A DESIGN-DRIVEN CREATION OF AN INNOVATIVE AND ENVIRONMENT-FRIENDLY NATURE-BASED YARN WITH MOISTURE WICKING AND FAST-DRYING EFFECT

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Certificate of Originality

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Abstract

Wicking in textiles is a key evaluation of fabric moisture permeability. Moisture transfer in textiles has been found to be dominative to the comfort-maintaining mechanism of apparel products, especially for sportswear that has high requirements for sweat transfer. To further develop apparel products with better moisture wicking performance, various approaches such as using polymers, multilayer fabrics, spacer knitting structures, and chemical additives have been proposed by both the academia and industry to help athletes achieve excellence. However, limitations exist in various aspects and a better solution is always required. Among all the moisture transport manipulation methods, fiber modification is the most direct and ideal way to improve fabric behavior since the performance of fabric is dominated by its main fibers' properties. By selecting appropriate fibrous material, fabrics with high moisture wicking ability can be achieved via various weaving constructions and thus less structure and design limitations during garment design processes. Synthetic fibers are widely used in current market-available sportswear products for the past decades due to their low cost and convenient moisture permeability management although they were found to be more suitable for bacteria growth. On the other hand, cotton fibers exhibit natural antibacterial properties as well as softness, comfortable touch feeling and environmentally friendly characteristics. However, cotton fibers are usually not preferred in sportswear because the tendency to retain water and cause burden, bringing challenges to the wearing experience under sweat condition. In our previous work, an innovative spinning technology was proposed with the aim to develop a structure-based fiber modification system for ecological yarns with high-moisture wicking properties and environmental sustainability. The developed yarn constructions combined the advantages of cotton and synthetic fibers, showing significant improvements on moisture wicking performance, fast-drying effects as well as high commercial values.

In this thesis, a design-driven yarn structure spinning model for moisture wicking improvement was established by using a helically shaped covering material to limit the inter-fiber spacings of the staple core yarn so that an improvement in effective capillary channels with better continuity can be achieved. A total of six batches of yarns were prepared and studied, whose results were adopted to revise the spinning parameters so that an optimal spinning method was explored. The method was developed based on yarn construction by pure physical modification involving yarn twisting technique and covering technology. Multiple materials were attempted and the results showed no specific limitations to the raw materials. The wicking heights of novel yarns were significantly improved compared with the control groups. Experiments of the fabrics made in accordance showed consistent results with the yarns. The structure of yarns was compared and analyzed using resin setting, optical microscope, infrared camera and MetLab. The curves of wicking heights versus time matched the square law with successful improvements on both wicking heights and rates of the novel yarns. The spinning parameters were modified for each batch of yarns and fast-drying effect was achieved. Besides, supplementary experiments about cotton shrinkage and yarn twisting were designed to have a better understanding on factors related to washing and spinning. The preferred spinning parameters were established based on series of experimental results.

The study in this thesis offered the possibility to a fiber moisture performance modification with high efficiency, low cost and environmental sustainability. Through various stages of experiments, the optimal spinning parameters were investigated, which provided methods and established foundations for subsequent research. The yarn performance is directly improved without affecting the subsequent processes of knitting, dyeing and garment design. In summary, the research conducted in this thesis has promoted the exploration and development of the innovative spinning technology, which would be more than promising in moisture wicking materials in the apparel market.

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Chapter 1 Introduction

1.1 Motivation of the Research

The movement of moisture, which is strongly related to insensible heat transfer, is a key property for the evaluation of the comfort level of textiles. It was found that moisture transfer, together with heat transfer between human body and the external environment can dominate the comfort-maintaining mechanism of textiles and clothing [1]. Therefore, the manipulation of moisture movement in textiles is of great significance for apparel products, especially those related to athletics, general summer sports, and other situations that require high quality of wearing experience.

Athletes could face a great deal of problems during training and competition, including but not limited to hot feeling, sweating (which causes sticking of fabrics on skin) and extra weight of the fabric [2]. The moisture kept in the fabric could increase the skin-textile friction, making it easier for skin to get blisters and inflammation under wet condition [3]. Such threats not only cause bad performance during competition, but also endanger the health of athletes in the long term. As a consequence, it is generally suggested that sports fabrics possess ultra-breathable and fast drying properties [4]. Basic requirements for sportswear include active stretch, lightweight, breathable, moisture move, quick-dry, packable, etc. Among all of the general requirements, high moisture transfer performance and fast-drying properties are the most important ones as they are crucial to a dry and comfortable wearing experience. It is supposed that high-functional sportswear can not only provide cool feeling but also maintain maximum comfort to improve the user's performance.

Various methods have been proposed by both the academia and industry to overcome the above imperfections. Although it is not possible to manage all the requirements for sportswear through a simple construction of a single fiber, relative researches to improve moisture transport performance have never stopped. By changing fiber type, using chemical treatments or modifying weave construction, fabrics with high moisture transport performance could be achieved and help to keep moisture away from the skin as well as maintain a relative dry condition of the body. Current common materials or structures for sportswear include using polymers, fibrous textile structure, special knitting combinations, layered fabrics and other modification in textile structures. Nonetheless, limitations exist for these methods and a better solution is always required for the improvement of moisture transport function. Typical limitations can be summed up as the following aspects: potential pollutions for materials using chemical additives, short duration after laundering, additional thickness and weight burdens, high price and complex manufacturing process, and inefficiency in wicking and drying improvement. Despite of the concerns mentioned before, there is material limitation for most of the current available moisture wicking techniques. Callewaert et al. [5] found that stink-causing bacteria problem is more serious on polyester, which causes such fabrics give off more stench after sweating than natural fibers such as cotton. Since many of the current moisture wicking fabrics use synthetic fibers, it would be a breakthrough if a material-free method could be proposed. Besides, practices showed that the performance of fabric is dominated by its main fibers' properties, indicating that fiber treatment would be a more direct and ideal way to improve fabric behavior with better duration and stability [2].

Depending on the situation of current market, the requirements for ideal moisture wicking products are summarized as follows:

1. The fabric should show high moisture absorbing ability and achieve fast dry property. The most important feature of the fabric would be absorbing sweat on the skin quickly and transporting it directionally to the outside. Despite of longitudinal transportation, it should allow sweat spread and diffuse in a large area so that the evaporation can be accelerated [6].

2. The additional weight gained by the material under various situations should be

limited and controlled to an affordable amount. For instance, some natural materials such as cotton and wool would absorb and retain large amount of moisture under high humidity conditions, resulting in a lower drying speed and poor water absorption ability. Unwanted burden will then be added due to the extra weight of water retained by the fabric, causing limitation to performances of the wearer, especially for athletes.

3. The material should keep a low friction with the skin and help to reduce the risk of skin injury. A high wicking ability and dry-keeping ability of material is required.

4. The material should be helpful to compress the growth of microorganism. Many synthetic fibers such as polyesters, provide an easier condition for bacteria microbes, especially in the warm and humid environment after sweating. The thrive of microorganism can not only lead to unfavorable stink but also bring about health problems.

In addition to the objective sportswear requirements, people are no longer satisfied with traditional thin and breathable fabric for summer with the development of advanced technology and improvement of living standard. Multifunctional and high-performance textiles have been occupying an important part in the market, especially for sportswear. Advanced performance sportswear is attractive not only for professional athletes, but also for general consumer and people who practice sports just for fun or fitness. The global smart textile market dynamics indicates a rapid growth of smart textiles due to rise in demand for higher quality fabrics. According to Global Industry Analysts, Inc., the global market for sports or fitness apparel is predicted to reach US$231.7 billion by 2024. Besides, Asia-Pacific region is expected to be one of the most fast-growing regions, with a compound annual growth rate of 6.9% [7]. It seems that the consumers are prepared to spend appreciable amount of money on such functional apparel products. In the competition for the market share, the innovative improvement of functions to fulfill the high-performance demand is especially crucial.

Therefore, the development of an environmentally friendly nature-based yarn with outstanding moisture transport performance and fast drying properties is desired both academically and economically.

1.2 Aim and Objectives

The proposed study aims to develop a structure-based spinning system for ecological yarns with high moisture-wicking properties. To achieve the aim of the study, three objectives were set and listed as follows:

1. Establish a yarn-structure spinning model for yarn moisture-wicking and fast-drying performance improvement.

2. Establish a new systematic yarn-structure-based technology (with natural materials > 80%) to find out the most effective yarn production plan based on the yarn testing results.

3. Establish the fabrication structures of fabrics and investigate the moisture transport and fast-drying improvements of fabrics made in accordance.

4. To explore the influence of cotton washing and spinning twist on the wicking performance of yarns.

1.3 Methodology

To fulfill the above aim and objectives, both theoretical and experimental approaches have been adopted. The overall workflow is summarized in the following flowchart as shown in figure 1.1.

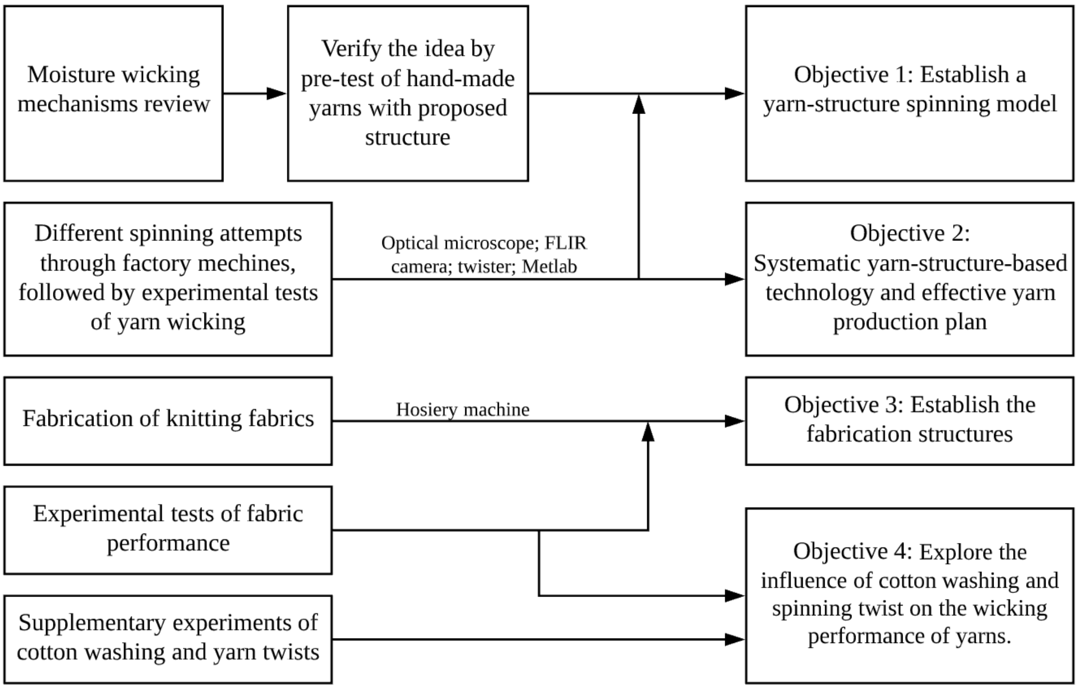


Figure 1.1. Flowchart of the research steps.

As a design-driven creation, the research step is oriented by the achievement of the objectives. Correspondingly, the subsequent research plan can be divided into four steps: 1) establishment of a yarn-structure spinning model and conduct a pre-test to verify the efficiency of the proposed structure; 2) establishment of a new systematic yarn structure-based technology by design and selection of yarn parameters; 3) fabrication structures of fabrics and test of performance; 4) supplementary experiments design.

After verifying the efficiency of the structure by a pre-test, wide range of parameters were set and attempted at the initial stage, followed by experiments and yarn selection according to the test results. After several rounds of yarn spinning and testing, the optimal parameter for yarns were established. Fabric performance investigation was then conducted. Due to the requirement of yarn covering technology, cooperation with factories was necessary. The tests of yarns mainly focused on capillary action, while the tests of corresponding composite fabrics have referred to PRC standard GB/T21655.1-2008 with necessary adaptions. The tests included capillary action test, drip diffusion time, water absorption rate, and evaporation rate.

The workflow details are explained as follows.

1. Pre-test of hand-made yarns to verify the efficiency. A pre-test with hand-made yarns was conducted to verify the efficiency of the assumption. Pure core yarn without treatment and covering material was used as the control group. The spinning of proposed structure included three gradients of tightness (thick): natural loose state, half-tightened by covering material and fully tightened by the covering material, in order to simulate the influence of yarn twists. Relation between covering tightness and wicking height was investigated. For the hydrophilicity of yarns, a comparison between capillary action of control group and novel yarns after treatment was managed as the tool to verify the efficiency.

2. Establishment of a new systematic yarn structure-based technology. The first batch of yarns with a wide range of parameters was prepared by three respective cooperative factories so that the most suitable and effective covering technology can be established by various attempts. Capillary tests of yarns were firstly conducted using ink and recorded by a regular camera. To eliminate the influence of pigments, forward-looking infrared (FLIR) camera was later adapted so that deionized water can be observed. Screening of yarn parameters was then conducted based on the moisture wicking ability. More batches of yarns and further experiments together led to final optimal yarn spinning parameters. For the yarn spinning after the first batch, components of yarns were controlled so that the percentage of natural materials was larger than 80%. The core materials could be either cotton or cotton/linen blended materials. Different ratio of materials for the core yarn were tried. PET and PA were adopted as the main source for covering materials, depending on the behavior and availability of yarns.

3. Experiments of fabrics made in accordance. Moisture wicking can be affected not only by structure of yarns but also by that of fabrics. Considering the wide range of parameters and categories of yarns, the most efficient way to fabricate knitting

fabrics would be by the hosiery machine, which could knit small quantity of knitting fabrics without yarn waste. The following experiments investigated moisture wicking ability of fabrics. Capillary action test, drip diffusion time, water absorption rate and evaporation rate were covered in the tests, generally following the PRC standard GB/T21655.1-2008.

4. Further investigation of wicking mechanisms by experiments of cotton washing and yarn twisting. Supplementary experiments were designed to have a better understanding on factors related to washing and spinning twists. Comparison between the control and novel groups were analyzed using optical microscope, infrared camera and MetLab.

1.4 Significance and Values

Successful application of the proposed structure would bring a breakthrough to the current apparel market which focuses on moisture transport. The structure is mainly based on physical modification, which does not include chemical additives and thus is environmentally friendly. The structure owns fabrication process that is relatively simple compared to current methods. More importantly, the material-free structure can be applied on a wide range of materials, making it possible to reuse the dead stocks by a simple step of reprocessing. In brief, the development of a new technology that fulfills the above requirements is more than promising in the market as heat and moisture balance between human body and clothing is essential to clothing comfort. The application of such technology would be especially significant to athletes who usually undergo high function activities.

1.5 Thesis overview

The thesis chapters are organized as follows:

Chapter 1 presents a general introduction to the study. Requirements and limitations of current market available sportswear products with improved moisture wicking performance are firstly introduced. With the purpose of fulfilling the requirements and overcoming the limitations, the aim and objectives of the study are listed. The methodology of the research is discussed to fulfill the objectives. Then, the significance and values of the study are presented to verify the research necessity. Finally, an overview of the study is provided as a reading guide to the thesis.

Chapter 2 reviews the previous relative studies and the representative moisture transport manipulation approaches. A research gap is identified. The mechanisms of moisture wicking in textiles are investigated. Then the factors that affect wicking performance are discussed, including the effects of twists and tension, roughness of yarns, and influence of moisture absorption.

Chapter 3 presents the innovative fiber modification methodology. The principles of the proposed yarn structure-based modification technology are introduced, followed by wicking improvement mechanisms and advantages of the novel structure.

Chapter 4 presents the experiments, results and analysis of the study. A summary of fabricated samples and introduction to experimental methodology is first introduced. A total of six batches of yarns were prepared and tested in five stages of experiments, including capillary wicking tests of yarns, moisture transport tests of fabrics made in accordance, as well as cotton shrinkage under different washing conditions.

Chapter 5 summarizes the conclusions and limitations of the study. Recommendations for future work are listed at the end of the thesis.

Chapter 2 Literature review

2.1 Introduction

Wetting, wicking and drying mechanisms are the main factors related to the comfort properties of fabrics. The diffusion of vapor was the major mechanism for moisture transport and it mainly occurs at high moisture content [8]. The amount and rate of water transport are affected by many factors such as the pore sizes and volumes of fabrics, external pressure, fabric thickness and the way that fabrics contact with other [9-11]. The time of drying was found to be dependent on the water holding capacity of the fibers [12]. The properties of fibers also affect the wetting and drying mechanism. For instance, water absorbent acrylic fibers could dry more easily [13]; and Çil et al suggested that longitudinal wicking ability increases with coarse yarns while drying ability increases with finer yarns. Both abilities increase with higher acrylic fiber ratio [14].

Although the wicking and drying mechanisms are complicated and not fully understood, we can still find many systematical calculations and model developed by previous researchers. Through this chapter a number of theories and mathematical calculations will be presented and discussed, with the purpose of addressing the research gap and developing a better fiber modification model in the next chapter.

2.2 Moisture transport improvements of sportswear fabrics

Comfort is an important and widely accepted criterion of selecting clothing for both daily life and sportswear. According to Goldman, moisture transport is a significant factor that affects “wearer feel” [15]. The mechanism of human body maintains heat balance through sweating. A person usually produces about 80 watts metabolic heat in normal condition, while during high function activities, the heat production may rise up to over a kilowatt in quite short time [16]. Sweating helps to reduce heat load and cool the body. People use clothing to help maintain a suitable body temperature and avoid environment hazards, especially under extreme cold conditions. However, despite of warm-keeping effect, inappropriate materials of apparel products might bring unnecessary thermal insulation and hinder free evaporation, thus affect equilibrium of the human-clothing system.

In addition to wearing experience, a warm and dry skin-clothing environment is also beneficial to human health. For Instance, the comfort of the vasomotor regulatory zone and sweat compensable temperature regulation could be largely affected by wicking effect of clothing. Fabrics with outstanding moisture transport performance can help to regulate body temperature and muscle functions, as well as delay the feeling of exhausted [17]. Although the definition of “comfort” is ambiguous, the importance of thermos-physiological comfort, i.e., the movement of heat and moisture is commonly accepted [18]. Hence the selection of fabrics with excellent wicking performance is significant during the production of high-performance clothing.

Moisture wicking performance of fabric can be improved either by managing the base fiber properties or by modifying the construction of the fabric. Research found that essential properties of fabric include material of base fibers, weave construction, dimensions of the fabric, and chemical additives [19]. Accordingly, common approaches for moisture transport improvement can be summarized as 1) hydrophilic surface treatment; 2) multi-layer fabric construction; 3) spacer knitted structure; and 4) fiber selection and modification.

2.2.1 Hydrophilic surface treatment

Hydrophilic treatment can be achieved by using chemical additives during the fabric finishing process. For instance, Lark proposed a fabric coating process that cures esterified acidic group onto fiber surfaces so that a hydrophilic fabric finish can be adopted to modify hydrophobic polyamide and polyester fibers into hydrophilic ones

[20]. Stockton and Ware proposed a hydrophilic surface treatment by applying additives, such as silica, on the surface of fabrics to attract water, helping to pull the moisture into the fabric and volatilize into the air so that moisture transfer from one side of the fabric to the other side can be attained [21].

Concerns of such chemical coating method include that the duration is usually unsatisfactory. The shedding of additives after repeated laundry destroys the additional hydrophilic property of the fabric, leading to the original behaviors of the base fiber. Besides, there might be pollution or toxicity problems of the wastewater both during production and washing. Pollution prevention has always been a major concern faced by the textile industry. Industrial practice found that in addition to the complying with regulations, there are also huge potential economic benefits from reducing treatment processes [22].

2.2.2 Multi-layer fabric construction

It has been quite common for functional sportswear to use dual or triple layers of fabric construction to regulate humidity and temperature of body-clothing environment. Layers with distinct functions jointly keep thermos-physiological comfort of clothing [23]. The inner layer is usually supposed to have good skin adaptability, appropriate warm keeping function and excellent wicking effect so that the perspiration of skin can be wicked into be outer layer. The outer layer is also supposed to have high air permeability so that water absorbed from the inner layer can evaporate to the atmosphere quickly. Aschwanden suggested a similar knitting method with two types of fibers. The hydrophilic fiber that touches skin can absorb moisture and wick it to the fiber that faces out [24].

The mechanisms of multi-layer structures do not always follow the same pattern. Structures with hydrophobic inner layer were also investigated. Dong et al proposed a dual layered non-woven structure for sportswear [25]. Fibers of the inner layer possess a core-shell structure, with hydrophobicity and low friction. Moisture is pushed into the inner layer and pulled away from skin by the outer layer, which is a hydrophilic thick base-treated cellulose acetate nanofibrous mat. The large hydrophobicity difference between the inner and outer layer provides driving force for the water transport and thus help moisture evaporation. Figure 2.1 depicts the mechanism of such non-woven mats.

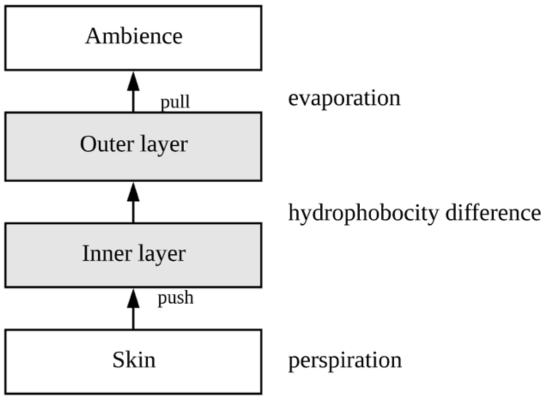


Figure 2.1. Schematic diagram of a dual layered moisture evaporation mechanism.

Another method is to use a three-layer structure which can absorb water by the inner layer and draw it to the outer layer, some also proposed as 3D spacer knitted fabric [26]. Miao et al proposed a tri-layer fibrous membrane with non-woven mats contain three layers, a hydrophobic polyurethane inner layer, a hydrolyzed transfer layer that can guide water directionally and an outer layer that can help water evaporation and achieve quick dry jointly [27]. The combination of the tri-layer composite and the progressive spread of moisture is depicted in figure 2.2.

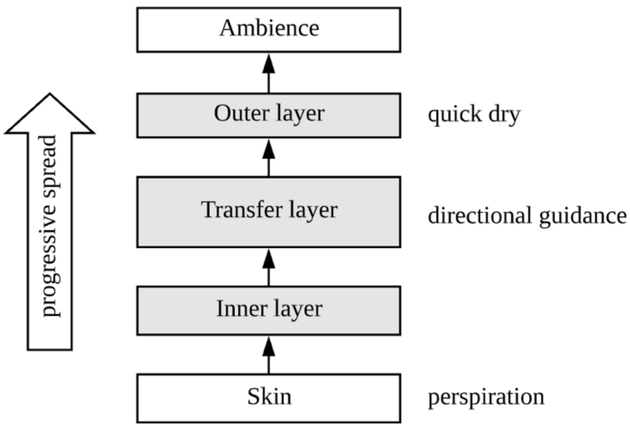


Figure 2.2. Schematic diagram of a triple layered moisture evaporation mechanism.

Although the multi-layer structure helps to improve moisture evaporation speed, limitations exist. One of the biggest problems is higher thickness. The non-woven structures as shown in the previous two cases bring about many limitations to the comfort and diversity during design of fabrics. It is inevitable that such multi-layer knitting fabric possesses a higher thickness and weight that would cause extra burden to athletes, especially after sweating. To avoid additional construction burdens, water absorption improvement from fibers would be more fundamental and effective.

2.2.3 Spacer knitted structure

3D knitted fabrics can be attained by combining multi-surface fabrics with pile yarns. Other than high air and moisture permeability, such fabrics can also be durable, breathable and protective. Companies such as Baltex. Co. provides various of three-dimensional knitted fabrics, named as XD Spacer, for multi purposes. Thicknesses of these fabrics ranges from 3mm to 20mm, as shown in figure 2.3 [28]. Although not suitable for sportswear, the technology still shows its' advantages of high air permeability.

figure 2.3. XD Spacer fabrics provided by Baltex. Co.

Recent technology introduced a new thermo-regulation fabric, named Coolcore. The fabric uses multiple fibers to construct a high-density network structure, which helps to control the slow evaporation of water and produce an instant cool feeling. Extra body heat and sweat are distributed by the fabric and managed through evaporation [29]. The fabric provides multiple improvements such as being chemical-free and durable, yet the knitting process remains complicated and the selection of fibers would be rather strict.

Figure 2.4. Coolcore fabric technology.

2.2.4 Fiber selection and modification

The behavior of fabrics is predominantly dependent on the properties of fibers [2]. Fiber selection would influence water uptake, which is critical to clothing comfort factor especially in the condition that the sweat-wetted area exceeds 60%. The performance of fibers can directly influence water permeability and wicking in different areas. By selecting appropriate fibrous material, fabrics with high moisture wicking ability can be achieved via virous weaving constructions and thus less structure and design limitation.

For the past decades, synthetic fibers are widely used in the design of sportswear due to their properties of being soft, light, thin and fast-dry, as well as convenient for moisture permeability management. Polyester, one of the most generally used materials in sportswear, has exhibited wide range of advantages. Fabrics made in accordance are light, stable and durable, with low friction, excellent elasticity and resistance to dirt [30]. Relatively low price is also a competitive quality to common consumers. In addition to the selection of materials, fiber shape modification is available on the market as well. Coolmax provided modified fibers with slightly oblong structure with grooves running lengthwise that draw the moisture away and increase evaporation over a wider surface area. The technology is applied on 100% man-made material [31].

However, with all of the pleasant properties, synthetic fibers are found to be more suitable for bacteria growth. The skin-fabric environment is not sterile. On the contrary, human skin and the external environment bring lots of microorganisms to the clothing textile, which is warm and humid after wearing, providing a favorable condition for bacterial reproduction. Experiments of Callewaert et al found that bacteria growth tends to be different in cotton and synthetic fabrics. By analysis and selective enrichment of the extractives, it was found that micrococci were detected almost only on synthetic clothes. The research made a good proof that the composition of synthetic fibers would promote growth and reproduction of the textile microorganisms, leading to stain, unpleasant odors, even allergies and skin infections [5].

On the other hand, cotton fibers and fabrics are usually not preferred in sportswear because the tendency to retain water and cause burden [32]. Wet and swollen cotton fabrics tend to be cold and adhere to the skin, greatly influencing the wearing influence. Nonetheless, the softness and comfortable touch feeling of dry cotton is irreplaceable for many consumers.

To conclude, current approaches to improve wicking performance are limited by various aspects. Treatment by chemical additives may cause potential pollutions and pure durations. For multi-layer construction and spacer knitted structures, additional thickness and weight burdens would bring design and practical application non-negligible inconvenience. Besides, most of the advanced market-available techniques are expensive, with complex manufacturing processes. Therefore, a structure modification of natural fiber by simple processes is presented in this dissertation, in the hope of fulfilling current research gaps.

2.3 Wicking in textiles

Capillary action, also referred to as wicking, has been found to be a ubiquitous phenomenon in the natural world. The most general examples include wicking in biological cell, in gaps between the hair of a brush, or in non-porous structure such as sand. By systematic comparison of wicking and wetting mechanisms, it was pointed out that wetting, which is the fiber-air interface displacement that takes place at the fiber-liquid interface, is the prerequisite for wicking [33]. Only the liquid that wet fibers can wick into it. Spontaneous wetting happens in a capillary system, no matter with assistance of external forces, e.g., gravitational force, or not. Such spontaneous flow of liquid driven by the capillary forces is referred to as wicking.

2.3.1 Wicking principles in a simple capillary tube

In order to describe wicking process in a straightforward way, a simple case of wicking in a tiny capillary tube was investigated. In a typical evenly distributed capillary tube, the cross section of the tube is much smaller than the wetted inner wall surface, i.e., the area of the liquid-air interface is much smaller compared with the solid-liquid interface. As wicking progresses, the liquid-air interface remains the same. Therefore, the only considerable difference would be the changes of interfaces of the inner capillary wall. The solid-liquid interface increases with wicking while the solid-air interface decreases. Hence a model of spontaneous displacement of theses interfaces can be utilized to envisage the wicking process. From the perspective of energy conservation, the system has to gain energy to keep the process spontaneous, which means a positive work of penetration (W_p). The relation between work of penetration and interfacial energy can be described by equation 2.1,

$$W_p = \gamma_{SV} - \gamma_{SL} \tag{2.1}$$

where γ represents the interfacial energy: γ_{SV} is the interfacial energy between solid and vapor surfaces; and γ_{SL} is the interfacial energy between solid and liquid surfaces.

In equation 2.1, work of penetration is defined as a required energy measurement of spontaneous happening of capillary action. In reality, it is excessively difficult to realize the measurement of γ_{SV} and γ_{SL}, so measurable quantities were introduced in the Young-Dupré equation to describe the solid-liquid boundary of an equilibrium states, as shown in equation 2.2 below,

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} cos\theta \qquad (2.2)$$

where γ_{LV} denotes the measurable interfacial tension at the liquid-vapor surface; and θ denotes the contact angle in equilibrium. It is suggested in both equation 1 & 2 that $\gamma_{LV} cos\theta$ is positive so that spontaneous capillary penetration can take place. Accordingly, equilibrium contact angle θ has to fall in the range from 0° to 90° since γ_{LV} is always positive. The diagram of wicking in a capillary tube can be therefore pictured in figure 2.5. A meniscus is formed in the liquid-vapor interface.

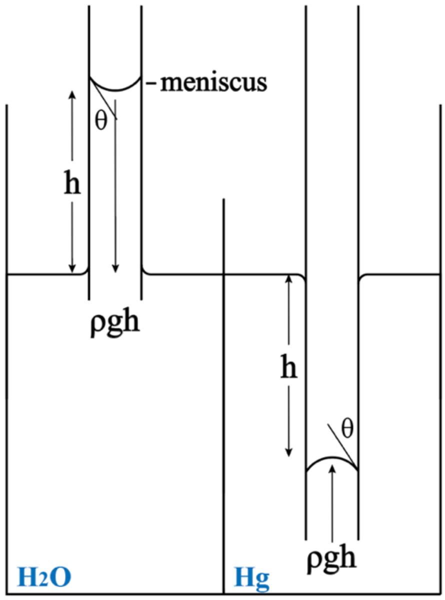


figure 2.5. Water (left) and Hg (right) wicking in capillary tubes.

At the liquid-vapor interface, a pressure difference is introduced by the liquid surface tension and cause the spontaneous flow. The Laplace equation shows the relation between capillary pressure and capillary penetration in an evenly distributed tube with circular cross section,

$$\Delta P = \frac{2\gamma_{LV}}{R} \qquad (2.3)$$

where ΔP is the pressure difference across the meniscus; and R is the radius of the meniscus formed by the liquid-vapor surface. By simple geometric analysis, the relationship between the capillary radius r and radius of the liquid-vapor interface is:

$$\frac{r}{R} = cos\theta \qquad (2.4)$$

which is the case when the inner wall of the capillary tube is not thoroughly wettable.

The Laplace equation can be further denoted as:

$$\Delta P = \frac{2\gamma_{LV}\cos\theta}{r} \quad (2.5)$$

where θ is required to be between 0 to 90° so that the capillary pressure is positive. The equation also demonstrates an inversely proportional relation between the capillary radius and the capillary pressure, i.e., a small radius of capillary tube relating to a higher capillary pressure, and probably have better capillary action compared with larger tube in the same condition.

The pressure difference ΔP is provided by the weight of the liquid column, which is ρgh as depicted in figure 2.5, i.e.,

$$\rho gh = \frac{2\gamma_{LV}\cos\theta}{r} \quad (2.6)$$

where ρ is the density of the liquid; g is the gravity coefficient; and h is the wicking height. The same equation can be achieved from the perspective of equilibrium of forces at the contact points between edges of the liquid surface and the inner capillary wall. By setting constant C and letting $C = 2\gamma_{LV}/\rho g$, equation 2.6 can be transformed into the following shape:

$$\mathrm{h} = \mathrm{C}\,\frac{\cos\theta}{\mathrm{r}} \quad (2.7)$$

where the only variables are θ and r.

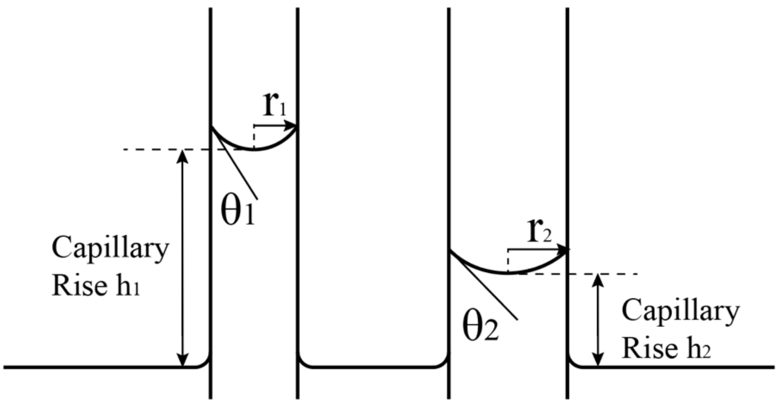


Figure 2.6. Capillary wicking with different radius in the same reservoir.

Figure 2.6 depicts the influence of capillary radius r on the wicking height h and contact angle θ. As r increases ($r_2 > r_1$), it becomes more difficult for the capillary wall to be completely wettable, and θ increases ($\theta_2 > \theta_1$) thus $cos\theta$ decreases, i.e., $1/r_2 < 1/r_1$; $cos\theta_2 < cos\theta_1$, which means $cos\theta_2/r_2 < cos\theta_1/r_1$, i.e., the height of capillary rise will decrease, $h_2 < h_1$.

For water wicking in a single-channel glass capillary in 25°C, capillary rise changes with the tube radii and contact angle, as shown in figure 2.7.

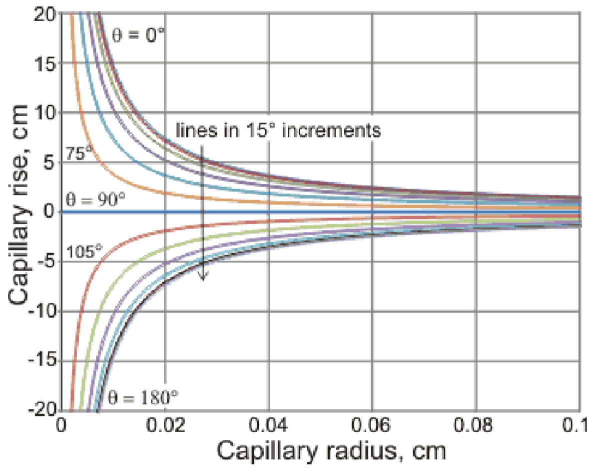


Figure 2.7. Capillary rises with different radii and contact angles [34]

The reciprocal relationship between wicking height and capillary radius is of great importance in practical applications. By limiting capillary spacings of yarn filaments to an appropriate level, wicking can be promoted so that the moisture wicking performance of yarns will be improved.

2.3.2 Kinetics of wicking in a single capillary channel

The rate of wicking is affected by several factors, the interfacial tensions, viscosity of the liquid, wettability of fibers, and capillary dimensions of the substrate [35-36]. The interfacial tension is related to the properties and composition of the liquid. Usually volatile liquids exhibit smaller interfacial tensions. In the normal wearing condition of textiles where all the environmental factors are similar, the interfacial tension can be considered as a constant. Viscosity of liquid and wettability of fibers are considered to be intrinsic properties of materials. Therefore, the dimensions of the substrate would be a crucial condition. To achieve better moisture transport ability, the rate of wicking as a result of dimensions of the textile is important.

Large amount of small capillary spacings are formed during the process of spinning. The fibrous assemblies in capillary action that take places in fabrics are generally considered as a set of parallel capillaries. A meniscus of liquid is formed when wetting happens in a capillary wall and stretched as the wetting line advances. Hence more water is pulled inside the capillary by the contraction of the meniscus, so that the meniscus can maintain an equilibrium state. In real cases, the fibrous assembly is non-uniform and irregular, resulting in a nonhomogeneous system for capillary action. Therefore, the wetting front movement in a capillary system can be viewed as small jumps. In nonideal fluid dynamics, the pressure drop in a given time is expressed in the following Hagen-Poiseuille equation,

$$\Delta P = \frac{8\mu l Q}{\pi r^4} \qquad (2.8)$$

and,

$$Q = \frac{\Delta P \pi r^4}{8\mu l} \qquad (2.9)$$

where Q denotes the volumetric flow rate, i.e., $Q = \frac{dV}{dt}$; μ is the dynamic viscosity; and l is the length covered by the liquid-vapor surface for the wicking time t. Since $V = \pi r^2 l$, the linear flow rate is given in equation 2.10.

$$\frac{dl}{dt} = \frac{\Delta P r^2}{8\mu l} \qquad (2.10)$$

Hagen-Poiseuille equation reveals a negative correlation between wicking distance l and the flow rate. As the wicking progresses, the flow rate decreases, which means the moisture absorb rate will slow done. By assuming a constant contact angle during the wicking process, equation 2.10 was further developed by Washburn and Lucas into equation 2.11 [37].

$$\frac{dl}{dt} = \frac{\gamma r cos\theta}{4\mu l} \qquad (2.11)$$

Despite of existence of limits, research found that quite a few of liquids have obeyed the kinetics of the equation [38]. Taking into account the inertia of the flow and considering the fully wettable condition, i.e., when the contact angle is zero, the flow rate can be further derived from the Poiseuille equation:

$$\frac{dl}{dt} = \frac{2\gamma r}{8\eta l} - \frac{\rho g r^2}{8\eta} \tag{2.12}$$

where ρ is the density of the liquid, and g is the gravitational constant. In order to find the correlation between wicking distance and time, terms α and β are introduced and defined as $\alpha = \frac{2\gamma r}{8\eta}$; $\beta = \frac{\rho g r^2}{8\eta}$. Equation 2.12 is thus simplified in the following form:

$$\frac{dl}{dt} = \frac{\alpha}{h} - \beta \tag{2.13}$$

At the beginning of the wicking process when $t = 0$, the wicking height is also zero. By integrating equation 2.13 and applying the zero-time condition, it gives

$$\beta t = h_m \, ln \frac{h_m}{h_m - h} - h \tag{2.14}$$

where h_m is the maximum of wicking height after infinite time. Plotting equation 2.14 gives a square law in the form of $h^2 = C_2 t$, where C_2 is a constant approximate to be $2\beta h_m$ by expanding the logarithmic term in equation 14 [39]. Figure 2.8 demonstrates approximate time relation of h in a single channel capillary wicking system.

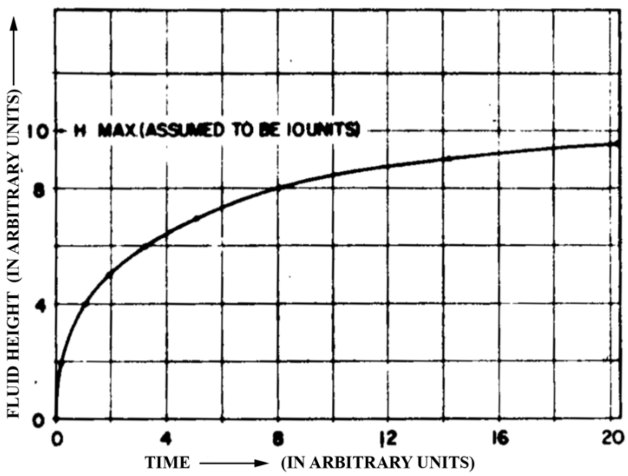


Figure 2.8. The square form relation of height versus time in an ideal single capillary channel [39].

There are quite a few reasons that might affect the happening of wicking. For instance, the morphology of the fiber surface could have large influence on wicking ability of yarns and wicking may also be influenced by the shape of fibers [33, 40]. Moreover, as a dynamic process, the kinetics of wicking might be complicated during the process. The term capillary penetration is used to describe pure wicking process that happens only in the capillary spacings, without diffusion or adsorption of liquid into fibers. However, when water wicking into a cotton fabric happens, it is accompanied by liquid diffusion. The absorption of liquid might result in swelling and then reduce the capillary spacings in the yarns. Therefore, it might be helpful to reduce water retain of wet cotton and improve moisture transportation by limiting the over-swelling of cotton fibers.

2.3.3 Wicking in a finite reservoir

Generally, there are two main reservoir conditions of fabric wicking process, one is the infinite reservoir such as wicking in a simple capillary tube; the other is the limited reservoir such as wicking of a water drop on the fabric. Figure 2.9 shows the diagram of these two wicking mechanisms. The dashed lines with arrows indicate the movement of liquid.

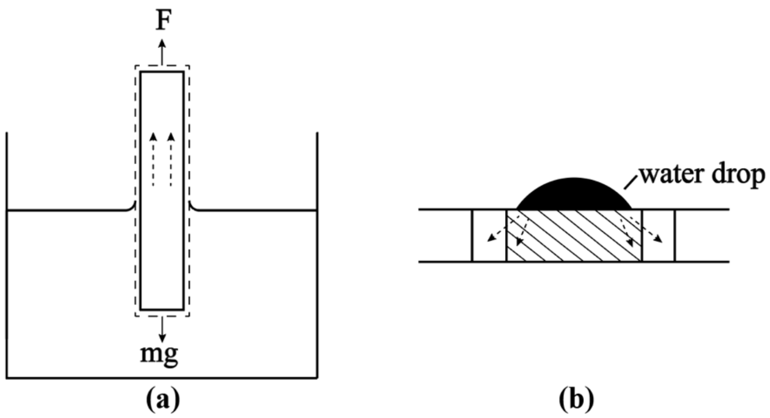


Figure 2.9 Wicking from (a) infinite reservoir; and (b) finite reservoir.

When wicking into textiles happens, the progress of absorbing respiration and other liquids from the skin and evaporating to the ambient is more similar to wicking in a finite reservoir. Horizontal wicking in an infinite longitudinal is given by the Washburn-Lucas equation:

$$l^2 = \frac{\gamma R_p cos\theta_a}{2\mu} t \quad (2.15)$$

where l is the distance covered by the liquid front; γ is the surface tension; R_p is the effective hydraulic radius of the yarn pores; θ_a is the apparent contact angle; μ is the viscosity; and t is the penetration time.

The wicking kinetics of a small liquid droplet absorbed into a horizontal yarn was investigated by X. Chen et al to develop the relationship between initial droplet volume and the time required by the droplet to disappear [41]. Figure 2.10 exhibits the disappearance of a hexadecane droplet into a polypropylene yarn.

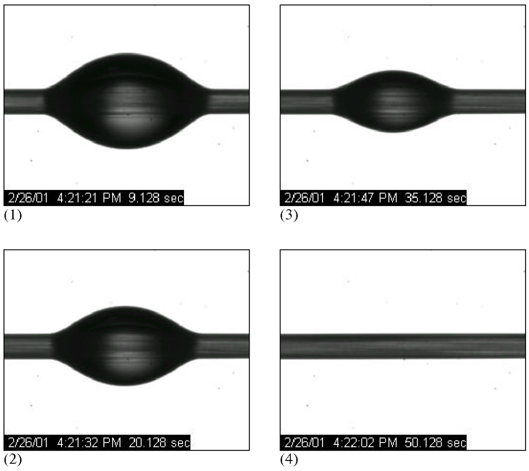


Figure 2.10. A hexadecane droplet was absorbed into a polypropylene yarn [41].

When the droplet is small enough so that gravitational force is negligible compared with the surface tension, it can be considered as an axisymmetric fusiform. By analyzing the pressure difference between the liquid front and the droplet and further calculations combining with the Washburn-Lucas equation, the general relationships between disappearance time and initial droplet volume were given in the following equation.

$$V_0^2 = \frac{2\varepsilon^2\pi^2 r^4 \gamma R_p cos\theta_a}{\mu} T_w \tag{2.16}$$

The denotations are: V_0 is the initial liquid volume that has been fully absorbed by the yarn at $t = T_w$; ε is the porosity of the yarn; r is the yarn radius; and T_w is the time required to absorb the droplet. The equation is suitable in the condition that the droplet is of wetting liquids. The equation falls into the Washburn-Lucas type, where the time required for fully absorption of the liquid droplet is linearly proportional to the square of initial droplet volume. The linear relationship has been verified by experimental data.

Wicking of a droplet into the surface of textile is a complicated process under the influences of both gravitational force and capillary forces. The process can be briefly divided into two steps. 1) Diffusion and penetration of the water droplet into the spaces in the weaving construction of the fabric; and 2) the liquids on the surface of yarns wick into the effective capillary channels of the fabric fibers, which is similar to the process of longitudinal wicking from an infinite reservoir [42]. Gillespie proposed two phases when spreading liquids in paper, Phase I: residual liquid remains on the paper surface; and phase II: the liquid is totally retained by the paper [43].

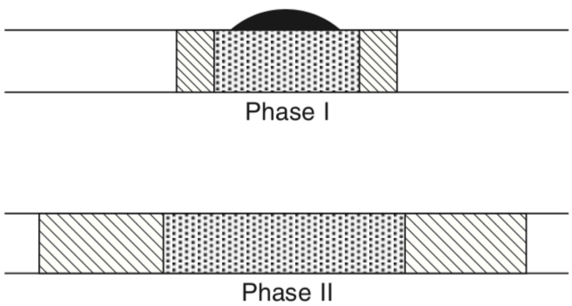


Figure 2.11. Two phases of wicking in paper from a droplet [44].

The liquid is totally contained within the paper substrate in phase II. Ideally a radial escalation will take place, resulting in a well circular shape of water absorption, as measured in Gillespie's experiment. Nonetheless, different from paper, one important feature of textiles is anisotropy. The irregular shapes of water diffusion on fiber assemblies of textiles made it exceedingly difficult to define a uniform radius. Therefore, the substitute method would be measuring the area covered by water so that the measurement of radius could be exempted. Kissa developed Gillespie's equation by measuring the spreading area and gave the following equation that defines the relationship between area covered by water spreading and time,

$$A = K\left(\frac{\gamma}{\mu}\right)^{e} V^{m} t^{n} \tag{2.17}$$

where *A* represents the spread area covered by water; *K* represents the capillary sorption coefficient; *V* represents the initial volume of the liquid; *t* is the time taken; and *e, m, n* are constants, which is usually 0.33, 0.67, and 0.33 [45-46]. In complicated cases when swelling exits, the exponent n might become a variable that changes according to the initial droplet volume.

The wetting process into textiles can be considered as the happening of two independent processes, the escape of air in the spacings; and penetration of liquid by advancing of the liquid-vapor surface [47]. As the capillary penetration happens, the inter-fiber spacings for further capillary wicking are decreased due to swelling, especially for cotton fibers.

To conclude, the wicking processes are complicated in fibers and fiber assemblies. It is of great significance to understand the essentials of wicking kinetics since most processes related to the wearing experience are greatly influenced by the time factor. The following section will discuss factors of textiles that influence wicking performance.

2.4 Factors that affect wicking

Wicking and wicking rate can be affected by many factors. One apparent factor is the material composition of yarns. A wicking test of acrylic-cotton yarns showed that when the acrylic ratio increases, the wicking height of yarns tend to increase accordingly [48]. Despite of intrinsic properties of materials, coarser yarns have a faster wicking rate compared with finer yarns [44, 49], which is consistent with Kissa's opinion that the surface morphology affects capillary action [33]. For fabrics, capillary spaces exist both inside the yarns and in the structure between the yarns. Usually, yarn wicking is the most significant role in fabric wicking no matter in course or wale direction [48]. Another influential factor is the tightness of fibers. Effect of twist in yarns showed two different responses at different stages. Generally wicking is reduced in more twisted yarns yet experiments also found a sudden increase in wicking could appear at higher twist levels as a result of spiral wicking [50].

The increase or decrease of wicking by parameter changes is a complicated process. This section discusses the factors that affect wicking of fibers or fiber assemblies, with the purpose of developing better moisture transport properties by physical modification of yarns. Leading factors include yarn twists, yarn uniformity and the effect of moisture induced changes will be covered in the following sub-sections.

2.4.1 Effects of twists and tension

Minor et al conducted an experiment of viscose yarns and found that the wicking rate of tightly packed yarns was largely diminished due to the reduction of the spacings between the fibers when tightened by tension and twisting [51]. When the irregular cross sections of fibers mesh like gear teeth, the yarn diameters seldom change during twisting, while the spacings between the fibers were greatly reduced. As a result, the wicking rate of the tightened yarns was adversely influenced. The result of the experiment indicated the importance of appropriate spacings during wicking processes. Nonetheless, further research found that tension and twisting have more complicate influences on wicking. An increasing load in yarns resulted in larger capillary forces, which would improve the wicking performance [52].

In order to establish a systematic method to investigate the influence of tension and twist on wicking performance of yarns, Liu et al developed a mathematical model by introducing a twist coefficient to the force equilibrium system of fibers in yarns [53]. To simplify the yarn construction and calculation, a typical yarn was considered as a uniform cylinder with fibers helically arranged in parallel around the central axis of the cylinder. Such helical paths have different radii for different bunches of fibers and therefore can be expanded into rectangles with different widths. Figure 2.12 demonstrates the helical path of an outer fiber and its rectangular expansion, where H is the height required for the fiber to wrap around the cylinder; r is the radius of the cylinder, in which case also the radius of the idealized yarn; L_f is the length of the fiber segment; and α is the angle between the fiber and the vertical line.

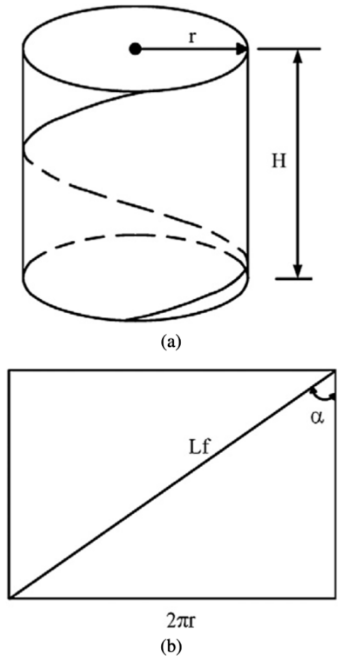


Figure 2.12 (a) Idealized helical path of an outer fiber; (b) Expansion the helical path by flatten the lateral surface of the cylinder [53].

For a vertically draped yarn, the wicking height of liquid in the yarn is determined by the capillary force, the gravitation force, the viscous drag and the inertia. The interaction on the liquid-solid interface provides an upward capillary force F_{cu} while the meniscus of the liquid-vapor interface provides a downward capillary force F_{cd}. Hence the capillary force F_c is given by

$$F_c = F_{cu} - F_{cd} = F_{cu} - P_1\gamma \tag{2.18}$$

where P_1 represents the liquid cross-sectional perimeter; and γ represents the surface tension of the meniscus, i.e., surface tension of the liquid.

To determine the viscous drag, a twist coefficient λ was introduced so that

$$F_v = \lambda kl\frac{dl}{dt} \tag{2.19}$$

where F_v is the viscous drag, k is the frictional coefficient; and l is the wicking height. Since the liquid acceleration is in a small-scale and hence the inertia can be neglected, according to the force balance of the capillary liquid,

$$F_c - G - \lambda kl\frac{dl}{dt} = 0 \tag{2.20}$$

where G is the gravitational force of liquid. By integration and applying the balances of forces in the initial and equilibrium states, the solution of t was determined as

$$t = N(l_e ln \frac{l_e}{l_e - l} - l) \tag{2.21}$$

where N is defined as $N = \frac{\lambda k}{\rho g A}$, ρ is the liquid density; g is the gravitational constant; and A is the cross-sectional area of the liquid. The term $\frac{k}{\rho g A}$ is a constant for a given liquid and idealized yarn in a specific wicking process, therefore N is dominated by the twist coefficient λ with a linear relationship, where the slope is determined by the term $\frac{k}{\rho g A}$.

Subsequent experiments showed a good consistent between the mathematical calculation and the experimental results, as exhibited in figure 2.13.

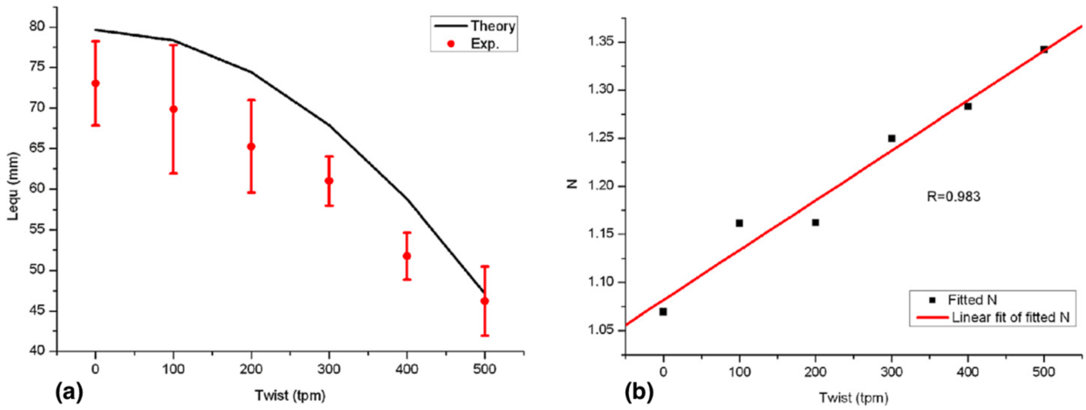
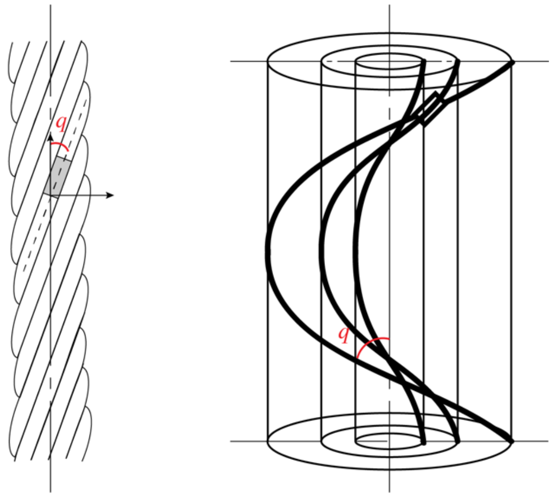


Figure 2.13 (a) The influence of yarn twist on equilibrium wicking height and comparison between the experimental result and mathematical calculation; and (b) Experimental linear fit of N as a result of yarn twist [53].

With explainable deviation, figure 2.13 (a) shows a good prediction of the trend of equilibrium wicking height as a result of changing yarn twists. The deviation of experimental data at lower twisting levels may be caused by fiber arrangement differences between real yarn and the idealized model. The calculation assumed an open packed arrangement of fibers while when twist is small, it was difficult for fibers to be packed ideally. When twist increases, the fibers were squeezed towards the yarn center and form a more ideal open packing arrangement. Therefore, the experimental results became better matched to the theoretical value as yarn twists increase. Figure (b) depicts a quite good match between theoretical and experimental value and further verified the linear dependence of *N* on the twist coefficient. The experimental results together showed a general negative correlation of equilibrium wicking length and yarn twists, which indicates that a smaller but appropriate twist value of yarn is preferred for the improvement of wicking performance.

The mechanical properties of a single fiber in a staple yarn are also closely related to yarn twisting. Assume figure 3.5 (a) is an ideal staple yarn with packing properties defined by Hearle [54]. Besides, the twist level of the yarn is high enough so that there is no slippage between the composite fibers, as defined in Pan's work [55]. Assume the yarn a model with a set of concentric cylinders on whose surfaces lie the fiber layers. A single fiber with length *l* is indicated in figure 2.14, where q is the surface helix angle.



(a) (b)

Figure 2.14 (a) a twisted staple yarn with high twisted levels; and (b) the fiber assemblies of the yarn assuming that all the fiber paths are on the side surfaces of concentric cylinders.

In a highly twisted staple yarn, the tensile stress of the fiber is given by Pan's calculation:

$$\sigma_f = E_f \epsilon_f [1 - \frac{\cosh(nx/r_f)}{\cosh(ns)}] \quad (2.22)$$

where E_f is the fiber tensile modulus; ϵ_f is the strain applied on the fiber by the yarn;

x represents the distance between the center and an arbitrary point on the fiber, i.e., $x = 0$ at the fiber center and $x = \frac{l}{2}$ at the fiber ends; r_f is the radius of the fiber; $s = \frac{l}{2r_f}$; and n is defined as the yarn cohesion factor and calculated to be

$$n = \sqrt{\frac{G_{TL}}{E_f}\frac{2}{ln2}} \tag{2.23}$$

where G_{TL} represents the longitudinal shear modulus. The transverse stress of the fiber is given as

$$g_r = \frac{n}{2\mu}E_f\epsilon_f\frac{\sinh{(nx/r_f)}}{\cosh{(ns)}} \tag{2.24}$$

where μ is the equivalent frictional coefficient that relates the shear stress and the transverse pressure by $\mu = \frac{\tau(r)}{g_r}$, where $\tau(r)$ is the shear stress.

The distributions of tensile and transverse stress as a function of x reflect a large extent of the yarn mechanism. Define

$$f(x) = coshx = \frac{e^x + e^{-x}}{2}$$

$$g(x) = sinhx = \frac{e^x - e^{-x}}{2}$$

where, $x \geq 0$. Differentiates of the above equations give extremes of *f(x)* and *g(x)*,

$$f(x)_{min} = f(0) = 1;$$

$$f(x)_{max} = f(x \to \infty);$$

$$g(x)_{min} = g(0) = 0;$$

$$g(x)_{max} = g(x \to \infty).$$

which further gives the extremes of σ_f and g_r

$$\sigma_{max} = \sigma_{x=0} = E_f\epsilon_f[1 - \frac{1}{\cosh{(ns)}}] \tag{2.25}$$

$$\sigma_{min} = \sigma_{x=\frac{l}{2}} = 0 \ ;$$

$$g_{max} = g_{x=\frac{l}{2}} = \frac{n}{2\mu}E_f\epsilon_f\tanh{(ns)} \tag{2.26}$$

$$g_{min} = g_{x=0} = 0$$

Both the tensile and transverse stresses vary across the fiber. The tensile stress ascends from the two ends and reaches its maximum at the fiber center, while the transverse stress descends from the fiber ends to a zero value at the fiber center. Further analysis related to yarn twist is given in figure 2.15.

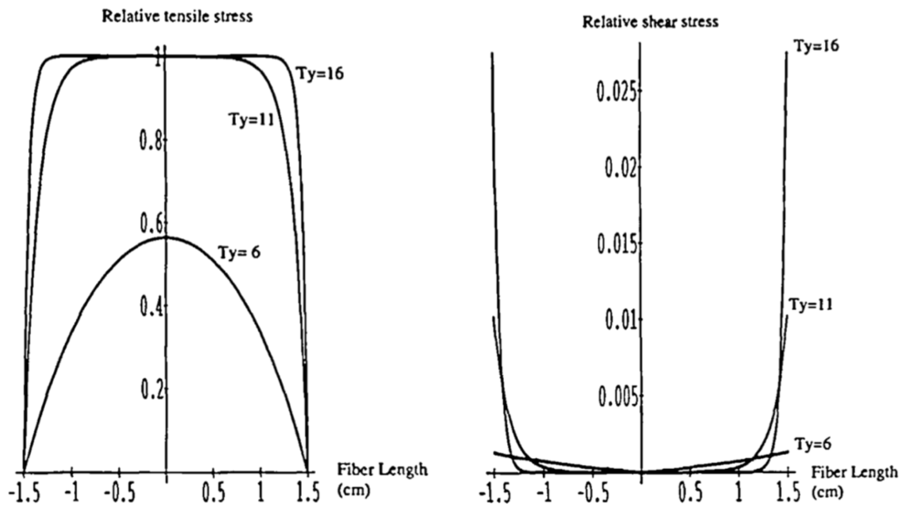


Figure 2.15 Relative tensile and shear stresses versus fiber length. Three twist conditions were given: *Ty = 6; 11;* and *16* [55].

The above curves indicate that yarn twist has a significant influence on the distribution of stresses in the fiber. When the twist reaches a high level, the stresses of fiber tend to change more drastically, depicted as abrupt increase or decrease at certain segments. The influence of yarn twist can be extended to many other properties including the physical structure of the yarn. An experimental study about the yarn packing density and yarn twist gave that

$$V_f = 0.7(1 - 0.78e^{-0.195T_y}) \tag{2.27}$$

where V_f represents the fiber-volume fraction. The function approaches to 0.7 when twist is large enough, as shown in figure 2.16 (a).

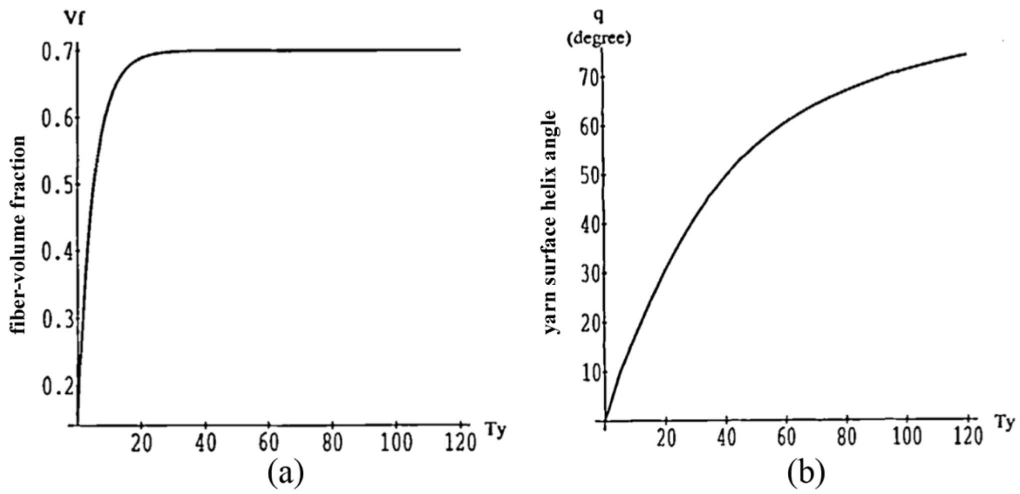


Figure 2.16. The influence of yarn twist on (a) fiber-volume fraction; and (b) yarn surface helix angle [55].

The yarn surface helix angle as a function of yarn twist:

$$q = \arctan\left[a_q 10^{-3} T_y \left(\frac{40\pi}{\rho_f V_f}\right)\right] \tag{2.28}$$

where a_q is a correlation factor of staple yarns and was chosen to be 2.5; and ρ_f is the fiber specific density. The yarn surface helix angle increases with yarn twist, while the increment of the surface helix angle per twist decreases with increasing twist, as shown by the concave curve in figure 2.16 (b). When the inclination of the fibers in the yarns is overlarge, the capillary channels are twisted into a helical shape, which is not favorable for the water transport in the yarn. Moreover, with increasing fiber-volume fraction, the influence of swelling is more obvious, leaving small spaces for further water transport.

On the other hand, tension on yarn during the wicking test can also result in difference equilibrium lengths.

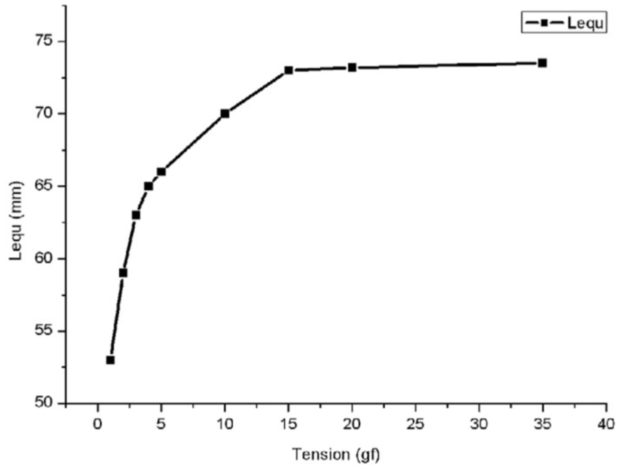


Figure 2.17. Equilibrium wicking lengths under increasing tensions [44].

The yarns were suspended by an adding weight, as shown in the horizontal axis of figure 2.17. When the tension is larger than 15g, the increase of equilibrium length is no longer obvious. As mentioned before, an increasing tension may cause a larger capillary force, and therefore improve moisture wicking. However, for yarns in the fabric, the tension is determined by the knitting method and even the body part where the fabric is worn. For example, for body parts like elbow and knee joint where the fabric is stretched, a larger tension in fiber will be introduced. Therefore, compared with simulation of real tension of yarns in the fabric, it is more important to unify the tension of yarns during wicking test.

2.4.2 Effect of roughness of yarns

Roughness of yarns is considered as a crucial parameter for capillary wicking, which is greatly dependent on the uniformity and continuity of capillary channels [56]. In fuzzy yarns with random fiber arrangements, the inter-spacings available for capillary action are interrupted and piecemeal. Moreover, yarn roughness may further influence the moisture transport behavior of fabrics made in accordance since the hydrophobicity of fabric is majorly dependent on properties of its fiber components. Rough surface of fabric is usually more repellent to water. Similar phenomenon can be observed from the nature such as the extreme hydrophobicity of lotus leaf surfaces due to the roughness of their surface morphology.

Figure 2.18. Surface morphology of hydrophobic lotus leaves [57].

The previous review showed that yarn twist has great influence on wicking performance by changing assemblies of fibers that constitute the yarn. Yarn twist can affect not only the tightness of fiber arrangements, but also the roughness of yarns., which can be explained by the work of Hollis et al [56]. When the yarn twist increases in low level, as shown in figure 2.19, from 4 to 12 TPI, the inter-fiber capillary channels are interrupted by twisting, resulting in a decrease in capillary rate.

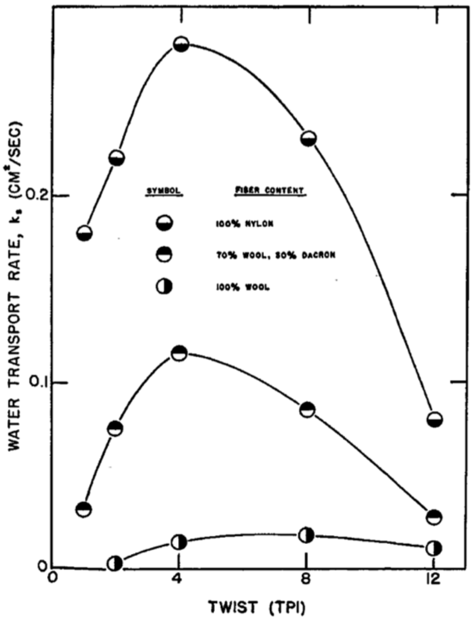


Figure 2.19. Change of water transport rate as a result of different yarn twists [56].

The change of water transport rate was further explained by research of Nyoni & Brook [50]. At lower twist levels as shown in figure 2.20 (a), the fibers are arranged in a manner of larger disorder with random inter-spacings. Spiked wicking may happen for yarns in this stage since the geometry of spacings that are available for capillary action is different for each yarn section. When twist increases as shown in figure (b), the fibers are arranged more closely. During the process to increase twist in low levels, it is easier for fiber to move in different layers, i.e., the helical radius of each fiber can be easily changed. Since the fibers are well-aligned now, long capillary channels are formed in this stage, resulting in a flat and gentle risen of liquid front, as well as a better capillary rate. When twist increases to a higher level, the fibers are squeezed into a compact arrangement and obvious helical paths are formed. The capillary channels are therefore twisted with poorer continuity. Spiral wicking is found in this stage. The change of fiber arrangements is consistent with Hollis work shown in figure 2.19.

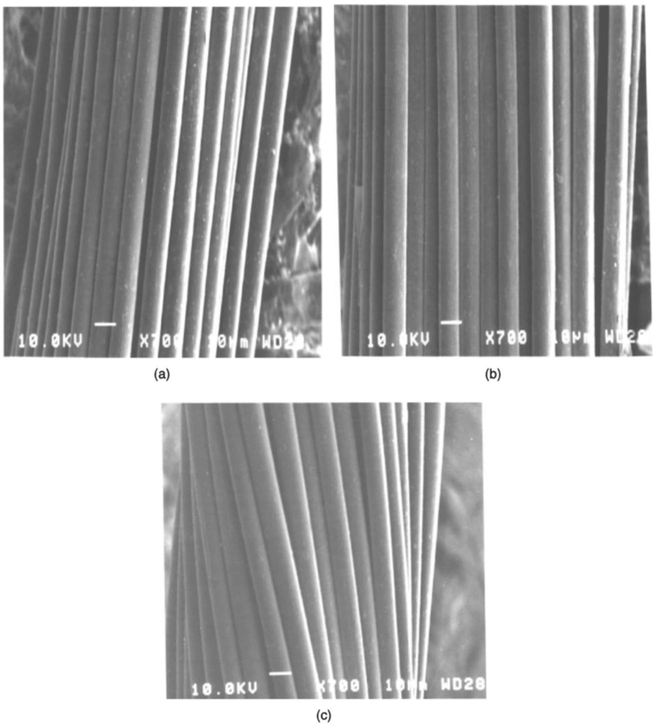


Figure 2.20. Fiber arrangements in (a) loose; (b) increased; and (c) tightened levels [50].

Hollis further investigated the contact angles of fibers and yarns. Comparison showed that the contact angle of single synthetic fiber is higher than yarns made in accordance, while that of single wool fiber is lower than a wool yarn consists of fiber bundles. According to the author, the natural crimping of wool fibers results in a more random arrangement when forming the wool yarn, and therefore less continuous channels available for capillary action. Besides, the radii of effective capillary channels in wool yarns vary from one yarn section to another. As a result, the wicking rate may change suddenly for different yarn sections. Sometimes the wicking might even cease due to such discontinuity. On the contrary, synthetic fibers are finer and smoother, easier to form parallel inter-fiber channels, which are essential for continuous and fast wicking behavior. In addition to wicking performance, studies also found that the blend uniformity of yarns can influence the dyeing evenness in later industrial processes [58]. To conclude, the wicking rate and other yarn behaviors are very likely to be improved by altering the fiber arrangements to get a finer assembly in yarn construction.

2.4.3 Effect of moisture absorption

With the advantage of being comfortable, economical and environmentally friendly, cotton has been widely used in daily clothing and other textiles. Using cotton as the main material of the proposed structure, it is necessary to have a review on cotton's typical properties, especially shrinkage. There are two essentials that causes shrinkage after washing. One is water gains and the other is swelling during water gain and release of strains [59]. Internal rearrangement of the fibers happens, resulting in shortening of yarn from the macroscopic view.

The mechanism of single cotton yarn shrinkage can be roughly divided into the following steps. To start with, the diameter of cotton yarn increases as swelling takes place, which means the distance for fibers to span around the yarn become longer. This causes stretch of fiber in order to maintain the previous position. There are two solutions for fiber to avoid stretching. One possible solution is untwisting, while in most cases the yarns are fixed in fabrics, this process is probably not allowed. As a result, the yarn must shrink so that the fiber can span as far both around and along the yarn. Such rearrangement performs as shrinkage in the macroscopic view. Collins also pointed out that the twist of yarn is closely related to shrinkage [59]. Yarns with large twists possess increased compactness and hence larger swelling when in contact with liquid. As a result, the shrinkage of yarns with larger twist after drying is supposed to be larger.

The case is similar for shrinkage of fabrics. The increase in diameter of yarns during swelling results in a longer path of the thread wrapped, as shown in figure 2.21 (c).

Tensions in the wrap threads are thus increased. In order to counteract with the tension and avoid stretching, which means maintaining a relatively shorter path for the warp yarn, the weft threads move closer to each other and thus lead to shrinkage.

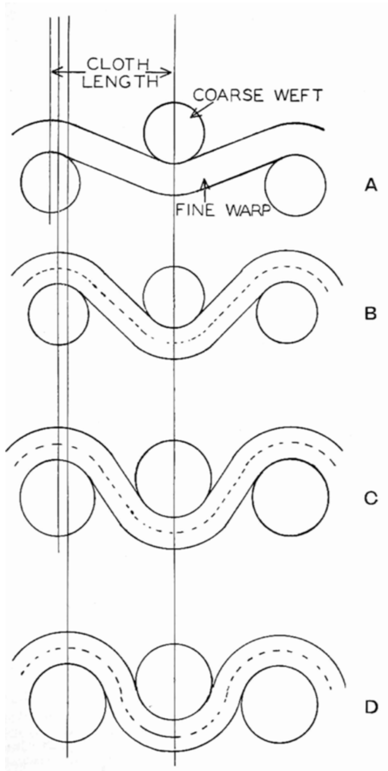


Figure 2.21. The shrinkage mechanism of weaving fabrics [59].

It is of great significance to understand the property change of yarns before investigating the behavior of fabrics in a changing environment. The change of fiber and yarn properties under different moisture conditions was studied by Maginnis [60]. Figure 2.22 shows the cross-sectional swelling of 40-filaments rayon yarns under different relative humidity. The three curves in each coordinate indicated different loads on the yarns during the experiment. Compared with the external stress applied by the loads on yarns, the twists of yarns play a major role on the diameter swelling when humidity increases. External weight was used to create stresses on yarns during the experiment, whereas in real cases the knitting construction of fabrics can cause stresses on yarns. The result indicated that what determines the fabric performances is the properties of yarns rather than the weaving construction of the fabric, which is in consistent with the earlier indications.

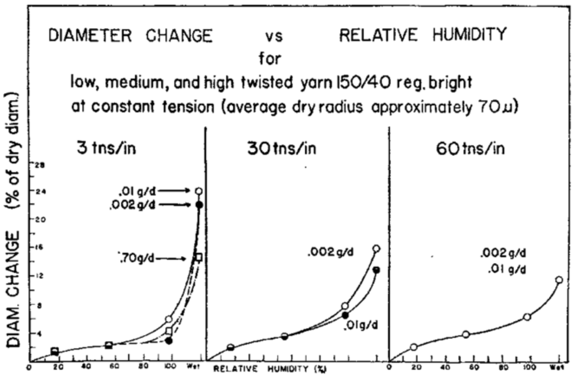


Figure 2.22. Dependency of yarn diameter change on the relative humidity.

By considering the rayon yarn as an arrangement of 40 individual cylindered packed together, a qualitive mechanism was developed to predict the shrinkage or elongation of yarns based on the yarn construction. The change in the length of yarn after wetting is determined by two reasons, one is the swelling of the yarn cross-section, which causes the length to become smaller; the other is the swelling in the linear dimension, which causes the length to become longer. As mentioned in section 2.4.1, fibers in the yarn can be considered as following helical paths with different radii around the yarn central axis. When cross-sectional swelling happens, the radius of such helical path increases and the fiber is pushed away from the central axis of the equivalent cylinder. Calculation found that the swelling in the linear direction, which tends to lengthen the yarn, is independent of the yarn twist while the swelling in the cross-sectional dimension, which tends to reduce the yarn length, is positively dependent on the yarn twist. A higher twist of yarn results in a larger cross-section swelling. Therefore, the lengthen or shorten of the yarn depends on which of these two factors is greater. For yarns with small twist numbers, the swelling in linear direction dominates hence the yarn becomes longer after wetting. For yarns with large twist numbers, the swelling in cross-sectional dimension dominates hence the yarn shrinks after wetting. Therefore, it is possible to determine a range of twists where the yarn length remains stable after wetting [60].

The influence of moisture absorption on fabrics can be reflected by air permeability, as investigated in the study of Wehner et al [61]. When a fabric is wet by water, both moisture transmission and moisture absorption happen at the same time and finally reach a steady state of water regain and transmission. For natural fibers with large moisture absorption capacity, the construction of fabrics might change after wetting due to huge swelling of yarns. Swelling in the cross-sectional dimension and shrinkage in the linear direction result in a tighter construction of the fabrics, which means smaller void spaces for water transmission.

The porosities of fabrics are usually low and thus can be treated as arrangements of small tubes. Therefore, pressure drop through a fabric can be determined by the viscous force and the inertial forces. The viscous forces are proportional to the liquid velocity, while the inertial forces are proportional to the square of velocity. By measuring the velocity and the pressure drop, it was found that the pressure drop across a fiber sample differed in different relative humidity (R. H.), at a certain liquid velocity. The difference can be ascribed to the change of fabric structure due to R. H. The intrinsic resistance of fabric changes at given R. H. and therefore influence the moisture absorption capacity of the fabric.

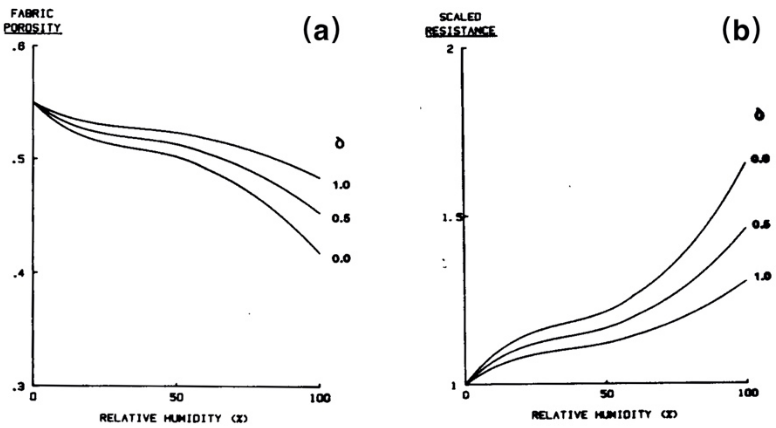


Figure 2.23. Influence of R.H. on (a) fabric porosity; and (b) air flow resistance of the fabric [61].

As shown in figure 2.23, moisture absorption has great influence on the porosity of fabric. With porosity decreases, the fabric tends to have larger resistance to air flow, and hence poor permeability of air, resulting in unsatisfactory wearing experience when wet. This result is consistent with the practical experience that when the humidity is large, it is usually less comfortable to wear clothes that are directly in contact with the skin. The study also found that the thickness of fabric is influenced by moisture regain. If the fabric is more flexible on changes of thickness, the influence of humidity on its porosity is less serious.

2.5 Conclusion

A number of literature studies related to wetting, wicking and drying mechanisms of fibers, yarns, and fabrics are discussed in the previous sections. Firstly, current major sportswear fabrics with improved moisture transport ability were investigated. Common approaches include hydrophilic surface treatment; multi-layer fabric construction; spacer knitted structure; and fiber selection and modification. A structure modification of yarns is preferred due to better duration and less limitations to fabric construction. Secondly, the general wicking mechanism in textiles was discussed, including capillary wicking principles; kinetics of wicking; and wicking in a finite reservoir. The real wicking processes into textiles are more analogous to wicking in a finite reservoir, which is exemplified by a liquid drop on the fabric surface. The kinetics of wicking is also important since most moisture related processes are dynamic. Then, major factors that affect wicking were discussed. It was found that the effect of yarn twists is crucial to wicking performance since twists can directly change the number and continuity of effective capillary channels. The roughness of yarns is also influenced by yarn twist. Besides, moisture absorption by the fabric in different humidity also induces change in moisture transport performance of the fabric. In order to achieve a better wicking and drying performance, appropriate twist of yarns and fiber assemblies are essential.

Although natural fibers such as cotton, silk and wool exhibit outstanding moisture absorption ability, the large amount of moisture regain of such fabrics limit their applications in active fabrics such as sportswear. Currently, synthetic fibers still occupy the mainstream sportswear market, despite of less skin affinity and poorer wearing experience. Therefore, a new type of natural fiber-based material with excellent moisture transport ability is demanded both academically and in the market. Such structure based on the modification of cotton yarns will be discussed in the following chapter.

Chapter 3 Fiber modification theory

3.1 Principle of the proposed structure-based modification

According to the previous research discussed in the Literature Review chapter, the comfort properties of fabrics are closely influenced by wetting, wicking and drying performances. Water transport can be affected by pore sizes, humidity of the environment, the contact of fabrics and the environment, and most significantly, the properties of single yarns. Drying time of fabrics are closely related to the water holding capacity and fabric thickness [8-12]. Therefore, improvement of yarn wicking performance with appropriate restrictions to water holding capacity would make a radical difference to the fabric properties.

As a natural common phenomenon, capillary action generally exists in staple yarns. The wicking height and rate of capillary action are both affected by the equivalent radius of inter-fiber spacings. The slack fibers in an ordinary cotton yarn increase the roughness of the yarn and reduce the continuity of capillary spacings, resulting in abrupt changes in wicking rate and even sudden ceasing of the wicking process. Besides, in a loosely spun yarn, the spaces between the fibers are very large, which is not preferred to the wicking process. By using a covering material to limit the inter-fiber spacings, an improvement in capillary height and speed can be achieved. With the intention of improving moisture wicking and achieving fast dry, a newly twisted yarn with covering technology was proposed by Dr. Li’s group as shown in figure 3.1.

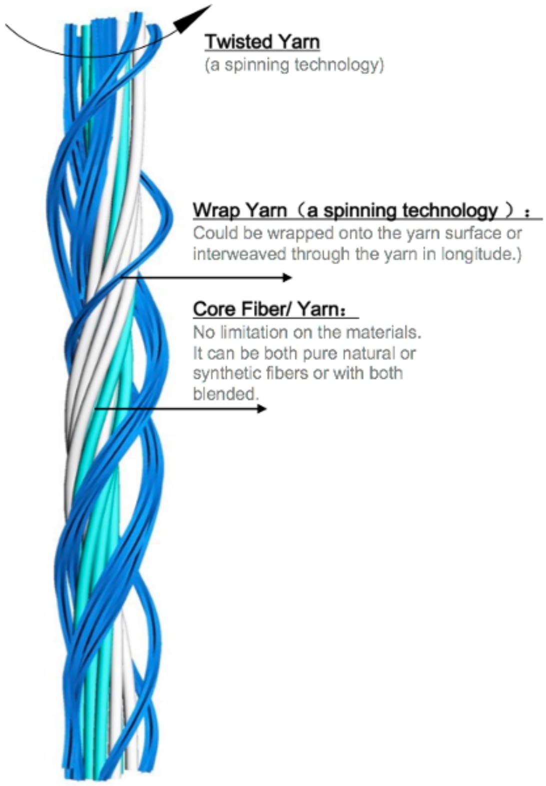


Figure 3.1. The structure of the novel yarn.

The technology was developed based on construction of yarn structure by physical modification involving yarn twisting technique and covering technology. Two kinds of yarns are spun together to form the new yarn. The core yarn is a twisted regular staple yarn with no specific limitation to the yarn materials. Theoretically, the core material can be either natural fibers or synthetic fibers or a blended yarn with both materials. In this and in subsequent experimental chapters, the core materials are mainly focused on cotton and cotton/linen blended yarns. The covering yarns are filaments wrapped onto the surface of the core yarn by a spinning technology. A helical shape with multiple capillary channels is therefore strengthened to help draw water through these channels and increase water absorption ability.

Since the core yarns are regular yarns available from the market, there exists two spinning directions when wrapping the covering yarn onto the core. Suppose the wrap yarn is fixed with S-twist, the core yarn can be either in S-twist or in Z-twist direction, resulting in different effects on the yarn structure. When the twist directions of the inner and outer yarns are the same, as shown in figure 3.2 (a), the wrapping technology tends to "screw" the overall construction and result in a more twisted and closely packed fiber assembly. The effect of such combination is similar to increasing twist of yarns and the final result depends on the initial twist levels of the inner yarn (also see figure 2.19). If the core yarn is loosely twisted with large amount of random spaces and slack fibers, the wrapping of the outer yarn will help to tighten the package mechanism of the inner fibers and eventually achieve an increase the wicking performance. If the twist level of the inner yarn is already high enough to create continuous capillary channels, the effect of the wrap yarn remains unknown and could either increase or decrease the overall wicking performance.

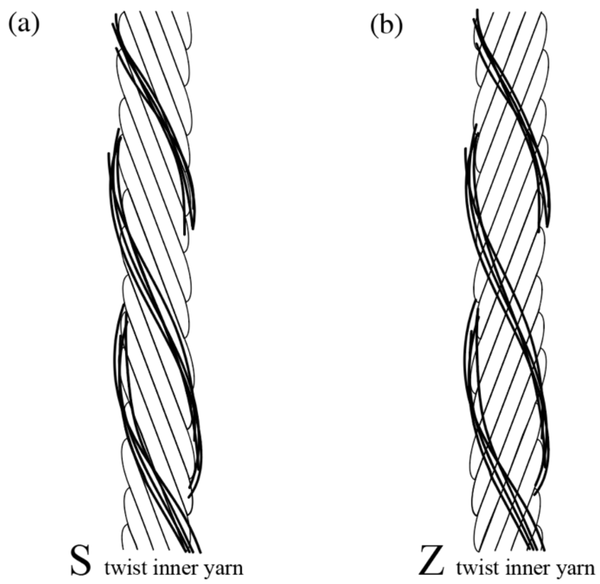


Figure 3.2. Wrapping the outer yarn on (a) S-twisted core yarn; and (b) Z-twisted core yarn.

When the twists of the two yarns are in opposite directions, the wrap yarn tends to band the inner fibers and apply forces that follow the anti-radial directions, i.e., point inwards to the center of the circle, as given in figure 3.3 (b). As indicated in chapter 2.4.2, the assemblies of fibers undergo three phases as twist increases. Phase I, when the twist level is very low, the fibers are loosely packed, with random capillary channels. Phase II, when the twist level increases to a slightly higher one, the fibers tends to be packed more closely and continuous capillary channels are formed. However, the diameters of these spacings are still uneven since the twist level still remains relatively low. Wicking height is increased with the increasing spacing continuity yet still limited by relatively large capillary spacing diameters. Phase III, when the twist increases to a high level, the fibers are arranged more closely. Diameters of the spacings are reduced. However, the continuity of capillary channels is interrupted by twisting. Spiral wicking channels with less continuity and uneven diameters dominate and result in an overall decrease of capillary wicking.

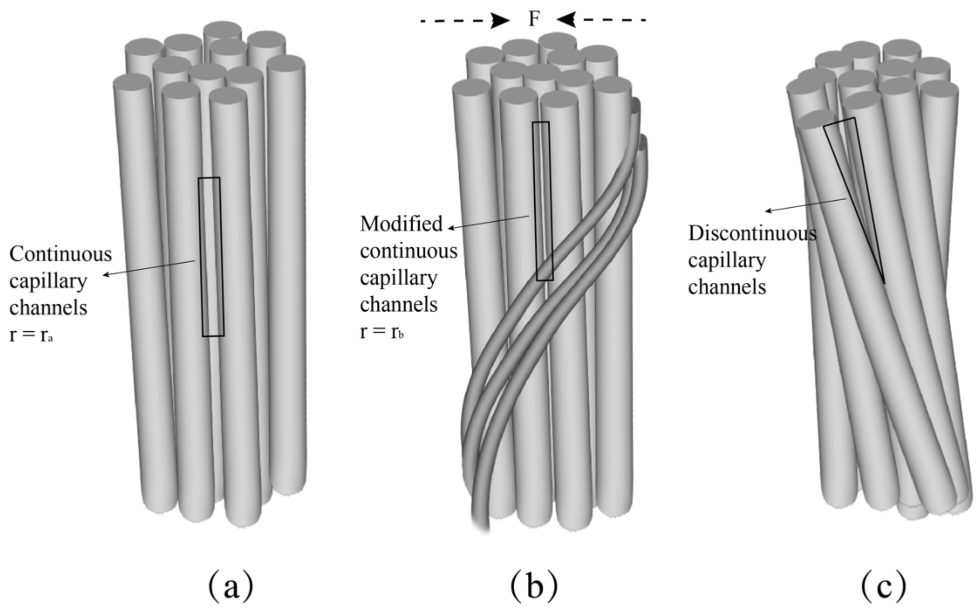


Figure 3.3. Capillary channels in (a) regularly twisted yarn; (b) the proposed novel yarn; and (c) increasingly twisted yarn.

As illustrated in figure 3.3, a regularly twisted yarn assumed in phase II provides continuous spacings that can be considered as parallel capillary tubes with equivalent radius of r_a, which is not small enough to induce high wicking rate. The reciprocal relation between wicking height *h* and capillary radius *r* indicate that the wicking height can be increased by a decreased capillary radius. Although the inter-fiber spacings can be limited by twisting, the continuity and evenness of the spacings are shattered (3.3c). Hence a better way would be applying a transverse pressure so that the inner fibers would be compressed towards the yarn center while the continuity and parallel of the capillary channels are seldomly influenced. With $r_b < r_a$, the wicking height will therefore be improved. Moreover, as shown in figure 3.4, swelling of wet fibers in a regular yarn would decrease the inter-fiber spacings, while the wrap yarn in the proposed structure can act as a binder to limit excessive water absorption so that the fabric would not be saturated by sweats.

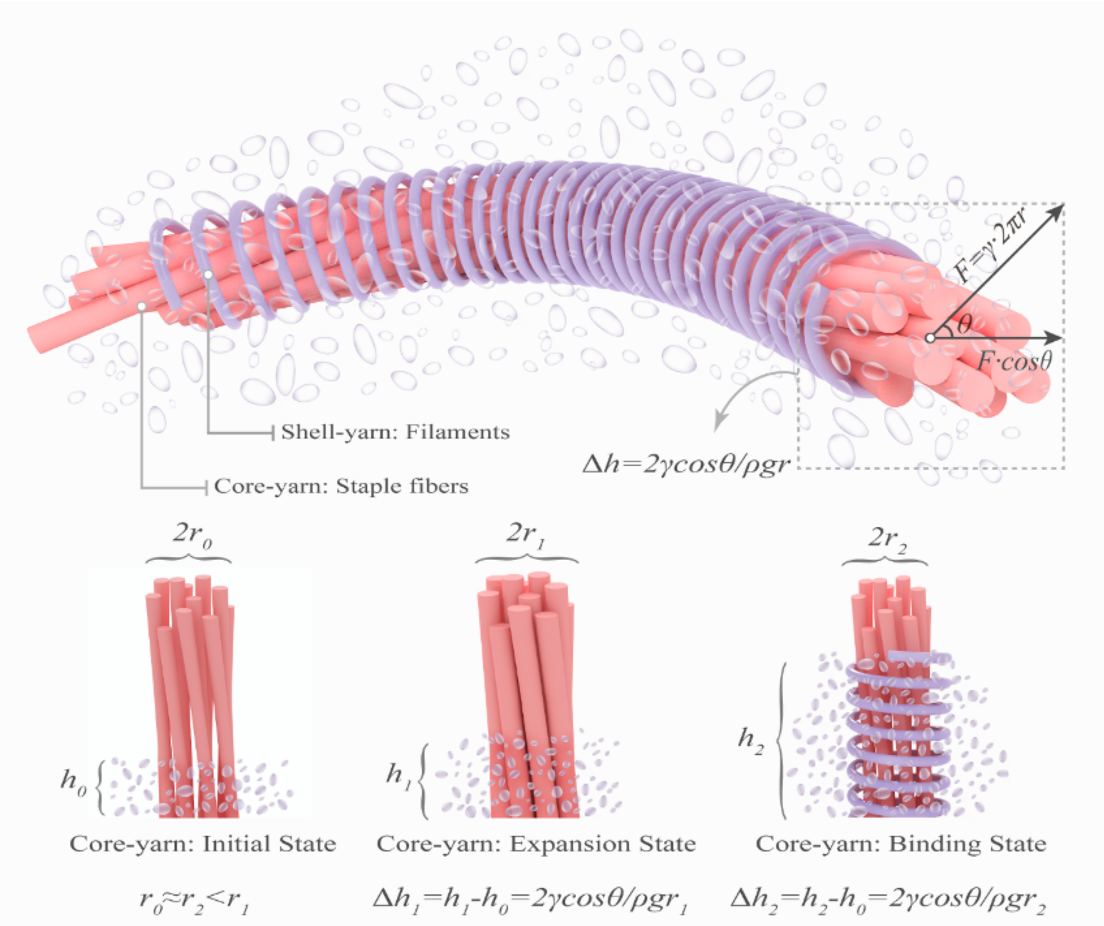


Figure 3.4 Binding mechanisms of the wrap yarn.

3.2. Wicking mechanisms

In order to have a better understanding of the principles of the innovative spinning structure, the wicking mechanism of staple yarns is of vital importance. During the moisture transport process in a yarn, capillary pressure is defined as the change in surface tension as the liquid flows through a unit volume, which are presented in the following equations.

$$P_c = \frac{\Delta E}{\Delta V} \tag{3.1}$$

$$\Delta E = (\gamma_S - \gamma_{LV})N2\pi r\Delta h = -\gamma cos\theta N2\pi r\Delta h \tag{3.2}$$

$$\Delta V = \frac{N\pi r^2 \varepsilon}{(1-\varepsilon)\Delta h} \tag{3.3}$$

$$R^2 = \frac{Nr^2}{(1-\varepsilon)} \quad (3.4)$$

where P_c is the capillary pressure; ΔE is the change in surface energy when the liquid flows through a volume of ΔV; N is the number of filaments in a yarn; r and R are the radii of the filament and of the yarn; Δh is the movement of liquid front; and ε is the porosity of the yarn cross section. The capillary pressure can be further denoted as

$$P_c = \frac{-2\gamma cos\theta\sqrt{(1-\varepsilon)N}}{R\varepsilon} \quad (3.5)$$

The porosity of a yarn is closely related to yarn twist. The influence of yarn twist can be extended to many other properties including the physical structure of the yarn. An experimental study about the yarn packing density and yarn twist gave that

$$V_f = 0.7(1 - 0.78e^{-0.195T_y}) \quad (3.7)$$

where V_f represents the fiber-volume fraction. The function approaches to 0.7 when twist is large enough, as shown in figure 3.5 (a).

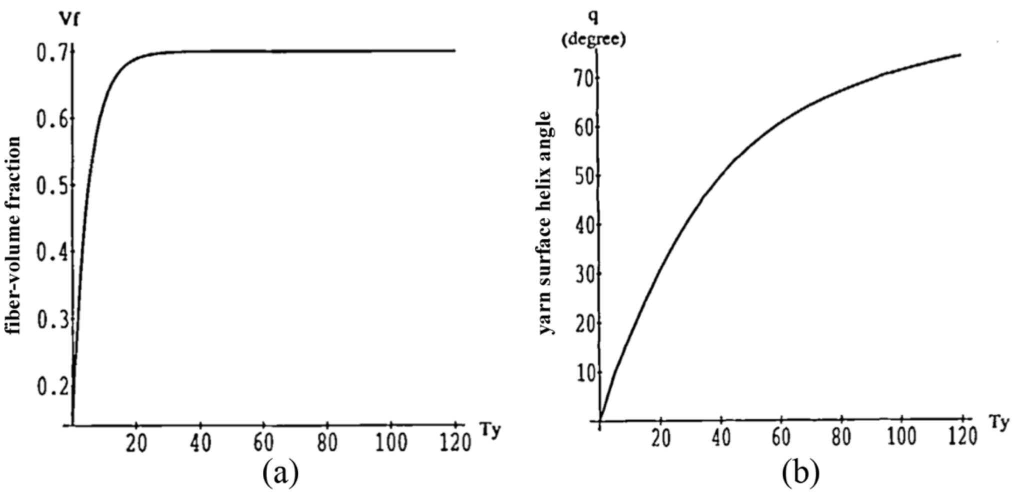


Figure 3.5. The influence of yarn twist on (a) fiber-volume fraction; and (b) yarn surface helix angle [55].

The yarn surface helix angle as a function of yarn twist is:

$$q = \arctan\,[a_q 10^{-3} T_y (\frac{40\pi}{\rho_f V_f})] \quad (3.8)$$

where a_q is a correlation factor of staple yarns and was chosen to be 2.5; and ρ_f is the fiber specific density. The yarn surface helix angle increases with yarn twist, while the increment of the surface helical angle per twist decreases with increasing twist, as shown by the concave curve. When the inclination of the fibers in the yarns is overlarge, the capillary channels are twisted into a helical shape, which is not favorable for the water transport in the yarn. Moreover, with increasing fiber-volume fraction, the influence of swelling is more obvious, leaving small spaces for further water transport.

On the other hand, by applying a cover yarn on a relatively lower twisted core yarn, the effect of the wrap yarn is to generate an inward force that band and squeeze the core yarn to be more tightly packed. Therefore, the novel yarn will be allowed with lower fiber-volume fraction and smaller yarn surface helix angle. Moisture wicking in the yarns can thus be more continuous since wicking is closely affected by fiber orientation.

Chapter 4 Experiments

4.1 A summary of materials and experiments

A series of experiments and attempts with various types of natural and synthetic fibers used as the core and covering materials was conducted. Considering the characteristics of different fibers, cotton and linen were selected as the core material, and nylon and polyester were selected as the wrap material. The reasons for selection and fiber properties are listed in table 4.1.

Table 4.1. Properties and reasons for selecting materials for the study.

Materials	Reason for selection	Properties
Cotton	Most common material; Hydrophilic nature	Higher strength; Breathable; Soft
Linen	Hydrophilic nature	Cool to touch; Durable and strong; Abrasion resistance
Nylon	Replacement of Silk; Hydrophilic nature but can be treated to be hydrophobic	Dyeability; Good handle; High strength; Dries quickly
Polyester	Commonly used as moisture wicking material; Hydrophobic nature but can be treated to be hydrophilic	High strength; Lightweight; Dries quickly

Totally six batches of yarns were prepared, the first batch was hand-made and the others were produced by different factories as required. Table 4.2 gives an overview on the yarns prepared.

Table 4.2. The detailed specifications of yarns prepared.

Batch	No.	Type of yarns	Yarn count	Component Content
I (Handmade)	1-0	Control	NA	Hollow polyester
	1-1~1.4	Novel	NA	Core: hollow polyester Wrap: polyester/PLA
II (Zhuhai factory)	2-0	Control	32S	Cotton
	2-1	Novel	-	Core: cotton Wrap: polyester
III (Jiangsu factory)	3-0	Control	32S	Cotton
	3-1	Novel	22S	Core: cotton (68%) Wrap: polyester (32%)
IV (Yuyue factory-bleached)	4-0	Control	30S	Cotton
	4-1	Novel (Z-twisted)	28S	Core: cotton (89%) Wrap: PA (11%)
	4-2	Novel (S-twisted)	28S	Core: cotton (88%) Wrap: PA (12%)
	4-3	Novel	24S	Core: cotton (76%) Wrap: PA (24%)
V (Yuyue factory-unbleached)	5-0	Control	30S	Cotton
	5-1	Novel	27S	Core: cotton (90%) Wrap: PA (10%)
	5-2	Novel	26S	Core: cotton (86%) Wrap: PA (14%)
	5-3	Novel	25S	Core: cotton (85%) Wrap: PA (15%)
	5-4	Novel	21S	Core: cotton (70%) Wrap: PA (30%)
	5-5	Novel	26S	Core: cotton (87%) Wrap: PA (13%)

VI (Jiangsu factory)	6-0	Control	-	PET 30D
	6-1	Control	-	Cotton
	6-2	Novel (400T)	-	Core: cotton Wrap: PET
	6-3	Novel (1000T)	-	Core: cotton Wrap: PET
	6-4	Control	-	Cotton-linen (70%-30%)
	6-5	Novel (400T)	-	Core: cotton-linen Wrap: PET
	6-6	Novel (1000T)	-	Core: cotton-linen Wrap: PET

To systematically test the hydrophilicity of the proposed yarns, the PRC standard *GB/T 21655.1-2008: Textiles-Evaluation of absorption and quick-drying* is referred during the design of experiments [62]. Three sets of experiments from the PRC standard were conducted, *water absorption rate, drip diffusion time and wicking height*, which will be further discussed in the following sections. The experiment procedure generally followed the PRC standard, with some necessary modifications. Fabrics made in accordance were prepared using Hosiery machine and cut in the sizes either following the PRC standard or in scaling-sown sizes, depending on the availability of yarns. All the fabrics were put in the control room with standard atmosphere for humidifying before experiments. For the wicking height tests, both yarns and knitting fabrics were tested to verify the assumption.

4.1.1 Water absorption rate

For the test of water absorption rate, five sets of samples for each kind of fabric were prepared during measuring. The water absorption rate of fabric is given by the following equation:

$$Water\ absorption\ rate = \frac{B-A}{A} \times 100\% \tag{4.1}$$

where A is the weight of the dry fabric and B is the weight of saturated surface-dried fabric. $B - A$ then represents the amount of water absorption. The water absorption rate was calculated by equation 4.1 based on the average of the five samples. The experiment procedures are summarized as follows.

1. Cut five pieces of fabrics with the same size of 6×6 cm.
2. Treat the samples in the control room for 24 hours and record the weight of a single sample after treatment as A.
3. Sink the sample in deionized water. Use a glass rod, if necessary, to make sure the sample is fully immersed for five minutes.
4. Hang the wet sample until no dripping. (When the time interval between two drippings is no smaller than 30s, it is considered there is no dripping.)
5. Immediately measure the weight of the wet fabric and record as B.

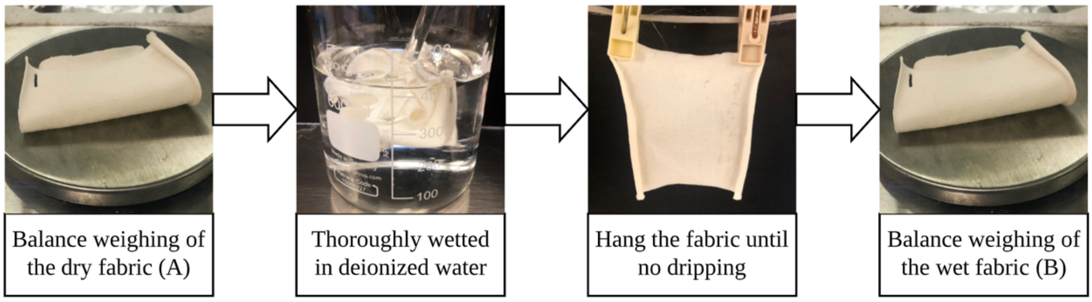


Figure 4.1. Process of the water absorption rate test.

4.1.2 Drip diffusion time

The diffusion of water could affect the evaporation rate and help to keep skin dry. A larger diffusion area helps moisture to evaporate and thus achieve fast dry of fabrics. Five sets of samples were used to test the diffusion of water. The final state of diffusion is defined as when the specular reflection of liquid is completely disappeared, or the state at 300s if the droplet could not be absorbed. The experimental procedures are listed as bellow.

1. Cut five pieces of fabrics with the same size of 6×6 cm.

2. Treat the samples in the control room for 24 hours and put them on a hydrophobic flat surface.
3. Use a pipette to drop 200 microliters of liquid on the surface of the fabric.
4. Record the time for complete diffusion, i.e., when the specular reflection is completely disappeared, or record 300s if the droplet could not be absorbed.

4.1.3 Capillary wicking height

The wicking height of samples directly reflect the hydrophilicity of the sample. Five sets of tests were conducted. Both yarns and fabrics made in accordance were tested, with experimental devices as shown in figure 4.2.

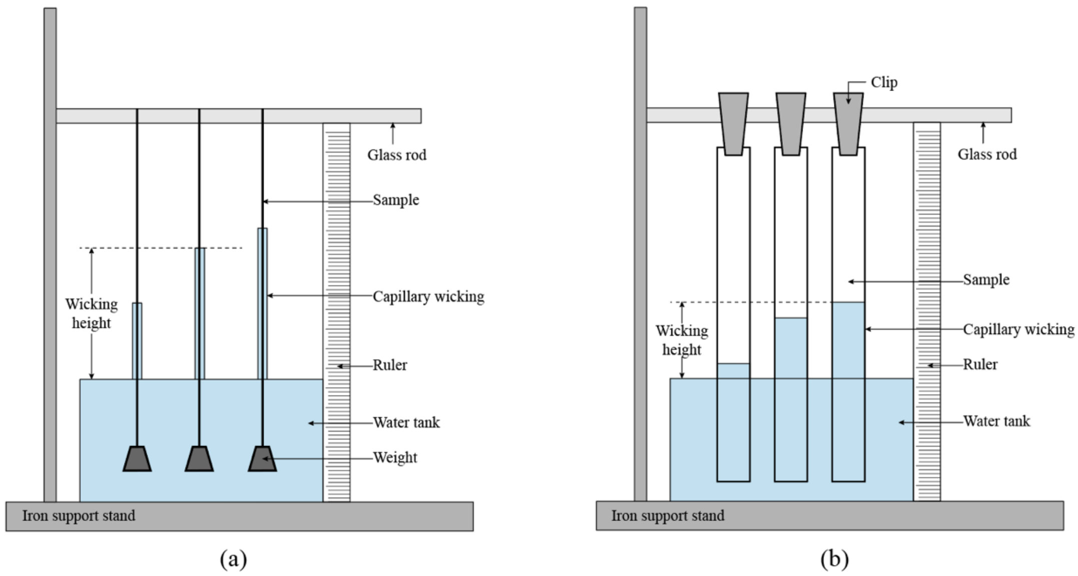


Figure 4.2. A diagrammatic sketch of the tests of wicking height for (a) the yarns; and (b) the fabrics made in accordance.

The experimental procedures for the measurement of yarns are listed as bellow.

1. Cut the yarn into 20cm segments.
2. Fix a glass rod horizontally on the iron stand.
3. Hang the samples on the glass rod with equal spaces between each sample. A weight of several grams is hanged on the other end of the yarn to introduce equal stress on each yarn.
4. Fill the water tank with dyed deionized water. Make sure the lower ends of the yarns

are immersed.

5. Use a vertical ruler to measure the height. Record the changes in wicking heights in 30 minutes or 60 minutes, depending on the hydrophilicity of samples.

The experimental procedures for the fabrics are slightly different with that of the yarns. For each set of samples, two experiments were conducted since the fabrics can be cut in either warp or weft direction.

1. Cut the fabrics into pieces of 3×15cm.
2. Fix a glass rod horizontally on the iron stand.
3. Fix the upper ends of the samples on the glass rod by clips and the other end hang.
4. Fill the water tank with dyed deionized water. Make sure the lower ends of the fabrics are immersed.
5. Use a vertical ruler to measure the height. Record the changes in wicking heights in 30 or 60 minutes, depending on the hydrophilicity of samples.

4.1.4 Evaporation rate

Water evaporation rate is a significant measurement of the fast dry effect. The test was conducted based on the PRC standard. A certain amount of water droplet is put on the sample and evaporate naturally in the standard atmosphere. An evaporation amount-time curve is plotted by measuring the weight of the wet fabric with equal time intervals. The experimental procedures are listed as below.

1. Cut five samples with same size for each kind of fabric. Put the samples in the control room for humidifying.
2. Measure the initial weight as m_0.
3. Put the samples on the laboratory console. Drop 0.2ml water on the sample and wait until completely diffusion. Measure the weight as m.
4. Hang the sample vertically in the standard atmosphere to evaporate moisture. Measure the weight every five minutes until the changing rate of two adjacent measurements does not exceed 1%.

The evaporation rate is then calculated as

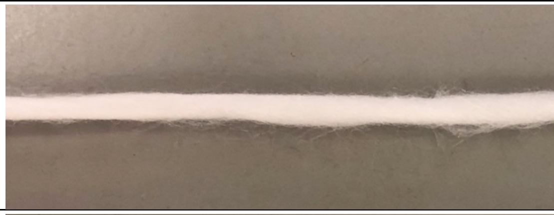
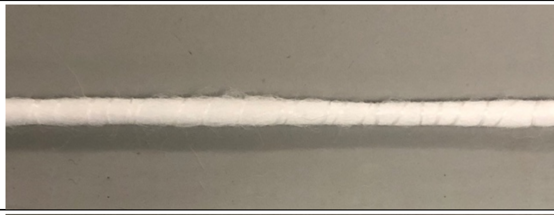
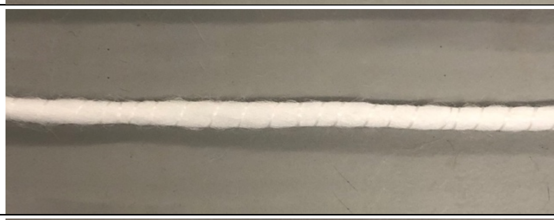
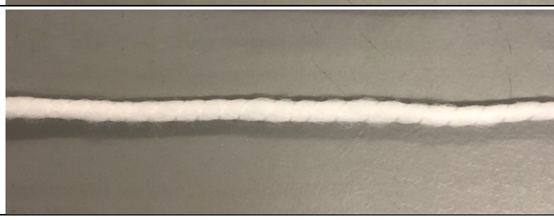
$$E_i = \frac{\Delta m_i}{m_0} \times 100\%$$

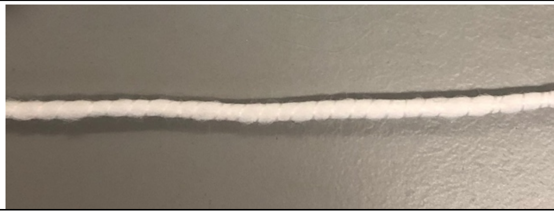
where m_i is the weight of the sample at certain time; and Δm_i is the amount of evaporation, which is calculated as $\Delta m_i = m - m_i$.

4.2 Capillary wicking tests of the hand-made yarns

With the purpose of verifying the validity of the proposed assumption and improving the efficiency of subsequent experiments, at the very beginning of the experimental period, a set of yarns were prepared manually by wrapping either polylactic acid (PLA) filaments or Polyester (PET) outside the hollow polyester roving yarns, i.e., the core material. Both the comparison of wrapping tightness and influence of hydrophilicity of covering materials were taken into consideration. Table 4.3 and figure 4.3 give the details and moisture wicking test results of the hand-made yarns.

Table 4.3 The details of the hand-made samples for pre-test.

No.	Sample	Component	Picture
1-0	Hand-made control	Hollow polyester	
1-1	Hand-made novel	Core: PET Wrap: PET	
1-2	Hand-made novel	Core: PET Wrap: PLA	
1-3	Hand-made novel	Core: PET Wrap: PET	

1-4	Hand-made novel	Core: PET Wrap: PLA	

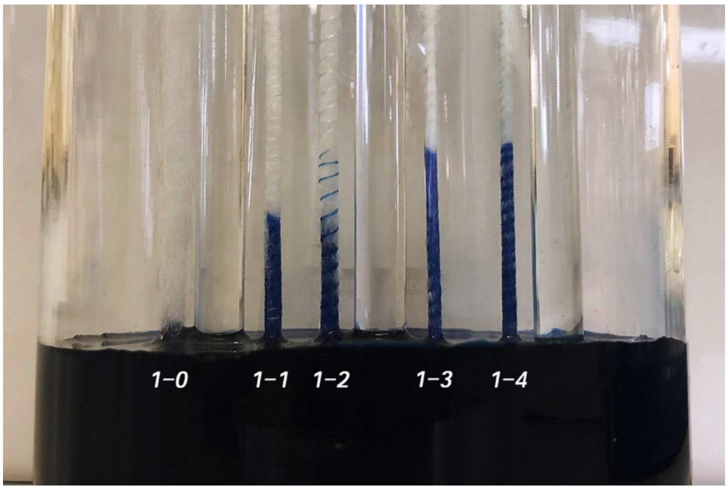


Figure 4.3. Moisture wicking test for 80 minutes.

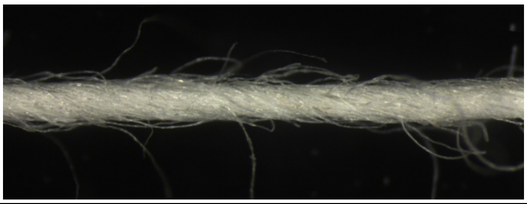
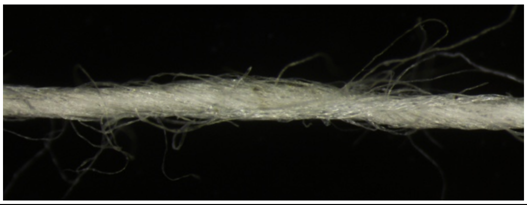
Dark blue dyes were used as the wicking medium in order to obtain direct visual effect. The pigments and its concentration in the dye have no measurable influence on the capillary wicking action. Three gradients of tightness were applied for these yarns. The first one is the control group (1-0), which is the natural-state hollow PET yarns used as core material. The fibers of the core yarn are loosely arranged, creating large spacings for capillary action. The second ones are yarns 1-1 and 1-2, whose winding tightness is very small so that little pressure was applied on the core yarns. The difference of these two yarns lies on the covering materials. Yarn 1-1 is covered with hydrophobic PET while yarn 1-2 is covered with hydrophilic PLA. Although the covering material of 1-2 absorbs the liquid to a higher level, by comparing water absorption in the core materials, there is no evident difference of wicking heights between these two groups. The third tightness gradients are yarns 1-3 and 1-4, whose diameters are half of the diameters of yarns 1-1 and 1-2. Correspondingly, yarn 3-3 is covered by hydrophobic PET and yarn 3-4 is covered by hydrophilic PLA. The result showed almost same height of wicking.

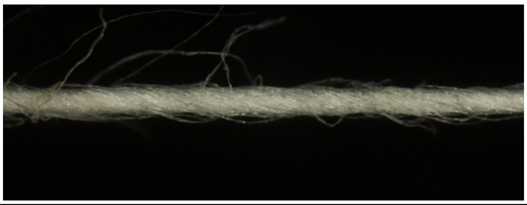
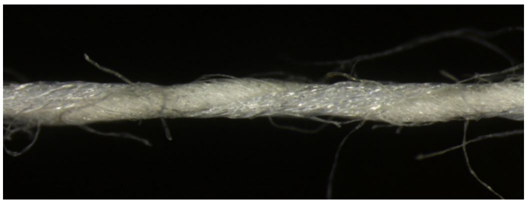
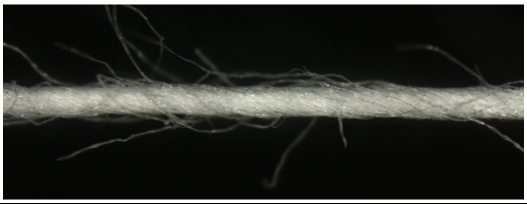
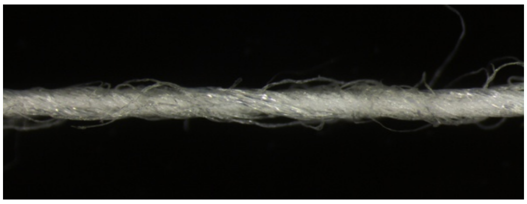
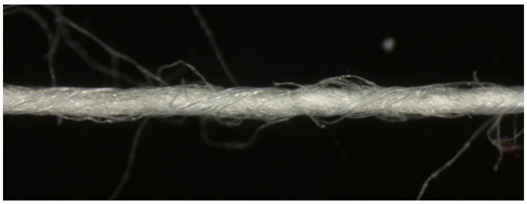
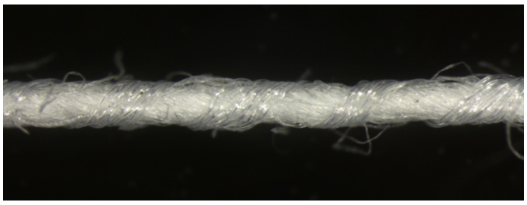
By both intra-gradient and inter-gradient comparison, it can be found that the hydrophilicity of covering material is insignificant to the capillary action. Instead, the wicking height is directly related to the tightness of wrapping. The control yarn showed little wicking height due to loosely arranged fiber assemblies. The result generally verified the assumption that the wrap yarn acts as a binder of the inner yarn, which decreases the diameters of the spacings between the fibers, leading to a better wicking effect. Moreover, the darkness of the wet yarn reflected the amount of water absorbed per unit volume. Yarns 1-3 and 1-4 showed better evenness and deeper color, while there were white areas observed in yarns 1-1 and 1-2, indicating uneven capillary channels with various diameters across the yarns. To sum up, through the binding effect of the wrap yarn, appropriate wicking radius will not only increase the wicking height and rate, but also increase the water absorption amount per unit volume.

4.3 Experimental tests of yarns II, III, and IV

Based on the preliminary work about manual yarn covering, moisture wicking tests of yarns produced following the proposed yarn twisting and covering technology were conducted. Experimental subjects included yarns II, III and IV, whose information is listed in table 4.4.

Table 4.4. The detailed specifications of yarns II, III and IV.

Batch	No.	Type	Component	Picture
II Zhuhai factory	2-0	Control	Cotton	
	2-1	Novel	Core: cotton Wrap: PET	

III Jiangsu factory	3-0	Control	Cotton	
	3-1	Novel	Core: cotton Wrap: PET (68%-32%)	
IV Yuyue factory	4-0	Control	Bleached cotton	
	4-1	Novel 1 (Z-twist)	Core: cotton Wrap: PA (89%-11%)	
	4-2	Novel 2 (S-twist)	Core: cotton Wrap: PA (88%-12%)	
	4-3	Novel 3	Core: cotton Wrap: PA (76%-24%)	

4.3.1 Capillary wicking tests

The control materials of yarns II and III were 32S unbleached raw cotton (2-0 and 3-0), which exhibited almost zero wicking height. Yarns from Yuyue factory adopted bleached cotton as the core yarn. Yarns 4-1 and 4-2 possess basically same structure but opposite twisting direction of the covering yarns. The core yarns are both Z-twisted and the wrap yarns of 4-1 were twisted on the core yarn in the same Z direction, while the wrap yarns of 4-2 were twisted on the core yarn in the S direction. The difference in twisting directions resulted in a difference in the wicking height, as shown in figure 4.4.

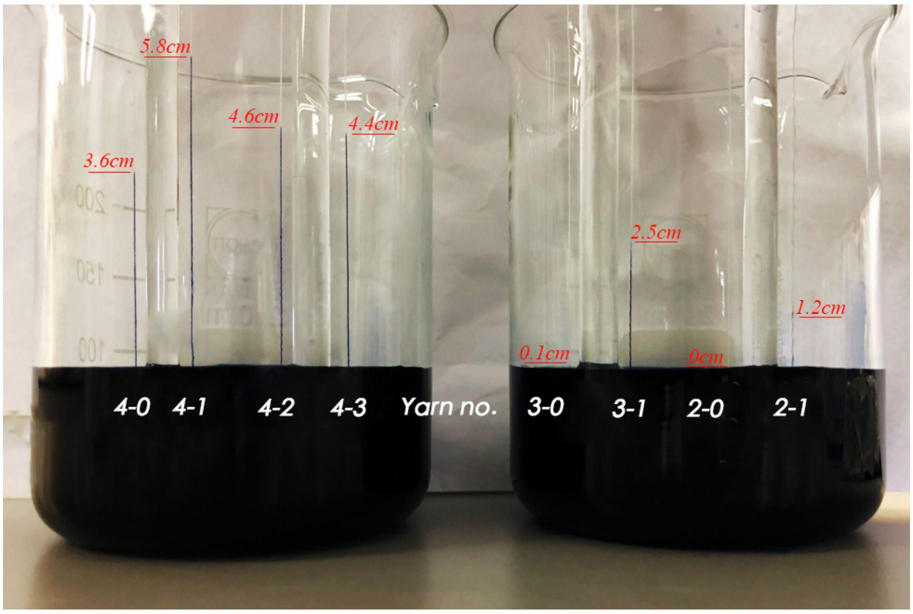


Figure 4.4. Capillary action test of yarns in 30 minutes.

The unbleached yarns II (control: 2-0; novel: 2-1) showed no notable improvement on capillary wicking. As shown in table 4.4, the helix angle of the wrap yarn is too low to induce an obvious improvement on the capillary wicking action since the wrap yarn could not provide inward forces that bind the core yarn.

The unbleached yarns III (control: 3-0; novel: 3-1) exhibited an obvious improvement of 2.4cm, which is the highest one of the yarns. It can be seen from the microscopic photos that the structure of the tested novel yarn is quite neat and clear. However, the percentage content of PET is 32%, which is higher than the desired percentage of 20%. The picture of the yarn also shows a large covering area by the wrap yarn. Therefore, further improvement on the yarn component is required.

Yarns IV (control: 4-0; novel: 4-1, 4-2 & 4-3) also achieved notable improvement on moisture wicking performance. The core cotton materials used in batch IV were bleached, which means the control group has high hydrophilicity initially. The net improvement of wicking height is 2.2cm, 1.0cm and 0.8cm, respectively. Yarn 4-1 achieved the best improvement. The superposed twist structure in the yarn strengthened the tightness of fiber assemblies, resulting in a better wicking performance. Whereas the opposite twist directions between the core material and covering material had less improvement on the reduction of capillary channel diameters. As indicated in the former chapter, the effect of twisting directions of the wrap yarn depends on the original tightness of the core material. In this case, the core cotton yarn exhibited lower twist levels, which means an increase in fiber tightness would bring a better capillary behavior. Yarn 4-3 was prepared with higher twist levels and the wrap yarns exhibited a more helical path, as shown in table 4.4. The smaller pitch resulted in a small tightness of wrapping, and thus only slight improvement was observed. The result was consistent with that of the hand-made yarns. The looser covering of the outer material resulted in a slighter capillary action improvement. A proper tightness of yarn is therefore essential for optimal moisture wicking.

4.3.2 Moisture transport tests of knitting fabrics made by yarns III

In order to have a better comparison between the wicking performances, knitting fabrics were prepared using yarns III and IV. There were no further experiments about the Yarns II due to the undesirable structure and poor wicking results. The Hosiery machine with same parameters was used to prepare knitting fabrics of both control and novel yarns. Moisture wicking tests of knitting fabrics prepared using yarns III will be discussed in this section. Three sets of experiments based on the PRC standard were conducted, including water absorption rate, drip diffusion time and wicking height.

The mean value of the five sets of samples was calculated and the result is shown in figure 4.5 below. The blue columns represent the fabrics before washing, and the gray columns represent the fabrics after washing. The water absorption rate of the novel yarn before washing is significantly improved. This means the novel fabric could absorb much more water in short time, providing a better wearing comfort. For after-washing fabrics, the results showed no significant difference. It was conjectured that the washing and drying conditions made notable influence on the structure of the cotton and thereby affected the results, which will be discussed in later sections.

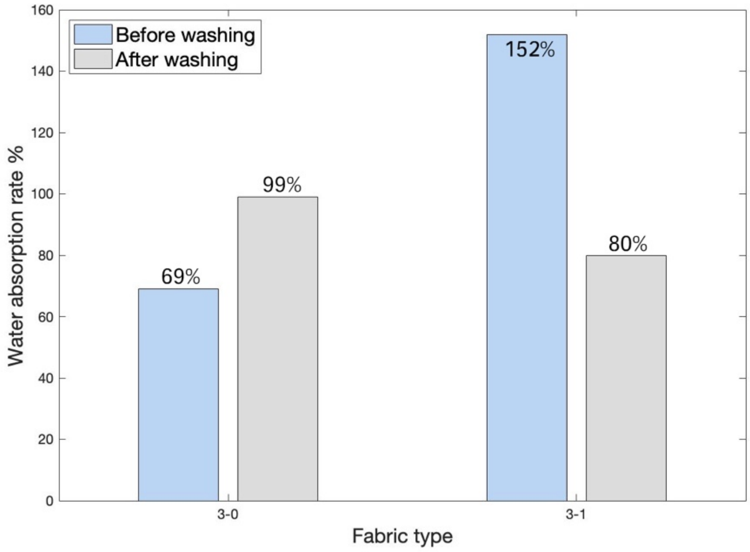


Figure 4.5. Water absorption rates of fabrics made of yarns III.

Drip diffusion test was conducted by recording the diffusion states after drop 1 milliliter liquid on the fabric. Figure 4.6 demonstrates the change of contact angles within 2 seconds after the droplet contacted the fabric. The time intervals between each picture are equal, that is, the interval between each adjacent picture is one-third of a second. The experimental subjects are fabrics before washing. It is explicit that the water diffusion of the novel fabric was enormously improved compared with the control cotton. The control fabric exhibited water repellency when the dye was dropped on the surface, leaving a nearly spherical water droplet. On the novel fabric, as shown in figure 4.6 (b), the droplet was immediately absorbed by the fabric, consistent with the model of wicking in a finite reservoir.

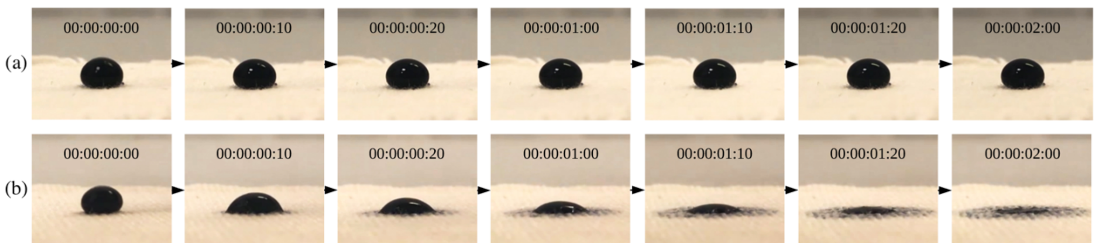


Figure 4.6. Change of contact angles within 2 seconds. (a) The control group: knitting fabric made by yarn 3-0; and (b) novel fabric made by yarn 3-1.

The final states of diffusion are given in figure 4.7, i.e., when the specular reflection completely disappeared, or the state at 300s if the droplet could not be absorbed. Further experiments of fabrics that after washing were conducted and only the droplet on the novel fabric before washing was completely diffused in seconds. The other three pictures are the state when the time is 300 seconds. The control cotton fabric exhibited water repellency no matter before or after washing. For the novel fabric before washing, diffusion was quick and the diffusion distance differed in the warp and weft directions. It was easier for water to be absorbed in the warp direction due to the knitting structure. For the novel fabric after washing, although time required for complete diffusion is larger than 300 seconds, the hydrophilicity of fabric still showed difference with that of the control fabric, as shown in figure 4.7 (b). Small amount of water was diffused into the fabric, indicating a slight improvement of wicking compared with the control cotton.

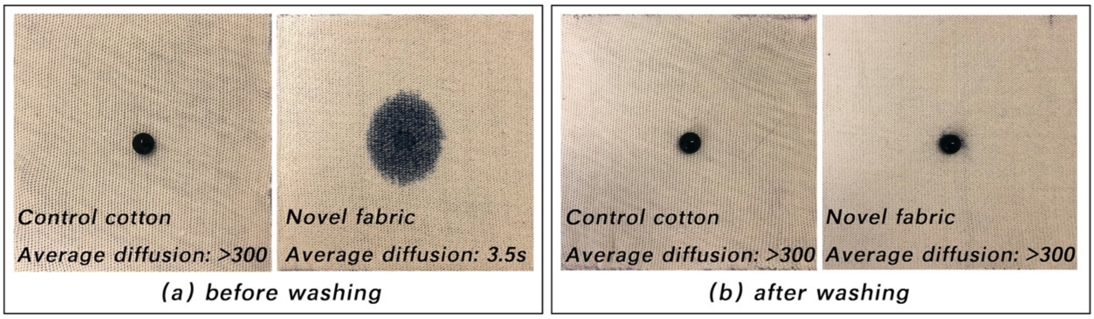


Figure 4.7. Liquid absorption state when the droplet was completely absorbed or at 300s. (a) Before washing; and (b) after one time washing using washing machine and dryer.

For the capillary action tests, the tested novel fabric presented an improved moisture wicking ability on both warp and weft directions, while the control fabric had very poor result as it absorbed even 0 cm liquid after 5 minutes. Due to the knitting structure of the fabric, the improvement of wicking height in warp direction is slightly larger than that in the weft direction, which is consistent with the elliptical diffusion during the drip diffusion test. Figure 4.8 gives the changes of wicking heights within 5 minutes. The wicking rate was highest at the beginning and decreased gradually with time. The curve of the novel fabric generally follows the square relation between wicking height h and wicking time t.

$$h^2 = Ct \tag{4.2}$$

where C is a constant depending on the liquid and yarn properties.

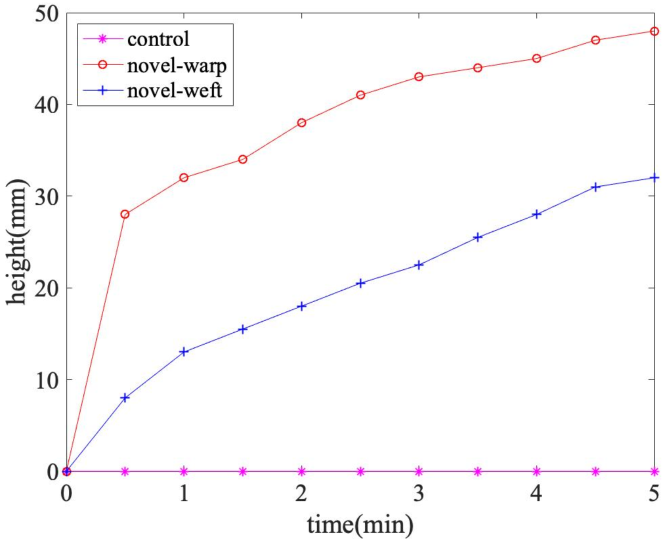


Figure 4.8. Wicking height verses time for yarns III.

Figure 4.9 shows the state at 5 minutes. In each beaker, the left sample was the control cotton and the right one was the novel fabric. (a) Samples before washing and cut in warp direction; (b) Samples before washing and cut in weft direction; (c) Samples after washing and cut in warp direction; and (d) Samples after washing and cut in weft direction. Significant improvement was achieved for the both samples before washing, whereas the result after washing was not ideal. For figure 4.9 group (c), although the wicking height of tested novel yarn was estimated to be 0, a trend of wicking could be observed on the detailed picture. Further experiments about wicking test after two times of washing was conducted, the result remained 0 for both controlled and experimental group.

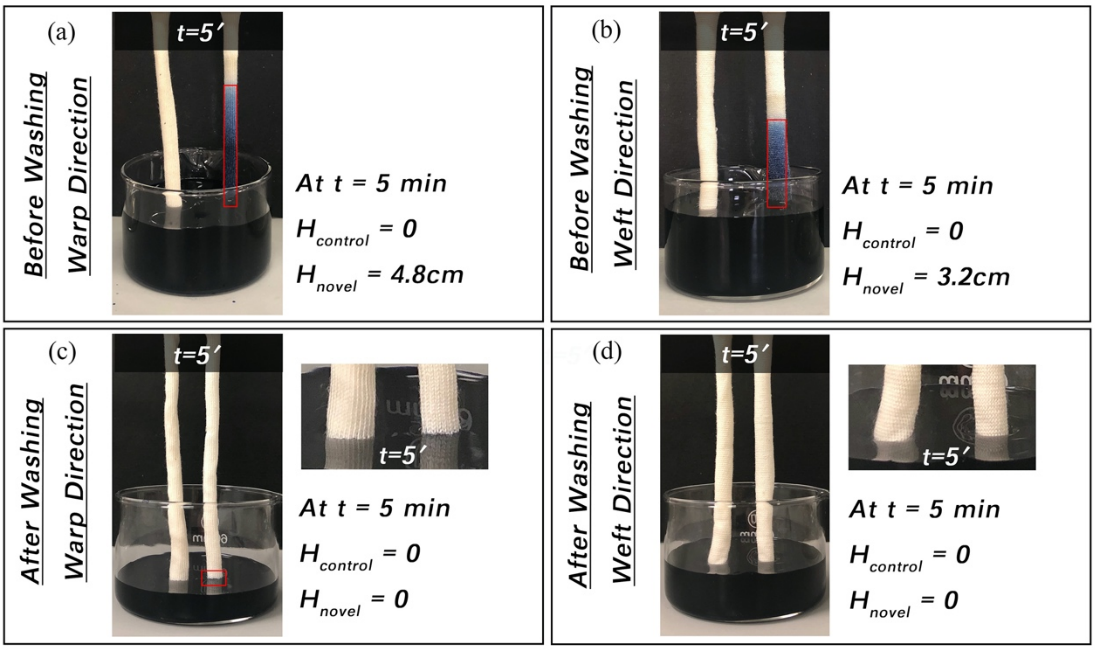


Figure 4.9. The wicking height of yarns III at 5 minutes.

4.3.3 Moisture transport tests of knitting fabrics made by yarns IV

Yarns IV were prepared by Yuyue factory under instruction. The batch contains 4 kinds of bleached yarns, one is the control cotton and the rest are novel yarns spun following the proposed covering technology. The core material used in this batch was bleached and thus had good water absorption ability. Experiments in this section showed that the proposed structure can also improve the moisture wicking of hydrophilic materials, leaving more choices for material selection.

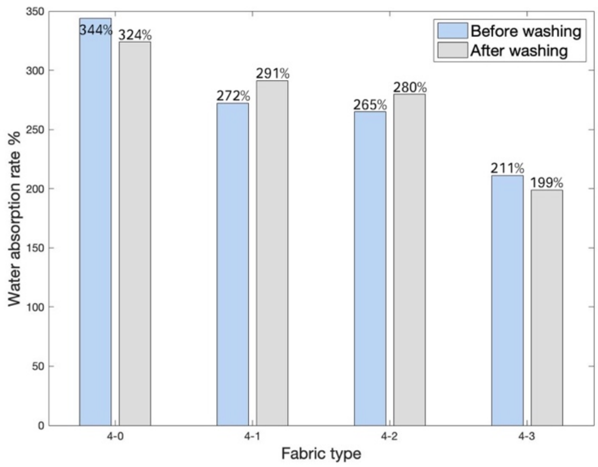


Figure 4.10. Water absorption rate of yarns IV.

Five samples for each kind of fabric were prepared for the measurement of water absorption rate. The mean value was calculated and the result is shown in figure 4.10. Water absorption ability is directed related to water holding capacity, which further impacts the drying speed of yarns in wet condition. For control cotton with a low water absorption rate, it is beneficial to have an increase in the rate for the novel yarn, as the water will be absorbed faster and guided to the air. However, in this case, when the control cotton already exhibited an excellent water absorption rate, a high rate will bring more burden to the wearer and even decrease the drying speed. For the novel yarns, the water absorption rate was limited to a lower level due to the decrease of hydrophilic nature fiber content. Moreover, the covering material can act as a binder to maintain the water holding capacity at a reasonable level and help to maintain a comfortable wearing experience.

The results demonstrated in figure 4.11 showed the liquid absorption state when the liquid droplet was completely diffused, i.e., when the specular reflection completely disappeared. Five groups of samples were tested and the mean diffusion time is shown on each picture.

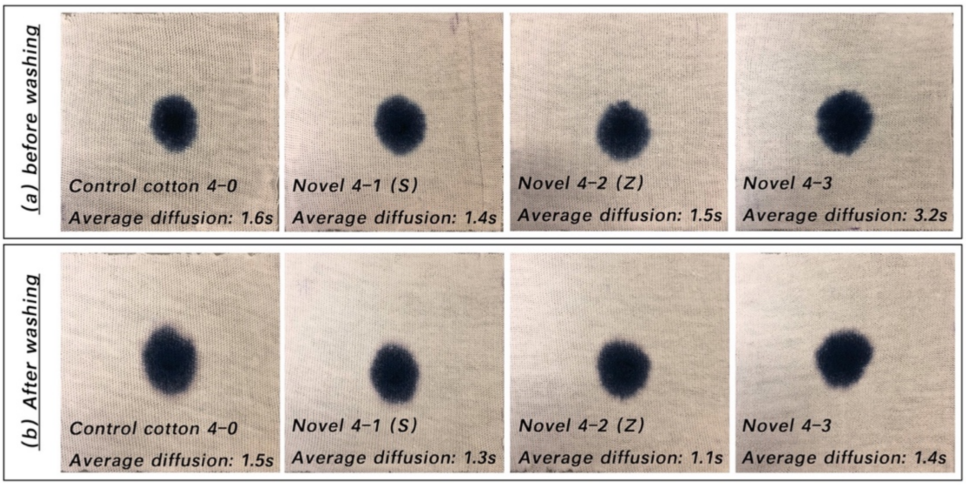
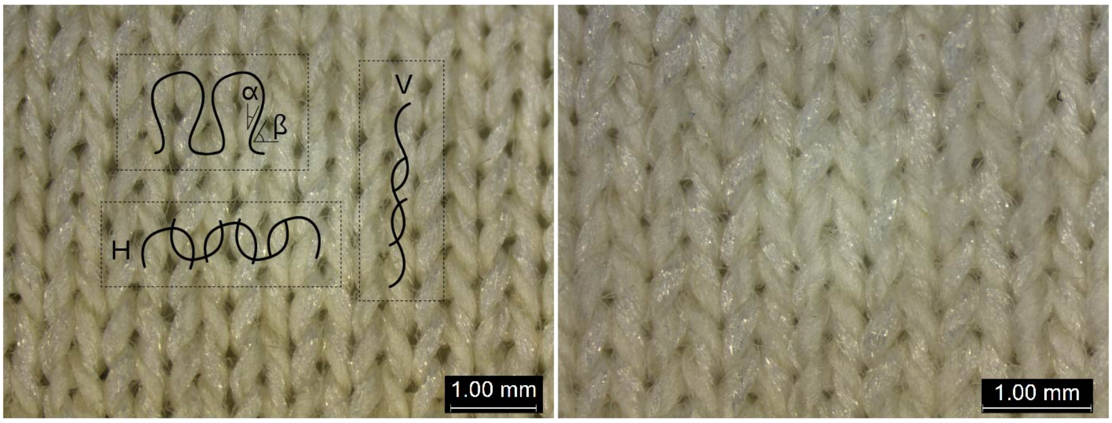


Figure 4.11. Liquid absorption state when the droplet was completely absorbed. a) Before washing. b) After one time washing using washing machine and dryer.

Since the cotton used as core material in this batch possesses high hydrophilicity, the average water diffusion time showed no significant difference. For each sample, the fabric was laid flat on the surface with the vertical direction of the picture as the warp direction. The elliptical diffusion shape of the liquid reflected the knitting structure of the fabric, as shown in figure 4.12 (a). The loops in the knitting structure determines the preferred directions of the yarns. Most of the yarn segments are lined in the vertical direction. For a typical loop, the angle between the yarn and the vertical direction is measured to be approximately $\alpha \approx 30°$, while the angle with the horizontal direction (i.e., the weft direction) is $\beta \approx 60°$. Consequently, when the liquid is transported along the yarns, it would be easier to diffuse in the warp direction. Moreover, the yarn segments from different loops form relatively continuous connections in the vertical direction, as shown by track V. The yarn connections in the horizontal direction (as shown by track H) is however less continuous. The discontinuity of yarns aggravated wicking in the weft direction and the diffusion of liquid hence showed an elliptical shape. Besides, the porosity of the fabric decreased significantly due to cotton swelling, as shown in Figure 4.12 (b).



(a) (b)

Figure 4.12. Constructions of knitting fabrics made of yarn 4-1. (a) Before washing; and (b) after washing.

The capillary wicking tests gave better comparison between the wicking rates of different materials. Figure 4.13 below shows quite satisfactory capillary action improvement of the tested yarns before washing. In each graph, the black line with the asterisk symbol records the wicking heights of the control cotton fabric in five minutes. The change of wicking heights for each sample generally follows the square law (equation 4.2), and the wicking rates gradually decrease with time. After five minutes of wicking, the 3 novel samples achieved different degrees of improvement in both warp and weft directions compared with the hydrophilic control group.

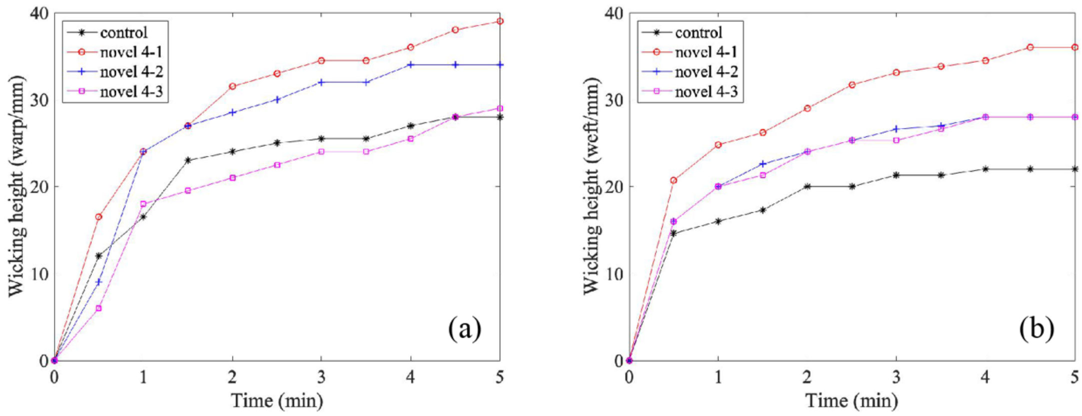


Figure 4.13. Capillary wicking height tests of fabrics made of yarns IV before washing. (a) Cut in warp direction; and (b) cut in weft direction.

The wicking states at five minutes are depicted in figure 4.14. For each fabric, two groups of samples were prepared with one cut in warp direction and the other cut in weft direction. Pictures (a) and (b) give the states before washing, while pictures (c) and (d) are the states after washing. In each beaker, the most left one is the control cotton sample and the other three novel samples achieved various degrees of improvement. The wicking results before washing are consistent with the result of wicking height test of the yarns, which is shown in figure 4.4, that is, novel 4-1 > novel 4-2 > novel 4-3 > control 4-0. The result verified that the moisture transport ability of fabrics is significantly influenced by the hydrophilicity properties of the yarns.

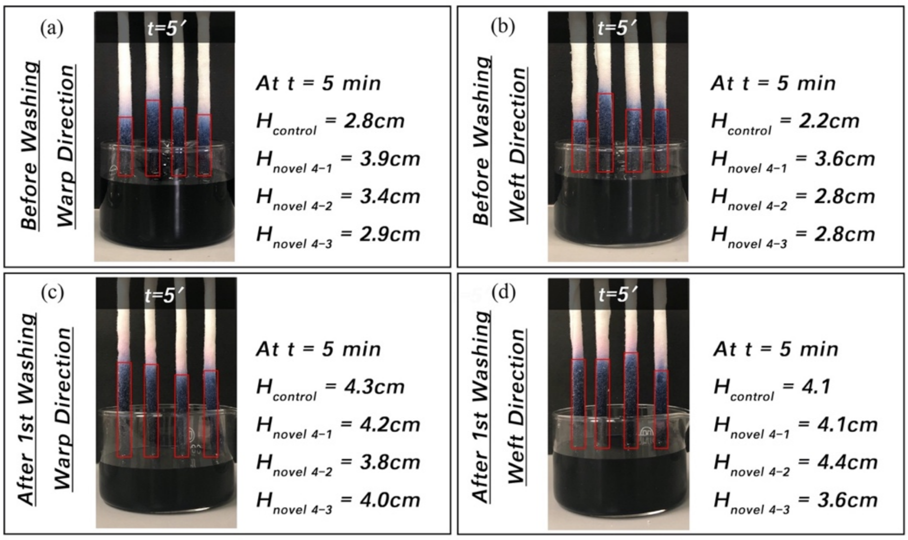


Figure 4.14. The wicking heights of knitting fabrics made of yarns IV. The samples in

each beaker are: control cotton 4-0; novel 4-1; novel 4-2; novel 4-3, following the order from left to right.

However, variance appeared after going through washing machine and dry. The samples were washed by city running water, with both washing machine and dryer applied during the process. After washing, the change in water absorption ability became unstable, as shown in figure (c) and (d). The fabrics generally became more hydrophilic, with higher wicking heights compared with that of before washing. Besides, the difference between the wicking heights in warp and weft directions were reduced, indicating relatively more isotropic moisture wicking properties after washing. In order to investigate the yarn deformation after washing, structures of yarns were observed under microscope, as shown in figure 4.15. For novel yarn 4-1 in group (b), the twists of the core and wrap yarns are both in Z direction. The yarn underwent un-twisting after washing, leaving the covering fibers spread out and sparsely distributed around the core yarn. The pressure of the covering material to the core yarn is therefore reduced, resulting in a poor effect of the wicking structure. For yarn 4-2 in group (c), the twists directions are Z and S for the core and wrap yarns, respectively. The core yarn was twisted and curved due to the shrinkage of cotton, resulting in a serious deformation of the yarn structure.

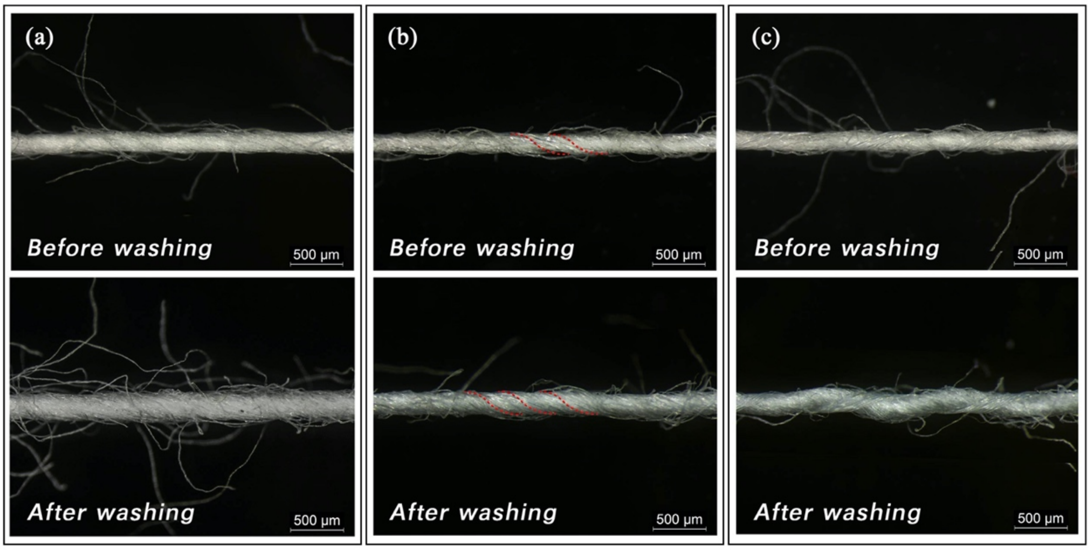


Figure 4.15. A comparison of microscopic pictures of yarns IV before & after washing. (a) Control cotton; (b) novel yarn 4-1; and (c) novel yarn 4-2.

A series of experiments with samples going through different washing conditions were arranged afterwards to find the influence of yarn deformation on the fabric moisture transport ability. The washing conditions include:

(a) Hand washing by deionized water in room temperature;

(b) Hand washing by city running water in room temperature;

(c) Hand washing by city running water in 70°C;

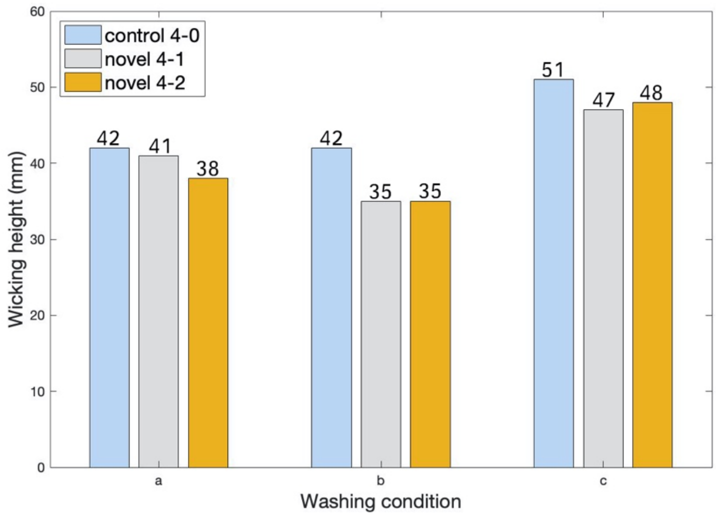


Figure 4.16. Wicking heights at five minutes after different washing conditions.

The wicking heights of fabric capillary wicking test at five minutes were compared in figure 4.16. The fabrics were cut in warp direction and tested under same environmental conditions. It was found that the influence of water source is less significant than that of the water temperature. Fabrics in groups (a) and (b) washed in room temperature exhibited similar wicking heights in five minutes, while the capillary wicking ability was improved in fabrics in group (c), which were washed by water around 70°C. The wicking heights of cotton is slightly larger than the novel materials. As shown in figure 4.15, the bleached cotton experienced less deformation after washing and thus exhibited better wicking performance.

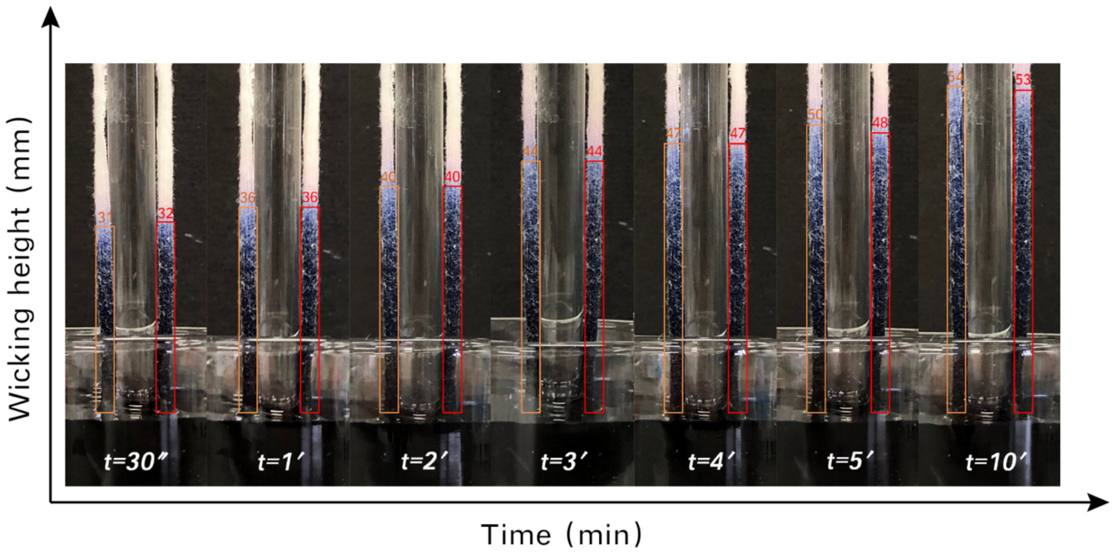


Figure 4.17. The wicking heights of yarns 4-0 and 4-1 after fully washing.

Fully washing by washing machine, including two cycles of cold water washing and four cycles of hot water washing were conducted on fabrics made by yarns 4-0 and 4-1. The water used was city running water. The change of wicking heights in 10 minutes was demonstrated in figure 4.17. The fabric selected by the orange rectangle was the control cotton. while the red rectangle selected the wet area of the novel fabric. At t = 5 mins, the wicking height of control cotton was around 50mm while the wicking height of novel yarn 4-1 was 48mm. Actually, the heights were very similar and it was difficult to distinguish the height of water. The improvement due to the wrapping structure became less obvious after fully washing. This brought about very useful inspiration to the investigation of cotton shrinkage.

4.4 Moisture transport tests of yarns V

After the moisture transport tests yarns II, III, and IV, it was found that the wrapping technology could be improved by modifying spinning parameters. Therefore, yarns V were prepared for further experiments. The yarns were produced by Yuyue factory with modified parameters as shown in table 4.5. A total of 6 kinds of unbleached yarns were prepared, one is the control cotton used as the core material, and the rest are novel yarns spun following the proposed covering technology. The core material used in this batch was unbleached with almost no absorption ability.

Table 4.5. The detailed specifications of yarns V.

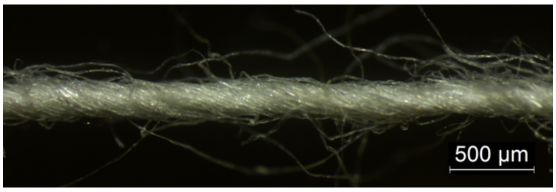
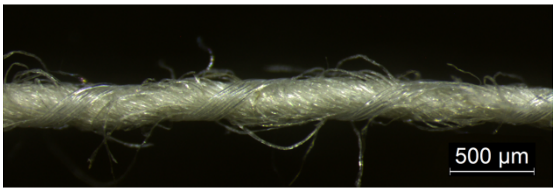
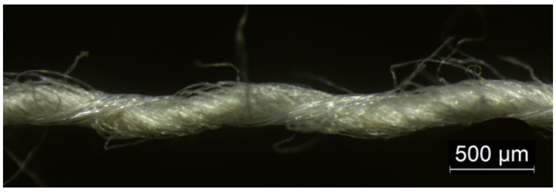
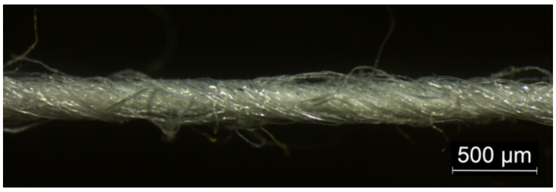
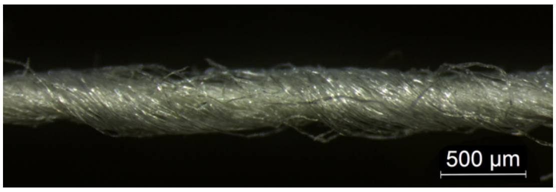
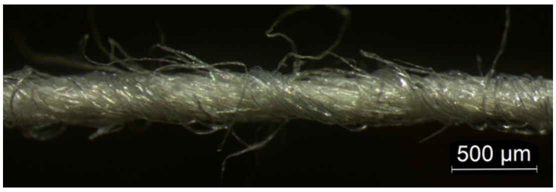
No.	Type	Component	Picture
5-0	Control	Unbleached Cotton	
5-1	Novel 1	Core: cotton Wrap: PA (90%-10%)	
5-2	Novel 2	Core: cotton Wrap: PA (86%-14%)	
5-3	Novel 3	Core: cotton Wrap: PA (85%-15%)	
5-4	Novel 4	Core: cotton Wrap: PA (70%-30%)	
5-5	Novel 5	Core: cotton Wrap: PA (87%-13%)	

Figure 4.18 shows the capillary action test of the yarns. It can be seen that only yarns 5-4 and 5-5 presented spiral capillary actions with unstained intervals. The microscopic photos of these dyeing sections revealed that the dyed area was located on the cotton yarn under the covering material. The cotton yarn itself had small capillary action. The pressure is the highest for those area under the covering material.

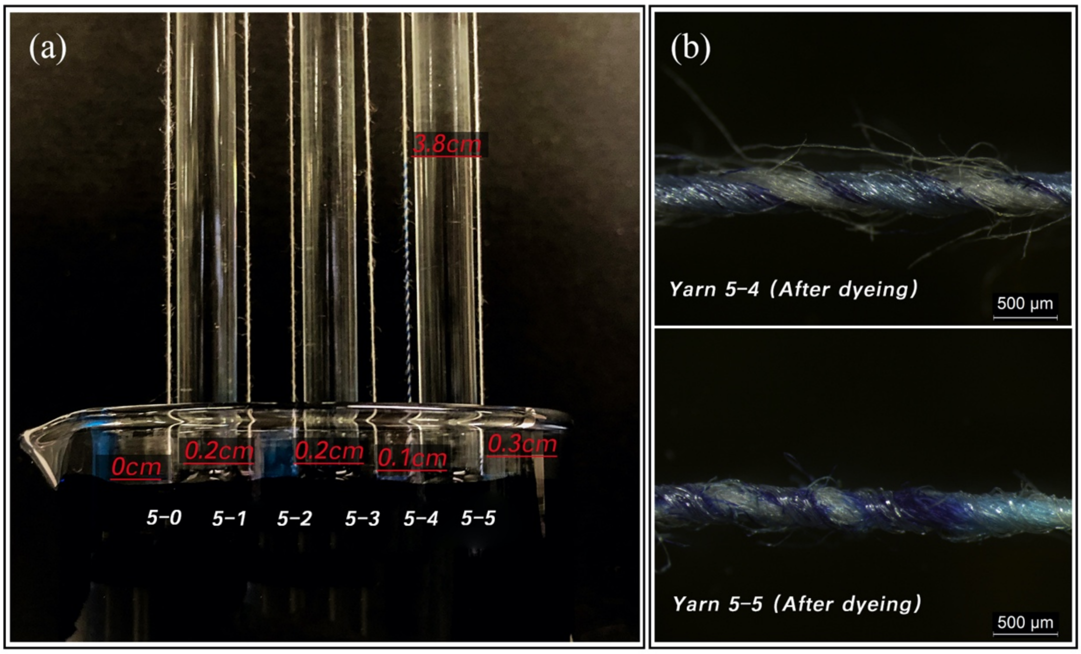


Figure 4.18. (a) Capillary action test of yarns V in 30 minutes; and (b) microscopic photos of dyed yarns.

For the drip diffusion time test, figure 4.19 recorded the final states of drop absorption. The first row of pictures was tested before washing and the second row was after 1 time washing by washing machine. Only yarn 5-4 achieved complete absorption, i.e., disappear of specular reflection, at time of 41.6s and 110s, respectively. The others did not absorb the water droplets within the required 300 seconds. The change of contact angles of fabric 5-4 was denoted in figure 4.20. Although the time required for complete diffusion increased after washing, the fabric maintained good wicking ability compared with the core cotton.

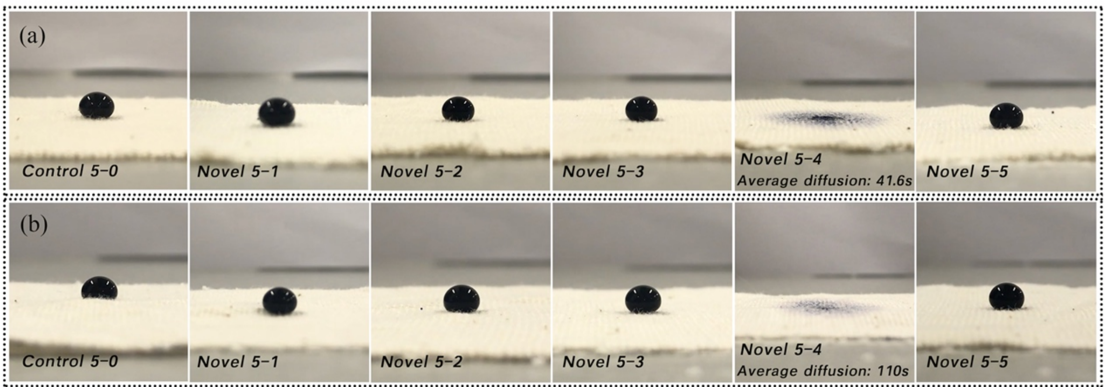


Figure 4.19. Liquid absorption state when the droplet was completely absorbed or at 300s. (a) Before washing; and (b) after washing.

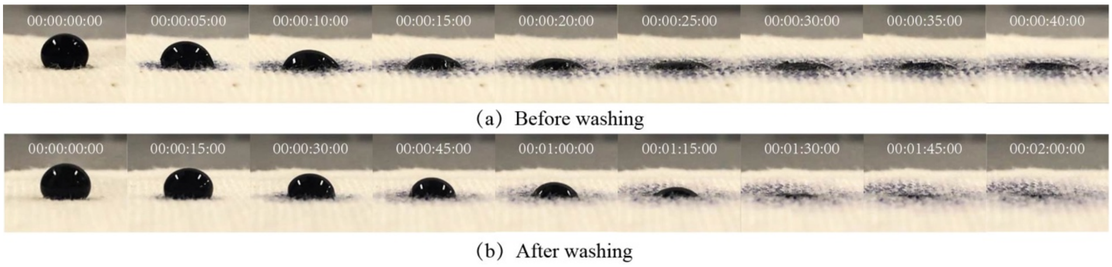


Figure 4.20. Change of contact angles of fabrics made of yarn 5-4. (a)Before washing, change in 40 seconds; and (b) after washing, change in 2 minutes.

Following the capillary action test of yarns, a wicking test of knitting fabrics made of the control yarn 5-0 and novel yarn 5-4 was conducted since only yarn 5-4 achieved notable improvement according to the previous tests. The results showed that both the before and after washing tested novel yarn had distinct improvement in wicking height. Although the wicking height was reduced after 1 time washing, the improvement remained obvious. Meanwhile, the control group (pure cotton) showed zero wicking height after 30 minutes.

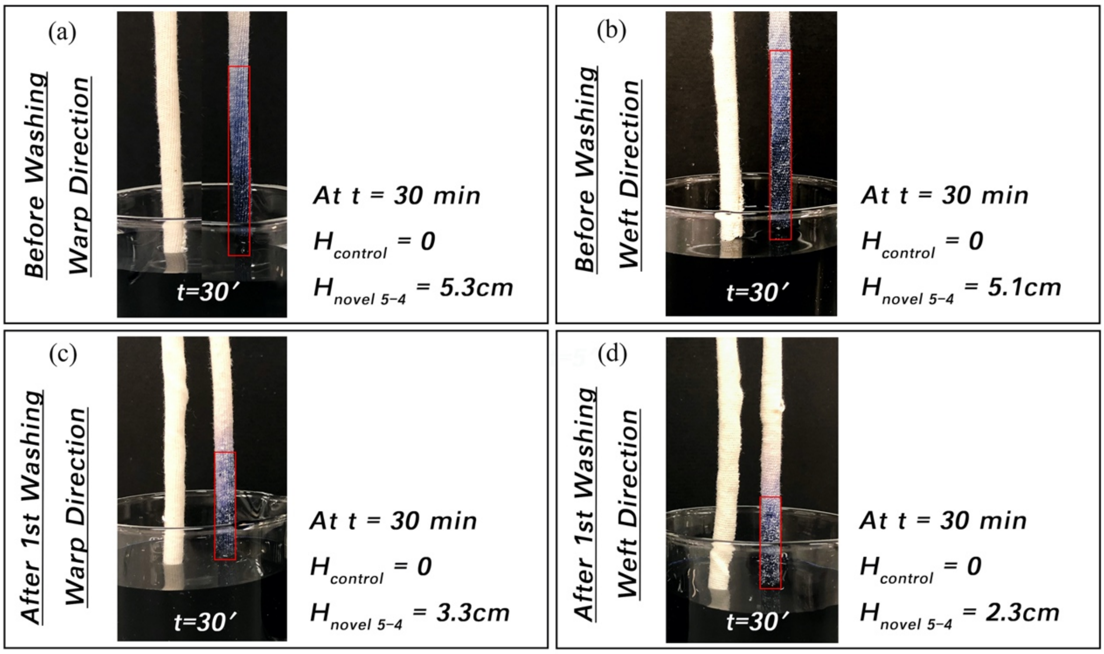


Figure 4.21. The wicking height test of fabrics 5-0 and 5-4.

Figure 4.21 shows the wicking height after 30 minutes. In each beaker, the left sample is the control cotton 5-0, and the right one is the novel fabric 5-4. Notable improvement was achieved for yarns cut in both warp and weft directions. Compared with yarns tested in section 4.3 (yarns II, III, and IV), the knitting fabric made of yarn 5-4 also achieved improvements on moisture wicking after washing, indicating the potential of commercial application although there still require further improvements. Yarn 5-4 consists of 70% cotton and 30% PA, which is higher than the expected value of 20%. Besides, the wicking front of liquid showed no explicit boundaries between the wet and dry fabric. Instead, an area with a gradual change from dark to light was observed for each fabric strip. The result indicated that limited amount of liquid was absorbed into the yarns, as shown figure 4.18 (b), only part of yarn was functional for moisture wicking.

The second stage of experiments included yarns II, III, IV, V and fabrics made in accordance (section 4.3-4.4). To sum up, the tests verified the improvement of water absorption ability of novel yarns compared with the control cotton yarns before washing. However, the effect after washing remains unstable. Since cotton could undergo up to more than 10% of shrinkage, deformation took place and the structure of the wrapped yarn might be altered. In order to explore the relationship between cotton shrinkage and water absorption ability, the third stage of experiments was conducted, focusing on the influence of different washing conditions.

4.5 Cotton shrinkage under different washing conditions

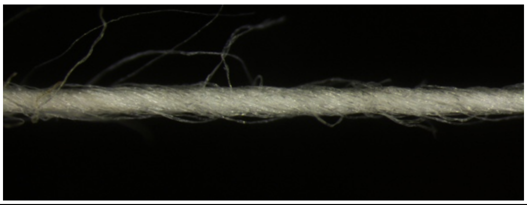
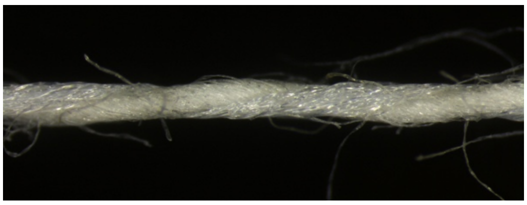
Based on the previous stages of experiments, washing could play an important role on the water absorption ability of yarns. Besides, the degrees of influence vary with different washing conditions. Therefore, experiments focused on the comparison of yarns before and after washing were conducted before spinning further yarns. Section 4.3.2 showed conflicting results that although the novel yarn 3-1 exhibited great improvement of capillary action before washing, the improvement almost disappears after washing and drying. Therefore, the two yarns of batch III, including the control cotton and the novel yarn, were selected for this stage. The objectives of the following experiments are:

1. Comparison of washing shrinkage of control cotton and novel yarns to explore the influence of proposed structure on the shrinkage and possible other properties of the yarn.
2. Measure the change of diameter after washing of both cotton and the novel yarns and try to figure out the shrinkage principle of cotton.
3. Investigating the influence of washing under different conditions on the structure of the proposed yarns.
4. By undertaking different washing methods, explore the most appropriate and practical washing conditions of the proposed yarns.

In order to compare both the influence of water temperature and existence of detergents, five sets of washing method were conducted as listed below:

(a) City water in room temperature (400ml)
(b) City water in room temperature & adding detergents (1g/400ml)
(c) Hot water (400ml, around 95°C)
(d) Hot water & detergents (1g/400ml, around 95°C)
(e) Hot water & detergent & stir during washing (1g/400ml, around 95°C)

Table 4.6. The detailed specifications of yarns III.

Batch	No.	Type	Component	Picture
III Jiangsu factory	3-0	Control 32S	Cotton	
	3-1	Novel 22S	Core: cotton Wrap: PET (68%-32%)	

4.5.1 Shrinkage of length under different washing conditions

As mentioned in the last section, totally 6 groups of yarns were tested, including one control group of yarns before washing and five experimental groups of yarns after washing. For each group, five identical samples were prepared to reduce error. The original length of yarns was measured to be 40cm. Then the yarns were immersed in the water tanks for 1 hour and put in standard environment for 20 hours for humidifying. Measure the length again and the shrinkage could be calculated by:

$$shrinkage = \frac{l_0 - l}{l_0} \times 100\% \tag{4.3}$$

where l_0 is the original length and l is the length after washing and humidifying. During the experiment, the phenomena of yarn sinking into water were quite different. For condition (a), i.e., city water in room temperature, it was difficult for the yarns to sink into water. After pushing the yarn into the water by glass rod for several times, the yarns float right beneath the water surface. For condition (b), where detergent was added compared with condition (a), the yarns could sink into water rapidly and undergo slight deformation. The phenomena changed dramatically for the rest conditions, i.e., for conditions with hot water, the yarns sank into water rapidly and curved seriously, resulting in large deformation in a short period of time. From the observation of experiment, hot water has great contribution to short time deformation. For quantitative analysis, take mean value of the length after washing and the change of shrinkage with different washing conditions can be drawn as figure 4.22 below.

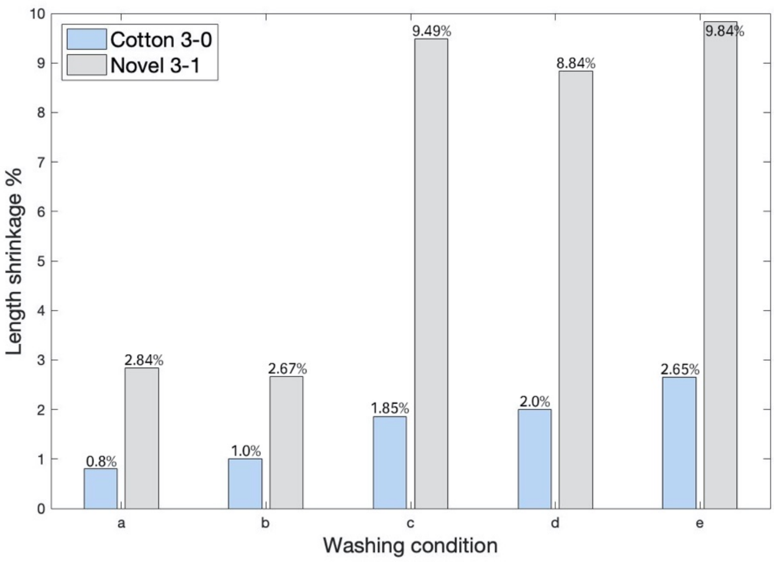
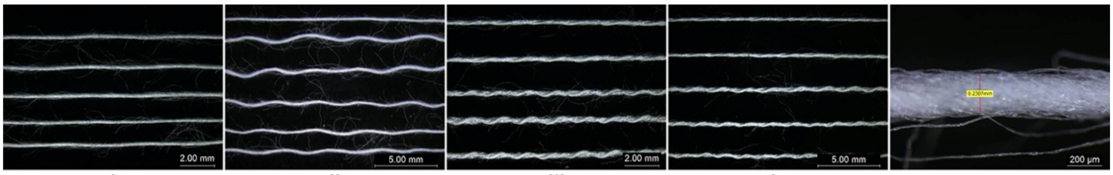


Figure 4.22. Comparison of shrinkage after different washing methods.

The shrinkage of the novel yarn is obviously much higher than that of cotton. The shrinkage of cotton is related to the water absorption ability, which means the water absorption of the novel yarn is much more than that of pure cotton during the soaking process. Adding of detergents had small influence on the shrinkage while raising the temperature could largely increase the shrinkage. By observation during the soaking of yarns III, high temperature of water made serious deformation to the yarns such as curve, shrinking and twinning. The relation between shape deformation and shrinkage coincides with the principle of cotton shrinkage.

4.5.2 Change of yarn diameter after washing

Same sample as those in section 4.5.1 were prepared by soaking in different water conditions for 1 hour and humidifying in the control room for more than 20 hours. Yarns were fixed on glass slides under same tension, then photographed and measured by microscope. Since the yarns were exposed to the air, diameters can be measure in both wet and dry condition. Figure 4.23 gives an overview on the yarn conditions. (i) The cotton yarn after washing in wet condition; (ii) the cotton yarn after washing and humidifying; (iii) the novel yarn after washing in wet condition; (iv) the novel yarn after washing and humidifying; and (v) a typical measurement of a random yarn.



i ii iii iv v

Figure 4.23. Overview on the yarn in different conditions.

Five groups of diameter data were recorded for each yarn to obtain an average value. Change of diameters was given by

$$D = \frac{1}{n}\sum_{i=1}^{n} D_i$$

$$Change\ of\ diameter = \frac{D - D_0}{D_0} \times 100\% \quad (4.4)$$

where D_0 is the original average diameter, D is the average diameter measured in different wetting or dried conditions, and n is the number of samples, in this case equal to 5.

As shown in the figure below, the diameters of yarns generally increased after wetting. Each group of bars include four yarns, i.e., the control cotton in wet condition; the control cotton after washing and humidified in the control room; the novel yarn in wet condition; and the novel yarn after washing and humidified in the control room. Washing condition (a) means that the yarn was washed by 400ml city water in room temperature; condition (b) means that the yarn was washed in 400ml city water in room temperature with 1g dissolved detergents; condition (c) means the yarn was washed in 400ml hot water; condition (d) means the yarn was washed in 400ml hot water with 1g dissolved detergents; and condition (e) represents the situation by stirring the yarn in the same condition as (d).

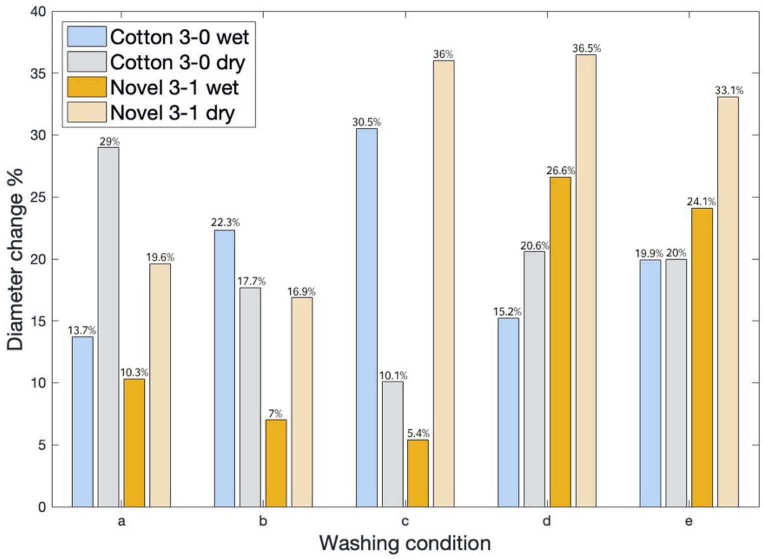


Figure 4.24. Diameter change of yarns after different washing conditions.

For the cotton yarn after wetting, as shown by the blue columns, the diameters of the yarn changed the most after wetted by hot water. The yarn curved into a wave shape immediately after immersed in hot water, bringing difficulties for the measurement of diameters due to the irregular shape. The diameters after dried in the control room exhibited different trends and degrees of change, which is probably due to the irregularity of yarns. For the novel yarn after wetting, as shown by the orange columns in the above picture, the yarns experienced serious deformation in the combination of high temperature and detergents (condition d and e). After drying in the control room (represented by the light-yellow columns), the diameters of yarns washed by hot water increased significantly. Using city water in room temperature had relatively small influence on the diameter of the yarn. The highest groups are c, d, and e. The difference between these three group is small and possibly due to experimental error. To conclude, the temperature of water had most serious influence on the diameter change. Yarns washed by hot water had larger diameter than that washed by water in room temperature and the change of diameter is closely related to the shrinkage of cotton.

However, similar to that of the cotton yarn, the novel yarn showed more irregularities with increased intensification of washing methods. As shown in figure 4.23, the diameters of the novel yarns can be extremely challenging to measure after wetting and washing. The irregularity of yarn diameters can be reflected by the standard deviation S, which is given by

$$S = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n-1}} \tag{4.5}$$

where n is the number of samples, in this case equal to 5; x_i is the measured value and $\bar{x}$ is the mean of the five measured values. The calculated sample standard deviations are given in figure 4.25.

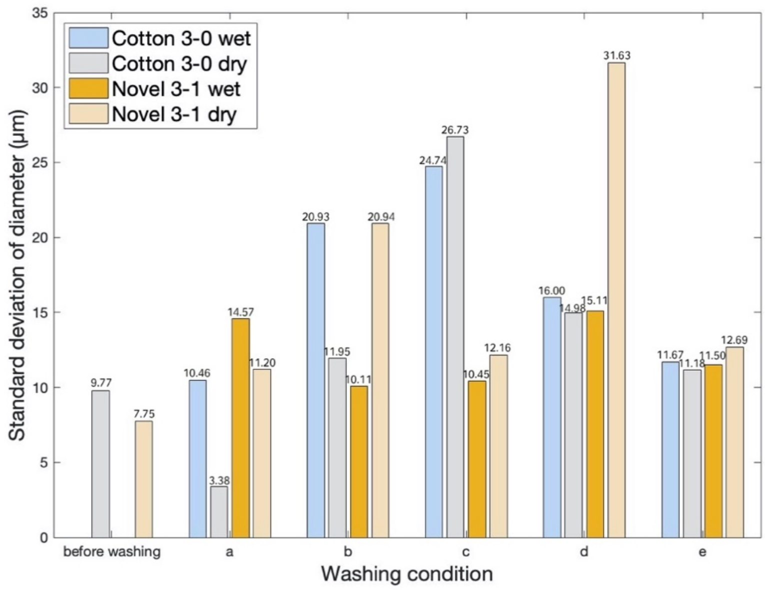


Figure 4.25. The sample standard deviation of yarns under different conditions.

The histograms can only reflect the influence of washing condition in a qualitative way. Although diameters of yarns in both the wet and dry conditions can be measured by this method, the results showed considerable errors. On the other hand, the diameter of a certain yarn can only be observed from a fixed point of view, resulting in limitations to the investigation on the yarn morphology. Therefore, diameter measurement by observing the yarn cross sections was adopted in the following experiments. Resin setting was conducted by sealing the novel yarn 3-1 in resin solution for a few hours. After the resin solution was completely solidified, yarns were cut from the direction vertical to the yarn so that samples of yarn cross section can be observed. Due to the limitation of resin setting, only humidified yarns were tested.

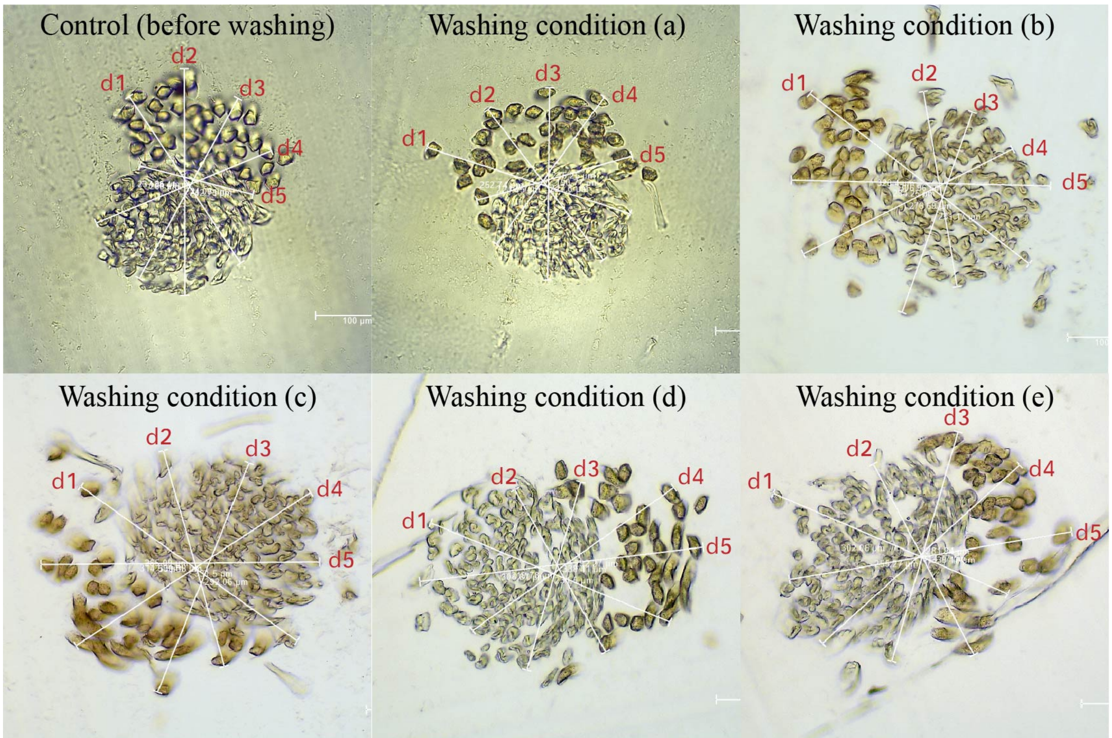


Figure 4.26. Measurement of yarn diameters through cross sections.

The above figure shows the measurement of yarn diameters of resin-setting samples. For each yarn, six slices of different yarn segments were prepared, i.e., six samples of yarns before washing, six samples of yarns after washing condition (a), six samples of yarns after washing condition (b), and so on. The pictures in figure 4.26 selected one representative for each condition. Hence the average diameter can be calculated by

$$D_i = \frac{1}{m}\sum_{i=1}^{m} d_i \quad (4.6)$$

$$\overline{D} = \frac{1}{n}\sum_{i=1}^{n} D_i \quad (4.7)$$

where m is the number of dimensions measured for each yarn cross section; and n is the number of cross-sectional samples for each condition. In this case, m equal to 5 and n equal to 6. The measurement of yarn diameters therefore takes into account the unevenness of different yarn segments and the irregular shape of cross sections after deformation. The diameter increments compared with the sample before washing is given in figure 4.27.

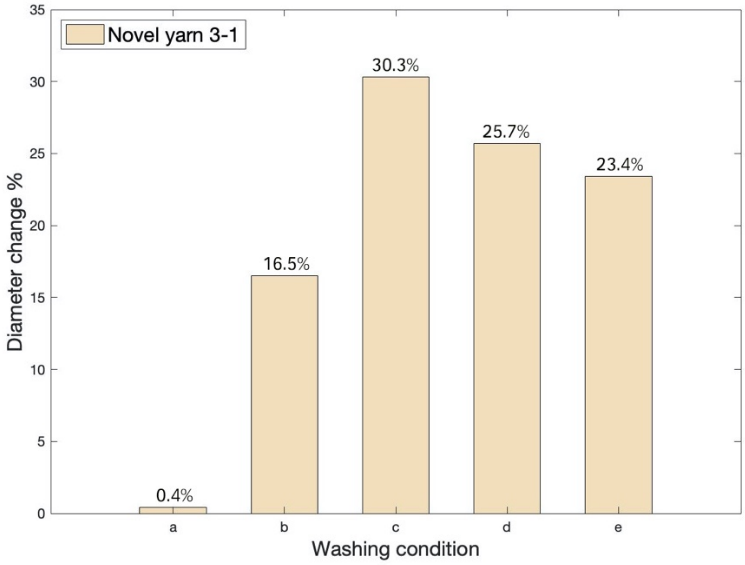


Figure 4.27. Diameters increment of novel yarn 3-1 under different washing conditions.

Yarns washed by hot water around 95°C (column c, d and e) demonstrated largest increment on diameters, which is consistent with the result in figure 4.24. By considering the dimensional irregularity of yarns, the influence of washing by city water in room temperature (column a) became insignificant. By comparing columns a and b, the influence of detergents gave around 16% increment on yarn diameter, while comparing columns a and c showed that using hot water can cause around 30% increment on yarn diameter. Although the accuracy of the data cannot be valid for all of the yarns, the result still indicated an overall influence of washing conditions.

The deviations of the measured diameters reflect the irregularity of the yarn. Define S_d as the standard deviation of the measured diameters from different directions on the same cross section; and S_D as the standard deviation of the average measure diameters from different cross sections. The calculation of S_d and S_D is

$$S_i = \sqrt{\sum_{i=1}^{m} \frac{(d_i - \bar{d})^2}{m-1}}$$

$$S_d = \frac{1}{n} \sum_{i=1}^{n} S_i \tag{4.8}$$

$$S_D = \sqrt{\sum_{i=1}^{n} \frac{(D_i - \bar{D})^2}{n-1}} \tag{4.9}$$

where m equal to 5 and is the number of dimensions measured for each yarn cross section; n equal to 6 and is the number of cross-sectional samples for each condition.

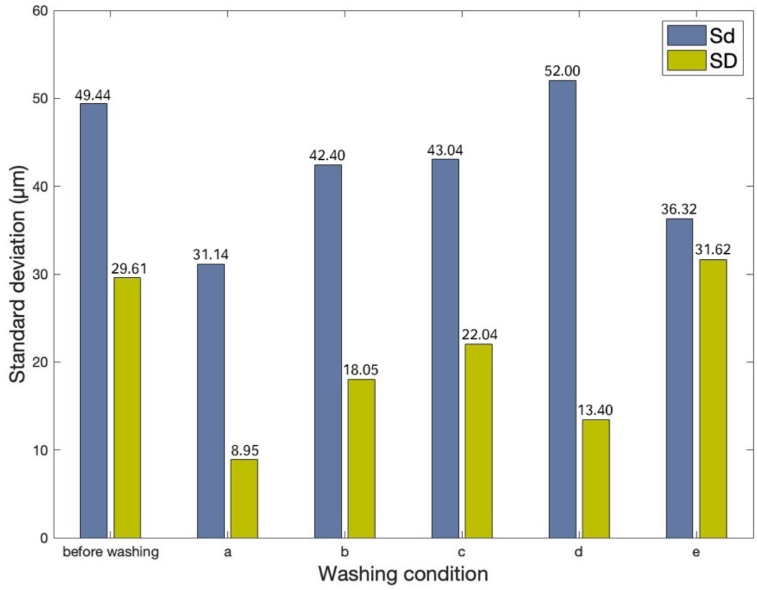


Figure 4.28. Standard deviations of cross-sectional diameters.

The parameter S_d reflects the irregularity of the cross sections. The smaller the value of S_d, the closer the yarn cross section is to a circle. Produced by spinning two individual yarns together helically, the novel yarn could possess cross sections of circles, ellipses, or overlaps of two circles. Therefore, the measurement of d_1 to d_5 can be very different. A smaller change of S_d after washing indicates a smaller deformation of the yarn's cross sections. The experimental results showed random changes of S_d after washing, which means that the cross-sectional shapes of the yarns underwent various deformations. Compared with the yarn before washing, the values of S_D after cold water washing became smaller, indicating that although the yarns absorbed large amount of water by soaking in cold water, the surface structures did not occur significant deformation. For the other conditions, the deviations of diameters across the yarns were not largely influenced by washing, which means the yarns still maintained certain uniformity after washing.

4.5.3 Typical deformations of yarns after washing

As discussed in the former section, the cross section of yarns became more irregular after washing. Figure 4.29 gives typical cross-sectional change of the novel yarn 3-1, where the first column is the cross section, the second column is the yarn in wet condition, and the third column is the yarn after washing in dry condition. It is worth mentioning that with the purpose of being more intuitive, the cross sections in the following figure are selected samples with representative severe deformation. As a matter of fact, only a small number of samples were observed to have such severe deformation, while most of them still maintained approximately round shape.

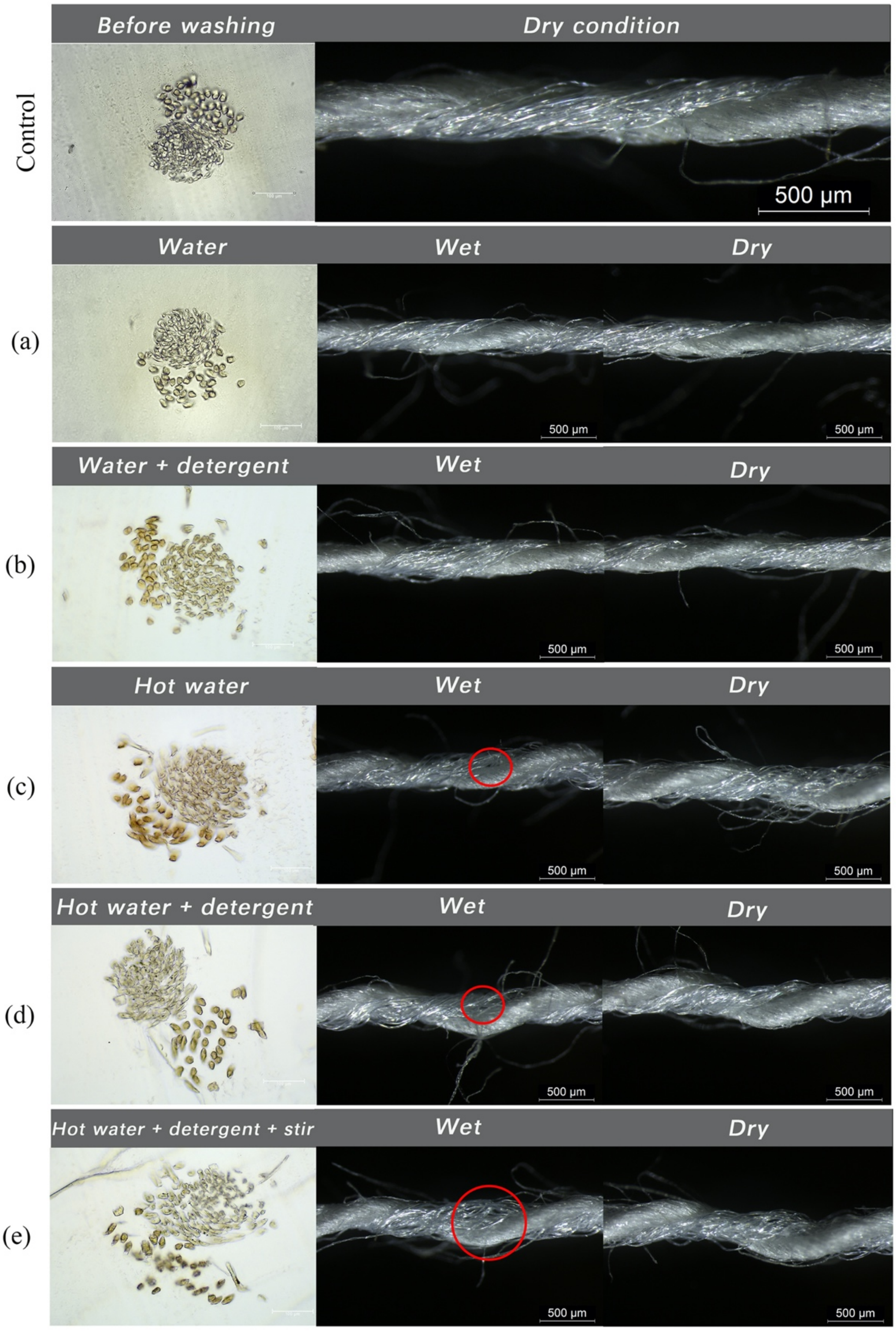


Figure 4.29. Typical deformations after washing.

The picture demonstrates 6 different stages of the novel yarn. Before washing, the covering material and the core material were wound tightly to keep relatively uniform thickness. There were only small intervals between the fibers. The compact intertwining structure provides enough pressure and formed small gaps between fibers so that wicking effect could be improved. When the yarn underwent washing (especially by hot water), deformation happened and diameters of yarns became uneven. Gaps between the covering material and the core material were increased and the wrapping structure became loose. Only few pressures of the covering material remained and hence little effect on capillary action ability. De-bunching of filaments and increasing of filoplume could be found on pictures of yarns after washed by hot water, no matter wet or dry. Besides, the diameter of yarns became uneven, some even showed seriously twisted structure with extremely uneven thickness. After drying naturally, filoplume were reduced compared with wet yarns. Compared with the water temperature, the influence of detergent is more moderate. Yarns washed by detergents usually became more softer, with less filoplume observed.

In addition to the deformation of the intertwining structure, washing could also bring influence on the wicking ability of the cotton. Further cross-sectional pictures of the yarns were taken by optical microscope to get a better view of the cotton fibers. During the experiment, the white tested novel yarn was combined with dark-colored 20 auxiliary yarns and then pass through the small middle hole of the steel carrier. By cutting off the excess yarns, the cross section of the novel yarn can thus be observed. The measurement of diameters through this method would be inaccurate since the yarn was squeezed during the sample-making process. However, the cross-sectional pictures gave a clear view on the porosity of cotton fibers. As shown in figure 4.30, cotton fibers naturally exhibit meniscus-shaped hollow structures, which could act as capillary channels during the moisture wicking process. The hollow structure could be destroyed in certain degree after washing, which is also detrimental to the moisture transport ability of the whole yarn.

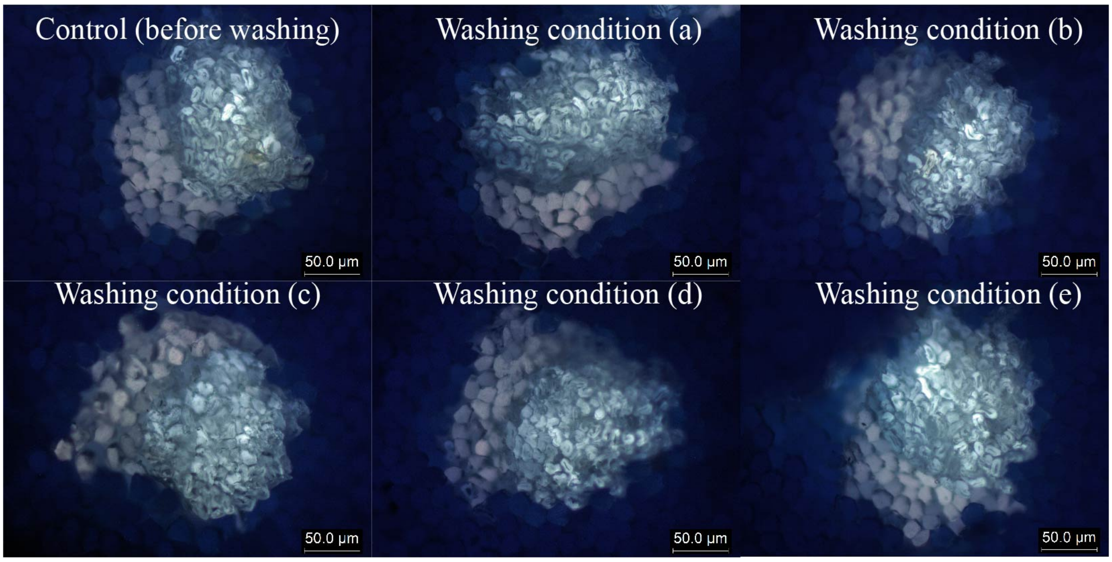


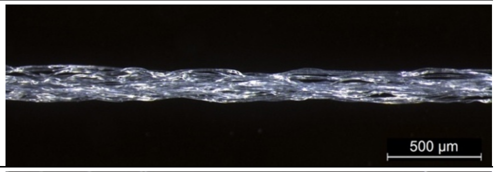
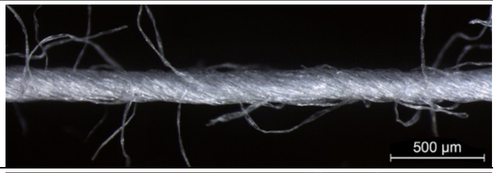
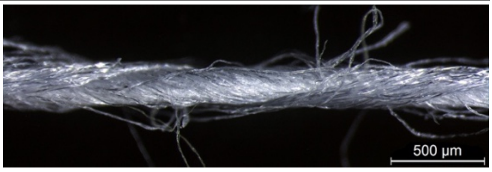
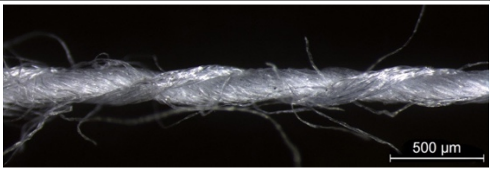
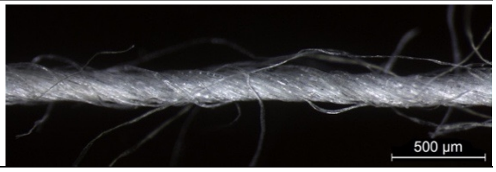
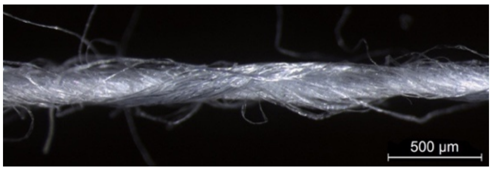
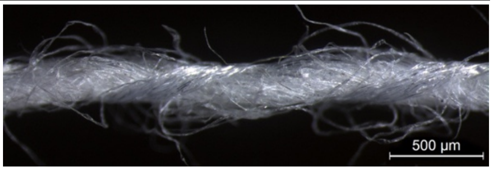
Figure 4.30. Change of cotton fibers after different washing conditions.

To conclude, yarn deformation caused by washing is closely related to the washing condition and method. Water temperature has the greatest influence on yarn structure. After washing in room temperature, the yarn can maintain a relatively stable and effective construction regardless of whether detergent is added. Nonetheless, washing with high temperature will cause serious shrinkage of cotton yarn, resulting in yarn curling and deformation of the overall structure, which will further affect the water absorption of the samples. In severely deformed areas, untwisting and copious filoplume were observed. Considering that the washing condition in daily household washing is usually room temperature water, it would be promising in practical application. Besides, the novel yarn shows variety in the shapes of cross sections, which could provide more invisible porosities to the knitting fabrics made in accordance and give improved permeability of the fabric.

4.6 Moisture transport tests of yarns VI

The previous experiments verified the efficiency of the proposed structure, as well as investigated the influence of washing conditions. In this section, new batch of yarns with contrasting yarn twists were prepared. Besides, cotton-linen blended yarns were adopted as the core material to compare the effects of presence of linen. The details of yarns VI are presented in table 4.7 and figure 4.31. The natural material contents of the novel yarns all meet the objectives.

Table 4.7 Details of yarns VI

No.	Type	Component	Twist	Yarn Count	Picture
6-0	Control	PET 30D	-	-	
6-1	Control	Cotton	-	33.7	
6-2	Novel	Core: cotton Wrap: PET30D (87%-13%)	400 T/m	29.5	
6-3	Novel	Core: cotton Wrap: PET30D (84%-16%)	1000 T/m	28.4	
6-4	Control	Cotton-linen (70%-30%)	-	33.4	
6-5	Novel	Core: cotton-linen Wrap: PET30D (89%-11%)	400T/m	29.6	
6-6	Novel	Core: cotton-linen Wrap: PET30D (82%-18%)	1000 T/m	29.2	

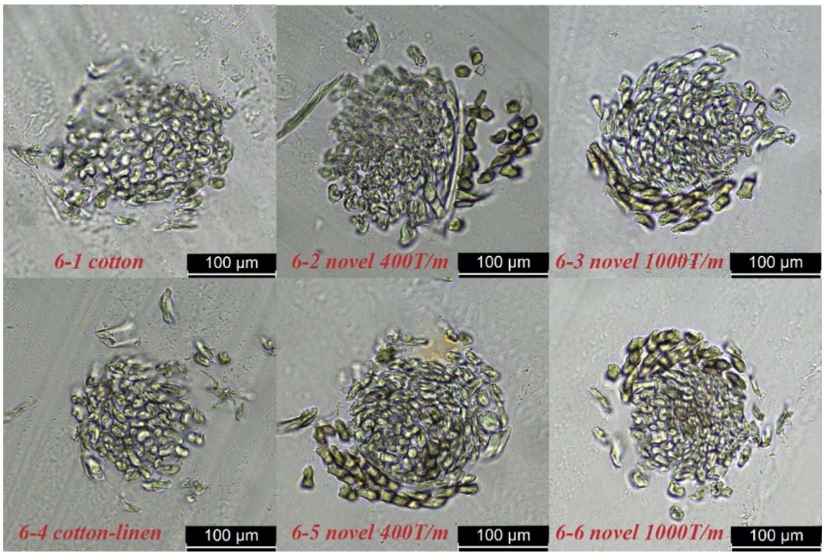


Figure 4.31. Cross sections of yarns VI.

4.6.1 Capillary action tests of yarns

In order to avoid the influence of pigments in the liquid, deionized water was used for the capillary action test. The experiment was carried out in an environment where the airflow and the temperature were stable. A forward-looking infrared (FLIR) camera was fixed in front of the experimental device so that the temperature distribution of the yarns was videoed to judge the change of wicking front. 7 yarns, including the control and novel yarns, were tested together. A weight of 2.0g was hung at the lower end of the yarn to ensure the same tension on each yarn. Five sets of identical experiments were conducted and a typical experimental result at 30 minutes is shown in figure 4.32.

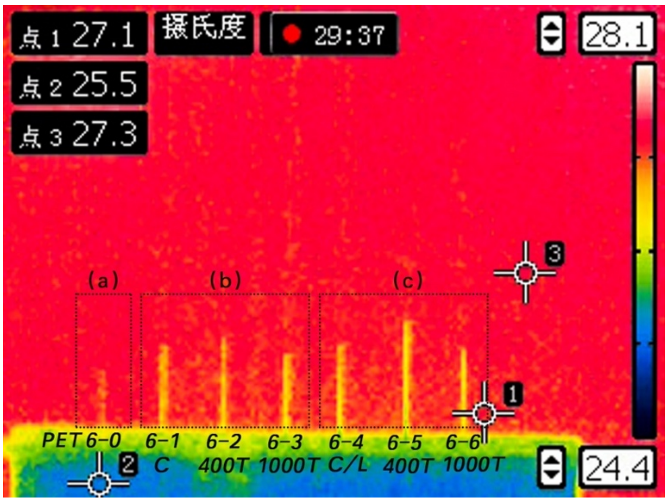
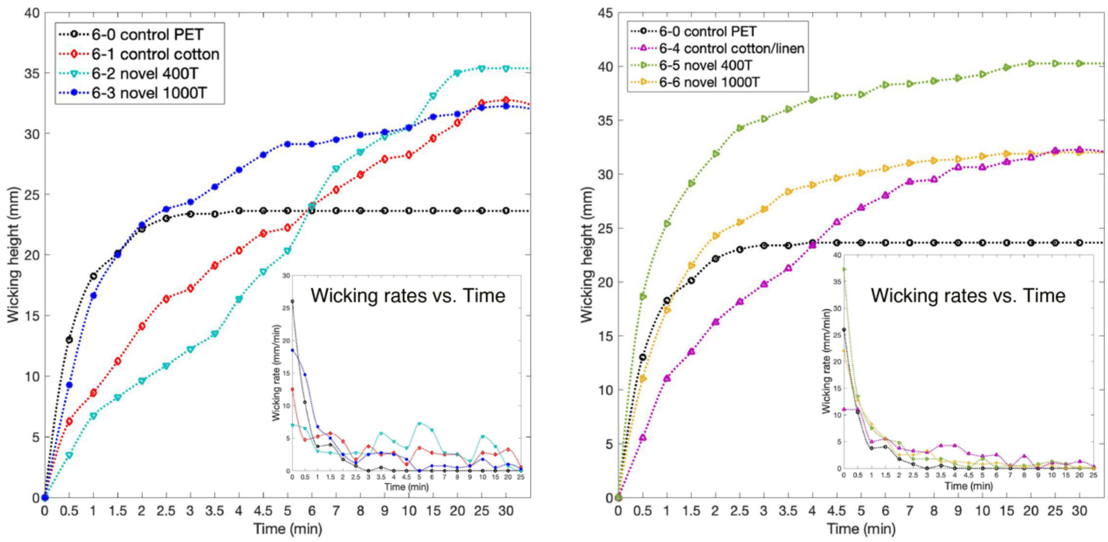


Figure 4.32. Moisture wicking heights at 30 minutes.

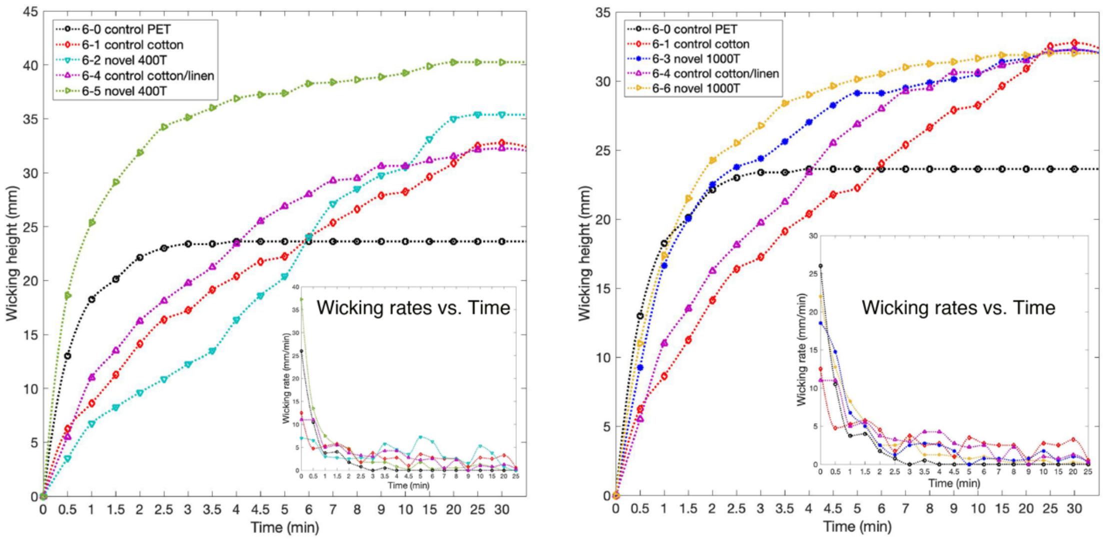
The yarns in figure 4.32 can be divided into three groups: (a) the wrap material (PET); (b) the novel and control yarns of cotton yarn; and (c) the novel and control yarns of cotton-linen yarn. The temperature range was 24.4~28.1°C. The environmental background possessed the highest temperature of 27.3°C while the water tank maintained around 25°C for the whole experimental process. Although the water kept in the yarns by wicking has a slight temperature increase, there was still a notable temperature difference to create an obvious color difference so that the wicking heights could be measured without using pigments. After 30 minutes of wicking, the novel yarns twisted in 400T/m achieved the highest wicking height, while the control yarns and the novel yarns twisted in 1000T/m showed no notable difference. Besides, the wicking of the wrap PET was quite quick, indicating small amount of water holding capacity. Therefore, the improvement of wicking is mostly due to the improvement of capillary actions. Although the novel yarns twisted in 400T/m (yarns 6-2 and 6-5) obtained highest wicking at 30 minutes, results showed that the wicking rate was not stable during the process, indicating unevenly distributed structures throughout the yarns. The wicking heights and wicking rates of cotton and cotton-linen yarns are shown in figure 4.33.



(a) Cotton group (b) Cotton-linen group

Figure 4.33. Wicking heights vs. time and wicking rates vs. time in 30 minutes.

In the curves of wicking heights versus time, the slope of the curves indicates the wicking rates, as pictured in the smaller squares. Figure 4.33 (a) shows the novel and control yarns of the cotton group; and (b) shows the novel and control yarns of the cotton-linen group. All of the novel yarns adopted the same 30D PET as the wrap material, whose wicking dynamics are illustrated by the black lines in the figure. The wrap material itself exhibited a wicking curve following the square law, with the highest wicking rates at the beginning and decreasing gradually with time. The average height of the stable state remained 20.5mm, which is the lowest among the tested yarns. The wicking of the control cotton (as shown by the red curve in figure a) and the control cotton-linen (as shown by the magenta curve in figure b) are relatively slow for the first 20 minutes and didn't achieve equilibrium until 25 minutes. By comparing these two curves, the presence of linen increased the hydrophilicity of the control yarns. For both of the groups, the wicking performance was improved either by wicking rates (novel 1000T vs. control) or by the final wicking heights (novel 400T vs. control).



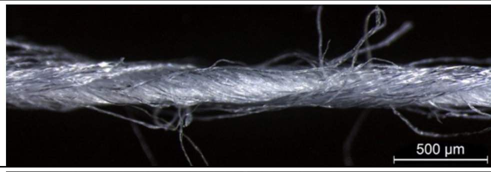
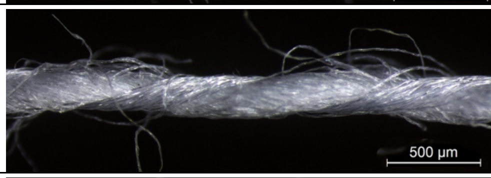
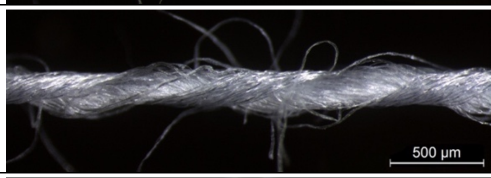
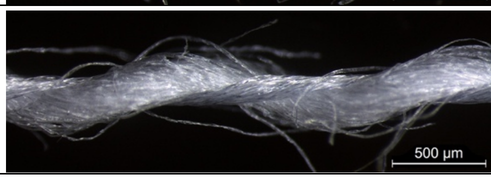
(a) Novel yarns of 400T/m (b) Novel yarns of 1000T/m

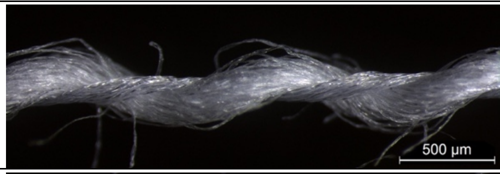
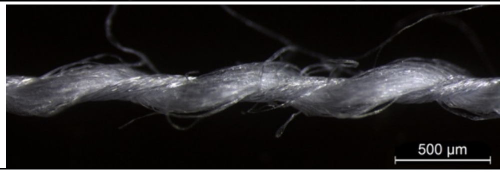
Figure 4.34. Wicking heights of yarns with specific twists vs. time and wicking rates vs. time in 30 minutes

The influences of core materials were depicted in figure 4.34 by comparing the effect of novel yarns with the same twists. As shown in figure (a), although the final wicking heights of the novel yarn with 400T/m were improved, the beginning wicking rates of the yarns were small for most of the experimental sets. The results indicated an ineffective spinning of wrap yarns when the twist is 400T/m. On the other hand, the novel yarns spun with cotton-linen as the core material exhibited better wicking performance with more stable results. In summary, yarns twisted by 1000T/m achieved significant improvement on wicking rates for both cotton and cotton-linen yarns, while the final wicking heights showed no significant change. The effect of yarns twisted by 400T/m is different for the cotton and cotton-linen yarns. Therefore, the novel yarn using cotton-linen as the core material and twisted in 400T/m achieved the best improvements on both wicking rates and heights, as shown by the green curve.

Based on the previous experiments, the effect of yarn twists when spinning the core and wrap yarns together is significant to the final improvements. However, due to the limitation of manufactory production, it would not be efficient to produce various kinds of yarns with small twist gradients. A further modification to the novel yarns were made by adding twists to the novel yarns with 400T/m by the experimental twister to simulate the effect of increasing yarn twists. The details of yarns modified based on novel yarn 6-2 (with cotton core) are listed in the following table.

Table 4.8 Details of cotton novel yarns with additional twists

No.	Type	Twist	Picture
6-2	Novel	400T/m	
6-2-1	Novel	400T/m+100	
6-2-2	Novel	400T/m+200	
6-2-3	Novel	400T/m+300	
6-2-4	Novel	400T/m+400	

6-2-5	Novel	400T/m+500	
6-2-6	Novel	400T/m+600	

The results of yarn wicking tests are depicted in figure 4.35. The type of yarns was simplified by their additional twists. For instance, yarn 6-2-1 was denoted as +100 in the following figure since it was prepared based on yarn 6-2. It was found that for the novel yarn using pure cotton as the core material, although wicking heights were improved compared with the control cotton, addition of twists had no significant influence on the wicking curves. Moreover, yarns with higher twists were deformed to a helical shape, which would be not favorable to the knitting processes. Therefore, for the novel yarns using cotton as the core material, the most efficient yarn twist would be 1000T/m, as shown by the curve of yarn 6-4 in 4.33(a).

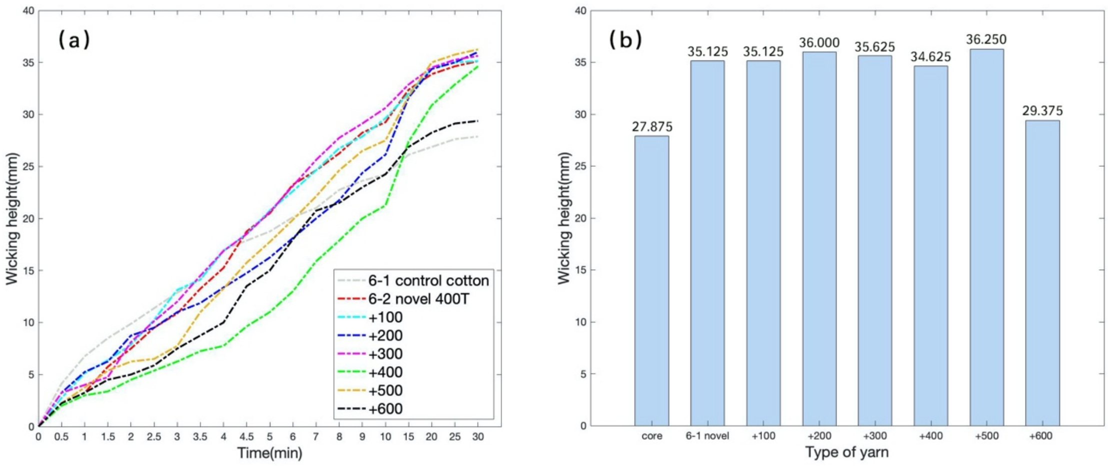
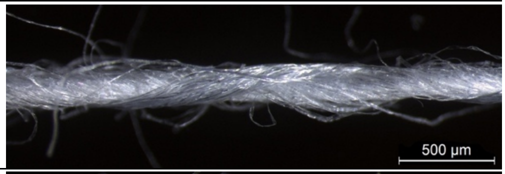
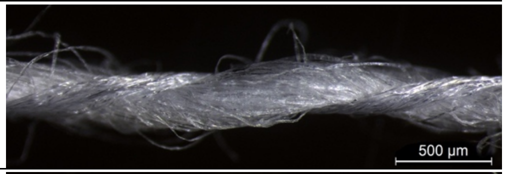
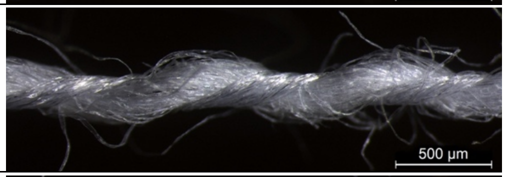
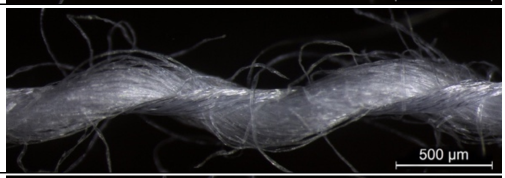
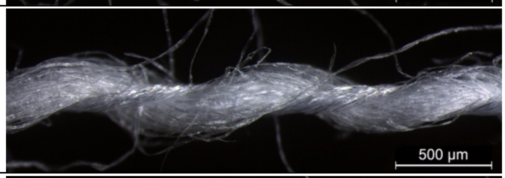
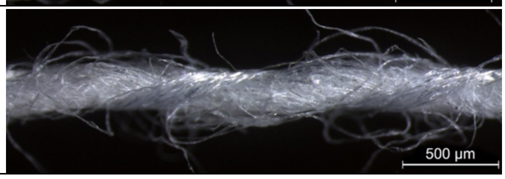


Figure 4.35. Wicking results of novel cotton yarns with additional twists. (a) Wicking vs. time in 30 minutes; and (b) wicking heights at 30 minutes.

Same modification was made to yarn 6-5, i.e., the novel yarn using cotton-linen as the core material and was produced with 400T/m. Details of the yarns made in accordance are listed in table 4.9.

Table 4.9 Details of cotton-linen novel yarns with additional twists

No.	Type	Twist	Picture
6-5	Novel	400T/m	
6-5-1	Novel	400T/m+100	
6-5-2	Novel	400T/m+200	
6-5-3	Novel	400T/m+300	
6-5-4	Novel	400T/m+400	
6-5-5	Novel	400T/m+500	
6-5-6	Novel	400T/m+600	
6-6	Novel	1000T/m	

The results of yarn wicking tests are given in figure 4.36. The novel yarn 6-5 was the most efficient yarn in the previous experiments. By adding additional twists to the novel yarn, it was found that the wicking performance was the best when the 300 twists per meter were added. With increasing twists of yarns, the capillary channels were further decreased to a less efficient degree. Moreover, as shown in table 4.8, yarns with additional 300T/m can still maintain a smooth and straight shape compared with yarns with larger additional twists. The yarn became helical when the additional twists are larger than 400T/m. On the other hand, the novel yarn 6-6 that was spun directly using 1000T/m maintains a straight and even shape compared with yarns with additional twists (yarn 6-5-6), indicating that the new spinning technology can obtain an effective binding effect to the core fibers without causing excessive distortion to the overall structure. It would be easier to knit smooth fabrics with yarns with better regularity and evenness.

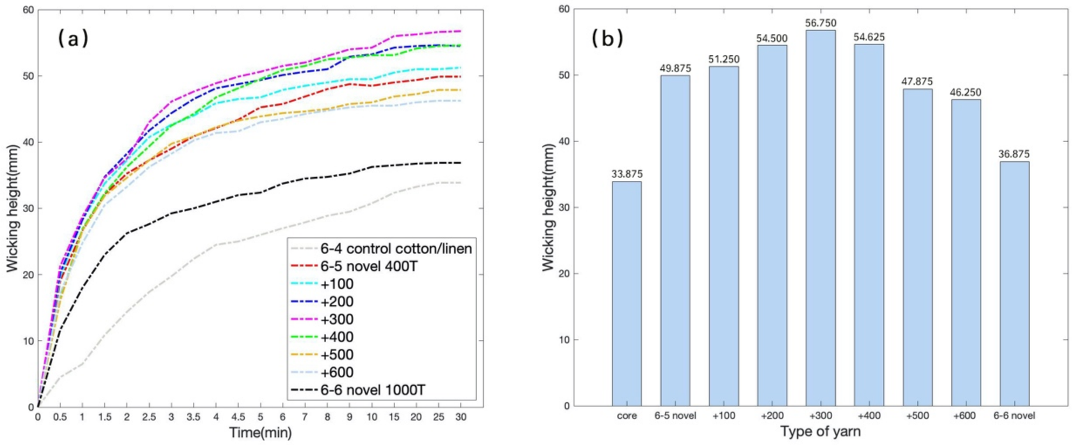


Figure 4.36. Wicking results of novel cotton-linen yarns with additional twists. (a) Wicking vs. time in 30 minutes; and (b) wicking heights at 30 minutes.

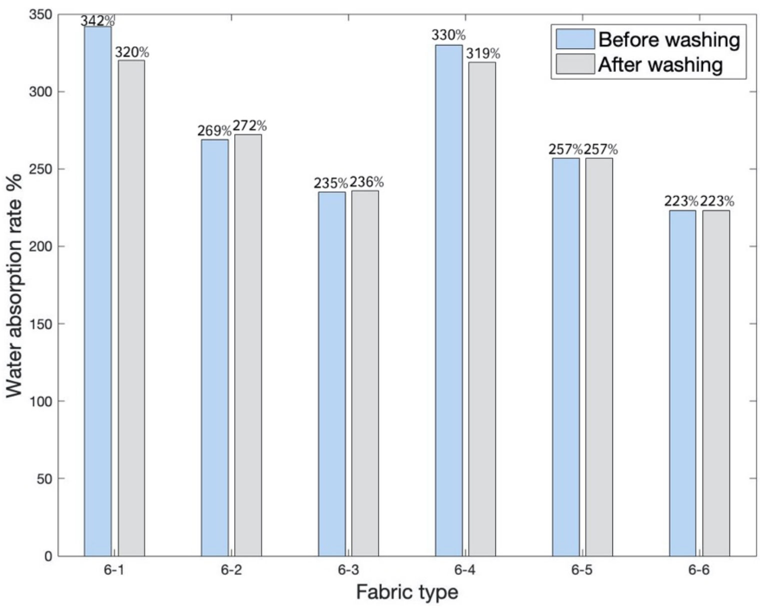
To sum up, there were two new parameters introduced in the new series of experiments, including the material of the core yarn; and yarn twist when spinning novel yarns. Two different core yarns were used in spinning, one was pure cotton and the other was 70%-30% blended cotton-linen yarn. For each core yarn, two twist levels (400T/m and 1000T/m) were applied when spinning the wrap yarn together with the core yarn, and the twist direction was opposite to the initial twist of the core yarns. Experiments have found that the addition of linen has a beneficial effect on the water absorption ability, while the effect of spinning twist is more complicated. The yarn wicking tests covered the first 30 minutes since all the wicking processes could reach equilibrium or nearly equilibrium state at the time interval. The novel yarns with 1000T/m exhibited great improvement on the initial wicking rates, but the equilibrium heights measured at 30 minutes were not improved, indicating a limited water absorption capacity. On the other hand, although the wicking height of the novel cotton yarn 6-3 was improved, the initial wicking rates remained slow. The novel cotton-linen yarn with 400T/m (yarn 6-5) achieved best improvement on both wicking rates and equilibrium heights. A new experiment was designed to simulate higher spinning twists by adding additional twists in the novel yarns. It was found that yarn 6-5 could achieve better results when an additional twist of 300T/m was added. Therefore, in the future experiments, spinning twists of 600~800T/m is recommended as the most effective structures.

4.6.2 Moisture transport tests of knitting fabrics made by yarns VI

In order to have a better comparison between the wicking performances, knitting fabrics were prepared using yarns VI. The Hosiery machine with same parameters was used to prepare knitting fabrics of both control and novel yarns. Three sets of experiments based on the PRC standard were conducted, including water absorption rate, drip diffusion time and evaporation rate. Experiments were conducted on fabrics both before and after washing to investigate the stability of the structure.

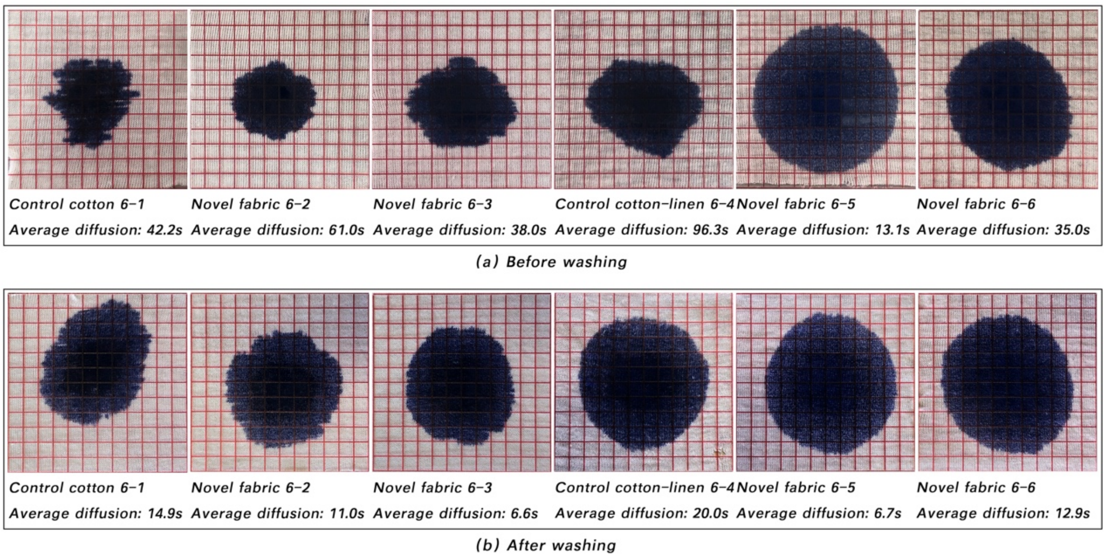
Water absorption ability is directly related to water holding capacity, which further impacts the drying speed of yarns in wet condition. Five samples for each kind of fabric were prepared and tested to reduce experimental error. The mean value was calculated and presented in figure 4.37. Yarns 6-1 and 6-4 are control groups, i.e., the cotton core yarn and the cotton-linen core yarn. Yarns 6-2 and 6-5 are novel yarns fabricated with twists of 400T/m; and yarns 6-3 and 6-6 are novel yarns fabricated with twists of 1000T/m. The core materials used to fabricate the novel yarn exhibit high hydrophilicity with water absorption rates higher than 300%. On the one hand, water and sweat can be absorbed fast into the fabric to keep a dry environment between the fabric and the skin. On the other hand, excessively high water-holding capacity would bring extra burden to the wearer and make the cloth stick to the skin surface, which is not desired. For the novel yarns, the covering material can act as a binder to maintain the water holding capacity at a reasonable level and help to maintain a comfortable wearing experience. The water absorption rates of novel yarn were conspicuously decreased compared with the control groups, i.e., the core yarns. The higher the twists, the larger the binder effect.

As recommended in the previous sections, it is better to use room temperature water to wash the fabrics in order to avoid untwisting and maintain an efficient spinning structure. Same experiments were conducted on fabrics after washing by water in the room temperature. The results are illustrated by the gray columns in the following picture. The water absorption rates of the control groups were slightly decreased after washing, while there was no obvious difference between the novel groups before and after washing, indicating relatively high stability of the novel structures.



4.37. Water absorption rates of fabrics made of yarns VI.

The diffusion of water could affect the evaporation rate and help to keep skin dry. A larger diffusion area helps moisture to evaporate and thus achieve fast dry performance of fabrics. Five sets of samples were used to test the diffusion of water. For each sample, the fabric was laid flat on the surface with the vertical direction of the picture as the warp direction. The average diffusion time when the droplet was completely absorbed was calculated and recorded in figure 4.38. The pictures presented the liquid absorption states at 2 minutes, assuming the state when the liquid dropped on the fabric as t=0. The results are in consistent with the wicking curves of the yarns. For the cotton group before washing, the novel fabric made of yarns 6-2 (400T/m) absorbed water slightly slower than the control group at the beginning, resulting in a smaller area and a larger drip diffusion time. For the cotton-linen group, the novel fabrics achieved a larger drip diffusion area with a more regular shape, indicating a better water absorption ability. Due to the high quality of raw materials and stability of the novel spinning structure, the moisture transport ability of fabrics was all improved after washing, indicating a satisfying durability under room temperature washing. In summary, the novel fabrics 6-3, 6-5, 6-6 achieved better and faster water absorption ability in general.



4.38 Liquid absorption states at t=2min.

In addition to water absorption rate and drip diffusion time, experiments about evaporation rate were conducted to test the fast-drying effect of the structure. Five samples were prepared for each kind of fabric. A pipette was used to drip exact 0.2ml water on the surface of the samples. After fully absorption, the samples were weighted immediately and hanged vertically to evaporate moisture. The evaporation amount in 90 minutes were recorded and calculated. An evaporation-time curve is shown in figure 4.39.

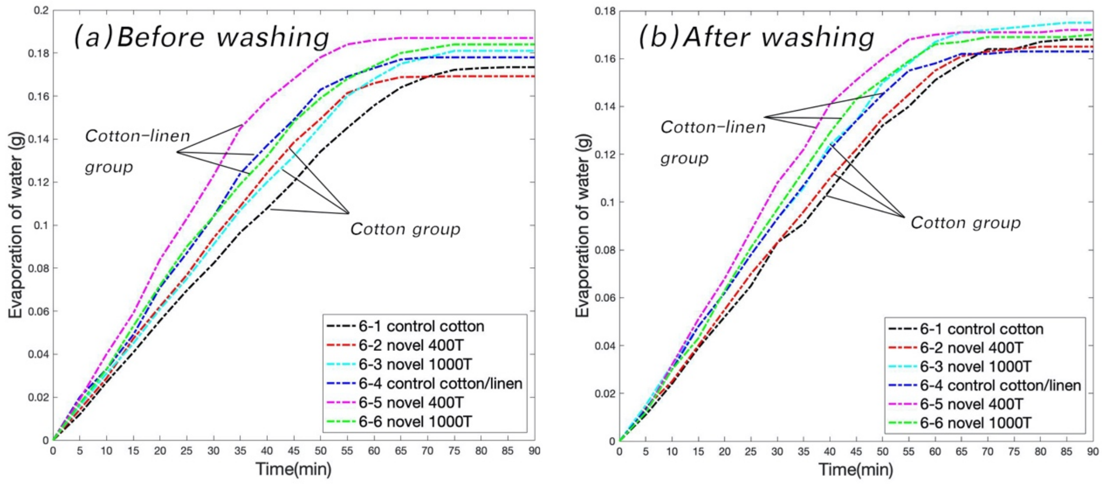


Figure 4.39. Evaporation of water in 90 minutes. (a) Before washing; and (b) after washing.

Excluding negligible errors during weight measurements, the equilibrium state was achieved for all the fabrics within 90 minutes. The time-evaporation curves tend to slow down significantly after a certain point. Take the curve closest to a straight line before this point, and the slope of the approximate straight segment is considered as the water evaporation rate. The water evaporation rates calculated based on this method are illustrated in figure 4.40.

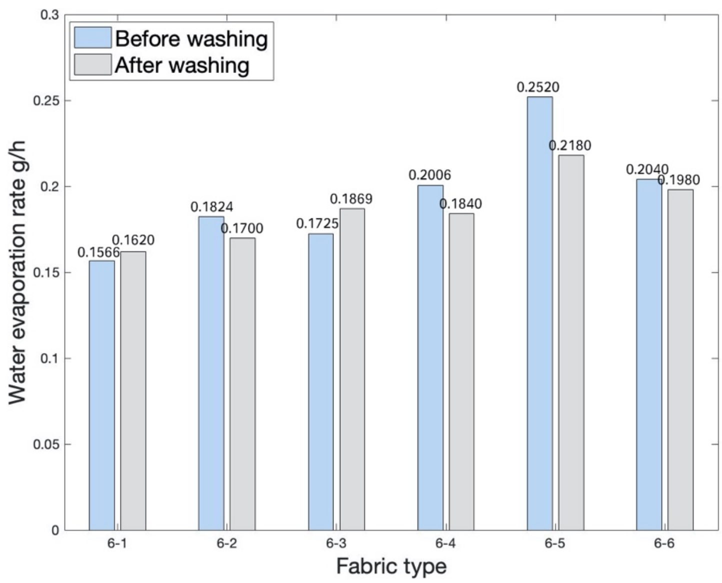


Figure 4.40. Evaporation rates of fabrics VI.

Based on the figures 4.39 and 4.40, significant improvement on evaporation rates were achieved for the novel fabrics compared with the control group. Due to the binding effect of the covering yarn, the efficiency of capillary channels was improved, resulting in a faster absorption of liquid. Besides, the water holding capacity is limited to avoid undesired excessive water absorption. With the same amount of the liquid droplets for every fabric, the area of liquid diffusion of the novel fabric is thus larger compared with that of the control yarn. Therefore, fast dry is achieved for yarns VI. In summary, yarn 6-5 exhibited the most excellent behavior. Cotton-linen blended core yarn and twist of 400T/m was adopted to fabricate the novel yarn, which is considered as the most appropriate parameters among all of the yarns prepared.

Chapter 5 Conclusions and Suggestions for Future Research

Moisture transport performance of textiles is a key property for the evaluation of wearing experience. This thesis presents a systematic research of an innovative spinning technology. The proposed study aims at developing a structure-based spinning system for ecological yarns with high moisture-wicking properties. The main objectives include to establish a yarn-structure spinning model for yarn moisture-wicking improvement based on the testing results; to establish the fabrication structures of fabrics with high moisture transfer and fast-drying performance; and to find out the most effective yarn production plan. The developed yarn constructions showed significant improvements on moisture wicking performance, fast-drying effect as well as high commercial values. The experimental investigation of cotton shrinkage and influence of spinning twists established a foundation for the future study of moisture-wicking yarns, fabrics and apparel products. The main discoveries and conclusions can be summarized as follows.

5.1 Conclusions

Totally 6 batches of yarns were prepared and tested, i.e., I) hand-made yarns to verify the structure efficiency; II) yarns prepared by Zhuhai factory with one cotton core yarn and one novel yarn covered by PET; III) yarns prepared by Jiangsu factory with one cotton core yarn and one novel yarn covered by PET; IV) the first batch of yarns prepared by Yuyue factory, including a bleached cotton core yarn and three kinds of novel yarns covered by PA; V) the second batch of yarns prepared by Yuyue factory, including and unbleached cotton core yarn and three kinds of novel yarns covered by PA; and VI) yarns prepared by Jiangsu factory, with 2 types of core yarns and 4 novel yarns covered by PET to investigate the influence of core materials as well as yarn twists.

5.1.1 Experimental findings

Totally five stages of experiments were conducted. Firstly, capillary action test of hand-made yarns was conducted to verify the practicality of the proposed structure. In addition, through both intra-gradient and inter-gradient comparison, it was found that the hydrophilicity of covering material has small influence on the capillary action. The wicking height is directly related to the tightness of wrapping in this case. The result verified the assumption that the covering yarns act as a binder of the inner yarn, which decreases the diameter of the spacings between filaments of yarns and results in a better wicking effect.

The second stage preliminary screened the yarns from Zhuhai, Jiangsu and Yuyue (yarns II, III, and IV) by comparing wicking heights of these yarns. It was found that both yarns II and III showed satisfactory results. The core cotton used in yarns III was hydrophobic and that of yarns IV was hydrophilic, while all the novel yarns achieved distinct improvement on wicking height. Hence it can be concluded that the proposed structure is efficient for both hydrophobic and hydrophilic materials. Together with the conclusion in the first stage, the proposed novel yarn showed promising material-free property.

The third stage of experiments was about knitting fabrics made from yarns III and IV. Three sets of experiments from the PRC standard were conducted, including water absorption rate, drip diffusion time and wicking height. On one hand, the novel yarns showed better performance on these properties before washing. For yarns III, water absorption ability was doubled compared with the control cotton. The novel fabric could completely absorb water droplet in a few seconds while the control cotton fabric was almost completely hydrophobic. For yarns IV with bleached core materials, although the control cotton itself showed impressive hydrophilicity, the wicking speed of the novel fabric was still largely improved. However, on the other hand, the influence after washing remained implicit. Therefore, a new batch of yarn was prepared by Yuyue factory and experiments in stage 4 were conducted.

The second batch of Yuyue yarns (yarns V) used hydrophobic unbleached cotton yarn as core material. Totally five kinds of novel yarns were prepared while only one yarn showed explicit influence on hydrophilicity of yarn. The improvements on wicking height were found both before and after washing. However, only cotton yarns under the covering material absorbed water as demonstrated by the microscopic pictures after dyeing.

Based on the previous results, yarns III were selected in the experiments related to cotton shrinkage and yarn deformation. It was found that washing temperature had most significant influence on the yarn. Yarns washed by higher temperature have higher shrinkage and larger deformation. Deformations included de-bunching of filaments, increasing of filoplume and uneven of diameter. For yarns washed by hot water, not only the shrinkage was large but also the diameter of yarn became larger. The result was consistent with the cotton shrinkage theory that the diameter of cotton became larger after absorbing water, resulting in shrinkage in length. The influence of detergents and stirring is however less notable compared with the water temperature. Therefore, it is recommended to use water in room temperature when washing the novel fabrics.

Lastly, to understand the effect of raw materials and yarn twists, yarns VI were prepared. Two different core yarns were used in spinning, one was pure cotton and the other was 70%-30% blended cotton-linen yarn. For each core yarn, two twist levels (400T/m and 1000T/m) were applied when spinning the wrap yarn together with the core yarn, and the twist direction was opposite to the initial twist of the core yarns. Experiments have found that the addition of linen has a beneficial effect on the water absorption ability, while the effect of spinning twist is more complicated. The novel cotton-linen yarn with 400T/m (yarn 6-5) achieved best improvement on both wicking rates and equilibrium heights. A new experiment was designed to simulate higher spinning twists by adding additional twists in the novel yarns. It was found that spinning twists of 600~800T/m is recommended as the most effective structures. Fabrics made of hosiery machine were prepared and the water absorption rate and drip diffusion time of samples both before and after washing were tested, showing consistent results with the yarns. Experiments about evaporation rate of fabrics were conducted on fabrics made of yarns VI to test the fast-drying effect. It was found that the novel fabrics generally achieved significant improvement on the evaporation rate both before and after washing.

To sum up, the structure was tested to be efficient with an explicit improvement on moisture wicking ability of both yarns and fabrics made in accordance. Experiments were conducted on different yarns with core and wrap materials of various hydrophilicity. The wrap materials included PLA, PET and PA, and the core materials included unbleached cotton, bleached cotton, and bleached cotton-linen blended yarns, all of which were tested to be efficient in moisture wicking improvement. Therefore, the proposed structure is applicable to multiple types of materials. The color distribution of microscopic pictures of dyed yarns showed that the improvement of wicking was a result of increase in effective capillary channels in the core yarn, as a result of binding effect of the wrap yarns. The proposed spinning structure is effective for core yarns with diverse hydrophilicities, and the effect depends on the spinning parameters and methods, including the initial water absorption ability of the core yarn; yarn twist when spinning; as well as washing conditions. The addition of linen made a better result of wicking performance, while the influence of yarn twist is more complicated. An appropriate twist is necessary to achieve a satisfactory improvement in both wicking rates and heights. Since the properties of the fabrics are closely dependent on yarn components, experiments also found that the wicking improvements of fabrics knitted in accordance had consistent results with the yarns. Besides, experiments have found that products from most manufacturers such as the first batch of Yuyue, Jiangsu and the second batch of Jiangsu factories have achieved considerable results, which indicated a potential for wide application and mass production. After parameter modification, yarns VI achieved satisfactory improvements on moisture wicking and fast dry both before and after washing. In addition to the above findings, two supplementary experiments were designed to have a better understanding on factors related to washing and spinning, whose results will be discussed in the following sections.

5.1.2 Cotton washing and washing conditions

For a regular yarn, the shrinkage of cotton will cause yarn deformation, affecting the efficiency of capillary channels inter fibers. Besides, the hollow channels inside cotton fibers can be diminished after washing. As a result, the water transport ability of the yarn would be influenced. For the novel yarns with special spinning structure, typical deformation such as untwisting between the core and wrap yarns caused by improper washing methods were observed in several segments. Washing conditions are hence important to maintain the structure efficiency. The experiments explored the influence of washing temperature, addition of detergents and stirring. Water temperature was found to be crucial for yarn deformation. It is recommended that room temperature water is preferred during washing. City water with temperature up to 95°C was used during the experiments, which will not be the usual case in daily life. Besides, the influence of detergents and stirring was found to be relatively less important, indicating a potential of the novel yarns and fabrics to be applied in daily life.

5.1.3 Yarn twisting and other spinning parameters

Yarn twist can affect various properties of staple yarns, including water absorption ability, strength, physical construction and so on. There are two twists involved in the spinning of the novel yarns, one is the initial twist of the staple core yarn, and the other is the twist that entangles the core and wrap yarns when spinning. The twist directions of the core and wrap yarns can be the same or opposite. When the twist directions are the same, the effect of wrapping is similar to increasing twist levels. The capillary channels can be too small for a proper amount of wicking if the core yarn already possesses and initial high twist level. Experiments have found that the improvement effect was more stable when the twist directions of the core and wrap yarns were opposite, which could not only bind the fibers in the core yarn, but also left enough space for moisture wicking. In addition to twist direction, the degree of twists is also critical for the final effect. If the twist of spinning is too small, the binding effect would not be noticeable, while an excessively large twist level would cause unevenness on the yarn morphology and difficulties in fabric knitting. Besides, an increased twist level of spinning would result in an increased helicity of the novel yarn. If the inclination of the wrap fibers is unreasonably high, the binding effects on the core yarn would be diminished. The optimal range of twists was found to be approximately 400~700T/m, which is recommended for future study.

5.2 Contributions

Moisture transport is a crucial measurement of fabric comfort. The manipulation of moisture movement in textiles is of great significance for apparel products, especially those related to athletics, general summer sports, and other situations that require high quality of wearing experience. Although various studies such as multilayer fabrics have been conducted to improve the moisture absorption performance, limitations exist and relative researches have never stopped. Besides, synthetic materials are widely used in sportswear, which is not environmentally friendly. In this thesis, a series of studies on the structure and moisture wicking performance of a newly developed spinning methods were conducted. The effects of yarn twist and cotton washing were explored to better understand the relationship between moisture transport and yarn construction. Through various stages of experiments, the optimal spinning parameters were investigated, which provided methods and established foundations for subsequent research. The novel spinning method is material-free, environmentally friendly, economically efficient, and with potential of wide application. Moreover, through physical modifications of yarn structures, the yarn performance is directly improved without affecting the subsequent processes of knitting, dyeing and garment design. In summary, the research conducted in this thesis has promoted the exploration and development of the innovative spinning technology, which would be a breakthrough for moisture wicking materials in the apparel market.

5.3 Limitations

Due to the constraints of time and experimental conditions, there are some limitations in the research conducted in this thesis. The main limitations are denoted as follows for future research reference.

1. Due to the lack of appropriate spinning machine, the yarns tested in this study have to be produced by cooperative factories after designing the parameters. In order to explore the optimal spinning method, we have cooperated with several manufacturers to fabricate different batches of yarns so that screening could be done by subsequent experiments. The various fabrication sources of yarns led to a limited quality control of raw materials and other factors during production processes. Some factors that are not directly related to the research are unavailable. These uncontrollable factors constrained the continuity and efficiency of the experiments.

2. Due to limited amount of novel yarns, the hosiery machine was adopted as the main knitting machine since knitting fabrics can be fabricated using a small amount of yarns. However, curling is inevitable for knitting fabrics. Therefore, fabric rolls instead of strips were used in the wicking test of the fabrics. The variance between liquid fronts on different areas of the fabric rolls were somehow concealed and the experimental results were therefore more of a qualitative reflection of the structure efficiency.

3. In the wicking test of the fabrics, the movement of water and pigments were found to be slightly different for several samples, which is probably due to

particles of the pigments were not fine enough. In the later tests of yarns, infrared camera and deionized water were used for testing to avoid the influence of pigments.

4. Due to the limitations of time and lack of spinning machine, the mechanism of washing has not been thoroughly explored. A systematic research is recommended after purchasing the required spinning machine.

5.4 Future recommendations

The yarn spinning parameters and moisture transport investigation demonstrated in this thesis established the foundation and broadened the possibility for future study of moisture wicking textiles based on physical modification of yarn structures. The spinning method and experiments of yarns and fabrics made in accordance can be further enhanced through the following aspects.

1. A spinning machine is strongly recommended in order to carry out a systematic research. Experiments with strictly controlled variables would be more effective to investigate the influence of different parameters on the final effects.

2. The effect of yarn structure on fabric porosity is suggested to be taken into consideration because porosity of fabrics is directly related to moisture and heat transfer. A qualitative comparison of porosity of fabrics made of control and novel yarns was conducted and found that the novel yarn could bring a larger porosity to its knitting fabrics. The dimensions of porosity can be considered in the future studies so that a quantitative research can be conducted with improved accuracy.

3. In future research, it is suggested to use diverse materials with different hydrophilic properties, including the core yarn and wrap yarn. Various environmentally friendly materials are recommended to explore the potential of the structure. Natural fibers

such as cotton or linen may be used as the wrap material, while synthetic fibers such as PET or PA may be used as the core material so that high wicking rates in the core yarn can be achieved.

References

1. K. Slater, "Comfort Properties of Textiles", *Textile Progress*, vol. 9, no. 4, pp. 1-70, 1977. Available: 10.1080/00405167.1977.10750095.
2. D. Uttam, “Active sportswear fabrics,” *International Journal of IT, Engineering and Applied Sciences Research,* vol. 2, no. 1, pp. 34-40, January 2013.
3. S. Derler, U. Schrade, and L.-C. Gerhardt, “Tribology of human skin and mechanical skin equivalents in contact with textiles,” *Wear,* vol. 263, no. 7-12, pp. 1112–1116, 2007.
4. "Sports and recreation textiles", *Technicaltextile.net*, 2020. [Online]. Available: http://www.technicaltextile.net. [Accessed: 13- Aug- 2020].
5. C. Callewaert, E. D. Maeseneire, F.-M. Kerckhof, A. Verliefde, T. V. D. Wiele, and N. Boon, “Microbial Odor Profile of Polyester and Cotton Clothes after a Fitness Session,” *Applied and Environmental Microbiology*, vol. 80, no. 21, pp. 6611–6619, 2014.
6. M. Çil, U. Nergis, and C. Candan, “An Experimental Study of Some Comfort-related Properties of Cotton—Acrylic Knitted Fabrics,” *Textile Research Journal*, vol. 79, no. 10, pp. 917–923, 2009.
7. Market Insider, *The Growth of Sales in Sportswear*, 2017. [Online]. Available: https://markets.businessinsider.com/news/stocks/the-growth-of-sales-in-sportswear-1002249734 [Accessed 30- Apr- 2019].
8. M. M. Adler and W. K. Walsh, “Mechanisms of transient moisture transport between fabrics,” *Textile Research Journal, vol. 54*, no. 5, pp. 334-343, 1984.
9. R. M. Crow and R. J. Osczevski, “The interaction of water with fabrics,” *Textile Research Journal, vol. 68*, no. 4, pp. 280-288, 1998.
10. Q. Zhuang, S. C. Harlock and D. B. Brook, “Transfer wicking mechanisms of knitted fabrics used as undergarments for outdoor activities,” *Textile Research Journal, vol. 72*, no. 8, pp. 727-734, 2002.

11. R. M. Laing, C. A. Wilson, S. E. Gore, D. J. Carr, and B. E. Niven, “Determining the Drying Time of Apparel Fabrics,” *Textile Research Journal*, vol. 77, no. 8, pp. 583–590, 2007.
12. L. Fourt, A. M. Sookne, D. Frishman and M. Harris, “The rate of drying of fabrics,” *Textile Research Journal, vol. 21*, no. 1, pp. 26-33, 1951.
13. K. Arai, “Wearing Comfort of Water Absobent Acrylic Fibers,” *Journal of the Textile Machinery Society of Japan*, vol. 30, no. 3, pp. 72–81, 1984.
14. M. Çil, U. Nergis, and C. Candan, “An Experimental Study of Some Comfort-related Properties of Cotton—Acrylic Knitted Fabrics,” *Textile Research Journal*, vol. 79, no. 10, pp. 917–923, 2009.
15. R. F. Goldman, “The four ‘Fs’ of clothing comfort,” *Elsevier Ergonomics Book Series,* Vol. 3, pp. 315-319, 2005.
16. G. M. Budd, “Clothing physiology,” *Fire Safety Journal*, vol. 4, no. 2, pp. 77-81, 1981.
17. "World sports active wear", *Sportstextiles.com*, 1996. [Online]. Available: https://sportstextiles.com/. [Accessed: 13- Aug- 2020].
18. A. Das and R. Alagirusamy, *Science in clothing comfort*. New Delhi: Woodhead Publishing India Pvt Ltd, 2010.
19. A. P. D’Silva, and S. C. Anand, “Responsive Garments for Sportswear, Proceedings on Smart Textiles, their production and market Strategies,” Ed.: S. Gupta, NIFT, New Delhi, India, 2000, pp 32-49.
20. J. Lark, "Hydrophilic finishing process for hydrophobic fibers", U.S. Patent 4073993, Feb. 14, 1978.
21. W. B. Stockton and W. Ware, “Methods for treating fabric to facilitate moisture transfer from one side to the other,” U.S. Patent 7 842 625 B1, Nov. 30, 2010.
22. L. Snowden-Swan, "Pollution prevention in the textile industries", *Osti.gov*, 2020. [Online]. Available: https://www.osti.gov/biblio/99387. [Accessed: 13- Aug- 2020].
23. G. Havenith, “Heat balance when wearing protective clothing,” *The Annals of Occupational Hygiene*, vol. 43, no. 5, pp. 289-296, 1999.

24. C. Aschwanden, *The Truth About Performance Apparel*, 2012. [Online]. Available: http://www.consumersdigest.com/special-reports/no-sweat-the-truth-about-performance-apparel/view-all [Accessed 30- Apr- 2019].
25. Y. Dong, J. Kong, C. Mu, C. Zhao, N. L. Thomas, and X. Lu, “Materials design towards sport textiles with low-friction and moisture-wicking dual functions,” Materials & Design, vol. 88, pp. 82–87, 2015.
26. R. Bagherzadeh, M. Gorji, M. Latifi, P. Payvandy, and L. X. Kong, “Evolution of moisture management behavior of high-wicking 3D warp knitted spacer fabrics,” *Fibers and Polymers*, vol. 13, no. 4, pp. 529–534, 2012.
27. D. Miao, Z. Huang, X. Wang, J. Yu, and B. Ding, “Continuous, Spontaneous, and Directional Water Transport in the Trilayered Fibrous Membranes for Functional Moisture Wicking Textiles,” *Small*, vol. 14, no. 32, p. 1801527, 2018.
28. "Mesh Fabric and 3D Spacer Fabrics", *Baltex.co.uk*, 2020. [Online]. Available: https://www.baltex.co.uk/spacerfabrics/. [Accessed: 13- Aug- 2020].
29. "Chemical-Free Cooling Apparel and Cooling Accessories", *Coolcore*, 2020. [Online]. Available: https://www.coolcore.com/. [Accessed: 13- Aug- 2020].
30. S. Adanur and W. Sears, *Handbook of Industrial Textiles*. Technomic Publishing, Inc, USA, 1995.
31. "COOLMAX", *Coolmax.com*, 2020. [Online]. Available: http://coolmax.com/en/. [Accessed: 13- Aug- 2020].
32. A. D. Sule, M. K. Bardhan and R. K. Sarkar, “Development of Sportswear for Indian Conditions,” *Man Made Textiles in India*, pp. 123-129, 2004.
33. E. Kissa, “Wetting and Wicking,” *Textile Research Journal*, vol. 66, no. 10, pp. 660–668, 1996.
34. M. Chaplin, "Water structure and science - Capillaries", *Www1.lsbu.ac.uk*, 2020. [Online]. Available: http://www1.lsbu.ac.uk/water/capillaries.html. [Accessed: 13- Aug- 2020].
35. S. Chwastiak, *J. Colloid Interface Sci*. 42, 298, 1973.
36. T. Gillespie and T. Johnson, *J. Colloid Interface Sci*. 36, 282, 1971.
37. E. W. Washburn, *Physical Review*. 27, 273, 1923.

38. K. T. Hodgson and J. C. Berg, *J. Colloid Interface Sci.* 121, 22, 1988.
39. R. Laughlin and J. Davies, "Some Aspects of Capillary Absorption in Fibrous Textile Wicking", *Textile Research Journal*, vol. 31, no. 10, pp. 904-910, 1961. Available: 10.1177/004051756103101011.
40. N. R. S.Hollies, M. M. Kaessinger and H. Bogaty, “Water transport mechanisms in textile materials, Part I: The role of yarn roughness in capillary-type penetration”. *Textile Research Journal*, vol. 26, pp. 829–835, 1956.
41. X. Chen, K. G. Kornev, Y. K. Kamath, and A. V. Neimark, “The Wicking Kinetics of Liquid Droplets into Yarns,” *Textile Research Journal*, vol. 71, no. 10, pp. 862–869, 2001.
42. T. Kawase, S. Sekoguchi, I. Fujii and M. Minagawa, *Textile Research Journal*, 56, 409, 1986.
43. T. Gillespie and T. Johnson, *Colloid Interface Science*, 36, 282, 1971.
44. A. Patnaik, R. S. Rengasamy, V. K. Kothari, and A. Ghosh, “Wetting and Wicking in Fibrous Materials,” *Textile Progress*, vol. 38, no. 1, pp. 1–105, 2006.
45. E. Kissa, *Journal of Colloid and Interface Science*, 83, 265,1981.
46. E. Kissa, *Pure and Applied Chemistry*, 53, 2255, 1981.
47. I. J. Gruntfest, “The Mechanism of the Wetting of Textiles,” *Textile Research Journal*, vol. 21, no. 12, pp. 861-866, 1951.
48. M. K. Öztürk, B. Nergis, and C. Candan, “A study of wicking properties of cotton-acrylic yarns and knitted fabrics,” Textile Research Journal, vol. 81, no. 3, pp. 324–328, 2010.
49. A. Das, V. K. Kothari and M. Balaji, “Studies on cotton– acrylic bulked yarns and fabrics. Part I: yarn character- istics,” *J Textile Inst,* vol. 98, no. 3, pp. 261–267, 2007.
50. A. B. Nyoni and D. Brook, “Wicking mechanisms in yarns—the key to fabric wicking performance,” Journal of the Textile Institute, vol. 97, no. 2, pp. 119–128, 2010.

51. F. W. Minor, A. M. Schwartz, E. Wulkow, and L. C. Buckles, "The Migration of Liquids in Textile Assemblies," *Textile Research Journal*, vol. 29, no. 12, pp. 931–939, 1959.
52. F. W. Minor, A. M. Schwartz, L. C. Buckles and E. A. Wulkow, "Pathways of Capillary Migration of Liquids in Textile Assemblies," American Dyestuff Reporter, 49 (12), pp. 37-42, 1960.
53. T. Liu, K. Choi and Y. Li, "Wicking in twisted yarns", *Journal of Colloid and Interface Science*, vol. 318, no. 1, pp. 134-139, 2008. Available: 10.1016/j.jcis.2007.10.023.
54. M. J. Denton and W. J. Morris, Heat setting and yarn texturing. In *The setting of fibres and fabrics*, (ed. J. W. S. Hearle & L. W. C. Miles), Merrow Publishing Co. Ltd., 1971, pp. 124–148.
55. Pan, N. (1992). Development of a Constitutive Theory for Short Fiber Yarns: Mechanics of Staple Yarn Without Slippage Effect. *Textile Research Journal, 62*(12), 749-765. doi:10.1177/004051759206201208
56. Hollies, N. R., Kaessinger, M. M., & Bogaty, H. (1956). Water Transport Mechanisms in Textile Materials1 Part I: The Role of Yarn Roughness in Capillary-Type Penetration. *Textile Research Journal, 26*(11), 829-835. doi:10.1177/004051755602601102
57. W. Barthlott and C. Neinhuis, "Purity of the sacred lotus, or escape from contamination in biological surfaces," *Planta* 202: 1-8,1997.
58. Su, C., Wu, W., & Lee, J. (1998). Blend Uniformity of a Filament and Staple Composite Yarn and Its Effect on Dyeing. *Textile Research Journal, 68*(7), 528-532. doi:10.1177/004051759806800710
59. G. E. Collins, "Fundamental principles that govern the shrinkage of cotton goods by washing," *Journal of the Textile Institute Proceedings*, vol. 30, no. 3, pp46-61, 1939.
60. Maginnis, J. B. (1950). The Effect of Moisture on Twisted Yarns. *Textile Research Journal, 20*(3), 165-171. doi:10.1177/004051755002000303

61. Wehner, J. A., Miller, B., & Rebenfeld, L. (1987). Moisture Induced Changes in Fabric Structure as Evidenced by Air Permeability Measurements. *Textile Research Journal, 57*(5), 247-256. doi:10.1177/004051758705700501
62. *Textiles-Evaluation of absorption and quick-drying*, PRC standard GB/T 21655.1, 2008.