Effects of hydrophobic yarns on liquid migration in woven fabrics

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Abstract

Liquid migration in woven fabrics was investigated by measuring the wicking coefficients of hydrophilic cotton and hydrophobic PVDF (polyvinylidene fluoride) monofilament fabrics and some other fabrics. The coefficients of fabrics with cotton warp yarns were essentially equal along the weft direction but differed along the warp because of variations in the warp yarn crimps. Then factors affecting the liquid migration along weft direction were investigated, especially the effect of hydrophobic weft yarns, by using three different warp weave densities for fabrics with both cotton and PVDF weft yarns. The results showed that in the warp direction, liquid moved along longitudinal yarns and migrated to hydrophilic but not hydrophobic transverse yarns. In the weft direction, similar results were obtained for fabrics with cotton weft yarns. Fabrics with PVDF weft yarns, however, showed no migration through the longitudinal yarns, although liquid did move along the transverse direction of connected cotton warp yarns. The largest wicking coefficient was associated with the highest warp weave density. Liquid did not move through transverse yarns separated from one another. It is apparent that liquids can migrate along transverse, adjacent, in-contact hydrophilic yarns of fabrics incorporating longitudinal hydrophobic yarns.

Keywords

Liquid migration, hydrophobic yarn, hydrophilic yarn, wicking coefficient.

Introduction

Liquid transport is an important phenomenon in the processing and application of fibrous materials and significant attention has been focused on liquid wetting, wicking, transport and retention[1]. Wetting[2], meaning the displacement of a solid-air interface by a solid-liquid interface, is of paramount practical importance in textile processing. In a broader sense, the term “wetting” can also be used to describe the replacement of a solid-liquid or liquid-air interface with a liquid-liquid interface, and also to describe a solid-air interface with a solid-solid interface.

Wetting of textiles involves several primary processes: (a) immersion of a solid in a liquid, (b) capillary sorption, (c) adhesion between the liquid and the solid and (d) spreading of the liquid over the solid[3]. Wicking can only occur when the liquid wets the capillary spaces between fibres.

Figure 1 shows capillary action along the horizontal direction, where the liquid viscosity is given as η. Based on the Washburn equation[4-5], the horizontal wicking distance of the liquid is given by

$$L = \left(R\gamma\cos\theta / 2\eta\right)^{1/2} t^{1/2}, \tag{1}$$

where L is the wicking distance, R is the equivalent radius of the capillary space, γ is the liquid-vapor surface tension, θ is the contact angle of the solid-liquid system, η is the liquid viscosity and t is time. According to Equation 1, a plot of L versus $t^{1/2}$ should be linear and pass through the origin. The slope of the line, referred to as the wicking coefficient W, is given by Equation 2 and is determined by fitting the experimental data to Equation 1.

$$W = (R\gamma\cos\theta / 2\eta)^{1/2}. \tag{2}$$

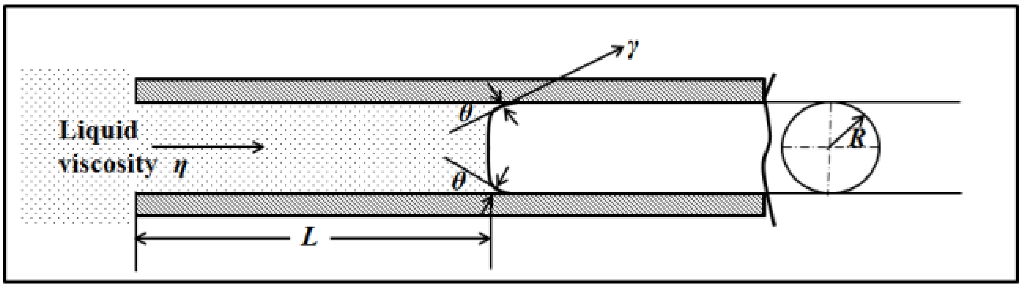


Figure 1. The main parameters associated with capillary action.

To date, three main measurement methods have typically been applied to the analysis of wetting and wicking through yarns and fabrics. The first involves measuring the height of capillary flow as a function of time, using a colored liquid or CCD camera to monitor the flow[6-13]. The BS 3424[14], DIN 53924[15] and Byreck methods[12] are based on this technique. The second approach consists of measuring weight variations or capillary forces with a microbalance during capillary wicking[6, 16-17]. The last technique uses liquid-sensitive sensors set at regular intervals along the fabric or yarn[18-21]. These liquid-sensitive sensors typically measure electrical capacitance, humidity or temperature variations.

On the basis of these measurement methods, many studies[23-27] on wetting and wicking of woven, knitted and nonwoven fabrics have been carried out. Ozturk et al.[22] discussed the wicking effect of cotton-acrylic rotor spun yarn on the wicking of knitted fabrics and found the wicking abilities of yarns and fabrics increased with increases in the acrylic content of the blend and also with the thickness of the yarn. Yanilmaz et al.[23] reported that tight-knitted structures had higher contact angles than slack structures owing to greater compactness of the surface and also that comfort parameters were significantly affected by the knitted structure. Wong et al.[24] discussed the wetting and wicking behaviors of linens treated with low-temperature oxygen and argon plasma, using contact angles and upward and downward water wicking methods, while Nyoni et al.[25] analyzed the wicking and liquid retention properties of high-performance woven fabrics and found that the heterogeneity of pore sizes, shapes and orientations affected the penetration of liquid into the yarn structure and hence the liquid-retention properties exhibited by textured continuous filament yarns.

Mhetre et al[26] carried out wicking experiments on a range of cotton and polyester fabrics, and showed that the wicking in fabrics was determined by the wicking behavior of the yarn, the thread spacing and the yarn migration rate. Zhu et al.[27] discussed the effect of weave density on the wicking coefficients of a series of woven fabrics and obtained results showing that the wicking coefficients were decreased with increases in weave density. Moreover, Francois L et al. [28] investigated fabric imbibition characterization and subsequent evaluation of the optimal flow front velocity during resin injection through fibrous reinforcements, helpful to building more robust liquid composites processing.

In previous studies, the effect of hygroscopic yarns on the wicking coefficient has been investigated and the wicking properties along the warp and weft directions have been examined. Fabrics with special functions, however, such as cloth diapers, require liquid water transport within the fabrics to proceed mainly along the longitudinal direction, which can be achieved by a combination of hygroscopic and hydrophobic yarns. It is therefore important to investigate the effects of hydrophobic yarns on the wicking coefficient. As PVDF (polyvinylidene fluoride) monofilament is hydrophobic yarn which can be used for weaving, and the liquid migration can be investigated simply using this kind of yarn, in this study, the effects of hydrophobic yarns on liquid migration in woven fabrics were investigated, using PVDF monofilament as the weft yarn and comparing the result (in terms of the wicking coefficient) to those obtained when employing hydrophilic cotton as the weft yarn. Applying different weave densities, the effects of contact between adjacent warp yarns on the wicking coefficient of woven fabrics was discussed.

Experimental

Test apparatus

The experimental trials were conducted using thermocouple array technology[21, 27] to determine the relationship between wicking length and time at 20 ± 1 °C, 65 ± 2%RH. Figure 2(a) shows a diagram of the test apparatus, which was composed of 12 thermocouple measurement points set 5 mm apart and placed on polystyrene foam for heat insulation. The thermocouples were made from copper and constantan element wires 0.1 mm in diameter[29]. One end of the fabric strip was clipped to a weight and, as the fabric absorbed water, changes in temperature were measured by the thermocouple array. Liquid used in this experimental was 20 ± 1 °C ion-exchanged water. Figure 2(b) presents the entire measurement system, in which the free end of each thermocouple was connected to the data collection device, which was interfaced with a computer to collect and record data.

Fabric samples

The fabric samples used in this study were woven on a sample rapier loom, using hydrophilic cotton yarn as the warp yarn. A range of plain fabrics were woven by changing the weft yarns or the warp weave density. Table 1 gives the weaving parameters of each sample woven with the same warp yarn and weft weave density. Moreover, fabrics C-5, C-5a and C-5b were woven with the same weft yarn but different warp weave density. Different warp weave density was also used for fabrics M-1, M-1a and M-1b. Fabrics C-5, C/P-1, C/P-2 and P are used in previous study[27]. Two kinds of hydrophobic monofilament were applied: copper (brass) and PVDF. The moisture retention of the PVDF monofilaments is less than 0.1%[30], and thus they are deemed sufficiently hydrophobic. As a kind of metal yarn, the moisture retention of the copper (brass) is 0[31], which is also deemed as sufficiently hydrophobic.

The fabrics were first pretreated to remove adhesives and impurities that may have resulted from the manufacturing process. Pretreatment[27] was accomplished by first immersing the fabric twice in an 80 ± 2 °C water bath, followed by immersion in a 80 ± 2 °C water bath containing a detergent (polyoxyethylene lauryl ether, EMULGEN 108; Kao Corporation, Japan) at a concentration of 1 g/10 L. The EMULGEN 108 is a kind of nonionic surfactants which is used for general cleaner, especially in fiber industry. Agitation was used with 30 times per minute. After each soaking, the fabric samples were washed carefully with water. Finally, the samples were dried under standard conditions for 24 h.

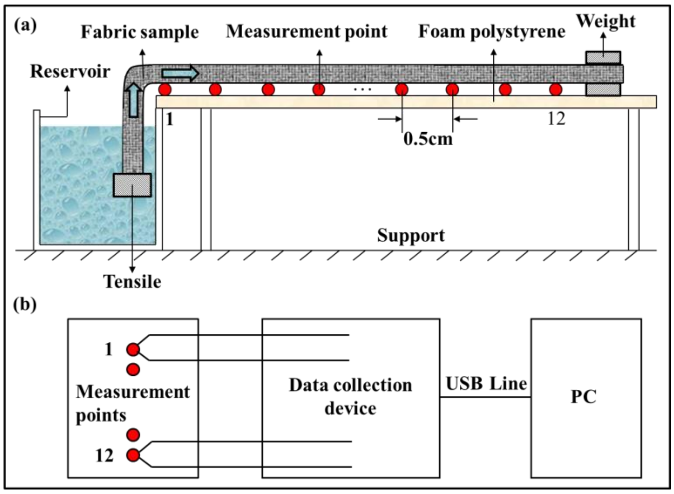


Figure 2. Schematics of the test apparatus showing (a) fabric wetting and (b) thermocouple instrumentation.

Test specimens[27] 20 by 3 cm in size were carefully cut from each fabric at varying locations along the warp and weft directions and were used to measure wicking length with respect to time. We tested eight samples in both the warp and weft directions of each fabric and thus obtained an average wicking coefficient and standard deviation for each fabric.

Table 1. Weaving parameters of fabric samples

Fabric sample	Warp yarn	Weft yarn	Weave density (cm^{-1})		Crimp (%)	
			Warp	Weft	Warp	Weft
C-5	100% cotton 13tex ($2/80^S$)	100% cotton,13tex ($2/80^S$)	47.2 (120/inch)	23.6 (60/inch)	17.4	3.4
C-5a			28.3 (72/inch)		7.2	3.5
C-5b			18.9 (48/inch)		5.5	7.3
C/P-1		cotton: polyester=50:50, 19tex	47.2 (120/inch)		25.5	1.1
C/P-2		cotton: polyester=50:50, 29.5tex	47.2 (120/inch)		25.8	1.5
P		100% polyester, 29.5tex ($2/40^S$)	47.2 (120/inch)		28.1	0.8
Co		100% copper monofilament, ϕ0.1mm	47.2 (120/inch)		11.7	0
M-1		100% PVDF monofilament, (Polyvinylidene Fluoride), ϕ 0.165 mm	47.2 (120/inch)		28.9	0
M-1a			28.3 (72/inch)		30.7	0
M-1b			18.9 (48/inch)		26.4	0

Results and discussion

Figure 3 summarizes the wicking coefficients of six woven fabrics (C-5, M-1, Co, C/P-1, C/P-2 and P) with different weft yarns in the warp and weft directions. It can be seen that, along the warp direction, the wicking coefficients of these fabrics are different from one another. The wicking coefficient of the cotton (C-5) and copper (Co) fabrics are higher than those of the other fabrics along this direction. However, along the weft direction, these fabrics show almost the same wicking coefficient, regardless of the presence of hydrophilic or hydrophobic yarns.

To investigate this phenomenon, the yarn crimp[32] (c) in both warp and weft directions for these fabrics was calculated based on Equation 3, by measuring length of yarns obtained from a 100 mm length of fabric.

$$c(\%) = \frac{l_Y - l_F}{l_F} \times 100. \qquad (3)$$

Here, l_F is the distance between two points on a yarn as it lies in the fabric and l_Y is the straightened distance of the yarn. 15 fabrics were measured in each directions and the average was obtained.

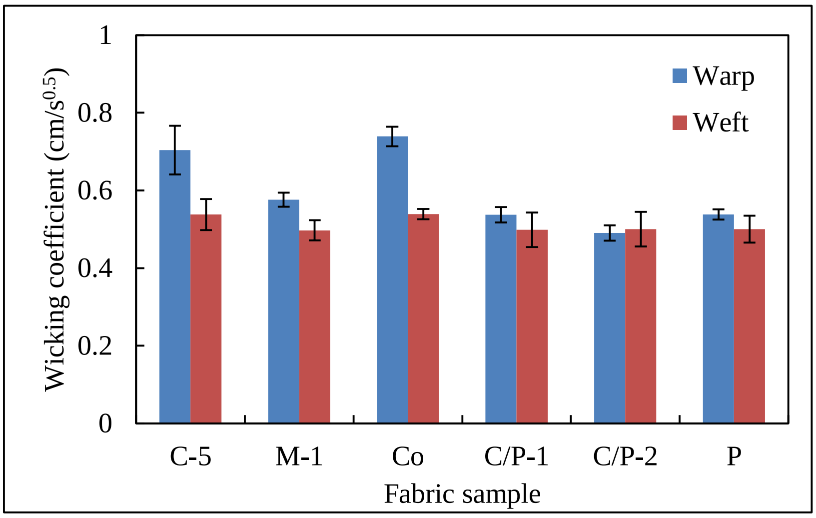


Figure 3. Wicking coefficients of woven fabrics of the same weave density with different weft yarns.

The relationship between wicking coefficient and yarn crimp is shown in Figure 4, from which it is evident that, in the warp direction, increasing the yarn crimp will decrease the wicking coefficient. There is a linear relationship between the two parameters with a correlation coefficient of –0.897, which means that there is high correlation between the warp yarn crimp and the wicking coefficient. These results demonstrate that the wicking coefficient varies with the application of different yarn crimps, which leads to wicking paths of differing lengths. Because the fabrics used in this experimental trial differed only in weft yarns, the warp yarn crimps were determined from the weft yarn diameters. The weft yarn diameter of the copper fabric (Co) was 0.1 mm, making it the finest of all the fabrics, thus it can be concluded that the copper fabric had the smallest warp yarn crimp and the highest wicking coefficient. In the case of the C/P-2 and P fabrics, the polyester fabric (P) incorporated a ply yarn which is more conducive to liquid migration even though the weft yarn density of the two fabrics were the same.

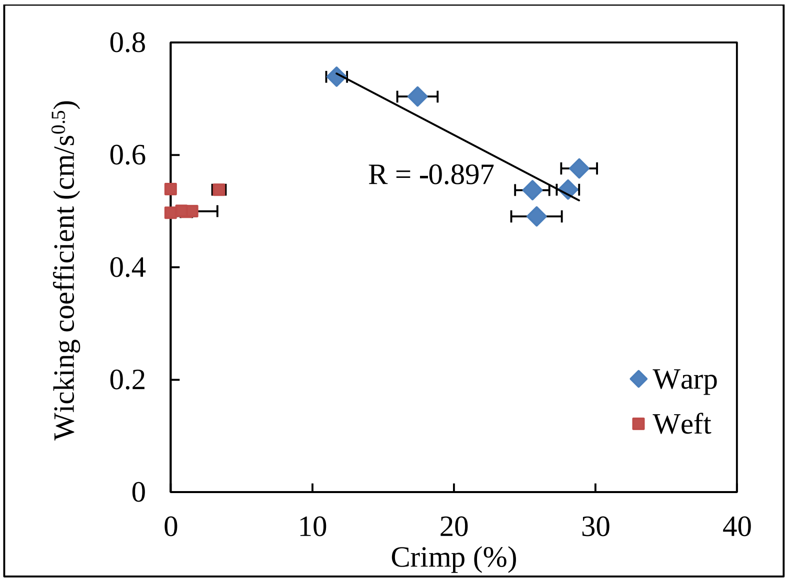


Figure 4. Relationship between wicking coefficients of fabrics and yarn crimp in the wicking directions.

Along the weft direction, at the same warp yarn and warp weave density values, the wicking coefficients of fabrics with different weft yarns are nearly the same and there is almost no variation in the weft yarn crimps. The wicking coefficient will be different according to the difference of weft yarns, though the weft yarn crimps are similar. Therefore, it is necessary to examine the factors affecting liquid migration along the weft direction, especially for those fabrics incorporating hydrophobic weft yarns.

The factors that affect water transport along the weft direction were elucidated using a series of fabrics, applying three different warp weave densities (47.2, 28.3, 18.9/cm) woven with both hydrophilic and hydrophobic weft yarns (100% cotton or 100% PVDF monofilament) and the wicking coefficients of these fabrics were obtained. The results are shown in Figure 5. The anisotropy of liquid migration within fabrics in warp and weft direction can be obtained from Figure 5; the same results were obtained in other study[20].

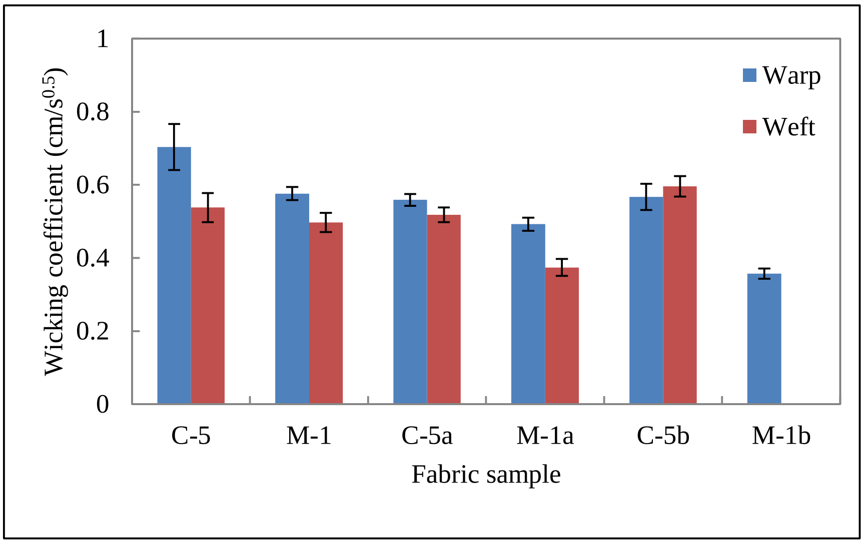


Figure 5. Wicking coefficients of different fabrics with different weft yarns or warp weave densities in both warp and weft wicking directions.

First, for the cotton fabrics (C-5, C-5a and C-5b), along the warp direction, the C-5 fabric exhibits the highest wicking coefficient, because the fabric has the highest warp weave density, leading to minimal yarn space and little liquid enough for accumulation to make a new reservoir and therefore rapid liquid transports results. In other study[20], the wicking coefficient fell down with the increase of weave density. It depends on the range of the density and structure of yarn and fabric[27]. In order to show the liquid migration in cotton fabrics, the photographic images were taken by colored liquid along both warp and warp directions of these fabrics. The results of cotton fabrics in the warp direction are shown in Figure 6. When the liquid moves along the longitudinal yarns, the spaces between these yarns are filled with liquid. However, because the warp weave densities of C-5a and C-5b fabrics are smaller, the spaces between the warp yarns are larger than in the case of the C-5 fabric. As can be seen from Figure 6(b), the quantity of accumulated liquid in C-5a fabric is greater than in C-5, which results in lower wicking coefficients. For C-5b fabric, because the spaces are too large for liquid accumulation, liquid migrates only through warp yarns, and migrates from warp yarns to separated weft yarns. Therefore, the wicking coefficient of C-5b fabric is lower than C-5 fabric.

(a) (b) (c)

Figure 6. Liquid migration in cotton fabrics along the warp direction of (a) C-5, (b) C-5a and (c) C-5b fabrics.

Along the weft direction, the wicking mechanism is the same as along the warp direction. Here, the weft yarns have the most significant effect on liquid transport and, because the weft weave densities are the same, the wicking coefficients are nearly equal. The wicking coefficient of the C-5b fabric is a little larger than those of the other fabrics because of the lower crimp associated with this fabric.

It is also evident that, at the same weave density, different wicking coefficients result from different weft yarns, such as can be seen from examining the C-5 and M-1 fabric data shown in Figure 5. The wicking coefficients of cotton fabrics are thus larger than those of monofilament fabrics. This phenomenon can be explained by considering the fabric structures and the yarn crimps. Figure 7 portrays a longitudinal cross section of a plain fabric, with the liquid transport direction indicated by an arrow. Here, the liquid migrates along the longitudinal direction until it encounters the weft yarn, at which point the liquid will accumulate in the pores between longitudinal and transverse yarns. If the transverse yarn is hydrophilic, the accumulated liquid will act as a reservoir and will be wicked away by the yarn. However, if the transverse yarn is hydrophobic, the accumulated liquid also forms a reservoir but cannot be wicked away by the transverse yarn and therefore can only be transported along the hydrophilic longitudinal yarn. Moreover, as the monofilament cannot be compressed, the warp yarn crimp of a monofilament is greater than that of cotton yarn, as shown in Figure 4, which leads to a longer wicking path and hence decreases the liquid transport speed. Therefore, in this study, the wicking coefficients of cotton fabrics are higher than those of monofilament fabrics.

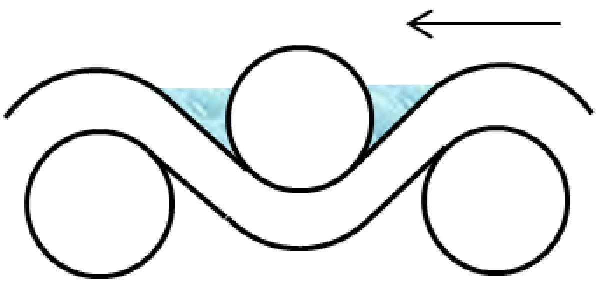


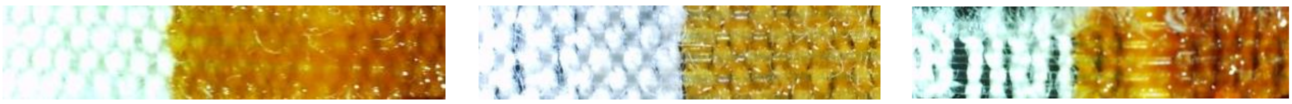
Figure 7. Longitudinal cross section of a generic fabric, showing liquid accumulation in the pores.

(a) (b)

Figure 8. Liquid migration along the warp direction in (a) C-5b, (b) M-1b fabrics.

Finally, based on the results obtained with monofilament fabrics (M-1, M-1a and M-1b) shown in Figure 5, it is evident that, regardless of the yarn direction, the wicking coefficient of the M-1 fabric is the highest, followed by the M-1a and M-1b fabrics. Along the warp direction, liquid migration occurs primarily through the warp yarn and, as the warp yarn density decreases, the space between yarns increases, large quantities of accumulated liquid are generated and the wicking coefficient of the fabric is reduced. Compared with C-5b fabric, the warp yarns in M-1b fabric become flat, shown in Figure 8, which shorten the yarn space and liquid will still accumulate in the fabric.

Along the weft direction, liquid cannot move through the longitudinal yarns, because those yarns are hydrophobic. Figure 9 shows the liquid fronts in the monofilament fabrics, from which it can be seen that the liquid front is straight and is positioned along the transverse yarns. These figures demonstrate that, along the weft direction, liquid can migrate in the transverse direction of the warp yarns if they are connected. Because the warp weave density of M-1 is the highest, providing the closest warp yarn arrangement, its wicking coefficient is the highest. The wicking coefficient of the M-1b fabric is nil, however, because the transverse yarns are separated from one another and therefore it can be concluded that liquid migration is possible in hydrophobic fabrics on the condition that the transverse yarn is hydrophilic and that adjacent yarns are in contact.



(a) (b) (c)

Figure 9. Liquid migration in monofilament fabrics along the weft direction in (a) M-1, (b) M-1a and (c) M-1b fabrics.

Conclusion

In this study, the effects of hydrophobic yarn on liquid migration in woven fabrics were investigated by measuring the wicking coefficients of various fabrics incorporating both hydrophilic and hydrophobic yarns with different weaving densities.

The wicking coefficients of fabrics with the same weave density and cotton warp yarns but with different weft yarns were nearly the same in the weft direction but differed in the warp direction. To clarify this phenomenon, warp and weft yarns crimps were measured. Along the warp direction, there was a negative correlation between warp yarn crimp and wicking coefficient. In the warp direction, higher yarn crimps resulted in extended wicking paths for the liquid and therefore the wicking coefficient was reduced when the yarn crimp was increased. In the weft direction, the crimps were almost the same.

To investigate the factors affecting liquid migration in the weft direction, especially for fabrics incorporating hydrophobic weft yarns, the wicking coefficients of three pairs of fabrics were measured and photographic images of the migration were obtained. Along the warp direction, liquid was seen to migrate along the cotton warp yarns, accumulating in the pores between longitudinal and transverse yarns when the pores are not too large for liquid to accumulate. The accumulated liquid can be considered to represent a new reservoir which, when coupled with hydrophilic transverse yarns, will allow migration to the dry yarns. However, the liquid will not migrate if it encounters hydrophobic transverse yarns.

In the weft direction, the mechanism of liquid migration in cotton fabrics is the same as in the warp direction. Because the weft weave density was the same between test fabrics, the wicking coefficients were nearly the same. For fabrics with hydrophobic weft yarns, liquid cannot pass through the longitudinal yarns but migrates along the transverse direction of cotton warp yarns if they are connected. The highest wicking coefficient was obtained when the warp weave density was the highest. However, if the transverse yarns are separated from each other, liquid cannot transport through the yarns. Therefore, for fabrics with hydrophobic yarns in the longitudinal direction, liquid migrates by transverse, adjacent and in-contact hydrophilic yarns.

In conclusion, the effects of hydrophobic yarns on the liquid migration in woven fabrics were clearly elucidated. The results of this study will be applicable to the future design of fabrics with special liquid migration requirements.

Acknowledgements

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References

1. Hsieh YL, Yu BL and Hartzell MM. Liquid wetting, transport, and retention properties of fibrous assemblies: Part II: Water wetting and retention of 100% and blended woven fabric. *Textile Res J* 1992; 62: 697-704.
2. Kissa E. Wetting and wicking. *Textile Res J* 1996; 66: 660-668.
3. Erik K. Repellent finishes. In B.M. Lewin and S.B. Sello (ed.) *Handbook of Fiber Science and Technology* (Part II B). New York: Marcel Dekker, 1984, pp.144-148.
4. Washburn EW. The dynamic of capillary flow. *Phys Rev* 1921; 17: 273-283.
5. Kamath YK, Hornby SB, Weigmann HD, Wilde MF. Wicking of spin finishes and related liquids into continuous filament yarns. *Textile Res J* 1994; 64: 33-40.
6. Hsieh YL. Liquid transport in fabric structures. *Textile Res J* 1995; 66: 299-307.
7. Rajagopalan D, Aneja AP, Marchal JM. Modeling capillary flow in complex geometries. *Textile Res J* 2001; 71: 813-821.

8. Kawase T, Sekoguchi S, Fujii T and Minagawa M. Spreading of liquids in textile assemblies. *Textile Res J* 1986; 56: 409-414.

9. Wang N, Zha AX, Wang JX. Study on the Wicking property of polyester filament yarns. *Fibers Polym* 2008; 9: 97-100.

10. Jiang XY, Zhou XH, Weng M, et al. Image processing techniques and its application in water transport through fabrics. *J Fiber Bioeng Inform* 2010; 3: 88-93.

11. Perwuelz A, Mondon P, Caze C. Experimental study of capillary flow in yarns. *Textile Res J* 2000; 70: 333-339.

12. Japanese Industrial Standard L 1907: 1994. Test method of water absorbency of textiles-5.1.2, Byreck method.

13. Hamdaoui M, Fayala F, Nasrallah SB. Dynamics of capillary rise in yarns: Influence of fiber and liquid characteristics. *J Appl Polym Sci* 2007; 104: 3050-3056.

14. BS 3424: *Part 18: Methods for determination of resistance to wicking and lateral leakage to air*. British Standards Institution, London, 1986.

15. Din 53924. *Velocity of suction of textile fabrics in respect of water- method determining the rising height*. Berlin: Deutsches Institut fur Normung, 1997.

16. Hsieh YL, Yu B. Liquid wetting, transport, and retention properties of fibrous assemblies. Part I: water wetting properties of woven fabrics and their constituent single fibers. *Textile Res J* 1992; 62: 677-685.

17. Bayramli E, Powell RL. Experimental investigation of the axial impregnation of oriented fiber bundles by capillary forces. *Colloids Surf.* 1991; 56: 83-100.

18. Ito H, Muraoka Y. Water transport along textile fibers as measured by an electrical capacitance technique. *Textile Res J* 1993; 63: 414-420.

19. Babu VR, Koushik CV, Capillary rise in woven fabrics by electrical principle. *Indian J Fibre Textile Res* 2011; 36: 99-102.

20. Yoneda M, Niwa M. Measurement of in-plane capillary water flow of fabrics. *Sen-I Gakkaishi* 1992; 48: 288-298.

21. Zhu CH, Takatera M. A new thermocouple technique for the precise measurement of in-plane capillary water flow within fabrics. *Textile Res J* 2014; 84: 513-526.

22. Ozturk MK, Nergis B, and Candan C. A study of wicking properties of cotton-acrylic yarns and knitted fabrics. *Textile Res J* 2011; 81: 324-328.

23. Yanilmaz M, Kalaoglu F. Investigation of wicking, wetting and drying properties of acrylic knitted fabrics. *Textile Res J* 2012; 82: 820-831.

24. Wong KK, Tao XM, Yuen CWM and et al. Wicking properties of linen treated with low temperature plasma. *Textile Res J* 2001; 71: 49-56.

25. Nyoni AB, Brook D. Wicking mechanisms in yarns-the key to fabric wicking performance. *J Textile Inst* 2006; 97: 119-128.

26. Mhetre S, Parachuru R. The effect of fabric structure and yarn-to-yarn liquid migration on liquid transport in fabrics. *J Text Inst* 2010; 101: 621-626.

27. Zhu CH, Takatera M. Effect of fabric structure and yarn on capillary liquid flow within fabrics. *J Fiber Bioeng Inform* 2013; 6: 205-215.

28. Francois LB, Amir EF, Edu E and et al. Prediction of optimal flow front velocity to minimize void formation in dual scale fibrous reinforcements. *Int J Mater Form* 2014; 7: 93-116.

29. Zhu CH, Takatera M. Change of temperature of cotton and polyester fabrics in wetting and drying process. *J Fiber Bioeng Inform* 2012; 5:433-446.

30. Li N, Xiao CF, An SL and et al. Preparation and properties of PVDF/PVA hollow fiber membranes; *Desalination* 2010; 250: 530-537.

31. Japanese Industrial Standard L 0105: 2006. General principles of physical testing methods for textiles.

32. Kang TJ, Choi SH, Kim SM and et al. Automatic structure analysis and objective evaluation of woven fabric using image analysis. *Textile Res J* 2001; 71: 261-270.