Apparatus and Method for the Assessment of In-plane Anisotropic Liquid Absorption in Nonwoven Fabrics

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Abstract

An instrumental method is described that enables real-time measurement of in-plane anisotropic liquid absorption in nonwoven fabrics. The system uses variations in electrical capacitance to monitor changes in the liquid absorbed by a fabric as a function of time. In the computer-integrated system, multiple capacitance transducers are arranged equidistantly around a central point to allow separate measurements in up to eight different in-plane directions. The design features of the system, its theoretical basis and examples of measured results are presented.

Introduction

In some medical and hygiene applications there is a need to control the manner in which liquid is distributed or stored by nonwoven fabrics. Depending on the particular application it may be necessary to distribute the fluid uniformly, distribute it more quickly in one direction than another or impair distribution completely. In addition to changing the chemical composition of the fabric, such requirements may also be influenced by modifying aspects of fabric structure such as porosity, fibre orientation or fibre dimensions. Since the structural architecture of nonwoven material is rarely uniform, anisotropy of physical properties such as liquid absorption is frequently observed [1]. In the development of high performance absorbent products, experimental techniques capable of measuring liquid absorption characteristics in more than one direction can be useful tools.

Adams and Rebenfeld [2] have described such a technique using quantitative image analysis and later, Lindsay [3] adopted the same method for obtaining the in-plane liquid permeabilities of paper. Laser-scanning methods have also been reported [4]. While such optical measuring techniques are very valuable for many applications, they do not usually give a direct measure of variation in the volume of liquid absorbed by a fabric. In this paper, an alternative instrumental approach is introduced that relies on variations in electrical capacitance to measure the liquid absorption in up to eight different directions (simultaneously) in a fabric.

Theoretical Considerations

It is well known that there is a large difference between the dielectric constants of air (ε=1), commonly used textile polymers (ε=2-6) and water (ε=70-80). The electrical capacitance of a system is dependent on the dielectric constant of the material. Consider a system consisting of two parallel capacitance plates spaced equidistantly along their length. When the space between the two parallel capacitance plates contains nonwoven material, the value of the capacitance, C, will be [5]:-

$$C = e_0 e_r \frac{A}{d} \qquad (3.1)$$

Where,

$e_0 = 8.854 * 10^{-12}$ (F/m) = the dielectric constant of a vacuum.

e_r = relative dielectric constant of the dielectric material.

A = area of the capacitance plate.

d = distance between the two capacitance plates.

If, in addition to fibre and air, there are other materials in the field between the two capacitance plates, the capacitance value of the system will be [5]:-

$$C = \frac{Ae_0}{(\frac{d_1}{e_1} + \frac{d_2}{e_2} + \frac{d_3}{e_3} + \dots + \frac{d_n}{e_n})} \tag{3.2}$$

where, d_1 d_2, d_3 and d_n are the thicknesses of the first, second, third, and n_{th} dielectric materials respectively. The terms e_1, e_2 , e_3 and e_n are the relative dielectric constants of these dielectric materials respectively.

If a nonwoven fabric is placed between the two capacitance plates, assuming its area, A, is equal to the area of the capacitance plate, the resulting capacitance, C, of the transducer, will be:-

$$C_0 = \frac{Ae_0}{\left(D - t(1 - \frac{1}{e_r}) - d_1(1 - \frac{1}{e_1})\right)} \tag{3.3}$$

$$D = t + d_0 + d_1$$

Where,

D = distance between the two capacitance plates.

t = thickness of the fabric.

d_0 = thickness of the air layer.

d_1 = thickness of any other materials in the field between the two plates.

e_r = dielectric constant of the fabric.

e_1 = dielectric constant of any other material in the field between the two plates.

If water is gradually introduced into the fabric (assuming the area of the fabric holding water is A_X), because of the effect of polarization of water on the fibre, the dielectric constant of the completely saturated fabric (which is a mixture of wetted fibre and water) may be taken to be nearly the same as the dielectric constant of water, m [7]. The liquid transport in the z-direction of the fabric is ignored because the fabric is thin. Thus, the capacitance value of the transducer (containing wet fabric), C_X, will be as follows:-

$$C_X = \frac{A_X e_0}{\left(D - t(1 - \frac{1}{m}) - d_1(1 - \frac{1}{e_1})\right)} + \frac{(A - A_X)e_0}{\left(D - t(1 - \frac{1}{e_r}) - d_1(1 - \frac{1}{e_1})\right)}$$

$$= C_0 + A_X\left(\frac{1}{a} - \frac{1}{b}\right) \tag{3.4}$$

Where a and b are constants depending on the particular fabric sample.

$$a = \frac{e_0}{\left(D - t(1 - \frac{1}{m}) - d_1(1 - \frac{1}{e_1})\right)}$$

$$b = \frac{e_0}{\left(D - t(1 - \frac{1}{e_r}) - d_1(1 - \frac{1}{e_1})\right)} \tag{3.5}$$

Therefore, the change in the capacitance value, ΔC_X, due to the introduction of water may be given as follows:-

$$\Delta C_X = C_X - C_0 = \Delta A_X \left(\frac{1}{a} - \frac{1}{b}\right) \tag{3.6}$$

From equation 3.6, it is clear that the capacitance value varies only with wetting and it is linearly related to the wetted area of the fabric. Changes in the capacitance value can therefore be used as a basis to study the liquid transmission in fabrics. This is a simple approach that avoids the difficulty of selecting an appropriate model for a specific fabric in order to determine the dielectric constant [7]. In our approach, we use the relative changes in capacitance to study the liquid transmission [8]. As we show in this paper, it is possible to do this in different in-plane directions simultaneously.

Experimental Approach

A new apparatus has been designed (see Figure 1) in which an electrical capacitance field is created between two transducer plates (upper and lower).

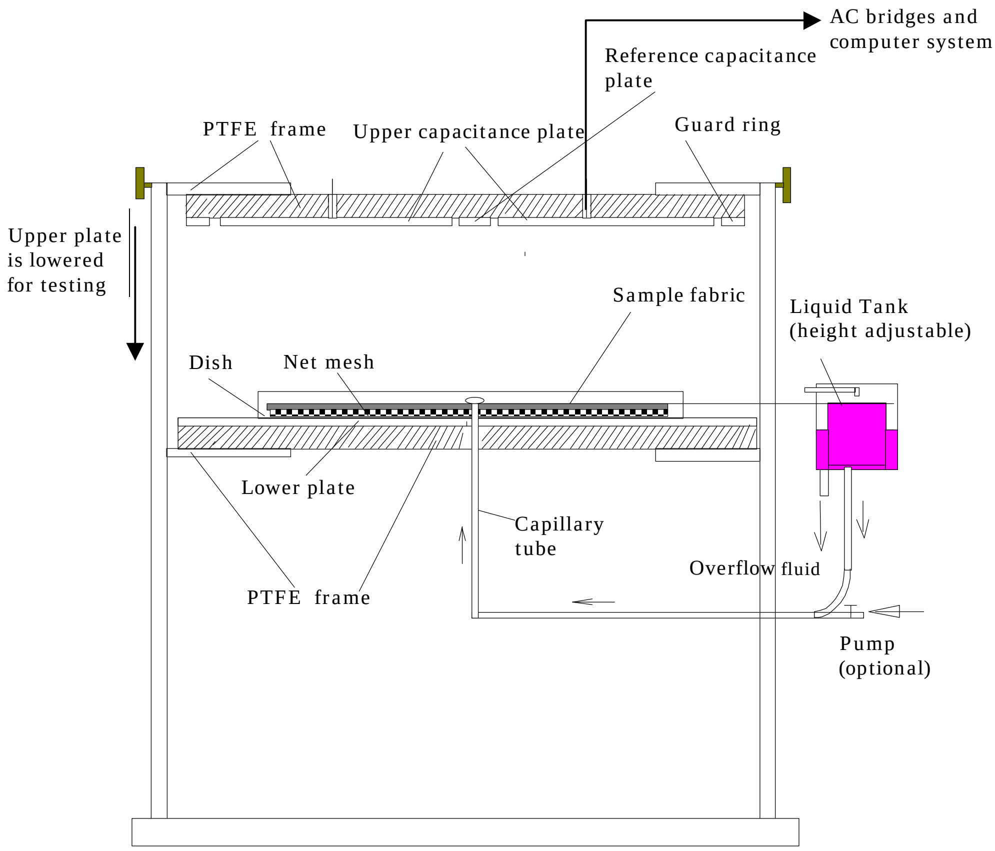

Figure 1: Schematic Diagram of the Measuring Instrument

The upper plate is segmented and consists of eight separate, equidistantly spaced sections as shown in Figure 2. Each segment comprises a thin stainless steel plate coated with a continuous layer of PTFE. A small circular plate also coated with PTFE is located at the centre of the upper plate and this provides a reference signal during testing (see Figure 2). The lower plate is not segmented and is composed of thin stainless steel coated with PTFE.

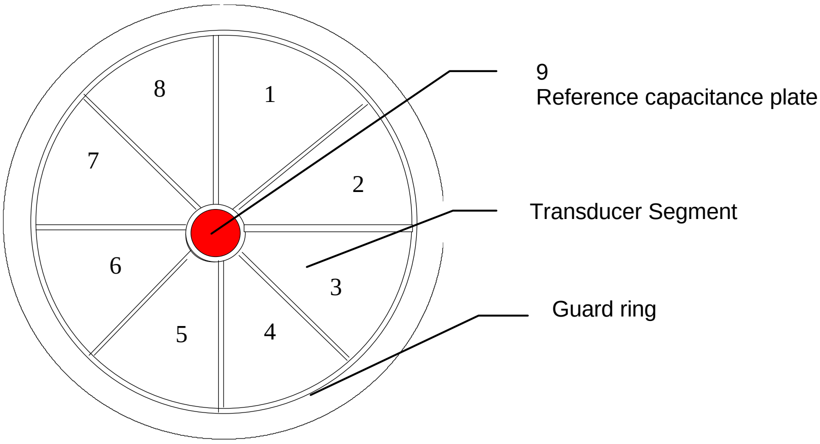

Figure 2: Alignment of transducer segments in the upper plate of the capacitance system

Capacitance values for the nine transducers (including the reference signal) are converted into voltage signals using an A.C. capacitance bridge. A square wave generator was used to provide an input signal of 10 KHz to a series of bridges (as shown in Figure 3), through which the output signals from the capacitance transducers are conditioned and converted into a suitable form for signal processing. In this system, two standard resistors and capacitors are used to form the A.C. bridges. Each capacitance transducer was paralleled with the standard capacitors of $10 \times 10^{-12} F$ in each A.C. bridge respectively (see Figure 3).

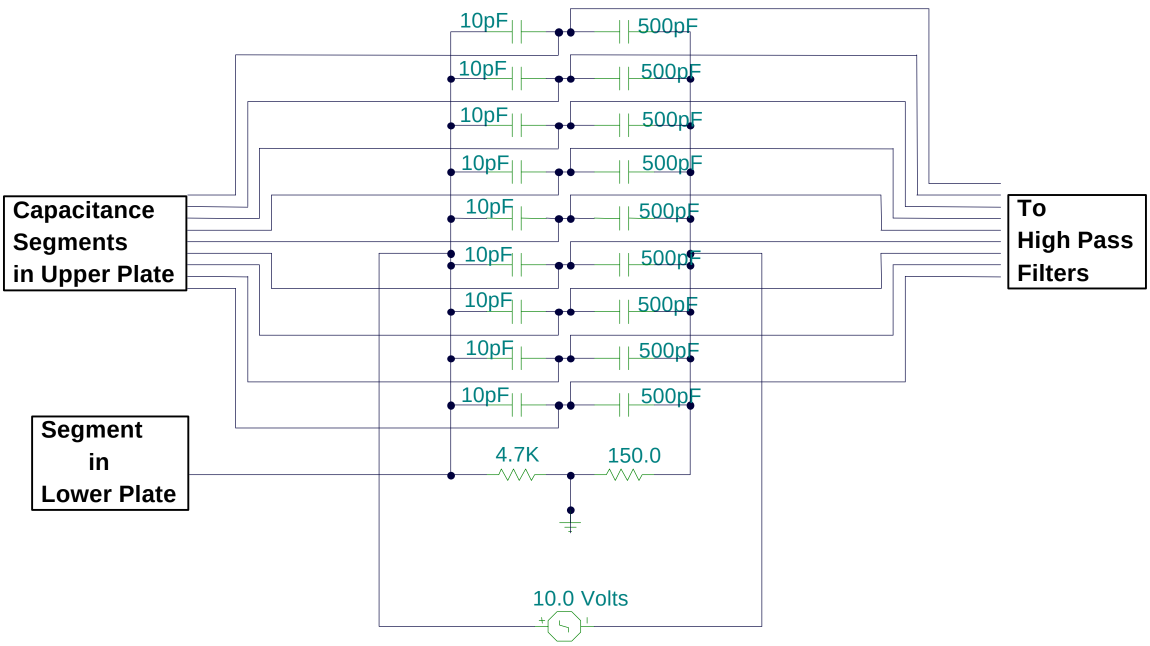

Figure 3: Schematic of the A.C. bridges set-up used in the system

Variations in the dielectric value between the upper and lower plates (resulting from the absorption of water by the fabric placed between them) changes the capacitance value. It has been established that the output voltage of each bridge is proportional to the capacitance value of the transducers, and therefore when the capacitance values of the transducers vary with changes in liquid absorption, the output signals of the bridges can be considered to be proportional to the liquid absorption.

The output signals from each bridge are amplified, filtered, demodulated and converted into a digital signal for computer processing using dedicated software produced in C and Visual Basic. The electronic set-up is shown in Figure 4.

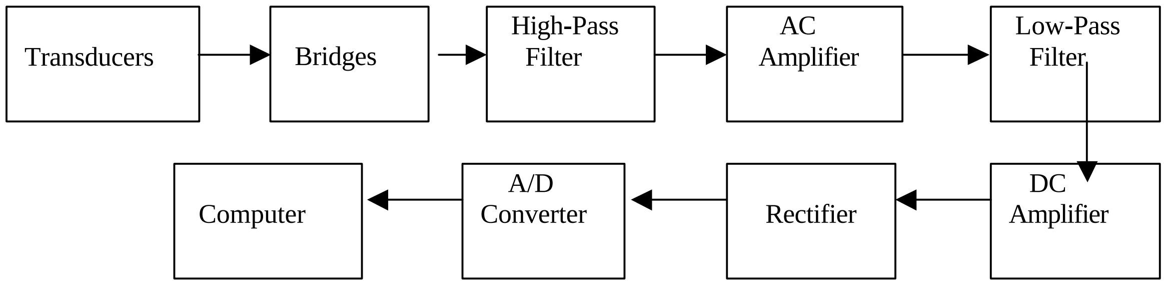

Figure 4: Schematic of the electronic components used in the system

In addition to water, we found that the capacitance value was sensitive to external effects (e.g. air humidity) and to the design, arrangement and geometry of the capacitance transducers. In order to ensure stability of the capacitance value, the entire measuring system was placed in a tube eliminating fugitive effects (caused by variations in ambient conditions) and operation of the instrument was carried out in a standard testing environment (20^0C and 65%RH). Guard rings (see Fig. 2) were used to regulate the electrical field of the transducer segments so that the field flux was perpendicular to the lower plate at the extreme edges of the segments [5]. These metallic guard rings were the same thickness as the transducer segments, and were designed to surround the eight segments to allow regulation of the electrical field at the outside edges. The central segment in the upper plate could also be used as a further guard ring to regulate the electrical field at the inner edges of the eight transducer segments if required.

During testing the fabric sample is placed in a circular dish (shown in Figure 1). Liquid is introduced into the fabric at the center of the dish via a fine capillary tube on top of which is fitted a tiny perforated cap designed to allow uniform distribution of the incoming fluid in all directions. In order to eliminate wicking of the fluid between the dish surface and the fabric, samples are placed on a PTFE mesh with projecting surface nodes fitted inside the dish. The rate at which liquid is introduced can be varied by changing the vertical position of the header tank (which maintains a constant head) or alternatively, by the use of a peristaltic pump (see Fig. 1). Typically, the system is operated at flow rates in the range 4 ml/min to 40 ml/min.

Using this approach it is possible to measure changes in the liquid absorbed by nonwoven fabrics in different directions and it is therefore possible to characterise the anisotropy of liquid absorption. Extensive testing has been carried out to validate the method and typical experimental results are shown in Figure 5(a). In this particular example, Figure 5 refers to a commercially available wound dressing fabric composed of 100% viscose rayon in a monolithic needle punched structure. In Figure 5(b), the absolute liquid absorption and the rate of change in the liquid absorption versus time are obtained in each direction for the fabric measured. In Figure 5, it should be noted that the rate of absorption in each direction of the fabric is not identical. The plot (labeled number 9) is the measured change in liquid absorption versus time for the reference transducer located in the upper plate immediately above the fabric over the introduction point of the liquid. In this central position, it is clear from plot 9 that there are apparently two phases in the absorption process. Initially, when the liquid is introduced into the fabric from the source point, the central area of the fabric is not saturated and the absorption of the fabric continuously increases with time. As would be expected, after a certain period of time, when the fabric in this area becomes saturated, the absorption remains constant as a function of time. In combination with an electronic balance, the measured results from the new system can be used to obtain the fabric absorbency by weighing the fabric before and after testing. The fabric absorption rate, the anisotropy of the fabric absorption rate and the saturation time can also be obtained. In forced fluid flow conditions, the permeability and anisotropy of permeability of the fabric can also be measured.

The development of further analytical tools for processing the experimental data produced by the system is currently on-going. This analysis and the interpretation of the measured results will be discussed in a subsequent paper.

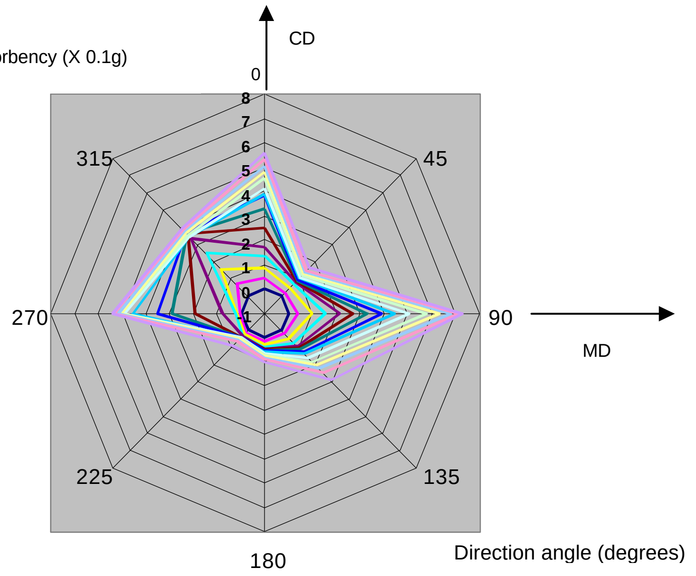

Figure 5(a) Example of the results produced by the system
Note: Polar diagrams of this type showing the absorption in different directions are updated in real-time by the system as the test proceeds

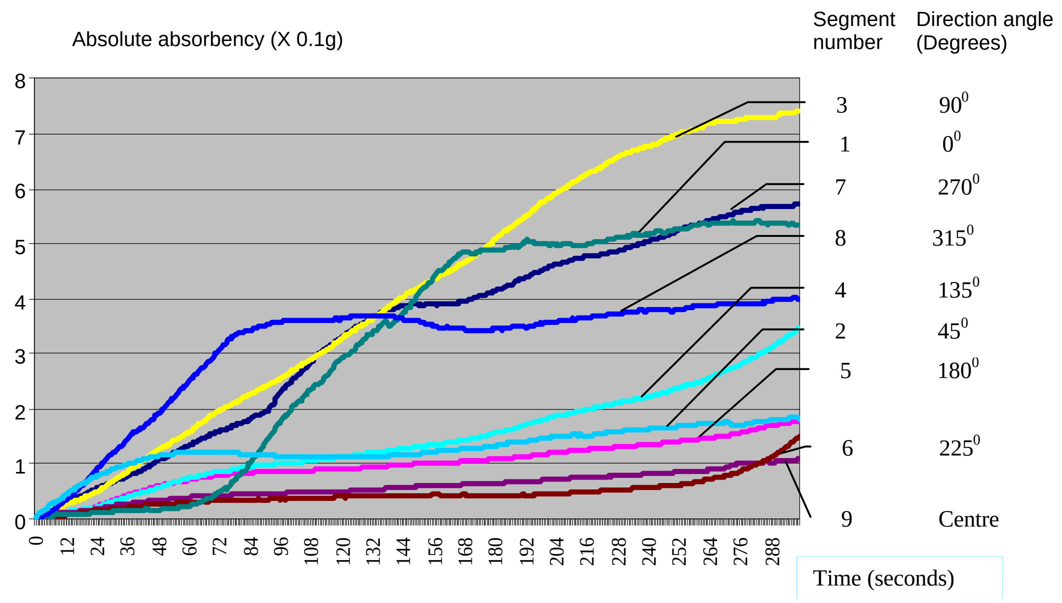

Figure 5(b) Example of dynamic liquid absorption measurements vs. time (Cartesian system**)**
Sample fabric: 100%viscose rayon, needlepunched, fabric weight =120g/m^2

Conclusion

Experimental studies of the anisotropic fluid transmission properties of nonwoven materials requires the availability of dynamic measuring methods. A novel capacitance apparatus has been described that permits dynamic measurements to be made. This method is capable of measuring fluid transmission in up to eight different in-plane directions in fabrics simultaneously. The system can be used to measure the fabric absorbency and the fluid transmission rate in different directions in the fabric plane.

The apparatus provides a basis for investigating anisotropic fluid flow in nonwoven structures and is proving to be a useful tool for engineering improved fluid handling characteristics in nonwoven materials. The test results for a large number of different fabrics will be reported in the next paper.

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