Martin and Lamb [18] to explain the dependence of measured values on the number of layers, has no noticeable effect in the case of the static method.

The higher tested thermal conductivity and the position dependence of the results of the dynamic method actually reveal an intrinsic characteristic of this approach. The dynamic method deals by nature with an unstable transient process. The thermal gradient in the specimen established during testing will incite air movement within the internal structure of porous materials, leading to the higher thermal conductivity and position dependence due to unstable residual air between specimen layers. We will discuss this issue in more detail later.

EDGE COOLING EFFECTS

To test the effects of heat loss through the sides of the measured sample, we placed thermo-insulating layers of glass microfiber material, whose thermal conductivity $\left(0.027\ \frac{W}{mK}\right)$ is close to that of air $\left(0.026\ \frac{W}{mK}\right)$, with an outer diameter of 210 mm and an inner diameter of 150 mm, to enclose the specimens. This insulation is effective if the total thickness of the specimens is less than 30 mm. Beyond this limit, further thermal insulation at the sides of the specimens is needed to prevent edge cooling effects.

THEORETICAL PREDICTION AND THE DYNAMIC METHOD

To further study the thermal properties of the materials, we compared the theoretical and experimental temperature-time curves obtained by the dynamic method. The time-temperature curves can be seen in Figures 6 and 7 for materials 2 and 3, respectively, with the sensor placed at various positions represented by the number of layers. As shown in the figures, for a given material at a specific position, the temperature of the specimen increases steadily along with time. For the same material, however, the thinner the total specimen thickness, represented by a smaller number of layers, the more quickly the temperature rises. From each curve, we can take a temperature reading $T(x, \tau)$ at time τ, which can then be used as the input of the aforementioned computer program to determine the thermal diffusivity α. Once the α value is known, a theoretical $T(x, \tau)$ prediction (*i.e.*, the time-temperature curve) can be readily obtained using Equation 4. These theoretical curves are also provided in Figure 6.

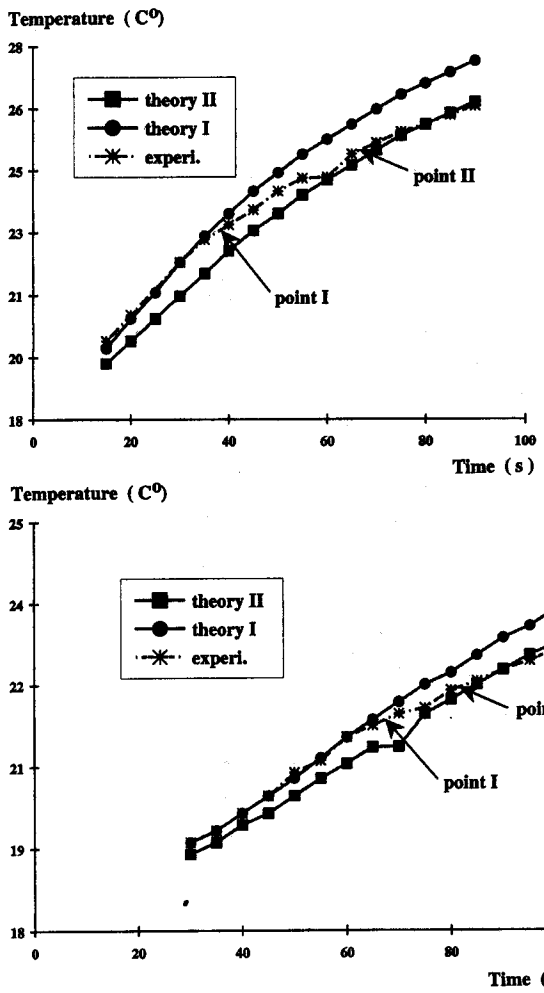

FIGURE 6. Experimental and theoretical time-temperature curves with the dynamic method for material 2: (top) result with one layer of the material, (bottom) result with two layers of the material.

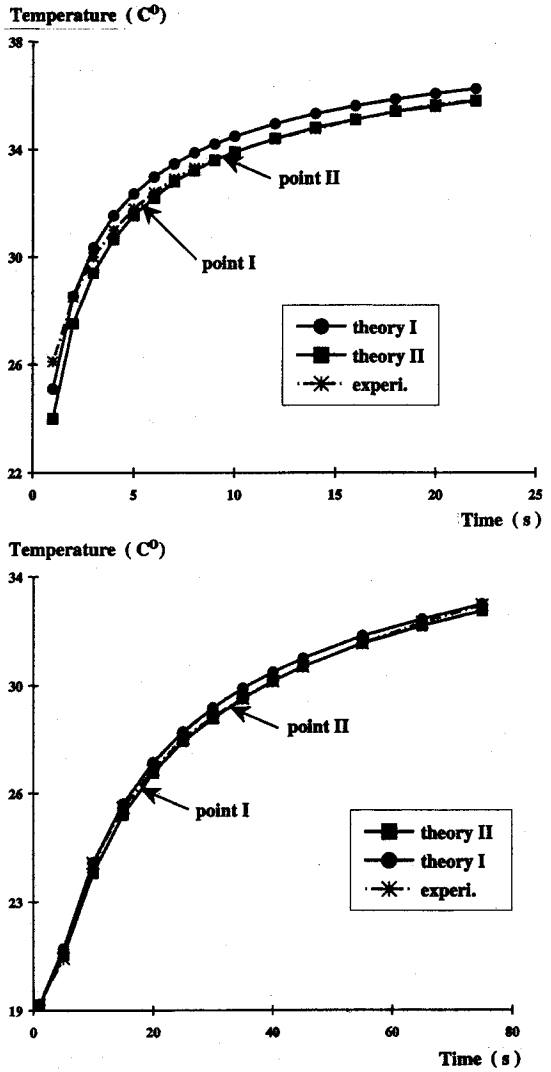

FIGURE 7. Experimental and theoretical time-temperature curves with the dynamic method for material 3: (top) result with one layer of the material, (bottom) result with five layers of the material.

In order to check for other possible errors, we have chosen two $T(x, \tau)$ readings (points I and II) at different times indicated by the arrows in Figures 6 and 7 from each of the experimental curves, and two values of thermal diffusivity and the corresponding theoretical curves are calculated and plotted in Figures 6 and 7. Because thermal diffusivity is supposed to be an intrinsic property of a material, it should be independent of external conditions such as specimen size and time. In

other words, the two values of thermal diffusivity thus determined should be identical, and the two curves thus generated should coincide with one another. However, although the two theoretical curves (theories I and II in the figures) are both in good agreement with the experimental result in each case, a certain discrepancy exists between the two theoretical curves.

In fact, the dynamic method deals with a transient period in which different kinds of dynamic mechanisms interact or compete with each other to determine the test result. For instance, during the process, the thermal gradient in the specimen changes with time and is a driving force for natural convection, which may be distorting the measured results. The extent of the convection depends on the changing rate in the thermal gradient, which is a function not only of time, but also of the thermal properties and internal structure (such as pore size, pore shape, and distribution) of the specimen. For example, Figure 6 for material 2 shows that there is a temperature drop at both experimental curves, representing a sudden increase in overall thermal conductivity and a change in the heat transport pattern. All the figures also show that the prediction using point I (theory I in the figures) is always greater than that using point II (theory II). This indicates that for the same fabric, the longer we wait before taking the estimated thermal diffusivity value from the experimental curve, the greater result we will get, which leads to faster heat transfer in the fabric and a smaller temperature reading at a given time.

The results are similar in Figure 7 for the denser material 3, in which heat transfer by fiber conduction rather than air convection is dominant. Also, from Equation 5 we find that for material 3, the observation time is $\tau > 7$ seconds, whereas for material 2, $\tau > 400$ seconds. In other words, the theoretical model is more applicable to material 3 than to material 2 at the time scale indicated in Figures 6 and 7. This may explain the smaller discrepancy between the two theoretical curves in Figure 7.

This mechanism of thermal convection in a porous material caused by its internal thermal gradient is very complex and unpredictable, and seems thus to present an inherent problem when applying the dynamic method to porous media. Therefore, we can conclude from this study that the static method is more suitable for porous materials such as textiles because the result is much more stable. Nevertheless, it is possible that a combination of both methods can be used to study the internal structure of porous media by examining the discrepancy between their results.

We should also mention that when a textile material is subjected to heating, there is likely to be some sorption or desorption of moisture from the fibers, and this could cause temperature variations due to phase change, as for instance, Simonson *et al.* [24, 25] pointed out. However, since the fibers in this study are all hydrophobic, this effect is considered negligible. We are currently working on some hydrophilic materials to study the moisture effect on textile thermal properties.

Conclusions

For both static and dynamic methods at the range investigated in this study, the pressure on the specimen has minor effects on the results of thermal conductivity. For the static method, there is a less significant dependence of the test results on the number of specimen layers. For the dynamic method however, when testing thick specimens, material thermal conductivity is strongly related to the vertical position of the thermocouple or the total specimen thickness tested.

A considerable difference exists between the results obtained by dynamic and static methods. For a specimen at the same testing conditions, the thermal conductivity measured by the dynamic method is generally higher, probably because of the thermal convection due to the thermal gradient associated with the transient period within the porous specimens.

Once the thermal diffusivity is determined using the experimental results, the theoretical model applied in this work provides the time-temperature relationship during the heating process of the materials. However, it fails to predict a change of heat transfer pattern, which we believe is again caused by thermal convection during the transient period of the heating process.

Since this convection process is complex, dynamic, and extremely sensitive to pore size, pore nature, and distribution and is thus very unstable, we do not recommend the dynamic method for porous media like textiles. Nevertheless, it is possible that the combination of static and dynamic methods can be used to study the internal structure of porous media by examining the discrepancy between the results of the two methods.

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Literature Cited

1. ASTM D1518-85 Standard Test Method for Thermal Transmittance of Textile Materials.
2. Bauer, S., and Ploss, B., A Heat Wave Method for the Measurement of Thermal and Pyroelectric Properties of Pyroelectric Films, *Ferroelectrics* **106,** 393–398 (1990).
3. Bristow, K. L., Kluitenberg, G. J., and Horton, R., Measurement of Soil Thermal Properties with a Dual-Probe Heat-Pulse Technique, *Soil Sci. Soc. Am. J.* **58,** 1288–1294 (1994).
4. Broughton, R., Hall, D., Brady, P., Shanley, L., and Slaten, B. L., The Use of a New Carbonaceous Fiber in Thermal Insulative Battings, *INDA J.* **5,** 38–42 (1993).
5. Crank, J., "The Mathematics of Diffusion," 2nd ed., Clarendon Press, Oxford, 1975.
6. Clulow, E. E., and Rees, W. H., The Transmission of Heat Through Textile Fabrics, Part III: A New Thermal Transmission Apparatus, *J. Textile Inst.* **59,** 285–294 (1968).
7. Coufal, H., Photothermal Methods for the Measurement of Thermal Properties of Thin Polymer Films, *Polym. Eng. Sci.* **31,** 92–98 (1991).
8. EDANA 40.3-90, Mass per unit area test, ERT, Feb. 1996.
9. EDANA 30.4-89, Thickness test, ERT, Feb. 1996.
10. Kreyszig, Erwin, "Advanced Engineering Mathematics," 7th ed., John Willey & Sons, NY, 1993.
11. Farnworth, B., Mechanism of Heat Flow Through Clothing Insulation, *Textile Res. J.* **53,** 717–752 (1983).
12. Hager, N. E., and Steere, R. C., Radiant Heat Transfer in Fibrous Thermal Insulation, *J. Appl. Phys.* **38,** 4663–4668 (1967).
13. Holzmuller, W., and Altenburg, K., "Physik der Kunstoffe," Academie Verlag, Berlin, 1993.
14. Jirsak, O., and Hes, L., Die warmeisolierenden Eigenschaften nichtgewebter Textilien als Funktion ihrer Zusammenpressung, *Melliand Textilber.* **69,** 325–329 (1988).
15. Kroschwitz, J., Ed., "Encyclopedia of Polymer Science and Technology," vol. 13, John Willey & Sons, NY, 1970, p. 781.
16. Luo, A. H., Youdelis, W. V., and Wang, W. Q., Measurement of Thermal Properties for Sand Molds—A Heat Balance Approach, *Can. Metallurg. Quar.* **31,** 73–77 (1992).
17. Mansanares, A. M., Bento, A. C., Vargas, H., and Leite, N. F., Photoacoustic Measurement of the Thermal Properties of 2-Layer Systems, *Phys. Rev. B Condensed Matter* **42,** 4477–4486 (1990).
18. Martin, J. R., and Lamb, G. E. R., Measurement of Thermal Conductivity of Nonwovens Using a Dynamic Method, *Textile Res. J.* **57,** 721–727 (1987).
19. McMenamin, C. S., Bird, J. P., Brewer, D. F., and Hussey, N. E., Heat Pulse Measurement of Thermal Properties—An Improved Fitting Technique, *Cryogenics* **33,** 941–946 (1993).
20. Micheew, M. A., "Osnovy Teploperedaci," Gosenerizdat, Moscow, 1949.
21. Omega, "Operator's Manual: Thin Film Heat Flux Sensors," Omega USA, 1994, p. 2-2.
22. Peirce, F. T., and Rees, W. H., The Transmission of Heat Through Textile Fabrics, Part II, *J. Textile Inst.* **37,** T181 (1946).
23. Rees, W. H., The Transmission of Heat Through Textile Fabrics, *J. Textile Inst.* **32,** T149 (1946).
24. Simonson, C. J., Tao, Y. X., and Besant, R. W., Thermal Hysteresis in Fibrous Insulation, *Int. J. Heat Mass Trans.* **36,** 4433 (1993).
25. Simonson, C. J., Tao, Y. X., and Besant, R. W., Thermal Performance and Hysteresis in Fibrous Insulation Exposed to Moisture and Step Changes in the Cold Temperature Boundary Condition, *Energy Build.* **21,** 251 (1994).
26. Stuart, I. M., and Holcombe, B. V., Heat Transfer Through Fiber Beds by Radiation with Shading and Conduction, *Textile Res. J.* **54,** 149–157 (1984).

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