(REFEREED RESEARCH)

MODELLING OF THE DRYING BEHAVIOUR OF REGENERATED CELLULOSIC FABRICS

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ABSTRACT

Drying behaviour of garments during wear after any activity resulted in sweating is of great importance in terms of clothing comfort as well as heat and water vapour permeability for functional clothing design. The aim of this study is to analyze and model the drying kinetics of regenerated cellulosic fabrics which have increasingly use in casual clothing and sportswear. Simulated drying experiments showed that modal and lyocell fabrics have similar drying behaviour although their supramolecular arrangement is quite different and drying rate is higher than viscose fabrics. Moisture management tests proved that the drying behaviour is directly connected to the liquid moisture spreading capability of regenerated cellulosic fabrics. A two-stage modelling approach which is a combination of linear fit and thin-layer drying equations was tested for modelling of drying behaviour. Logarithmic model was found to be the best fitted equation to represent the falling-rate drying period of regenerated cellulosic fabrics. Moreover the sufficiency of the proposed model for the computation of drying rate was also proved.

Keywords: Regenerated cellulose, clothing comfort, drying curve, thin-layer drying models, moisture transport

ÖZET

Giysilerin terleme ile sonuçlanan herhangi bir aktivite sonrasındaki kuruma davranışları giysi konforu açısından büyük önem taşımaktadır. Bu çalışmanın amacı, günlük ve spor giysilerde giderek artan kullanıma sahip rejenere selüloz liflerinden elde edilen kumaşların kuruma kinetiklerinin analizi ve modellenmesidir. Kurutma denemeleri, modal ve liyosel kumaşların kuruma davranışlarının benzer ve kuruma hızlarının viskon kumaşlara göre daha yüksek olduğunu göstermiştir. Nem yönetim testleri, rejenere selüloz kumaşların kuruma davranışlarının direkt olarak sıvı nem yayma kapasitesiyle ilişkili olduğunu doğrulamıştır. Kuruma davranışının modellenmesi için doğrusal regresyon ve ince-tabaka kurutma eşitliklerinin kombinasyonu olan iki aşamalı bir model yaklaşımı kullanılmıştır. Logaritmik model, rejenere selüloz kumaşların azalan hızda kuruma periyodunu en uygun açıklayan eşitlik olarak bulunmuştur. Ayrıca, önerilen modelin kuruma hızlarının hesaplanması için yeterliliği de kanıtlanmıştır.

Anahtar Kelimeler: Rejenere selüloz, giysi konforu, kurutma eğrisi, ince tabaka kurutma modelleri, nem iletimi

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1. INTRODUCTION

Regenerated cellulose fibres which play an important role in textile industry [1] are produced by wet spinning of the solutions of purified cellulose obtained from biomass such as wood, cotton linter and other vegetable wastes. They have a significant consumption rate within total world fibre consumption (around 6.4% [2]). Moreover the demand for regenerated cellulosics is expected to increase due to the limited cotton supply and environmental problems of cotton production [3]. Viscose, modal and lyocel are the most commonly used regenerated cellulose fibres from casual clothing to sportswear. Viscose fibres are produced by conventional xanthate process [4]. Modal fibres are produced by modified xanthate process to obtain high wet modulus [5]. As a third generation of regenerated cellulose fibres, NMMO process is used to produce lyocell fibres [6, 7]. Although each type of fibre is produced from the same material, their physical properties are differing from each other due to the production method. Each production process leads to a difference in molecular and supramolecular arrangement. As a consequence, crystallinity and molecular orientation of lyocell fibres are the highest, followed by modal and viscose [8]. This structural differentiation is believed to affect the drying behaviour which is one of the most important comfort properties of fabrics.

With regard to textile technology, natural drying of fabrics during wear is of great importance, as well as industrial drying. Especially in summer and/or after any physical activity, the liquid sweat which cannot be removed by evaporation leads to wetting of garment. Thus a fast drying property is one of the main prerequisites for a garment with higher clothing comfort. Wetting problem is more significant for highly hygroscopic fibres such as regenerated cellulosics, which led to the lengthening of the drying time and therefore unavoidable post-exercise chill [9].

A number of studies on the comfort properties of regenerated cellulose fibres can be found in literature [i.e. 10-16]. However, studies on drying properties are limited. Moreover, a study on the drying kinetics of regenerated cellulosic fabrics and comparison according to the type of the fibre has not yet been encountered. Here, the drying related articles in which regenerated fibres were incorporated will be discussed. Some researchers applied drying tests to fully wetted samples. In the study of Cimilli et al. [17], in which comfort properties of socks has been investigated, drying times of the samples has been also tested. Viscose, bamboo and modal fibres have been also within the selected fibres. When regenerated cellulosic samples were considered, it has been noted that the drying time of modal fabrics were lower compared to viscose and bamboo fabrics. Alay and Yılmaz [18] were also regarded drying properties as a critical comfort parameter and compared the fabrics according to the fibre type. Drying tests were carried out by wetting of the whole sample and a further 30’ drying at 30 ^{o}C ambient temperature. It was shown that the amount of water evaporated in 30’ for bamboo regenerated cellulosic sample has been higher than those for cotton and acrylic samples, but lower than engineered poliester samples. Another method to examine the drying behaviour of the fabrics is the dropping of a certain amount of water onto the samples to simulate sweating conditions. By this means, the initial amount of water (i.e. sweat) is kept constant. In example, in the study of Oğlakcıoglu et al. [19], thermal comfort properties of knitted fabrics produced from engineered polyester yarns and their blends with cellulosic yarns such as lyocell and cotton have been investigated. Drying tests have been showed that samples with %100 engineered polyester dries faster; however the drying time of lyocell blends has been found to be comparable with cotton blends. Onofrei [20] analysed the significant thermal comfort properties of selected fabrics and compared %30/70 viscose/cotton and %100 channelled polyester samples. The author has been applied principle component analysis to determine the most significant properties that influence thermal comfort. Drying properties has been found to be one of the principal components. The samples including viscose fibres has been reported to demonstrate fair drying ability compared to polyester ones.

The drying of textiles as a porous material is very complex and requires simple representation to predict the drying kinetics. Thin layer drying equations are practical tools for description of drying kinetics of porous materials [21, 22]. Thin layer drying denotes the drying of materials as one layer of sample particles or slices [23]. Especially in the fields of food and agricultural material drying, thin layer drying models are found to be the most applied models adopted in the literature [i.e. 22, 24-32]. It should be kept in mind that thin layer drying models are applicable for falling-rate period of drying, as discussed in the paper of Kemp [33] in detail. Although they can adequately fit the drying curves, major errors occur when it comes to the prediction of drying rates which is the first order derivative of drying curve if there is a constant-rate period. Since fabric drying (natural or industrial) includes a constant-rate period of varying length according to the fibre type and process parameters, the application of thin layer drying models to the whole drying curve is incorrect for textile fabrics. The studies on the application of thin layer drying equations to textile drying are quite limited. Thin layer drying models for viscose [34], wool [35], and wool/acrylic blended [36] yarn bobbin industrial drying were investigated. Application of thin-layer drying models to the drying of textile materials in fabric form has appeared in the study of Cay et al. [37]. Drying behaviour of knitted fabrics produced from different types of fibres has been compared and it was reported that the drying time of lyocell fabric has been lower than those of polyester blends and cotton. A two stage model approach, including thin layer drying equations for falling-rate drying period, has been proposed and the logarithmic model has been found to be the best model to describe the falling-rate drying behaviour.

In the view of such information, the aim of this study is to investigate to what extent the structural differences of regenerated cellulosic fibres affects the drying kinetics of the fabrics and to model the drying behaviour of regenerated cellulosic knitted fabrics using thin layer drying models in simulated conditions.

2. EXPERIMENTAL

2.1. Materials

Three types of regenerated cellulose fibres (viscose, modal and lyocell) were selected and supplied in yarn form. Yarn count and twist factor (α_e) of the yarns were Ne 30 and 3.5-3.8 respectively. Interlock knitted fabrics were produced with each yarn by a circular knitting machine (double jersey machine, E13) in three tightness (loose, medium and tight). The properties of knitted fabrics are given in Table 1.

Table 1. Properties of regenerated cellulose knitted fabrics

Fibre type	Tightness	Abbreviation	Thickness (mm)	Mass per unit area (g/m^2)	cpc (course/cm)	wpc (wale/cm)
Viscose	Loose	V-1	0.80	178.20	9	11
	Medium	V-2	0.88	190.06	10	11
	Tight	V-3	0.81	212.56	12	12
Modal	Loose	M-1	1.03	167.76	9	11
	Medium	M-2	0.92	181.33	10	11
	Tight	M-3	0.96	209.16	13	12
Lyocell	Loose	L-1	1.07	177.20	9	11
	Medium	L-2	1.00	185.93	10	11
	Tight	L-3	0.92	196.23	13	12

2.2. Drying experiments

The aim of the drying experiments was to simulate the drying of textile fabrics after sweating. Drying experiments were carried out in a laboratory scale climate chamber (Binder, Climatic test chamber). The ambient temperature in the chamber was set to be 35 ^{o}C to simulate summer conditions. The samples were cut by a circular cutting die with an area of 50 cm^2 and three samples were taken from each fabric type. The samples were conditioned for 4 hours in the chamber prior to drying experiments. Conditioned samples including equilibrium moisture content was regarded as dry samples, since garments include their equilibrium moisture content during wear. After placement of each sample on a digital scale and recording of dry weight, 1 g of pure water was dropped onto the sample. It should be indicated that, the dropped water did not wet the entire sample, which is a desired condition to simulate sweating. By this way, the water was allowed to spread or be absorbed depending on the fabric type. Immediately after wetting, the weight of the sample was continuously recorded in every 2 minutes till reaching the conditioned weight (including equilibrium moisture).

2.3. Moisture transport characteristics

The moisture transport characteristics of the samples were tested by Moisture Management Tester (MMT, SDL Atlas). This apparatus simulates the dynamic moisture transport properties of the fabrics during sweating [38]. During the test, the sample was placed horizontally in the instrument between upper and lower sensors. Model sweat solution was automatically dropped on the centre of the upper facing (represents the skin side of the fabric) of the test sample. The changes in electrical resistance due to the movement of the solution through and across the sample were measured and moisture transport profile of the sample was revealed [39].

2.4. Modelling of drying curves

Dimensionless mass of moisture (*MR*) was expressed as in Eq (1), where M_0 is the initial mass of moisture before drying; M_t is the mean mass of moisture at time *t*.

$$MR = \frac{M_t}{M_0} \tag{1}$$

Drying rate denoting the change in *MR* over unit drying time was calculated as;

$$\dot{w} = \frac{MR_{t+dt} - MR_t}{dt} \quad \left(g\Big/\frac{g}{min}\right) \tag{2}$$

where, *w* is the drying rate, MR_t and MR_{t+dt} are the dimensionless mass of moisture at drying time *t* and *t+dt* (min), respectively.

Drying curves (*MR* vs *t*) were processed to find the most convenient thin layer drying model. However, drying curve of textile fabrics (especially regenerated cellulosics due to higher hydrophilic character) includes both constant rate period and falling rate period. Therefore, as proposed in Cay et al. [37], a two stage drying model was used to model the drying curves of regenerated cellulosic fabrics. First stage incidental to the constant-rate period is a linear fit to the drying curve, as given in Eq. (3), where *t* is the drying time (min), *m* and *n* are the constants and t_{cr} is the drying time at the critical moisture content.

$$MR = mt + n, \qquad t < t_{cr} \tag{3}$$

In the second stage with regard to the falling rate period, ten different thin-layer drying equations [30, 40-52] were selected to determined the most convenient equation as given in Table 2.

Table 2. Selected thin layer drying models applied to falling-rate period of drying curves

Model name	Model equation	References
Newton	$MR=\exp(-kt)$	[30]
Page	$MR=\exp(-kt^n)$	[40]
Modified Page	$MR=\exp(-(kt)^n)$	[41]
Henderson and Pabis	$MR=a\exp(-kt)$	[42- 44]
Logarithmic	$MR=a\exp(-kt)+c$	[45, 46]
Two term	$MR=a\exp(-k_0t)+b\exp(-k_1t)$	[47, 48]
Two term exponential	$MR=a\exp(-kt)+(1-a)\exp(-kat)$	[49]
Wang and Singh	$MR=1+at+bt^2$	[50]
Diffusion approach	$MR=a\exp(-kt)+(1-a)\exp(-kbt)$	[51]
Midilli et al.	$MR=a\exp(-kt^n)+bt$	[52]

Regression analyses were carried out by using MATLAB software for each stage. The coefficient of correlation (R^2) and root mean square error (*RMSE*) were used to determine the quality of the fit. *RMSE* can be calculated as following;

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \tag{4}$$

where, $MR_{exp,i}$ is the experimental dimensionless mass of moisture, $MR_{pre,i}$ is predicted dimensionless mass of moisture, *N* is the number of observations [30].

3. RESULTS AND DISCUSSION

3.1. Drying behaviour of regenerated cellulosic fabrics

Natural drying characteristics of regenerated cellulosic fabrics in simulated conditions depending on fabric tightness and fibre type were investigated. Figure 1 illustrates the effects of fabric tightness on drying curves. It was observed that the fabric tightness did not have a significant effect on the drying behaviour of regenerated cellulosic fabrics independent of fibre type. This indifference was possibly due to the highly hygroscopic character of regenerated cellulose fibres. Water dropped onto the fabrics was totally absorbed by the fibres, therefore the water content between the yarns are thought to be negligible.

Figure 2 shows the effects of fibre type on the drying curve of regenerated cellulosic fabrics. Modal and lyocell fabrics exhibited similar drying characteristics and times. On the other hand, it was observed that the drying time of viscose fabrics was longer. Drying curves of viscose fabrics differed from the others especially during the falling-rate period of drying. Regenerated cellulosic fibres consist of highly ordered crystalline regions and less ordered amorphous regions [5]. During wetting, water can only penetrate into amorphous regions of the fibres resulting in swelling of the structure. Thus, degree of crystallinity, the dimensions of crystallites and amorphous region, pore size and distribution are the decisive properties for the interaction of regenerated cellulosic fibres with water. The difference between the aforementioned properties of viscose, modal and lyocell fibres has already been investigated. The degree of crystallinity has been reported to be the highest for lyocell due to a higher orientation, followed by modal and viscose [8, 53, 54]. The amorphous regions of lyocell fibres are smaller compared to modal and viscose [55]. On the other hand, the pore structures of viscose and lyocell fibres have been found to be similar and the pore volume of modal fibres is the smallest [8, 53]. Water adsorption and retention and swelling ratio of modal is the lowest, followed by lyocell and viscose [5, 53, 56]. However, these data do not directly clarify the natural drying behaviour after sweating, although a synergetic effect of each factor is thought to occur. It should be indicated that, during wear, the generated sweat do not wet the entire garment. This phenomenon is similar to the dripping of one drop of water onto a fabric, which was used to simulate sweating in this study. Hence, water has a chance to spread through the fabric as well as absorption. It is clear that the spreading diameter increases the drying rate due to the increase in effective surface area, thus the liquid moisture spreading capability of fabrics is of importance. Based on this, liquid moisture transport characteristics of the samples were tested.

3.2. Moisture transport properties

Table 3 shows the moisture management test results of the samples. In this test method, horizontal and vertical transfer of the water was analysed. Inner and outer definition in Table 3 means the surface of the fabric in contact with the skin during clothing and the surface of the fabric in contact with the ambient air, respectively. Inner and outer wetting time denotes the time when each of the surfaces of the sample begins to be wetted and the absorption rate is the average speed of water absorption of each surface [57]. It was observed that inner and outer wetting time and absorption rate of viscose, modal and lyocell fabrics are comparable. However, in general, absorption rate decreased with the increase in fabric tightness.

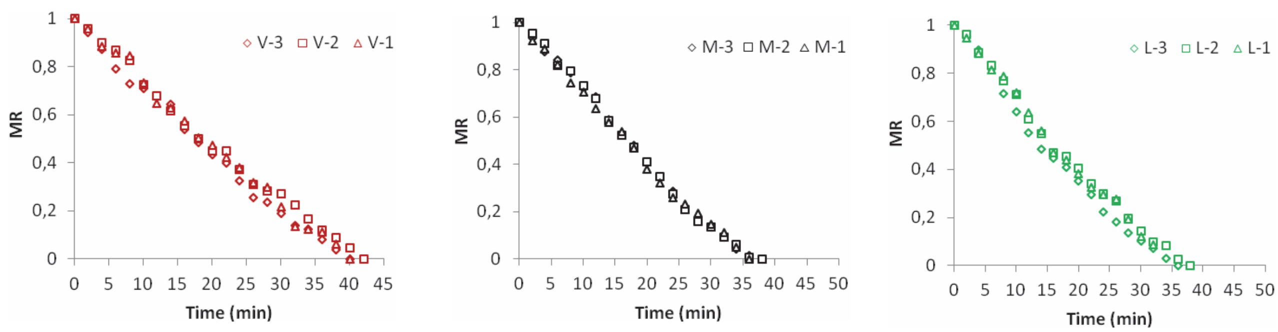

Figure 1. Comparison of drying characteristics of regenerated cellulosic fabrics according to fabric tightness

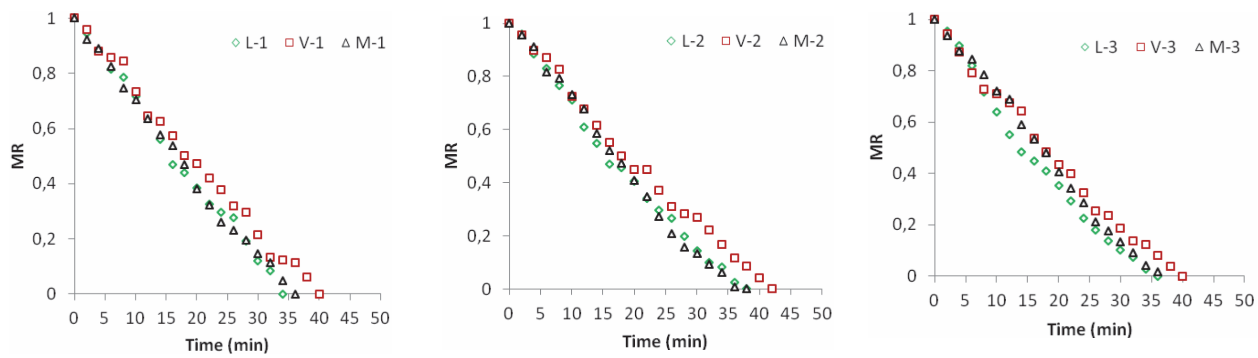

Figure 2. Comparison of drying characteristics of regenerated cellulosic fabrics according to fibre type

Table 3. MMT test results

	Inner wetting time (s)	Outer wetting time (s)	Inner absorption rate (%/s)	Outer absorption rate (%/s)	Inner maximum wetted radius (mm)	Outer maximum wetted radius (mm)	Inner spreading rate (mm/s)	Outer spreading rate (mm/s)
V-1	3.9	4.2	38.9	30.1	15	15	2.5	2.4
V-2	3.6	3.6	38.5	32.2	15	15	2.7	2.6
V-3	3.8	4.1	32.5	27.1	15	15	2.4	2.3
M-1	3.4	3.7	39.2	36.1	20	20	3.9	3.8
M-2	3.7	3.8	42.1	34.3	20	20	3.6	3.5
M-3	3.3	3.3	38.2	32.2	20	20	3.6	3.5
L-1	2.9	3.1	39.4	32.4	25	25	4.6	4.5
L-2	3.8	4.0	37.6	30.7	20	20	3.5	3.4
L-3	3.4	3.7	28.0	26.8	20	20	3.3	3.1

Maximum wetted radius (MWR) represents the maximum ring diameter of the wetted area of each surfaces of the sample. This property indicates the horizontal liquid moisture spreading capacity of fabrics. Inner and outer MWR of the samples are the same due to the high degree of hygroscopic character of the samples and it was not affected by the fabric tightness. On the other hand, as shown in Figure 3, it was observed that viscose fabrics have the smallest MWR and modal and lyocell fabrics have the same MWR values, which is higher than those of viscose. Spreading rate is defined as the accumulative spreading speed from centre to MWR. Inner and outer spreading rate of modal and lyocell fabrics were found to be comparable, however viscose fabrics showed lower spreading rates. Liquid moisture spreading behaviour of regenerated cellulosic fabrics was found to be similar to the drying behaviour. Accordingly, viscose fabrics which displayed lower MWR and spreading rate dried more slowly. On the other hand, modal and lyocell fabrics which had similar (and higher than viscose) MWR and spreading rates showed similar drying behaviour. Therefore, it was concluded that the difference in the drying behaviour of regenerated cellulosic fabrics is connected with the capability of liquid moisture spreading through the fabric surface. It is known that the spreading rate of liquid moisture is related to the contact angle [58] and lower contact angle results in higher wicking rates [59]. Persin et al. [56] have measured the contact angles of regenerated cellulosic fabrics and have found that modal and lyocell fabrics have approximately similar contact angles and higher than that of viscose fabrics. This difference has been attributed to the lower crystallinity and bigger amorphous regions of viscose fibres. Contact angle data obtained by Persin et al. [56] is in a good confirmation with the drying behaviour of regenerated cellulosic fabrics given in this contribution.

Thus as a consequence, for lyocell fabrics, the higher spreading rate, and thus lower drying time might be due to both higher crystallinity and smaller amorphous region. Also, the nano-fibrillary structure of lyocell fibres was thought to led to a better transportation of moisture through the microcapillaries as reported in Männer et al. [60] and Abu-Rous et al. [61]. For modal fabrics, due to smaller pore volumes and moderate crystallinity compared to viscose and lyocell fibres, therefore lower swelling, drying behaviour was similar to lyocell fabrics. On the other hand, viscose fabrics have biggest amorphous regions and less crystallinity, thus the swelling degree is higher, which prevents the spreading of liquid moisture and lengthens the drying time.

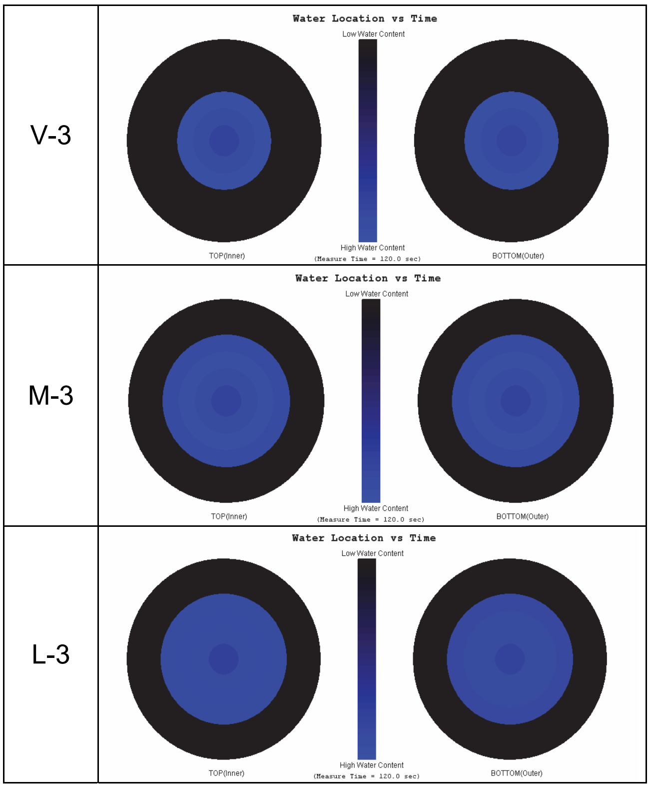

Figure 3. Inner and outer water spreading

3.3. Modelling of drying curves

Natural drying of regenerated cellulosic knitted fabrics during wear was simulated and modelled by two-stage modelling approach. Linear fit was used for constant-rate period. Ten thin layer drying equations were tested for falling-rate period to select the best fitting model. Each model was validated by comparing the experimental and computed data. The results of the statistical analysis of each model are given in Table 4. The results showed that the highest values of the coefficient of correlation (R^2) were obtained with Logarithmic and Midilli et al. models for all samples. Additionally, Wang and Singh model gave the same R^2 values with Logarithmic and Midilli et al. models for lyocell fabrics. On the other hand, since the root mean square error (*RMSE*) of Logarithmic model was lower, it was assumed that the Logarithmic model can represent the falling-rate period of the natural drying of regenerated cellulosic knitted fabrics.

Based on this approach, the proposed two-stage model can be represented as in Eq. (5), where t_{cr} is the drying time at critical moisture content, and m, n, a, k and c are the constants. Figure 4 shows that the proposed model fits the data well. This result also conform with the previous study [37] in which the Logarithmic model has been found to be the most suitable model for the natural drying of knitted textile fabrics although the fibre type, fabric structure and ambient conditions were differed from the present study.

$$MM = \begin{cases} mt + n, & t < t_{cr} \\ a\exp(-kt) + c, & t \geq t_{cr} \end{cases} \tag{5}$$

Table 4. Statistical parameters of the models

	Viscose		Modal		Lyocell	
	R^2	RMSE	R^2	RMSE	R^2	RMSE
Constant-rate period						
Linear	0.990	0.0197	0.995	0.0150	0.983	0.0207
Falling-rate period						
Newton	0.760	0.0702	0.712	0.0753	0.883	0.0701
Page	0.980	0.0214	0.986	0.0179	0.976	0.0328
Modified Page	0.980	0.0214	0.986	0.0179	0.976	0.0328
Henderson and Pabis	0.961	0.0298	0.963	0.0286	0.955	0.0453
Logarithmic	0.994	0.0127	0.998	0.0080	0.996	0.0135
Two term	0.961	0.0338	0.963	0.0331	0.955	0.0496
Two term exponential	0.961	0.0297	0.963	0.0286	0.965	0.0401
Wang and Singh	0.991	0.0141	0.989	0.0156	0.996	0.0128
Diffusion approach	0.967	0.0290	0.969	0.0282	0.969	0.0393
Midilli et al.	0.994	0.0132	0.997	0.0092	0.996	0.0139

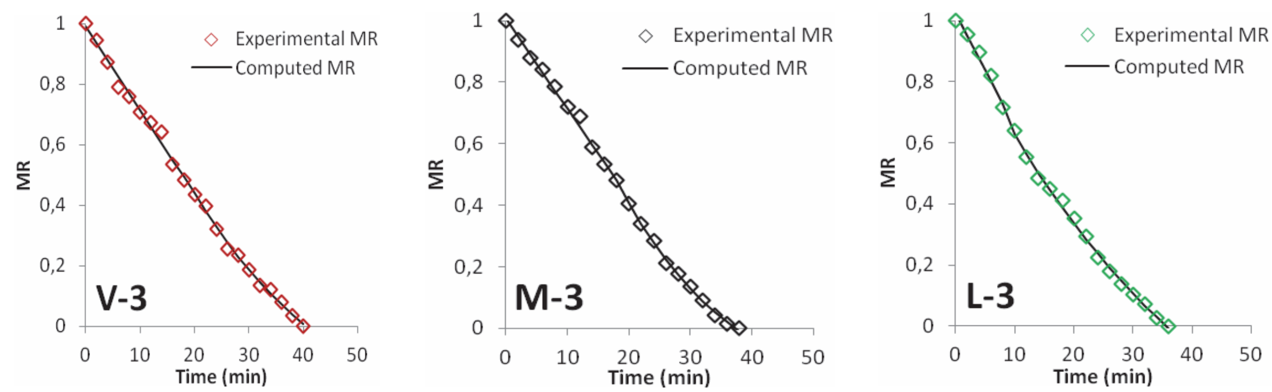

Figure 4. Experimental and computed drying curves of regenerated cellulosic fabrics

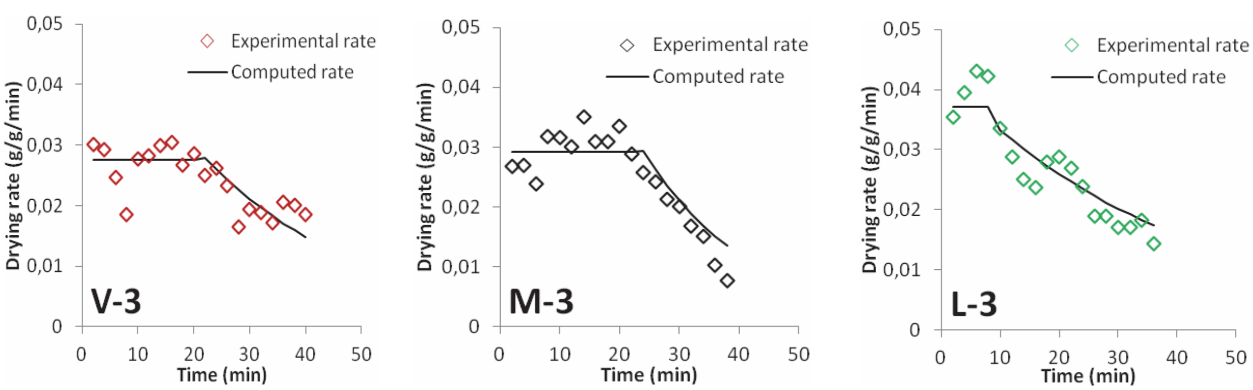

Figure 5. Experimental and computed drying rates of regenerated cellulosic fabrics

As aforementioned, standard drying curve splits the drying curve into the constant-rate and falling-rate periods, thus it is highly essential to check whether the first-order drying kinetics adequately fits the data [33]. To predict the drying rate, the first-order derivative of the proposed model was used as in Eq. (6). Figure 5 shows the sufficiency of the two-stage model for the estimation of drying rate as well as dimensionless mass of moisture. Finally Figure 6 shows the strong correlation between the experimental *MR* and drying rate values and computed data by two-stage model in general for all types of regenerated cellulosic fabrics.

$$\dot{w} = \begin{cases} m, & t \leq t_{cr} \\ ka\exp(-kt), & t \geq t_{cr} \end{cases} \qquad (6)$$

4. CONCLUSIONS

Natural drying kinetics of regenerated cellulosic fabrics during clothing after sweating were investigated in simulated conditions. It was observed that the fabric tightness did not affected the drying behaviour due to the highly hygroscopic character of regenerated fibres. Viscose samples showed the longest drying time. Modal and lyocell fabrics were found to dried faster than viscose, and their drying behaviour was quite similar. In order to explain the effect of fibre type on drying time, liquid moisture transport characteristics of the samples were tested. Maximum wetted area and liquid moisture spreading rate of modal and lyocell fabrics were observed to be similar and higher than viscose fabrics. Thus, it was concluded that the difference in the drying behaviour of regenerated cellulosic fabrics is directly connected to the liquid moisture spreading capability, which was attributed to the supramolecular arrangement.

In the second stage of the study, modelling of the drying behaviour of regenerated cellulosic fabrics was presented. Two-stage model which is a combination of linear fit for constant-rate period and thin layer drying equations for falling-rate period was tested to predict the mass of moisture during drying. Ten thin layer equations were tested for falling-rate period. It was found that the logarithmic model can be assumed to represent the falling-rate period of the natural drying of regenerated cellulosic fabrics at given conditions. Furthermore, it was verified that the proposed model can predict drying rate.

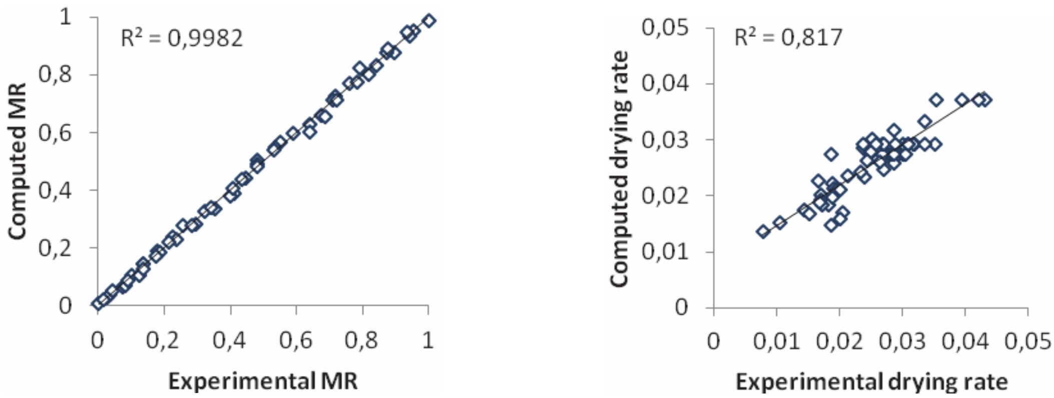

Figure 6. Comparison of computed and experimental MR and drying rate for all types of regenerated cellulosic fabrics

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