The Influence of Woven Fabric Structure on Kinetics of Water Sorption

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ABSTRACT

In this paper, the results of an experimental study designed to determine the kinetics of water sorption on cotton fabrics are presented. The dynamic water sorption of cotton fabrics was gravimetrically investigated at 20°C by using an experimental device, which assured the vertical suspension of the cloth surface and permitted the measurement of the mass of liquid rising in the fabric. A good fit of the experimental data with the parallel exponential kinetics model was found. The results show that the weave structure and the number of yarns per centimeter had a significant influence on the model parameters and the kinetic rate of sorption.

INTRODUCTION

The textile industry consumes large amounts of water in its various processing operations. Almost all dyes, specialty chemicals, and finishing chemicals are applied to textile substrates from water baths. In addition, most fabric preparation steps, including desizing, scouring, bleaching, and mercerizing use aqueous systems. In textile wet processing, water is used mainly for two purposes: as a solvent for processing chemicals and as a washing and rinsing medium.

Water absorption ability changes from one fiber to another. For example, a cotton fiber has a more water absorption ability than a polyester fiber [1], and the quantity of water transported along viscose was found to be more important than that of cotton [2]. The absorption of water molecules on the fabric surface is strongly influenced by the presence of hydrophilic functional groups which play the role of primary adsorption centers due to the formation of hydrogen bonds between the water molecules and the functional groups.

For these reasons, it is very important to study the liquid water transport along textile materials to optimize various processes of dyeing and finishing. In this case, the dynamic phenomenon of capillary penetration has been studied by various investigators. Perwuelz et al [3, 4] studied the capillary flow in textile yarns and glass fibers using a colored liquid to calculate the diffusion coefficient. Hamdaoui et al [1, 5] studied the dynamics of capillary rise in yarns and fabrics. They developed an experimental device which assured the vertical suspension of the tested textile structure and permitted the measurement of the mass of liquid rising in textile materials and the governing diffusion coefficient. Another technique based on an electrical method [6, 7] was used to determine the water content in viscose and cotton fiber materials at different height levels.

The sorption mechanisms of individual fiber material have been studied by various investigators [8, 9, 10, and 11]. They proposed different theories and models to describe this phenomenon. Gouanvé et al [10] used the Fick’s law solutions valid for a cylinder of radius r to interpret the experimental gravimetric data. They determined water diffusion coefficients D_1 for short times and D_2 for longer times. Xie et al [11] examined the water vapor sorption behavior of three celluloses which were originally derived from cotton fibers. They found that the sorption kinetics behavior is very accurately described by the PEK model.

In this study, we present the sorption kinetic experimental data and their interpretation in terms of diffusion rate of water molecules and mass of water absorbed in different cotton fabrics by using a parallel exponential kinetics (PEK) model.

EXPERIMENTAL DEVICE

The experimental system (*Figure 1*) is composed of a device which assures the vertical suspension of fabric surface on the liquid as well as a lighting system. In order to measure the mass of the raised liquid, the fabric is attached to a sensitive electronic balance (AND GX-2000 precision balance) with an accuracy of 0.01 g. The balance has the capability of recording the weight of the absorbed water (g) versus time (s) with its special software (RsCom program of WinCT data communication software Version 2.40 compatible with Windows, Window 95, 98, and NT.

MATERIALS

Experiments were carried out on different woven fabrics. The weave structure and the thread densities of these fabrics are presented in the *Table I*. All fabric samples were woven under the same technological conditions.

To remove the warp sizes that were applied to yarns prior to weaving, a desizing treatment was used. The fabric was treated for 15 minutes at 65°C with a solution containing 5 mL/L of biolase PCL 50, 2.5 mL/L of wetting agent (Lavotan TBU) and 1 mL/L of acetic acid.

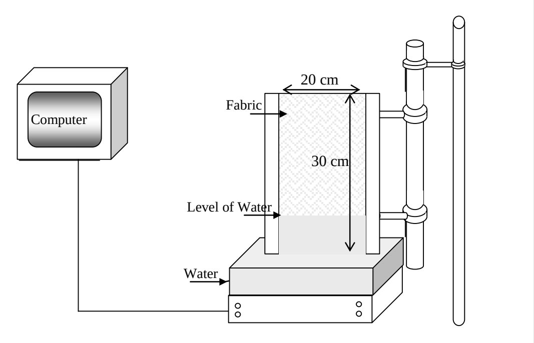

FIGURE 1. Experimental Device.

TABLE I. Specifications of fabric.

Sample N°	Composition	Structure	Weft count (yarns per cm)	Warp count (yarns per cm)	Fabric weight (g/m²)
1	100% Cotton	Plain	20	24	175.95
2	100% Cotton	Twill	20	24	169.52
3	100% Cotton	Satin	15	24	157.79
4	100% Cotton	Satin	20	24	166.18
5	100% Cotton	Satin	26	24	173.85

Also, to remove the waxes and oils attached to greige fabrics that interfere with proper dyeing, a scouring treatment passing fabrics in a bath containing 1.5% of caustic soda, 0.2% of nonionic surfactant (Kemonecer NI) and 0.1% of sequestrant (E.D.T.A) at 100°C for 20 minutes was employed.

RESULTS AND DISCUSSION

Experimental Data Treatment

In this section, the determination of the mass of water absorbed by the cotton fabric is discussed. We used three different weft counts (15, 20 and 26). The experiments were conducted in the laboratory under the same conditions of (20±2)°C and (65±2)% humidity. The dimension of the dry sample used in experiments was 20 cm x 30 cm (*Figure 1*). reported In *Figure 2* the evolution of the experimental data of the mass of water absorbed by the textile fabrics as a function of time are presented.

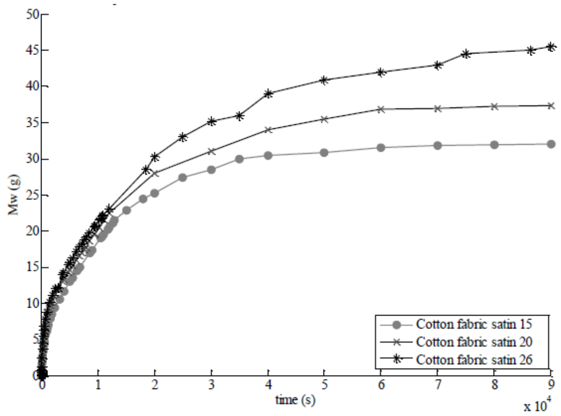

FIGURE 2. Evolution of mass of water absorbed by different cotton plain fabrics.

Figure 2 shows that, at the same time, the mass of water absorbed by cotton fabric increases with the weft count (number of weft yarn per centimeter). This can be explained by the augmentation of the quantity of the material: when the weft counts increase, the absorption ability of the fabric does the same.

Also, we can observe that the three curves have a positive slope but decrease with time and reach zero at full saturation. So, this result indicates that the evolution of mass of water absorbed by cotton fabrics as a function of time can be modeled by two parallel independent processes. The first one is the rapid phase and the second one is the slow phase.

Water Kinetics Sorption

In order to interpret the sorption kinetics of water molecules in the cotton fabric, the experimental data of mass of water absorbed by the fabric at each time was curve fitted using MatLab to the parallel exponential kinetics model. PEK model has a double exponential form as given by the Eq. (1) [12, 13]:

$$Mw = M_{1_\infty}(1 - \exp(-K_1 t)) + M_{2_\infty}(1 - \exp(-K_2 t)) \qquad (1)$$

Where M_w is the mass of water absorbed by the fabric at time t. As demonstrated in *Figure 3*, the sorption kinetic curve is composed essentially of two exponential terms which represent both a fast and a slow process.

The terms M_{1_∞} and M_{2_∞} are the masses of water absorbed at an infinite time associated respectively with the fast and slow processes (see *Figure 3*). K_1 and K_2 are the kinetic sorption of water, respectively at the fast and slow processes.

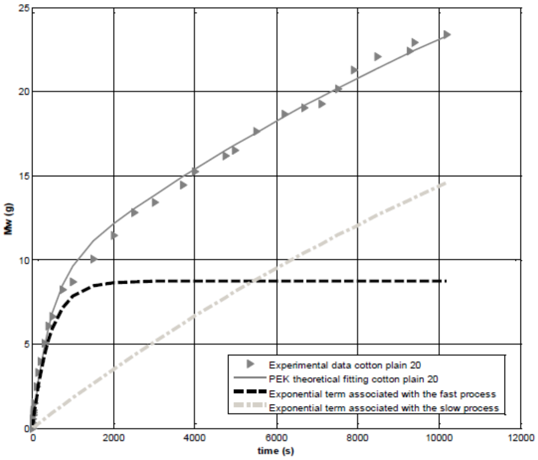

FIGURE 3. Mass of absorbed water by cotton plain fabric 20 versus time.

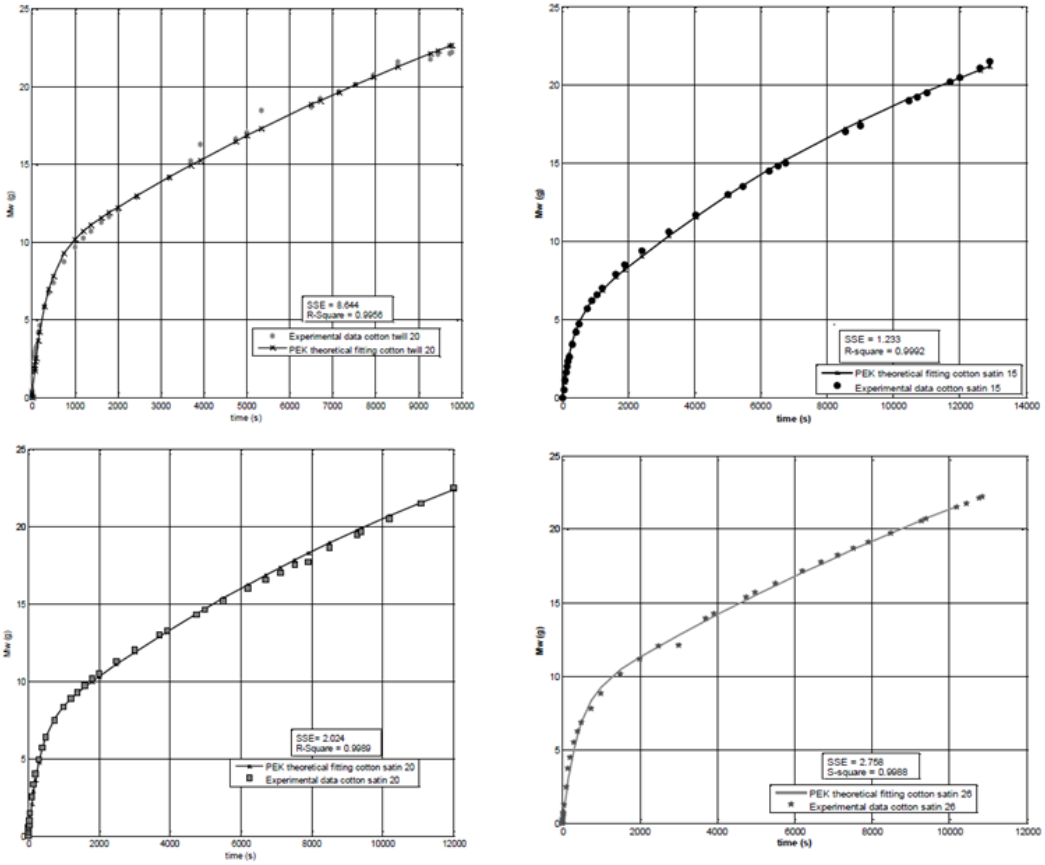

FIGURE 4. Mass of absorbed water by cotton fabrics versus time.

In *Figure 3* and *Figure 4*, the lines were the best fit for the PEK model to the kinetics experimental data. The validity of the PEK model in the five fabric cases in describing the kinetic data is checked by the correlation coefficient (R-square) and the sum of square due to error (SSE). R-square and SSE were defined as:

- Sum of Squares Due to Error (SSE) which measures the total deviation of the response values from the fit to the response values. A value closer to 0 indicates that the model has a smaller random error component;
- R-square is the square of the correlation between the response values and the predicted response values. It can take on any value between 0 and 1, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the model.

Table II summarizes the PEK model fitting parameters, the (R-square) and the (SSE) coefficient.

TABLE II**.** PEK model fitting parameters.

Sample N°	M_{1_∞} (g)	M_{2_∞} (g)	**K_1 (s^{-1})**	**K_2 (s^{-1})**	**SSE**	**R-square**
1	8.736	35.27	$2.27\ 10^{-3}$	$5.23\ 10^{-5}$	6.230	0.9972
2	8.733	32.36	$3.10\ 10^{-3}$	$5.75\ 10^{-5}$	8.644	0.9956
3	4.702	27.12	$3.30\ 10^{-3}$	$7.24\ 10^{-5}$	1.233	0.9992
4	6.890	30.57	$3.12\ 10^{-3}$	$5.79\ 10^{-5}$	2.024	0.9989
5	8.249	37.15	$2.68\ 10^{-3}$	$4.36\ 10^{-5}$	2.758	0.9988

As shown in *Table II,* the values of R-square (greater than 0.99 for all fabrics) and the low SSE values (lower than 10 for all fabrics) indicate that experimental data were well correlated to the PEK equation.

K_1 values were greater than K_2 for all the fabrics' structure. This phenomenon can be the result of the fast sorption of water at the sites of the readily accessible internal and external surfaces and amorphous regions because the sites for water sorption are completely free. Also, in cotton fiber, there are three hydroxyl groups attached to each anhydroglucose which can be attacked directly by the water molecules; thus an important water quantity will be absorbed by cotton cellulose at the fast process when the groups are free. This first fast process corresponds to a direct sorption of the water molecules. In contrast, the indirect sorption onto the inner surface, crystallites and additional water molecules which can absorb on the water molecules binding the fiber directly could be relatively slow, and correspond to the second and slow processes.

Effect of Weft Count

On the basis of the results presented in *Table II*, it is worth noting that the weft count influences the water mass absorbed by the textile and the kinetics rate of water sorption. $M_{1\infty}$ and $M_{2\infty}$ increase when the weft count increases. The fabric made of a weft count of 26 has a higher specific mass than those made of a weft count of 20 or 15, because in a volume unit, they contain the biggest amount of fibrous material. Thus, the number of hydroxyl groups, the sites of the readily accessible internal, external surfaces and amorphous regions increase thereby giving higher water absorption ability.

It is also apparent that the woven fabric made of a weft count of 15 yarns per cm is characterized by a loose structure. That's why this sample is associated with a higher kinetics rate of water sorption (K_1 and K_2). On the contrary, the fabric is more tightened when the weft count increases and consequently the size of micro and macro-pores decrease. This proves that the woven fabric made of weft count of 26 yarns per cm have the lowest kinetics rate of water sorption (K_1 and K_2).

Effect of Weave Structure

From the results presented in *Table II*, it was noted that the weave structure significantly influenced the mass of water absorbed by the fabric and the kinetics sorption. The highest mass absorbed, $M_{1\infty}$ and $M_{2\infty}$, was noted for the plain fabric. The second highest mass absorbed, $M_{1\infty}$ and $M_{2\infty}$, was found for the twill weave fabric. The plain weave structure is characterized by the highest specific mass, meaning that in a volume unit, it contains the biggest amount of fibrous material (cotton fiber), in which water is absorbed and takes place.

It is probable that the reason for such a relatively high kinetics rate of water sorption (K_1 and K_2) onto satin fabric may be related to the higher float length of the weft yarns in this type of fabrics.

Water Diffusion Process

A plot of the amount of water per unit weight, Qt, at any time, t, versus square root of time, $t^{1/2}$, allows us to study the water diffusion process.

The amount of water (Qt) adsorbed per gram of cotton (mg/g cotton) at any time was calculated by Eq. (2) as follows:

$$Q_t = \frac{q_f(t)}{M_f} \tag{2}$$

Where:

$q_f(t)$ (mg) is the amount of water adsorbed by the fabric at any time t, and M_f (g) is the mass of the fabric tested.

As shown in *Figures 5 and 6*, the regression of the amount of water (Q_t) adsorbed per gram of cotton (mg/g of cotton) versus $t^{1/2}$ is linear and passes through the origin. So the intra-particle diffusion rate constant can be given by Eq. (3) as follows:

$$Q_t = K_{\text{int}}\, t^{1/2} \tag{3}$$

K_{int} (mg/g $\text{min}^{-1/2}$) is the intra-particle diffusion rate constant. It is directly evaluated from the slope of the regression line.

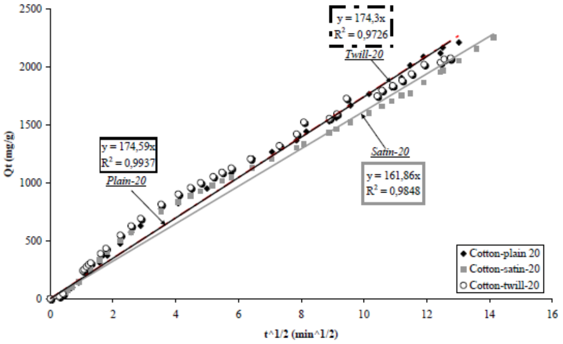

FIGURE 5. Influence of fabric structure on water diffusion parameter.

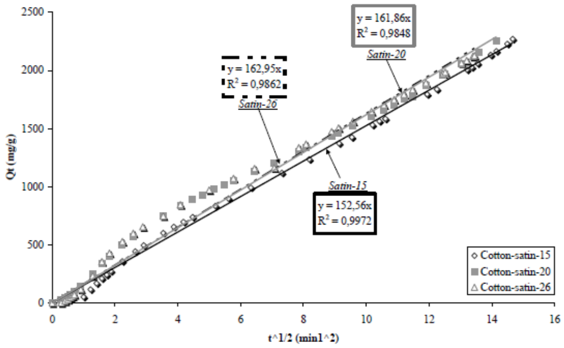

FIGURE 6: Influence of weft count on water diffusion parameter.

The linearity of the plots demonstrated that the intra-particle diffusion played a significant role in the uptake of the water by cotton weave fabrics. It can be also observed that the intra-particle diffusion is involved in the rate-limiting step.

It has been reported that if the intra-particle diffusion is the sole rate-limiting step, it is essential for the Q_t versus $t^{½}$ plots to pass through the origin [14], which is the case in this study.

Table III gives the intra-particle diffusion rate constant and the R-square coefficient for different samples tested.

TABLE III. Water diffusion parameter.

Sample	**K_{int} (min^{-1})**	**R²**
Plain	174.59	0.9937
Twill	174.30	0.9726
Satin 15	152.56	0.9972
Satin 20	161.86	0.9848
Satin 26	162.95	0.9862

The obtained rate constants K_{int} are shown in *Table III*, as well as the R-square. R² confirms that the rate-limiting step was actually the intra-particle diffusion process.

Depending on the weave structure of the fabric and the weft count (yarn per cm), values of K_{int} varies from 152.56 to 174.59 mg/g $\text{min}^{-1/2}$.

CONCLUSION

In this work, we conducted an experimental study of the dynamic water sorption of five different cotton fabrics using a PEK model. The water sorption was gravimetrically investigated at 20°C and 65% of humidity.

The simulation curves by MatLab show good agreement with the experimental data of the water mass absorbed by the textile structure. The validity of the mathematical model in describing the kinetic data was checked by the correlation coefficient (R-square) and the sum of square due to error (SSE). We observed that the water sorption in the textile structure is based on two different mechanisms occurring simultaneously in fast and slow processes.

Finally, we noted that the weft count and the weave structure had a significant influence on the kinetics rate of water sorption (K_1, K_2) as well as on the water mass $M_{1\infty}$, $M_{2\infty}$ absorbed at infinite time associated respectively with the fast and slow processes.

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