Experimental Study and Mathematical Model to Follow the Drying Phenomenon of Knitted Textile Fabric

Mohamed Hamdaoui, PhD, Ayda Baffoun, PhD, Khouloud Ben Chaaben, Fayçal Hamdaoui, PhD

Ecole Nationale d'Ingénieurs de Monastir, Université de Monastir, Monastir TUNISIA

Correspondence to:
Mohamed Hamdaoui email: hamdaouimohamed@yahoo.fr

ABSTRACT
In this paper, the results of an experimental study on textile thermal drying after wet processing pre-treatments are presented. The mass variation of the studied samples as a function of drying time was determined using the gravimetric method at three different temperatures: 100°C, 110°C and 120°C. A polynomial model was found and established to follow the drying phenomenon of wet textile fabric.

INTRODUCTION
Textile fabrics either as knits or woven have to be cleaned, prepared, dyed, or printed and undergo subsequent finishing after these wet processing treatments. Drying is the stage between wet processing and dry finishing treatments. It is a very important step which aims to free the textile of moisture and to extract water from the material. In industry, it is very important to choose the appropriate instrument and to control the systems for the achievement of uniform drying and avoid its negative effects on quality. Therefore, the study of this phenomenon becomes very important and has attracted the attention of several authors [1-6].

Drying techniques may be classified as mechanical or thermal. Mechanical processes are used in general to remove the water which is mechanically bound to the fiber. This is aimed to improve the efficiency of the following step. Thermal processes consist in heating the water and converting it into steam.

The dynamics of drying textile fabric after treatment with foam solutions is studied by M. S. Ivanov et al [7]. The drying curves for fabric and base treated with warp-sizing foam were experimentally obtained and discussed. The experiment was conducted on samples of base and fabric from a blend of natural, synthetic, and man-made fibers. Finally, transfer functions corresponding to transients and reflecting the dynamics of drying for the three drying objects indicated above were determined. They found a well-defined model for each sample.

The influence of initial moisture content, drying temperature, and air velocity was observed and studied by Luiza H. C. D. Sousa et al [8]. They used an individual knitted fabric samples (150x150mm) of cotton fiber of approximately 0.60 mm thickness and ambient moisture content ranging from 7 to 10%. They used the equation proposed by Page [9]. But this model was effective where accurate modeling of initial drying behavior was not important. They found that the influence of the three operational variables studied on cellulose drying (initial moisture content, surface temperature, and air velocity) could be analyzed with the generalized drying curve.

In the literature, the study of textile drying is limited. However, there are numerous studies of the technique of drying of foods [10-15]. For example, samples of plums were pretreated in alkali solution containing ethyl-oleate and dried in a laboratory dryer at 65 °C and 1.2 m/s air velocity [10]. Doymaz et al [10] have studied the effect of pretreatments on drying plums under hot-air. They found that convective drying of pretreated plums was 29.4% shorter than that for untreated plums. According to these experimental results, they considered two different models. The empirical exponential model (Eq.1) for untreated plums and Eq. 2 for treated plums.

$$MR = a \exp(-k_0 t) + b \exp(-k_1 t) \quad (1)$$

$$MR = 1 + at + bt^2 \quad (2)$$

Where:
a, b, k_0 and $k_1$were an empirical constants in drying models and MR was the moisture ratio.

In this paper, because no information is available on the drying behavior of textile fabrics, a mathematical model was developed to follow the drying phenomenon of textile fabric after wet processing pre-treatments by determining of the mass variation at different instants using the gravimetric method.

MATERIALS

The textile fabrics used in this study were single jersey knitted fabric. The various samples used in the experiments are listed in *Table I*. The samples were analyzed after a conditioning for at least 48 h under standard laboratory conditions. To remove the waxes and oils attached to greige fabrics that affect hydrophilicity, we have applied a scouring treatment.

TABLE I. Fabric characteristics.

Sample	Composition	Structure	thickness (mm)	Fabric weight ratio (g/m²)	Length of the stitch loop
1	Cotton	Single jersey	1.41	434.78	6.1
2	Cotton/PES	Single jersey	1.37	421.11	5.5
3	PES	Single jersey	1.39	385.84	5.9

EXPERIMENTAL APPARATUS

The experimental apparatus consists in a Mathis KTF-S continuous dryer in which the textile fabric samples were placed (*Figure 1*). This apparatus is intended to perform several operations such as coating, heat setting, and drying fabrics. The system is subjected to convection provided by an adjustable blower.

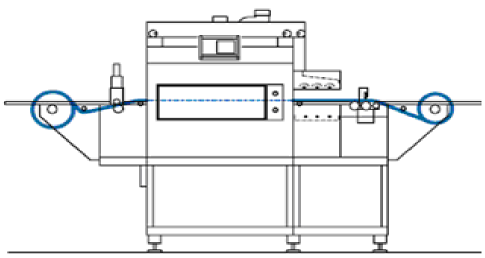

FIGURE 1: Mathis KTF-S continuous dryer.

From each fabric, we cut samples of equal masses while avoiding areas of faults and folds.

Before starting the experiment, the adjusted drying temperature must be stabilized. After that, fabric samples of 5 grams were immersed in water and then squeezed while maintaining common initial moisture content for all samples. They were then introduced into the continuous dryer. After a given drying time "t", a sample was removed and placed in an airtight bag to avoid possible moisture loss by evaporation and then weighted with a precision balance. Finally, the dry mass of samples was determined after a stay in a drying oven. To minimize the experimental error, every experiment was repeated three times and the mean value was calculated.

RESULTS OF THE EXPERIMENTAL STUDY

In order to determine the moisture content variation, the mass variation of the studied samples as a function of drying time was recorded. Afterward, for the different studied combinations the desorption isotherms: MR = f(t), were plotted.

$$M_R = \frac{R_t}{R_0} \tag{3}$$

Where:

R_t : The moisture content of the wet studied sample at different instant, is defined as:

$$R_t(\%) = \frac{W_w - W_d}{W_d} x100 \tag{4}$$

R_0 : The moisture content of the wet studied sample in the beginning of the experiment is defined as:

$$R_0(\%) = \frac{W_w - W_d}{W_d} x100 \tag{5}$$

With:

W_w : Weight of the wet sample (g);

W_d : Weight of the dried sample (g)

When a wet cotton fabric is subject to thermal drying, three processes occur progressively (*Figure 2*), namely:

- First Stage: Transfer of heat to raise the wet cotton fabric temperature. At this stage, MR is normally constant. The stage is also fast compared to the total duration of the drying and cannot be detected.

- Second Stage: Transfer of free water in the form of internal moisture contained in macro and micropores to the surface of the solid and its subsequent evaporation. In this stage, the curve is linear.
- Third Stage: Transfer of water linked to hydroxyl groups attached to each anhydroglucose. This elimination requires additional energy and is marked by the fall of the drying rate.

Mathematical Model to Follow the Drying Phenomenon

The processing of the experimental drying curves using Matlab program yields an adequate general mathematical equation to follow the drying phenomenon by modeling dimensionless moisture content with time.

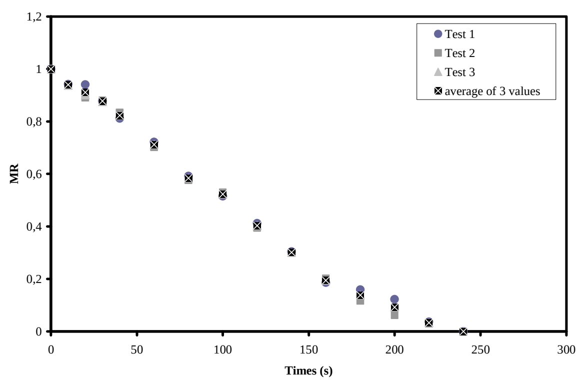

FIGURE 2. Experimental dimensionless moisture contents as function of time (Sample 1, T=100°C).

The results given in *Figure 2* illustrate the evolution of desorption of water (average values of the three experimental tests) from the sample at 100°C. The applicability of a mathematical model to the experimental results was studied by checking the possibility of fitting the curves obtained by adapting some of the exponential and polynomial models. Finally the most precise one using goodness-of-fit statistics parameters was selected (with minimum SSE and maximum R-Square):

- Sum of Squares Due to Error (SSE) which measures the total deviation of the response values from their fitting. 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 ones. 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.

Figures 3, 4, 5, 6, 7 and 8 present the variation of experimental and predicted moisture ratio with times for the three samples (cotton, cotton/PES, and PES) at 100°C using the exponential and the polynomial models given, respectively, by Eq. (6) and Eq. (7):

$$MR = a\,e^{-\left(\frac{t-b}{c}\right)^2} \quad (6)$$

$$MR = at^3 + bt^2 + ct + d \quad (7)$$

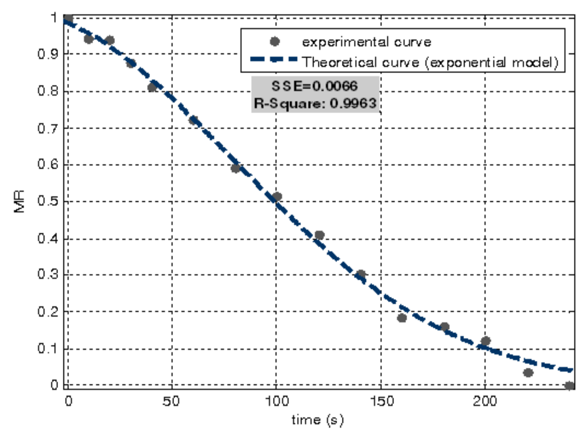

FIGURE 3. Evolution of dimensionless moisture content with time (Cotton sample: Exponential model).

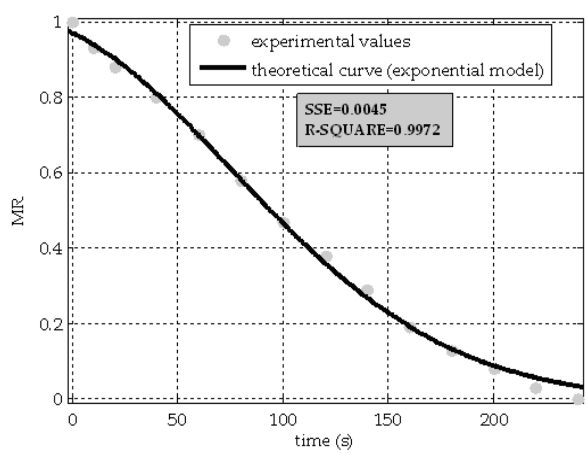

FIGURE 4. Evolution of dimensionless moisture content with time (Cotton sample: Polynomial model).

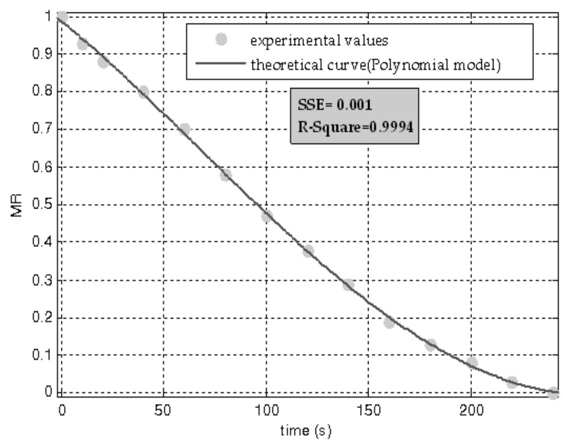

FIGURE 5. Evolution of dimensionless moisture content with time (Cotton/PES sample: Exponential model).

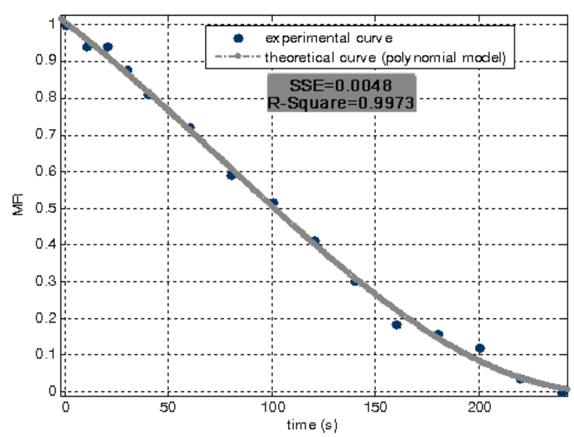

FIGURE 6. Evolution of dimensionless moisture content with time (Cotton/PES sample: Polynomial model).

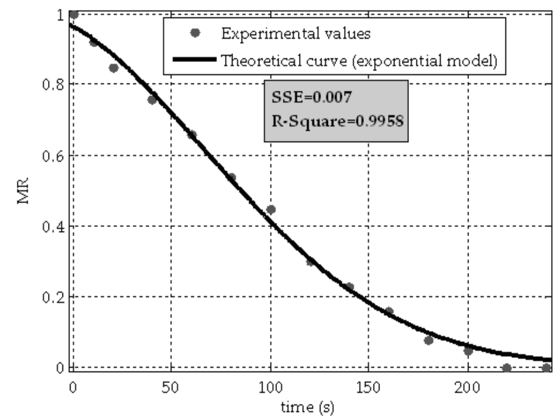

FIGURE 7. Evolution of dimensionless moisture content with time (PES sample: Exponential model).

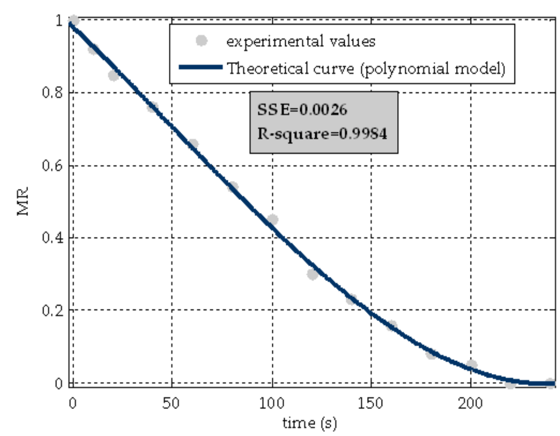

FIGURE 8. Evolution of dimensionless moisture content with time (PES sample: Polynomial model).

The parameters of Eq. (6) and Eq. (7) for all samples are regrouped in *Table II*:

TABLE II. Goodness-of-fit statistics parameters in the case of the cotton sample.

Sample	Model\parameters	a	b	c	d	SSE	R-square
Cotton	Exponential	1.018	-26.99	149.4	*	0.0066	0.9957
	Polynomial	$5.312\ 10^{-8}$	$-1.193\ 10^{-5}$	-0.00434	1.006	0.0048	0.9973
Cotton/PES	Exponential	1.008	-28.74	146.7	*	0.0045	0.9972
	Polynomial	$5.072\ 10^{-8}$	$-1.011\ 10^{-5}$	-0.00459	0.988	0.001	0.9994
PES	Exponential	1.015	-31.50	138.7	*	0.0069	0.9958
	Polynomial	$5.385\ 10^{-8}$	$-8.024\ 10^{-6}$	-0.00527	0.981	0.0026	0.9984

As observed in *Table II*, the mathematical laws (polynomial and exponential) modeling the evolution of dimensionless moisture content with time give an accurate description of the experimental data for all samples, corroborated by the statistical indices as coefficient of Sum of Squares Due to Error and R-square. But the observation of goodness-of-fit statistics values for the three samples show that the polynomial model is the most precise one to follow the drying phenomenon of wet textile fabric (with minimum SSE and maximum R-Square).

Influence of Composition on the Drying Kinetics

In this part, the influence of the fabric composition on the kinetics of drying was studied. The three samples defined in *Table I* were used. So using the polynomial model previously proposed, it can be shown that the instantaneous drying kinetic (*dMR/dt* (s^{-1})) follows the Eq. (8):

$$\frac{dMR}{dt} = (3at^2 + 2bt + c) \qquad (8)$$

The drying kinetics curves for various materials (*Figure 9*), obtained at the same drying temperature (100°C) for a jersey knitted structure, show that drying kinetics aren't constant. In the beginning, the kinetic raises with an increasing rate until reaching a maximum, than begins to decrease to attain zero after a definite time which depends on the nature of the fiber.

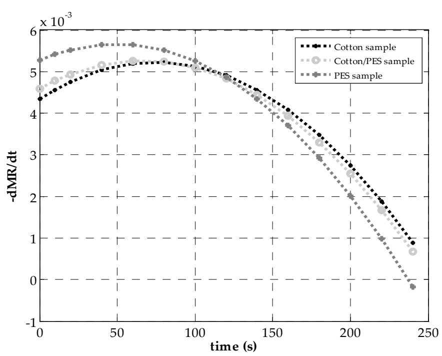

FIGURE 9. Evolution of drying kinetics with time.

In order to understand the influence of composition on the drying phenomenon correctly, the average values of the drying kinetics were determined.

TABLE III: Means values of drying kinetics.

Sample	Average Values of Drying Kinetics x 10^{-3}
Cotton	3.6857
Cotton/PES	3.9692
PES	3.9769

It is clear from *Table III* that composition has an influence on the drying kinetics. The cotton fabric has the smallest coefficient and the polyester fabric has the greatest one. Generally, polymers have a mix of amorphous and crystalline regions, but some are more highly crystalline than the others.

Cotton fibers have the lowest degree of crystallinity and a great number of amorphous regions compared to PES fibers, which means that they have good absorption ability and water can penetrate in the interior of the structure during the wet pre-treatment. On the contrary, polyester has the smallest absorption ability because of the higher degree of crystallinity and water was adsorbed in surface during the wet pre-treatment. Also, in cotton fiber there are three hydroxyl groups attached to each anhydroglucose which can be attacked by the water molecules and therefore an important water quantity will be absorbed by cotton cellulose. These explain why the drying of cotton fabrics was more difficult than polyester/cotton or 100% polyester.

Influence of Temperature on the Drying Kinetics

In this paragraph, the influence of the temperature on the kinetics of drying is studied. In the beginning, the mathematical model proposed (*Figure 10*) is verified. After that, the evolution of the drying kinetics with time is determined (*Figure 11*).

As observed in *Table IV*, goodness-of-fit statistics values show that the polynomial law modeling evolution of dimensionless moisture content with time (Eq. (7)) corresponds correctly to the experimental data at the three chosen temperatures of 100°C, 110°C and 120°C.

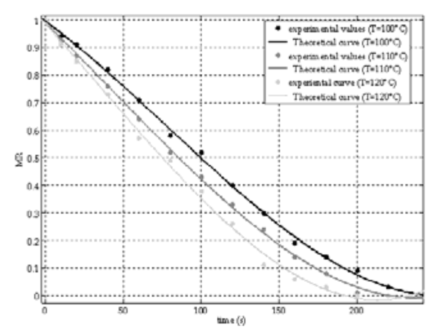

FIGURE 10. Evolution of dimensionless moisture content with time for three different temperatures (T=100°C, 110°C and 120°C).

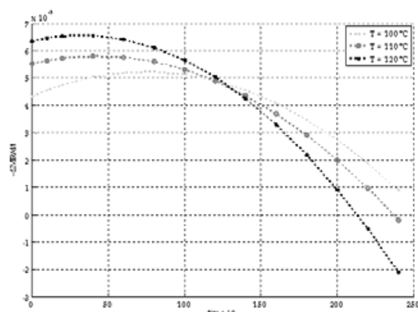

FIGURE 11. Evolution of drying kinetics with time for three different temperatures.

TABLE IV. Goodness-of-fit statistics parameters in cotton sample at different temperature.

Sample	Temperature	a	b	c	d	SSE	R-square
Cotton	100°C	$5.312\ 10^{-8}$	$-1.193\ 10^{-5}$	-0.00434	1.006	0.0048	0.9973
	110°C	$5.162\ 10^{-8}$	$-6.691\ 10^{-6}$	-0.00552	0.9894	0.0011	0.9991
	120°C	$6.727\ 10^{-8}$	$-6.599\ 10^{-6}$	-0.00635	0.9859	0.0050	0.9972

Using Eq. (8), instantaneous drying kinetics curves for a jersey knitted structure at different studied temperatures can be determined. *Figure 11* shows that drying kinetics was influenced by temperature. The curves obtained are similar (*Figure 11*). All three had a high evaporation rate in the beginning, but after 50-100 seconds the speed slowed down. As shown in *Table V*, the drying temperature had an influence on average drying kinetics. It is clear that the average value of drying kinetics of cotton jersey knitted fabric increased with temperature.

TABLE V. Average values of drying kinetics.

Sample	average values of drying kinetics 10^{-3}
100°C	3.6857
110°C	4.1428
120°C	4.2285

CONCLUSION

A mathematical model to study the drying phenomenon of fabrics has been developed and validated. As was demonstrated, the polynomial model is more precise than the exponential one. This mathematical model allows a successful determination of instantaneous drying kinetics. It is clear that the coefficients of the model (a, b, c and d) depends on the nature of the fiber and the drying temperature.

The instantaneous drying kinetics was determined by deriving the polynomial law modeling drying phenomenon. Results show that the kinetics were raised with an increasing rate until reaching a maximum. After that, they began to decrease to zero. The average values of this parameter change from one fiber type to another and were influenced by the drying temperature. This was found to be important for polyester fabric, which is a hydrophobic. Also, it was found to important at a temperature of 120°C.

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AUTHORS' ADDRESSES
Mohamed Hamdaoui, PhD
Ayda Baffoun, PhD
Khouloud Ben Chaaben
Fayçal Hamdaoui, PhD
National School of Engineering of Monastir
Ecole Nationale d'Ingénieurs de Monastir,
Université de Monastir
ENIM, Avenue Ibn Eljazzar
Monastir, Monastir 5019
TUNISIA