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Characterizing the effects of controlled temperature and relative humidity on liquid water transport behavior of cotton/lycra elastic woven fabric

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Abstract

Liquid transport (wicking) has great effect on the physiological comfort, since it directly determines the moisture management of fibrous assemblies. For elastic fabric structures, the wickability primarily depends on several factors, such as tensile strain and ambient conditions (e.g. temperature, relative humidity). The main purpose of this work was to systematically clarify the effects of water temperature and relative humidity on vertical liquid water transport of as-prepared cotton/lycra elastic woven fabric experimentally and theoretically. On the experimental side, the results indicated that our as-prepared fabric exhibited a water temperature-strengthening effect, while a humidity-weakening effect was produced simultaneously. In other words, a higher water temperature results in a higher equilibrium wicking height, whereas a higher relative humidity results in a decreased wicking height. Furthermore, the underlying wicking mechanism in each case was graphically unraveled. On the analytical side, the proposed Laughlin-Davies model turns out to be appropriate, it can replicate the wicking characteristics of fabric in both of these cases qualitatively and quantitatively. These findings are expected to provide a deep understanding of fabric wicking under a realistic regime.

1. Introduction

Liquid transport (wicking), defined as absorption and passive spreading of liquid into a porous substrate, is viewed as one of the crucial factors, since it has a great influence on physiological comfort of textile materials [1,2]. Recently, fabric structures especially elastic fabric structures have been extensively used in sportswear, flexible composites, tissue engineering, personal protection, and smart textile fields [3–8]. Knowledge of liquid transport behavior on fibrous textile is essential in the reasonable design. As a result, it is of vital importance to give a comprehensive understanding of the wicking behavior of such elastic fabric structures.

The liquid-textile interaction primarily depends on the wettability of constituent fibers, surface geometry, the capillary geometry of fibrous assemblies, the amount and nature of the liquids, and external factors (e.g. forces, temperature and relative humidity) [1,2]. More specifically, wicking falls into two categories: at the yarn scale, yarn parameters that affect the wicking behavior are fiber type (natural, e.g. cotton, wool, and synthetic, e.g. polyester, acrylic, polyamides) and geometry features (e.g. diameter, cross-section, surface characteristics), linear density, twist and the forces applied, etc. Among these, the influence of applied loads/strains on yarn wickability has received less attention [9,10]. For example, the wicking ability of elastic-conductive composite yarn under different levels of stretch were investigated by Wang et al [9]. The influence of short interval cyclic...
loading on the wicking behavior of nylon 66 yarns was investigated by Nyoni et al[10]. Fabrics including woven, knitted, and braided, which can be considered as the ordered arrangement of yarns, have quite regular structures. At the fabric scale, wicking occurs not only inside each yarn but also between the adjacent yarns. Fabric parameters that influencing wickability are yarn type, fabric structure, thread count, finishing treatments and external factors, etc. For example, Fangeiro et al revealed that yarn type plays an important role in deciding wicking behavior of knit fabrics, and the drying capability is temperature dependent [11]. The effect of hydrophobic weft yarns on liquid migration in woven fabrics (using different weave densities) with both cotton and polyvinylidene fluoride yarns was discussed by Zhu et al[12]. The effect of weaving structures on water wicking-evaporating behavior of woven fabric was studied by Lei et al[13]. The influence of polyethylene film lamination on the water absorbency of polypropylene non-woven fabric was studied by Wang et al[14]. Hassan et al pointed out that the vertical wicking of 100% polyester knit fabric was significantly improved after various finish treatments on a whole [15]. Similarly, only a few works are focused on the effects of external factors, e.g. applied forces and surrounding condition, on the wicking behavior of fabrics [10, 16]. Influence of short interval cyclic loading on wicking characteristics of nylon 66 woven fabrics was investigated by Nyoni et al[10]. Guo et al found that the water removal rate of a wicking geotextile increased with an increase in air temperature or a decrease in relative humidity [16].

A minor review of the literature revealing that there are very inadequate researches performed on fabric wickability under different environmental conditions. Bearing this in mind, the vertical wicking properties of as-prepared cotton/lycra elastic woven fabric under controlled water temperature and relative humidity were systematically studied in this paper. The respective possible underlying wicking mechanism as a function of water temperature and relative humidity was also unraveled. Such fundamental work is expected to provide a deep understanding of textile fabric wicking under a realistic environmentally regime.

2. Experimental

2.1. Fabrication of cotton/lycra elastic woven fabric

In this study, 100% cotton roving of 450 tex preparing from cotton fibers (1.4 dtex × 30.8 mm) was employed as the cover material, and a lycra multifilament of 40 denier was employed as the core material. As illustrated in figure 1(a), for preparing an elastic core yarn, the conventional ring spinning system was retrofitted with a grooved roller and positive feed rollers, and the pre-stretched lycra filament was stably located in the center of the flat ribbon-like drafted cotton assemblies, as per the work by Wang et al [17]. The key spinning parameters were given as follows: total break/break draft 24.68/1.20, draw ratio of lycra 2.5, twist 680 T m⁻¹, and spindle speed 8500 rpm, respectively. Finally, a wavy-shape elastic core yarn was prepared, as shown in the inset of figure 1(a).
Further, an elastic woven fabric (3/1 left twill; 170 ends/in × 93 picks/in) was fabricated using a CCI Studio automatic rapier loom, and the warp and weft were pure cotton yarn of 18.22 tex and as-prepared elastic core yarn, respectively, as shown in figure 1(c). Then, the as-fabricated fabric was subjected to washing, drying and ironing in order, as shown in figure 1(b). It can be extended substantially up to 20.6% in weft direction (figure 1(c)), demonstrating its elastic stretchability. Note that the fabric was allowed to relax at least 24 h in ambient temperature of 25 ± 2°C and 65 ± 3% relative humidity.

2.2. Fabric wicking test under different temperatures
A self-made experimental setup was built to measure the wicking height of as-prepared elastic fabric under three different temperature values (25°C, 45°C, and 65°C), keeping the relative humidity constant, as per the work by Wang et al [9]. The size for fabric strip samples were 30 mm width × 150 mm length. Herein, a hot plate was used to adjust and maintain the temperature of liquid bath, as illustrated in figure 2. Note that, if not otherwise specified, the term “temperature” refers to liquid temperature rather than the air temperature. The whole wicking process was recorded in 5 min Image frames were then extracted from the video files using Adobe Premiere Pro 2020. Image brightness was adjusted digitally to enhance the contrast of the liquid front, and the wicking height was then measured at the centerline position of the liquid front using ImageJ software. The experiments were performed in triplicate for each condition.

2.3. Fabric wicking test under different relative humidity levels
A self-made experimental setup was built to measure the wicking height of fabric under different relative humidity levels (30%, 65%, and 95%), keeping temperature constant. Note that the fabric sample should be placed at the designated relative humidity value at least 24 h before testing. After that, a fabric strip (30 mm width × 150 mm length) was immersed into a liquid water reservoir placed inside an environmentally controlled chamber. A humidifier and a temperature/humidity sensor were employed to adjust the relative humidity of the chamber, as illustrated in figure 3. Similarly, the whole wicking process was recorded in 5 min. Also, the softwares of Adobe Premiere Pro 2020 and ImageJ were used. The experiments were performed in triplicate for each condition.

2.4. Theoretical modeling of fabric wicking and validation
2.4.1. Theoretical wicking model
Currently, the most widely used wicking model is Lucas-Washburn equation where the progression of liquid front is taken to be proportional to the square-root of wicking time [18]. Since the macro/micro-scale structures of fibrous fabrics are complex, their capillaries are neither cylindrical nor arranged in parallel, the classical Lucas-Washburn equation does not hold in general. To obtain a good fit of the experimental curve, a time exponent \( k (k > 0) \) was introduced to modify the Lucas-Washburn model [19, 20], we call it Laughlin-Davies model, and the wicking kinetics can be written as follows:

\[
 h = Ct^k \quad (k > 0)
\]

where \( h \) is vertical wicking height, \( t \) is wicking time, \( C \) is the coefficient of capillary rise rate, and \( k \) is time exponent. As per the work by Laughlin et al [19], \( C \) is closely related to the ultimate height reached by the fluid in infinite time \( h_{\text{max}} \) (which is determined by the balance between upward forces of capillary action and downward forces of gravity), the fluid density, the capillary radius, the gravitation constant, and liquid viscosity.

Figure 2. (a) Schematic sketch and (b) real photo of experimental set-up for measuring the vertical wicking height of as-prepared fabric under controlled temperature.
2.4.2. Numerical Simulation

The numerical simulation of the proposed fabric wicking model was conducted using the Levenberg-Marquardt algorithm with 1stOpt software, and the fitting aptness was further evaluated using correlation coefficient ($R$), average-absolute-relative error (AARE), and root-mean-square error (RMSE) [$9$, $21$].

$$
R = \frac{\sum_{i=1}^{N} (E_i - E)(P_i - P)}{\sqrt{\sum_{i=1}^{N} (E_i - E)^2(P_i - P)^2}}
$$

$$
\text{AARE}(\%) = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{E_i - P_i}{E_i} \right| \times 100
$$

$$
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (E_i - P_i)^2}
$$

where $E_i$ and $P_i$ are the respective experimental and predictive data of wicking height for the $i$th time, and $E$ and $P$ are the mean values; and $N$ is the total test number.

3. Results and discussion

3.1. Temperature-enhanced effect of fabric vertical wicking

3.1.1. Experimental data analysis and modeling

The wicking behavior of as-prepared fabric as a function of wicking time under different water temperatures is shown in figure 4. The consecutive images of wicking heights as a function of wicking time with water temperatures of 25 $^\circ$C and 65 $^\circ$C were captured in figure 4(a). By contrast, wicking heights under higher water temperatures were higher than that under lower temperatures. Besides, the water front across fabric is relatively uniform, irrespective of wicking time considered. The experimental results of wicking kinetics of fabric at temperatures of 25, 45 and 65 $^\circ$C are shown in figure 4(a). As can be seen, on a whole, the wicking height increased with an increase of water temperature. More specifically, the wicking height increased quickly with an increase of temperature from 25 $^\circ$C to 45 $^\circ$C, beyond which the wicking height increased marginally up to 65 $^\circ$C. Furthermore, the whole wicking curve can be divided into two stages. Penetrating velocity of liquid in the earlier stage is much higher than that in subsequent stage, then the advancement of liquid water gradually becomes slower and slower until reaches an approximately equilibrium [$22$]. The corresponding wicking rates and the captured images shown in figures 4(b)–(c) confirm this. In addition, as shown in figure 4(d), the Laughlin-Davies model turns out to be appropriate, it can replicate the wicking characteristics of fabric under different temperature regimes.

3.1.2. Temperature-enhanced wicking mechanism

Why the equilibrium wicking height increase when the fabric is subjected to elevated temperatures? Since Lucas-Washburn equation may not be perfectly valid for porous textile materials, it indicates that the liquid transport behavior is influenced by several factors. The possible underlying mechanism is revealed from two aspects:

On the one hand, the surface tension and the viscosity of liquid water are temperature dependent [$23$–$25$], and play an important role in determining the moisture management that enters the porous materials through
the capillary pores.

\[ A_{\text{cap}} \propto \sqrt{\frac{\gamma}{\mu}} \]  

(5)

where \( A_{\text{cap}} \) is the capillary absorption coefficient, \( \gamma \) is the surface tension of liquid water (N·m\(^{-1}\)), \( \mu \) is viscosity of liquid water (Pa·s). The viscosity of liquid falls more rapidly with the increase of temperature than that in the case of surface tension. The elevated temperature results in an increase of \( (\gamma/\mu)^{1/2} \) for liquid, and thus the capillary absorption coefficient increases. It is reported that there is a linear dependence of the capillary absorption coefficient with liquid water temperature \([26]\). Consequently, the absorption coefficient enhances as water temperature increases.

On the other hand, according to Arrhenius equation (equation (6)), the kinetic constant of diffusion of water molecules increase as temperature increases, indicating a positive relation. In other words, the increased water molecules diffusion across capillary pores is responsible for the enhanced wicking height with elevated temperature.
temperature, as graphically illustrated in figure 5(a).

\[ k = A e^{-\frac{E_a}{RT}} \]  

(6)

where \( k \) is the rate constant of diffusion, \( T \) is the absolute temperature (in kelvin), \( A \) is the pre-exponential factor, \( E_a \) is the activation energy for the reaction (in Joules), and \( R \) is the universal gas constant.

Further, the reliability of the proposed temperature-enhanced wicking mechanism is verified. As shown in figure 5(b), under environmental conditions of 25 °C air temperature and 65% relative humidity, fabric wicking height with water temperature of 25 °C seems to be slightly higher than that of with unheated water within the range of testing time, indicating the positive effect of water temperature on the liquid front across fabric.

### 3.2. Humidity-weakened effect of fabric vertical wicking

#### 3.2.1. Experimental data analysis and modeling

The experimental results of wicking kinetics of fabric under relative humidity levels of 30, 65 and 95% are shown in figure 6(a). As can be seen, the wicking heights decrease with an increase of relative humidity. More specifically, the wicking height decreases sharply at higher relative humidity (e.g. 95%). Similarly, the whole wicking curve can also be primarily divided into two stages. Penetrating velocity of liquid in the earlier stage is much higher than that in the subsequent stage, and then the advancement of liquid gradually becomes slower and slower until reaches a final equilibrium state [22]. The corresponding wicking rates and the captured consecutive images presented in figures 6(b)–(c) confirm this. In addition, as shown in figure 6(d), the proposed Laughlin-Davies model turns out to be properly explained the wicking characteristics of as-prepared fabric under different relative humidity levels.

#### 3.2.2. Relative humidity-weakened wicking mechanism

Why the equilibrium wicking height decreases when the fabric is subjected to elevated relative humidities?. The possible underlying wicking mechanism is revealed from two levels: On the fabric structure side, the adjacent yarns within fabric irrespective of warp or weft become shorter to a certain extent when the fabric being exposed to a higher humidity, which is similar to the common fabric shrinkage phenomenon after washing, causing smaller internal macro pore sizes, as illustrated in figure 7(a). A reduction in the size of macro pores within the fabric may have accelerated the wicking behavior [27]. Since the macro-pores become saturated at higher relative humidity level compared with that at a lower level, a decreased equilibrium wicking height is found with an increase of relative humidity. On the fiber side, cotton fibers, the main composition of as-prepared woven fabric, are hydrophilic, which means that they have bonding sites (hydroxyl and other oxygen containing groups) for water molecules. When the fabric is exposed in a higher humidity environment, the water molecules penetrate into the internal spaces of cotton fiber more easily until reaches a dynamic equilibrium state [28]. In that case, water travels vertically faces greater resistance. In short, the more hydrogen bondings between bonding sites and water molecules are responsible for the reduced wickability of textile fabric at a higher relative humidity level, as illustrated in figure 7(b).
Figure 6. (a) The heights and (b) captured consecutive images of fabric wicking as a function of wicking time under different humidity levels; (c) The corresponding wicking rates; (d) Predicted curves of fabric at different relative humidities.

Figure 7. The possible relative humidity-weakened wicking mechanisms of fabric: (a) Macro-pore effect; (b) Hydrogen-bond effect.
4. Conclusions

The vertical wicking properties of cotton/lycra elastic fabric in initial tension-free state under different controlled temperature and relative humidity levels were systematically clarified. The main conclusions can be drawn as follows:

A combined experimental and predictive investigation has been performed to elucidate the vertical wicking behavior. On the experimental side, the results indicate that the fabric exhibited a temperature-strengthening effect, while a humidity-weakening effect took place. In other words, a higher temperature results in a higher equilibrium wicking height, whereas the higher relative humidity results in a decreased equilibrium height, and vice versa. Additionally, the underlying wicking enhanced/weakened mechanism of such fabric was revealed. On the analytical side, the Laughlin-Davies wicking model was used to replicate the wicking characteristics of fabric within the range of testing time (total 5 min) under the above conditions qualitatively and quantitatively.

As a popular elastic textile fabric, apart from fabric wicking characterization under different environmental conditions, the strain-dependent vertical and horizontal wicking behavior of such fabric also needs to be systematically clarified. Furthermore, we aim to establish other wicking prediction models to compare with Laughlin-Davies model proposed in this article. Such fundamental work is of topical interest. This research is expected to provide an in-depth understanding of porous textile materials with superior elastic stretchability.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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References

[1] Kiss E 1996 Wetting and wicking Textile Res. J. 66 660–8
[2] Parada M et al 2017 A review on advanced imaging technologies for the quantification of wicking in textiles Textile Res. J. 87 110–32
[3] Kosajnsek K et al 2021 Functionalization of woven fabrics with PBT yarns Polymers 13 260
[4] Senthilkumar M and Anbumani N 2011 Dynamics of elastic knitted fabrics for sports wear J. Ind. Text. 41 13–24
[5] Chen J, Wen X, Shao Y et al 2020 Highly stretchable, stability, flexible yarn-fabric-based multi-scale negative poisson’s ratio composites Compos. Struct. 250 112579
[6] Yin Y, Mo J and Feng J 2020 Conductive fabric patch with controllable porous structure and elastic properties for tissue engineering applications J. Mater. Sci. 55 17120–33
[7] Wang Y et al 2021 A highly stretchable, easily processed and robust metal wire-containing woven fabric with strain-enhanced electromagnetic shielding effectiveness Textile Res. J. (https://doi.org/10.1177/0040517521994891)
[8] Zhu M et al 2020 Fluidic fabric muscle sheets for wearable and soft robotics Soft Robotics 7 179–97
[9] Wang Y, Gordon S, Yu W and Li C 2020 Twist-dependent behavior of helical-shaped elastic composite yarns containing metal wire produced on a modified ring spinning system Polym. Text. 91 106822
[10] Nyoni A B and Brook D 2010 The effect of cyclic loading on the wicking performance of nylon 6.6 yarns and woven fabrics used for outdoor performance clothing Textile Res. J. 80 720–5
[11] Fanguerre R et al 2010 Wicking behavior and drying capability of functional knitted fabrics Textile Res. J. 80 1522–30
[12] Zhu C and Takatera M 2015 Effects of hydrophobic yarns on liquid migration in woven fabrics Textile Res. J. 85 479–86
[13] Lei M et al 2020 Effect of weaving structures on the water wicking-evaporating behavior of woven fabrics Polymers 12 422
[14] Wang Z et al 2019 Effect of polyethylene film lamination on the water absorbency of hydrophilic-finished polypropylene non-woven fabric Fibers Polym. 20 1404–10
[15] Hassan T et al 2020 The assessment of finishing properties on the mass per unit area, pilling, bursting strength, and wicking behavior of polyester weft-knitted jersey fabric Coatings 10 723
[16] Guo J et al 2016 Quantifying water removal rate of a wicking geotextile under controlled temperature and relative humidity J. Mater. Civ. Eng. 29 4016181
[17] Wang Y, Yu W and Wang F 2019 Structural design and physical characteristics of modified ring-spun yarns intended for e-textiles: a comparative study Textile Res. J. 89 121–32
[18] Castro C, Rosillo C and Tsutsui H 2017 Characterizing effects of humidity and channel size on imbibition in paper-based microfluidic channels Microfluid. Nanofluid. 21 21
[19] Laughlin R D and Davies J E 1961 Some aspects of capillary absorption in fibrous textile wicking Textile Res. J. 31 904–10
[20] Nyoni A B and Brook D 2006 Wicking mechanism in yarns — the key to fabric wicking performance J. Textile Inst. 97 119–28
[21] Wang Y, Yu W and Wang F 2019 Structural evolution and predictive modeling for nonlinear tensile behavior of tri-component elastic-conductive composite yarn during stretch Textile Res. J. 89 487–97
[22] Erdumlu N and Saricam C 2013 Wicking and drying properties of conventional ring- and vortex-spun cotton yarns and fabrics J. Textile Inst. 104 1284–91
[23] Feng C and Janssen H 2016 Hygric properties of porous building materials (II): analysis of temperature influence Build. Environ. 99 107–18
[24] Feng C and Janssen H 2018 Hygric properties of porous building materials (III): impact factors and data processing methods of the capillary absorption test Build. Environ. 134 21–34
[25] Songok J, Salminen P and Toivakka M 2014 Temperature effects on dynamic water absorption into paper J. Colloid Interface Sci. 418 373–7
[26] Karagiannis N et al 2016 Effect of temperature on water capillary rise coefficient of building materials Build. Environ. 106 402–8
[27] Novakovic M S et al 2020 Liquid transfer properties of textile fabrics as a function of moisture content Hemijska Industrija 74 119–32
[28] Yang X, Wang W and Miao M 2018 Moisture-responsive natural fiber coil-structured artificial muscles ACS Appl. Mater. Interfaces 10 32256–64