WICKING & SORPTION ABILITY ON KNITTED FABRICS: EXPERIMENTAL AND THEORETICAL STUDIES

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ABSTRACT

The main idea of this work is to study the effect of knitted fabric characteristics on capillary rise and sorption ability by combining experimental and mathematical approaches. An experimental device performing the vertical suspension of fabric-liquid surface and permitting the penetration of water molecules through the tested samples is used. Experimental values of vertical wicking were gravimetrically measured using an electronic microbalance, and theoretically studied using the linear logarithmic model (LLM). The results show that the theoretical predictions are in reasonable agreement with the experimental data with high correlation coefficients values. It is also demonstrated that capillary rise kinetics are influenced by knitted fabric features, such as composition, knit structure, type of yarn and of couliering depth value. Water sorption kinetics of cotton fabrics have also been studied and modeled by using mass measurements of the water absorbed by the textile and the LLM equation in order to interpret the experimental data in terms of sorption ability.

Keywords: Knitted fabric, capillary rise, linear logarithmic model, water sorption kinetics, sorption ability.

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INTRODUCTION

The process of making textiles can require several dozen gallons of water for each pound of clothing, especially during the dyeing process. In fact, water is the most common solvent: All dyes, specialty chemicals and finishing chemicals are applied to textiles in water baths. Most fabric preparation steps, including desizing, scouring, bleaching and mercerizing, require the use of water. Textile dyes consume 10.95 billion litters of water each day, a huge amount of water for a highly polluting activity. Thus, it is necessary to optimize and control the sorption kinetics of this natural resource in textile materials during the industrial textile wet processing.

On the other hand, global demand for knitwear is growing at a faster rate. Currently around 50% of clothing needs in the developed countries is met by knit goods. So, ensuring the required quality in a knitted fabric is a vital issue for the manufacturer. In fact, liquid transfer through knitted fabrics is a critical factor affecting physiological comfort especially in sportswear, underwear, working garment or protective clothing [1,2]: When the metabolism is very high, people sweat and perspiration spreads all over the skin, that's why, knitted clothes should transfer quickly the sweat outside to provide tactile and sensorial comfort for the wearer and even to prolong sport exercise performance [3,4]. So, it is so important to understand moisture and liquid transport mechanisms.

That's why, in recent years, experimental and theoretical studies of the wicking rate in porous media have received significant attention: Extensive publications on liquid flow through porous media are available [5-22] and many investigations [15-18] were used the well-known equation of Lucas [24] and Washburn [25] to study dynamic invasion of fluid into straight, vertical circular capillaries. They showed that a liquid which has a viscosity ‘μ’ and surface tension ‘γ’ rises in a vertical tube of radius ‘r’ according to the following law:

$$h^2(t) = D\,t \quad (1)$$

Where h is the distance penetrated by the liquid and D is the capillaries rate coefficient which is related at the same time to the surface properties, capillaries radius and liquid characteristics according the following equation:

$$D = \frac{r\gamma\cos\theta}{2\mu} \quad (2)$$

Where θ is the contact angle between the liquid and the inside surface of the capillary.

The Lucas-Washburn equation has been tested over the years [26-28] and has been used to characterize porous media which was considered as a bundle of cylindrical capillaries by calculating its mean pore radius ‘r’ from slope of the curve $\mathbf{h^2}$ versus t. This approach is very useful. However, it can be applied as long as gravity and evaporation are negligible. Only the viscosity restricts the maximum reachable height. That’s why, many researchers [17,18] focused on this weak point of Lucas-Washburn law and they developed a generalized equation which was applicable for short and long experimental time as shown below:

$$h\dot{h} = \frac{D}{2}\left[1 - \frac{h}{h_e}\right]$$

(3)

Where $\mathbf{h_e}$ is the maximum height attained at the equilibrium.

In order to study experimentally the wicking in textiles, different techniques have been employed: we note, the weight variation measurement of liquid rising in textiles recorded by a microbalance [21,23,29], the direct observation using colored solution [15] which have been enhanced by many researchers [15-18]: they developed another method based on image analysis taken with CCD camera of raised colored liquid in textiles. However, the main deficiency of this method is the fact that the addition of the dye changes the liquid properties and modifies its velocity [29]. It has been demonstrated that kinetic of the dye can be less important than those of the water which can significantly falsify the results.

In this paper, kinetics of the water capillary rise onto cotton knitted fabric is investigated using an ameliorated experimental system (without addition of dye, UV lighting system in a darkroom). And the complete profile of vertical wicking has been predicted using the linear logarithmic model (LLM), which was the simplified linear form of the double exponential model (DEM) [21,22,23] as a function of the fabric characteristics, i.e. composition and structure. A good fit of the experimental data with the mathematical model was done.

Thereafter, the sorption kinetics of different cotton fabrics has been studied and modelled by using the LLM in order to interpret the experimental data in terms of diffusion parameters and sorption ability.

MATERIALS AND METHODS

MATERIALS

The fabric samples used in this study were knitted by using the same machine: the STOLL CMS 320 TC automatic straight knitting machine which has a double fall electronic jacquard selection on both needle beds and “E” gauge equal to 7.

The samples were knitted with the same yarns properties (yarn count and twist). Nevertheless, in order to investigate the effect of knitted parameters on wicking behaviors, we change fabric structural parameters, the kind and the composition of yarn...

Table 1 gives the knitting parameters and geometrical properties of each sample used in this study.

The dimension of the dry sample used in our experiments was 20 cm 30 cm. To remove the natural wax and paraffin oil applied to yarns prior to knitting, a chemical treatment was used.

The fabric was treated for 20 minutes at 65°C with a solution containing 2 mL/L of caustic soda and 2.5 mL/L of wetting agent (Lavotan TBU).

We used the distilled water which is used frequently in textile industry.

METHODS

Figure 1 shows a sketch of the system prior to wicking experiments. It is composed of a device permitting the vertical suspension of the fabric-surface on the liquid, a UV lighting system and a video camera to record the wicking liquid front height versus time.

Table 1. Characteristics of knitted fabrics tested

Sample	Composition	Knit structure	Yarn spinning	Couliering depth	Yarn count Nm(m/g)	Thickness (10^{-3}m)	Weight (g/m^2)
1	100% Cotton	Jersey	Carded	14	12,5	1,99	359,5
2	80% Cotton-20% PES	**Jersey**	Carded	14	12,5	2,13	378,1
3	100% Cotton	Rib 1&1	**Carded**	14	12,5	2,85	461,1

4	100% Cotton	Jersey	**Open-end**	14	12,5	2,03	419,2
5	100% Cotton	Jersey	Carded	12	12,5	2,33	349,0

In order to measure the mass of liquid raised, the fabric is attached, in the course direction, to a sensitive electronic balance (AND GX-2000 precision balance) with the accuracy of 0,001 g which has the capability of recording the weight of the total raised 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 & NT).

All the experiments were done in a conditioning darkroom (20±2°C and 65±4%) which allows us, under UV lamp, to have a good resolution and quality of images without addition of a dye.

Three rinsing baths are applied after scouring; a simple average is calculated on the remaining data.

RESULTS AND DISCUSSION

Experimental Data

In this section, we are interested in the determination of the height attained by the water raised along tested knits. For this, two knit structures (jersey and Rib1&1), two different fabric compositions (100% Cotton and 80%Cotton– 20% Polyester), two different kinds of yarn spinning (carded and Open-end) and two various tightening (12 and 14) are used.

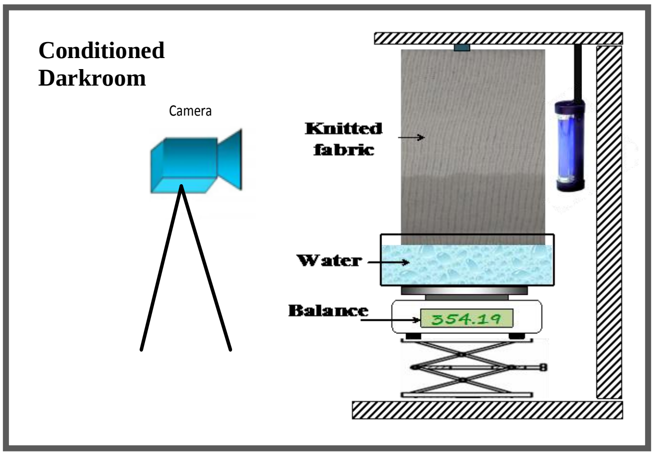

Figure 1. Experimental device

Figure 2 and figure 3 describe respectively the evolution of the water raised height and the water absorbed mass along the knitted fabrics as function of time. The values of the height "ht" and the mass "mt" at each instant "t" are the average values calculated after three wicking tests.

It is shown that all curves of experimental data of knitted fabric have a positive slope which decreases with time and attains zero at full saturation. So, this result indicates that capillary rise of water into knitted fabrics could be divided into two steps, namely the rapid phase and the slow phase.

Analysis of Capillary Rise Study

In order to study the capillary kinetic of water molecules in cotton knitted fabric, the experimental reached height of water raised in fabrics at each time were curve fitted using MatLab to the double-exponential function (DEM) proposed by Hamdaoui et al. [21, 22,23] in order to interpret the sorption kinetics of vertical capillary rise of water in cotton woven fabrics. This approach, which has a double exponential form, is valid for short and long time and given by the following equations:

Mass Approach [22,23]

$$\mathbf{m_t = m_e - a\,exp(-K_1 t) - b\,exp(-K_2 t)} \quad (4)$$

Where $\mathbf{m_e}$ is the quantity of water absorbed at equilibrium (saturation of fabric), $\mathbf{K_1}$ (min^{-1}) and $\mathbf{K_2}$ (min^{-1}) are the sorption kinetic coefficients of the rapid step and the slow step, respectively.

Height Approach [24]

$$\mathbf{h_t = h_e - a\,exp(-K_1 t) - b\,exp(-K_2 t)} \quad (5)$$

Where $\mathbf{h_e}$ is the height attained by the water at equilibrium (saturation of fabric), $\mathbf{K_1}$ (min^{-1}) and $\mathbf{K_2}$ (min^{-1}) are the capillary kinetic coefficients of the rapid step and the slow step, respectively.

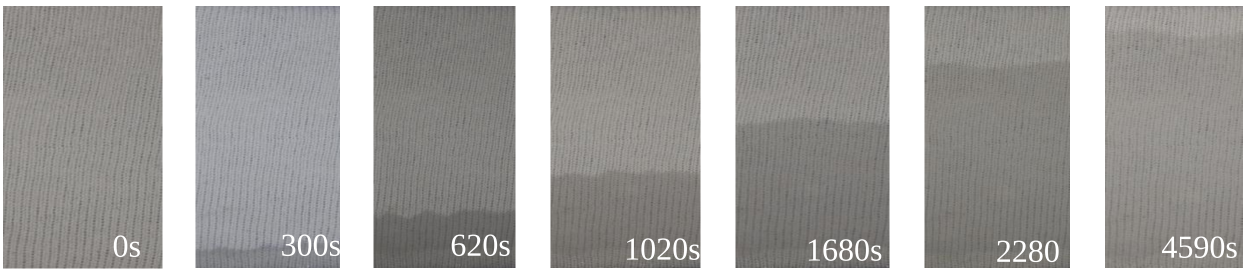

Figure 2. Wicking of distilled water into jersey-100% Cotton knitted fabric (sample 1)

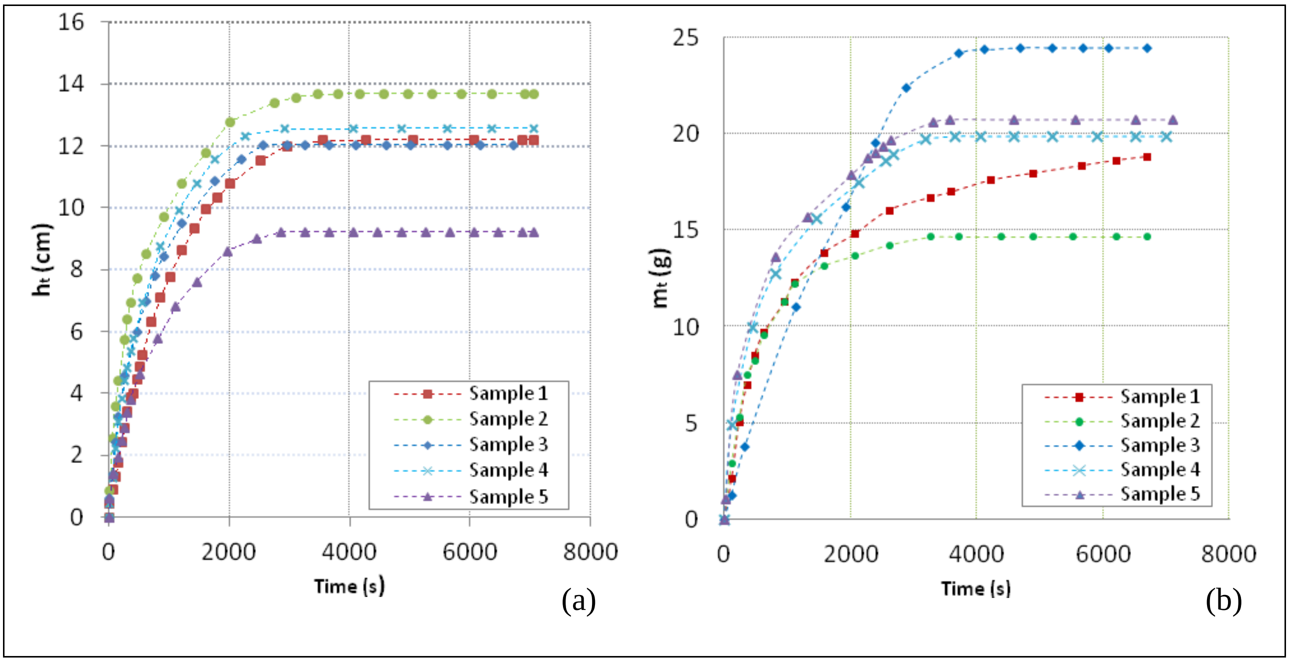

Figure 3. Experimental results of capillary rise: (a). Water height evolution (b). Water absorbed mass evolution

Hamdaoui et al. found that the parallel double exponential kinetics model (DEM) fit well the experimental data with higher determination coefficient. However, it has been confirmed that $\mathbf{K_1}$ was, in the both cases, very larger than $\mathbf{K_2}$, which allows considering that the first and rapid process can be assumed to be negligible on the overall vertical capillary kinetics into woven fabrics [22, 23]. Moreover, the exponential term associated with the slow processes and the DEM equations have the same appearance and they are almost confounded. So, the DEM equation can be simplified to be as:

Mass Approach [22,23]

$$\mathbf{m_t = m_e - m_e \exp(-K\,t)} \quad (6)$$

Height Approach [24]

$$\mathbf{h_t = h_e - h_e \exp(-K'\,t)} \quad (7)$$

Where (min^{-1}) and $\mathbf{K'}$ (min^{-1}) are, respectively, the sorption kinetic coefficient and the capillary kinetic coefficient of the vertical capillary rise of water through fabrics. To explain the reason of this deceleration of capillary rise velocity over time, we must analyze correctly the porous medium structure and understand by which effects the capillary rise has been restrained.

In fact, for short time, when the extent of the water flow in porous fabric is significantly less important than the maximum equilibrium height, the influence of gravity can be neglected. Consequently, the liquid rises quickly through the macro pores (pores between yarns) and the meso pores (pores between fibers) which are responsible for the diffusion during the first seconds (the rapid process) [24]. After full saturation of pores which have largest radius, liquid tries to enter the fiber in its accessible sites of amorphous regions known by micro pores which makes the diffusion more difficult. Moreover, gravity effect, for long time, shall not be neglected; it limits the inserting of water into these micro pores which are responsible for the long time diffusion (the slow process).

In this work, experimental data of water capillary rise into knitted fabrics will be analyzed directly by the Linear Logarithmic Model (LLM), which is the simplified linear form of the DEM, given by the following equation:

$$\mathbf{Ln\,(h_e - h_t) = Ln\,h_e - Kt} \quad (8)$$

The results of the linear fitting curves of experimental data of capillary rise in five different knitted fabrics are listed in table 2:

Table 2. The **LLM** fitting parameters and the (R-square) coefficient for the tested samples

Sample N°	$\mathbf{h_{e,\ experimental}}$, cm	$\mathbf{h_{e,\ theoretical}}$, cm	$\mathbf{K,\ min^{-1}}$	R-Square
1	12,19	12,46	0,0012	0,9713
2	13,67	11,65	0,0017	0,9845
3	12,03	11,64	0,0013	0,9903
4	12,56	12,89	0,0016	0,9759
5	9,22	9,35	0,0010	0,9838

The high values of R-square (>0,97) presented in the table indicate that the experimental data of knitted fabrics were well correlated with the **LLM** equation. Even, the theoretical values of maximum reachable height $h_{e,\ theoretical}$ were approximately equal to those found experimentally. So, we can confirm that the rapid step is negligible in comparison with the slow step also for capillary rise on knitted fabrics.

It is clear from experimental and theoretical results presented in figure 3(a) and table 2 that the diffusion parameters of water sorption is influenced by knitted fabric structure, composition and yarns properties.

We note that the capillary kinetic coefficients $K\,(\min^{-1})$ of the cotton/polyester fabric (sample 2) is greater than that of 100% cotton fabric (sample 1). And the highest maximum height attained by the water was detected for the cotton/polyester knitted fabric. This is explained by the fact that the polyester is a synthetic fiber which its crystallinity is very important (80-90%), its micro pores occupy a smaller volume which leads to a poor sorption ability and promote the capillary rise of water. However, cotton fiber has a great number of amorphous regions, where water molecules can penetrate and be very well linked to the hydroxyl groups. Consequently, it has better sorption ability than the blended polyester fiber.

We observe also that diffusion parameter of rib knit (sample 3) is more important than the diffusion parameter of jersey fabric (sample 1): In fact, we note that rib fabric contains more quantities of cotton per centimeter than jersey fabric knowing that it is knitted on both needle beds of knitting machines. But, water maximum height reached in this complicated structure is not important.

Concerning the effect of the couliering depth, according to figure 3(a) and table 2, it is shown that diffusion parameters and h_e values of samples 5 are less important than those of sample 1: Water diffuses more rapidly into the less tightened knitted fabric (sample 1). Indeed, when couliering depth value decreases, the fabric is, then, tighter, the number of stitches per centimeter of the fabric increases and pores between loops become smaller. Consequently, liquid rises slowly and with difficulty. Moreover, an increasing of the stitches number per centimeter causes the rise of the material amount used for knitting per centimeter which leads to good sorption ability.

It can also be seen that capillary rise of water is influenced by the type of yarn spinning: In fact, open-end yarn is considered a hollow yarn, like cylinders, as seen that the fibers constituting are subjected to a very fast rotation. This increases the fabric meso porosity and explains the high values of capillary kinetic coefficient (**K**) and the maximum reached height (h_e) of sample 4 than those of sample 1 made out carded yarns which are characterized by their good cohesion between fibers.

Analysis of Sorption Ability using LLM Equation

As soon as it has been explained previously, capillary rise of water on knitted fabric is strongly influenced by the sorption ability of samples. So, the second goal of this study is to calculate total sorption ability values (SA_T) for all knitted fabrics. That can provide information about the sum of macro, meso and micro pores. In fact, from the knowledge of the mass of water absorbed by knits at equilibrium, the total sorption ability **(**SA_T**)** of knitted fabric is given by the following equations [24]:

$$SA_T = \frac{W_v}{F_v} = \frac{m_e}{\rho_w * (L_F * W_F * T_F)}$$

(9)

Where W_v is the total water volume, F_v is the fabric volume, ρ_w (g/cm^3) is the density of water, L_F, W_F and T_F are respectively the length, the width and the thickness of fabric.

However, it is shown, previously, that pores intervene at different times of the capillary rise depending on their size. That's why, we propose to determine the evolution of water sorption ability (SA_t) of knitted fabrics versus time using the water absorbed mass (m_t) as function of time (every 30 s) [Fig. 3(b)]:

$$SA_t = \frac{m_t}{\rho_w * (L_F * W_F * T_F)}$$

(10)

The results of the experimental data are reported in figure 4, which shows the evolution of the textiles sorption ability versus time.

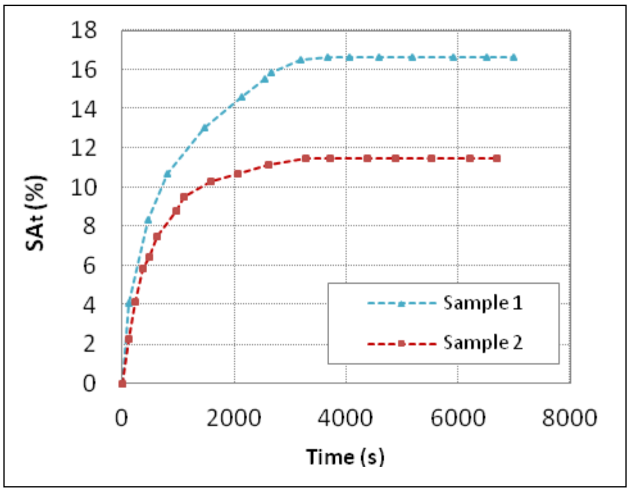

Figure 4. Experimental data of sorption ability of the Sample 1 and 2 versus time

Using the linear form of **DEM** (equation 6), sorption ability (SA_t) equation can be expressed as:

$$SA_t = \frac{m_e - m_e \exp(-Kt)}{\rho_w * (L_F * W_F * T_F)} \qquad (11)$$

Using equation 9, (SA_t) equation takes the following form:

$$SA_t = SA_T - SA_T\ exp(-Kt) \quad (12)$$

Then, it can be rearranged in the **linear logarithmic form** as shown below:

$$Ln\,(SA_T - SA_t) = Ln\,SA_T - Kt \quad (13)$$

Experimental quantities of absorbed water at equilibrium (saturation of the fabric) by all the knitted samples and experimental values of their total sorption ability $(SA_{T,\,exp})$ are presented in table 3. In addition, the best fit model parameters (total sorption ability $(SA_{T,\,the})$ and sorption kinetic coefficient corresponding to the higher determination coefficient (R^2) of the **LLM** fitting curves of experimental kinetic sorption were determined and regrouped in table 3.

Based on the high values of (R^2) for all cases as shown in table 3, we conclude that experimental data of sorption kinetic are well correlated to the linear model equation. In fact, it can be seen that experimental and theoretical values of sorption ability, respectively,

$(SA_{T,\,exp})$ and $[(SA]_{T,\,the})$ are very close. In addition, it is clearly visible that kinetic of water sorption is influenced by the construction parameters, the composition of fabrics materials and their yarn properties.

Influence of fabric composition

Experimental and theoretical results presented in table 3 confirm that sorption ability of 100% cotton knitted fabric (sample1) is greater than that of the blended Cotton/ Polyester (sample 2). However, it can be seen that blending cotton with Polyester fibers improves the fabric sorption kinetic coefficient**)**. In fact, because of its hydrophobic character, the water does not penetrate into the polyester fiber pores and continue the capillary progression through the other vacant pores. Nevertheless, cotton fiber has more available hydroxyl groups in its amorphous regions which are capable to bind more water molecules. That explains its best sorption ability.

Influence of fabric structural parameters

Comparing the sorption ability values of samples 1, 3 and 5, we observe that, as knitted structure is more tightened (sample 5) and more complicated (sample 3), the sorption ability of the fabric is less important. In fact, as the couliering depth value increases and the stitches number per centimeter is more important, macro porosity of the knitted structure raises. As a consequence, sample (1) presents the best sorption kinetic coefficient (**K**) and the total sorption ability (SA_T).

Influence of yarn spinning type

Experimental and theoretical results show that capillary sorption kinetic of water on knitted fabric is influenced by the type of yarn spinning: In fact, the (SA_T) of sample 4 made out of open-end yarns has the most important (SA_T) theoretical values and the higher diffusion parameter than those of sample 1 made out of carded yarns. In fact, by changing the cotton carded yarn with cotton open-end yarns, we increase the fabric meso pores rate. As a consequence, the total absorbed water volume improves.

CONCLUSION

Along this study, mathematical model was established and has been demonstrated to be satisfactory describing the water capillary rise and the sorption ability of knitted fabrics. In fact, the experimental data have been interpreted using the linear logarithmic model (**LLM**) and have analyzed in terms of diffusion parameter, maximum reached height and total sorption ability.

We conclude that capillary height at equilibrium h_e and capillary kinetics coefficient (K) of raised water on knitted fabrics are influenced by the size of the pores responsible for water molecules migration. Indeed, we found that the blended fabric with hydrophobic synthetic fibers (polyester) and the knit made out with open-end yarns have the best wickability due to their poor sorption abilities ($[SA]_{\downarrow T})$. However, the water rises with difficulty through the more tightened sample and the more complicated structure (Rib 1&1) which have low sorption ability values.

We conclude that the fabric sorption ability (SA_T) can be affected by the way of the arrangement of fibers or yarns in the knitted fabric.

Table 3. Influence of fabric characteristics on linear logarithmic model (**LLM**) parameters

Sample	M_e,g	$Pw * (L_F * W_F * T_F)$, g	$SA_{T,exo,}$ %	$SA_{T,the,}$ %	K, min^{-1}	R-Square
1	19,81	119,40	16,65	14,82	0,0008	0,9877
2	14,68	127,80	11,49	9,77	0,0013	0,9909
3	24,49	171,00	14,32	13,64	0,0004	0,8974
4	18,81	121,80	15,44	15,04	0,0010	0,9837
5	20,75	139,80	14,84	13,29	0,0003	0,9897

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