ABSORBENCY - AN OVERVIEW

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Introduction

One of the most significant applications of nonwovens is in the field of absorbency. Some examples of products supporting this application are sanitary napkins, baby diapers, adult incontinent pads, and tissues, towels, and sponges. In these materials, the ability to imbibe rapidly and hold large amounts of fluid under pressure is important requirements. The performance of an absorbent product is affected by the properties of the fibers, the structure of the fabric, the properties of the fluid, and the manner in which the product is tested or used. In this paper, the objective will be to briefly examine the theoretical models that have been used to account for the behavior when a fluid interacts with a fibrous structure and discuss the effects of some of the fiber, fabric, and fluid factors, studied experimentally.

Different Modes of Wicking

Fluid can be imbibed into a fabric in a variety of ways. In one, it can be wicked vertically by holding the top end of a rectangular strip fixed and letting the lower end immerse in a container of fluid. The height, L_0, the fluid rises to at equilibrium, or the height, L, it rises to after a specific length of time, or vice-a-versa, the time, t, it takes to reach a given height, L, are some of the parameters determined. In the second, the fluid is wicked horizontally, i.e. linearly along the length. One end of a rectangular strip, laid horizontally, is contacted with the fluid, and the rate at which the fluid front advances along the length is determined, much in the same way as done in the case of the vertical wicking. In the third, the fluid, presented at a point in the middle of a circular specimen, laid flat on a surface, spreads radially outward. In this mode, one can have two variations. In one, limited amount of fluid is presented, such as from a drop. In this, the fluid first saturates the area in the vicinity of the drop and then spreads horizontally outward. In the second situation, absorption takes place from a source of unlimited supply. The fluid front advances radially outward (Figure 2) continuously until the specimen is saturated. Since the test is usually conducted at zero hydrostatic head, the absorption process ceases abruptly as soon as the point of saturation is reached.

Flow Models

Linear Wicking

The most basic model used is that due to Hagen-Poiseuille (Chatterjee 1985). According to it, the flow through a channel of radius r is given by the following equation:

$$\frac{dL}{dt} = \frac{\Delta P \; r^2}{8\eta L} \tag{1}$$

In this, L is the distance reached, t is the time taken, ΔP is the driving force or the pressure drop existing across the channel, and η is the viscosity of the fluid. For capillary assisted flow, the pressure drop can be replaced by P_c, given by the Laplace equation:

$$P_c = \frac{2\gamma \cos\theta}{r} = L_0 \rho g \tag{2}$$

Where L_0 is the height or the distance the fluid reaches at equilibrium, γ is the surface tension of fluid, θ is the contact angle for the fluid-fiber system, ρ is the fluid density, and g is the acceleration due to gravity. As the fluid rises in the capillary, gravity opposes the advance and affects the rate:

$$\frac{dL}{dt} = \frac{r^2}{8\eta L}\left(L_0 \rho g - L \rho g\right)$$

Integration from L = 0 to L = L leads to the following solution:

$$\ln\left[1 - \frac{L}{L_0}\right]^{-1} - \frac{L}{L_0} = \frac{r^2 \rho g}{8\eta L_0} t$$

At, $t \ll t_0$, or $L \ll L_0$, expansion by Taylor's series and neglecting of higher order terms gives:

$$L^2 = \frac{r^2 \rho \; g \; L_0}{4\eta} t$$

Substituting from (2) for L_0, one gets the following well-known Wasburn-Lucas equation (Lucas 1918, Washburn 1921):

$$L = \sqrt{\frac{r \gamma \cos\theta}{2\eta}} \; t^{1/2} \tag{3}$$

Equation (3) characterizes the wicking rate for flow through a channel oriented horizontally, as well as for a channel oriented vertically, if the concern is only with the initial rate. If the height reached is more than about 10% of the equilibrium height, the gravity term should be included as it starts to play significant role and affect the rate.

Areal or Volumetric Flow from Limited Source

The work of Gillespie (Gillespie 1959) and Kissa (Kissa 1981) have shown that the areal flow is given by the following form of the general flow model:

$$A = k\left(\frac{\gamma}{\eta}\right)^u v^m t^n \tag{4}$$

In this, v is the volume of fluid used and k, u, m and n are the constants, the values of which are determined experimentally. From the work of Kawase et al (Kawase et al 1986), one can conclude that for low swelling materials, the value of the exponent n is about 0.33. Accordingly, the flow occurs relatively more slowly in this case than it occurs in the example considered above.

Areal or Volumetric Flow from Unlimited Source

Introduction

This is the mode highly suited for characterizing the performance of a large number of products, such as the sponges, towels, diapers and the adult incontinent pads. These are the materials that normally encounter large amounts of fluid and in which the performance is usually assessed in terms of the maximum amount the material can absorb and the rate at which it absorbs. The test method generally used for characterizing the performance is the one that works on the principle of demand wettability. A commercially available apparatus is the well-known GATS, the "Gravimetric Absorbency Testing System." A schematic of the equipment, used in our research, is shown in Figure 1.

The Demand Wettability Device, GATS

The device is equipped with a specimen cell that allows measurement of web thickness at two positions diagonally across from each other while

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holding the test material in place for absorbency. The fluid is delivered from a single hole in the middle, which spreads radially outward through the sample. The latter is of circular shape obtained by cutting the fabric with a die of given size. The tests are conducted under the desired hydrostatic pressure head, ΔP, and the environmental pressure, the latter obtained by placing fixed weights on the material. The outputs from the balance and the sensors are collected and evaluated using commercial software.

Two parameters are assessed: the absorbent capacity, C (cc fluid / g dry mass), and absorbency rate, Q (cc fluid / g dry mass. sec). The former is given by the volume of fluid absorbed at equilibrium divided by the dry mass of the web. The latter is given by the slope of the fluid uptake - time elapse line, divided by the dry mass of the specimen.

Model for Absorbent Capacity

Absorbent capacity is determined by the amount of fluid held within the pores and that, which diffused into the fibers. Its value is given by the following equation (Gupta 1988, Gupta and Hong 1995)

$$C = A\frac{T}{W_f} - \frac{1}{\rho_f} + (1-\alpha)\frac{V_d}{W_f} \qquad (5)$$

In this, A is the web area, T is the final thickness of the specimen (Figure 1), W_f is the dry mass of the specimen, ρ_f is the density of the fiber, V_d is the amount of fluid diffused into the fibers, and a is the ratio of the increase in volume of fibers to the volume of fluid diffused. Since swelling usually occurs by local exchange between water and fiber molecules, the value of a can be assumed to be 1. This causes the third term to drop out. The second term also, as compared to the first, is small and could be neglected, particularly in products that tend to be bulky, such as the carded and the needled nonwovens. Capacity, therefore, is mostly given by the first term, in which the important variable is the thickness of the web in the wet state per unit dry mass.

Model for the Rate of Absorbency

To develop an equation for the rate, the model of Washburn-Lucas (Equation 3) is used. Figure 2 shows the manner in which the fluid front advances to distance L in time t. The amount of fluid imbibed in the saturated region is given by

$$V = \pi\ L^2\ T\ \phi \qquad (6)$$

Where ϕ is the packing factor, or the fraction of the interstitial volume available for absorption per unit web volume, and is given

$$\phi = 1 - \frac{W_f}{A\ T\ \rho_f} \qquad (7)$$

Substituting (3) and (7) in (6) and simplifying, we get the following model for the volumetric flow rate,

$$Q = \frac{V}{W_f\ t} = \frac{\pi\ r\ \gamma\ \cos\ \theta}{2\eta}\left[\frac{T}{W_f} - \frac{1}{A\ \rho_f}\right] \qquad (8)$$

The values of all parameters in the above equation, except of T/W_f and r, are either known or measured using standard procedures. The value of T/W_f can be computed from the measured values of the dry mass, W_f, prior to each test and the thickness, T, on the GATS during each test. The value of the remaining parameter, the pore size, r, can be predicted by a model due to Gupta (Gupta 1988). This model is based on the assumption that a capillary is bounded by three fibers, oriented parallel or randomly, and the specific volume of the capillary unit cell equals that of the parent web. The three fibers that lie at the apexes of the triangle could belong to two different materials, having different deniers. The number of fibers of each type, out of three, will be determined by the blend ratio and the deniers. The equation characterizing the pore size is as follows:

$$r = \left[\frac{1}{6\pi\xi}\left(A\frac{T}{W_f}\cdot\frac{\rho_1\,\rho_2}{f_1\,\rho_2 + f_2\,\rho_1} - 1\right)\left(\frac{d_1 n_1}{\rho_1} + \frac{d_2 n_2}{\rho_2}\right)\right]^{1/2} \qquad (9)$$

$$n_2 = \frac{3\,f_2 d_1}{f_1 d_2 + f_2 d_1}$$

$$n_1 = 3 - n_2$$

In the above equations, subscripts 1 and 2 represent different fiber types, ξ is constant ($9X10^5$), d is fiber denier, ρ is fiber density (g/cc), and f is mass fraction of a fiber in the blend ($f_1 + f_2 = 1$).

Results and Discussion

Models

A number of models have been presented which represent the absorbency behavior of a fabric tested in different ways to suit different applications. It is noted that the equations for the rate are somewhat different for different modes but they all involve essentially the same variables that affect the performance. Accordingly, one could employ any of the methods discussed for determining, on a relative scale, the potential different materials present for absorbent applications. However, for obtaining precise performance data on a product for a specific application, the test method selected must be the one that closely simulates the actual use conditions.

According to the equations presented, capacity is primarily determined by the thickness of the web, in the wet state, per unit dry mass (T/W_f). The rate is also affected by this factor directly but, additionally, by the pore size (r), the cosine of the contract angle (θ), and the surface tension of the fluid (γ), directly, and the viscosity of the fluid (η), indirectly. The factors that affect T/W_f are the environmental pressure, the size, the shape, and the wet mechanical properties of the fiber, and the type and the extent of bonding in the web. Pore size is also affected by the same factors that affect web thickness per unit mass but, additionally, by fiber size.

Contact angle is an interaction parameter whose value is affected by the chemical and the physical nature of the fiber surface and the properties of the fluid. With water as the fluid, a hydrophilic surface, such as that of cellulose, gives low value of θ and, therefore, leads to high value of the rate. However, it should be noted that if the fluid reacts with the fiber, such as it occurs when water contacts cellulose, it can lead to a loss in resiliency, a decrease in T/W_f and, therefore, to a decrease in the values of C and Q on this account.

The results from a number of investigations are now briefly examined and discussed in light of the models presented.

Results from Experiments

Large size, trilobal shape and/or high wet modulus fibers have been found to lead to high values of T/W_f and r and, thus, to high values of capacity and rate [Gupta and Hong 1988, 1994 and 1995). In an investigation in which polypropylene and polyester fibers of deniers ranging from 1.5 to 9 were used, an increase in fiber denier gave increases in the values of C and Q (Gupta and Hong 1994). Since pore size is not only affected by web thickness but also by fiber denier (Equation 9), the effect of denier was generally found to be greater on Q than C. In studies involving webs made of cotton and rayon, those of cotton, in spite of the former having lower denier (1.8) than the latter (3.0), have provided higher values of capacity and rate. This could be attributed to the natural cellulosic fiber having 6 to

8 times greater wet modulus than rayon, which more than compensated for the fiber's lack of size.

On the effect of fiber shape, it was noted that in rayon, in which trilobal and round fibers were available, the trilobal material provided higher absorbency values than did the round material. This was obviously due to the trilobal fiber having greater bending rigidity and, therefore, led to bulkier structures than did the round fiber.

Entangling a web by needling process is assumed to create channels in the direction of flow, which impart resiliency to the web and an ability to resist collapse when subjected to pressure. This leads to higher values of T/W_f and r and, therefore, to higher values of C and Q (Gupta and Hong 1995 and 1998). The fractional change in the value of Q has usually been significantly greater than that in the value of C, and this is because the needling process created a structure that favored flow.

In studies involving hydroentangling process for bonding cellulosic webs, it was found that the greater the entangling energy used (Gilmore et al 1997), the lower the absorbency values obtained (Gupta 1998). This result has been attributed to the process causing the web to compact into a flattened sheet (giving low values of T/W_f and r) and the fibers to bond by hydrogen linkages. Comparison of the transverse dimensions of the needled and the hydroentangled structures have shown that, in general, the former were bulkier and more resilient than the latter.

Another web factor that has been found to produce significant effect on absorbency is areal density. In a recent investigation, cotton and rayon webs of areal densities varying from 40 to 160 g/m^2 were produced (Gupta 1998). The results showed that the lower the areal density used the higher were the values of the absorbency parameters obtained. The increase in capacity and rate with increase in areal density from 40 to 80 g/m^2 were, respectively, 21% and 29%, and that from 40 to 160 g/m^2 were, respectively, 34% and 54%. These results were explained by illustrating that an increase in areal density led to a decrease in the values of the web parameters T/W_f and r.

Fiber surface plays a strong role in influencing the rate. Differences in the rate values of webs containing different fibers can be linked to the differences existing in their chemical structures, reflected in the differences in the values of contact angle. On a given fiber, application of a finish can alter wettability and, therefore, absorbency. In a study involving cotton, the finish present on the as received fiber, usually applied as an aid to processing, was removed by scouring. GATS tests showed that the webs containing the scoured fiber had much higher rate than the one containing the as received material (Gupta 1998). These results indicated that the surface of the natural cellulosic material free of impurities and finish was more hydrophilic than the one containing a finish.

Fluid properties affect absorbency by influencing absorbate/absorbent interaction. The fluids encountered by absorbent products are largely aqueous but contain biological particles and chemicals, particularly salts. Differences in fluids can lead to differences in absorbency values due to differences in the values of surface tensions, viscosities, and contact angles. A model used by industry to represent body fluids is 1 % saline solution.

In one of the studies, involving regular cellulosic fibers, the effect of saline concentration on absorbency was determined by using a 0 % and a 1 % solution. The results showed that the addition of salt gave a small increase in capacity but a significant decrease in the rate (Gupta and Hong 1995). The increase in capacity was explained as being due to the shielding effect the electrolyte molecules produced on the fixed charges of fiber molecules [Flory 1967]. This led to a decrease in penetration and, therefore, to a decrease in the tendency of web to collapse under pressure. The decrease in the rate was considered as being due to an increase in the contact angle and the viscosity [Gupta and Crews 1989]. In a study involving super absorbent fibers, on the other hand, the effects of saline concentration found were opposite. Addition of salt to water caused a decrease in the capacity but an increase in the rate. The increase in capacity was due to a decrease in penetration and absorption of fluid into the internal structure of the fiber, and the increase in rate was due to a decrease in gel blocking.

Summary

The models for different modes of wicking involved similar variables for influencing the rate although the absolute value depended on the manner in which the fluid was imbibed. The main factor affecting the capacity was the pore volume available for absorbing fluid, which was largely given by the web final thickness per unit dry mass. The rate was also affected by this factor but, additionally, it was affected by the pore size, the properties of fluid (surface tension and viscosity), and the magnitude of the absorbate/absorbent interaction parameter, θ. The results from experimental investigations could be understood and explained in view of the effects the fiber, the fabric structure and the fluid properties produced on the values of the parameters in the models.

The knowledge gained from the theoretical exercise and experimental investigations could be used to design structures with optimum performance.

It should be noted that the work only considered the behavior of a single but specific layer of absorbent article, i.e. the core. An absorbent product is a composite of multiple materials, frequently consisting of a cover sheet, a distribution layer, the absorbent core, and a barrier material. Except the last component, all others are involved in handling and managing fluid, i.e. transporting, distributing and absorbing. The challenge in the next phase of the work will lie in understanding, modeling and optimizing the absorbency performance of such a composite.

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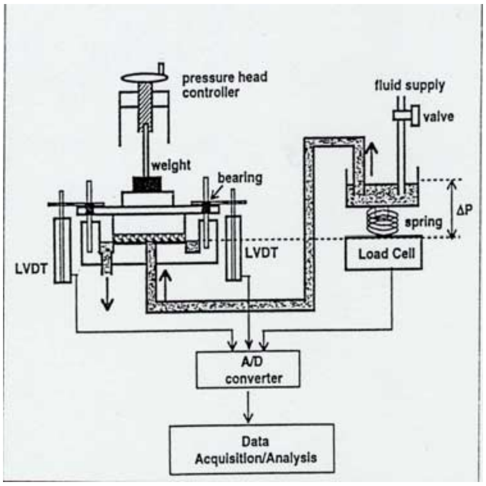

Figure 1. The demand wettability testing device (GATS).

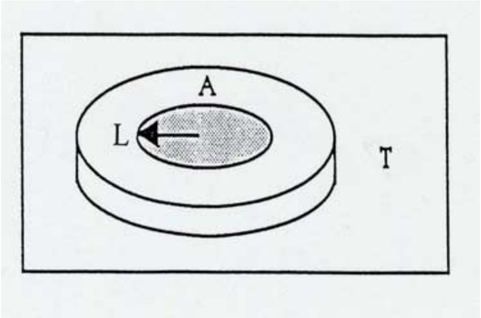

Figure 2. The Web Element.