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Research Article Open Access

Study of the Dyeing Kinetics: Influence of Pre-Treatments and Woven Fabric Structure

Hamdaoui M[1,2]*, Charfi A[2] and Khoffi F[3]

[1]Laboratoire d'Etudes des Systèmes Thermiques et Energétiques, Ecole Nationale d'Ingénieurs de Monastir, University of Monastir, Tunisia
[2]Département de Génie Textile, Ecole Nationale d'Ingénieurs de Monastir, University of Monastir, Tunisia
[3]Laboratoire de Physique et Mécanique Textile, ENSISA, Mulhouse, France

Abstract

In this paper, we present the results of an experimental study of dyeing kinetics after finishing treatments. We have considered a woven fabric of which we have varied the structure, the number of warp and filling yarns per cm and the weight ratio of the fabric. The results of experimental study show that exhaustion rate and the coefficient of diffusion depending on the characteristics of fabrics and the type of the pre-treatment.

Keywords: Woven fabric; Chemical pre-treatment; Exhaustion rate; Diffusion coefficient; Fick's law

Introduction

Dyeing processes are very dynamic as they involve the transport of diverse products from the dyeing medium into the fibers. The process is divided into three phases. In the first one, the direct dye was adsorbed through substantively. In the second phase, it penetrated (diffused) into the fibers. Finally, it fixed to the fibers. The kinetics of the dyeing process is related to these three phases. There are, also, many reports on the relationship between the fiber fineness and dye ability [1]. So, for a professional, it is very important to control the necessary time to achieve high bath exhaustion and optimize the processes. For this reason, we must calculate the dyeing kinetics (diffusion velocity).

The dyeing kinetics of some fibers is the subject of numerous studies [2-7]. Vassileva et al. [2] determined the kinetic relations describing relative dyes fixation on cellulose textile materials on the ground of the methods of the heterogeneous chemical kinetics. They studied the effect of temperature on the dyeing kinetics by measuring Kubelka-Munk function "K/S". The latter is directly proportional to the dye concentration in the textile material and is used as a kinetic variable in their investigation. To develop a method for measuring the kinetic coefficients, Telegin et al. [3] proposed solutions for the diffusion sorption problem with consideration of the rate saturation of the surface sorption layer applied to different conditions of conducting the experiment. The obtained results demonstrate the broad possibilities of controlling dyeing of synthetic polymer and also the possibility of practical use of the mathematical description of the process for assessing the applicability of auxiliary substances of different natures in finding the optimum technology for high-temperature dyeing of polyester fibers.

In practical terms, the dyeing method to be selected depends on the type of the dyeing equipment, the nature and characteristics of materials to be dyed and the properties of the dye (solubility and affinity). In this study we dyed cotton fabrics using direct dye. In the beginning, we prepare the dye bath by using water, the wetting agent and the fabric. After that, the dye is diluted with water, boiled up and then added to the dye bath. Next, the bath heats up to the optimum temperature (98°C in this study), the electrolyte is added at this instant. Dyeing takes 45 minutes. After the exhaustion of the dye bath, the dyed fabric is rinsed with water at 80°C.

In this paper, we try to better understand the effect of some characteristics of the fabric by using different samples fabricated by 100% cotton and the chemical pre-treatments realized on exhaustion rate and on the dyeing kinetics.

Mathematical Formulation

"C" stands for the concentration of dye particles which is described as:

$$C(x,y,z,t) \tag{1}$$

"J" stands for the course density of dye particles which is described as:

$$J(x,y,z,t) \tag{2}$$

Or the conservation of the particles gives the following mathematical equation [8]:

$$\frac{\partial\, C(x,y,z,t)}{\partial\, t} dV = J(x,y,z,t)\, S\text{-}J(x,y,z,t)\, S \tag{3}$$

This equation can be re-writing as:

$$\frac{\partial\, C}{\partial\, t} = -\, divJ \tag{4}$$

Fick describes the diffusion processes of the dye by the following equation:

$$J = -D\, gradC \tag{5}$$

Combining the equations (4 and 5) leads to:

$$\frac{\partial\, C}{\partial\, t} = -D\, \Delta C \tag{6}$$

Where D (cm^2/s) is the diffusion coefficient and C is the dye concentration

Or, a simplified solution to Fick's second law of diffusion (equation

***Corresponding author:** Mohamed Hamdaoui, Assistant Professor, National School of engineering of Monastir, University of Monastir Tunisia, E-mail: hamdaouimohamed@yahoo.fr

Received September 25, 2012; **Published** November 24, 2012

Citation: Hamdaoui M, Charfi A, Khoffi F (2012) Study of the Dyeing Kinetics: Influence of Pre-Treatments and Woven Fabric Structure. 1:479. doi:10.4172/scientificreports.479

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6) was presented by Crank. The specific surface of the fiber appears in this solution:

$$\frac{C_{ft}}{C_f\infty} = A\sqrt{t} = \frac{\dfrac{C_{ft}}{C_{b(t=0)}}}{\dfrac{C_{f\infty}}{C_{b(t=0)}}} = \frac{E_t}{E_\infty} \qquad (7)$$

Where:

$$A = \frac{4}{r\sqrt{\pi}}\sqrt{D} \qquad (8)$$

and r is the radius of the fiber (m)

So inserting the diffusion coefficient in equation (7),

$$\left(\frac{4}{r\sqrt{\pi}}\sqrt{D}\right)t^{1/2} = \frac{E_t}{E_\infty} \qquad (9)$$

Equation (9) has been used to determine the diffusion coefficient from the slope of the curve of $\frac{E_t}{E_\infty}$ versus $t^{1/2}$.

Materials Characteristics

Experiments were carried out on different cotton woven fabrics. The weaving structure, the number of warp yarns and filling yarns per cm of the fabric, the fabric thickness and the weight ratio of fabrics are presented in tables 1 and 2. All fabric samples were woven under the same technological conditions.

Wet preparation treatments

Preparation treatments are the first stage in textile wet processing. After these wet processing pre-treatments, textile materials can be dyed.

To remove the warp sizes that were applied to yarns prior to weaving, desizing treatment was realized. The fabric was treated 15 minutes at 65°C with a solution containing 5 mL/L of biolase PCL 50, 2.5 mL/L of wetting agent and 1 mL/L of acetic acid. Also, to remove the waxes and oils attached to greige fabrics that interfere with proper dyeing, we realized a scouring treatment by running fabrics in a bath containing 1.5% of caustic soda, 0.2% of surfactant and 0.1% of sequestrant at 100°C for 20 minutes. At times, we realized bleaching to remove color bodies from cotton. Fabrics were bleached at 90°C for 30 minutes in a solution containing 4 mL/L hydrogen peroxide 35%, 2 g/L sodium carbonate and 2 g/L stabilizer. Finally, in some of the cases, we realized mercerization: the treatment of cotton fabrics with 2 g/L of sodium hydroxide at 80°C for 30 minutes to increasing dye affinity.

Experimental details

The four cotton woven fabrics presented in table 1 and 2 were used to develop this study. The dyestuffs were 1.5% of the direct Red “SOLOPHENYL 7 BE”. Chemical auxiliaries were 0.5 g/L of sodium carbonate, 20 g/L of sodium sulfate and 1 mL/L of wetting agent. The dyeing processes were carried out in a laboratory apparatus (AHIBA Nuance, DataColor), with a liquor-to-fiber ratio of 40:1 and pH 9.5, under the dyeing conditions indicated in figure 1.

Sample	Structure	Thickness (mm)	weight ratio (g/m²)	The number of filling yarns (yarns/cm)
PC18	Plain	0.48	134.43	18
PC23	Plain	0.49	150	23
PC29	Plain	0.52	171.93	29
4S29	4-Satin	0.40	122	29

Table 1: Fabrics structure.

After each 5 minutes in the dyeing process, a 2 mL sample was taken from the exhausted dye bath and was analyzed using a BIOCHROM spectrophotometer to measure the concentration of dyestuff and calculate the exhaustion rate. Then, the curve of the evolution of the exhaustion of the bath with time was established.

Exhaustion rate was calculated using this equation:

$$E\% = \frac{C_0 - C_f}{C_0} x100 \qquad (10)$$

Where C_0 was the initial concentration of the dye in the bath in g/L, and C_f was the reduced concentration of the dye at time t.

For any substantial conclusions to be drawn from the work, a number of repeat dyeing and associated standard deviation on values obtained would therefore necessary. In this study, we repeated the same experiment process three times. Figure 2 shows results of evolution of exhaustion (E%) of the bath with time in the dyeing process of three tests of the same sample PC18 and the Standard Deviation (SD) of the three values for each time.

Sample	The number of warp yarns (yarns/cm)	Linear densities of warp	Linear densities of weft
PC18	24	38	32
PC23	24	38	32
PC29	24	38	32
4S29	30	38	32

Table 2: Number of yarns per cm.

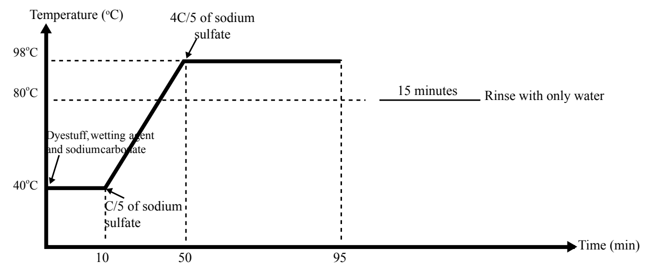

Figure 1: Dyeing conditions.

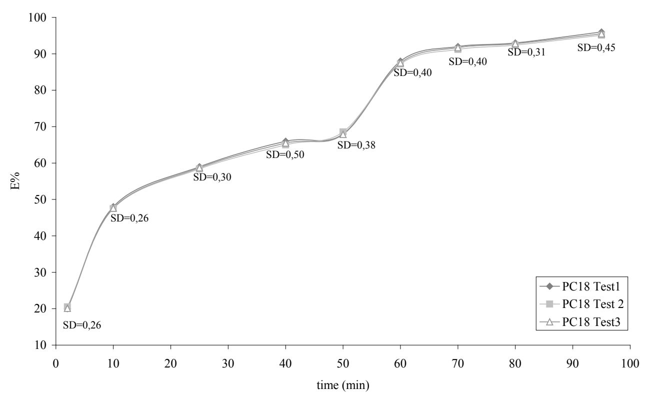

Figure 2: Evolution of the exhaustion rate of the bath with time: results of 3 tests of the same sample.

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

For example, Figure 3 shows the evolution of the exhaustion rate of the bath with time in the dyeing process of the tree samples PC 18, PC 23 and PC 29:

Finally, we calculate the evolution of the rate with time as it is presented and shown in figure 4. After that, the diffusion coefficient for all cases were computed and compared.

From figure 4, we can calculate the coefficient of diffusion D of dye in sample PC18:

$$A = \frac{4}{r\sqrt{\pi}}\sqrt{D} = 0.1132 \pm 0.00015$$

$$\Rightarrow D = \frac{r^2 \ \pi \ 0.1113^2}{16} = 0.509505 \pm 0.001495 \ \ 10^{-11} cm^2 / s$$

Results of the Experimental Study

In this part, we are interested in the determination of the exhaustion rate, dyeing kinetics and the coefficient of diffusion in order to study the influence of the characteristics of the fabrics.

Influence of the structure

Results regrouped in the following table show the influence of the structure on the exhaustion rate at equilibrium "E%" (after 95 minutes of dyeing) and the coefficient of diffusion "Dmoy (cm²/s)". In this experimental study, we have used two different structures: plain and 4-satin.

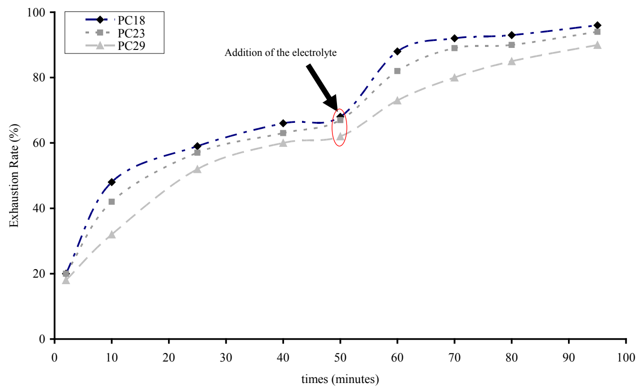

Figure 3: Evolution of the exhaustion rate of the bath with time.

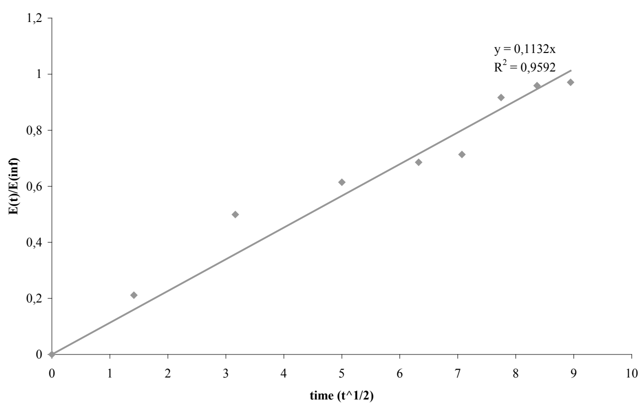

Figure 4: Evolution of the rate $\frac{E_t}{E_\infty}$ (sample PC18).

As it is shown in table 3, the exhaustion rate at equilibrium was influenced by the structure of the dyed fabric. It is clear that the dye absorption of plain fabric is higher than satin fabric. This can be explained in terms of two factors. First, as shown in table 4, the cover factor value is more important to the 4S29 sample which gives a more compact structure. In this condition, the dye diffusion was slow and difficult. Second, the PC29 fabric with higher aerial density (171.93 g/m²) as compared to 4S29 fabric (122 g/m²) has more quantity of material (cotton fibers) and presents a larger absorption ability of the dye.

Also, table 3 gives the variation of coefficient of diffusion of dye with structure. It is clear that this parameter is more important in the plane structure. This observation can be explained by the increase in the number of cover factor of the 4S29 structure (Table 4) which leads to a decrease of the size of the pores and the colorant migration in the woven fabric that seems to be difficult.

Influence of filling yarn's number

Table 5 showed the influence of the number of filling yarns on the parameters of dyeing (E%) and (D_{moy}).

The results show that the exhaustion rate of the dyeing bath of PC 23 sample are higher than that of the dyeing bath of PC 29 sample and PC 18 sample which had the highest exhaustion rate value among the samples. It is, also, clear that the coefficient of diffusion D_{moy} decreases with the increase of the number of yarns per centimeter. As it has been explained above, when the weft number per cm increases, the fabric structure is more tightened and presents a large tortuosity. In this condition, the diffusion and migration of dye are rather slow and difficult.

Influence of preparation treatments

In this part of the study, as it is mentioned, both treatments desizing and scouring have been realized for all samples to guarantee the best possible wetting of the fabrics. Then, we have studied the influence

Sample	E (%)	D_{moy} (cm²/s) 10^{-11}
PC29	90±0.30%	0.441 ± 0.00129
4S29	87 ± 0.43%	0.373 ± 0.00109

Table 3: Influence of the fabric's structure on E, and D_{moy}.

Sample	Cover factor
PC29	3.182
4S29	3.977

Table 4: Cover factor calculated.

Samples	E (%)	D_{moy} (cm²/s) 10^{-11}
PC18	96 ± 0.45%	0.492 ± 0.00144
PC23	94 ± 0.32%	0.463 ± 0.00135
PC29	90 ± 0.30%	0.441 ± 0.00129

Table 5: Influence of the number of weft per cm on E and D_{moy}.

Sample	E (%)	Dmoy (cm²/s) 10^{-11}
Without mercerizing	94 ± 0.32%	0.463 ± 0.00135
With mercerizing	98 ± 0.53%	0.526 ± 0.00154

Table 6: Influence of the mercerizing treatment E and D_{moy}.

Sample	E (%)	Dmoy (cm²/s) 10^{-11}
Without bleach	90 ± 0.30%	0.441 ± 0.00129
With bleach	95 ± 0.42%	0.463 ± 0.00134

Table 7: Influence of the bleach treatment E and D_{moy}.

of mercerizing and bleach treatment on exhaustion rate, kinetics of dyeing and coefficient of diffusion.

Mercerization treatment

The PC 23 sample, as defined in tables 1 and 2, is used to develop this part of study. The results obtained are given in table 6.

We have realized the treatment of cotton fabric with high concentration of sodium hydroxide to achieve increased dye affinity. The chemical properties of the material have changed and we have obtained a new orientation of the cellulose crystallites and the size of the pores increase. The reason is that once the alkali concentration reached to some extent, fiber would swell and crystalline form would transform from cellulose I to cellulose II, this would lead to the decrease of degree of crystalline and structure loosening [9], thus a greater number of free hydroxyl groups in water would be able to participate in reaction, so enhance fiber hygroscopicity capability [10]. All these modifications explain the highest exhaustion value and coefficient of diffusion D_{moy} in the dyeing process of the mercerized sample.

The coefficient of diffusion of the dye (D_{moy}) was increased with the treatment due to the improvement of the ability of the textile to absorb dye. So, the dyeing bath is exhausted quickly (in short time) and at the end of the process, the dye concentration in fiber surface is minor which gives a less dyeing kinetics.

Bleach treatment

The PC 29 sample, as defined in tables 1 and 2, is used to develop this part of study. The results obtained are given in table 7.

Hydrogen peroxide bleaching is carried out exclusively in the alkaline range. The activator employed in our case is the sodium hydroxide. This chemical treatment on cellulosic textile reduces the degree of polymerization and influence on the fiber's absorbency and swelling capacity. As a result, the size of the fiber pore increases and the water penetration is easier [11]. All these bleached fabric properties explain the highest exhaustion value and coefficient of diffusion D_{moy} in the dyeing process of the bleached sample.

Conclusion

In this work, satin and three different plain woven fabrics have been produced and then have been processed under preparation treatments and identical dyeing conditions. The dyeing bath is tested to calculate the exhaustion rate of the dye and the coefficient of diffusion and study the influence of structure, filling number per cm and chemical treatment on these parameters. The experimental results show that Exhaustion rate and the diffusion of dye tested depend on both the characteristics of the fabrics and nature of the preparation treatment realized.

The calculation of the coefficient of diffusion of the dye should help dyers and specialist of the domain to optimize their process and to obtain the desired quality of dyed fabrics.

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