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Theoretical Development of Mathematical Model to Predict Vertical Wicking Behavior of Flow through Terry Towels

تطوير نظرى لموديل رياضى للتنبؤ بسلوك ارتفاع السائل رأسياً خلال اقمشة الفوط الوبرية

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الملخص العربي:-

فى هذا البحث تم اقتراح عدة موديلات رياضية للتنبؤ بسلوك ارتفاع السائل رأسياً على أساس اختلاف متغيرات الشعيرات والخيوط والاقمشة . موديلات الخيوط والاقمشة التى أمكن تطويرها على أساس معادلة العالم (هاجن بوازليه) الخاصه بسريان السوائل وهندسة المساميات أمكن التوصل إليها. بعض العوامل مثل مسامية الخيوط وعدد الشعيرات فى مقطع الخيط ودنير الشعيرات ودنير الخيوط ونسبة تشريب الخيوط فى القماش وقطر المساميات داخل الخيط و زاوية تلامس الشعيره مع سطح الماء المقطر امكن اخذها فى الاعتبار لتطوير موديل الخيط . ايضاً بعض العوامل مثل قطر الخيوط وعدد خيوط السداء واللحمه فى وحدة الطول وسمك القماش وقطر المساميات بين الخيوط وبعضها ومسامية القماش امكن أخذها فى الاعتبار لتطوير موديل القماش . المعادله الرياضيه التفاضليه الخاصه بالعالم (بوازليه) امكن تطويرها لتساعد فى التنبؤ بارتفاع مستوى السائل فى القماش عند أى زمن آخذاً فى الاعتبار قوة الخاصيه الشعريه التى تؤثر لأعلى وقوة الجاذبيه الأرضيه التى تؤثر لأسفل وللتأكيد على صحة موديل القماش امكن اجراء بعض التجارب المعمليه على اقمشة الفوط القطنيه . المتوسط الحسابى لمستوى ارتفاع السائل المحسوب من موديل الخيط والقماش امكن تعيينه للتنبؤ بمستوى سطح السائل فى القماش كداله فى الزمن ووجد أن هناك تطابق تام للنتائج النظريه عند مقارنتها مع النتائج المعملية .

KEYWORDS:
Vertical wicking height , Porosity , Hydraulic pore radius , Inter – yarn pores , Capillary , Contact angle , Surface tension

Abstract— **Theoretical models have been proposed in this paper to predict the vertical wicking behaviour of fabrics based on different fibre, yarn and fabric parameters. The yarn and fabric models have been developed based on Hagen – Poiseuille's equation on fluid flow and pore geometry through the yarns (inter–fibre pores) and fabrics (inter–yarn pores) have been determined. Factors such as yarn porosity, number of fibres in a yarn cross-section, fibre denier, yarn denier, yarn crimp, hydraulic pore diameter and fibre contact angle have been taken into account for development of the yarn model. Also, factors such as yarns diameters, ends & picks/ cm, fabric thickness, hydraulic pore diameter and fabric porosity have been taken into account for development of the fabric model. Differential mathematical equation has been incorporated, which helps to predict vertical wicking height at any given time considering the capillary and gravitational effects. Experimental verification of the fabric model has been carried out using cotton terry woven fabrics. The average of theoretical values of vertical wicking heights obtained from the yarn and fabric models were found to predict the vertical the vertical wicking height as a function of time through the fabrics with a good agreement compared with the experimental results.**

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I. INTRODUCTION

TOWELS are the most used textile structures in water – related usage of terry – woven fabrics. The users prefer that ready – made bathrobes and towels by comfortable and fresh, made of a light and soft structure, remain dry as quickly transfer the water and sweat accumulated on the body, and be hygienic and naturally formed. Thefore comfort, an important property for the textile products, is also an important need for terry fabrics in water – related usage. However, the comfort properties of terry fabrics such as towels should be specific. The comfort parameters of air permeability, water vapour permeability, liquid transfer velocity, drying time, and water absorption will stand out in such products.

In terms of up to date theoretical studies, the most convenient fibre type and fabric construction are identified in this paper and the experimental study with certain changes , will provide a guide for the piled – products group. .

Cotton fibres were chosen in this study. And in that choice, the previous studies have been the guide. Cotton is the most important of the natural cellulosic fibres. It still accounts for about 50 % of the total fibre production of the world. Cotton is almost pure cellulose [1]. Cotton has excellent hand and the drapeability of cotton fabrics is quite acceptable. Cotton fabrics have a low luster unless mercerized or resin finished. The cotton fibres are selected in this study because of their superior characteristics of water absorption, higher wet breaking strength, dyeing affinity, washability and post – weaving softness [2]. The properties of cotton fibres for use in products such as towel, bathrobe and waist cloth in terms of comfort are considered as convenient for use for pile warp in the terry fabric [3].

Comfort is a complex concept that involves many physical, psychological and physiological factors. It can be defined as the feeling of pleasure deriving from the physical, psychological and physiological harmony between the body and the environment [4]. For better comfort, it is necessary for the fabric system to have some comfort parameters.

The basic parameters include heat and moisture transfer, air permeability, heat retention capability and electrification tendency [5]. Besides these parameters, the comfort parameters change in accordance with the usage, purpose and environment of the towels and bathrobes. These include water, vapour and air permeability, moisture permeability and water absorption, no feeling of wetness, drying period, liquid transfer velocity , and being non – allergic , soft handling .

Several papers [6-9] have discussed the problems involved in measuring the rate of fluid absorption in capillary absorbing media. Some of these have considered absorption in textile assemblies such as yarn and cloth while others have considered single textile fibres.

The performance property that comes out as a result of flow through the fabric is named "fabric permeability "the total porosity that determined the flow was named as "effective porosity ". The effective porosity was formed by two components that were named as inter-fibre and inter-yarn porosity. The total porosity responsible for flow was defined as a function of inter-fibre and inter-yarn pores; however woven fabric structures are complex structures. That consists of different parameters. Consequently, the permeability performance of fabric was a complex three – dimensional mechanism and its prediction was hard [10].

In the theoretical models that were formed to estimate the flow, Poiseuille (1840), Darcy (1846) and Kozeny (1927) equations, which were modified according to properties of pore medium, were generally used. Van Den Brekel and De Jong [11]. Predicted the fluid flow of the porous medium in both inter – fibre and inter-yarn regions by investigating. Kozeny and drag theory in their calculations. In the fabric, the inter-fiber and inter-yarn pores were assumed as parallel regions, accordingly, the permeability coefficient for both inter-fibre and inter-yarn transmission was calculated by the continuity equation and local porosity .In another study, the fluid flow that took place in the fabric at the laminar flow region of yarn groups was approximately explained by Darcy, s Law. The fluid flow model , which was developed in inter – fibre and inter-yarn capillaries by assuming the cross-section of the yarn being race track was formed by evaluating it together with a geometrical model that depended on hydraulic radius theory [12].

In the first part of their study , Das et al [13] formed a yarn model depending on yarn parameters that would affect the vertical wicking behavior of yarn and calculated the capillary flow with Hagen – Poiseuille equation by using the parameters obtained from the model .In the second part of the study , they first improved a mathematical model by modeling the yarn geometry in the fabric as an inclined tube in order to predict the vertical wicking behavior of plain woven fabric and then calculated the wicking height by defining the yarn geometry according to Pierce geometry [14]. Experimental and theoretical results showed that the starting wicking rate was higher in yarn than in fabric. However, it was observed that wicking height was higher in the fabric than yarn at the state of equilibrium and this situation was interpreted as the fact that weft yarns continued providing fluid in the warp yarns by functioning as a reservoir during wicking.

In the studies [15,16], it was presented that the fabric parameters , such as linear density of the yarn , yarn packing rate , fabric density ,crimp factor ,the cross – section shape of the yarn , the total cover factor , weave type and raw material properties , affected the fabric geometry and the flow behaviour of fluid . The yarn diameter is an important property in defining the pore properties and the diameter values obtained by different methods result in differences at the calculated pore parameters.

This paper was aimed at developing a more practical mathematical model (Poiseuille flow law) to predict the capillary flow of liquid water though the terry woven fabrics by suggesting new geometrical models for calculating the porosity and hydraulic pore radius separately in inter – fibre and inter – yarn capillaries. Thus, the predicted vertical wicking height results were obtained depending on the structural parameters of fabric. Obtained theoretical results were tested by being compared with the experimental results.

II. MATHEMATICAL MODEL DEVELOPMENT

The proposed model is based on Hagen – Poiseuille equation (1839). For the development of the fabric mathematical model, the following assumptions have been considered:

* Threads are uniform along the length.
* Threads are equally spaced in the fabric.
* There is no flattening in the threads.

The following aspects have been proposed and proved by experiment before moving forward with the mathematical work.

The pore properties of fabric were first defined by dividing the fabric into two regions as inter – fibre and inter – yarn pore regions , the flow rates of the two regions were calculated by assuming that the 3D flow mechanism was formed through inter – fibre and inter – yarn regions separately .

The capillary laminar flow mechanism in the inter – fibre and inter – yarn regions was modeled by capillary theory, depending on fabric structure in order to predict the vertical wicking flow behavior of fabric theoretically.

The geometrical model presented here is based on the hydraulic radius theory and starts from the first principles of fluid flow. Using Hagen – Poiseuille law for laminar flow through noncircular and irregular in the pore structure and spacing is employed as the following equation [17, 18].

$$Q = \frac{R_h^2.\Delta p.A_o}{8K.\eta.\ell}, \quad m^3/\sec \ldots\ldots (1)$$

Where Q = rate of flow through the capillary, Δp= pressure difference, A_o = area of the pore space in the channels, η = viscosity of the fluid, ℓ = length of the capillary, K= a shape constant that depends on the shape of the pore along the channel (tortuosity) (τ) and orientation of the pore system and R_h = the hydraulic radius of pore defined as follows [19].

$$R_h = \frac{2A_p}{P_p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where A_p,P_p and R_h are the area , the watted perimeter and the hydraulic radius of the pore .

The cross – sectional area of the pores (A_o) in the channels will be (Aε) , where (ε) is the porosity and (A) is the total cross – sectional area . Therefore, Equation (1) can be written as follows:

$$Q = \frac{R_h^2.\Delta p.A\varepsilon}{8K\eta\ell}, \quad m^3/\sec \ldots\ldots\ldots\ldots\ldots (3)$$

Now if the hydraulic radius (R_h) and the porosity (ε) of both the inter – fibre and inter – yarn flow paths are determined, along with (K), the flow velocity (V) i.e. (dℓ/dt) or (dh/dt) occurring in yarns or fabrics respectively can by defined by Equations (4, 5):

$$V = \frac{Q}{A} = \frac{d\ell}{dt} = \frac{\varepsilon.R_h^2.\Delta p}{8K\eta\ell}, \quad m/\sec, \text{ (For yarns) } \ldots. (4)$$

Or

$$V = \frac{Q}{A} = \frac{dh}{dt} = \frac{\varepsilon R_h^2.\Delta p}{8K\eta h}, \quad m/\sec,$$

(For fabrics) …………………… (5)

The flow velocity (dℓ/dt) occurring in a capillary tube with a hydraulic radius (Rh) was a function of pressure difference (Equation (4)). The effective forces during the capillary flow occurring in the vertical direction were capillary forces that affected upwarp and gravity forces that affected down. Accordingly, the pressure difference (ΔP) during the capillary flow at a straight capillary tube was defined by Equation (6), described by the Laplace equation as follows [20]:

$$\Delta p = Pc - Pg = (\frac{2\gamma\cos\theta}{R_h} - \rho gh) \ldots \quad (6)$$

$$\frac{d\ell}{dt} = \frac{\varepsilon}{8k\eta}.\frac{R_h^2}{\ell}(\frac{2\gamma\cos\theta}{R_h} - \rho gh) \ldots\ldots (7)$$

In Equation (6), capillary pressure (P_c) was a function of capillary radius (R_h), the contact angle between the fluid surface and the fibre (θ) and the surface tension of the fluid (γ). The gravitational pressure (Pg) depended on the height of the fluid (h), acceleration of gravity (g) and the density of the fluid (ρ). The capillary rise of the fluid according to time, namely flow velocity (dℓ/dt), was defined by Equation (7). At the equilibrium condition in which the capillary force was equal to gravity force in Equation (6), the maximum capillary rise was reached (Equation (8)) at Δp=o.

$$h_{\max} = h_m = \frac{P_c}{\rho g} = \frac{2\gamma\cos\theta}{\rho g R_h} \quad \ldots\ldots\ldots\ldots (8)$$

The capillary mechanism of a fluid in the fabric was more complex than the capillary flow occurring in a straight tube , because the fabric system has a 3D complex structure and the flow in this structure occurred depending on both inter – fibre and inter – yarn pore regions . Due to the fact that the inter – fibre and inter – yarn regions were in contact with each other, modeling of the flow mechanism became more difficult – For this reason, in vertical wicking flow occurring in inter – fibre and inter – yarn regions was first defined separately according to capillary theory; the capillary rise value of the fabric system was then evaluated by these two mechanisms

2.1-Calculation of Velocity of Capillary Rise of the Inter – Fibre Region within Yarns:

Vertical capillary rise in the yarn was calculated depending on yarn porosity (ε_y) and the hydraulic pore diameter (D_h) of the inter – fibre region by assuming that the inter – fibre pores were equal to each other and they were continuous. The obtained capillary rise result was found to be equivalent to the rise value that occurred in a straight tube having the same diameter. However, yarn had a defined geometry in the fabric. The shape of the pore along the channel was named (Tortuosity) (τ). The (tortuosity) (τ) of the inter – fibre capillary was accepted to be equal to the crimp factor (1+crimp %) of the yarn for the yarn geometry defined by structural and geometrical parameters of fabric (Figure 1.c) [21].

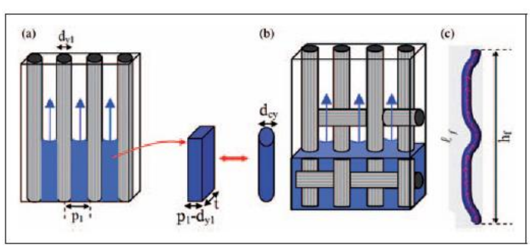


Figure 1 (a) Simplified capillary flow between parallel yarns , (b) Capillary flow mechanism in the inter – yarn regions of the fabric ,(c) Capillary flow mechanism in inter – fibre regions [21]

The theoretical capillary wicking rise was calculated depending on UN – crimp yarn length (ℓ_f) (Equation 9).

$$\frac{d\ell_f}{dt} = \frac{\varepsilon_y}{8k\eta} \cdot \frac{R_h^2}{\ell_f} \left(\frac{2\gamma\cos\theta}{R_h} - \rho g \ell_f\right) \quad \dots (9)$$

Where cos (θ) = cosine contact angle between the fluid surface and the coton fibre = 0.9063, i.e (θ =25°)

R_h = hydraulic pore radius within yarns, metre

ε_y = yarn porosity.

And the function of inter – fibre capillary height (h_f) depending on time (the capillary rise velocity) was then modified by using the crimp factor (1+ C %) as shown in Equation (10)

$$\frac{d\ell_f}{dt} = \frac{\varepsilon_y}{8k\eta} \cdot \frac{R_h^2(1+C\%)}{\ell_f} \left(\frac{2\gamma\cos\theta}{R_h} - \frac{\rho g \ell_f}{(1+C\%)}\right) \quad \dots (10)$$

Put $h_{f(t)} = \frac{\ell_f}{(1+C\%)}$)

Thus, the capillary rise height of the inter-fibre region as a function of time can be calculated as follows:

$$\frac{dh_f}{dt} = \frac{\varepsilon_y}{8k\eta} \cdot \frac{R_h^2}{h} \left(\frac{2\gamma\cos\theta}{R_h} - \rho g h\right) \quad \dots\dots (11)$$

Equation (11) can be rewritten as follows:

$$\frac{dh_f}{dt} = \frac{1}{k}\left(\frac{\varepsilon_\gamma R_h \gamma\cos\theta}{4\eta.h} - \frac{\varepsilon_\gamma R_h^2 \rho g}{8\eta}\right) \quad \dots\dots\dots (12)$$

Where $\frac{1}{k} = ko =$ 0.106319 (experimental coefficient)

$h = \frac{\ell_f}{(1+C\%)}$) =capillary rise height

2.2-Calculation of Velocity of Capillary Rise of the Inter – Yarn Region between Yarns:

The fabric system was modeled as structure that consisted of parallel yarns to each other in order to model the capillary flow mechanism in the vertical direction at the inter – yarn pore regions (Figure 1(a)) . Then, considering the 3Dstructure of the fabric system (Figure 1(b)).

In the fabric structure , the inter – yarn regions were formed by different intersecting of warp and weft yarns (Figure 1 (b)) so the fabric system had a more complex capillary mechanism than a straight tube . The hydraulic pore diameter that was effective for vertical wicking flow for the inter –yarn region was related to the cross – sectional structure of the fabric. The inter – yarn capillary structure of the fabric changed depending on the intersecting order, while the fabric was considered in a rectangular cuboid. The overall porosity value (ε_F) , determined depending on the structural and geometrical properties of the fabric in a previous paper [22] , was used in order to predict the inter – yarn capillary mechanism occurring in the vertical wicking flow direction of the fabric structure . Thus, the velocity of capillary rise (dhy/dt) of the inter – yarn region in the vertical direction was determined in Equation [13].

$$\frac{dh_y}{dt} = \frac{\varepsilon_F}{8k\eta} \cdot \frac{R_h^2}{h} \left(\frac{2\gamma\cos\theta}{R_h} - \rho g h\right) \quad \dots\dots (13)$$

Equation (13) can be rewritten as follows:

$$\frac{dh_y}{dt} = \frac{1}{k}\left(\frac{\varepsilon_F R_h \gamma\cos\theta}{4\eta.h} - \frac{\varepsilon_F R_h^2 \rho g}{8\eta}\right) \quad \dots\dots (14)$$

Where ε_F = Fabric overall porosity

R_h = hydraulic pore radius between yarns, metre.

Cosθ = cosine contact angle between the fluid surface and the yarn = 0.97, i.e. ($\theta = 14.07$).

$\frac{1}{k}$ = Ko = 0.00132 (experimental coefficient).

K= shape constant that depends on the shape of the pore along the channel (tortuosity) and orientation of the pore system.

g = acceleration of gravity = 9.8 m/ sec^2

The variables in Equations (12, 14) for distilled water at 20 °C are:

γ = the surface tension energy $=7.28\times10^{-2}$ kg/ sec^2

ρ = the fluid density = 998.29 kg / m^3

η = dynamic viscosity = 0.001003 kg / m.sec

2.3-Calculation of Velocity of Capillary Rise in Fabric:

The inter – fibre and inter – yarn capillary regions did not follow a straight path. In addition, the fluid transferred to the inter – fibre pore regions of the perpendicular yarn at the contact condition of the fluid and flow slowed down at those regions. In this study, this state, which made the capillary flow mechanism more complex, was neglected and the velocity of the vertical capillary rise (dh/dt) was solved for inter – fibre and inter – yarn regions, separately. In these fabrics, the inter – fibre and inter – yarn pore regions influenced the flow mechanism of one another because they were in contact with each other. In order to model the change of flow velocity as a result of this interaction , the integrated capillary flow velocity of the fabric was obtained by averaging the capillary rise height of the inter – fibre (dhf/ dt) (Equation (12)) and inter – yarn (dhy/dt) (Equation (14))regions as a function of time as follows[21] :

$$\frac{dh_F}{dt} = \frac{1}{2}\left(\frac{dh_f}{dt} + \frac{dh_y}{dt}\right) \quad \dots\dots\dots\dots\dots (15)$$

Equations (12, 14) were solved by using MATLAB software and the capillary rise height (h) according to time (t) was obtained for inter – fibre and inter – yarn regions separately. In this study, vertical wicking tests were realized within a time period of 600 seconds, thus, the velocity of capillary rise (dh/dt) was defined for this time period.

To determine the deviation from capillary flow, the exact treatment for height as a function of time must be made.

In Equations (12, 14) let

$$\alpha = \left(\frac{\varepsilon R_h \gamma\cos\theta}{4\eta} \quad , \quad \beta = \frac{\varepsilon R_h^2 \rho g}{8\eta}\right) \quad \dots (16)$$

Using these definitions, Equations (12, 14) become

$$\frac{dh}{dt} = \frac{1}{k}(\alpha / h - \beta) = ko(\alpha / h - \beta) \quad .. (17)$$

Integration of this relation combined with the condition that (h) equals zero at time zero gives:

$$Ko\beta t = h_m \,\ell n\left|\frac{h_m}{h_m - h}\right| - h \quad .... (18)$$

In this equation (h_m) is the maximum height reached by the fluid in infinite time and is equal to (α / β) as shown by Washburn [8]. From a knowledge of (h), (h_m), (β) and (ko) the time (t) can be calculated.

Washburn equation is the only available equation till the date which directly provides the vertical wicking height through a capillary channel for specified time (t) and not for the complete wicking profile.

Now if the hydraulic pore radius (R_h) and the porosity (ε) of both inter – fibre and inter – yarn How flow paths for both yarns and fabrics respectively are determined , along with (Ko) , the relationship between vertical wicking height (h) and time (t) can be estimated using Equation (18) as listed in Tables (5,6,8,9,) for both warp and weft directions .

From Equations (15, 18), the curves in Figures (6, 7) for different fabric samples were calculated and plotted. All experimental data taken fitted this general form of curves.

2.3.1- Fluid flow within yarns (Inter – fibre pore):

A number of useful calculations can be made on the basis of yarn and terry construction, such as porosity, hydraulic pore diameter within the pile yarns, and so on.

2.3.1.1–Suggested method for calculating yarn porosity (ε_y):

Taking into consideration the construction of the terry woven fabric, the yarn porosity can be determined by a simple calculation. The porosity indicates how much water a terry fabric can hold when completely wet.

The yarn porosity (ε_y) can be calculated by the following equation [23].

$$\varepsilon_y = 1 - \phi y \quad .... (19)$$

Where ϕ y = packing density of yarn i.e. the ratio of the total fibres area to the yarn area.

The circular cross–sectional theoretical diameter of the fibre (df) was calculated using Equation (20).

Fibre tex = $\frac{\pi}{4} d_f^2 \times 10^5 \times \rho_f$ .... (20)

Where Fibre tex = $\dfrac{micronaire\ reading\ for\ cotton\ (5.4)}{25.4}$

$df = fibre\ diameter, cm$

$\rho_f = cotton\ fibre\ density (1.54), g/cm^3$

The equivalent diameter of the fibres can also be obtained using Equation (21) [7]:

$$d_{fibre} = 0.01189\sqrt{\frac{Den\ fiber}{\rho_f}} \quad , \ mm \quad .. (21)$$

$$d_{fibre} = 0.01189\sqrt{\frac{9 \times 0.212598}{1.54}} = 0.013253261 \ \ mm$$

By assuming that the cross – sections of the yarns are circular and the volume percentage of fibres is 60% Thus yarn diameter can be obtained by the following Equation [7]:

$$dy = 0.01189\sqrt{\frac{Den}{\rho_f \times 0.6}} \quad , \ mm \quad ... (22)$$

Where dy = yarn diameter in mm,
Den = yarn denier and
ρ_f = fibre density, g/cm^3

The average number of fibres (n_f) in the cross- section of the yarn was found theoretically by using Equation (23)

$$n_f = \frac{N_{mf}}{N_{my}} = \frac{yarn\ \ tex}{fibre\ \ tex} = \frac{yarn\ \ tex}{\frac{\pi}{4} d_f^2 \times 10^5 \times \rho_f} \quad ... (23)$$

Also, the packing density of the yarn (ϕ y) can be calculated based on the theoretical fibres number (n_f), the area of the one fibre (A_f) and the yarn area (A_y) as follows:

$$\phi_y = \frac{n_f \times A_f}{A_y} = \frac{yarn\,tex}{10^5 \times \rho_f \times \pi d_y^2 / 4} \quad ... (24)$$

Where dy = yarn diameter, cm

Thus, by substituting in Equation (19) from Equation (24) yarn porosity can be calculated easily as follows:

$$\varepsilon_y = 1 - \frac{4 \times yarn\,tex}{10^5 \pi \rho_f \pi d_y^2} \quad .... (25)$$

2.3.1.2-Suggested method for calculating hydraulic pore diameter (Dh):

Considering circular cross – sectional filaments, if the diameter of a single fibre in a yarn of circular geometric shape is (d_f), then we can derive the hydraulic pore radius (R_h) for the flow within the yarn.

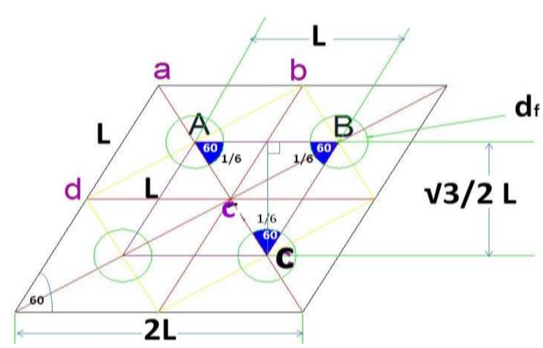


Figure 2. Ideal unit cell within the yarn

In Figure (2), we now divide the cross – section of the yarn into (nf) rhombuses, each with side (L). Assuming the fibres are evenly distributed inside the yarns, each rhombus contains one fibre. (L) Can be obtained by the following Equations:

Area of triangle (ABC)= $= \frac{1}{2} \times L \times \frac{\sqrt{3}}{2} L = \frac{\sqrt{3}}{4} L^2$

Area of the yarn cross- section =

$$\frac{\pi}{4} d_y^2 = (area\ abcd) \times n_f$$

$$= (2 \times area\ ABC) \times n_f$$

$$= (2 \times \frac{1}{2} \times \frac{\sqrt{3}}{2} L^2) \times n_f$$

$$\frac{\pi}{4} d_y^2 = \frac{\sqrt{3}}{2} L^2 . n_f$$

$$L^2 = \frac{\pi d_y^2}{2\sqrt{3} n_f}$$

$$L = dy \sqrt{\frac{\pi}{2\sqrt{3} n_f}} = dy \sqrt{\frac{\pi}{3.4641 n_f}}$$

$$L = 0.9523\, dy \times \frac{1}{\sqrt{n_f}} \quad , \ mm \quad \ldots (26)$$

Hydraulic pore diameter $(Dh) = \frac{4 \times pore\ area}{pore\ perimeter}$

In ΔABC , $pore\ \ area = \frac{1}{2} L \times \frac{\sqrt{3}}{2} L - \frac{3}{6} \times \frac{\pi}{4} d_f^2$ .... (27)

Pore perimeter $= 3(L - d_f) + \frac{\pi df}{2}$ … (28)

$$D_h = \frac{4(\frac{\sqrt{3}}{4} L^2 - \frac{\pi}{8} d_f^2)}{3(L - d_f) + \frac{\pi d_f}{2}}$$

Hydraulic pore radius (R_h) $= \frac{2(\frac{\sqrt{3}}{4} L^2 - \frac{\pi}{8} d_f^2)}{3(L - d_f) + \frac{\pi d_f}{2}}, mm$ … (29)

Values of yarn porosity (εy) and hydraulic pore radius (R_h) of inter – fibre flow path for both warp and weft yarns are listed in Table (4). Also values of wicking height (h) within warp and weft yarns at different times are listed in Tables (5, 6).

2.3.2. - Fluid flow between yarns (Inter –yarn pore):

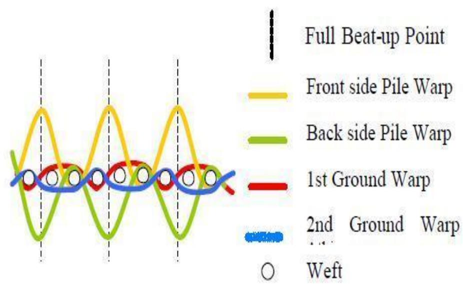
2.3.2.1-Suggested method for calculating fabric porosity (ε_F):

The overall porosity of a terry woven fabric (ε_F) can be theoretically calculated on the basis of packing factor (ϕ) as follows [22]:

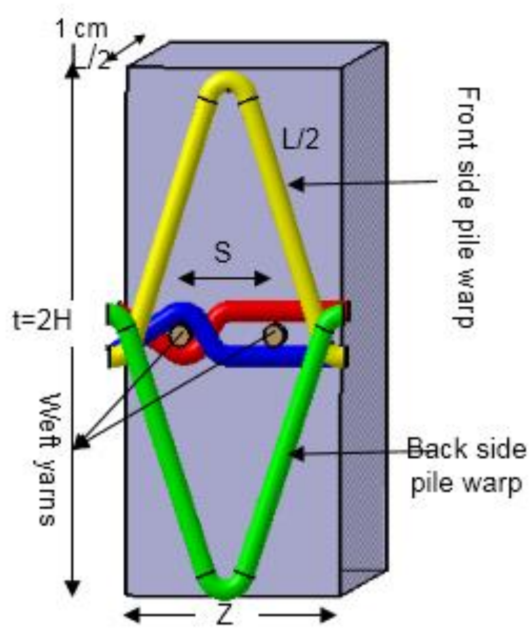
$$\varepsilon_F = 1 - \phi \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

The fabric packing factor expresses the ratio of fibre volume (V_f) with regard to the fabric volume (V_F) as follows:

$$\phi = \frac{V_f}{V_F} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (31)$$



(a)The cross – section of a towel through the warp [25]



(b) Cuboid sector of fabric sample in the terry fabric in warp direction

Figure 3. Geometrical model of repeat of terry woven fabric.

By considering the geometry of terry woven fabric shown in Figure (3), the volume of the cuboid (Vc) of the fabric sample can be calculated by using the following Equation (32):

Vc =Length of fabric x width x thickness, cm^3
= 1cm x (S_n /n_2) cm × t cm
= (S_n/ n_2) * t , cm^3 ………….. (32)

Where, Fabric thickness (t) is measured under a pressure of $10 g_f /cm^2$, (n_2) is picks / cm and (S_n) is number of spaces (weft spacing) displaced from the beginning of pile loop of warp yarn to the next one.

Thus, the length of loop of pile yarn (Lp) through the width (Z) can be calculated as follows:

$$Lp = 2\sqrt{H^2 + \left(\frac{Z}{2}\right)^2} = 2\sqrt{\left(\frac{t}{2}\right)^2 + \left(\frac{Z}{2}\right)^2} \quad , cm$$

$$= 2\sqrt{\frac{t^2}{4} + \left(\frac{S_n}{2n_2}\right)^2} = 2\sqrt{\frac{t^2}{4} + \frac{Sn^2}{4n_2^2}} \quad ,cm \text{ ….. (33)}$$

The width of the cuboid, Z, can be given as follows:

$Z = S_n$x weft spacing (P_2) $= Sn/n_2$, cm… (34)

As a result, total volumes of yarns (Pile (V_p), ground (Vg) and weft (V_w) in the cuboid can be calculated as follows:

$V_{total} = Vp + Vg + Vw$, cm^3 … (35)

Where

(Pile yarn volume) Vp=

$$Vp = \frac{2Lp(metre)}{Nmp \times \rho f} \times \frac{ends/cm}{2} \quad ,cm^3 \text{ … (36)}$$

Where N_{mp} is the metric count of pile warp yarn

(Ground yarn volume)Vg =

$$\frac{\text{No.of ground warp yarns per cm} \times 1cm \times Zcm \times \left(1 + \frac{C_1}{100}\right)}{Nmg \times \rho_{yg} \times 100} \quad ,cm^3 \text{ (37)}$$

Where N_{mg} is the metric count of ground warp yarn

ρ_{yg} is the density of ground warp yarn, g/ cm^3

C_1 is the crimp of ground warp yarn, %

(wett yarn volume) V_w =

$$\frac{picks/cm \times Z \times 1cm \times \left(1 + \frac{C_2}{100}\right)}{Nmf \times 100 \times \rho_{yf}} \quad ,cm^3 \text{ ….. (38)}$$

Where N_{mf} is the metric count of weft (filling) yarns

ρ_{yf} is the density of weft (filling) yarns, g/ cm^3

C_2 is the crimp of weft (Filling) yarns, %

Then from Equations (36 -38), total overall porosity can be calculated as follows:

Overall Porosity

$$(\varepsilon_F) = 1 - \frac{(Vtotal)}{volume\ of\ cuboid(V_c)}$$

Hence, Overall Porosity

$$(\varepsilon_F) = 1 - \frac{V_P + V_g + V_\omega}{(S_n / n_2 \times t \times 1cm)} \text{ ……. (39)}$$

2.3.2.2–Suggested method for calculating hydraulic pore diameter (D_h):

The capillary rise between yarns can be regarded as an equivalent to a flow between two distant parallel plates of capillary distance (p_1-d_1) or (p_2-d_2).

Vaccume or void volume in the cuboid =

= total Volume of cuboid – yarn volume

$$= Z \times t \times 1cm - (V_p + V_g + V_w)$$

$$= \frac{Sn}{n_2} \times t \times 1cm - (V_p + V_g + V_w)$$

This volume is equivalent to parallel piped volume having Length (Z) , width (1 cm) and thickness (t) , parallel piped volume in warp direction=

$$= Z \times t \times (p_1 - d_1) \times (n_1/cm)$$

* Hydraulic pore diameter (D_h) = (P_1- d_1)

$$= \frac{\frac{Sn}{n_2} \times t \times 1cm - (V_p + V_g + V_w)}{\frac{Sn}{n_2} \times t \times (n_1/cm)} \quad ,cm \text{ … (40)}$$

Parallel piped volume in weft direction=

$$= (p_2 - d_2) \times t \times 1cm \times (\text{No. of picks / Z})$$

* Hydraulic pore diameter (Dh) between weft yarns

= (P_2-d_2) =

$$= \frac{\frac{S_n}{n_2} \times t \times 1cm - (V_p + V_g + V_\omega)}{t \times 1cm \times 3} \quad ,cm \text{ ... (41)}$$

Values of fabric porosity (ε_F) and hydraulic pore radius (R_h) of inter – yarn flow path for both warp and weft directions are listed in Table (7).

Also values of wicking height (h) in both warp and weft direction at different times (t) are listed in Tables (8, 9).

2.4-Prediction of Overall Vertical Wicking Height Flow in Fabric:

If the constructional parameters of the yarn and the fabric are Known, the porosity of the inter – fibre and inter – yarn porous media can be calculated using Equations 25 and 39, respectively. Also, the hydraulic pore radii of the inter – fibre and inter – yarn porous media can be calculated using Equations 29 and (40, 41) respectively. From these , the wicking height (h) of water passing through each of the segments as a function of time (t) can be calculated using Equation (18), if the appropriate shape constant (K) is known. Therefore, the reciprocal of shape constants for yarns & fabrics are 0.106319 and 0.00132 respectively. The relationship between vertical wicking height (h) and time (t) are listed in Tables (10, 11) and shown in Figures (5 6).

III. EXPERIMENTAL VERIFICATION

In this study, in order to compare the values of vertical wicking height calculated from theoretical modeling and that using experimental vertical wicking height, six woven terry samples with different pile heights, weft densities and weft linear densities were carried out.

The pile of the terry fabrics used in this research was constructed on both sides of the fabric as can be seen in Figure (3-a). Generally, this structure consists of three components, namely, pile warp yarn, ground warp yarn and weft yarn which form the terry woven fabric. The specifications of each fabric are summarized in Table (1). The pile and ground warp density was 24 ends/cm and the values of weft density range from 10 to 20 picks/cm. The pile and ground warps were plied cotton yarns of 24/2 Ne, whereas the values of weft counts range from 12/1 to 20/1 Ne and were made from cotton yarns. Pile loops were embedded using basic 3-pick terry toweling and manufactured with different pile heights. Warps are ordered throughout the fabric width 2:2 piles and ground warps. In 2:2 warp order each two ground warp ends are followed by two pile warp ends.

Sample No.	Fabric Weight (g/m2)	Fabric Thickness At/og/cm2 (cm)	Warp/weft Linear Density (Tex1/Tex2)	Warp/weft Setting (n1/n2) (cm-1)	Warp/weft Crimp percent C1/C2	Pile ratio	Pile Height (mm)	No. of Piles/cm2 For each face
1	337	0.12300	49.21/49.20	24/10	5.74/6.53	3.545	5.318	20
2	366	0.07629	49.21/49.20	24/20	8.03/7.92	2.645	1.948	40
3	266	0.11371	49.21/29.53	24/10	4.72/8.49	2.604	3.906	20
4	399	0.11897	49.21/49.20	24/15	5.14/5.48	4.253	4.253	30
5	299	0.12394	49.21/36.91	24/10	5.93/5.39	3.113	4.670	20
6	361	0.12434	49.21/36.91	24/15	5.88/7.71	3.545	3.545	30

The cotton terry fabrics used in the experimental work were woven by Eng. Mahmoud Mohamed El-Fowaty, Chairman of the board of directors of (Fowaty Tex) Company in Aga, Egypt. In Figure (4), the weave notation of 3 weft pile is given in 2:2 warp orders.

For the experimental investigation of vertical wicking height, different types of terry woven fabrics with constant sett of warp and varying sett of weft and varying yarn fineness and varying warp pile height were produced on PROMATECH, Vamatex Leonardo Dyna Terry model Double Flexible Rapier, 230 cm Terry Weaving m/c. with a jacquard shedding mechanism using the Staubley-Cx870.

Produced fabrics are intended to be used for face towel, where water absorbency is a necessary product feature. The incorporation of these hydrophobic samples aims to verify the Variability of the test. These woven fabric samples were conditioned in the test environment (20±2ºC and 65 ± 2% RH) for at least 24 hours before testing.

Fig 4. The weave repeat of the terry fabric (Basic 3-pick terry weave in 2:2 warp order) [25]

Vertical strip wicking tests were performed on the apparatus shown in Figure (5) . For each fabric type, five specimens of 200 mm x25 mm cut along the warpwise and weftwise directions were prepared. The specimen was suspended vertically with its bottom end dipped in a reservoir of coloured distilled water at 21ºC. In order to ensure that the bottom ends of the specimens could be immersed vertically at a depth of 30 mm into the water, the bottom end of each specimen was clamped with 2.25g clip, as shown in Figure (5).

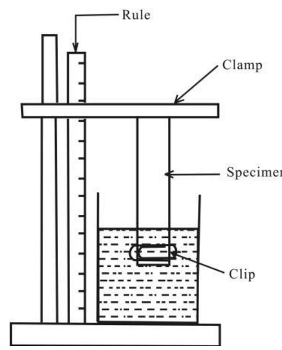


Figure 5.Vertical wicking apparatus [26]

Vertical capillary rise tests were carried out in both warp and weft directions in order to determine the flow mechanism of the fabric in the vertical direction according to the DIN 53924 standard [27]. A diluted blue ink solution (o.o5% solution of blue ink) was used for tracking the movement of the water. The vertical wicking height values of the liquid were measured onto a ruler placed parallel to the fabric specimen at reqular time intervals in 100 sec.

The wicking heights (h), measured for 600 seconds (10 minutes), were recorded along the warpwise and weftwise directions for a direct evaluation of the wickability of the test fabric. Vertical wicking test results in warp and weft directions were given in Tables (2, 3).

4. Results and Discussion

In this study, the vertical capillary wicking behavior of terry woven fabric was modeled in order to predict the fluid flow rate or flow velocity. The theoretical capillary rise value carried out in inter-fibre and inter-yarn regions depending on time was calculated by a program written in MATLAB software. Then the obtained results were compared with the experimental results.

The experimentally vertical wicking rise test results of terry fabrics having different pile heights, weft linear densities and weft settings are given in Tables 2 and 3 respectively.

TABLE (2)
VERTICAL WICKING TEST RESULTS IN WARP DIRECTION.

Sample No.	Vertical wicking height, h (mm)					
	100 sec	200 sec	300 sec	400 sec	500 sec	600 sec
1	23	30.0	38.0	42.0	45.0	50.0
2	25	31.0	33.0	40.0	40.0	43.0
3	23	29.4	34.8	40.8	48.6	50.6
4	25	30.0	33.0	39.0	41.0	45.0
5	27	36.0	43.0	50.0	56.0	60.0
6	25	31.0	36.0	45.0	45.0	46.0

TABLE (3)
VERTICAL WICKING TEST RESULTS IN WEFT DIRECTION.

Sample No.	Vertical wicking height, h (mm)					
	100 sec	200 sec	300 sec	400 sec	500 sec	600 sec
1	23.0	30.0	35.0	38.0	40.0	45.0
2	15.0	20.0	26.0	30.0	33.0	37.0
3	28.0	30.0	33.0	39.0	41.0	45.0
4	24.4	31.4	35.4	37.8	42.4	44.8
5	17.0	28.0	30.0	37.0	41.0	43.0
6	23.0	28.0	33.0	35.0	37.0	40.0

4.1- The Predicted Vertical Wicking Height Results of Yarns:

Vertical wicking height (h), which was related with pore properties, was obtained by calculating flow equations for inter – fibre and inter- yarn regions, separately. Hydraulic pore diameter within yarns was one of the most important pore parameters, which was effective at calculating vertical wicking height of the flow through the yarns. However, by using yarn porosity in the calculation of the capillary rise of inter – fibre regions, the variation in the capillary structure was taken into consideration. In addition, warp and weft crimp ratios determined experimentally were used in order to predict the flow of the inter – fibre region. In the beginning of the study, fibre & yarn diameters, number of fibres in yarn cross – section, yarn porosity and hydraulic pore radius were calculated by using the suggested theoretical models and the vertical capillary rise test results of the fluid flow through warp and weft yarns were calculated according to calculated parameters in order to get information about the pore size distribution theoretically.

Inter – fibre pore size and porosity values obtained from mathematical models for each yarn type are given in Table (4).

TABLE (4)
INTER – FIBRE PORE PROPERTIES, YARN CRIMP, YARN POROSITY AND HYDRAULIC PORE RADIUS OF INTER-FIBRE REGIONS WITHIN YARNS.

No.	Yarn diameter, mm		No. of fibres in Yarn cross-section		Yarn crimp, %		Yarn porosity		Hydraulic pore radius, μ m	
	Warp	weft	Warp	weft	Warp	weft	Warp	weft	warp	Weft
	d1	d2	nf1	nf2	C1	C2	$\varepsilon 1$	$\varepsilon 2$	Rh1	Rh2
1	0.2603	0.2603	231.46	231.42	5.74	6.53	0.3995	0.39965	3.0715	3.0722
2	0.2603	0.2603	231.46	231.42	8.03	7.92	0.3995	0.39965	3.0715	3.0722
3	0.2603	0.2016	231.46	138.88	4.72	8.49	0.3995	0.39937	3.0715	3.0697
4	0.2603	0.2603	231.46	231.42	5.14	5.48	0.3995	0.39965	3.0715	3.0722
5	0.2603	0.2254	231.46	173.59	5.93	5.39	0.3995	0.39943	3.0715	3.0702
6	0.2603	0.2254	231.46	173.59	5.88	5.71	0.3995	0.39943	3.0715	3.0702

The theoretically calculated vertical wicking height results of the fluid flow within both warp and weft yarns are given in Tables (5, 6).

TABLE (5)
THEORETICAL CALCULATED VERTICAL WICKING HEIGHT RESULTS AS A FUNCTION OF TIME WITHIN WARP YARNS

h,mm	Time, sec					
	Sample (1)	Sample (2)	Sample (3)	Sample (4)	Sample (5)	Sample(6)
5	5.5139	5.3968	5.5680	5.5449	5.5040	5.5066
10	22.0715	21.6030	22.2868	22.1976	22.0318	22.0423
15	49.6966	48.6409	50.1818	49.9809	49.6073	49.6309
20	88.4133	86.5339	89.2770	88.9194	88.2543	88.2960
25	138.2454	135.3046	139.5968	139.0372	137.9965	138.0620
30	199.2171	194.9763	201.1660	200.3589	198.8583	198.9526
35	271.3525	265.5719	274.0090	272.9089	270.8633	270.9919
40	354.6759	347.1149	358.1507	356.7117	354.0361	354.2042
45	449.2115	439.6285	453.6157	451.7918	448.4006	448.6135
50	554.9838	543.1359	560.4290	558.1740	553.9811	554.2446
55	672.0172	657.6608	678.6156	675.8830	670.8020	671.1216

TABLE (6)
THEORETICAL CALCULATED VERTICAL WICKING HEIGHT RESULTS AS A FUNCTION OF TIME WITHIN WEFT YARNS

h,mm	Time, sec					
	Sample (1)	**Sample (2)**	**Sample (3)**	**Sample (4)**	**Sample (5)**	**Sample(6)**
5	5.4696	5.3992	5.3789	5.5242	5.5355	5.5187
10	21.8945	21.6121	21.5307	22.1128	22.1581	22.0911
15	49.2980	48.6618	48.4782	49.7899	49.8916	49.7408
20	87.7037	86.5709	86.2439	88.5793	88.7604	88.4924
25	137.1352	135.3626	134.8507	138.5052	138.7884	138.3681
30	197.6161	195.0601	194.3216	199.5919	199.9999	199.3939
35	269.1704	265.6864	264.6793	271.8635	272.4194	271.5933
40	351.8220	347.2650	345.9471	355.3445	356.0712	354.9906
45	445.5947	439.8188	438.1478	450.0592	450.9796	449.6100
50	550.5123	543.3715	541.3049	556.0323	557.1694	555.4762
55	666.5994	657.9467	655.4413	673.2882	674.6650	672.6134

4.2. The Predicted Vertical Wicking Height Results of Fabrics between Yarns:

Not only the inter – fibre pore properties but also the inter – yarn pore properties played a big role in the vertical wicking rise flow mechanism. The inter – fibre porosity (εy) and inter – yarn porosity or fabric porosity (ε_F) were calculated theoretically.

In this study , the size of pores in inter –fibre and inter– yarn regions were calculated depending on fibre diameter , yarn diameter , yarn settings , yarn bulk density and fabric thickness in order to predict the vertical wicking height of the fluid flow through the fabric .

In Table (7), the following are summarized: fabric porosity and hy- draulic pore radius between both warp and weft yarns through the fabrics.

TABLE (7)
THE CALCULATED VALUES OF FABRIC POROSITY AND HYDRAULIC PORE RADIUS OF INTER – YARN PORE REGIONS IN THE WARP AND WEFT DIRECTIONS

Sample No.	Fabric porosity (ε_F)	Hydraulic pore radius, μm	
		warp	**weft**
		Rh 1	**Rh 2**
1	0.82538	171.9544	206.3450
2	0.63165	131.5930	78.9558
3	0.83277	173.4931	208.1918
4	0.78587	163.7224	130.9779
5	0.83832	174.6507	209.5808
6	0.80997	168.7439	134.9952

TABLE (8)
THEORETICAL CALCULATED VERTICAL WICKING HEIGHT RESULTS BETWEEN WARP YARNS

h,mm	Time, Sec					
	Sample (1)	**Sample (2)**	**Sample (3)**	**Sample (4)**	**Sample (5)**	**Sample (6)**
5	**3.9483**	**6.6765**	**3.8804**	**4.3467**	**3.8299**	**4.0968**
10	**16.4861**	**27.5809**	**16.2091**	**18.1094**	**16.0032**	**14.0913**
15	**38.8167**	**64.1778**	**38.1825**	**42.5336**	**37.7106**	**40.2028**
20	**72.4129**	**118.1704**	**71.2703**	**79.1296**	**70.4173**	**74.9198**
25	**119.1201**	**191.5552**	**117.3063**	**129.7534**	**115.9547**	**123.0858**
30	**181.2548**	**286.6932**	**178.6191**	**196.7207**	**176.6535**	**187.0215**
35	**261.8257**	**406.4050**	**258.2282**	**282.9724**	**255.5432**	**269.7056**
40	**364.8118**	**554.0978**	**360.1476**	**392.3229**	**356.6636**	**375.0495**
45	**495.6383**	**733.9408**	**489.8765**	**529.8433**	**485.5698**	**508.3328**
50	**661.9746**	**951.1104**	**655.2374**	**702.4831**	**650.2007**	**676.9267**
55	**875.1730**	**1212.1434**	**867.9017**	**920.1302**	**862.4737**	**891.5690**

The theoretically calculated vertical wicking height results of the fluid flow between both warp and weft yarns are given in Tables (8, 9).

The values of hydraulic pore radius calculated for warp and weft direction (Rh_1 & Rh_2) were given in Table (7) in order to determine the capillary rise at the inter – yarn region . The hydraulic pore, radius at the inter – yarn region which was used to predict the capillary rise height that occurred as a result of the vertical wicking test , was calculated from the unit pore cell cross- section of the cuboid of the fabric sample depending on yarn diameter , yarn spacing and fabric thickness . However, by using overall porosity in the calculation of the capillary rise of inter – yarn regions, the variation in the capillary structure was taken into consideration.

TABLE (9)
THEORETICAL CALCULATED VERTICAL WICKING HEIGHT RESULTS BETWEEN WEFT YARNS

h,mm	Time, Sec					
	Sample (1)	**Sample (2)**	**Sample (3)**	**Sample (4)**	**Sample (5)**	**Sample (6)**
5	3.3180	10.9887	3.2609	5.3906	3.0554	5.0794
10	13.9858	44.7926	13.7521	22.2651	12.8903	21.0019
15	33.2846	102.7512	32.7479	51.7995	30.7095	48.9165
20	62.8631	186.3259	61.8923	95.3601	58.0702	90.1648
25	104.8928	297.1147	103.3577	154.5473	97.0351	146.3273
30	162.3151	436.8698	160.0981	231.3065	150.4177	219.2833
35	239.2556	607.5185	236.2770	327.7295	222.1976	311.2912
40	341.7582	811.1871	338.0325	446.7029	318.2701	425.0981
45	479.1984	1050.2291	474.9650	591.4982	447.9149	564.0915
50	667.2941	1327.2591	663.3587	766.2386	627.0143	732.5159
55	935.5423	1645.1925	934.3201	976.1211	886.3294	935.7882

4.3- The Integrated Predicted Capillary Rise Flow in Fabrics (Overall Flow in Fabrics):

In the studied Fabric, the inter – fibre and inter – yarn pore regions influenced the flow mechanism of one another because they were in contact with each other. In order to calculate the change of capillary rise height as a a result of this interaction, the integrated predicted capillary rise heigt results of the fabrics in warp and weft directions were obtained were obtained from the mean values of the capillary rise height calculated for inter – fibre (dhf/ df) and the inter – yarn (dhy / dt) regions as a function of time were summarized in Tables (10, 11) and shown in Figures (6, 7) for both warp and weft directions.

During the movement of liquid along the capillary system, the flow velocity slowed down at both inter – fibre and inter – yarn regions because of the intersecting, which were done with the yarns in opposite directions. Moreover these two regions were in contact with each other and with the pore regions of opposite yarn continuously.

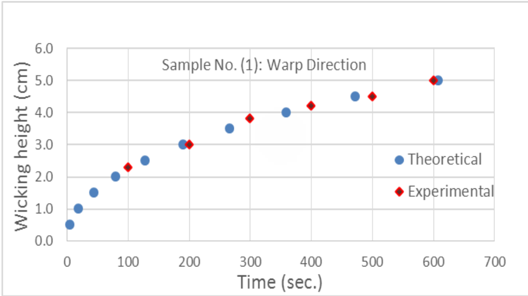
The predicted inter – yarn capillary rise results for both warp and weft directions obtained from average theoretical calculations from both yarns and fabrics are listed in Tables (10, 11). The inter– yarn capillary wicking height was calculated with overall porosity of the fabric structure, was lower compared with inter – fibre capillary wicking height. However, the flow that occurred in the fabric was a function of structural and geometrical parameters of the fabric. The inter-yarn flow rate calculated by considering the overall porosity of fabric was important because it reflected the variation of fabric depending on structural properties.

TABLE (10)
AVERAGE VERTICAL WICKING HEIGHT VERSUS TIME IN WARP DIRECTION

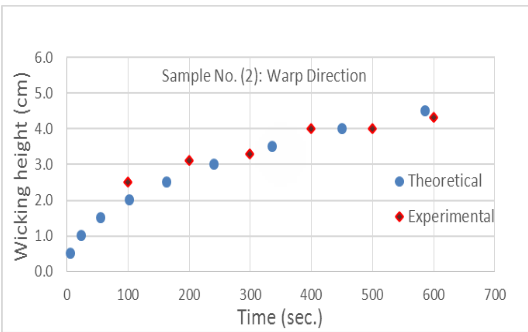
h.mm	Time, Sec					
	Sample (1)	**Sample (2)**	**Sample (3)**	**Sample (4)**	**Sample (5)**	**Sample (6)**
5	4.7311	6.0367	4.7242	4.9458	4.6670	4.8017
10	19.2788	24.5920	19.2480	20.1535	19.0175	19.5668
15	44.2567	56.4092	44.1822	46.2573	43.6590	44.9169
20	80.4146	102.3522	80.2737	84.0245	79.3358	81.6079
25	128.6828	163.4299	128.4516	134.3953	126.9756	130.5739
30	190.2360	240.8348	189.8926	198.5398	187.7559	192.9871
35	266.5891	335.9885	266.1186	277.9407	263.2033	270.3488
40	359.7439	450.6064	359.1492	374.5173	355.3499	364.6269
45	472.2440	586.7847	471.7461	490.8176	466.9852	478.4732
50	608.4792	747.1232	607.8332	630.3286	602.0909	615.5857
55	773.5951	934.9021	773.2587	798.0066	766.6379	781.3453

TABLE (11)
AVERAGE VERTICAL WICKING HEIGHT VERSUS TIME IN WEFT DIRECTION

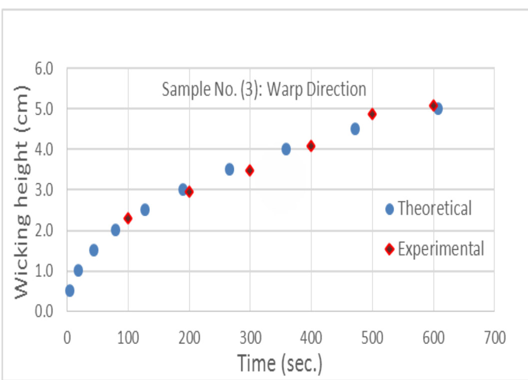
h,mm	Time, Sec					
	Sample (1)	**Sample (2)**	**Sample (3)**	**Sample (4)**	**Sample (5)**	**Sample (6)**
5	4.3938	8.1940	4.3199	5.4574	4.2955	5.2991
10	17.9402	33.2024	17.6414	22.1890	17.5242	21.5465
15	41.2913	75.7065	40.6131	50.7947	40.3006	49.3286
20	75.2834	136.4484	74.0681	91.9697	73.4153	89.3286
25	121.0140	216.2387	119.1042	146.5263	117.9118	142.3477
30	179.9656	315.9650	177.2099	215.4492	175.2088	209.3386
35	254.2130	436.6025	250.4782	299.7965	247.3085	291.4423
40	346.7901	579.2261	341.9898	401.0237	337.1707	390.0444
45	462.3966	745.0240	456.5564	520.7787	449.4473	506.8508
50	608.9092	935.3153	602.3318	661.1355	592.0919	643.9961
55	801.0709	1151.5696	794.8807	824.7047	780.4972	804.2008



Sample No. (1)

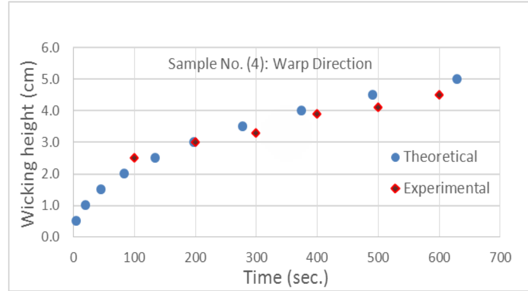


Sample No. (2)

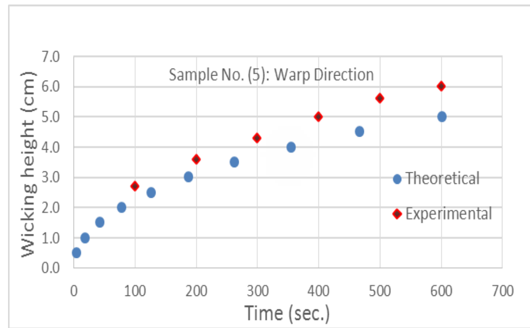


Sample No. (3)

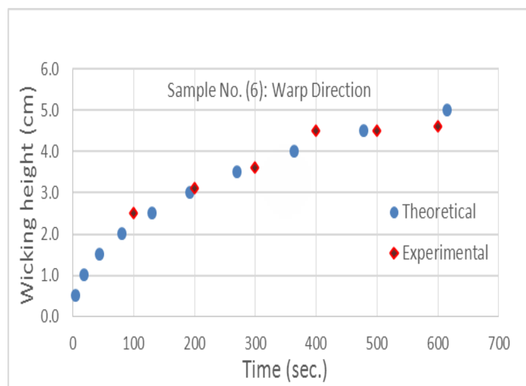
Fig 6. The comparison of theoretical and measured capillary rise results of Fabrics (Samples 1, 2 &3) in warp direction



Sample No. (4)

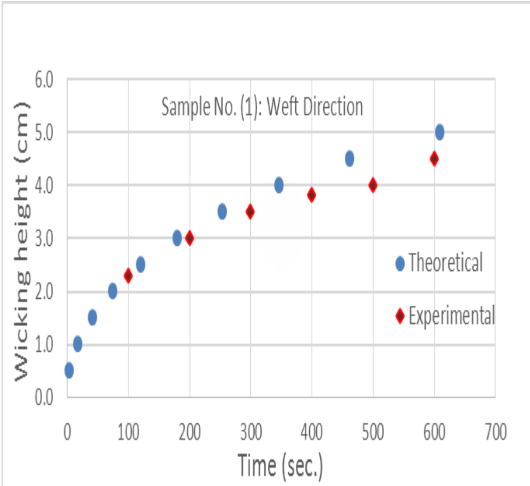


Sample No. (5)

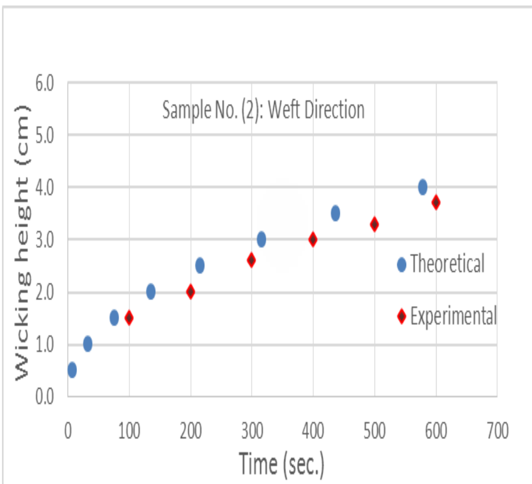


Sample No. (6)

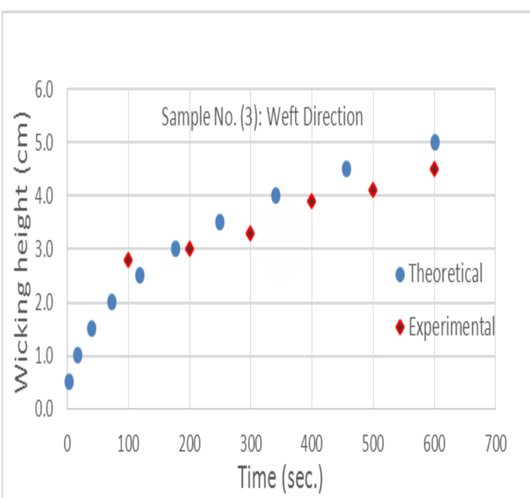
Fig 6. The comparison of theoretical and measured capillary rise results of fabrics (Samples 4, 5 & 6) in warp direction (Continued)



Sample No. (1)

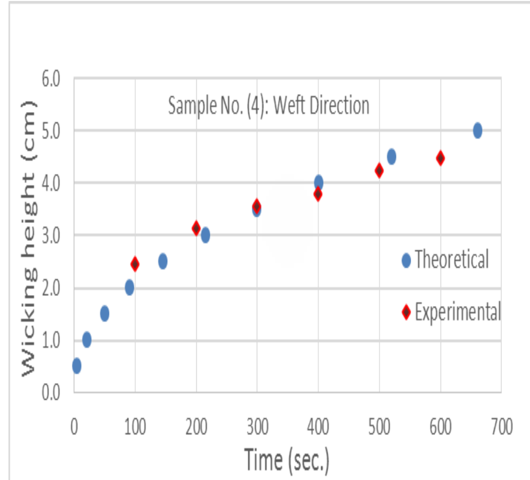


Sample No. (2)

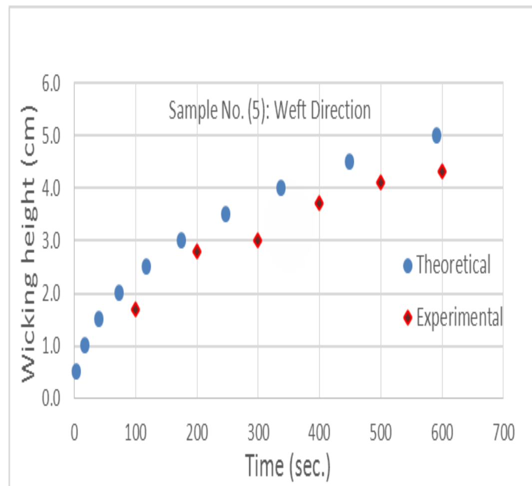


Sample No. (3)

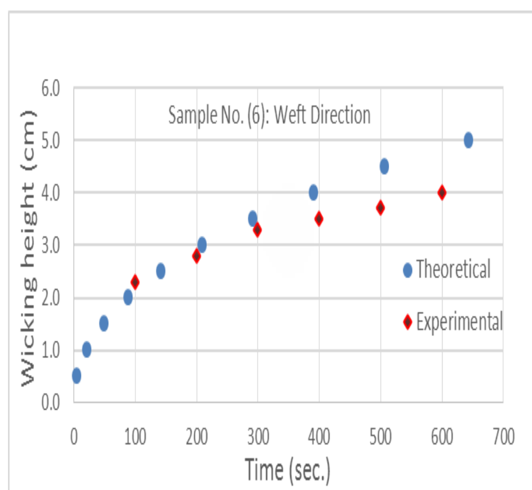
Fig 7 .The comparison of theoretical and measured capillary rise results of fabrics (Samples 1, 2&3) in weft direction



Sample No. (4)



Sample No. (5)



Sample No. (6)

Fig 7.The comparison of theoretical and measured capillary rise results of fabrics (Samples 4, 5&6) in weft direction (continued).

The relationship between the predicted vertical wicking height and the measured results as shown in Figure (8)

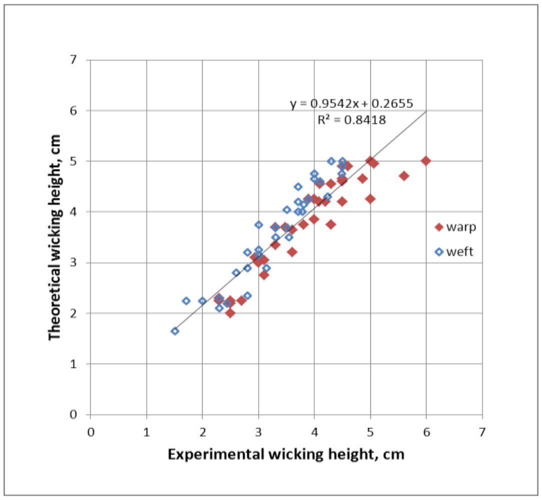


Fig 8. Correlation between the values obtained from vertical wicking test and the theoretical model

When the relationship between experimental and theoretical results was examinded in Figure (8), it was found to be significant. When the integrated capillary wicking behaviour calculated with the average of inter – fibre and inter – yarn capillary rise results was investigated , it was observed that the predicted and experimental results were very close to each other particularly in the warp direction . But in weft direction, inter – fibre regions play a significant role at the transfer of the liguid because the capillary diameter was larger, the inter – yarn regions behaved like a reservoir for the continuousness of the flow.

The difference between the predicted vertical wicking height values and experimental ones were approximately within the $\pm 8\%$ range for the mathematical model. The difference between the predicted and measured results could be explained by the variation of yarn diameter, yarn spacing and fabric thickness parameters along the length and thickness directions. Besides, the difference between the predicted and experimental results was evaluated as being within acceptable limits due to the fact that swelling could occur in the fabric structure when water is absorbed.

When the relationship between the predicted vertical wicking height results and measured one was investigated, the correlation coefficient (R) was found to be 0.9504 this situation presented the validity of the mathematical model with a good agreement. As a result, the predicted vertical wicking height results were very close to the measured results and the relationship between them was significant at the 95% confidence limit. Thus, the improvement applied model was useful in the prediction of vertical wicking height of fabrics having different structures as shown in Figure (8)

When investigating the effect of different weft setting on the vertical wicking height, it was observed that the increase of setting caused decrease in the vertical wicking height. In this study, the vertical wickng height test results, of terry fabrics have smaller pile height were found to be less than terry fabrics have larger pile height. This was due to the pore distribution in the weave type.

IV. Conclusion

In the present paper, the integrated predicted vertical capillary rise results were calculated for inter – fibre and inter – yarn regions separately, depending on capillary theory. The yarn crimp and yarn porosity were used as an input parameters in order to reflect the variation of capillary diameter (hydraulic pore diameter) due to the yarn geometry on the theoretical results. Also, the fabric porosity was taken into consideration while predicting the vertical capillary rise flow that occurred inter – yarn region. The vertical wicking height of these two regions was evaluated as the mean of these two regions, and the integrated capillary behavior of terry fabrics was predicted. Consequently, the integrated predicted capillary rise results showed higher correlation coefficient with the experimental results.

References

[1] Morton W.E. and Hearle M.A., Physical Properties of Textile Fibres , The Textile Institute , Manchester , 1993,pp.725.

[2] Needless H.L.,Textile Fibres , Dyes , Finishes and Processes , Noyes Publications , New Jersey , 1986 , pp.(34-40) .

[3] Taylor J.," Human Thermal Behavior ", Physics Group Conference, London, 1972, pp. (117-118).

[4] Slater K., Human Comfort, Springfield, IL: Charles C. Thomas Publisher, New York. 1985, pp. (4-5).

[5] Huang J.,Thermal Parameters For Assessing Thermal Properties of Clothing , Journal of Thermal Biology , 2006,31,p.(461-466).

[6] Minor F.W., Schwartz A.M., Wulkow F.A. and Buckles I.C., Textile Research Journal, 1959, Vol. 29, P.931.

[7] Zhou W. and Warner S.B., "Pore Size in Carpets", Textile Research Journal, June 1999, Vol. 69, No.6, P. (423 – 430).

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

[9] Winch A.R., Textile Research Journal, 1959, Vol .29, p.193.

[10] Burleigh E.G., Wakeham H.J.R., Honold E. et al., Pore –Size Distribution in Textiles, Textile Research Journal, 1949 Vol.19, P. (547-555).

[11] Van Den Brekel L.D.M and De Jong E.J., Hydrodynamincs in Packed Textile Bends, Textile Research Journal. 1989, Vol. 59, P. (433-440).

[12] Ar ndurai S.A. Potluri P. and Whyte I.L., Modeling the in- plane Permeability of Woven Geotextiles. Textile Research Journal, 1999, Vol. 69, P. (345-351).

[13] Das B., Das A., Kothari V.K. et al., Development of Mathematical Model to Predict Vertical Wicking Behaviour. Part I: Flow through yarn. Journal of Textile Institute, 2011, Vol .102, P. (957-970).

[14] Das B., Das A., Kothari V.K., et al, Mathematical model to Predict Vertical Wicking Behaviour. Part II: Flow through Woven Fabric, Journal of Textile Institute, 2011, Vol. 102, P. (971-981).

[15] Goglia M.J., LaVier H.W.S. and Brown C.D., Air Permeability of Parachute Cloths. Textile Research Journal, 1955, Vol. 25, p. (296-313).

[16] Kulichenco A.V., Theoretical Analysis, Calculation and Prediction of the Air Permeability of Textiles. Fibre Chem.2005, 37, P. (371-380).

[17] Lord E., Air Flow through Plugs of Textile Fibres. Part (1): General Flow Relations,Journal of Textile Institute , Vol. 46, No.3, T. (191-213) , (1955).

[18] Barrer R.M, Disc. Farady Soc., No.3, (1948).

[19] Brojeswari Das , Apurba Das , Vijay K. Kothari & Raul Fangueiro , Development of Mathematical Model To Predict Vertical Wicking Behaviour . Part (I): Flow through yarn, The Journal of The Textile Institute, Vol. 102 No.11, November 2011, P. (957- 970).

[20] Miller B .and Tyomkin I., Spontaneous Transplanar uptake of Liquids by Fabrics, Textile Research Journal, (1983), 53.P. (706-712).

[21] Befru Turan R. and Ayse Okur, "Prediction of the in – Plane and through – Plane Fluid Flow Behaviour of Woven Fabrics ", Textile Research Journal, September 2012, P. (1-18).

[22] Abou – Taleb H .A., EL-Fowaty H. and Sakr A., " Theoretical Prediction of Overall Porosity of Terry Woven Fabrics " , Journal of Textile Science & Engineering , Vol. 5, No.6, 2015,P.(1-7).
[23] (1982) Textile Materials: Textile Industry Publishing House, Beijing China.
[24] Hsieh Y.L. (1995), Liquid Transport in Fabric Structures. Textile Research Journal. Vol. 65, P. (299-307).
[25] Terry Weaving. Terry – Towel. Pdf.
[26] Sharabaty T., Biguent F., Dupuis D. and Viallier P., Indian Journal of Fibre & Textile Research, Vol. 33, December 2008 , PP. 419-425
[27] DIN 53924: 1997. Testing of Textiles, Velocity of Soaking Water of Textile Fabrics (method by determining the rising heigt), and German National Standard.