

Wicking and Evaporation of Liquids in Knitted Fabrics: Analytic Solution of Capillary Rise Restrained by Gravity and Evaporation

N. S. Achour, M. Hamdaoui, S. Ben Nasrallah

Abstract—Wicking and evaporation of water in porous knitted fabrics is investigated by combining experimental and analytical approaches: The standard wicking model from Lucas and Washburn is enhanced to account for evaporation and gravity effects. The goal is to model the effect of gravity and evaporation on wicking using simple analytical expressions and investigate the influence of fabrics geometrical parameters, such as porosity and thickness on evaporation impact on maximum reachable height values. The results show that fabric properties have a significant influence on evaporation effect.

In this paper, an experimental study of determining water kinetics from different knitted fabrics were gravimetrically investigated permitting the measure of the mass and the height of liquid rising in fabrics in various atmospheric conditions. From these measurements, characteristic pore parameters (capillary radius and permeability) can be determined.

Keywords—Evaporation, experimental study, geometrical parameters, model, porous knitted fabrics, wicking.

I. INTRODUCTION

WICKING occurs in the presence of evaporation in many practical situations of interest [1]. Penetration and evaporation dynamics of liquids wicking into porous materials is relevant to various engineering applications such as body fluids adsorption by medical dressings and sanitary pads or moisture migration in tiles and porous buildings claddings and surfaces, spreading of stain or sweat in fabrics, coating processes, ink-jet printing and dye transport in paper and textiles [2]-[4].

Moisture transfer through textile fabrics is critical factor affecting physiological comfort especially in sportswear, underwear, working garment or protective clothing [5], [6].

When the metabolism is very high, people sweat and perspiration spreads all over the skin, that's why, clothes should transfer quickly the sweat outside to make people feel comfortable and even to prolong sport exercise performance [2], [7]. In fact, it is important that if the body produces a sweat, the moisture is transported away from the skin to the

surface of the garment where it can evaporate quickly [1]. Due to this, optimization of various processes involving liquid-fiber contact [8], penetration of liquids into capillaries and textiles [9], [10], and kinetic sorption of water onto textile fabric [11], [12] have been studied for many years. Various investigators [13]-[16] were used the well-known equation of Lucas and Washburn to describe the phenomenon of dynamics of capillary penetration and determine the diffusion coefficient. And many researchers [1], [17] focus on the influence of the evaporation on the wicking performance and propose a new evaporation model that allows predicting optimum geometrical fabric parameters. They are based on the Darcy's law to develop new model which describes capillary rise restrained by gravity and evaporation employing a suction pressure at the moving liquid interface [18]-[21].

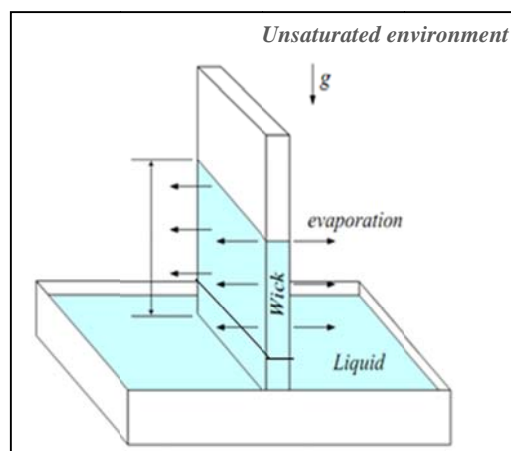


Fig. 1 Porous fabric in contact with liquid at the bottom in unsaturated environment: $(25\pm 2)^\circ\text{C}$ and $(65\pm 4)\%$ humidity

When a wetting liquid encounters a solid medium, initially dry, which has a porosity " ϵ " and a permeability " K " (as shown schematically in Fig. 1), besides of the external wetting (a rapid rise of the liquid on the external surface), there will be also an internal wicking. Both processes rely on the capillary pressure, but in contrast to the wetting process, the internal menisci that drive the wicking are bound to the pore radius " R_c ".

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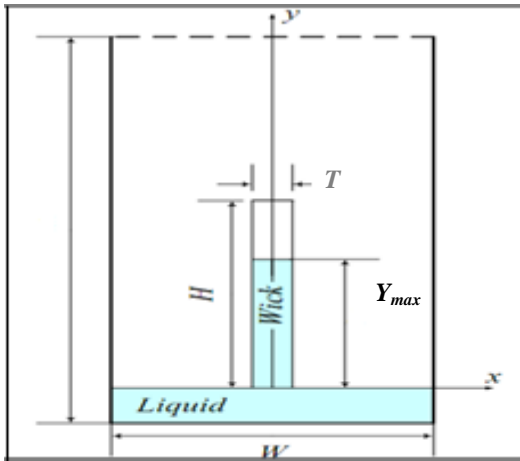


Fig. 2 Two dimensional sketch of the situation studied in [17]

A. Differential Equation of Capillary Rise in Presence of Evaporation

To look at the problem in more detail the momentum balance of a volatile liquid inside a porous medium shall be presented: In presence of evaporation, [17] gives the differential equation of capillary progression as:

$$\frac{2\gamma\cos\theta}{R_c} = \rho g y + \frac{\varepsilon}{K} \mu y \frac{dy}{dt} + \frac{\mu j_e (W+T)}{\rho K W T} y^2 \quad (1)$$

where " μ " is the dynamic viscosity of the liquid, " ρ " the liquid density, " g " the gravity, " γ " the surface tension of the wetting liquid and " θ " the static contact angle formed between solid and liquid, " W " the fabric width, " T " the thickness, " H " the height which is much greater than the width ($H \gg L$) and j_e the evaporation flow. " y " is the position of the capillary rise front in the porous fabric.

Equation (1) can be transformed as:

$$\frac{dy}{dt} = \frac{a}{y} - b - c y \quad (2)$$

where

$$a = \frac{2\gamma\cos\theta}{\varepsilon\mu} \frac{K}{R_c} \quad (3)$$

$$b = \frac{\rho g}{\mu} \frac{K}{\varepsilon} \quad (4)$$

and

$$c = \frac{j_e (W+T)}{\rho \varepsilon W T} \quad (5)$$

B. Maximum Reachable Height

As pointed out in many researches [1], [17], different cases are distinguished from this previous equation as regards the final height of the liquid within the wick.

Solving

$$\frac{dy}{dt} = 0 \quad (6)$$

We have many cases:

- No evaporation occurs ($c=0$): in this case, the competition between gravity and capillary forces governs the maximum reachable height given by Jurin's Law [22], [23]:

$$y_{max1} = \frac{a}{b} = \frac{2\gamma\cos\theta}{\rho g R_c} \quad (7)$$

- Negligible gravity effects ($b=0$): in this case, the competition between capillary effects and evaporation sets the maximum reachable height which is given by:

$$y_{max2} = \sqrt{\frac{a}{c}} \quad (8)$$

- Both gravity and evaporation must be considered which leads to:

$$y_{max3} = \frac{-b}{2c} + \sqrt{\frac{b^2}{4c^2} + \frac{a}{c}} \quad (9)$$

- Finally, no gravity and no evaporation are affecting the capillary rise, only the viscosity restrict the maximum reachable height as is also predicted by the Lucas-Washburn equation [13], [14], [23]- [26].

To relate the liquid mass absorbed to the observed wicking height the following linear relation is assumed to be hold [17], [27]:

$$m = \rho_l * T * W * \phi_f * h \quad (10)$$

The Lucas-Washburn modified equation gives the mass gain (m) versus time instead the height [17], [25], [28]:

$$m^2 = (WT\phi\rho)^2 \frac{4\gamma_L\cos\theta}{\phi\eta} \frac{K}{R_c} \quad (11)$$

In this paper, wicking with evaporation at the knitted fabric lateral surfaces is studied using the analytical model, presented previously, as a function of knitted fabric properties and the evaporation rate.

II. EXPERIMENTAL MATERIAL AND METHODS

A. Knits Properties

All knitted fabrics are produced on a 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 at different tightness factor. Table I presents the characteristics of knitted sample tested: The construction parameters (the knit structure), the composition and the yarn properties (kind of spinning and fineness) are varied.

The dimension of the dry sample used in experiments was 25 cm x 30 cm. We used one kind of liquid: distilled water.

- Fabrics relaxation: Full relaxation of the samples was carried out by wet relaxing and conditioning for 24 hours in standard atmospheric condition ((20 ± 2) °C and (65 ± 4) % humidity) as per Standard procedure – ISO 139:2005.

TABLE I
 CHARACTERISTICS OF KNITTED FABRICS TESTED

Sample	Composition	Knit structure	Yarn spinning	Yarn Fineness Metric count	Tightening	Thickness (mm)	Weight (g/m ²)	Porosity
1	100% Cotton	Jersey	Combed	28	14	1,99	359,5	0,883
2	80% cotton 20% Polyester	Jersey	Combed	28	14	2,13	349,1	0,888
3	100% Cotton	Rib 1&1	Carded	12,5	14	2,85	461,2	0,895
4	100% Cotton	jersey	Carded	12,5	14	2,07	418,7	0,869
5	100% Cotton	Jersey	Open-end	12,5	14	2,03	378,0	0,879

- Fabric Porosity: The porosity " ϵ " is defined by the volume fraction of empty. This parameter can be expressed as a function of the weight (m_s (g/m²)), the thickness of the fabric (T (m)), and the density of the fiber (ρ (g/m³)) [29], [30]:

$$\epsilon = 1 - \frac{m_s}{\rho T} \quad (12)$$

To remove all the waxes and the oils attached to greige fabrics and consequently to increase its hydrophilic properties, we make a scouring treatment for the sample: the fabric was treated 1 hour at 100°C with a solution contained 2 mL of caustic soda, 3 g/L of wetting product and 3g/L of reducing agent.

B. Experimental Device

The experimental system (see Fig. 3) is composed of a device assuring the vertical suspension of cloth-surface on the liquid, a lighting system and video camera to record the wicking liquid front height versus time. In order to measure the mass of liquid raised, the fabric is attached to sensitive electronic balance with the accuracy of 0,001 g which has the capability of recording the weight of the absorbed water by the sample "g" versus time "s" [31]. All the experiments were done in a conditioning test-chamber which allows us to control the temperature and the humidity.

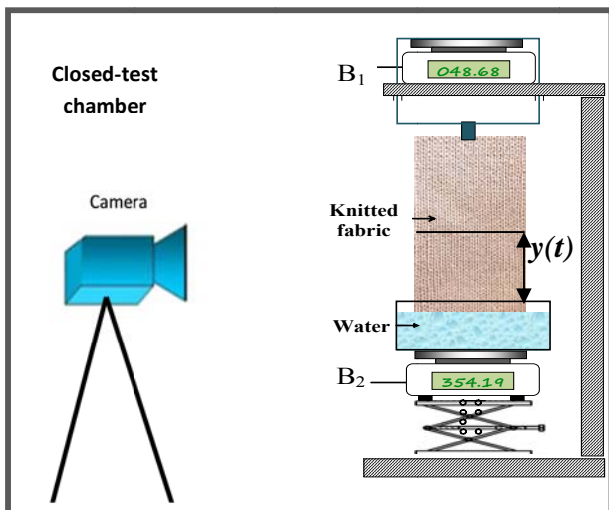


Fig. 3 Experimental device

III. RESULTS AND DISCUSSION

A. Determination of Knitted Fabric Parameters (Static Capillary Radius " R_c " and Permeability " K ")

1. Evaluation of Experimental Results_Height Approach

The experiments are performed in:

- A saturated environment (absence of evaporation): atmosphere of (25±2)°C and 99% of humidity, in order to reach the maximum height y_{max1} (7) practically in absence of evaporation.
- An unsaturated environment: atmosphere of (25±2)°C and (65±4)% humidity.

A comparative study between the two water kinetics allows us to confirm the presence of the evaporation phenomenon.

The recording of the wicking front is done with a camera with high resolution. Data acquisition is controlled and processed using Matlab. Fig. 4 shows a sketch of the arrangement. By measuring the maximum reachable wicking height y_{max1} that occurs due the equilibrium between the capillary and gravity forces (7), the static capillary radius can be calculated for each knitted fabric and presented in Table II.

2. Evaluation of Experimental Results_Mass Approach

According to 11 mass measurements can be used to calculate pore structure parameters like the permeability of the knitted fabric. Fig. 5 shows the squared wicking mass gain plotted versus time.

From the slope of the $m^2(t)$ curves, " $\frac{K}{R_c}$ " results for different samples and their correlation coefficients are determined and presented in Table III.

A comparison of the results showed that there is a small deviation in the permeability values between the measurements made with different knitted fabrics. But it's clear that there is a significant effect of the knits structure (Sample 3, Rib 1&1) on the permeability of the fabrics. An increase of the thickness causes an augmentation of the permeability value.

B. Impact of Evaporation on Wicking

Fig. 6 describes the evolution of experimental data of water mass absorbed by jersey cotton fabric (sample 4) as a function of time in saturated and in unsaturated atmosphere, thus the effect of evaporation is fairly important and clearly visible.

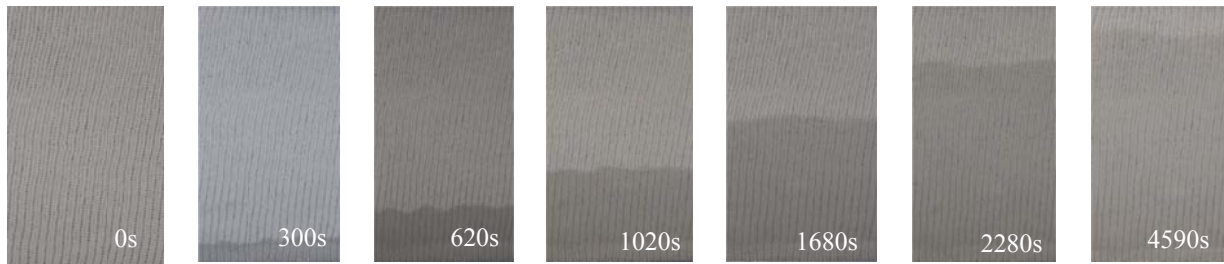


Fig. 4 Wicking of distilled water into jersey knitted fabric in saturated environment (sample 4)

TABLE II
 MAXIMUM HEIGHTS AND STATIC CAPILLARY RADIUS (R_c) FOR ALL KNITTED FABRICS

Sample	1	2	3	4	5
$y_{max1} (m)$	0,1219	0,1203	0,1367	0,1461	0,1256
$R_c (10^{-4}m)$	1,2151	1,2313	1,0836	1,0138	1,1793

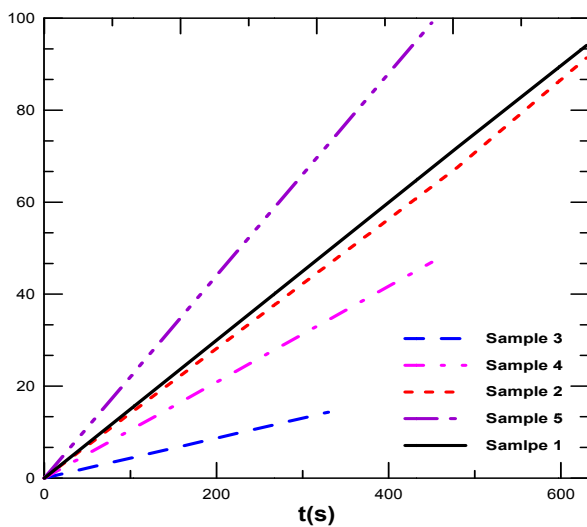


Fig. 5 Squared mass over time of different knitted fabrics

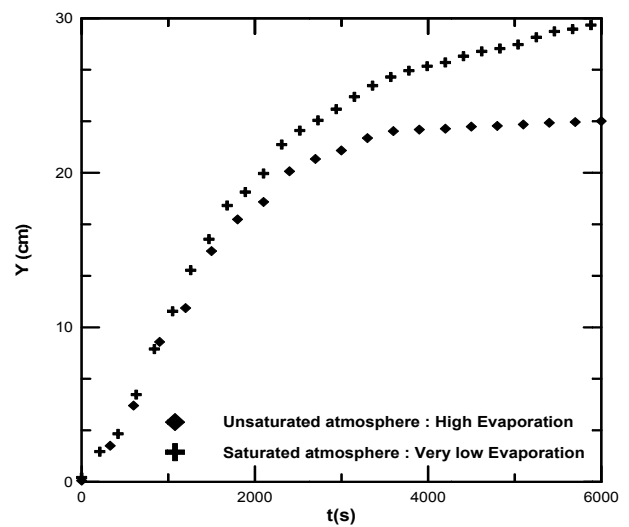


Fig. 6 Wicking height Evolution of sample 4 (jersey cotton fabric) in saturated and unsaturated atmospheres

TABLE III
 PERMEABILITY VALUES CALCULATED FROM MASS MEASUREMENTS

Sample	1	2	3	4	5
Slope	0,1495	0,1440	0,0434	0,1043	0,22
R-square	0,999	0,999	0,996	0,998	0,999
$\frac{K}{R_c} (mm)$	2,36	1,97	0,33	1,55	3,37
$K(mm^2)$	0,287	0,243	0,035	0,157	0,397

Using theoretical model, described previously, we can investigate the influence of evaporation phenomenon on wicking behavior of water in porous fabrics, especially, the maximum reachable height and predict the deviations from unaffected capillary rise confirming the experimental results. Moreover, simple and efficient way to study the impact of fabric properties is to vary the capillary radius " R_c " which has direct impact on both permeability " K " [20] and capillary pressure [32].

As can be seen from Fig. 7, evaporation has here a strong influence on the height reached by the liquid. The evaporation effect is dominant in limiting the rise for lower capillary radius: Micropores intervene at short instants (absence of

gravity), whereas both gravity effects and evaporation limit the rise for a greater pore size, macropores intervene at long moments (presence of gravity). As a consequence, there is a maximum in the impregnation height when both limiting effects, i.e. evaporation and gravity, are comparable (see Fig. 7). As can be seen also, the fabric would be fully saturated in the absence of evaporation for capillary radius lower than about 45 μm .

C. Effect of Thickness on Evaporation Impact

Fig. 8 shows that the influence of evaporation becomes negligible for a sufficiently thick porous fabric: In fact, the term " c " containing the evaporation flux (5) varies as " T^{-1} ", where " T " is the thickness of the fabric.

It's shown that porous fabric, having thickness equal to $2 \cdot 10^{-3}$ m or more, would be fully saturated for capillary radius lower than about 45 μm .

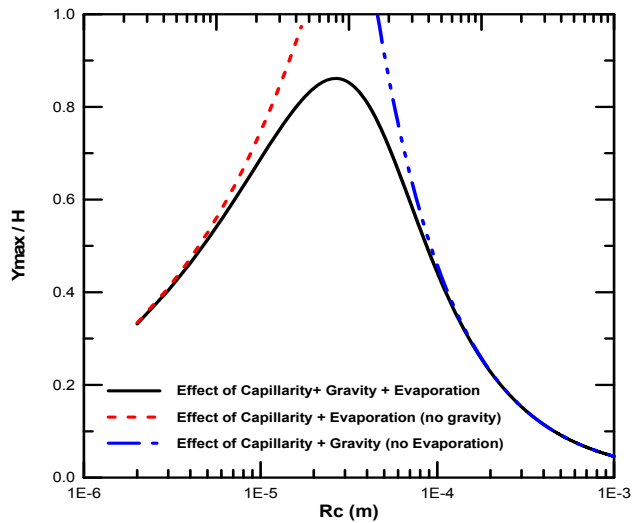


Fig. 7 Evolution of final maximum impregnation height as a function of capillary radius

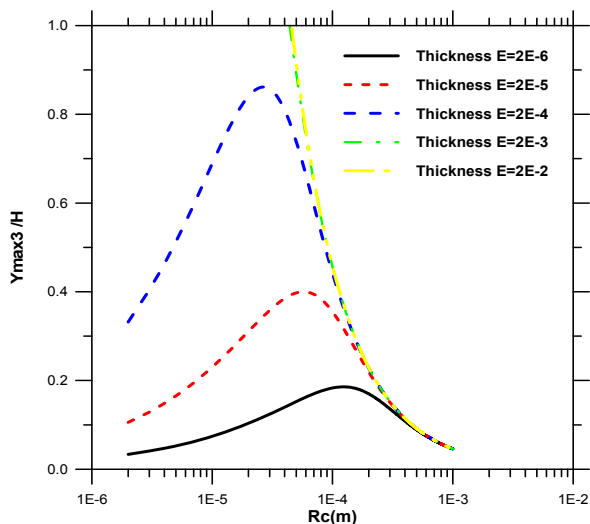


Fig. 8 Effect of thickness on wicking in presence of evaporation

D. Effect of Porosity on Evaporation Impact

As can be seen from Fig. 9, the influence of evaporation on capillary rise becomes more important when the porosity of the fabric decrease, in this case the equilibrium reached height reduce. Notice that in the right hand side of (2) the term "c" containing the evaporation flux (5) varies as " ε^{-1} ".

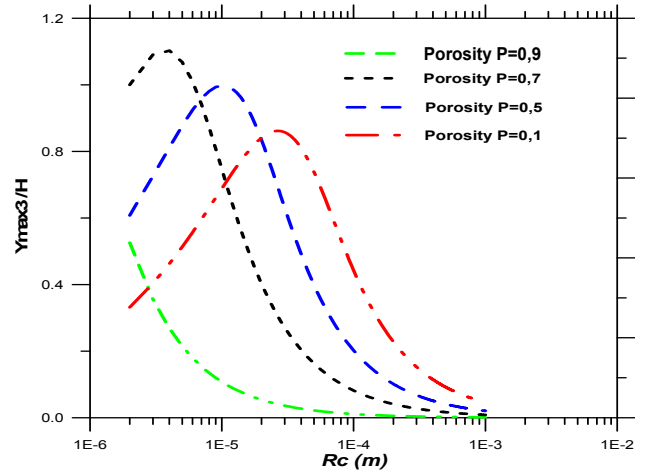


Fig. 9 Effect of porosity on wicking in presence of evaporation

IV. CONCLUSION

In this study, the water sorption onto knitted fabrics was gravimetrically investigated at different conditions (saturated and unsaturated atmosphere) in order to study the role of evaporation for capillary rise. Moreover, from the experimental measurements, characteristic pore parameters " R_c " and " K " can be determined.

This experimental procedure and an analytical model, which is proposed to study the water sorption onto knitted fabrics, demonstrated that gravity and evaporation phenomena have a strong influence on wicking behavior, especially, the maximum reachable height. Finally, it is noted that the fabric properties, porosity and thickness, have an important impact on the evaporation effect on the capillary rise. In fact, the influence of evaporation becomes negligible for a sufficiently thick and porous fabric.

REFERENCES

- [1] S. V. Tissoires, S. Geoffroy, M. Marcoux, and M. Prat, "Evaporation and wicking," Toulouse..
- [2] A. Gat, A. Vahdani, H. Navaz, A. Nowakowski and M. Gharib, "Asymmetric Wicking and Reduced Evaporation Time of Droplets. Penetrating a Thin Double-Layered Porous Material," *Applied Phy Letter*, vol. 103, 2013.
- [3] Z. Romdhani, A. Baffoun, M. Hamdaoui and S. Roudesli, "Drying Morphologies and Emport Rate Effect on Wetting and Spreading Behaviours," *Fibers and Polymers*, vol. 14, 2013, pp. 1157-1164.
- [4] D. A. Lockington, J. Y. Parlange, and M. Lenkopane, "Capillary absorption in porous sheet and surfaces subject to evaporation," *Transport in porous Media*, vol. 68, no. 1, pp. 29-36.
- [5] R. Stämpfli, P. A. Brühwiler, I. Rechsteiner, V. R. Meyer, and R. M. Rossi, "X-ray tomographic investigation of water distribution in textiles under compression - Possibilities for data presentation," *Measurement*, vol. 46, no. 3, april 2013, pp. 1212-1219, Switzerland.
- [6] J. Youngmin, H. P. Chung, and J. K. Tae, "Effect of heat and moisture transfer properties on microclimate and subjective thermal comfort of caps." *Textile research journal*, vol. 80, no. 20, (2010), pp. 2195-2203.
- [7] K. Atkins, and M. Thompson, "Effect of textile hygroscopicity on stratum corneum hydration, skin erythema and skin temperature during exercise in the presence of wind and no wind," *J. Exerc. Sci. Fit.*, Vol. 9, no. 2, December 2011, pp. 100-108, Australia.
- [8] D. Saïhi, A. El-Achari, A. Ghenaim, and C. Cazé, "Wettability of grafted poly(ethylene terephthalate) fibers," *Polymer Testing*, vol. 21, no. 6, 2002, pp. 615-618.

- [9] A. Marmur, "The radial Capillary," *J. Colloid and interface sci*, vol. 124, no. 1, July 1988, pp. 301-308.
- [10] F. A. Dullien, M. S. El-Sayed, and V. K. Batra, *J. Colloid and interface sci*, vol. 60, 1977.
- [11] J. A. Wehner, B. Miller and L. Rebenfeld, "Dynamics of water vapor transmission through fabric barriers," *Text. Res. J.*, vol. 58, January 1988, pp. 581-592.
- [12] Y. Li and Z. Luo, "An improved mathematical simulation of the coupled diffusion of moisture and heat in wool fabric," *Text. Res. J.*, vol. 69, pp. 760-768.
- [13] A. Perwuelz, P. Mondon, and C. Cazé, "Experimental Study of Capillary Flow in Yarns," *Textile Res. J.*, vol. 70, no.4, 2000, pp. 333-339.
- [14] A. Perwuelz, P. Mondon, and C. Cazé, "Liquid organization during capillary rise in yarns – influence of yarn torsion" *Polymer Testing*, vol. 20, 2001, pp. 553-561.
- [15] M. Hamdaoui, F. Fayala, and S. Ben Nasrallah, "Experimental Apparatus and mathematical model for determination of parameters of capillary rise in fabrics," *Journal of Porous media*, vol. 9, no. 4, 2006, pp. 381-392.
- [16] M. Hamdaoui, F. Fayala, and S. Ben Nasrallah, "Dynamics of capillary Rise in Yarns: influence of Fiber and Liquid Characteristics," *J. Appl. Polym. Sci*, vol.104, pp. 3050-3056.
- [17] N. Fries, K. Odic, M. Conrath, and M. Dreyer, "The effect of evaporation on the wicking of liquids into a metallic weave," *J. Colloid Interface Sci*, vol. 321, no. 1, may 2008, pp. 118-129.
- [18] R. Massodi, K.M. Pillai, and P.P. Varanasi, "Darcy's law based models for liquid absorption in polymer wicks," *AICHE J*, vol. 53, no. 11, November 2007, pp. 2769-2782.
- [19] S. Beyhaghi, K. M. Pillai, D. T. Qadeh, and M. L. Dietz, "Evaporation and transport of non-dilute, multi-component liquid mixtures in porous wicks: Simulation and experimental validation," *Int J Heat Mass Transfer*, vol. 54, 2011, pp. 5216-5230.
- [20] S. Beyhaghi, S. Geoffroy, M. Prat, and K. M. Pillai, "Wicking and evaporation of liquids in porous Wicks: A simple Analytical Approach to Optimization of Wick Design," *AICHE J*, vol. 60, no. 5, May 2014, pp. 1930-1940.
- [21] A. D. Gat, A. Vahdani, H. Navaz, A. Nowakowski and M. Gharib. "Asymmetric Wicking and Reduced Evaporation Time of Droplets. Penetrating a Thin Double-Layered Porous Material". *Applied Physics Letters*, vol. 103, no. 13, 2013.
- [22] A. W. Adamson, "Physical Chemistry of surfaces," 5th ed, Wiley Intersciences, New York, 1990.
- [23] E. Raphael, *J. Phys*, vol. 50, 1989, pp. 485.
- [24] F. K. Cameron and J. M. Bell, *J. phys. Chem*, vol. 10, 1906, pp. 658.
- [25] R. Lucas, *Kolloid-Z*, vol. 23, 1918, pp. 15-22.
- [26] A. Siebold, A. walliser, M. Nardin, M. Oppliger and J. Schultz, "Capillary Rise for thermodynamic characterization of solid Particle Surface," *Journal of colloid and interface science*, vol. 186, no. 1, february 1997, pp. 60-70.
- [27] A. Majumdar, S. Mukhopadhyay, and R. Yadav, "Thermal properties of knitted fabrics made from cotton and regenerated bamboo cellulosic fibres," *International journal of thermal sciences*, vol. 49, no. 10, October 2010, pp. 2042-2048, India.
- [28] E.W. Washburn, *Phys. Rev*, vol. 17, no. 3, 1921, pp. 273-283.
- [29] N. Ozdil, A. Marmarah, and S. D. Kretschmar, "Effect of yarn properties on thermal comfort of knitted fabrics," *International journal of thermal sciences*, vol. 46, no. 12, December 2007, pp. 1318-1322, Turkie.
- [30] S. S. Bhattacharya, and J. R. Ajmeri, "Investigation of Air Permeability of Cotton & Modal Knitted Fabrics," *International Journal of Engineering Research and Development*, vol. 6, no. 12, May 2013, pp. 01-06.
- [31] M. Hamdaoui, N.S. Achour, and S. Ben Nasrallah, "The Influence of woven fabric structures on Kinetics of Water Sorption". *Journal of Engineered Fibers and Fabrics*, vol. 9, no. 1, March 2014.
- [32] P. G. De Gennes, F. B. Wyart, and D. Quéré, *Gouttes, Bulles, Perles et ondes*, Ed Berlin, 2002, pp. 100.