MECHANISM OF LIQUID WATER TRANSPORT IN FABRICS; A REVIEW

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Abstract: *Liquid water transportation through textiles plays an important role in comfort properties. Transport mechanism takes place from liquid's first behavior when get in touch with fabric to last behavior when evaporated to atmosphere. Wetting phenomena has been carried out by liquid and air interface with textile materials. Basically wetting is physical interaction of fabric with liquid, air and their surface energies results into wicking. Wicking is unconstrained liquid movement, driven by capillarities. Capillarity deals with the penetration ability of liquid into fine pores of fibre to travel along its walls. Wetting, wicking and capillarity are influential parameters to relate the fluid transport in textile fibrous media. This paper is focused on wetting, contact angle, wicking and capillarity, executes in measuring comfort and liquid moisture transport behavior of fabric.*

Keywords*: wetting, wicking, contact angle, liquid transportation, capillarity.*

1 INTRODUCTION

Liquid transport through fabrics is well desired phenomenon in many fields. It has been studied for both fundamental and applied points of view. It plays an important role not only in textile industry but also in the success of many other industrial processes, such as oil recovery, lubrication and fluid filtration. Also it judges the performance of clothes, in different activities, either they are comfortable or not. In fact, liquid transmission behavior of fabrics is one of the most important factors that affect thermo-physiological clothing comfort, especially in sweating conditions [1-4].

When perspiration takes place to cool the human body, the water exuded from the skin appears initially in its liquid form [5]. Evaporation of perspiration is major mean of body cooling, so fabric must intercept the build-up of perspiration on human body to keep it dry by enabling the body water to outer layer of clothing [6-8].

The build-up of sweat on the skin is considered as the main factor contributing to discomfort [9-11]. This problem can be solved with the use of appropriate fabrics that have excellent water absorption and transport properties. Thus extensive researches are focused on the study of the processes which are involved in liquid transportation through fabrics especially wetting and wicking theories [12-16].

Furthermore, when fibres come into contact with water, firstly the fibre surfaces must be wet and after that water can be transported through the inter-fibre pores to the amorphous regions. Thus the interaction between solid-air interfaces in the fibre is replaced by a solid-liquid interface and this phenomenon is called ‘wetting’ [12].

Wicking, wetting, absorbency or transportation is belonging to "Moisture Management" which means the ability of a textile fabric to transport moisture away from the skin to fabric’s outer surface in multi-dimensions. It is one of the key performance criteria in today’s apparel industry since it has a significant effect on the human perception of moisture sensations [17].

2 WETTING AND WICKING

Wetting and wicking are considered the most important parameters for absorption and transportation of liquid in textile clothing. Kissa [12] made a clear distinction between wetting and wicking. In fact, liquid transport takes place through these two sequential processes of wetting followed by wicking [18-19] as shown in Figure 1. 'Wettability' is defined as the first impression of fabric when get into touch with liquid however, 'wickability' is defined as the capacity to sustain capillary motion. It occurs when fibres with capillary spaces in between them are wetted by a liquid. The resultant capillary forces draw the liquid into the capillary spaces. The interaction between the forces of cohesion (within the liquid) and the forces of adhesion (between the fibers and the liquid) determines whether wetting takes place or not and also determines spreading and absorption of the liquid over the surface of the textile material [20].

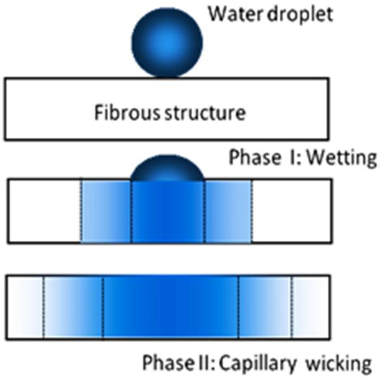

Figure 1 Liquid transport process through fabrics

2.1 Wetting

Wetting is a fundamental phenomenon that takes place at the first moments when fabrics come into touch with liquid [12]. Wetting is characterized by the displacement of fiber-vapor interface to fibre-liquid interface. Wettability studies usually involve the measurement of contact angles as the primary data, which indicates the degree of wetting when a solid and liquid interact [12].

The wettability of fibrous assembly [21-23] is affected by the chemical nature of fiber surface, the fiber geometry and the surface roughness [24-26].

2.1.1 Contact angle

The contact angle is related to general thermodynamic quantities and it presented as the angle formed between the tangent of the liquid-vapor interface and the solid-liquid interface at the line of intersection of the three interfaces (liquid-vapor, liquid-solid, solid-vapor) [27] as shown in Figure 2. According to Young-Dupre equation [28]:

$$\cos\theta = \frac{\gamma_{sv} - \gamma_{sl}}{\gamma_{lv}} \tag{1}$$

where *s*, *v* and *l* are the solid, vapor and liquid surfaces for γ (interfacial tension) with *θ* (equilibrium contact angle).

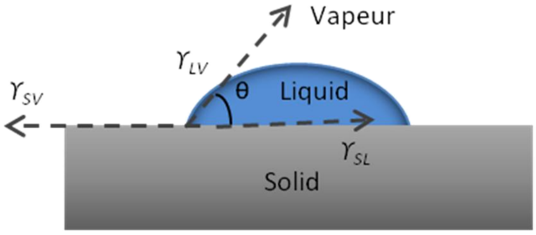

Figure 2 Contact angle on ideal surface, Young contact angle

When the contact angle between a liquid drop and the paper surface is lower than 90°, there is an attraction between the liquid and the solid phase, while when the contact angle exceeds 90°, there is repulsion between the liquid and the solid phase [19]. According to Figure 3, contact angles (<90°) correspond to high wettability, while contact angles (>90°) correspond to low wettability.

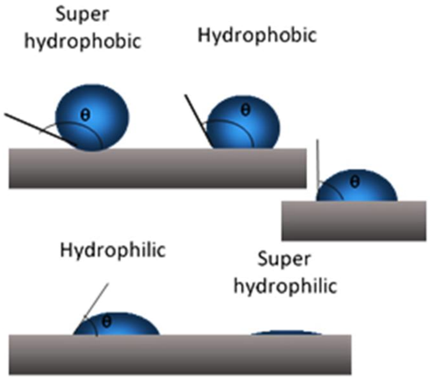

Figure 3 Illustration of different contact angles

The wetting of a fabric depends upon the nature of the wetting liquid and the surface energy of the textile substrate, which is largely dependent upon the structure, perimeter, surface purity and molecular orientation of the fibre, yarn, fabric, capillary forces, cover factor, area density and surface roughness [18]. Due to the heterogenic surface of textile materials, the previous equation of contact angle becomes invalid.

Wenzel model

Wenzel [29] defined the relationship between roughness and wetting. In fact, he state that in case of solid with rough surface (like textile materials), contact angle between the liquid and solid is defined as apparent contact angle (*θ**). Cosine apparent contact angle (*θ**) is function of the surface roughness of solid (r_g) and the contact angle obtained in the case of ideal surface of the same solid (Young contact angle (*θ*)). The following equation was proposed by Wenzel [29]:

$$\cos\theta^* = r_g . \cos\theta \tag{2}$$

Cassie- Baxter model

In case of chemically heterogeneous surfaces with two chemistries, Cassie [30] developed the above equation:

$$\cos\theta^* = \phi_1 \cos\theta_1 + \phi_2 \cos\theta_2 \tag{3}$$

where *Φ* is the area fraction characterized by the given chemistry and subscripts 1 and 2 indicate two different surface chemistries. If the second area is air instead of having different chemistries of surface, then equation (3) can be written as:

$$\cos\theta^* = \phi_1(\cos\theta + 1) - 1 \tag{4}$$

2.1.2 Wetting hysteresis

As known, textile materials are characterized by their rough surface and heterogeneity that caused changes in surface energy and affect adsorption of liquid. Hence the contact angle exhibits hysteresis which is defined as the gap between the receding contact angle and the advancing contact angle. The receding contact angle (θ_r) is obtained when the contact line recede of static liquid and the advancing contact angle (θ_a) is measured in advance of line contact. Although, the advancing contact angle is usually used with wicking. Hence, capillary flow depends on dynamic contact angle that is defined as the contact angle of moving liquid front and it can depend on the velocity of moving contact line and/or on time [31, 32]. The difference between θ_a and θ_r is called the hysteresis (H) [33]:

$$H = \theta_a - \theta_r \tag{5}$$

The principle of measurement of these two angles is as shown in Figure 4.

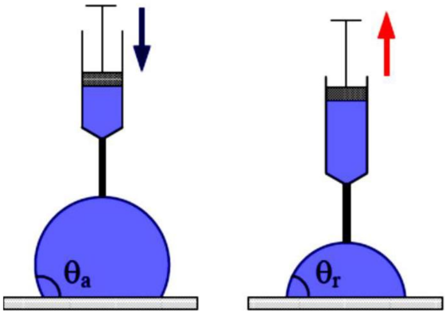

Figure 4 Advancing angle and receding angle

2.1.3 Measurement of contact angle

Wetting is a result of the work of adhesion between the solid and liquid (W_{SL}). In fact, it is the work necessary to separate these two phases (liquid and solid) from each other against the adhesive forces between them. Dupre reported the relations between the work of adhesion and tension surface as follows [34]:

$$W_{SL} = \gamma_{SV} + \gamma_{LV} - \gamma_{LS} \tag{6}$$

By combinning equation (1) and equation (6) and with the elimination of unknown surface tension, we get [34]:

$$W_{SL} = \gamma_{LV} + \gamma_{LV} \cos\theta \tag{7}$$

Above equation explain why the contact angle has been used as the main parameter to measure the wettability of a surface by a liquid [35]. The methods used for the measurement of contact angle can be classified into two categories, direct and indirect methods.

Direct Method

In this method, a liquid drop is placed on the surface and a microscope allows the drop image to be shown. Image analysis software is used to analyze the image. Contact angles are measured at tangent lines to the surface and they are calculated on both sides of drop [36].

Another direct method suggested by Barnell et al [37] and used by Hollies [14] where the solid is vertically immersed in horizontal liquid interface, in the form of rod. The solid-liquid-vapour contact angle is measured using a microscope in horizontal position focusing on the material with the contact line. The contact angle is the angle between the edge of the solid surface and the tangent line of liquid-solid interface as shown in Figure 5.

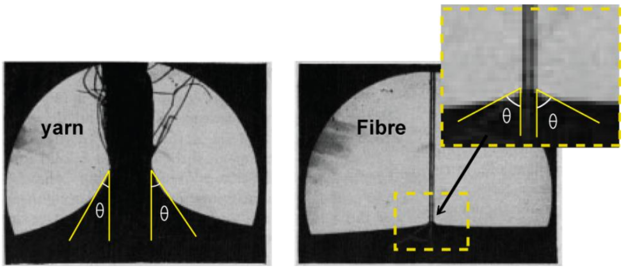

Figure 5 Measurement of contact angle on yarn and fibre using the vertical rod method [14]

Indirect Method

The most effective method for measuring liquid contact angle on fibers indirectly is the Wilhelmy wetting force technique [34]. In fact, when a solid is partially immersed in liquid, there is an attractive force exerted by liquid on solid (F_w). Wilhelmy reported that the source of this attractive force is the surface tension of liquid and express the following equation [16]:

$$F_W = p.\gamma_{LV} \cos\theta \tag{8}$$

where F_W is the measured force and p is the perimeter of the solid.

If the liquid-solid contact angle becomes zero (total wetting liquid), $\cos\theta$ is 1.0. Thus the perimeter (p) can be calculated with known liquid surface tension (γ_{LV}) as follow [16]:

$$p = \frac{F_W}{\gamma_{LV}} \tag{9}$$

The cosine contact angle and the contact angle can be derived if the liquid surface tension and liquid-solid interface dimension are known [16]

$$\cos\theta = \frac{F_W}{p.\gamma_{LV}} \tag{10}$$

2.2 Wicking

When a textile material is placed in contact with liquid, spontaneous uptake of liquid may occur, the term ‘spontaneous’ meaning that the movement of liquid takes place against a zero or negative liquid-head pressure gradient [38]. Regarding the direction of water flow, spontaneous uptake in the plane of a fabric is always called wicking. Wicking is an unconstrained transport of liquid in a porous substrate, driven by capillary forces which are caused by wetting [12]. Hence, wicking is a result of wetting.

Wicking is based on two important characteristics, which are capillary pressure and permeability [39]. With an increase in the saturation of pores with liquid, the capillary pressure decreases and it reaches zero for totally saturated material. However, the permeability of the media increases with the increase in saturation [40]. When saturation level is low, small pores of the media fill up first than larger pores. Hence, liquid flow would be faster in small pores and then it will be distributed, uniformly, to interconnected pores [41, 42].

Wicking through the inter-fibre and inter-yarn channels is affected by the way the fibres or yarns are arranged into a fabric [12]. The capillary radius and the number of capillaries formed affects wicking [43]. Moreover, fibrous assembly are known by their irregularities in fiber diameter or pore interfiber and intrafiber, which is represented by the tortuosity. The wicking process can be affected by the tortuosity of the pores. Hence, an increase in the tortuosity of pores produces a decrease in its wicking potential [42, 44]. Rossi et al. [45] pointed out that the moisture absorption capacities of the fibres (hygroscopicity) as well as its surface properties (hydrophilicity or hydrophobicity) are very important parameters determining the wicking effect. Figure 6 presented the moisture regain of some fibers at standard conditions.

Wicking is also affected by the properties of the liquid, decreasing for liquids with higher viscosity and/or surface tension. Further to these factors, the moisture content of the sample, the ambient temperature and humidity also affect the penetration process [49].

2.2.1 Wicking calculation

Wicking is a salient feature in moisture management which permits an idea about absorbency and dye intake along with the fabric comfort. Wicking got the attention of scholars from every field of study, generally engineers, especially textile engineering and technology.

Lukas-Washburn equation

Washburn and Lucas were two scientists who set the base of wicking and describe the capillary flow [50].

The law, which is commonly applied to describe the flow as a result of a pressure drop gradient along the tube, is the Hagen-Poiseuille law for laminar flow through pipes. The law describes the velocity of the liquid front as follows:

$$\frac{dL}{dt} = \frac{r^2}{8\mu} \cdot \frac{\Delta P}{L} \qquad (11)$$

where *dL/dt* is the liquid velocity, *ΔP* is the pressure drop, μ the liquid velocity, *r* pipe radius and *L* is the wetted length. When the pressure applied is the capillary pressure only, Lucas and Washburn derived the well-known equation for flow through horizontal pipes [51]:

$$L^2 = \frac{r_c \gamma_{LV} \cos\theta}{2\mu} \qquad (12)$$

where r_c is the capillary radius and t is the time taken for the liquid to travel the distance L.

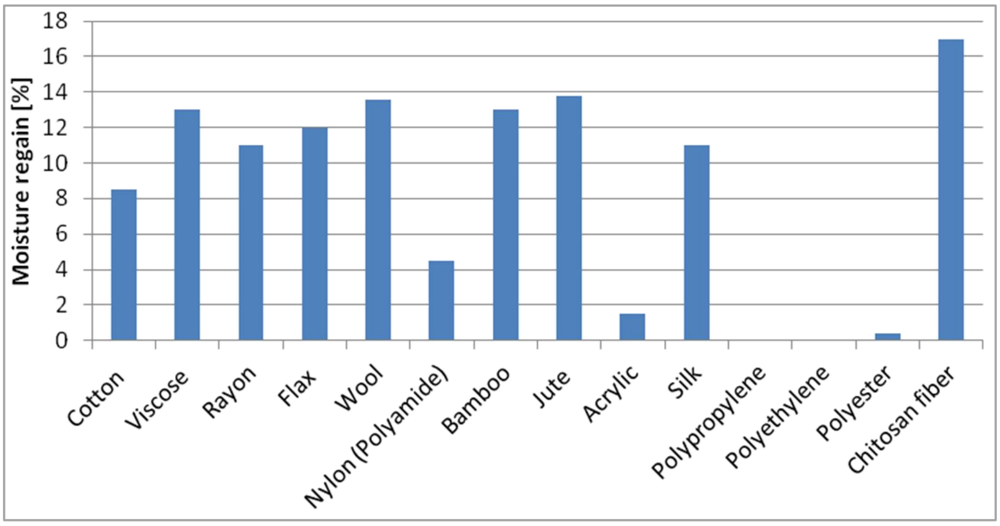

Figure 6 Moisture regain of different fibers at 20°C and RH 65% [46-48]

Darcy law

Darcy's law is one of the early theories that investigated in fluid flow through porous media. It describes laminar flow through porous media, and it is given by the equation below:

$$Q = -K\frac{\Delta P}{L_0} \tag{13}$$

where Q is the rate of flow, ΔP is the pressure drop across the material, L_0 is the length of the sample and K is a constant. This constant K depends on the characteristics of the fluid and the pore structure of the media. The constant K is often defined as:

$$K = \frac{k}{\eta} \tag{14}$$

where k is the permeability of the medium and η is the viscosity of the liquid.

2.2.2 Wicking measurement

Table 1 illustrated the various methods used for the measurements of absorption and wicking behavior of fabric, namely: longitudinal wicking strip test, transverse wicking plate test and vertical strip wicking test. Harnett and Mehta [41] summarized four popular laboratory test methods for measuring wicking. It represents the basis of future review articles where lists of practical test methods were discussed. In 2006, Patnaik et al [52] conducted a more comprehensive review on which they initially differentiated the methods into two aspects: wetting and wicking. Moreover they classified wicking processes that are with finite (limited) reservoir and infinite (unlimited) reservoir. Additionally, since Patnaik's review, many novel measurement methods have been developed, e.g. the Transplanar water transport Tester [53], Moisture Management Tester [54, 55], and some international standard test methods have been introduced, such as vertical-wicking test method [56] and horizontal-wicking test method [57].

3 CAPILLARITY

Capillarity can take place under various conditions and situations. To define these conditions [63] propose to distinguish between two phenomena related to the transport of liquid through a textile fabric: wettability and capillarity. According to Harnet and Mehta [41], capillarity is the ability to cause capillary flow, while wettability describes the initial behavior of a fabric, yarn, or fiber contacted with water. Although wettability and capillarity are well studied as two separate phenomena, they can be_described by a unique process: fluid flow caused by capillary pressure [40], that is, in the absence of external forces, the liquid through a porous medium is entrained by capillary forces resulting from wetting of a fabric. Capillary progression can be defined as a macroscopic flow of a liquid under the influence of its own interface forces [63]. Since capillary forces are caused by wetting, capillarity is a result of spontaneous wetting in a capillary system [12]. Therefore, these two phenomena are coupled and one of them cannot occur in the absence of the other. Physically, impregnation is the flow in a porous medium under the action of capillary forces. This type of flow depends on the properties of the liquid, the solid-liquid surface interactions and the geometrical configuration of the pores of a porous medium [13, 64-67].

Capillary action is responsible for the movement of liquid flow in fibrous material and mainly depends on the geometry of pore structure and capillary force. Before being transported, liquid wet the fibrous material which causes to determine its liquid's effect and fibre surface wetting characteristics [13].

Capillary forces caused by wetting and due to the pressure difference created by surface tension of liquid across the curved liquid-air interface drive the liquid into the capillary spaces.

Table 1 Well known wicking methods

	Methods	References	Comments
Infinite reservoir	Transverse wicking	Kissa 1981 a-b[58] [59] Harnett & Mehta 1984 [41] Saville 1999 [60]	The fabric is laid flat while water is supplied from beneath and the amount absorbed is recorded.
	Vertical wicking	BS3424 [61] AATCC 197Vertical Wicking of Fabric [56] Person et al [62] Hsieh&yu[13]	An electronic microbalance,an Oriel reversible translator additive in the testing liquid may change its surface tension as well
	Horizontal wicking	AATCC 198 horizontal wicking of textiles [57]	It used to evaluate the ability of horizontally aligned fabric specimens to transport liquid along and/or through them.
Finite reservoir	Contact angle	Kissa 1996 [12] Harnett & Mehta 1984 [41]	See section 2.1.3

The capillary pressure is commonly described through the well known Laplace equation which idealizes capillary tubes as follows:

$$\Delta P = \frac{2\gamma_{LV} \cos\theta}{r} \tag{15}$$

where P is the difference capillary pressure, γ_{LV} is the surface tension of the interface liquid-vapor, θ is the solid-liquid contact angle and r is the capillary radius.

In fibrous assembly, the capillary spaces are not uniform so that it is preferred to use the effective capillary radius instead of the radius r. The surface energy of fibers depends on many characteristics such as perimeter, surface purity and molecular orientation of fibers [68].

As the pressure gradient increases, the amount of liquid wicks through capillaries increases. According to the Lucas-Washburn equation, it is expected that, at a specific time, with a larger pore size, we will obtain a faster capillary rise. However, Miller [69] showed that in some cases, wicking through capillaries with larger diameter has been overtaken by those with smaller diameter. Thus, the distance of liquid advancement is higher in smaller radius pores. This is can be explained by the fact that when the capillary radius decreases, the capillary pressure will be higher and causes faster liquid flow through the capillary.

4 CONCLUSIONS

Comfort of human body is directly related to the liquid water vapor permeability of a material used for clothing. Test methods used to measure the material properties are extremely significant because of getting accuracy. Methods must simulate all the environmental conditions, closely related to wearer. Many patents and research articles report different results due to different testing conditions for wetting, wicking and transport of liquid water in fabric. By considering actual wear condition, results predicted by mathematical models and tested by experiments are excessively helpful in understanding the theory behind the scientific behavior of materials, leads to betterment in product development. Textile material properties are influential parameters for heat and moisture transmission phenomena. Diffusion, convection and moisture content are the hidden parameter affects the wetting and wicking of textile material whereas fabric structure, thickness, density, permeability, porosity and yarn used are main physical factors helps in capillary action. Fabric used for hard weather conditions or sportswear, must acquire best comfort properties by liquid transportation to get rid of perspiration. Twist multiplier (TM) and capillary pressure in the yarn also affects the transport performance, lower the yarn twist, more obvious the transient transport of liquid water in the wearing fabric. Similar fiber behavior with its pore size is quite important with wicking point of view, responsible for instant wicking velocity, wicking height and wicking time. Transportation of liquid water in fabric cannot be defined at only one condition – but a range of conditions should be measured regarding the fabric ability to transport liquid moisture.

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