



Convection/diffusion test method for porous textiles

Phillip Gibson, Donald Rivin and Cyrus Kendrick
*US Army Natick Research, Development and Engineering Center,
Massachusetts, USA*

Received 2 June 1998
Accepted 2 December 1999

Keywords *Convection, Gas, Textiles, Porous materials*

Abstract *Reports on an automated apparatus and test procedure to determine the convective and diffusive gas and vapor transport properties of small pieces of woven and nonwoven fabrics, membranes, and foams. The apparatus allows measurement of these properties in the very small quantities typical of material development programs, where the largest sample available may only be 1-10cm² in area. The convection/diffusion test method is useful for determining the gas flow resistance property and water vapor diffusion properties from a single experimental run. This eliminates the need for two separate tests, which is the usual procedure. The apparatus may also be used to perform separate tests for the diffusion property or the air permeability property, which may have some advantages when materials exhibit strongly concentration-dependent transport properties. The convection/diffusion test method is well-suited for rapid screening and comparison of the properties of a large number of materials with widely-varying transport properties.*

Introduction

Vapor transfer through clothing systems may occur due to diffusion (driven by vapor concentration gradients), and convection (driven by air pressure differences). Convective heat and mass transfer in porous media such as textiles is often more important than transport due to diffusion, especially if such materials are used in conditions where a large pressure gradient is present. Laboratory test methods for textiles usually concentrate on one transport mechanism, to the exclusion of the others. Diffusion test methods are particularly easy to perform, and often become the primary ranking and evaluation method for determining the transport properties of textiles. Such test methods can be very misleading for textiles, particularly those which have high air permeability, since a very small pressure gradient can produce large convective flows through the porous structure, far outweighing any diffusive transport which takes place.

The usual procedure is to determine the water vapor diffusion properties and the air permeability properties separately. For textiles, water vapor diffusion test methods include the ASTM test method for water vapor transmission of materials (E 96), and the ISO test method for measurement of thermal and water vapour resistance under steady-state conditions (ISO 11092). Air permeability properties may be determined by a textile test method, ASTM D737-75, standard test method for air permeability of textile fabrics. This method, however, is quite limited in that it is more useful for quality-control

testing due to its prescription for testing at a single pressure differential (124.5 Pa). A more accurate test method is ASTM F778-88, standard methods for gas flow resistance of filtration media.

All the methods mentioned above are time-consuming, require large amounts of material, and are not capable of a very wide range of test conditions. They also require two separate kinds of tests to be run to characterize the potential of a given material to transport water vapor through its structure: a water vapor diffusion test and an air permeability test. It would be very appealing to have a test method available that can determine the diffusion and convection properties from the same test, and to be able to directly compare the results obtained between materials as different as air-impermeable membrane laminates, very air-permeable knitted fabrics, woven fabrics, and complicated nonwoven and polymeric foam structures. It would also be appealing to have this test method able to measure these properties in very small quantities typical of material development programs, where the largest sample available may only be 1-10cm² in area.

The method described here, based on the dynamic moisture permeation cell (DMPC) (Gibson *et al.*, 1995a, 1995b) satisfies the need for a quick, automated method that can test the mass transport properties of very small pieces of woven and nonwoven fabrics, membranes, and foams. The focus of this paper is to describe the use of this test method to obtain the water vapor diffusion property and the air permeability property from a single test. The DMPC may also be used to perform separate tests for the diffusion property or the air permeability property, which may have some advantages when materials exhibit strongly concentration-dependent transport properties.

Experimental method

A schematic of the DMPC test arrangement is shown in Figure 1.

Nitrogen streams consisting of a mixture of dry nitrogen and water-saturated nitrogen are passed over the top and bottom surfaces of the sample. The relative humidity of these streams is varied by controlling the proportion of the saturated and the dry components. By knowing the temperature and water vapor concentration of the entering nitrogen flows, and by measuring the temperature, water vapor concentration, and flow rates of the nitrogen flows leaving the cell, one may measure the fluxes of gas and water vapor transported through the test sample.

With no pressure difference across the sample, transport of water vapor proceeds by pure diffusion, driven by vapor concentration differences. If a pressure difference across the sample is present, transport of vapor and gas includes convective transport, where the gas flow through the sample carries water vapor with it, which may add to or subtract from the diffusive flux, depending on the direction of the convective gas flow.

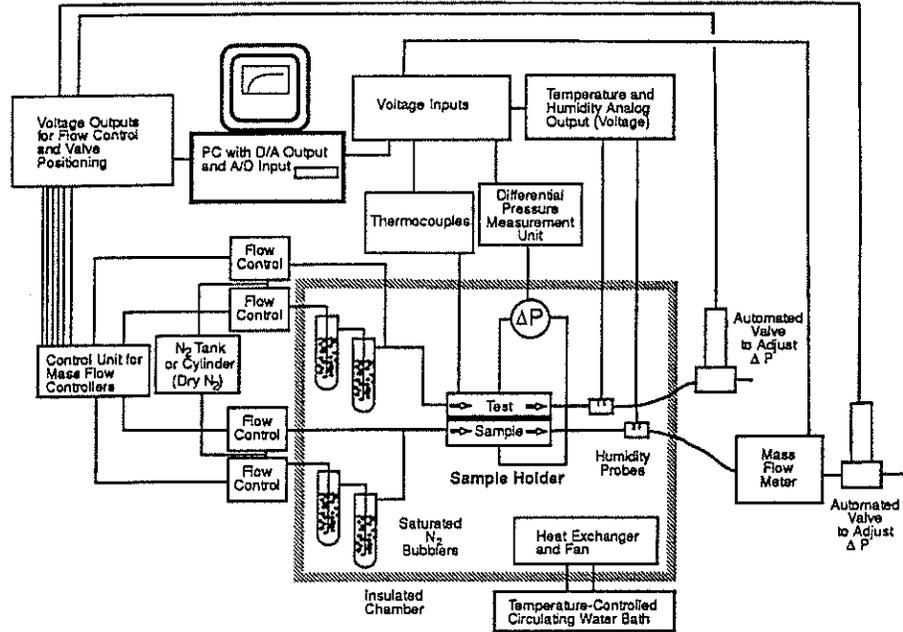


Figure 1.
Schematic of DMPC test
arrangement

Review of water vapor diffusion test method

The use of the DMPC for determining water vapor diffusion properties will be reviewed first, followed by a description of the diffusion/convection test method. The following equations for calculating water vapor flux apply to either the top or bottom flows in the cell. Strictly speaking, only one measurement on one side of the cell is necessary; the use of two separate humidity transducers for the top and bottom flows allows two measurements of water vapor flux to be made at the same time, using the equations given below for either the top or bottom flow, as appropriate. Further details on this test method are available (Gibson *et al.*, 1995a, 1995b, 1997a).

For this type of test, the mass flow rate of water vapor diffusing through the test sample from one side of the cell to the other is given by:

$$\frac{\dot{m}}{A} = \frac{Q(\delta C)}{A} = \frac{Q(C_2 - C_1)}{A} \quad (1)$$

\dot{m} = mass flux of water vapor across the sample [kg/s]

A = area of test sample [m²]

Q = volumetric flow rate through top or bottom portion of the cell [m³/s]

δC = $C_2 - C_1$, water vapor concentration difference between incoming stream (C_1) and outgoing stream (C_2) in top or bottom portion of the moisture permeation cell [kg/m³]

The incoming water vapor concentration is determined by the ratio of the mass flows of the saturated and the dry nitrogen streams. The mass flow rates are controlled by MKS model 1259C mass flow controllers, with a Model 247C 4-Channel Readout (MKS Instruments, Inc.). These mass flow controllers can control mass flow rate at an accuracy of ± 0.8 per cent of full scale, with a response time of less than two seconds. At constant mass flow, the true volumetric flow rate will vary with temperature; the flow rate set by the MKS controllers is indicated in terms of volumetric flow rates at standard conditions of 0°C and atmospheric pressure ($1.01325 \times 10^5\text{Pa}$). The actual volumetric flow rate at different temperatures may be found from the mass flow rate, the temperature, and the pressure of the actual flow.

For water vapor diffusion, the critical measurement is the outgoing flow water vapor concentration C_2 , which can be measured in a variety of ways. In the work reported here, capacitance-type relative humidity probes (Vaisala HMI 32 or 38) with Type HMP 35 or 37 sensors were used (Vaisala Inc.), which are adequate for materials which have significant vapor flux across them. The advantage of these probes is that they have a relatively fast response time (5-30 seconds: response time slower at higher humidities), which is useful for transient studies. The probes are listed by the manufacturer as having an accuracy of ± 1 per cent from 0-90 per cent relative humidity, and ± 2 per cent from 90-100 per cent relative humidity.

The measurement accuracy of these probes may be improved to ± 0.5 per cent by determining a calibration curve *in situ*. This is done by placing an impermeable aluminum foil sample in the cell and varying the relative humidity of the gas flow in the top and bottom of the cell by means of the flow controllers. The resulting curves (at increments of 10 per cent r.h.) of measured relative humidity versus true relative humidity (set by the flow controllers) are used as calibration factors to correct the measured relative humidity for subsequent tests. Sorption hysteresis of the hygroscopic polymer used in the capacitance probe make any further improvements in probe accuracy difficult.

For test materials which have small vapor fluxes, requiring measurements at very low concentrations, an 1100DP Dew Point Hygrometer (General Eastern Instruments, Inc.) may be used. For the highest accuracy, an M200 Gas Chromatograph (MTI Analytical Instruments, Inc.) has also been used as the concentration measurement device, but this is much less convenient in the practical sense of a routine test.

To obtain the water vapor concentration in the outgoing air stream, one must be able to convert from the known values of relative humidity and temperature to water vapor concentration. The vapor pressure of saturated water vapor, in air is obtained from an empirical formula (or tables) as a function of temperature, and then converted to concentration using the perfect gas law.

Automated
Valve
to Adjust
 ΔP

will be
on test
apply to
ly one
separate
ements
s given
on this

ugh the

(1)

[m^3/s]

coming
n of the

We may express the water vapor transmission rate in terms of the indicated volumetric flow rate at standard conditions, the humidity difference, and the temperature:

$$\frac{\dot{m}}{A} = \frac{\delta\phi Q_s p_s M_w}{ART_s} \quad (2)$$

100

- M_w = molecular weight of water vapor [18.015kg/kmole]
 Q_s = volume flow rate at standard conditions of 0°C and atmospheric pressure [m³/s]
 R = universal gas constant [8314.5N·m/kg·°K]
 T_s = reference temperature at standard conditions of 0°C in degrees K (273.15K)
 p_s = saturation vapor pressure of water [Pa]
 $\delta\phi$ = $\phi_2 - \phi_1$, relative humidity difference between incoming stream (ϕ_1) and outgoing stream (ϕ_2) in top or bottom portion of the moisture permeation cell
 ϕ = p_v/p_s , relative humidity
 p_v = vapor pressure of water [Pa]

For the present test apparatus, various sample holders are available, which have different test sample measurement areas, and which have different downstream locations from the flow inlet. All test results given in this study used a sample measurement area of $1.0 \times 10^{-3} \text{m}^2$, and the sample was located equidistant from the inlet and outlet ports of the cell. The typical volumetric flow rate used was $3.33 \times 10^{-5} \text{m}^3/\text{s}$ (2,000cm³/min). The dimensions of the DMPC were chosen to assure flow velocities of at least 0.5m/s over the sample to minimize the contribution of boundary air layer resistances to the test measurements. Details of the sample holder are shown in Figure 2.

The sample sizes are kept quite small to make it possible to evaluate novel membranes and laminates, which are often produced in quantities too small for testing by some of the standard water vapor diffusion test methods. The small sample area makes it necessary to test at different locations across a typical roll of fabric to adequately characterize a given material. Sample mounting methods vary according to the material being tested. Thin materials, such as laminated materials and woven cloth, were originally tested with rubber sealing gaskets to prevent leakage, but the sealing proved to be unnecessary for most materials; the clamping force provided by the mounting bolts has proven to be sufficient to prevent any leakage. Thick materials which are highly permeable require special sealing methods such as edge sealing by molten wax, or the use of a curable sealant. The testing of thicker materials also requires a larger sample area to minimize factors such as edge effects.

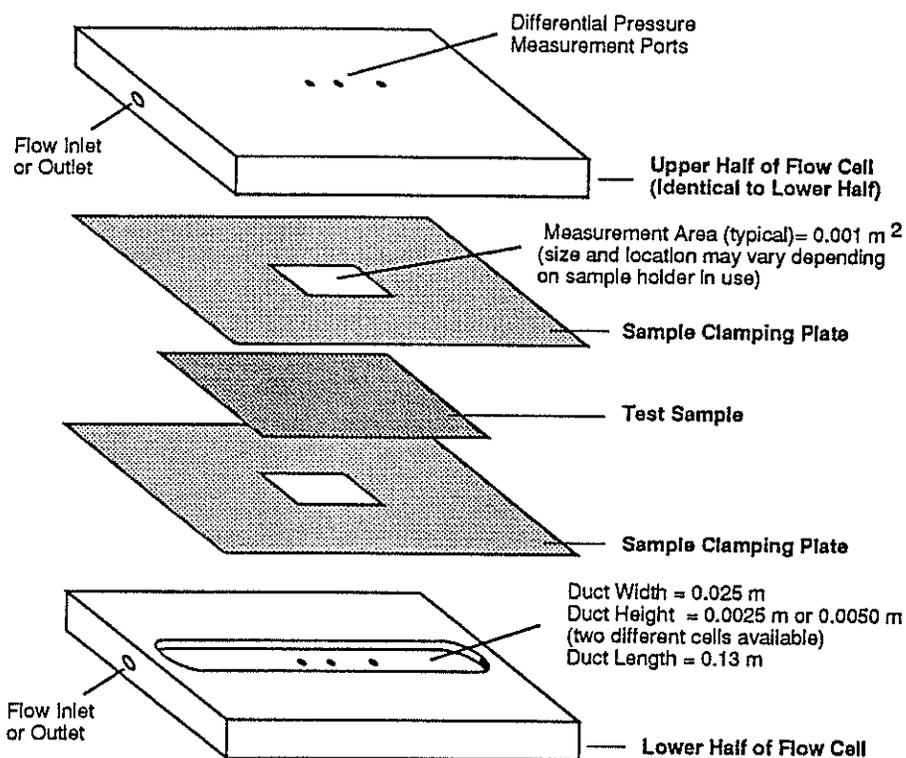


Figure 2.
Schematic and
dimensions of the
sample holder for the
DMPC

Diffusion test procedure

The actual test is conducted under the control of a personal computer (PC) connected to the flow controllers, automated valves, and the various measurement transducers through input and output boards (see Figure 1). Various options exist within the software for operator input setpoint information, or preset files containing the setpoint information. The computer applies the proper setpoint voltage to each controller to produce the desired relative humidity in the upper and lower gas streams entering the DMPC. The A/D board in the PC reads analog voltage outputs of the relative humidity, RTD, thermocouples, differential pressure transducer, mass flow meters, etc., records the data on disk, calculates parameters of interest, and plots results to the PC screen. The software applies operator-determined equilibration criteria to determine when equilibration has been reached for that setpoint. Once equilibration is reached, the results (humidity, calculated flux, etc.) may be output to a printer and to a data file on disk. The computer then proceeds to the next setpoint and repeats the process.

The pressure drop across the sample is monitored by means of an MKS Baratron Type 398 differential pressure transducer, with a Type 270B signal conditioner (MKS Instruments, Inc.). For measurement of pure diffusion, especially for materials such as fabrics, which may be quite permeable to

convective flows, it is important to make sure that the pressure drop across the sample is zero, so that transport takes place only by pure diffusion. The pressure drop is continuously monitored and displayed, and is controlled by means of two automated valves at the outlets of the cell. For the permeable fabrics, this system also allows one to do testing under controlled conditions of a defined pressure drop across the sample, so that transport takes place by both diffusion and convection (which will be described later). This makes it possible to determine an air permeability value from the apparatus, in addition to the water vapor diffusion properties of the test sample.

Materials which have a constant mass transfer coefficient show a linear slope on plots of flux versus concentration difference across the sample. These materials do not change their transport properties as a function of water content or test conditions.

For materials which do not have a constant slope, the data points for a test series will not superimpose, but will form a set of curves for each test condition. From an evaluation of the flux versus concentration difference curve at various points we can calculate values for the material diffusion resistance, which will be a function of the concentration of water in the material.

We define a total resistance to mass transfer as the simple addition of an intrinsic diffusion resistance due to the sample (R_i) and the diffusion resistance of the boundary air layers (R_{bl}):

$$\frac{\dot{m}}{A} = \frac{\Delta \bar{C}}{R_i + R_{bl}} \quad (3)$$

$$R_i = \left[\frac{\Delta \bar{C}}{\left(\frac{\dot{m}}{A} \right)} \right] - R_{bl} \quad (4)$$

\dot{m} = mass flux of water vapor across the sample (kg/s)

A = area of test sample (m²)

$\Delta \bar{C}$ = log mean concentration difference between top and bottom gas streams (kg/m³)

R_i = intrinsic diffusion resistance of sample (s/m)

R_{bl} = diffusion resistance of boundary air layers (s/m)

The log mean concentration difference across the sample is appropriate since there is a significant change in the concentration of the gas stream both below and above the sample. In addition, the gas streams may not necessarily be in parallel unidirectional (cocurrent) flow, but may be run in counter flow to

maintain a more constant concentration gradient across the sample. The log mean concentration difference (Geankopolis, 1972) is defined as:

$$\Delta \bar{C} = \frac{\Delta C_a - \Delta C_b}{\ln(\Delta C_a / \Delta C_b)} \quad (5)$$

ΔC_a = concentration difference between the two gas streams at one end of the flow cell (kg/m^3)

ΔC_b = concentration difference between the two gas streams at other end of the flow cell (kg/m^3)

For parallel cocurrent flow, the concentration differences are between the top and bottom incoming flow at one end of the cell (ΔC_a), and the difference between the top and bottom outgoing flows at the other end of the cell (ΔC_b). For countercurrent flow, the concentration differences are between the incoming and outgoing flows at one end of the cell (ΔC_a), and the incoming and outgoing flows at the other end of the cell (ΔC_b).

Use of DMPC for convection/diffusion studies

The DMPC may also be run with a specified pressure drop across the sample so that transport takes place by both diffusion (driven by concentration differences) and convection (driven by gas phase pressure differences). The simplest experiment to run is shown in Figure 3. Gas enters the DMPC at a relative humidity of 0.90 (90 percent r.h.) on the top portion of the cell, and 0.0 (0 percent r.h.) on the bottom of the cell. The automated valves are used to restrict the flow on one or the other sides of the cell. This causes the pressure in one side of the cell to be higher than in the other, causing convective flow across the sample, in addition to the diffusion flux taking place due to the concentration gradients.

Measurements are taken as a function of pressure drop across the sample, where the convective flow and pressure drop are gradually increased in stepwise increments. In addition to the pressure drop, it is useful to have an actual measurement of gas flow through the sample. An electronic mass flow

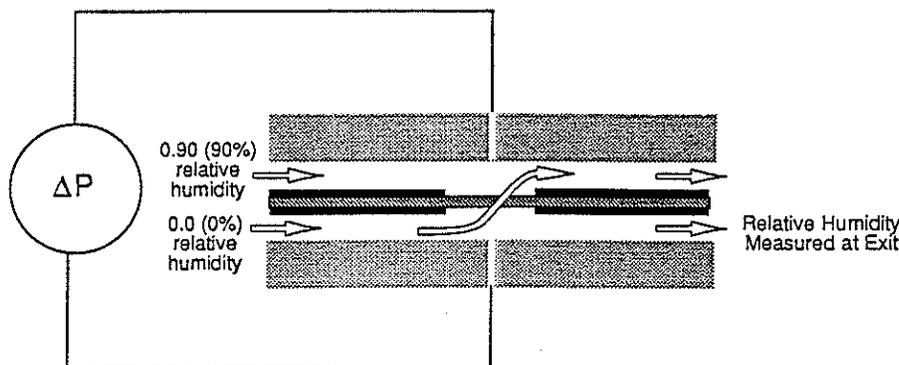


Figure 3.
Convection/diffusion
experiment in the
DMPC: example shows
bottom outlet flow
restricted to force
convective flow across
sample, which opposes
diffusive flux of vapor

meter (Model 822 Top-Trak, Sierra Instruments, Inc.), connected to the lower outlet of the cell as shown in Figure 1, is used to record the mass flow rate of gas through the test material.

In this paper, the diffusion/convection test method will be demonstrated for three typical materials:

- (1) A microporous polytetrafluorethylene (PTFE) membrane, with low water vapor diffusion resistance, but a high resistance to convective gas flow (low air permeability).
- (2) A knit polyester fabric with a slightly greater resistance to water vapor diffusion, but very low air flow resistance (high air permeability).
- (3) A woven nylon fabric with still higher water vapor diffusion resistance, and an air flow resistance intermediate between the other two materials.

Further diffusion/convection test results are available for a wide variety of woven fabrics, nonwoven filter materials, clothing insulation layers, novel electrospun nanofiber membranes, and military chemical protective clothing systems (Gibson *et al.*, 1998). In addition, correlations and comparisons are available for results obtained with the DMPC and standard water vapor diffusion tests (Gibson *et al.*, 1995a, 1995b, 1997a) or standard air permeability tests (Gibson *et al.*, 1998).

Typical measurements of water vapor diffusion resistance, and mass flow rate as a function of pressure drop, are shown in Figures 4 and 5 for the three materials.

Figure 4, which shows flow rate as a function of pressure drop, is directly related to the air permeability of the material. The greater the slope of the line for a given material, the greater the air permeability. Figure 4 shows that the

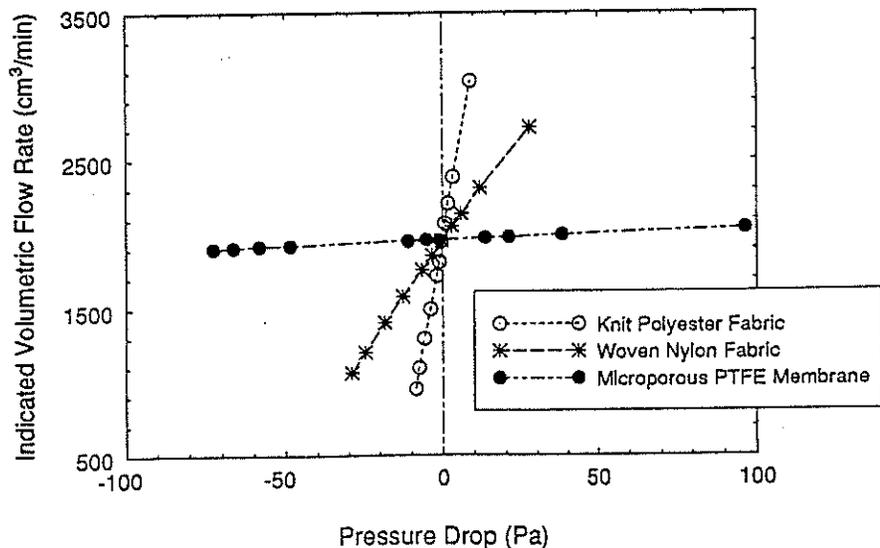


Figure 4.
Flow rate through fabric
as a function of pressure
drop

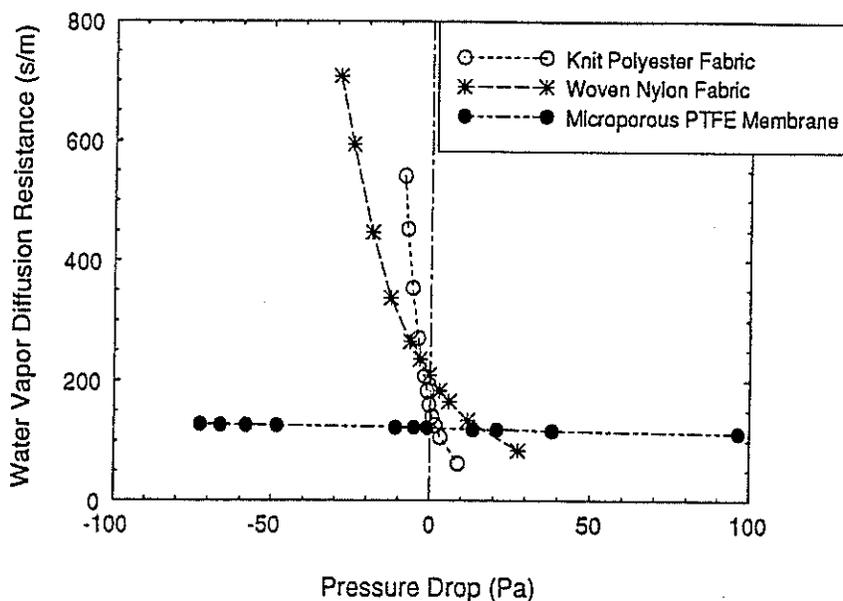


Figure 5.
Diffusion resistance as a
function of pressure
drop

microporous PTFE membrane has a very low air permeability (high flow resistance), the knit polyester fabric has a high air permeability, and the woven nylon fabric is intermediate between the other two materials. Calculation of the air flow resistance from the data in Figure 4 will be discussed later.

Figure 5 shows the apparent water vapor diffusion resistance as a function of pressure drop. This plot illustrates the interaction of convective and diffusive transport. The intersection of each material's curve with the $\Delta P = 0$ point on Figure 5 defines the true water vapor diffusion value for that material. This is illustrated with an expanded scale in Figure 6.

At the condition of 0 pressure drop, the PTFE membrane has the lowest diffusion resistance, followed by the knit polyester, with the nylon fabric having the highest diffusion resistance. This PTFE membrane has previously been shown to have a diffusion resistance of about 6-8 s/m (Gibson *et al.*, 1995a). This means that the boundary layer resistances in this flow cell (defined by flow rates and flow geometry) are approximately 115 s/m. Thus the true diffusion resistance of each material is equal to the difference between its total resistance from Figure 6, and the boundary layer resistance. The resulting intrinsic diffusion resistances are 6 s/m for the PTFE membrane, 96 s/m for the nylon fabric, and 36 s/m for the polyester fabric. These values agree well with those obtained previously for these materials (Gibson, 1996).

However, since these materials differ greatly in their air permeability properties, the change in apparent diffusion resistance as the pressure drop increases is quite different for the various materials. The PTFE membrane has a nearly constant diffusion resistance, due to its low air permeability. Because

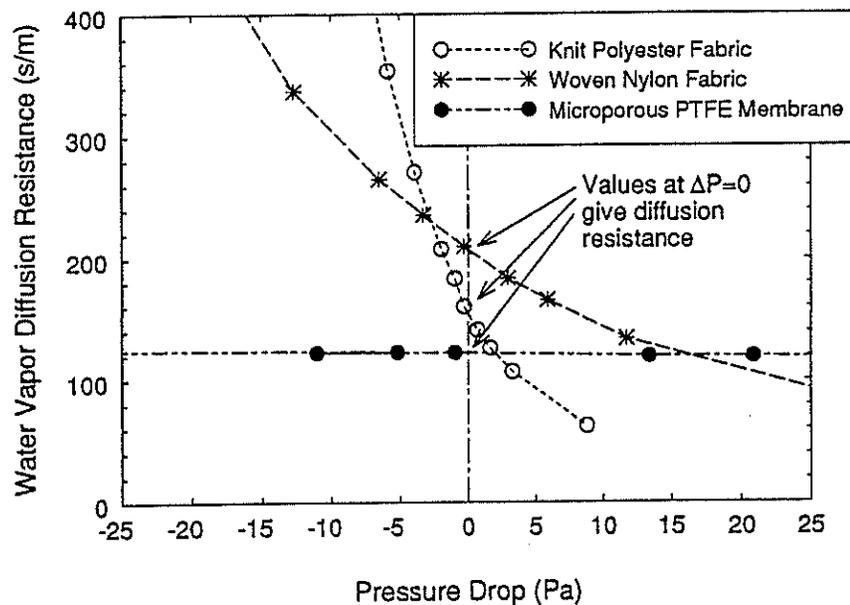


Figure 6.
Use of diffusion/
convection data to
define true diffusion
resistance

of the polyester fabric's high air permeability, even at very low pressure drops (for example at 10 Pa), its apparent diffusion resistance is less than that of the PTFE membrane.

The ability to conduct testing over a range of pressure drops increases the accuracy of the water vapor diffusion value. It is clear that slight variations in pressure drop across a sample with high air permeability will greatly influence the measured water vapor diffusion resistance. Diffusion test methods which do not control or monitor the convective flow through the sample are prone to measurement and ranking errors caused by air flow through the sample.

The characteristic curve shown in Figure 6, which illustrates the interaction between diffusive and convective transport, is more realistic in terms of the transport processes taking place in clothing systems, where both modes of transport take place at the same time. Water vapor diffusion properties alone, which may rank materials such as the PTFE membrane as superior to more air-permeable materials, can be very misleading when ranking candidate materials for comfortable or breathable clothing systems.

Calculating air flow resistance

There are many definitions of the permeability or the flow resistance; most often the permeability is given by Darcy's Law (Dullien, 1979) such that:

$$v = \frac{-k_D \Delta p}{\mu \Delta x} \quad (6)$$

v = apparent gas flow velocity (m/s)

- k_D = permeability constant (m^2)
- μ = gas viscosity (17.85×10^{-6} kg/m-s for N_2 @ $20^\circ C$)
- Δp = pressure drop across sample (N/m^2 or Pa)
- Δx = thickness (m)

For low velocity flows, where the apparent Reynolds number (based on nominal particle diameter or pore sizes) is much less than ten, a plot of pressure drop versus volumetric flow rate or velocity will give a constant value for the permeability constant k_D . At higher flow rates, where inertial effects begin to compete with viscous flow effects, pressure drop – flow rate plots will begin to deviate from linearity, and inertial effects need to be considered. Previous work on air penetration through clothing systems has shown that air pressure differences across textile layers, due to factors such as wind or body movement, are usually less than 100 Pa (Kind *et al.*, 1991; Take-uchi, 1989; Stuart and Denby, 1987; Fedele *et al.*, 1986). For the testing presented in this paper, flow rates and pressure drops are low enough so that inertial effects are not readily apparent in the experimental results.

The DMPC operated in the diffusion/convection mode provides plots of pressure drop versus either mass flow rate or volumetric flow rate, seen previously in Figure 4. Volumetric flow rate is the most convenient to use, so the permeability constant may be found from:

$$k_D = \left(\frac{\mu Q}{A} \right) \left(\frac{\Delta x}{\Delta p} \right) \quad (7)$$

- μ = gas viscosity (17.85×10^{-6} kg/m-s for N_2 at $20^\circ C$)
- Q = total volumetric flow rate (m^3/s)
- A = apparent sample flow area ($1.0 \times 10^{-3} m^2$ for DMPC sample holder)
- Δx = thickness (m)
- Δp = pressure drop across sample (N/m^2 or Pa)

For textiles, although thickness measurements seem simple, they are often problematic, and can be a large source of error if they are incorporated into reported measurements of Darcy permeability. It is preferable to present the pressure-drop/flow rate results in terms of an apparent flow resistance defined as:

$$(6) \quad R_D = \left(\frac{A \Delta p}{\mu \Delta_{total}} \right) \quad (8)$$

- R_D = apparent Darcy flow resistance (m^{-1})

The volumetric flow rate shown in Figure 4, measured by the electronic mass flow meter, is the equivalent volumetric flow rate at the reference temperature (T_0) of 0°C (273.15 K), and reference atmospheric pressure (p_0) of 1.01325×10^5 Pa. The actual volumetric flow rate at a given temperature may be found from the mass flow rate indicated by the electronic mass flow meter (Q_0), the ambient temperature (T_a), and the ambient pressure of the actual flow (p_a). The pressure correction is negligible ($p_0/p_a \cong 1$), so only the temperature correction needs to be made. The correction to obtain the actual volumetric flow rate (Q_{total}) from the indicated mass flow rate (Q_0) is:

$$Q_{total} = Q_0(T_a/T_0)(p_0/p_a) \cong Q_0(T_a/T_0) \quad (9)$$

Note that the quantity ($\Delta p/Q_{total}$) is equal to the inverse of the slopes of the curves shown in Figure 4 (after correcting to the proper temperature as shown above). Figure 4 may be replotted as shown below in Figure 7.

Thus the air flow resistance can be found from the slope of each curve in Figure 7, using the known flow area and gas viscosity according to equation (8). For the three materials shown in Figure 7, the equivalent air flow resistance is $2.78 \times 10^7 \text{ m}^{-1}$ for the polyester fabric, $1.14 \times 10^8 \text{ m}^{-1}$ for the nylon fabric, and $4.25 \times 10^9 \text{ m}^{-1}$ for the PTFE microporous membrane. These values agree with those obtained previously for these materials by another method (Gibson *et al.*, 1997b).

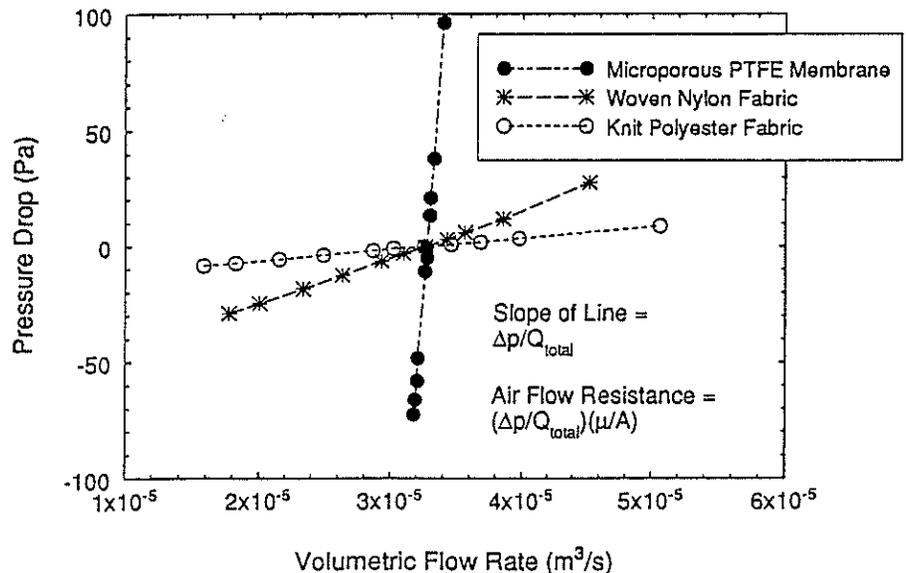


Figure 7.
Pressure drop across
sample as function of
flow rate

If the material thickness is known, the Darcy permeability (usually reported in units of m^2) can be found from the apparent flow resistance as:

$$k_D = \frac{\Delta x}{R_D} \quad (10)$$

Complicating factors

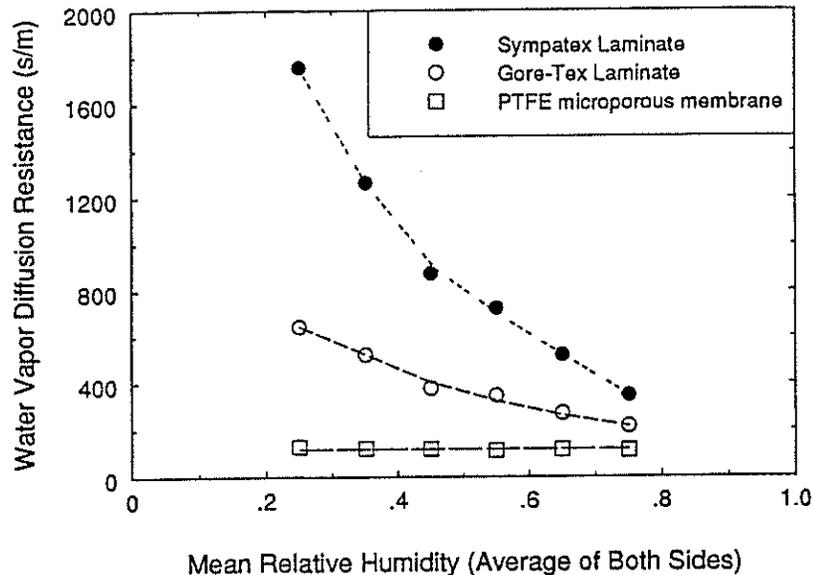
The convection/diffusion test method is most appropriate for air permeable materials such as porous textiles, membranes, or foams. It can be used for air-impermeable materials, and this is useful to show the relative importance of convective flow versus diffusive flow. The convection/diffusion test method is quite convenient for screening a large number of samples – particularly developmental materials, since it gives an air permeability and a water vapor diffusion value from a single test.

However, for materials such as semipermeable membrane laminates, or porous textiles which have humidity-dependent air permeability, the single air flow resistance and single diffusion resistance number obtained from a convection/diffusion test can be misleading, and it would be preferable to perform a separate diffusion test, and a separate air permeability test to separate out these two effects. Both of these complicating factors are discussed below.

Concentration-dependent diffusion in polymer membrane laminates

Vapor transport across nonporous hygroscopic polymer membranes and films is often highly dependent on the amount of water present in the polymer. Many commercially available semipermeable membrane laminates such as Gore-Tex and Sympatex exhibit this concentration-dependent behavior to varying degrees. The DMPC, when operated in the pure vapor diffusion mode (no pressure drop across the sample) is capable of showing this concentration-dependent transport behavior (Gibson *et al.*, 1995a, 1995b, 1996, 1997a). For samples which are air-impermeable, convection/diffusion testing does not provide any extra information, and it is better practice to conduct pure diffusion testing which evaluates water vapor transport under a variety of environmental conditions corresponding to different levels of water content in the hygroscopic polymer membrane or membrane laminate. This concentration-dependent behavior is illustrated in Figure 8. Two semipermeable membrane laminates (Gore-Tex and Sympatex) are shown which exhibit concentration-dependent transport behavior. They may be compared to the microporous PTFE membrane, also shown in Figure 8, which does not show the same type of concentration dependence. Further information on concentration-dependent transport is available (Gibson *et al.*, 1995a, 1995b, 1996, 1997a).

Figure 8.
Concentration-
dependent water vapor
transport behavior of
two semipermeable
membrane laminates



If one were to blindly apply the convection/diffusion test method to these kinds of materials, one would obtain a diffusion resistance that is only representative of one mean relative humidity, which would not capture the true variability of the transport behavior of these particular materials.

Humidity-dependent air permeability

The convection/diffusion test method results in a single number for the air flow resistance of a porous material. Porous hygroscopic materials often exhibit humidity-dependent air permeability due to the swelling of the solid matrix as it takes up water vapor from the environment. These effects are most evident in materials such as tightly-woven fabrics, low porosity hygroscopic membranes, and nonwoven fiber mats.

Humidity-dependent air permeability is usually evident from the volumetric flow rate versus pressure drop plot. The plot will no longer have a line of constant slope, but will show some curvature according to the relative humidity of the gas flowing through the sample.

This is illustrated in Figure 9 for a tightly-woven cotton fabric.

For a material such as this, the DMPC can be used to conduct a more traditional air flow resistance test as a function of relative humidity (Gibson *et al.*, 1997b). The corresponding humidity-dependent air flow resistance curve for the tightly woven cotton fabric shown in Figure 9 is given in Figure 10.

It is possible to account for the non-linearity of the convection/diffusion test due to this humidity dependence (Gibson *et al.*, 1997c), but it is usually simpler to perform the separate air flow resistance test as a function of relative humidity (Gibson *et al.*, 1997b) to produce plots similar to that shown in Figure 10.

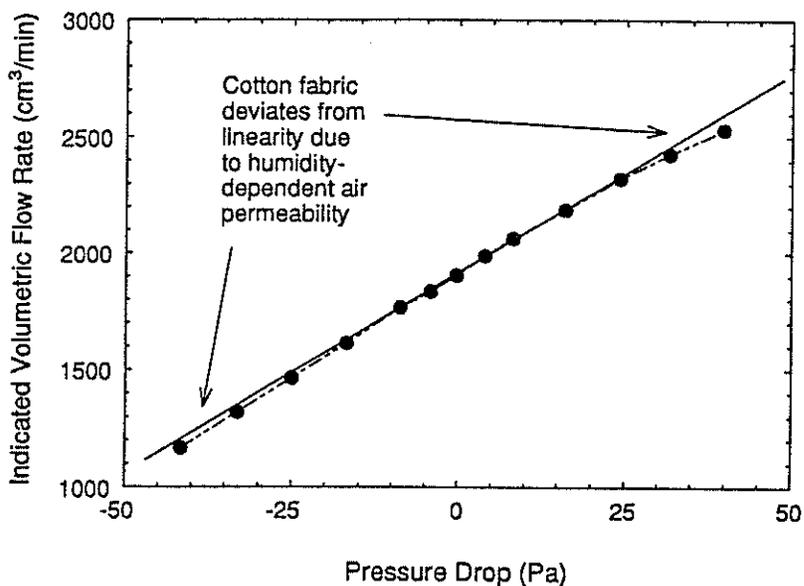


Figure 9.
Convection/diffusion
test exhibiting humidity-
dependent air
permeability

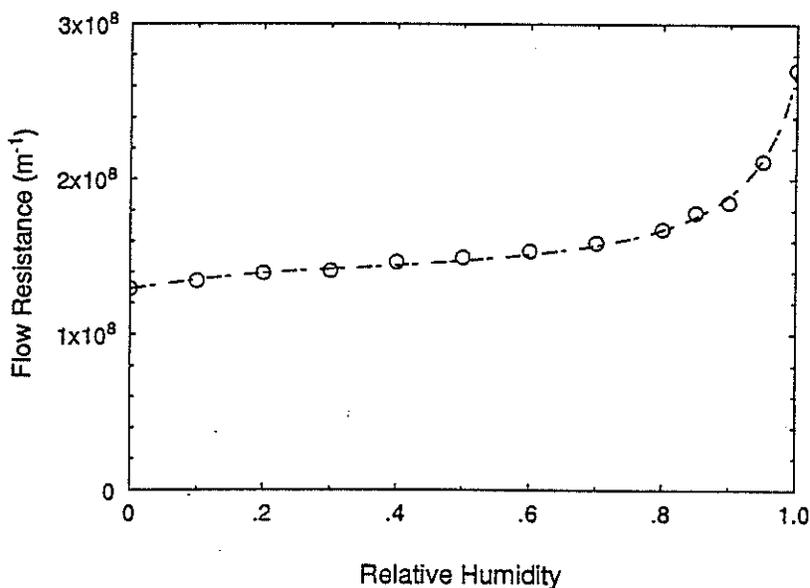


Figure 10.
Humidity-dependent air
flow resistance of tightly
woven cotton fabric

Another minor complicating factor is due to the zero drift of the mass flow sensor. This is usually not a problem since it is the slope of the pressure drop/flow rate curve which is used to calculate the air flow resistance. A more fundamental factor is the changing composition of the convective gas flow through the sample. The mass flow meter is calibrated to give mass flow rates for pure dry nitrogen. As the nitrogen stream's humidity changes, the indicated

mass flow rate is affected by the lower density of the humidified gas stream. In addition, the mass flow meter uses a thermal sensor, which is affected by the changes in heat capacity and thermal conductivity of the humidified gas stream. These effects can be accounted for analytically, since the relative humidity of the gas stream is being measured, but the increased accuracy is usually within the inherent variability of the test anyway, so these minor effects are ignored.

Conclusions

The convection/diffusion test method outlined in this paper is useful for determining the gas flow resistance property (air permeability) and water vapor diffusion resistance property (water vapor transmission rate), from a single experimental run. This eliminates the need for two separate tests, which is the usual procedure.

The convection/diffusion test method is ideal for rapid screening and comparison of the properties of a large number of materials. Because the required test sample size is much less than that required for most other standard types of air permeability and water vapor diffusion test methods, the convection/diffusion test method is particularly well-suited for material development efforts aimed at developing porous woven and nonwoven textiles, coating processes for porous substrates, polymeric foams, and microporous polymer membranes and laminates.

References

- Dullien, F. (1979), *Porous Media - Fluid Transport and Pore Structure*, Academic Press, New York, NY, p. 157.
- Fedele, P., Bergman, W., McCallen, R. and Sutton, S. (1986), "Hydrodynamically induced aerosol transport through clothing", *Proceedings of the 1986 Army Science Conference*, Vol. I, pp. 279-93.
- Geankopolis, G. (1972), *Mass Transport Phenomena*, Holt, Rinehart, and Winston, Inc., New York, NY, pp. 277-8.
- Gibson, P.W. (1996), "Multiphase heat and mass transfer through hygroscopic porous media with applications to clothing materials", US Army Natick Research, Development, and Engineering Center Technical Report, *Natick/TR-97/005*.
- Gibson, P.W. and Charmchi, M. (1997c), "Modeling convection/diffusion in porous textiles with inclusion of humidity-dependent air permeability", *International Communications in Heat and Mass Transfer*, Vol. 24 No. 5, pp. 709-24.
- Gibson, P.W., Rivin, D. and Kendrick, C. (1998), "Convection/diffusion test method for porous materials using the dynamic moisture permeation cell", US Army Natick Research, Development, and Engineering Center Technical Report, *Natick/TR-98/014*.
- Gibson, P.W., Kendrick, C., Rivin, D. and Charmchi, M. (1997a), "An automated dynamic water vapor permeation test method", in Stull, J.O. and Schwoppe, A.D. (Eds), *Performance of Protective Clothing*, American Society for Testing and Materials (ASTM) Special Technical Publication (STP) 1273, American Society for Testing and Materials, Vol. 6, pp. 93-107.
- Gibson, P.W., Kendrick, C., Rivin, D., Charmchi, M. and Sicuranza, L. (1995a), "An automated water vapor diffusion test method for fabrics, laminates, and films", *Journal of Coated Fabrics*, Vol. 24, pp. 323-45.

- Gibson, P.W., Kendrick, C., Rivin, D., Charmchi, M. and Sicuranza, L. (1995b), "An automated dynamic water vapor permeation test method", US Army Natick Research, Development, and Engineering Center Technical Report, *Natick/TR-95/032*.
- Gibson, P.W., Elsaid, A.E., Kendrick, C.E., Rivin, D. and Charmchi, M. (1997b), "A test method to determine the relative humidity dependence of the air permeability of textile materials," *Journal of Testing and Evaluation*, Vol. 25 No. 4, pp. 416-23.
- Kind, J., Jenkins, J. and Seddigh, F. (1991), "Experimental investigation of heat transfer through wind-permeable clothing", *Cold Regions Science and Technology*, Vol. 20, pp. 39-49.
- Stuart, I. and Denby, E. (1987), "Wind induced transfer of water vapor and heat through clothing", *Textile Research Journal*, Vol. 57, pp. 247-56.
- Take-uchi, M. (1989), "Analysis of wind effect on the thermal resistance of clothing with the aids of Darcy's law and heat transfer equation", *Sen-i Gakkaishi* 39, No. 3, pp. 39-48.

Note

US Department of Defense Technical Reports are available on order from: National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161-0111; <http://www.dtic.mil/>