

# Dynamics of Capillary Rise in Yarns: Influence of Fiber and Liquid Characteristics

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**ABSTRACT:** Liquid transport and movement in yarns were studied using an experimental system based on the analysis of charge couple device images taken during the capillary rise of a colored liquid in the yarn. The generalized dynamic model of the liquid penetration into vertical cylindrical capillary used was based on the Lucas–Washburn equation. It had the advantage of independently characterizing the equivalent pore radius and the contact angle by determining the coefficient of diffusion of the liquid noted  $D$  and the height attained at equilibrium noted  $h_e$ . We studied cotton and viscose yarns and found that the diffusion of liquid and the height attained at equilibrium depending on the fiber type. These results were discussed on the basis of the wettability of the fibers. We used

water and a chemical agent added to water to investigate the effect of the characteristics of liquid on the capillary rise in yarns. The capillary parameters values ( $D$  and  $h_e$ ) depended on the concentration of the chemistry agent added to water. These results were discussed by studying the evolution of the characteristic of the porous media and the liquid properties by calculating the equivalent pore radius and the contact angle and measuring the surface tension and the viscosity of the fluid. © 2007 Wiley Periodicals, Inc. *J Appl Polym Sci* 104: 3050–3056, 2007

**Key words:** textile yarns; capillary rise; kinetics; diffusion; capillary radius; contact angle

## INTRODUCTION

The study of the liquid water transport along textile materials is very important. Practically, all industrial processes of preparation, dyeing and finishing need the control of capillary penetration kinetics in yarns and fabrics.

Optimization of various processes involving liquid–fiber contact,<sup>1,2</sup> characterization of textile materials structures,<sup>3–5</sup> penetration of liquids into capillaries,<sup>6–9</sup> and penetration of drops, such as spray coating, ink-jet printing, etc., have been studied for many years. Also, numerous other fields of textile application have been studied: technical textiles, coating of composites, the dynamics of polymer impregnation of textiles, and comfort in textile<sup>10–12</sup> by the determination of the kinetics of the spontaneous diffusion of water in fabrics.

The phenomenon of dynamics of capillary penetration has been studied by various investigators.<sup>6,13–16</sup> It was initiated by Lucas<sup>17</sup> and Washburn.<sup>18</sup> They used the well-known equation for the penetration of the

liquid into cylindrical capillary,

$$z^2 = \frac{\sigma r \cos \theta}{2\mu} t \quad (1)$$

where  $z$  is the distance penetrated by the liquid,  $\sigma$  is the surface tension of the liquid,  $\mu$  is its viscosity,  $\theta$  is the contact angle between the liquid and the inside surface of the capillary,  $r$  is the internal radius of the capillary, and  $t$  is the time. In the same case, Perwuelz et al.<sup>13,14</sup> studied the capillary flow in polyester and polyamide yarns and glass fibers using a colored liquid. They used Washburn model as defined in eq. (2), which is applicable only for short experimental time and attempt to validate it through the experimental behavior of the capillary moistening in filaments.

$$h^2 = \frac{\gamma R \cos \theta}{2\eta} t = At \quad (2)$$

This equation has been used and tested over the years to study the capillary flow and to characterize porous media by calculating  $R \cos \theta$  from the slope of the curve of  $h^2$  vs.  $t$ .

This approach is very useful. However, the main deficiency of this law is the fact that only the product  $R \cos \theta$  can be elucidated and not  $R$  or  $\cos \theta$  separately. Also, as it is demonstrated by Perwuelz et al.,<sup>13</sup> this approach can be applied as long as gravity forces are negligible, which means that, it is applicable at short experimental time. So, before using this law, we must

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determine from the time the gravity forces are not negligible, which is difficult.

In this article, we are interested in the flow of liquid in a yarn. The equilibrium height and the diffusion coefficient of the liquid were determined by using a generalized Lucas–Washburn equation, which was applicable for short and *long experimental time*. Also, using this approach, we calculated  $R$  and  $\cos \theta$  separately [eqs. (13) and (14)]. These parameters were used to study the influence of characteristics of fiber and liquid on capillary rise in textile structure.

### CAPILLARY THEORY

A wetting liquid placed in contact with a textile yarn penetrates it. The yarn can be considered as assemblies of vertical capillary tubes of radius  $r$ . In a capillary of radius  $R$ , from a dynamic view point, the fluid progression is described by the following relation.<sup>19</sup>

$$\frac{d}{dt}(Mv) = F - F_{\eta} - P \quad (3)$$

where  $M$  is the liquid mass,  $v$  is the liquid speed, and  $F$  is the capillary force<sup>20</sup>:

$$F = 2\pi R\gamma \cos \theta \quad (4)$$

where  $\gamma$  is the surface tension,  $\theta$  is the contact angle, and  $R$ : is the radius of the capillary.

In a vertical capillary, it is given by<sup>21</sup>:

$$F_{\eta} = 8\pi\eta v h \quad (5)$$

where  $F_{\eta}$  is the friction force,  $\eta$  is the viscosity,  $v$  is the rise speed of the liquid, and  $h$  is the liquid front height.

$$P = \rho g \pi R^2 h \quad (6)$$

where  $P$  is the column weight,  $g$  is the gravitational constant, and  $\rho$  the liquid density.

Generally, the progression of the fluid is slow and the inertia of the fluid can be neglected. Replacing every expression by its value, the rise, in these conditions, is given by the equation:

$$2\pi R\gamma \cos \theta = 8\pi\eta h \frac{dh}{dt} + \rho g \pi R^2 h \quad (7)$$

If the equilibrium state is achieved, the maximum liquid height  $h_e$  is given by

$$h_e = \frac{2\pi R\gamma \cos \theta}{\rho g \pi R^2} = \frac{2\pi\gamma \cos \theta}{\rho g R} \quad (8)$$

This relation allows us to rewrite eq. (7) as

$$h\dot{h} = \frac{\rho g R^2}{8\eta} [h_e - h] = \frac{\rho g R^2}{8\eta} h_e \left[1 - \frac{h}{h_e}\right] = \frac{R\gamma \cos \theta}{4\eta} \left[1 - \frac{h}{h_e}\right] \quad (9)$$

In the beginning of the experience and for a short experimental time, the column weight  $P$  is negligible.

The eq. (7) allows to write the following one:

$$R\gamma \cos \theta = 4\eta h \frac{dh}{dt} \quad (10)$$

An integration of the equation gives:

$$h^2 = \frac{R\gamma \cos \theta}{2\eta} t = Dt \quad (11)$$

Equation (11) shows that  $h^2$  is proportional to time and  $D$  is the capillary rate coefficient. It is related at the same time to the interfiber pore structure to the chemical composition of the fiber surface and to the surface properties of the liquid. In fact  $D$  is in millimeter square per second. In this work, we referred to  $D$  as the diffusion coefficient.

Inserting the diffusion coefficient in eq. (9),

$$h\dot{h} = \frac{D}{2} \left[1 - \frac{h}{h_e}\right] \quad (12)$$

Knowing the values of  $h_e$  and  $D$ , the equivalent capillary radius and the equivalent contact angle could be deduced:

$$R = \frac{2\sqrt{2D\rho g h_e \eta}}{\rho g h_e} \quad (13)$$

$$\cos \theta = \frac{\sqrt{2D\rho g h_e \eta}}{\gamma} \quad (14)$$

### EXPERIMENTAL APPARATUS

The experimental system is composed of a charge couple device camera (I2S) to take images during the capillary flow, a device assuring the vertical suspension of yarn on the liquid and a lighting system.

The signal video given out by the camera was managed by software (PCSCOPE) through an intermediary graphic digitalization card.

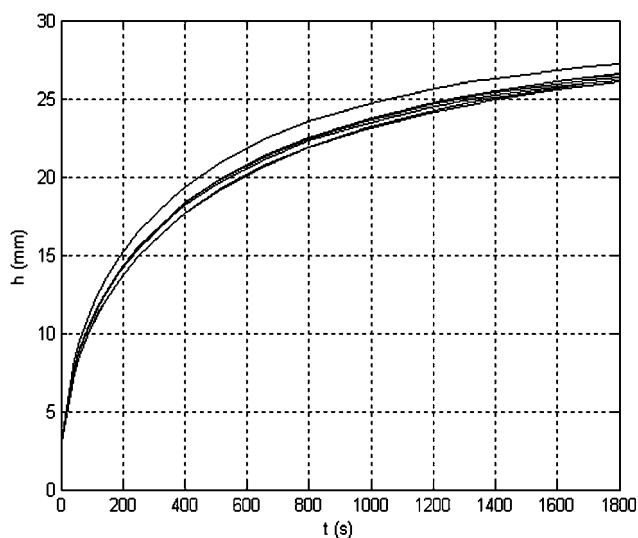
The card received the signal standard video and transformed it into an image of  $512 \times 512$  pixels describing a scale of intensity or levels of gray (0–255).

The yarn chosen to make the experiment was maintained vertically in contact with the liquid. The image of colored liquid rising in textile was received by the CCD camera, observed and smoothed on a video monitor (Philips) at instant  $t$ .

The color of the dry region of yarn was ecru (white) and corresponded to a high gray level. The rest of the

TABLE I  
Characteristics of Materials Used in This Study

Materials	Twist	Density	Degree of crystallinity (%)
Cotton yarn	125	1.54	69
Viscose yarn	125	1.51	40



**Figure 1** Water capillary rise in cotton yarns: results of 10 pieces of the same cotton yarn.

yarn was wet; its color was black, and corresponded to a small gray level.

### MATERIALS AND LIQUID USED

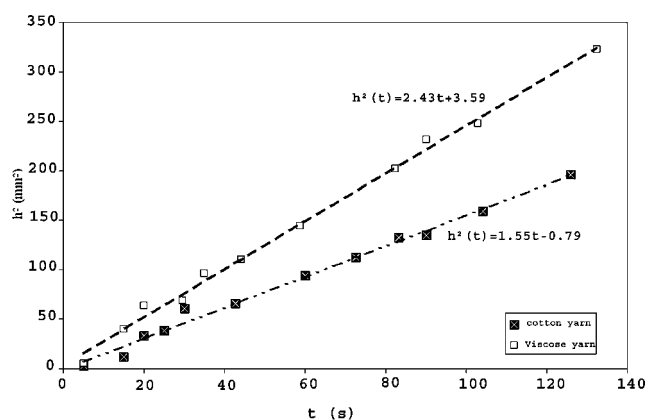
The experimental work was done on cotton and viscose (Table I). To guarantee the best possible wetting of the yarn, a desizing treatment was realized.

We used two kinds of liquids: distilled water and wetting agent or alkali added to distilled water.

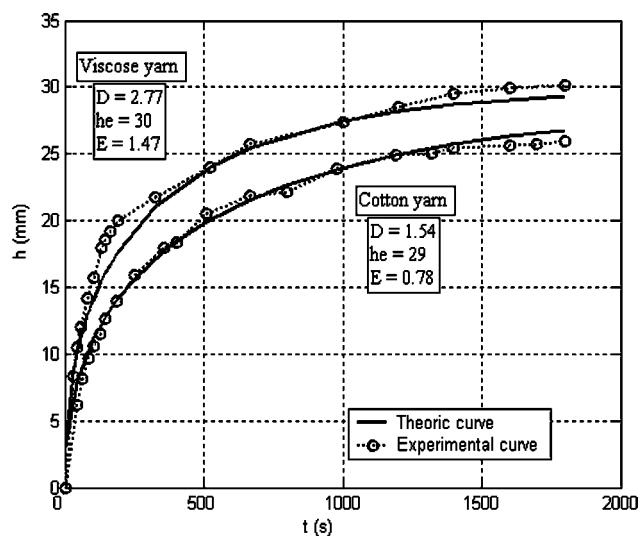
To visualize the rise of liquid in yarns, we used an acid dye (the acid red). In fact, the dye was chosen because cotton and viscose do not have an affinity for these dyestuffs.

### RESULTS AND DISCUSSION

In this section, we are interested in the determination of liquid diffusion coefficient  $D$  and equilibrium



**Figure 2** Evolution of the liquid height with time in viscose and cotton yarns (short experimental time).



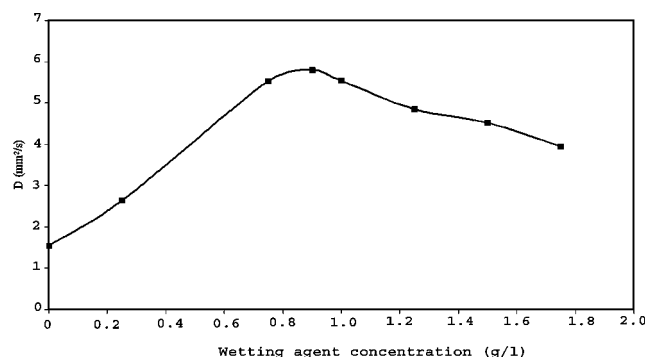
**Figure 3** Evolution of the liquid height with time in viscose and cotton yarns.

height of the liquid column in *yarns*. The experiments were conducted in the laboratory under the same conditions of  $(20 \pm 2)^\circ\text{C}$  and  $(65 \pm 2)\%$  of humidity.

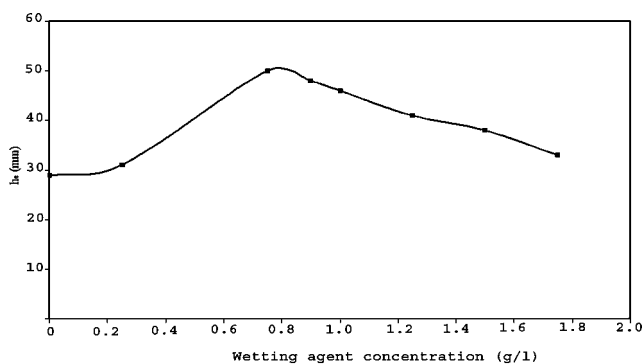
First, we fixed the level of reference gray that corresponds to the passage of wet part to a dry part of the yarn and we determined the height in pixels. This height was then transformed to millimeters. To determine, experimentally, the diffusion coefficient of liquid, we used eq. (11). Thereafter, the parameters ( $D$ ,  $h_e$ ) were determined using the method of the least squares that consisted in minimizing the middle quadratic error between the experimental and theoretical results obtained by resolving numerically eq. (12). Finally, a comparison between results found by both models was made.

### Influence of nature of fiber

A great number of experiments were required to give a good statistical representation of the  $D$  coefficient of



**Figure 4** Evolution of  $D$  in cotton yarn with the wetting agent concentrations.



**Figure 5** Evolution of  $h_e$  in cotton yarn with the wetting agent concentrations.

liquid in yarn. In this study, we repeated the same experiment process for 10 pieces of yarn.

As can be seen in Figure 1, the diffusion coefficient of the liquid was not unique along the cotton yarn and this was related to the geometry of fiber interspaces, which varied along the yarn. All this formed pores with different sizes and shapes.

For the rest of our research, we chose to determine the average value of 10 experiments. To evaluate the heterogeneity of the diffusion coefficient, we referred to the standard deviation.

Figure 2 shows the evolution of the average distilled water height at short capillary rising times in the viscose and cotton yarns as defined in eq. (11). The figure allows deducing the average diffusion coefficient values  $D$  for cotton and viscose yarn, respectively, from the model presented by the eq. (11). In this case, the average diffusion coefficient of the distilled water in cotton yarn was equal to  $1.55 \pm 0.119 \text{ mm}^2/\text{s}$  whereas for the viscose was  $2.43 \pm 0.148 \text{ mm}^2/\text{s}$ .

Figure 3 shows the experimental and theoretical curves obtained from eq. (12) of the distilled water height at different times in the cotton and viscose yarns.

We found the capillary parameters  $D$  and  $h_e$  by comparing theoretical and experimental results. In this case, the average value of the diffusion coefficient of

the distilled water in cotton yarn was equal to  $1.54 \pm 0.159 \text{ mm}^2/\text{s}$  whereas for viscose was  $2.77 \pm 0.212 \text{ mm}^2/\text{s}$  and the average value of the equilibrium height is equal to  $29 \pm 0.601 \text{ mm}$  in cotton yarn and  $30 \pm 0.681 \text{ mm}$  in viscose yarn. Comparing the diffusion values found in both models, we observed, practically, a minor difference between them, which is negligible in a number of cases.

The results obtained showed that the values of  $D$  and  $h_e$  in a cotton yarn were lower than those in a viscose yarn. The decrease of  $D$  can be explained by the ability of viscose fiber to absorb water more than cotton. The viscose fibers had a lower degree of crystallinity (40–50%), and a great number of amorphous regions, which means that they have good absorption ability. It has moisture retention of 80–120% at 65% RH and 20°C. It is contrary to cotton that has moisture regain of 40–45% in the same conditions.<sup>22</sup>

During the impregnation, the viscose swelled more than the cotton, and consequently, the mean capillary radius increase more in the case of the viscose. So, according to the expression of  $D$ , we can explain why the diffusion coefficient of the liquid was lower in the case of cotton.

### Influence of liquid characteristics

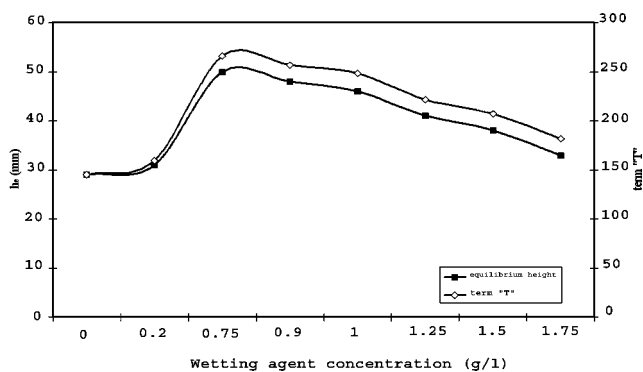
To facilitate the dye of cotton and viscose fabrics, we used a special wetting agent. That is why in this study, we used water added to a wetting agent at different concentrations to demonstrate the influence of liquid composition on the wettability of cotton yarns.

On the other hand, the dyeing of cotton and viscose fiber was done in an alkaline medium. Thus, it is very important to study the influence of alkali on rising liquid and kinetics phenomena of cotton yarns.

The evolution of the diffusion coefficient  $D$  determined using mathematical model presented by eq. (12), which is generalized (applicable at every instant: short or long experimental times) and the liquid column height in equilibrium position  $h_e$  in the cotton

**TABLE II**  
Surface Tension of Liquid Used in This Study

[Dye] (g/L)	[Wetting agent] (g/L)	[NaOH] (g/L)	Surface tension (mN/m)	Viscosity (mP s)	Capillary radius ( $\mu\text{m}$ )	Cos $\theta$
0	0	0	$72.31 \pm 0.022$	$1.0020 \pm 0.0007$	–	–
2	0	0	$47.15 \pm 0.039$	$1.0060 \pm 0.0004$	6.56	0.020
2	0.25	0	$44.71 \pm 0.031$	$1.0233 \pm 0.0052$	8.18	0.029
2	0.75	0	$43.68 \pm 0.028$	$1.0231 \pm 0.0055$	9.22	0.056
2	0.90	0	$43.25 \pm 0.013$	$1.0233 \pm 0.0051$	9.61	0.057
2	1	0	$42.38 \pm 0.025$	$1.0233 \pm 0.0069$	9.56	0.055
2	1.25	0	$41.62 \pm 0.020$	$1.0232 \pm 0.0071$	9.47	0.050
2	1.5	0	$41.58 \pm 0.029$	$1.0233 \pm 0.0056$	9.45	0.047
2	1.75	0	$41.52 \pm 0.022$	$1.0233 \pm 0.0055$	9.44	0.041



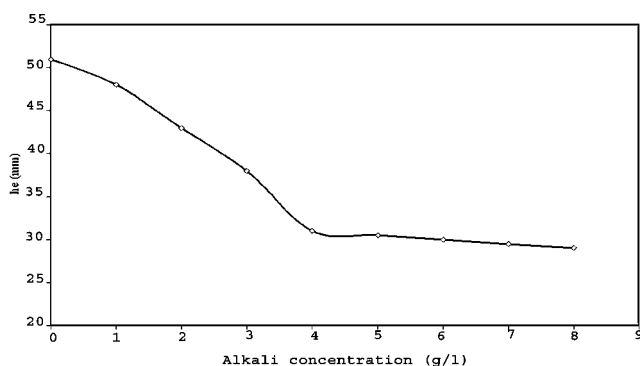
**Figure 6** Evolution of the liquid height and the term "T" versus the wetting agent concentration.

yarn with the wetting agent concentrations are represented in Figures 4 and 5.

From Figure 4, we can observe that at a moderate concentration of wetting agent lower than 0.9 g/L, the diffusion coefficient  $D$  increased. At a concentration higher than 0.9 g/L, the diffusion coefficient  $D$  decreased and the opposite situation can be observed. Figure 5 shows that the liquid height at equilibrium  $h_e$  increased with the increase of the wetting agent concentration, attaining a maximum and decreased. As a result, we can recapitulate that  $D$  and  $h_e$  had the same evolution behavior by adding the wetting agent at a different concentration.

This can be explained by the swelling of the yarns to absorb water and ease water diffusion inside the fabric pores. We can observe from Table II that the capillary radius deduced using eq. (13) increases with concentrated wetting agent and attains a maximum at 0.9 g/L. For a higher concentration, it became approximately constant. This phenomenon explained the increase of  $D$  at moderate concentration and its decrease at elevated concentration (more than 0.9 g/L). Indeed, eq. (11) shows that  $D$  varies proportionally with  $R$ .

In the same case, the data presented in Table II shows the evolution of the liquid surface tension ver-



**Figure 7** Evolution of  $h_e$  in cotton yarn with the alkali concentration.

sus wetting agent concentration. First, a notable decrease in the surface tension value was observed by addition of the dye. But, addition of wetting agent had probably no influence on the surface tension (as shown in Table II). So, the surface tension had no influence on the evolution of  $D$ .

The contact angle (Table II) deduced using eq. (14) decreases with increased of wetting agent concentration and attained a minimum at the concentration of 0.9 g/L. For a higher concentration than 0.9 g/L, the contact angles increases. Consequently, the diffusion coefficient  $D$  increased at moderate concentration and after that decreases. The viscosity values were approximately constant in used concentration range of the wetting agent. So, the evolution of  $h_e$  and  $D$  cannot be explained by viscosity variation.

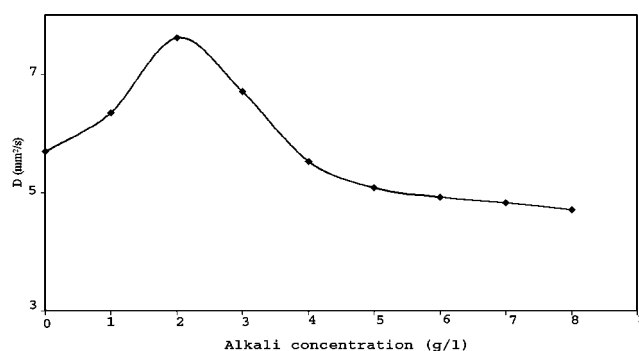
Evolution of  $h_e$  cannot be explained by the value of capillary radius and contact angle, which have no significance. To interpret the equilibrium height of liquid evolution with wetting agent concentration, we calculated the term  $\gamma \cos\theta/R$  noted  $T$ , which is represented in the same figure with the equilibrium height of liquid. This figure (Fig. 6) shows that each of the curves of  $h_e$  and  $\gamma \cos\theta/R$  has the same pattern.

The influence of the alkali concentrations on the diffusion coefficient  $D$  and the liquid column height in equilibrium position  $h_e$  in the cotton yarn was represented in Figures 7 and 8.

Figure 7 shows that the liquid height at equilibrium  $h_e$  decreases rapidly when the alkali concentration was lower than 4 g/L.

For alkali concentration higher than 4 g/L, the liquid height at equilibrium  $h_e$  became almost constant. This can be explained by the fact that the inflation of the cellulose and the degradation of cuticle attained their maximum degree. Also, Table III shows that the capillary radius increases with the alkali concentration increased and attain a maximum at (2 g/L). After that, an inverse situation occurred.

Figure 8 shows that the diffusion coefficient of wetting liquid  $D$  increased with alkali concentration and attained a maximum at 2 g/L and then decreased.



**Figure 8** Evolution of  $D$  in cotton yarn with the alkali concentration.

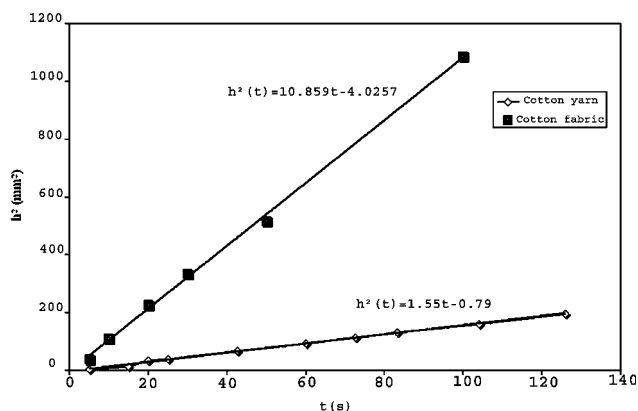
**TABLE III**  
Influence of NaOH Concentration on Liquid Surface Tension

[Dye] (g/L)	[Wetting agent] (g/L)	[NaOH] (g/L)	Surface tension (mN/m)	Viscosity (mP s)	Capillary radius ( $\mu\text{m}$ )	Cos $\theta$
0	0	0	$72.31 \pm 0.022$	$1.0020 \pm 0.0007$	–	–
2	0	0	$47.15 \pm 0.039$	$1.0060 \pm 0.0004$	6.56	0.020
2	0.8	0	$43.32 \pm 0.013$	$1.0233 \pm 0.0052$	9.56	0.056
2	0.8	1	$42.71 \pm 0.028$	$1.0650 \pm 0.0028$	10.51	0.060
2	0.8	2	$41.74 \pm 0.032$	$1.0722 \pm 0.0027$	12.12	0.064
2	0.8	3	$41.20 \pm 0.017$	$1.0722 \pm 0.0029$	12.07	0.058
2	0.8	4	$40.40 \pm 0.024$	$1.0724 \pm 0.0028$	12.01	0.048
2	0.8	5	$39.87 \pm 0.020$	$1.0724 \pm 0.0027$	11.66	0.047
2	0.8	6	$39.40 \pm 0.011$	$1.0724 \pm 0.0029$	11.56	0.046
2	0.8	7	$39.10 \pm 0.028$	$1.0725 \pm 0.0031$	11.57	0.046
2	0.8	8	$38.72 \pm 0.013$	$1.0725 \pm 0.0028$	11.56	0.045

This can be explained by the decrease of the surface tension of the liquid (Table III) and by the swelling of the cotton fiber and the variation in pore size (Table III). Normally, the diffusion coefficient  $D$  is related to the capillary radius and to surface chemical characteristics of the liquid as noted in eq. (11). The evolution of  $D$  with alkali concentration after 2 g/L cannot be done because of the term  $(\gamma \cos \theta / 2\eta)$ , as surface tension values (Table III) have shown a miniature modification for 4 and 8 g/L of NaOH concentration and the viscosity had no significant variation with NaOH concentration (Table III). Thus, these evolutions of  $D$  can be explained by the heterogeneity of the yarn pores.<sup>23</sup> So, it is not only the size of the pore, which influenced this coefficient, but also the shape of the pores, which had to be taken into the account.

### Study of capillary flow in fabric

In this section, the fabric was considered as a bundle of parallel capillaries (yarns) of constant radius. We used eqs. (12) and (11) to determine capillary parameters ( $D$  and  $h_e$ ). The experimental study was done on



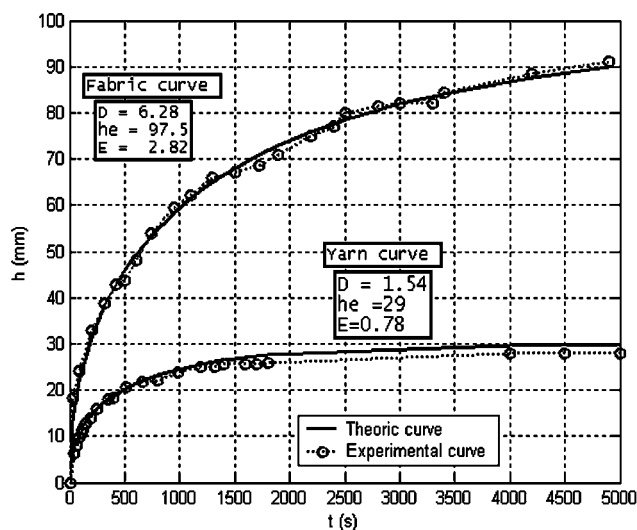
**Figure 9** Evolution of the liquid height versus time in cotton fabric for short experimental instants.

plain cotton fabrics (17 wefts/cm). The liquid used was the distilled water.

The experiment consisted in the determination of the diffusion coefficient  $D$  and the liquid height  $h_e$  attained by the distilled water at equilibrium in the fabric. As shown in Figure 9, at time  $t < 130$  s, the evolution of the liquid height versus time in the fabric was linear and verified low as given in eq. (11). The average value of the diffusion coefficient of water in the fabric was equal to  $10.85 \pm 0.729$  mm<sup>2</sup>/s.

Results for similar experiments at long time until  $t = 5000$  s are shown in Figure 10. In these cases, we determined the diffusion coefficient and the liquid height at equilibrium in fabric using eq. (12). The average value of the diffusion coefficient of water in the fabric was equal to  $6.28 \pm 0.420$  mm<sup>2</sup>/s and the average value of the liquid height attained at equilibrium was equal to  $97.5 \pm 2.584$  mm.

Results shown in Figure 9 are particular case of the results shown in Figure 10. In reality, Figure 9 represents a zoom of the Figure 10 in the interval of time  $t$



**Figure 10** Evolution of the liquid height versus time in cotton fabric for long experimental instants.

< 130 s. We noticed that the value of diffusion determined using eq. (11) was more important than the value determined by eq. (12). In the case of yarn, we observed that values of diffusion determined by eqs. (12) and (11) were, practically, similar and the difference between them was negligible, as shown in Figures 9 and 10.

As shown in Figure 10, we can observe that the liquid rise in yarn attained rapidly the equilibrium height. On the contrary, the liquid rise in fabric needed more than 5000 s to attain the equilibrium height. This explained clearly the difference between the values of diffusion of liquid determined by eq. (12) and<sup>11</sup> in fabric structure. Consequently, we can conclude that the law ( $h^2 = Dt$ ) can be applied for the study of yarns, which are saturated by liquid in a short experimental time. However, to study capillary rise in fabric, we had to use the generalized law given by eq. (12), which was more precise.

### CONCLUSIONS

In this work, we have investigated for the first time the experimental study of the liquid rise kinetics in textile structure using the generalized Lucas–Washburn equation. As it was demonstrated, this mathematical model is more precise than the simplest well known law given by ( $h^2 = Dt$ ) especially in the case of fabrics. Along this study, we evaluated liquids transport behavior in cotton and viscose. We noted that  $D$  and  $h_e$  were a function of fiber type, bath composition, and textile structure.

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