Capillary Rise in Macro and Micro Pores of Jersey Knitting Structure

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Wicking in textile materials is a very complicated, multi-faceted phenomena. This paper investigated capillary rise in a jersey knitting structure. A mathematical model was developed based on the industrial construction parameters and the capillary mechanism. The capillary is studied in two pore's scales: macro and micro. In order to validate our model, a series of experiments was conducted on cotton jersey knitting varying the construction parameters. The results showed reasonably good correlation between experimental data and the theoretical prediction for the wicking phenomenon in different pore's scales. Further refining of this model will be the subject of future research.

INTRODUCTION

Moisture/liquid transport in textile fabrics is one of the critical factors affecting physiological comfort. Fabrics that rapidly transport moisture/liquid away from the surface of the skin make wearers feel more comfortable by keeping the skin dry.

In conditions where wearers sweat a lot (e.g., high level bodily activity), it is not only desirable for the fabric next to the skin to absorb liquid rapidly but also to transport it through the fabric promptly to avoid the discomfort of the fabric sticking to the skin. The comfort afforded by textile fabrics can be improved by understanding the liquid transport mechanism. Mathematical modelling of surface-tension-driven flow in yarns and fabrics can provide a way to develop such an understanding.

In capillary flow through textile fabrics, the constituent yarns are responsible for the main portion of the wicking action (Hollies et al., 1956, 1957). Therefore many researches have been conducted to study the wicking behaviour in textile structure. Among the extensive research in this field, textile yarns were treated either as porous media (Amico, 2000, 2002), the liquid transport through which can be described by Darcy's law (Rahli et al., 1997, Chatterjee , 1985), or as capillary tubes (Kamath et al., 1994, Nyoni, 2006, Perwelz et al., 2000, 2001 and Washburn, 1921), the liquid flow through which can be modelled by Lucas–Washburn kinetics (Washburn, 1921). In the first case, however, the characteristic parameters, such as permeability, are difficult to quantify and are always obtained empirically (Benltoufa et al., 2007). In the second case, similarly, the effective radius of the capillary tube, the effective contact angle, etc., are also determined by fitting the experimental data. An extensive literature review shows that although broad research has been carried out in this area, a comprehensive model to simulate capillary flow through textile based on construction parameters is still lacking.

In this work, capillary flow through jersey knitting is studied. A theoretical model was developed based on capillary mechanism and geometrical conformation (existence of two pores scales). This model can be useful to determine whether the structure can rapidly absorb and transport liquid using construction parameters. An experimental validation showed that our model can predict correctly the flow in textile structures.

CAPILLARY RISE MODELLING

In this section the two pores scales are studied and capillary rise is developed for each channels model.

Macro and Micro Porosity

We mean by "porous media" a solid of an unspecified form delimiting and including vacuums called "pores" filled with fluid. These vacuums can communicate between each other to exchange matter and energy. The solid part, called "matrix", can be deformable but it must have cohesion (Oxarango, 2004).

Phenomena taking place in porous media depend on the geometry of the solid matrix which can be consolidated or not.

Porosity (ε) is characterized by a certain number of average, geometrical or static sizes and usually defined as being the volumetric ratio of the pores accessible by total volume (Bories and Prat : Techniques de l'Ingénieur (B8 250)):

$$\varepsilon(\%) = \frac{V_a}{V_T} \quad (1)$$

Where:

- V_a: volume of the accessible pores through which the flow of the fluid take place
- V_T: Total volume of the sample

Knitting structures (*Figure 1*), are porous media that offer several advantages. Physically, they present properties of comfort such as high elasticity, conformity with the shape of the body, softer and better touches feeling of freshness, and others. Porosity is one of the important physical properties, which has an influence on comfort and the aspect of use.

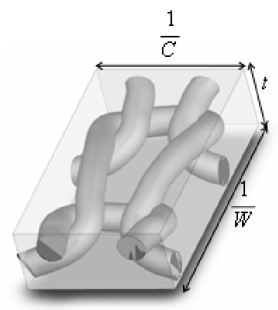

FIGURE 1. Three dimensional elementary jersey loop shape.

Analysing the textile fabric structure (*Figure 2*), we observe two porosity scales:

- Macro pores: vacuums between yarns in the structure
- Micro pores: vacuums between fibers in the yarn

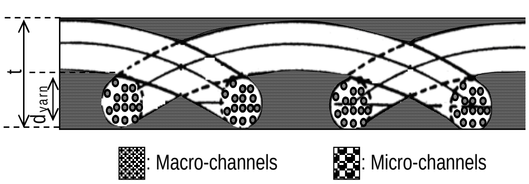

FIGURE 2. Side view of jersey loops (macro and micro-channels)

Macro porosity:

In our previous study (Benltoufa et al., 2007), the porosity of the macro channels is determined as follow:

$$\varepsilon_{macro} = 1 - \frac{\pi d^2 lCW}{2t} \quad (2)$$

Where:

- t : sample's thickness (cm)
- l : elementary loop length (cm)
- d : yarn diameter (cm)
- C : number of Courses per cm
- W: number of Wales per cm

Micro porosity:

The porosity in the yarn is defined as:

$$\varepsilon_{micro} = 1 - \frac{V_{of\ n_s\ fibers\ in\ the\ yarn}}{V_{Yarn}} \quad (3)$$

As has been pointed out by Norwick (Suh, 1967) there are a wide variety of yarn cross sections in knitted structures. Therefore, some simplifications are required when an attempt is made to develop a theoretical geometric model. For the purpose of geometrical modelling, we assume the yarn to have a circular cross section and uniform diameter.

So:

$$V_{yarn} = \frac{\pi d_{yarn}^2 L_{loop}}{4} \quad (4)$$

Where, L_{loop} is the elementary loop length. But as seen in *Figure 3*, $d_{yarn} = \frac{t}{2}$ here *t* is the fabric thickness. Thus:

$$V_{yarn} = \frac{\pi t^2 L_{loop}}{16} \quad (5)$$

Also the volume of n_s fibers in the yarn cross section is:

$$V_{n_s\ fibers} = n_s \pi \frac{d_{fiber}^2}{4} L_{loop} \quad (6)$$

Substituting (5) and (6) in (3) we obtain:

$$\varepsilon_{micro} = 1 - \frac{4 n_s d_{fiber}^2}{t^2} \quad (7)$$

The Study of Capillary in Pore's Scales:

The capillary progression of a liquid in a porous media is generally described by the Washburn law, by regarding the channels as tortuous capillary tubes of average radius R_s and tortuosity τ. R_s depends on the distribution of the inter-connected pores.

The textile materials are hierarchical porous media. The equivalent geometry to describe the capillary progression is not the same in the fabric scale or the yarn scale.

In fact, the capillary progression between yarns (on fabric scale) can be simulated to a flow between two distant parallel plates of e_{mac} (capillary distance) (*Figure 3*). Whereas, on the scale of yarn (between the fibers), it can be analyzed like a flow in a capillary tube of radius R_{mi} (*Figure 4*).

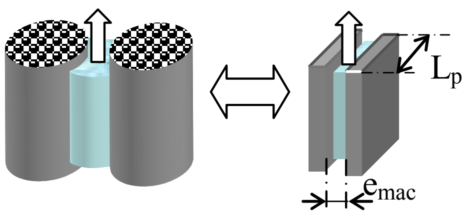

FIGURE 3. Capillary progression between yarns (macro channels)

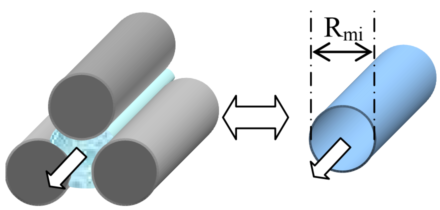

FIGURE 4. Capillary progression between fibers (micro channels)

Capillary in micro channels:
The knitting yarns are composed of fibres or the continuous filaments, more or less parallel between them. Thus the capillary progression can be regarded as equivalent to the progression in a tortuous capillary tube of R_{mi} radius and tortuosity τ .

Mean pores radius determination
Yarns are supposed to have cylindrical section with diameter d_{yarn}. Also the average arrangement between fibers is triangular and the average distance between fibers is d (*Figure 5*). Before calculating R_{mi} , it is important to estimate the average distance (d) between fibers:

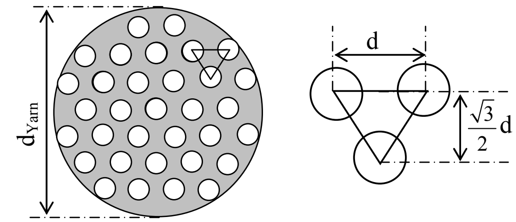

FIGURE 5. Micro channels geometrical arrangement

It is possible from geometric conditions to estimate the distance (d) between fibers:

$$S_{yarn} = \frac{\pi d_{yarn}^2}{4} = n_s \frac{\sqrt{3}}{2} d^2 \qquad (8)$$

Thus

$$d = d_{yarn} \sqrt{\frac{\pi}{2\sqrt{3} n_s}} \qquad (9)$$

Also we have $d_{yarn} = \frac{t}{2}$.

So:

$$d = \frac{t}{2} \sqrt{\frac{\pi}{2\sqrt{3} n_s}} \qquad (10)$$

Based on geometrical conformation, the mean micro pores radius is determined as follows:

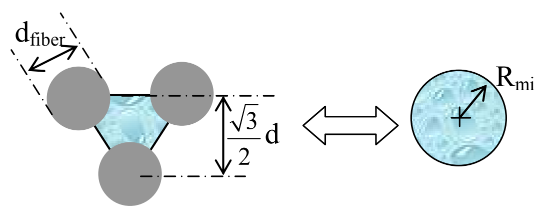

FIGURE 6. Micro pores radius (Rmi) calculation

Based on *Figure 6*, the vacuum surface is:

$$S = \pi R_{mi}^2 \qquad (11)$$

And also it is:

$$S = \frac{\sqrt{3}}{4} d^2 - \frac{3\pi}{6} \frac{d_{fiber}^2}{4} = \pi \left(\frac{t^2}{32 n_s} - \frac{d_{fiber}^2}{8} \right) \qquad (12)$$

Using equation 11 and 12 we have:

$$R_{mi} = \sqrt{\frac{t^2}{32n_s} - \frac{d_{fiber}^2}{8}} \qquad (13)$$

Tortuosity

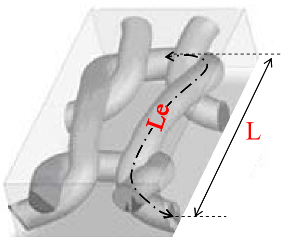

FIGURE 7. Tortuosity in knitting structure

The tortuosity illustrated in *Figure 7*, is defined as below:

$$\tau = \frac{L_e}{L} \qquad (14)$$

By analyzing the geometry of the jersey loop length we have $L_e = \frac{L_{loop}}{2}$ and $L = \frac{1}{W}$. Where l_{loop} is the loop length and W is is the number of wales per centimetre. Substituting those expressions in (14), the tortuosity is:

$$\tau = \frac{L_{loop}W}{2} \qquad (15)$$

Capillary rise in micro pores:
The capillary kinetics of liquid in yarn is described by Washburn law:

$$\frac{dh}{dt} = \frac{\left(\frac{R_{mi}}{\tau}\right)^2}{8\eta h}\left(\frac{2\gamma_L \cos\theta}{R_{mi}} - \rho g h\right) \qquad (16)$$

At equilibrium, $\frac{dh}{dt} = 0$ so:

$$h_{mic-eq} = \frac{2\gamma_L \cos\theta}{R_{mi}\rho g} \qquad (17)$$

Where, $R_{mi} = \sqrt{\frac{t^2}{32n_s} - \frac{d_{fiber}^2}{8}}$, $\tau = \frac{L_{loop}W}{2}$, ρ and η are liquid density and viscosity, γ_L surface tension, g gravity acceleration.

Capillary in macro channels:
The capillary rise between yarns (on fabric scale) can be regarded as equivalent to a flow between two distant parallel plates of capillary distance e_{mac}.

Equivalent distance determination
The vacuum volume of the elementary stitch of jersey is as follow:

$$Vaccuum\ Volume = Total\ Volume - Yarn\ Volume \qquad (18)$$

However

$$Yarn\ volume = \frac{\pi d_{yarn}^2 2l_{loop}}{4} = \frac{\pi d_{yarn}^2 l_{loop}}{2} \qquad (19)$$

And

$$Total\ volume = \frac{1}{C}\frac{1}{W}t = \frac{t}{WC} \qquad (20)$$

Thus, the macro vacuum volume is

$$Vaccum\ Volume = \frac{t}{WC} - \frac{\pi d_{yarn}^2 l_{loop}}{2} \qquad (21)$$

This volume is equivalent to a parallelepiped volume having as length $\frac{1}{W}$, width e_{mac} and thickness t:

$$Parallelepiped\ Volume = \frac{1}{W} t e_{mac} \qquad (22)$$

Using (21) and (22) the equivalent distance between two plates is:

$$e_{mac} = \frac{1}{C} - \frac{\pi W d_{yarn}^2}{2t} l_{loop} \qquad (23)$$

Capillary rise in macro pores:
The equation describing the capillary kinetics of progression between two parallel plates where ($L_p >> e_{mac}$) is given by the equation of Poiseuille:

$$\frac{dh}{dt} = \frac{e_{mac}^2}{12\eta}\frac{\Delta P}{h} \qquad (24)$$

Where $\Delta P = \Delta P_c - \rho g h$, ΔP_c is the difference in pressure related to the capillary forces (law of Laplace). In the case of two distant parallel plates of e_{mac} the Laplace law is:

$$\Delta P_c = \frac{2\gamma_L \cos\theta}{e_{mac}} \tag{25}$$

Thus the capillary kinetics of liquid in macro channels is:

$$\frac{dh}{dt} = \frac{\left(\frac{e_{mac}}{\tau}\right)^2}{12\eta h}\left(\frac{2\gamma_L \cos\theta}{e_{mac}} - \rho g h\right) \tag{26}$$

At equilibrium, $\frac{dh}{dt} = 0$ so:

$$h_{mac-eq} = \frac{2\gamma_L \cos\theta}{e_{mac}\rho g} \tag{27}$$

METHOD AND MATERIALS

A series of experiments on jersey knitting structure was conducted with distilled water as the wicking liquid. Radii of fibers were assumed to be identical. The experimental apparatus is shown in *Figure 8*.

In the apparatus, the lab jack was used to hoist the liquid reservoir containing the wicking liquid, and the steel ruler to measure the wicking height.

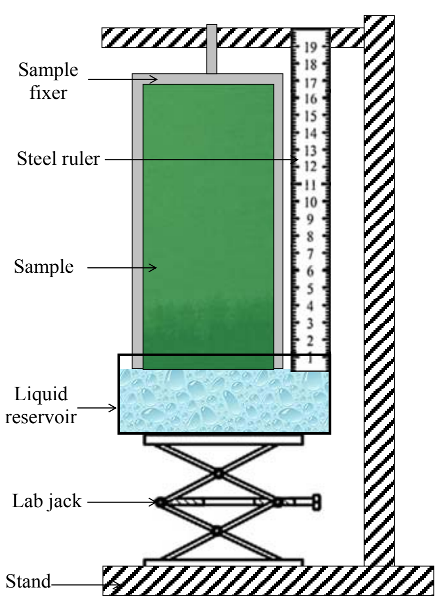

FIGURE 7. Experimental Apparatus

The experiments were conducted in a standard atmosphere of 20 ± 2 ◦C and 65 ± 2% relative humidity, and the samples were conditioned for 24 hours before testing.

The capillary rise at different times was observed and measured by taking snapshots periodically with the CCD camera. The time and the corresponding capillary rise were continuously recorded until equilibrium was established.

The height of liquid at different times is determined by image processing based on the difference of grey level. For example, *Figure 9* shows a typical image of liquid rising in jersey knitting at different times. The dry regions are white having 255 as grey level. The saturated regions have about 180 as grey level. A small amount of saturation variation is also observed.

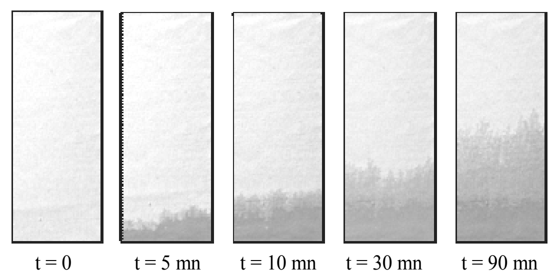

FIGURE 8. Liquid rising in a jersey as function of time

A cotton fiber has been used to make all capillary rise experiments. The 88 fibers per section have an average diameter about 15 µm. The yarn count is 15 Nm with an average diameter 7.44 10^{-04} m. The characteristics of jersey knitting structure are presented in *Table I*.

TABLE I. Characteristics of used jersey knitting structure

Sample	t (mm)	W (/cm)	C (/cm)	L_{loop} (cm)	τ
1	2.00	6.00	5.00	0.51	1.53
2	2.06	4.80	3.40	1.10	2.65
3	1.89	5.80	3.80	0.93	2.69
4	1.01	3.00	2.80	0.74	1.11

The used liquid is the distilled water with good wetting on cotton fiber. Its characteristics are presented in *TableII*.

TABLE II. Characteristics of distilled water at 20°C

Parameters	Value
Density	998.29 kg/m^3
Dynamic viscosity	0.001003 Kg/m.s
Surface energy	72.5 mJ/m^2
Contact angle/cotton fiber	cosθ = 0.97

RESULTS AND DISCUSSIONS

The simulated wetting parameters: R_{mi}, e_{mac} and equilibrium height are presented in *Table III*.

TABLE III: Calculated wetting parameters

Sample	R_{mi} (10^{-05} m)	e_{mac} (10^{-04} m)	h_{mic-eq} (m)	h_{mac-eq} (m)
1	3.73	6.70	0.388	0.021
2	3.84	7.01	0.378	0.020
3	3.53	1.58	0.410	0.091
4	1.82	16.6	0.798	0.008

According to *Table III*, it is noticed that there is an enormous difference between a micro and macro scale (pores dimension and equilibrium height). But the equilibrium state does not give complete information on the kinetics of wetting. Thus, it is necessary to study the evolution height as function of time in the macro using equation 26 (*Figure 10*) and micro scale using equation 16 (*Figure 11*)

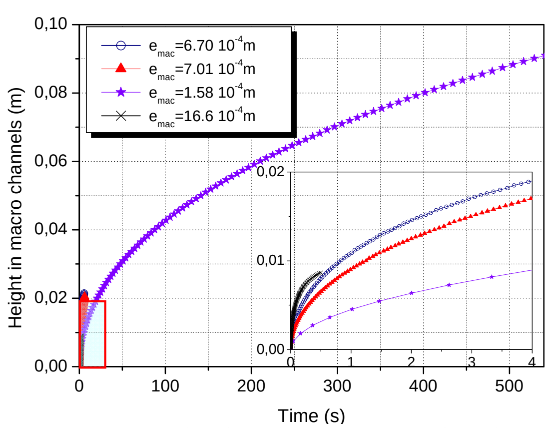

FIGURE 9. Predicted capillary rise in macro channels

According to *Figure 10*, it is noticed that sample 4 reached the equilibrium more quickly but it has the minimal equilibrium height. The sample 3 reached the maximum equilibrium height in a slow way. This is due to the dimension of the macro pores.

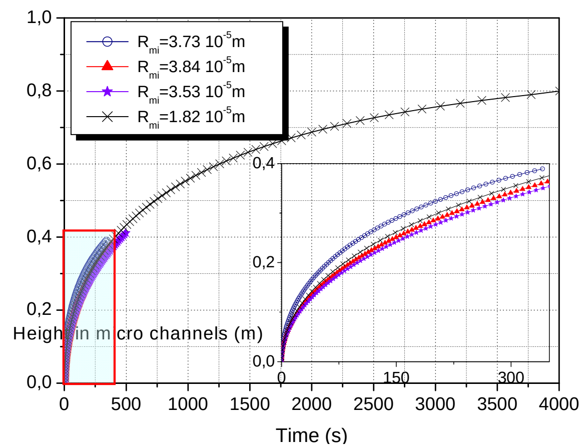

FIGURE 10. Predicted capillary rise in micro channels

In *Figure 11*, the capillary rise in the micro channels is studied. It is observed that samples 1, 2 and 3 have almost the same shape of a curve; this is due to the dimension of micro pores which are close. However, sample 4 reached a height with balance h_{mic-eq} = 0.798 m for R_{mi} = 1.82 10^{-05} m in 4000 seconds.

Thus, the liquid is diffused less quickly in the micro channels but higher than in the macro channels. So, in fabric experiments, we can observe, initially, the capillary diffusion in the macro channels, then it takes place in the micro channels.

According to results prediction, the macro pores are responsible for the diffusion during short time and micro the pores for long times diffusion.

While conducting experiments, it is difficult to follow in the capillary rise in the macro and the micro pores at the same time. Therefore, experimentally, the kinetics of the capillary rise through knitting, as function of time, is studied and compared to simulated results.

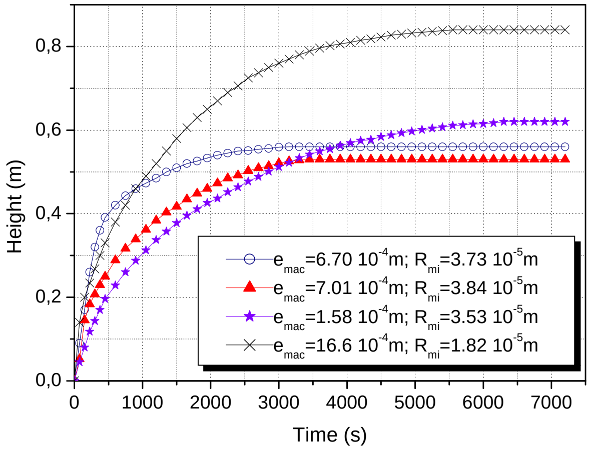

FIGURE 11. Capillary rise in jersey

The experimental data of capillary rise as function of time are presented in *Figure 12*. In *Figure 12*, and for all samples, not surprisingly, the penetration velocity (gradient of tangent with respect of y axis) of liquid in early stage is much higher than in subsequent stages. With time passing, the advancement of liquid becomes slower and slower until equilibrium is established. *Figure 12* also suggests that the same phenomenon as for the simulated results is observed; the sample 4 which initially absorbs quickly then the diffusion is attenuated to reach an equilibrium height of about 0.8 m in 4000 seconds. Indeed, once the macro pores are saturated they will be useful as reservoir for the micro pores where the rise will take place (macro then micro). This attenuation is due to inter-connection between the two scales of porosity, which is difficult to model. The same phenomenon is noticed for the other samples.

Comparing the rise between the various samples, it is necessary to make a compromise between the absorption velocity and the absorption rate. The sample 4 has the best compromise since it absorbs quickly and has the best equilibrium height.

CONCLUSIONS

The capillary rise in jersey knitting fabrics is investigated in this paper. Using a macro and micro scales of porosity the capillary is firstly modeled in each pore's type, by means of geometrical arrangement. Secondly the experimental results are compared to simulated ones at short and long times.

As it is difficult to evaluate the interconnection between macro/micro scales, the capillary kinetic was analyzed at different wicking moments. In short times, the macro pores absorb liquid rapidly. In long times, the micro channels are responsible for reaching the maximum height with slow diffusion rate and transport liquid through fabric to avoid the discomfort of fabric sticking to skin.

So, to have a best comfort feeling, it is necessary to make a compromise between the absorbed height and the absorption velocity in order to make fabric absorbing rapidly and evacuate the fluid through its pores. The sample 4, having the minimum R_{mi} and the maximum e_{mac}, has the best compromise because it not only absorbs quickly but also has the maximum equilibrium height.

However, as we know, modelling the pore's scales is much more complex than an idealized assembly of cylinders, and packing of fibers in the yarn is always non-uniform. Especially for staple fiber yarns, composed fibers may migrate in the radial direction and capillaries between fibers are not continuous. In fact several other parameters have to be considered, for instance in addition to the yarn diameter such characteristics as twist, yarn and fabric structure, raw or synthetic material, fabric finishing, etc.

Therefore wicking in textile materials is very complicated, and the mechanism has not been fully understood.

Nevertheless, this research attempts to gain an insight into this area and to construct a framework for further study. Because this model predicted an overall higher capillary rise than observed experimentally, some additional parameters and refinements are being considered. Modelling of wicking in more complicated structures and using a different liquid will also form the subject of subsequent research.

REFERENCES

[1] Norman R. S. Hollies, Martha M. Kaessinger, and Herman Bogaty, 1956, Water Transport Mechanisms in Textile Materials: Part I-The Role of Yarn Roughness in Capillary-Type Penetration, Textile Research Journal 26: 829-835, 1956.

[2] Norman R. S. Hollies, Martha M. Kaessinger, Barbara S. Watson, and Herman Bogaty, 1957, Water Transport Mechanisms in Textile Materials: Part II-Capillary-Type Penetration in Yarns and Fabrics Textile Research Journal 27: 8-13, 1957.

[3] S.C.Amico and C.Lekakou, 2002, axial impregnation of a fibre bundle: Part 1-Capillary experiments, Polymer Composites, 23(2), pp.249-263, 2002.

[4] S.C.Amico and C.Lekakou, 2002, axial impregnation of a fibre bundle. Part 2. Theoretical analysis, Polymer Composites, 23(2), pp.264-273, 2002.

[5] S.C.Amico and C.Lekakou, 2000, Axial impregnation of a fibre bundle; Part 1- Capillary experiments through woven fabrics, Composites A, 31(12) special issue, pp.1331-1344, 2000.

[6] O. Rahli, L. Tadrist, M. Miscevic, R. Santini, J. Fluid Eng. Trans. ASME 119 (1997) 188.

[7] P.K. Chatterjee, Absorbency, Elsevier Scientific, New York, 1985.

[8] Y.K. Kamath, S.B. Hornby, H.-D. Weigmann, and M.F. Wilde, 1994, Wicking of Spin Finishes and Related Liquids into Continuous Filament Yarns, Textile Research Journal 64: 33-40, 1994.

[9] A.B. Nyoni, D. Brook, J. Text. Inst. 97 (2006) 119.

[10] Perwuelz, P. Mondon, C. Caze, 2000, Experimental study of capillary flow in yarns, Textile Research Journal 70 (4): 333-339, 2000.

[11] Perwuelz, M. Casetta, C. Caze, 2001, Liquid organisation during capillary rise in yarns-influence of yarn torsion, Polym. Test. 20 : 553-561, 2001.

[12] E.W. Washburn, 1921, The Dynamics of Capillary Flow, Phys. Rev. 17, 273 - 283 (1921).

[13] S. Benltoufa, F. Fayala, M., Cheikhrouhou and S. Ben Nasrallah; 2007, Experimental device for fabric water permeability determination, Melliand International 2: 140-143, 2007.

[14] Oxarango, L., "Transferts de Chaleur et de Masse dans des structures poreuses multi échelles", thèse de l'Institut de Mécanique des Fluides de Toulouse (2004).

[15] Bories, A., et Prat, A., "Transferts de chaleur dans les milieux poreux", Techniques de l'Ingénieur, traité Génie énergétique, B 8 250.

[16] S. Benltoufa, F. Fayala, M., Cheikhrouhou and S. Ben Nasrallah; "Porosity Determination of Jersey Structure "Autex Research Journal, N°1, March 2007 (pp 63-69).

[17] Suh, M. W., 'A Study of the Shrinkage of Plain Knitted Cotton Fabric, Based on the Structural Changes of the Loop Geometry due to Yarn Swelling and Deswelling'. Text. Res. J. 37, 417-431 (1967)

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