

Eco-friendly and economical dyeing of double-sided cotton/polyester fabric

Elamri Adel^{1,a}, Zarrouk Hamza², Charfi Adnene¹ & Hamdaoui Mohamed¹

¹MPTex UR17ES33, ENIM, Monastir University, 5000 Monastir, Tunisia

²LPMT UR 4365, ENSISA, UHA, F-68093, Mulhouse Cedex, France

This study has been carried out to dye double-sided cotton/polyester fabric by single bath method, with disperse and reactive dyes, without draining out the liquor after polyester side dyeing and with no extra chemicals. Three different dyeing procedures (two-bath two-step, one-bath two-step and one-bath one-step) have been used. The findings were evaluated in terms of dyebath exhaustion (E) and color strength (K/S) parameters. The experimental dyebath exhaustion values are found acceptable and fit well with the exponential model. Color strength for the one-bath dyeing procedures is found comparable with those of the two-bath method. The performed one-bath dyeing method is found more productive and environment friendly as compared to two-bath technique, because it saves the consumption of water, energy, time and chemicals.

Keywords: Dyeing, Double faced cotton-polyester fabric, One-bath dyeing

1 Introduction

For life quality improvement and the increasing demand of customer comfort, more new and complex woven fabrics have been developed, which enhance the structural and functional properties of the fabrics used in various fields. Moreover, due to economical and environmental concerns, a new fabric structure should have the desired quality at minimum production costs, and most eco-friendly processes¹.

Complex woven structure encompasses multilayer, multicomponent and double-faced (called also double-sided) fabrics. Double woven fabrics have been used for various purposes, such as clothing, blankets, and upholstery. In fact, it has become a popular choice among designers and artists due to its versatility and unique texture, as it has a different color, pattern, or texture on the top and bottom layers of the fabric. Examples of double-faced fabrics include the fabrics used for technical textiles, functional jackets, aprons, umbrella cloths, diapers and work wears². Whereas simple woven fabric is characterized by the orthogonal interlacing of two sets of yarns, warp and weft yarns, double faced woven fabric consists of two sets of yarnswoven together and interlaced with a set of yarns (warps or wefts) that stitch the two layers together³. Woven double-faced fabrics could be composed either by one set of warps and two or more sets of wefts (weft fabric), or by two or more sets of warps and a single set of weft yarns (Fig. 1).

In textile industry, cotton/polyester double faced fabrics have dominant market share due to their aesthetic value and user friendly performance. The main challenge with these cotton/polyester fabrics is their dyeing. They are not generally dyed in the same process (dyestuff, pH , temperature) as polyester shows a hydrophobic character while cotton shows a hydrophilic character making it inevitable to dye them with chemically different classes of dyes⁴. Conventionally, cotton/polyester fabric dyeing was carried out separately in two-bath two-step (2-bath 2-step) system using disperse and reactive dyes with adequate control of temperature and pH , creating large volumes of untreated wastewater that disgrace the entire environment.

To address the issue of productivity and raising environmental concerns, several attempts have been made in the past to shorten this to one-bath two-step (1-bath 2-step) process⁵. The 1-bath 2-step dyeing procedure offers lower usage of water and chemicals and a reduction in effluent volume⁶. The one-bath two-step dyeing process uses a separated high pH and low temperature reactive fixation step after the high

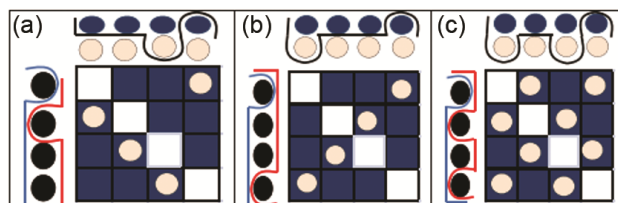


Fig. 1 — Double-sided fabrics, (a) warp fabric, (b) weft fabric, (c) double layer fabric

^aCorresponding author.
E-mail: amri.adel2201@gmail.com

temperature, low pH disperse dyeing to avoid a high rate of hydrolysis of both disperse and reactive dyes at high temperature, or high pH dyeing environment. The developed 1-bath 2-step dyeing procedure is shorter as compared to conventional two-bath method, but the drawbacks are lower dyeability and poor reproducibility.

Researchers have studied the one-bath one-step (1-bath 1-step) dyeing method of cotton/polyester with reactive-disperse dyes. In fact, the one-bath one-step dyeing process of cotton/polyester with reactive-disperse dyes has the advantages over the previous dyeing processes on reducing the dyeing cycle and is far more efficient in terms of productivity, energy conservation and ecological safety⁷. Some methods are used to improve the performance of dyed blended fabric, such as using a heat transfer fastness enhancer (disperse fixing agent) and special detergent⁸, optimizing the pretreatment process and selecting a suitable disperse dye⁹, making disperse dye microcapsules by double-layer wall building¹⁰, choosing dispersants and alkali-resistant disperse dyes¹¹ and preparing novel reactive and disperse dyes¹². However, there has been little success in industrial applications mainly because reactive dyeing requires alkaline condition for dye fixation, but disperse dyes require an acidic dyeing environment.

In another study, dyeing of cotton/polyester with disperse dyes was studied using sodium 2-(2,3-dibromopropionylamino)-5-(4,6-di-chloro-1,3,5-triazinylamino)-benzenesulphonate modification of cotton with disperse dyes containing amino groups¹³. The 1-bath 1-step dyeing of cotton/polyester with disperse dye after acetylation of cotton was investigated to reduce the dyeing cycle, as well as energy consumption. The effect of acetic anhydride and time on per cent acetyl content at 20 °C was studied¹⁴. Recently, a novel strategy for dyeing cotton/polyester blends has been proposed, involving pre-treatment with the biopolymer chitosan and subsequent dyeing using direct dyes¹⁵. A similar approach has been taken, which includes corona discharge pre-treatment of cotton/polyester to improve the dyeability of both the components. In a very recent work, Tegegne *et al.*¹⁶ performed 1-bath 1-step dyeing of polyester/cotton blends with disperse dye after cotton esterification, because disperse dye has a stronger affinity and dyeability to esterified fibres. Although these proposed dyeing processes showed good results in terms of color strength and

fastnesses, they still remain time and chemicals consuming and less eco-friendly.

In the present work, a double faced cotton/polyester fabric has been studied. Each face of the prepared fabric was dyed with a different color, the cotton face with a blue reactive dye, and polyester (PES) face with a yellow disperse dye. Then, the focus of the study is mainly on the color strength and the dyebath exhaustion properties of the one-bath one-step dyeing process for designed cotton/polyester fabric and comparing the results with those of 2-bath 2-step and 1-bath 2-step dyeing methods. The one-bath one-step dyeing technique was carried out without any fabric surface treatment and at boiling temperature to reduce the consumption of time, energy and chemicals.

2 Materials and Methods

2.1 Fabric Weaving

Double faced cotton/polyester fabric was prepared on the Jacquard loom (DORNIER) of our Textile Department in the College of Engineering of Monastir (Tunisia). One set of cotton warp yarns (30 tex) and two sets of polyester weft threads (13.5 tex and 18 tex) were used to prepare double-sided (by weft) fabric. The obtained fabric has a composition of 35:65 cotton/ polyester, a weight of 231.8 g/m² and a thickness of 0.61 mm. Before dyeing operations, the cotton/polyester fabric was bleached in H₂O₂ and sodium hydroxide bath at 90 °C for 45 min.

2.2 Dyes and Chemicals

Reactive dye used in this study is C.I. Reactive Blue 4 supplied by Sigma Aldrich, with low substantivity that was used at high temperature (70°C) to enhance its fixation on cotton fibres. The disperse dye used for polyester dyeing is C.I. Disperse Yellow 79 from Colourtex.

Sodium chloride, sodium hydroxide, sodium hydrosulphite, acetic acid, sodium carbonate, wetting agent (Widet WS) and dispersing agent (Denpol SR) used in this study were of analytical grade.

2.3 Dyeing Processes

2.3.1 Two-bath Two-steps Dyeing

Here dyeing of polyester and cotton faces was carried out in separate baths. First, disperse dyeing bath for polyester face was prepared using 1% (weight basis) of disperse dye, pH was maintained at 4-5 using acetic acid. As shown in Fig. 2(a), the

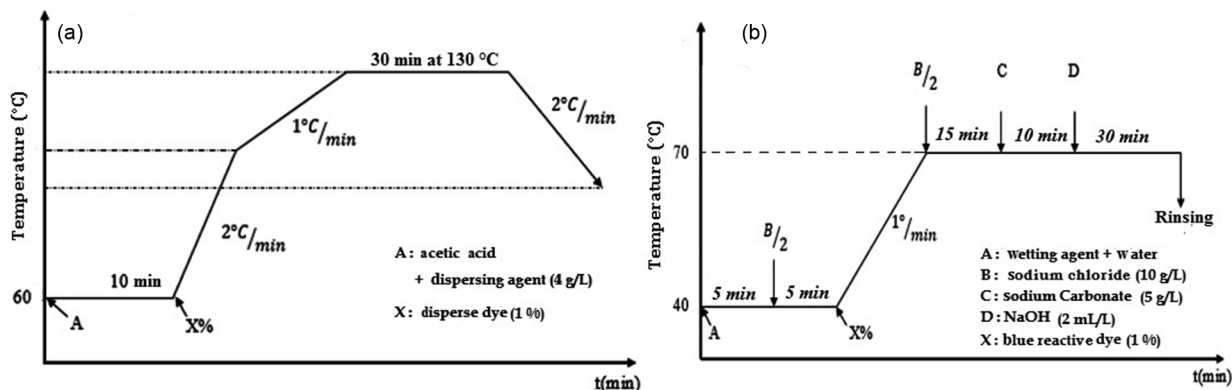


Fig. 2 — Dyeing profile of (a) PES face and (b) cotton face

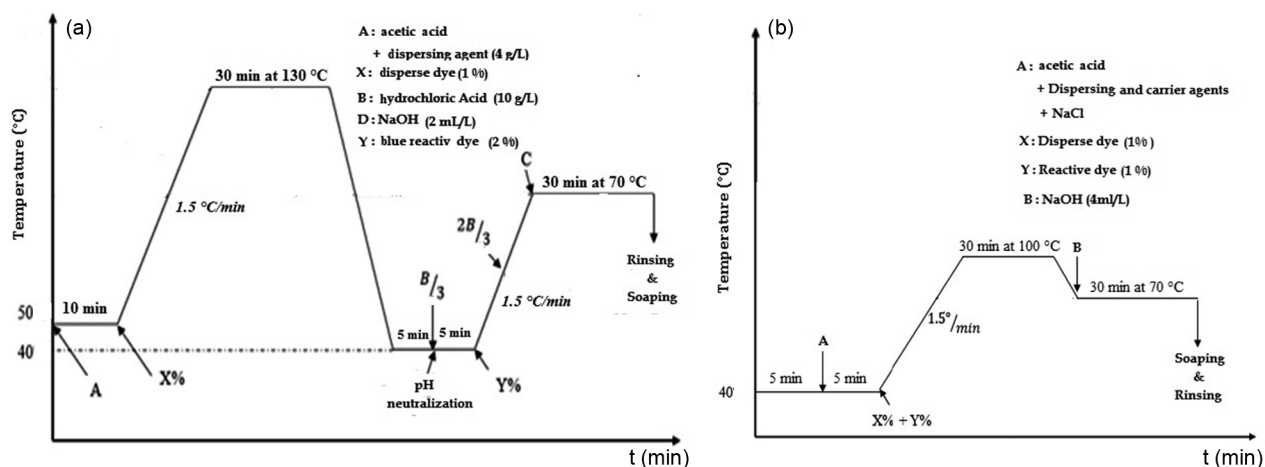


Fig. 3 — Procedural steps of (a) 1-bath 2-step dyeing and (b) 1-bath 1-step dyeing

dyebath temperature was raised to 130 °C, maintained at this temperature for 30 min and rapidly cooled to 70 °C. The dyeings were rinsed and then reduction cleared in an aqueous solution of 2 g/L sodium hydroxide and 2 g/L sodium hydrosulphite at 80 °C for 30 min.

Then, second dyebath for reactive dyeing of 1 % shade of cotton part was prepared. The dye pot was filled with the predissolved reactive dye and salt, water and fabric. It is clear from diagram [Fig. 2 (b)] that dyeing was started at 40°C and temperature was allowed to rise to 70°C. After holding the temperature at 70°C for 15 min, required amounts of sodium hydroxide and soda ash were added and dyeing was continued for 30 min. After the completion of cotton part dyeing, cotton/polyester fabric was rinsed and then dried.

2.3.2 One-bath Two-step Dyeing

In the first step, for polyester face dyeing, all the existing chemicals and disperse dye (1% shade) are

used as previously mentioned in two bath method. The problem of draining the liquor after polyester face dyeing is removed in this one-bath dyeing method. In the second step, cotton part reactive dyeing (1% shade) is done using soda and sodium chloride. The whole process is shown in Fig. 3 (a).

2.3.3 One-bath One-step Dyeing

Cotton/polyester fabric was placed in dyebath with wetting agent at 40 °C. Auxiliaries (sodium chloride, acetic acid, dispersing agent and carrier) were added after 5 min and dyes (disperse and reactive at 1% shade) after 10 min. Then, temperature was raised to 100 °C, maintained at this temperature for 30 min and then cooled to 70 °C, when sodium hydroxide for exhaustion and fixation respectively of the reactive dye were added to dye bath. The bath was maintained at 70 °C for 30 min as shown in Fig. 3b. After the completion of dyeing, dye bath was drained, and then soaping was carried out. Finally, fabric was rinsed and dried.

2.4 Color Strength Measurement

Using a spectrophotometer (Data Color) the evolution of color strength (*K/S*) of dyed cotton/polyester fabric samples was done in 5 min intervals throughout the dyeing processes. The color strength of dyed fabric samples was determined using the reflectance value at its maximum wavelength (λ_{max}), and the surface color strength was determined using the *K/S* value as per Kubelka and Munk equation.

2.5 Dyebath Exhaustion Assessment

The dyebath exhaustion (*E*) measurements were carried out by spectrophotometry and calculated, according to the following relation :

$$E (\%) = \left(1 - \frac{A}{A_0}\right) \times 100 \quad \dots (1)$$

where *A* is the absorbance of the residual bath; and *A*₀, the initial absorbance.

In the case of 1-bath 1-step dyeing, where disperse and reactive dyes are blended in a single bath, simultaneous analysis of organic dye mixtures using spectrophotometric methods is difficult due to the complexity in their absorption spectra and spectral interference. So, in this study, an analytical methodology based on a matrix determination of the concentration and exhaustion of the dye mixture was proposed. The following array formula was used to calculate dyebath exhaustion in 1-bath 1-step dyeing method:

$$E (\%) = \left[1 - \frac{(A_Y + A_B)_t}{(A_Y + A_B)_0}\right] * 100 \quad \dots (2)$$

where *A*_Y is the absorbance of yellow disperse dye; and *A*_B, the absorbance of Blue reactive dye.

2.6 Dyeing Kinetics Analysis

In order to study the kinetics of dyeing processes, bath exhaustion experimental data were fitted using MatLab software. The exponential model, proposed in a previous study by Hamdaoui *et al.*¹⁷, was used for mathematical analysis and modeling :

$$E (t) = E_{\infty} - E_{ft} * e^{-k*t} \quad \dots (3)$$

where *E* is the bath exhaustion at the instant “*t*”; *E*_∞ the maximal bath exhaustion; *E*_{ft}, the bath exhaustion at dyeing end; and *k*, the dyeing kinetic (mn⁻¹).

3 Results and Discussion

3.1 Two-bath Two-step Dyeing Performances

3.1.1 Disperse Dyeing of Polyester Face

The evolutions of color strength and dyebath exhaustion rate of disperse dyeing of the polyester face are reported on Fig. 4 (a).

The color strength increases progressively with time, that could be explained by the absence of chemical bonds between polyester fibres and the disperse dye. In fact, at the beginning of dyeing process, dye molecules adsorbed on fibre surface develop Van der Waals interactions. Then, at elevated temperatures [above polyester's transition temperature *Tg* (≈ 80 °C)], dye molecules are well fixed into fibres, resulting in *K/S* increase until the maximal affinity (130°C) temperature is reached, where equilibrium is established and *K/S* variation is no longer significant proving fibre saturation.

Similarly, dyebath exhaustion increases continuously with time until the equilibrium is established at a maximal exhaustion rate of 89%. In fact, the diffusion rate of disperse dyes into polyester fibres rises with temperature, which can be attributed to an increase in the kinetic energy of dye molecules, as well as the mobility of PES chains above *Tg*.

In order to deeply analyse the adsorption kinetics of disperse dye onto polyester face, the bath exhaustion experimental data were fitted with the exponential model on MatLab software (Fig. 5 (a)).

As seen in Fig. 5, the proposed exponential model fits well with experimental data. The validity of the

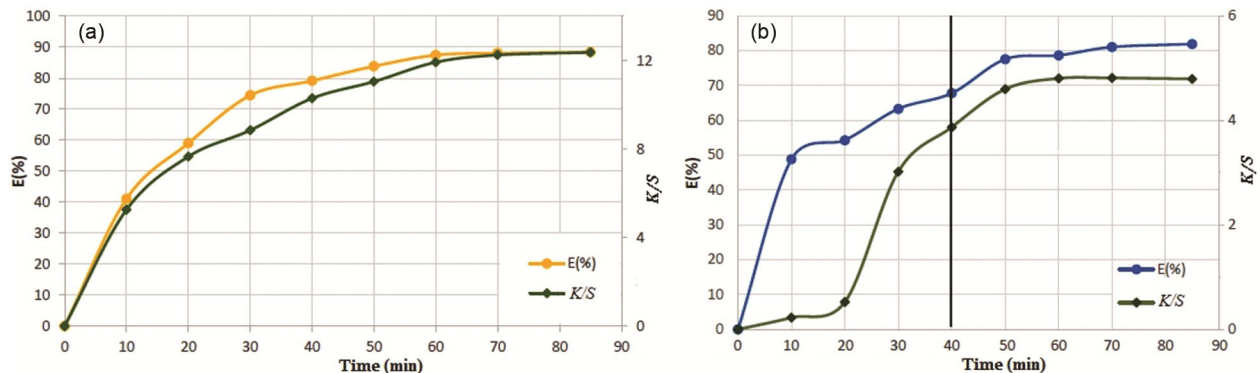


Fig. 4 — *K/S* and *E* of (a) PES face dyeing and (b) cotton face dyeing, in 2-bath 2-step process

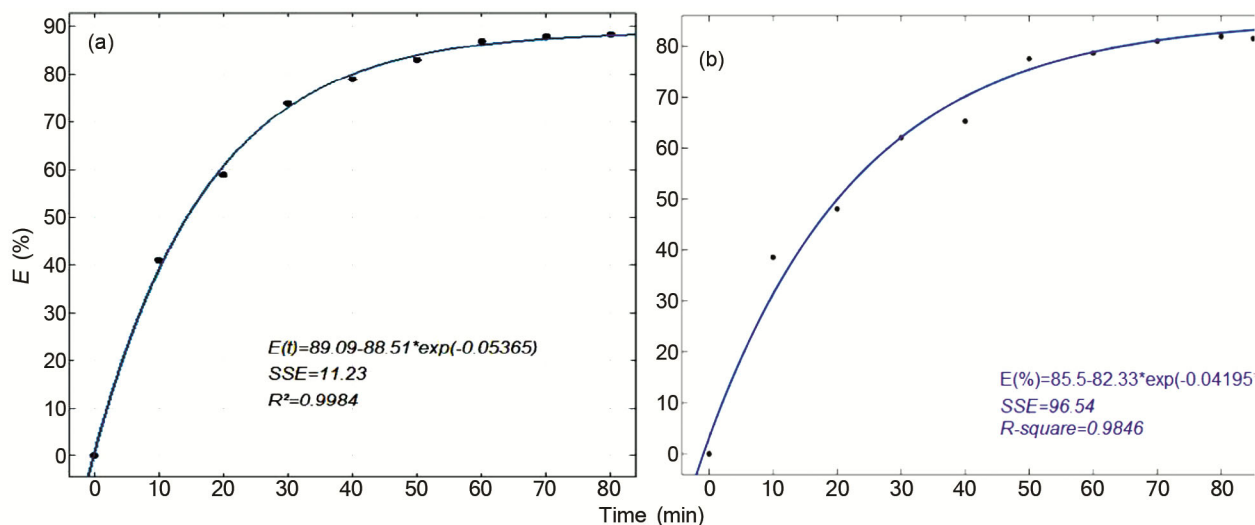


Fig. 5 — (a) Disperse and (b) reactive dye bath exhaustion fitting

Table 1 — Coefficients of exponential model for the three dyeing processes

| Dyeing | Dye | E_{∞} | E_{ft} | K | SSE | R^2 |
|---------------|----------|--------------|----------|-------|-------|--------|
| 2-bath 2-step | Disperse | 89.09 | 88.51 | 0.053 | 11.23 | 0.9984 |
| | Reactive | 85.5 | 82.33 | 0.041 | 96.54 | 0.9846 |
| 1-bath 2-step | Disperse | 84.5 | 84.38 | 0.039 | 8.419 | 0.9986 |
| | Reactive | 68.58 | 67.01 | 0.058 | 62.9 | 0.9858 |
| 1-bath 1-step | Disperse | 73.5 | 73.07 | 0.041 | 22.11 | 0.9953 |
| | Reactive | 67.35 | 66.34 | 0.07 | 82.34 | 0.9775 |

model in describing the kinetics data is checked by the correlation coefficient ($R^2 = 0.9984$) and the sum of square due to error ($SSE = 11.23$).

The values of various coefficients of the tested theoretical model, obtained after smoothing of the curves of experimental values of disperse and reactive dyes in all tested dyeing processes are reported in Table 1. Analysis of results shows that kinetic parameters of disperse dye bath in 2-bath 2-step dyeing process are:

- the global kinetic of dye molecules diffusion onto polyester fibres is 0.053 min^{-1} ,
- the experimental maximal dye bath exhaustion ($\approx 88.5\%$) is in accordance with theoretical value ($\approx 89\%$),
- the fastest kinetic of dye uptake in the first 19 minutes of dyeing process, where 60% of dye molecules are adsorbed on PES fibres.

3.1.2 Reactive Dyeing of Cotton Face

In order to study reactive dye uptake and fixation on cotton face, dye bath exhaustion and color strength (K/S) were measured during the dyeing process. The variation in these dyeing criteria with time is presented in Fig. 4 (b).

During first 20 min of dye process, K/S values are low. This could be explained by poor diffusion and fixation of dye molecules into cotton fibres. Then, as the time increases, the cotton molecular structure becomes open, and more dye molecules get separated from the aggregates, which facilitate the dye uptake and hence higher K/S values are reached after 60 min. From the evolution of dye bath exhaustion as function of time [Fig. 4 (b)], it is concluded that reactive dye adsorption kinetic is composed of three different phases. During the first 10 min of dyeing process, the adsorption of dye molecules is rapid. In the second phase, the adsorption behaviour slows down. Finally, after 60 min the adsorption becomes almost constant.

The kinetic adsorption and fixation of reactive dye onto cotton part are analyzed with the exponential model. Fig. 5(b) represents the evolution of the experimental values of dye bath exhaustion and the theoretical curve associated with the tested model on MatLab software.

Reactive dyeing kinetic parameters of cotton face (table 1) shows the following:

- the average kinetic of dye molecules diffusion in cotton fibres is 0.042 min^{-1} ,

- the theoretical maximal dye bath exhaustion ($\approx 85.5\%$) is slightly higher than experimental value ($\approx 82.33\%$),
- the maximal dye uptake is obtained in the first 24 min of dyeing process, where 59 % of reactive dye molecules are adsorbed on cotton .

The two-bath two-step dyeing process shows high performances (high color strength and dyebath exhaustion values) without staining cotton face with disperse dye, nor staining polyester face with reactive dye. Nevertheless, this conventional process is costly and non eco-friendly, as it requires the use of huge water, energy and chemicals. In addition, duration of this dyeing procedure is high, which decrease productivity. To overcome these problems, in the next section one-bath two-step dyeing method will be applied to our double faced cotton/polyester fabric.

3.2 One-bath Two-step Dyeing Properties

The evolution of color strength of disperse dye with time for this double-tone dyeing method is presented in Fig. 6(a). Indeed, K/S of disperse dye presents high values, as in case of 1-bath 2-step process.

Color strength on the polyester face reached to its maximum during the first five minutes of dyeing process and has not shown additional increase at further stages of dyeing. For reactive dye, K/S values are slightly decreased as compared to previous conventional dyeing process, but remains within acceptable limit.

It can be observed from Fig. 6 (b) that dyebath exhaustion, for both disperse and reactive dyes, in 1-bath 2-step dyeing procedure have the same evolution behavior as monochromatic 2-bath 2-step dyeing method. Dyebath exhaustion always increases with time and reaches a maximal value of 85 % for

disperse dye and 67% for reactive dye. However, these values are slightly lower than those of 2-bath 2-step dyeing process.

The resulting values issued from the modelization of 1-bath 2-step dyeing method with exponential model (Table 1) shows that dyeing kinetic of disperse dye ($k = 0.039 \text{ mn}^{-1}$) becomes more faster than that of conventional monochromatic process ($k = 0.053 \text{ mn}^{-1}$). This could be explained by a rapid adsorption and diffusion of disperse dye molecules onto polyester material accentuated by instant formation of amorphous zones and high free volumes permit to receive dye molecules. On the contrary, the global dyeing kinetic of the reactive dye is increased in 1-bath 2-step process, which leads to dyebath exhaustion slight decrease.

The main advantage of the use of 1-bath 2-step dyeing rather than 2-bath 2-step method is to reduce the cost of dyeing process. It offers lower usage of water, energy and chemicals and a reduction in polluting effluent volumes^{18,19}.

3.3 One-bath One-step Dyeing

In order to reduce even more time, energy and chemicals, the 1-bath 1-step method seems to be a solution of choice toward sustainable and environment friendly cotton/polyester fabric dyeing process^{20,21}.

One-bath one-step dyeing of double faced cotton/polyester fabric has been performed at boiling temperature ($100\text{ }^{\circ}\text{C}$) in presence of a carrier, rather than at high temperature ($130\text{ }^{\circ}\text{C}$) to avoid hydrolysis of reactive dye and was added simultaneously in the same bath with disperse dye. The evolution of obtained color strength of reactive dye is reported in [Fig. 7 (a)]. K/S is measured on both faces of fabric to check if eventually, cotton face is

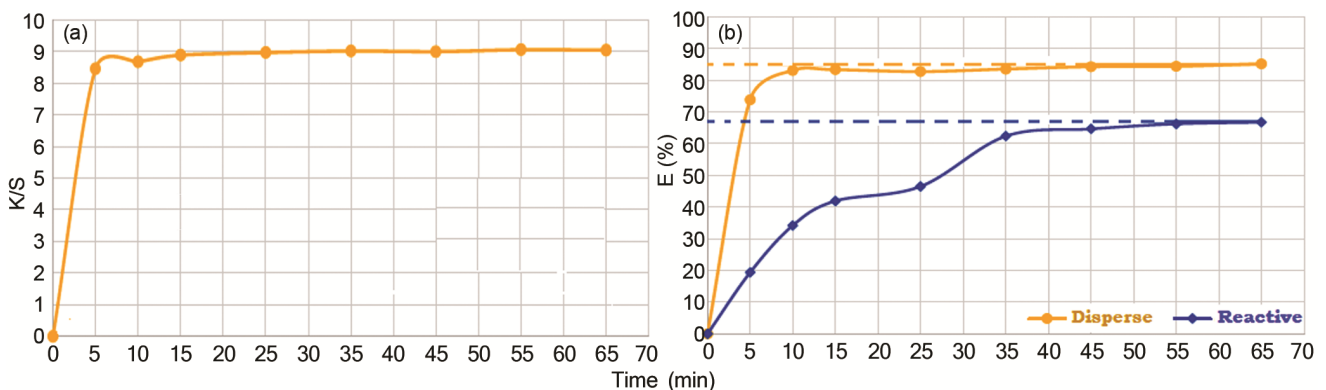


Fig. 6 — Evolution of (a) K/S and (b) E with time in 1-bath 2-step dyeing process

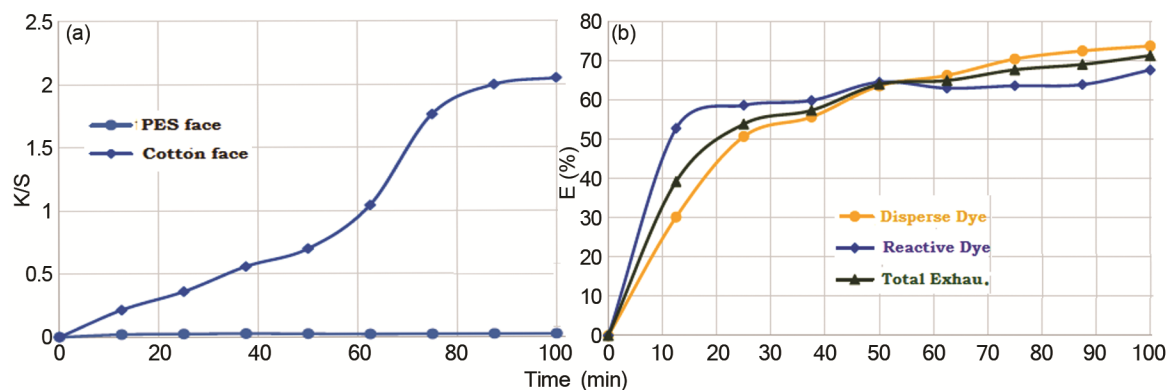


Fig. 7 — Evolution of (a) K/S and (b) E with time in 1-bath 1-step process

stained by disperse dye, or reactive dye molecules are fixed on polyester part.

K/S of reactive dye [Fig. 7 (a)] shows a slow increase on first part of the dyeing process, then significant augmentation of color strength is observed in the second stage of dyeing. This could be explained due to the fact that the dyebath medium is initially acidic (low pH values) which couldn't fasten reactive dyeing. Nevertheless, this slow diffusion of reactive dye molecules into cotton fibres shows good color uniformity, as observed on obtained dyed samples. In addition, reactive dye molecules are not fixed on PES fibres as confirmed by no dye uptake on PES face.

On the other hand, color strength behavior of disperse dye on polyester face in the present 1-bath 1-step process is slightly lower than those of the two previously tested dyeing processes (2-bath 2-step and 1-bath 2-step). Dyeing performance of disperse dyeing carried out at 100 °C in the presence of a carrier is close to that performed at 130 °C, which allows energy saving and cost reduction.

The variation of dye exhaustion as a function of time in the 1-bath 1-step dyeing process is shown in Fig. 7 (b). The global dyebath exhaustion increase is rapid during first 25 min of dyeing process, then decelerates and finally reaches at its maximal value of 70%.

In fact, when both dyes are present in the dyebath from the starting of the dyeing process, the reactive dye is adsorbed with rapid kinetics during the first 20 min, then kinetics slow down due to saturation of cellulose fibres with disperse dye. Then, gradual adsorption of disperse dye occurs with slower kinetics initially and with progress of dyeing process disperse dye molecules' adsorption increases at a faster rate till the end of dyeing. The resulting values of kinetic

modeling of these experimental values with exponential model (Table 1) confirm these findings. It could be concluded that dyeing output of one-bath one-step dyeing process (color strength and dye bath exhaustion) are in accordance with those obtained with two-steps dyeing method.

4 Conclusion

In the present study, the dyeing of the designed double-sided cotton/polyester fabric has been carried out with three different dyeing methods (two-bath two-step, then one-bath two-step and finally one-bath one-step). Although the 1-bath 1-step dyeing procedure shows good dyeing performances, it has the advantages over the conventional 2-bath 2-step and 1-bath 2-step dyeing processes on reducing the dyeing cycle improving productivity, as well as energy consumption, and eliminating the use of sodium hydrosulphite, an environmentally harmful and very toxic chemical in dyeing industry. So, the 1-bath 1-step dyeing method is more economically advantageous and could give eco-friendly solutions to environmental dyeing problems of blend fabrics.

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