In-Plane and Through-Plane Porosity in Coated Textile Materials

AKSHAYA JENA* AND KRISHNA GUPTA
Porous Materials, Inc.
83 Brown Road
Ithaca, NY 14850

ABSTRACT: Many industrially important textile materials are in the form of sheets. Their porosity is generally determined by measuring their flow characteristics parallel to the thickness. However, their properties parallel to the thickness direction (through-plane porosity) and parallel to the plane of the sheet (in-plane porosity) are not the same. For many applications, such porosity data are essential for designing more efficient materials. Equipment has been designed to measure pore characteristics in such materials in both in-plane and through-plane directions. The equipment yields reproducible data. The bubble points in the two directions are considerably different from each other. The results are consistent with the fibrous nature of the textile.

INTRODUCTION

MANY INDUSTRIALLY IMPORTANT materials such as filters, battery separators, hygienic items, clothes, and other textiles are produced in the form of sheets. Fluids migrate through the sheets in directions perpendicular to the sheet as well as parallel to the sheet. Porosity of the material responsible for flow parallel to the sheet is the in-plane porosity, and that responsible for flow perpendicular to the sheet is the through-plane porosity. These two kinds of porosity are illustrated in Figure 1.

Coated fibers used in the manufacture of textiles can considerably modify the in-plane porosity as well as the through-plane porosity. Textiles that are composites of several textiles may exhibit widely different porosity in the in-plane

*Author to whom correspondence should be addressed.

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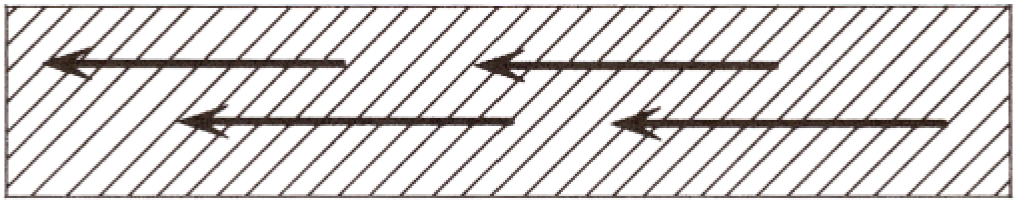

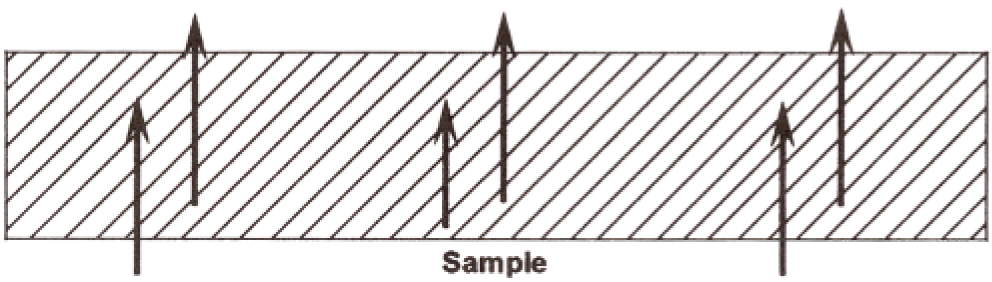

FIGURE 1. In-plane porosity and through-plane porosity.

and the through-plane directions of the constituent layers of the textile. Figure 2 illustrates the difference between the two layers of a composite textile.

In many applications, performance of textiles used as filters, hygienic products, and textile biomaterials are determined by relative values of in-plane and through-plane permeability. However, only through-plane pore structure is measured, while the in-plane pore characteristics are completely ignored. The purpose of this investigation is to design and fabricate equipment to accurately measure the through-plane as well as the in-plane pore characteristics and demonstrate the difference between the two kinds of porosity in textile materials.

FIGURE 2. In-plane and through-plane porosity in a composite textile.

EQUIPMENT

The principle of the test is very simple [1]. The sample of the textile is soaked in a liquid that fills the pores in the sample spontaneously. The pressure of a gas on one side of the sample is raised so as to push the liquid out of the pores. The largest pore in the sample is emptied at the lowest pressure and gas flow is initiated. The flow rate increases with increase in pressure as small pores are emptied (Figure 3). The flow rate and pressure are accurately measured, using dry and wet samples. These data are used to determine the largest pore size, the mean flow pore size, pore size distribution, liquid permeability, gas permeability and through pore surface area.

The fully automated PMI Capillary Flow Porometer is designed to measure the flow rate and pressure accurately and reproducibly [2,3]. It incorporates innovative design concepts, state-of-the-art components, and sophisticated Windows based software. The instrument is shown in Figure 4.

The through-plane and the in-plane characteristics are measured using two different sample chambers. The sketches in Figures 5 and 6 illustrate the differences between the two sample chambers.

RESULTS AND DISCUSSION

Change of Flow Rate with Pressure

Figure 7 shows the typical variation of flow rate with differential pressure. The dry curve is for the dry sample and the wet curve is for the sample containing the wetting liquid. Unique software based on a special flow arrangement in the initial stages of the test detects the pressure at which gas flow is initiated.

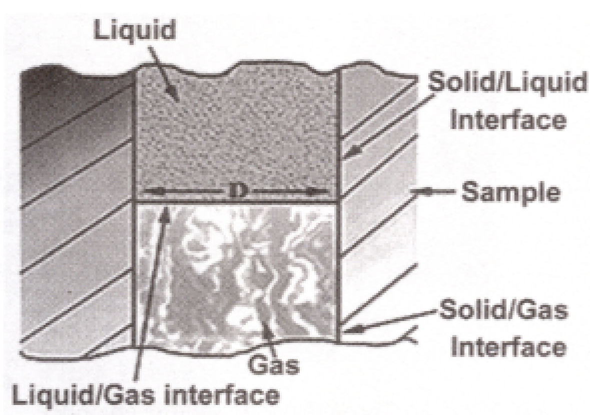

FIGURE 3. Displacement of liquid in the pore by the gas.

FIGURE 4. The Capillary Flow Porometer.

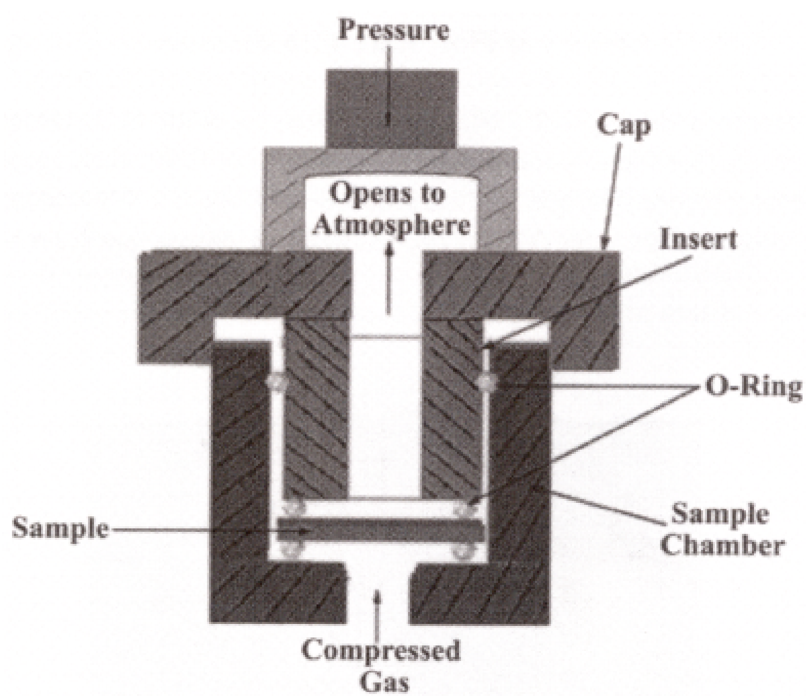

FIGURE 5. Through-plane sample chamber.

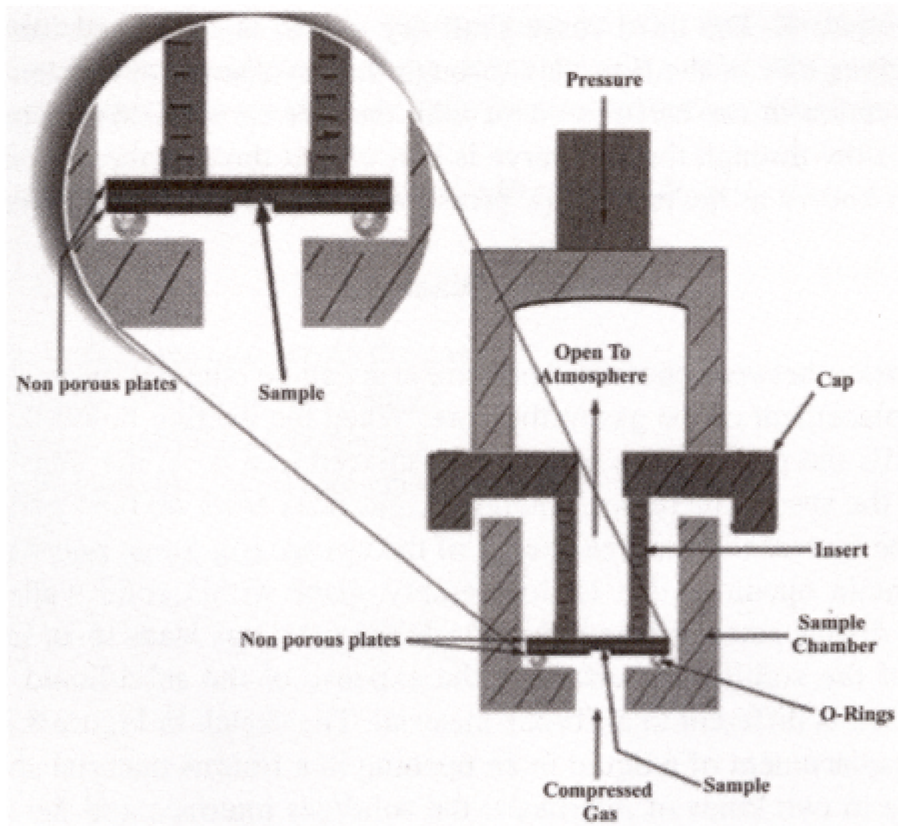

FIGURE 6. In-plane sample chamber.

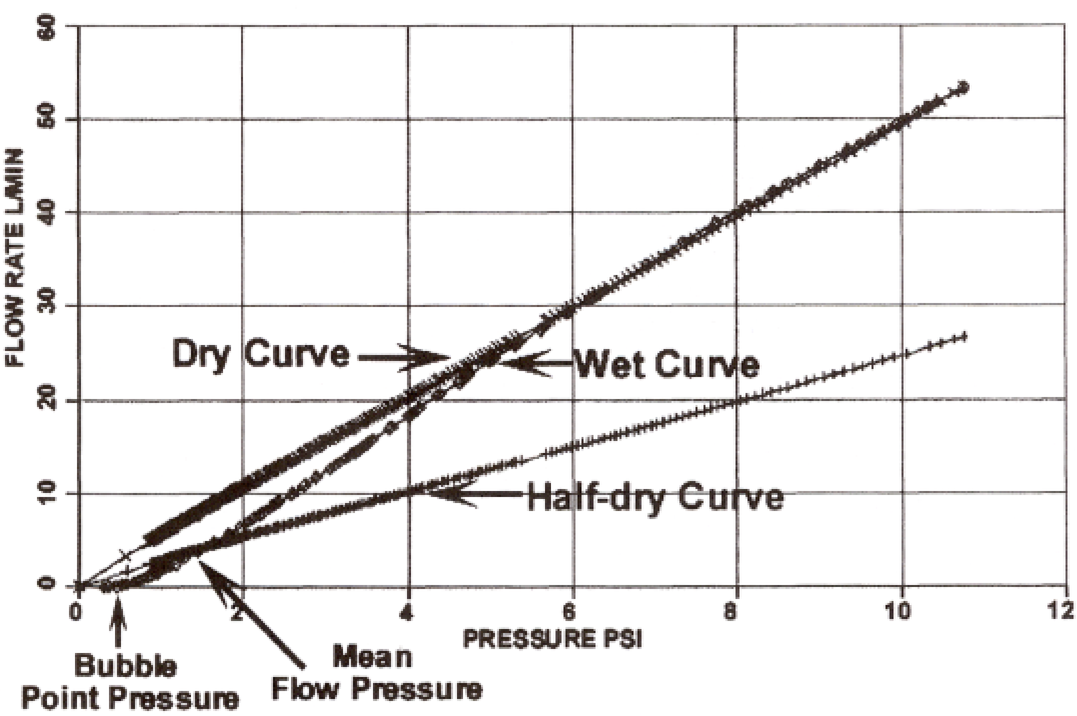

FIGURE 7. Typical variation of gas flow rate with pressure in a textile sample.

This pressure is the bubble point pressure. The bubble point pressure is indicated in Figure 7. The third curve (half-dry curve) is calculated from the dry curve. It gives half of the flow rate through the dry sample at a given pressure. The intersection of the half-dry curve with the wet curve yields the pressure at which the flow through the wet curve is half of that through the dry curve. This pressure is known as the mean flow pressure. It is also shown in Figure 7.

Pore Diameter

The relation between pressure and pore size can be obtained from an analysis of the displacement of the gas in the pore. When the wetting liquid that spontaneously fills the pores in the sample is displaced in a pore, the interfacial free energy of the system increases. Therefore, gas does work on the system to provide for the increase in the free energy of the system [4]. Some non-fibrous materials contain openings that enclose empty space within solid walls. In such materials, displacement of the liquid inside the openings leads to an increase of the area of the solid/gas interface at the expense of the solid/liquid interface. The situation is different in a fibrous material. The sketch in Figure 8 illustrates that the displacement of a liquid in an opening in a fibrous material should lead to increase in two kinds of interfaces: the solid/gas interface and the liquid/gas interface.

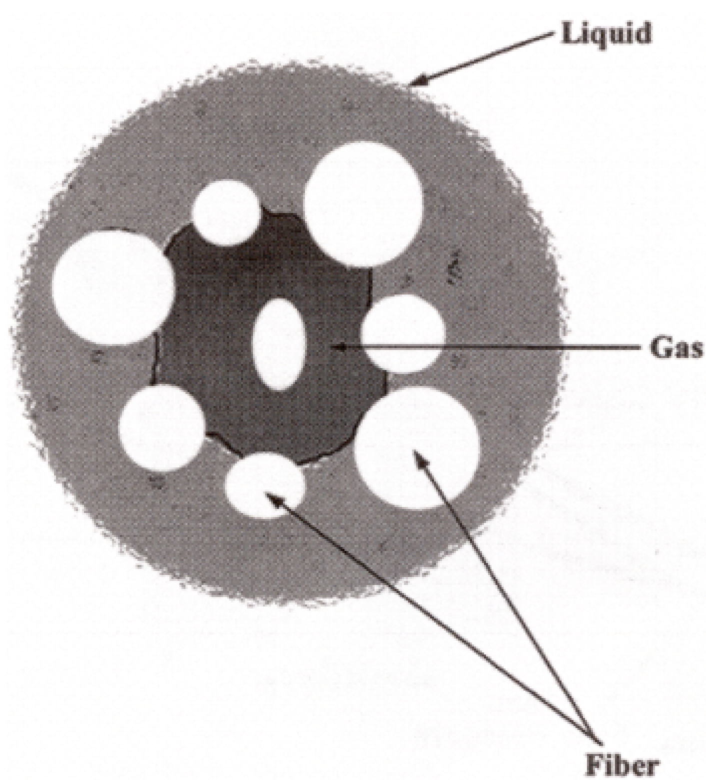

FIGURE 8. Opening containing gas in a fibrous material.

Consider a small displacement of the gas inside an opening. Let the increase in the volume of the gas inside the opening be dV, and the increase in the solid/gas and the liquid/gas surface areas be $dS_{s/g}$ and $dS_{l/g}$, respectively. Equating the work done by the gas to the increase in surface free energy:

$$pdV = (\gamma_{s/g} - \gamma_{s/l})dS_{s/g} + \gamma_{l/g}dS_{l/g} \tag{1}$$

where

p = differential pressure across the sample
$\gamma_{l/g}$ = liquid/gas interfacial free energy
$\gamma_{s/g}$ = solid/gas interfacial free energy
$\gamma_{s/l}$ = solid/liquid interfacial free energy

Equation 1 may be written as:

$$p = \gamma_{l/g}\beta(dS_{s/g} / dV)[1 + (f/\beta)] \tag{2}$$

where

$\beta = (\gamma_{s/g} - \gamma_{s/l})/\gamma_{l/g}$
$f = (dS_{l/g}/dS_{s/g})$

Equilibrium between the three surface tensions [5] suggests that:

$$\cos\theta = (\gamma_{s/g} - \gamma_{s/l}) / \gamma_{l/g} \tag{3}$$

where θ is the contact angle, and $\beta = \cos\theta$. β has a value ≤ 1. However, if the surface free energies are such that equilibrium is not possible, β would be > 1 [3]. It has been shown [3] that when wetting liquids with small values of surface free energies are used, β may be taken as 1.

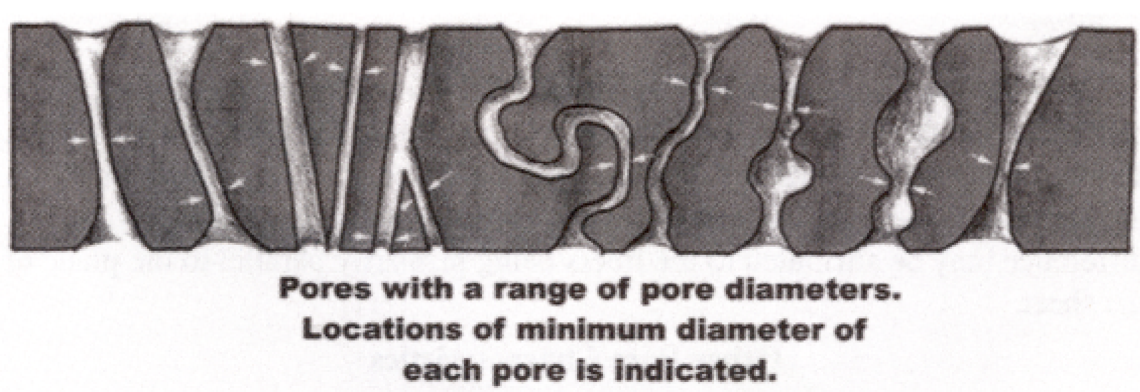

FIGURE 9. Range of pore diameters.

The value of f in Equation (2) is not known. However, the magnitude of f is generally much less than one. Under these conditions Equation (2) reduces to:

$$p = \gamma_{l/g}(dS_{s/g} / dV) \tag{4}$$

We define pore diameter as the diameter of a cyclindrical opening such that ($dS_{s/g}/dV$) (of pore) = ($dS_{s/g}/dV$) (of cylindrical opening of diameter D).

Consequently,

$$D = 4\gamma_{l/g} / p \tag{5}$$

The gas follows any accessible path. Therefore, pore diameter is a function of path (Figure 9). The pressure necessary for the gas to flow along a given path is determined by the smallest value of D along that path. Thus, D corresponds to the diameter of the pore at its most constricted part.

The Bubble Point Pore Diameter

The bubble point pressure is the pressure required to clear the path through which the gas first escapes the sample. Hence, the bubble point pressure is used to calculate the bubble point pore diameter, which is the largest most constricted pore size. The measured through-plane and in-plane bubble point pore diameters of a number of textiles are listed below.

Textile	Material Thickness, mm	Bubble Point Pore Diameter, μm		Ratio of Pore Diameters
		Through-Plane	In-Plane	
Felt	1.90	80.4	43.3	1.86
Meltblown sheet	1.80	114.3	68.8	1.66
Polyfelt blanket	2.00	51.8	19.8	2.62
Filter	0.49	51.1	24.1	2.12

These results were highly reproducible. They show that the equipment is capable of reliably measuring the in-plane and through-plane pore characteristics. The data demonstrate that the in-plane pore diameter is not only different from the through-plane pore diameter, but the difference can be considerable. The difference may be attributed to the fibers being primarily parallel to the plane of the sheet.

Other Pore Characteristics

In case of coated textiles and composite textiles the in-plane and the through-plane pore structures are expected to be appreciably different from each other. The results like those reproduced in Figure 7 can be used to find the mean flow pore diameter and pore size distribution for in-plane as well as through-plane flow. The required analytical technique is the same as that used for data obtained with other materials [6].

CONCLUSIONS

1. Through-plane and in-plane pore structures are expected to be different particularly in coated and composite textiles.
2. Equipment has been fabricated to accurately characterize the in-plane and the through-plane pore structures of textiles.
3. The bubble point pore diameters of a number of textiles have been measured in the in-plane and the through-plane directions.
4. The acquired data demonstrate that the in-plane and through-plane pore characteristics are indeed considerably different from each other.

REFERENCES

1. R. V. Webber, Filtration News, Jan./Feb., p. 52, 1994.
2. C. R. Stillwell, Proceedings of the 7th World Filtration Congress, Budapest, Hungary, May 1996.
3. V. Gupta and A. K. Jena, Advances in Filtration and Separation Technology, American Filtration and Separation Society, Vol. 13b, p. 833, 1999.
4. K. Denbigh, The Principles of Chemical Equilibrium, Cambridge University Press, 1968.
5. A. W. Adamson, Physical Chemistry of Surfaces, Interscience, New York, 1967.
6. A. K. Jena and K. M. Gupta, Power Source 17, Elsevier, 1999.