Doctoral Dissertation (Shinshu University)

Study on wicking property of silk filament yarns considering interlacing

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YAN，JIAWEI

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Introduction

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1.1 Wetting and wicking

1.1.1 Surface wetting phenomenon

The wetting phenomenon caused by surface tension is very common in our world. In our daily life, the wetting phenomenon caused by surface tension is everywhere.

Various wetting phenomena are shown in our daily life, including our clothing, food, and transportation. In clothing and textiles, undergarments often use absorbent materials to wick away body sweat, ensuring comfort and cool. Sportswear is designed with good breathability to speed up air circulation. Waterproof jackets typically feature special coatings, allowing water to slide off and avoid penetration, which is resistance to wetting phenomena.

In the digestion process of food and beverages, wetting occurs when food is moistened by stomach acid for digestion. Enzymes in digestive fluids wet the food, making nutrients more easily absorbed by our bodies. When it comes to construction and materials, high-quality paints and coatings possess wetting properties, enabling even wetting of surfaces and providing lasting protection.

Additionally, some materials for buildings are designed to have low wetting properties to prevent water penetration and maintain structural stability. Moreover, everyday items such as sweat-wiping tissues and floor-cleaning sponges rely on wetting phenomena. Sweat-wiping tissues typically exhibit excellent wetting properties, enabling them to quickly absorb moisture. This wetting ability helps the tissues absorb sweat more effectively, keeping the body comfortable and dry.

Floor-cleaning sponges also rely on wetting phenomena. They usually have an open-cell structure, allowing them to rapidly absorb water from the floor. Wetting phenomena enable sponges to expand quickly when in contact with moisture, enhancing their absorbency.

In biology and botany, plants absorb water and nutrients through the capillary structures in their roots. This process involves wetting phenomena between the plant's internal fluids and the soil.

In a word, wetting phenomena find diverse applications in various fields, providing convenience and benefits in our everyday lives.

1.1.2 Surface tension

The relationship between the phenomenon of wetting and the surface tension of liquids has been widely studied and discussed in the scientific community. A key concept in the phenomenon of wetting is "wettability," which describes how the liquid spread on a solid surface. Understanding and controlling this phenomenon is crucial for many practical applications, including materials science, chemical engineering, biology, and more.

In Pierre-Gilles de Gennes’ speech, , the Nobel laureate in Physics in 1991, summarized the category of substances known as "complex fluids." Complex fluids encompass a variety of substances, among which the phenomena caused by liquid surface tension are significant components. These phenomena can involve the shape of liquid droplets, the behavior of liquids at the microscopic level, and the wetting properties of liquids on different surfaces.

The interactions between molecules in a liquid result in surface tension, where molecules on the surface of the liquid are mutually attracted, creating a certain tension on the surface. When a liquid contact with a solid surface, these intermolecular attractions affect how the liquid spreads on the solid surface. If the liquid can spread completely over the solid surface, it is termed wetting. In-depth research on wetting phenomena not only helps us understand the reasons behind these occurrences but also provides guidance for designing new materials and improving wettability performance.

These studies have significant importance in the manufacturing of microdevices, improving coating technologies, and understanding the behavior of cells and tissues in biology. Understanding the wetting properties of liquids on different surfaces enables scientists to develop more efficient coating techniques, enhance drug delivery systems, and find widespread applications in the field of nanotechnology. These research efforts not only deepen our understanding of material behavior but also provide valuable references for practical applications.

1.1.3 Contact angle

The wetting characteristics of different liquids on various solid surfaces reflect the differences in interactions between liquids and solids.

When mercury contact with a glass surface/ acrylic substrate, it does not adhere to the glass but forms a spherical shape. This phenomenon occurs because the intermolecular interactions between mercury and glass are weak; mercury tends to maintain its own shape and does not adhere to the glass surface. This phenomenon, where a liquid does not adhere to a solid surface, is called non-wetting or non-wettability.

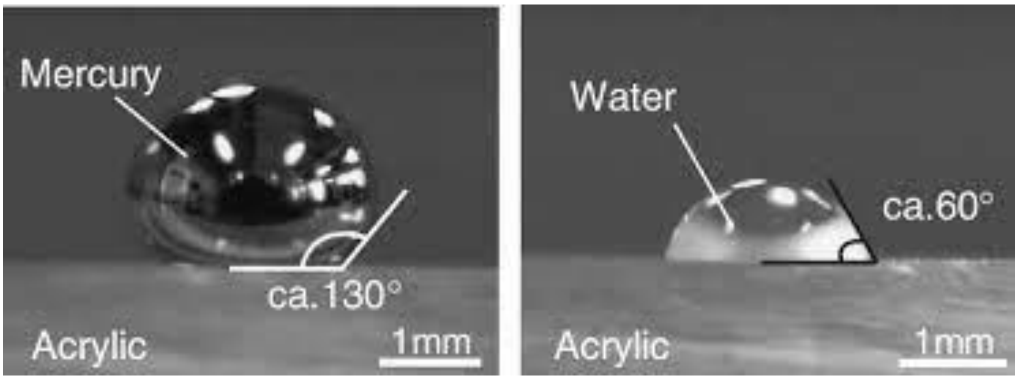


Figure 1.1Mercury and water droplets on an acrylic substrate in air Takashi Naoe[1] (2008)

Unlike mercury, water has stronger interactions with glass/ acrylic substrate. The attractive forces between water molecules and glass molecules cause water to spread on the glass surface, forming a thin liquid film. This phenomenon, where a liquid adheres to a solid surface, is called wetting. This is because hydrogen bonds and other chemical interactions formed between water molecules and the glass surface enable water to wet the glass surface instead of forming a spherical shape.

When water encounters paraffin (a hydrophobic solid), it does not wet the surface; instead, it forms spherical droplets. The surface of paraffin is hydrophobic, resulting in weak interactions with water. Consequently, water does not spread over the paraffin surface but retains a compact droplet shape. In contrast, mercury has strong interactions with zinc, allowing it to wet the zinc surface. This is due to the formation of robust metallic bonds and mutual attractive forces between mercury and zinc, enabling mercury to spread across the zinc surface rather than forming spherical droplets.

The differences in liquid wetting properties have significant implications for fields such as materials science, surface coating technology, and lubrication studies. The wetting properties of solid surfaces are a complex issue, influenced not only by the surface's chemical composition but also by the surface microstructure of the substrate. To quantitatively describe the wetting properties characterizing solid surfaces, Thomas Young studied the phenomenon of liquid wetting on solid surfaces and proposed the famous Young's equation to describe this phenomenon. This equation quantitatively describes the contact angle of a liquid droplet on a solid surface, indicating the angle at which the droplet contacts the solid surface.

Young's contact angle is the angle used to describe the interaction between a liquid droplet and a solid surface, typically represented by the Greek letter θ (theta). This angle signifies the angle formed by the contact between the liquid droplet and the solid surface. On surfaces with good wettability, the angle at which the droplet contacts the surface is small, and contact angle is smaller than 90°. Conversely, on surfaces that are less wettable, the angle at which the droplet contacts the surface is larger, and the contact angle is larger than 90°.

In summary, on surfaces with good wettability, a liquid droplet can spread completely and uniformly cover the solid surface. At this point, the contact angle between the liquid droplet and the solid surface is less than 90 degrees. For example, water droplets formed on glass or metal surfaces exhibit small contact angles.

On surfaces with weak wettability or hydrophobicity, liquid droplets cannot spread completely and uniformly cover the solid surface. In this case, the contact angle between the liquid droplet and the solid surface is greater than 90 degrees. The droplet does not fully spread out and instead forms a spherical or nearly spherical shape. For instance, water droplets on a candle surface exhibit a large contact angle.

These two types of contact angles reflect the nature of the interaction between the liquid droplet and the solid surface. A small contact angle typically indicates good wettability, where the liquid easily spreads on the solid surface. In contrast, a large contact angle represents poor wettability, where the liquid has difficulty expanding on the solid surface.

1.1.4 Capillary wicking

Before delving into this explanation, we need to clarify two concepts: imbibition and wicking.

Imbibition: Imbibition refers to the process of liquid diffusion within porous solids or fibrous materials, especially when the liquid is spreading into the material's interior through channels, pores, or cellular structures without external force. This phenomenon commonly occurs in porous materials like soil, paper, and wood, where the liquid is pulled into the material's interior due to capillary action, capillary forces, and surface tension. Imbibition is a passive process and does not require external driving forces.

Wicking: Wicking refers to the process by which a liquid spread within porous or fibrous materials. When a liquid enters porous materials such as fibers, paper, or fabrics, it moves along the material's capillaries or fibers. This phenomenon is typically driven by capillary action, surface tension, and the porous structure of the material. Wicking is widely utilized in various applications, such as in absorbent paper and the production of wet towels.

Therefore, the main differences are the driving force and the path of propagation. Imbibition is a spontaneous process, requiring no external force, and usually involves porous solids. Wicking, on the other hand, typically requires an external driving force. The materials involved can be porous or fibrous, but the liquid propagation usually occurs along specific directions or paths.

The concept of capillaries was first introduced to describe the micro-vessels in the human body. Before this understanding emerged, people had relatively limited knowledge about the circulatory system, knowing little about how blood transported nutrients and oxygen within the body.

Modern quantitative scientific research on the phenomenon of wetting can be traced back to the early 19th century. In 1805, British scientist Thomas Young published a paper titled *An Essay on the Cohesion of Fluids*, in which he extensively discussed the wetting phenomenon of liquids on solid surfaces. He introduced the concept of the "contact angle," which refers to the angle at which a liquid droplet contacts a solid surface. This concept became a fundamental basis for subsequent studies on wetting phenomena.

The simplest demonstration of capillary action involves inserting a capillary tube into water, a highly viscous and surface-tension-dominated liquid. When a glass tube is placed in water, the surface tension of water attempts to minimize the surface area of the liquid. This attraction causes water to rise inside the capillary tube, demonstrating the clear phenomenon of capillary action.

The shape of the liquid meniscus inside the tube should be solved using the Laplace equation. However, due to the tube's small size, it can be approximated as circular. Let the radius of the tube be r, the height of water rise inside the tube be h, and the density of the liquid be ρ. g represents the gravitational acceleration. We can easily determine the height of liquid rise(h)

$$h = \frac{2\gamma \cos\theta}{\rho g r}$$

Hence, it can be observed that when the solid surface is more hydrophilic and the tube diameter is smaller, the height of the liquid rise is greater. When $\theta = 0$, the liquid can completely wet the capillary tube, and the height of liquid rise is $h = \frac{2\gamma}{\rho g r}$. when $\theta = 90$, the rise height is 0, indicating the absence of capillary effect. When $\theta > 90$, a negative rise height indicates that the liquid not only does not rise but instead descends.

In real life, due to the exceptionally high surface tension of mercury and its tendency to minimize its surface area upon contact with solids, it often exhibits non-wetting behavior on most surfaces. In experiments, replacing water with mercury results in a scenario where, after inserting the capillary tube, the mercury inside the tube is observed to descend, and the liquid level near the tube wall curves downward. Similarly, the smaller the inner diameter of the tube, the lower the mercury level inside.

Capillary pressure refers to the pressure difference between a liquid and gas or between two different liquids in a capillary tube or porous medium due to capillary action. This concept is crucial in understanding the movement and propagation of liquids within tiny pores, capillaries, or porous materials.

Factors Affecting Capillary Pressure:

1. **Capillary Diameter:** Capillary pressure is inversely proportional to the capillary diameter. The smaller the diameter, the more significant the capillary action, leading to

higher capillary pressure.

2. **Surface Tension:** Surface tension arises from the interaction between liquid molecules and acts as the driving force behind capillary action. Greater surface tension results in higher capillary pressure.
3. **Contact Angle:** The contact angle refers to the angle formed by a liquid droplet and the solid surface when they come into contact. Capillary pressure is positively correlated with the contact angle.
4. **Liquid Density:** The density of the liquid also affects capillary pressure, although its impact is relatively smaller.

There are numerous examples of capillary phenomena in nature and daily life. For instance, plants and bricks absorb water, towels soak up sweat, and chalk absorbs ink; these are common instances of capillary action. These objects contain tiny pores that function as capillaries. However, capillary action can be detrimental in certain situations. For example, during the construction of buildings, the compacted foundation contains numerous fine capillaries.

These capillaries can draw moisture from the soil, leading to indoor dampness. To prevent this, builders often lay asphalt felt above the foundation to counteract the dampness caused by capillary action. The phenomenon of water rising along capillaries significantly impacts the textile industry. Soil contains numerous capillaries, and groundwater often ascends to the surface through these capillaries. To conserve groundwater, it's essential to loosen the soil surface and disrupt the capillaries to minimize water evaporation.

1.2 Previous study on the wicking of fabric

The research on fabric water absorption mainly involves the development of new materials and the exploration of the performance of existing fabric materials through testing.

Scientists and engineers are constantly working on the development of new types of fabric materials to improve their water absorption properties. This includes searching for new fiber materials, improving fiber structures, and developing coatings and treatment methods with special water-absorbing properties.

The study of water absorption properties not only involves the development of new materials but also includes testing and exploring the performance of existing fabric materials. These tests typically include various experiments such as water absorption speed, water absorption amount, and wet retention capacity. Through these tests, researchers can evaluate the performance of different fabrics in terms of water absorption and determine their suitability for various practical applications.

1.2.1 Develop new materials

The research and development of new materials can provide more efficient water absorption performance for various applications, such as medical supplies, sanitary pads, sportswear, and more.

Sportswear: In sportswear, water absorption performance is a crucial factor. Fabrics with high water absorption capabilities can help absorb sweat, keeping the wearer's skin at an appropriate level of humidity or temperature, thus enhancing comfort. Additionally, some sportswear also needs to have quick-drying properties to ensure rapid sweat evaporation, preventing the wearer from getting too cold. X Zhuang[2] (2022) has developed a wet-active cooling layered super fabric based on a nanofiber membrane, combining selective optical cooling with permeation evaporation cooling, achieving efficient temperature and humidity management. This layered super fabric has high sunlight reflectance, selective infrared emissivity, and good humidity permeability, effectively reducing the overheating temperature of simulated skin and offering excellent wearing comfort.

Bath Towels and Towels: The primary task of bath towels and towels is to absorb moisture. Cotton fabric is the preferred material due to its natural absorbency. The fiber channels in cotton fibers can quickly absorb moisture, helping to remove moisture from the body's surface rapidly. This is crucial for drying the body quickly after a bath, especially in cold seasons when damp skin can feel chilly. Bath towels and towels are typically made from highly absorbent cotton fabrics to quickly absorb moisture, aiding in swift drying of the body after a shower. HA Eren[3] (2020) investigates the absorbency of different fabric samples, including woven cotton fabrics and terry towels, through various tests such as the droplet test, sinking time test, and wicking height tests. The higher void content in towels contributed to their excellent absorbency, making them suitable for everyday use and travel due to their high absorbency and lightweight nature.

Outdoor Functional Clothing: In outdoor settings, such as during rainy or snowy weather, waterproof performance is crucial for keeping the body dry and warm. Certain fabrics are equipped with special waterproof coatings or membranes that prevent rainwater or moisture from seeping inside. This helps prevent the clothing from absorbing water, reducing weight, and preventing excessive drop in body temperature. Waterproof performance is also essential for protecting valuable items inside the clothing, such as smartphones and wallets. Some fabrics come with waterproof coatings or membranes that prevent water infiltration while maintaining breathability, preventing internal moisture from evaporating. Q. Zhuang[4]（2002）explores liquid transfer and interaction between fabric layers in clothing systems. External pressure affects transfer wicking onset, with an optimal pressure for maximum water transfer. The amount of water transferred depends on fabric type and how they contact each other, with Aquator fabrics performing best in liquid transfer.

Medical Use: Medical bandages are often used to treat various types of wounds, including small cuts, abrasions, burns, and large surgical wounds. Highly absorbent bandages can quickly absorb the blood or exudate from the wound to ensure it stays dry and clean. This is crucial for preventing infections, promoting wound healing, and reducing the risk of contamination. Absorbency is highly important in the medical field. Medical bandages and surgical drapes typically use highly absorbent fabrics to absorb wound bleeding or bodily fluids during surgery. A Tarbuk[5]（2019）examined moisture management in cotton fabrics intended for hospital use, including surgical gowns and linen. It found that standard cotton fabric exhibited excellent hydrophilicity and moisture absorption, making it a moisture management fabric. Hospital white linen had a water-repellent finish, while hospital green fabric for gowns had fast absorption and quick drying properties. The study suggested that special treatment was effective for cotton fabric processing based on wetting, wicking, zeta potential, and antimicrobial activity results.

The primary function of sanitary pads and diapers is to absorb bodily fluids, including urine, menstrual blood, and other secretions. Highly absorbent fabrics and filling materials can quickly absorb many bodily fluids, locking them inside the product, thereby keeping the external surface dry. This is crucial for maintaining hygiene and preventing fluid leakage. Sanitary pads and diapers need to have high absorbency to absorb bodily fluids and keep the surface dry, ensuring hygiene and comfort. NC Brown[6] (2022) proposes a novel origami-inspired adult diaper design that improves discretion by reducing sag and increasing wicking across the entire diaper pad. N singn 2003 added an absorbent layer to disposable diapers to achieve more uniform and rapid liquid absorption.

Kitchen Towels and Dishcloths: In the kitchen, frequent cleaning and wiping are necessary, including wiping countertops, cleaning utensils, mopping spills, and drying dishes, among other tasks. Absorbency is crucial for cleaning, wiping, and absorbing liquids; therefore, these items are typically made from cotton or other highly absorbent fabrics.

Bedding: While sleeping, it is normal for us to sweat. If bed sheets and pillowcases are made from highly absorbent fabrics, they may absorb the sweat released by the body, causing the surface of the sheets, pillowcases, and mattress to become damp and affecting the quality of sleep. Therefore, to ensure a dry, comfortable, and undisturbed sleeping environment, it is more appropriate to choose fabrics with lower absorbency to prevent nighttime sweat absorption and maintain a dry and comfortable sleep.

1.2.2 Wicking performance testing and exploration

Additionally, some researchers explore the influence of various materials, different fabric materials, and fabric structures on fabric water absorption. By delving into the impact of different materials and fabric structures on fabric absorbency, valuable insights can be gained for tailored textile design, ensuring the final products possess outstanding water absorption capabilities to meet specific application requirements.

Different materials (such as cotton, polyester, wool, etc.) have varying water absorption capabilities. Studying the water absorbency of different materials allows understanding their behavior in humid conditions, aiding in the selection of the most suitable fiber materials for specific applications.

J. De Sousa[7] (2014) conducted research on the moisture-wicking and sweat absorption properties of different fabric shirts. The study compared pure cotton fabric with synthetic fiber fabric (81% polyester and 19% elastic fiber) in terms of sweat retention and fabric breathability after exercise. The experimental results indicated that moisture-wicking shirts could reduce body temperature during physical activity, and breathability played a crucial role in cooling the body while exercising. Furthermore, compared to pure cotton fabric, synthetic fiber fabric exhibited superior evaporation characteristics and a lower regain rate. G. Zhu[8] (2015) studied the water absorption of cotton fabric, and the research findings revealed the wicking rate was higher in the weft direction than that in the warp, especially at the beginning of the wicking process.

Different fabric structures (such as plain weave, twill, satin, etc.) as well as factors like fabric thickness, yarn density, etc., can influence a fabric's water absorption. Plain weave is the most common and simple fabric structure, where yarns interlace alternately, providing stability and durability. Twill weave presents a diagonal pattern as the yarns interlace diagonally, making the fabric stronger and more elastic than plain weave due to non-vertical or horizontal intersections. Satin weave is relatively loose, featuring fewer interlacing, resulting in a smooth surface. This structure is often used for smooth, shiny fabrics but is relatively delicate. Jacquard fabric is produced using special Jacquard devices, creating intricate patterns and textures, commonly used for high-end decorative textiles. In contrast to woven fabrics, knitted fabrics are formed by looping yarns together rather than the traditional interlacing. Knitted fabrics are usually softer and more elastic, suitable for stretchy garments like T-shirts and sweaters. Non-woven fabric is created by bonding fibers or fiber short cuts chemically or mechanically, bypassing traditional weaving processes. Fabrics of this structure are commonly used for disposable products and filtration materials. Studying the influence of different fabric structures on water absorption can guide manufacturers in selecting appropriate weaving methods to meet the specific requirements of products.

Cheol Jae Hong[9] (2007) conducted research on the water absorption properties of different materials (cotton, polyester) in various knitted fabric structures (interlock, honeycomb). The experiment found that pure cotton fabric exhibited the highest water absorption height. Additionally, this study developed a water absorption model using permeability coefficient, capillary pressure, and fabric thickness to describe the core absorption behavior. Fiber type and fabric structure were chosen as variables for simulation and testing. In highly porous knitted fabrics, the gravitational effect during core absorption was significant. The higher the capillary pressure, the greater the core absorption.

Meltem Yanılmaz[10] (2012) investigated the influence of different knitted fabric structures on thermal physiological comfort parameters. The study revealed that the knitted structure significantly affected core absorption height, core absorption weight, contact angle, transfer core absorption ratio, and water vapor permeability, among other properties. Fabric tightness and structural factors such as loop length and pore size also played a role in these comfort-related parameters.

kumar [11](2014) studied the vertical wicking behavior of various knitted fabrics, with experimental variables including fiber types, machine specifications, yarn feed rates, and elastic yarns. The experimental results showed that fabrics made from cotton or viscose yarn exhibited lower wicking rates compared to PET samples. Introducing elastic yarns into the knitted structure resulted in a relatively denser fabric construction and provided greater resistance to water rise, thus demonstrating poorer wicking properties compared to other fabrics.

Mlei [12](2020) investigated the two processes of moisture transfer, core absorption, and evaporation, in eight different cotton fabric structures. The research defined two stages: Stage I for the first 10 minutes and Stage II for the last 110 minutes. The experimental results indicated that

Stage I dominated the entire process of core absorption and evaporation. The moisture transfer rate during Stage I varied with different fabric structures, whereas the moisture transfer rate during Stage II remained similar and constant, independent of fabric structure.

Meltem Yanılmaz[10]（2012）investigated the impact of different knitted fabric structures on thermo-physiological comfort parameters. The research found that the knitted structure significantly influenced properties such as wicking height, wicking weight, contact angle, transfer wicking ratios, and water evaporation rate. Fabric tightness and structural factors like loop length and pore size also played a role in these comfort-related parameters.

The necessity of studying the water absorption properties of materials lies in its direct impact on people's comfort and health, as well as the functionality of functional apparel. Materials with strong water absorption capabilities enhance the wearer's comfort, especially in hot weather or during physical activities, preventing health issues caused by dampness. Additionally, researching water absorption properties contributes to the functionality of specialized garments and promotes sustainability by reducing water usage.

1.3 Previous study on the wicking of yarns

The impact of yarn's water absorption can be divided into two main aspects.

The first part involves the direct exploration and research of the water absorbency of yarn itself. This area of research typically encompasses different types and varieties of yarn, such as single yarn, composite yarn, cotton yarn, polyester, and so on. Scientists and engineers employ various experimental and testing methods to study the water absorption characteristics of yarns made from different materials under humidity and temperature variations. This deeper understanding helps in exploring the changes in yarn's water absorption properties and the influencing factors.

The second part involves the direct study of the water absorption of fabrics formed by different yarns. By examining the ultimate water absorbency of fabrics, researchers theoretically explore the impact of various parameters of yarns forming the fabric on water absorption. This is because testing the water absorbency of individual yarns is more complex in experimental setup and operation.

In the study on the water absorption properties of cotton and polyester, Ansari[13] (2000) differed from other researchers by repeatedly using the same yarn after drying. He investigated the impact of two yarn twist levels and thicknesses on water absorption height. However, due to the limited availability of only two twist levels, the data set was not comprehensive enough for a detailed analysis.

In the study conducted by Li [14](2016), the core absorption properties of natural short staple yarns made from cotton and wool were explored. The research revealed that when twist level and yarn count were consistent, the fiber diameter of wool influenced the water absorption rate, with thicker fiber diameter yarns exhibiting optimal core absorption. The study also found that compared to pre-washing treatment, plasma treatment was the most effective method to enhance yarn water absorption rate.

In the research conducted by Wang[15] (2008), the impact of twist level on the wicking ability of polyester filament yarn was studied. It was found that as the yarn twist increased, the water absorption height rose until reaching the maximum, after which the water absorption height decreased with further increases in twist level. The optimal twist level varied for different yarn types. For yarns without any twist, the initial twist added was beneficial for capillary formation. However, excessive twist hindered the capillaries that had already formed.

However, in a study conducted by T. Liu[16] (2008), the water absorption height of polyester yarns at different twist levels was investigated. In this experiment, the twist level varied from 0 to 500, and the water absorption height gradually decreased. This result contrasts with the findings of the previous study by N. Wang, where the twist level ranged from 0 to 1200, and the water absorption height showed a different pattern.

AB Nyoni[17] (2006) conducted a study on the water absorption properties of nylon 6.6. The research involved applying different tensions and twist levels to the yarn. Interestingly, the direction of the twist was found to have no effect on the yarn's wicking ability. Additionally, microscopic images of the yarn revealed distinct zones: unsaturated, saturated, and dry, providing valuable insights into the water absorption behavior of the material.

MK Ozturk[18]（2011）studied the wicking properties of cotton-acrylic rotor yarns and knitted fabrics. He found that the wicking abilities of yarns and fabrics increased with the increase in acrylic content in the blends and with the use of coarse yarns. Besides, yarn wicking had a significant effect on fabric wicking.

In a study conducted by HS Kim[19] (2020), the water absorption of yarns in double rib knitted fabrics was investigated. It was found that the water absorption within the fabric occurred through the transfer between yarns; moisture traveled along the yarns, highlighting the inter-yarn moisture transfer mechanism. In the study conducted by P. Mallick[20] (2021), the wicking effect of cotton woven fabrics was examined in different directions, along with the wicking effect of its constituent yarns. They found that as the yarn thickness increased, the water absorption height also increased. However, when the yarn thickness was further increased, the water absorption height decreased. Additionally, compared to plain weave fabrics, the correlation between yarn water absorption and the wicking height was higher in twill weave fabrics.

In a study conducted by R. Fischer[21] (2022), PET (polyethylene terephthalate) was used to simulate twisted yarn, and the wicking behavior of the interlaced yarn was analyzed. Fischer discovered that a network of long and narrow pores between fibers facilitated irregular core wicking behavior. Moisture tended to flow along the yarn axis, moving a considerable distance forward until saturation was reached. Although the research couldn't directly predict the capillary absorption of individual yarns, it qualitatively represented the water absorption dynamics of PET yarns.

Studying yarn water absorption is essential for enhancing textile performance and developing specialized fabrics for various applications, such as sportswear and medical textiles. This research is instrumental in creating comfortable and moisture-managing clothing, ensuring wearers stay dry and comfortable. Additionally, it aids in establishing quality standards for consistent textile production and promotes eco-friendly practices by reducing water wastage and chemical usage in the industry.

1.4 Previous study on the wicking of fibers

Due to yarns being typically composed of many intertwined fibers, studying the water absorption of fibers becomes more challenging. Compared to individual fibers, the water absorption of yarns is relatively easier to observe because they are structurally more stable than single fibers, which can be difficult to observe and measure in terms of water absorption.

In the textile industry, the relationship between fibers and yarns is crucial. Fibers are the fundamental building blocks of textiles and can be natural (such as cotton, wool) or man-made (such as polyester, nylon). These fibers undergo spinning processes to be organized into yarns. Yarns can be single-stranded or composed of multiple fibers twisted together to form composite yarns.

Y zhang[22]（2007） conducted a study on the water absorption and simulation of heterogeneous fiber bundles, and provided an initial discussion on the effective geometric dimensions of gaps formed between fibers. By analyzing and calculating parameters such as fiber count, core suction height, instantaneous core suction rate, and core suction time of fiber bundles, it was concluded that irregular fiber bundles such as cross-shaped or double cross-shaped configurations are optimized for enhanced water transfer.

T Stuart[23]（2015） conducted a study on the water absorption properties of linen and viscose fibers. The research indicated that the water absorption curves of viscose fibers were similar to those of linen. However, the core absorption and swelling mechanisms differed between linen fibers with inner cavities and viscose fibers without inner cavities. The core absorption of viscose fibers was primarily attributed to inter-fiber core absorption, while the core absorption in linen resulted from a combination of inter-fiber core absorption and contributions from its inner cavities.

In practical research, it is common to twist several fibers together to form composite yarns for studying their water absorption properties, rather than examining the water absorption of individual fibers. In actual textiles, fibers are usually interwoven in the form of yarns, not existing as standalone individual fibers. Therefore, studying the water absorption properties of composite yarns better reflects the performance of textiles in humid environments. This research method can more accurately simulate real-world conditions, providing data that is more practical and meaningful. It serves as a guiding principle for the design and improvement of textile products and their performance.

When studying the performance of textiles, the water absorption capacity of fibers is a crucial parameter. Research on water absorption not only affects the comfort of textiles in everyday use but also pertains to the characteristics of fibers and yarns. Since yarns are composed of intertwined fibers, understanding the water absorption of individual fibers helps predict and improve the overall water absorption performance of the entire yarn. However, as mentioned earlier, studying the water absorption of individual fibers is challenging, posing a difficulty for textile researchers.

Therefore, to gain a comprehensive understanding of the water absorption performance of textiles, researchers need to continuously explore new methods and techniques for accurately measuring and analyzing the water absorption of individual fibers. Such research not only contributes to enhancing the performance and quality of textiles but also provides vital support for innovation and development in the textile industry.

1.5 The significance and purpose of this study

1.5.1 The significance of this study

The importance of studying yarn water absorption extends across multiple facets in the textile industry and related fields: it can enhance product performance and improve user wearing experiences. Additionally, having prior knowledge of yarn water absorption can conserve resources and provide a competitive advantage in brand competition.

Understanding the water absorption properties of yarns helps manufacturers choose appropriate fibers and spinning methods to enhance the comfort and absorbency of fabrics. Yarns with good water absorption can swiftly absorb bodily fluids, reducing the chance of bacterial growth and minimizing odor. This is particularly crucial for products like underwear, which are in close contact with the skin, providing a long-lasting feeling of freshness. Especially in the production of items such as activewear, outdoor gear, and undergarments where quick drying and comfort are essential, optimizing water absorption capabilities is paramount. When products can absorb and wick away sweat more efficiently, it helps maintain a dry body, preventing discomfort and wear caused by moisture.

Understanding the water absorption properties of yarn can help manufacturers effectively utilize fiber materials in product design, thus avoiding wastage of resources. Fabrics with excellent water absorption typically require fewer fibers as they efficiently absorb moisture. Manufacturers can employ fibers more intelligently, promoting efficient resource utilization, reducing production costs, and enhancing product sustainability and market competitiveness. Research on water absorption also contributes to the creation of environmentally friendly textiles. Fabrics capable of rapid moisture absorption often require less water and chemicals during the washing process, aiding in reducing water wastage and lessening the environmental burden.

In summary, the purpose of studying yarn water absorption is to enhance the performance, comfort, and versatility of textiles. Simultaneously, it supports environmentally friendly production, resource conservation, and industry innovation.

As mentioned earlier, in actual textiles, fibers are usually interwoven in the form of yarns rather than existing as standalone individual fibers. Therefore, studying the water absorption properties of composite yarns better reflects the performance of textiles in humid environments. However, most researchers tend to focus on studying the water absorption of fabrics rather than delving into the water absorption of yarns and textiles.

Traditional methods for water absorption testing may not accurately assess the water absorption performance of yarns, as these methods are typically designed for larger fabric samples. Furthermore, the outer surface and internal structure of yarns can undergo changes due to processes like stretching and twisting during spinning, affecting their water absorption properties. These alterations make studying yarn water absorption more challenging. When researching yarn water absorption, factors such as stretching, twisting, density, and others need to be taken into account, as these elements can influence water absorption performance. Therefore, experimental studies on yarn water absorption require more precise and intricate experimental controls.

Studying the water absorption of yarns is indeed more complex and challenging compared to studying the water absorption of fabrics. However, precisely because yarns constitute the fundamental building blocks of fabrics, gaining in-depth knowledge about yarn water absorption is crucial for producing high-performance, comfortable textiles. Therefore, researchers are continually striving to develop new methods and technologies to study the water absorption properties of yarns more accurately.

1.5.2 The purpose of this study

The water absorption of fabrics cannot be known in advance before the final fabric production. It requires time and other production resources during the fabric manufacturing process. With the advancement of technology, modern techniques such as Computer-Aided Design (CAD) allow simulation of the final form of clothing before production. If the prediction of fabric water absorption can be integrated into the yarn stage of CAD systems, it can provide more accurate information before fabric production. This way, manufacturers can plan production processes more effectively, reduce resource wastage, and enhance production efficiency. By understanding the water absorption properties in the early stages of fabric design, producers can choose appropriate materials and techniques, ensuring the final product meets the required specifications. This integration also promotes innovation, encouraging researchers to find more environmentally friendly and efficient production methods, positively impacting the entire industry chain.

Taking plain woven fabric as an example, yarn forms the foundation of the fabric. The water absorption properties of yarn directly impact the overall water absorption performance of the fabric. If we understand the water absorption of individual yarns and how moisture moves along the yarns in the interlaced state at the yarn stage, we can predict the water absorption of the fabric in the future. This prediction can assist manufacturers in making informed material choices before production, avoiding the production of fabrics that do not meet the requirement.

As mentioned earlier, studying the water absorption properties of yarn directly is more challenging compared to researching the water absorption properties of fabrics. Yarn is composed of fibers, which are extremely fine and often not visible. Therefore, high-resolution instruments and techniques are required during the yarn water absorption process. Additionally, there might be some irregularities in the manufacturing process of silk yarn, including variations in fiber distribution and structure. These irregularities can impact the measurement results of water absorption properties. Thus, when studying yarn water absorption properties, ensuring the uniformity and consistency of samples is crucial to obtaining reliable experimental data.

Moreover, to accurately measure the water absorption properties of yarn, experiments need to be conducted under controlled conditions, including humidity and temperature control.

Controlling these experimental conditions is more complex than fabric experiments because yarn is easier to be influenced by the environment. Yarns are typically finer and more delicate than fabrics, making them more vulnerable to environmental factors that are difficult to stabilize in a laboratory setting. Hence, studying the water absorption properties of yarn is more challenging than studying the water absorption properties of fabrics.

The purpose of this study:

1 Develop new equipment to get the wicking ability of the single yarn and interlaced yarn directly.

2 Explore the wicking ability of single silk yarns and interlaced silk yarn

3 Discuss the impact of twist and thickness on the water absorption of silk yarn.

4 Preliminary exploration of the effect of humidity on yarn water absorption.

1.6 Composition of this study

In this study, a new wicking equipment for single yarn and interlaced yarn was proposed. The wicking ability of the silk yarn has been discussed.

In Chapter 2, the wicking measurement method for the yarn and fabric are discussed.

In Chapter 3, the wicking theory and the measurement method used in this study are proposed. The wicking ability of the single yarn and interlaced yarn are discussed.

In Chapter 4, the wicking relationship between single and interlaced yarns was discussed. Further discussion on the effect of silk yarn parameters (twist and fineness) on wicking are discussed.

Finally, in Chapter 5 the conclusion of this study is described.

Reference

1. T. Naoe, S. Hasegawa, A. Bucheeri, and M. Futakawa, *Journal of nuclear science and technology*, **45**, 1233 (2008).

2. Z. Zhang, G. Wang, W. Gu, Y. Zhao, S. Tang, and G. Ji, *J Colloid Interface Sci*, **605**, 193 (2022).

3. H. A. Eren, E. K. Çeven, G. Günaydın, M. S. Güler, and E. Akdemir, in "III International conference Contemporary trends and innovations in the textile industry"Ed.^Eds.), Year of Converence.

4. Q. Zhuang, S. Harlock, and D. Brook, *Textile Research Journal*, **72**, 727 (2002).

5. A. Tarbuk, S. Flinčec-Grgac, and T. Dekanić, *Advanced technologies*, **8**, 5 (2019).

6. N. C. Brown, H. T. Pruett, D. S. Bolanos, C. Jackson, B. Beatson, S. P. Magleby, and L. L. Howell, *Wearable Technologies*, **3**, e6 (2022).

7. J. D. Sousa, *Applied Ergonomics*, **45**, 1447 (2014).

8. G. Zhu, J. Militký, Y. Wang, B. V. Sundarlal, and D. Křemenáková, *Fibres & Textiles in Eastern Europe*, (2015).

9. C.-J. Hong and J. B. Kim, *Fibers and Polymers*, **8**, 218 (2007).

10. M. Yanılmaz and F. Kalaoğlu, *Textile Research Journal*, **82**, 820 (2012).

11. B. Kumar and A. Das, *Fibers and Polymers*, **15**, 625 (2014).

12. M. Lei, Y. Li, Y. Liu, Y. Ma, L. Cheng, and Y. Hu, *Polymers (Basel)*, **12** (2020).

13. N. Ansari, *The Journal of The Textile Institute*, **91**, 1 (2000).

14. Q. Li, J. J. Wang, and C. J. Hurren, *Journal of Natural Fibers*, **14**, 400 (2016).

15. N. Wang, A. Zha, and J. Wang, *Fibers and Polymers*, **9**, 97 (2008).

16. T. Liu, K. F. Choi, and Y. Li, *J Colloid Interface Sci*, **318**, 134 (2008).

17. A. B. Nyoni and D. Brook, *Journal of the Textile Institute*, **97**, 119 (2006).

18. M. K. Öztürk, B. Nergis, and C. Candan, *Textile Research Journal*, **81**, 324 (2010).

19. H.-s. Kim, S. Michielsen, and E. DenHartog, *Journal of Materials Science*, **55**, 7816 (2020).

20. P. Mallick and S. S. De, *Journal of Natural Fibers*, **19**, 5297 (2021).

21. R. Fischer, C. M. Schleputz, J. Zhao, P. Boillat, D. Hegemann, R. M. Rossi, D. Derome, and J. Carmeliet, *J Colloid Interface Sci*, **625**, 1 (2022).

22. Y. Zhang, H. Wang, C. Zhang, and Y. Chen, *Journal of Materials Science*, **42**, 8035 (2007).

23. T. Stuart, R. D. McCall, H. S. Sharma, and G. Lyons, *Carbohydr Polym*, **123**, 359 (2015).

Chapter 2

Wicking measurement method for the yarn and fabric

Chapter 2 Wicking measurement method for the yarn and fabric

In the process of textile manufacturing, different fabrics may need to meet specific water absorption performance standards. By outlining the methods of water absorption testing, manufacturers can ensure their products comply with quality standards, thereby providing consistent and reliable products. Additionally, the water absorption performance of fabrics may vary under different environmental conditions. For instance, fabrics used in high humidity or rainy climates may require higher water absorption capabilities. Testing the water absorption performance under various environmental conditions ensures the adaptability of the fabric in different settings. In certain industries, fabric products must adhere to specific water absorption performance standards and regulations. Providing detailed explanations of water absorption testing methods can ensure product compliance, avoiding potential legal issues.

The methods for measuring the water absorption of materials are divided into two parts: fabric water absorption testing methods and yarn water absorption testing methods. These two aspects of testing methods have different focuses but both provide detailed evaluations of the material's water absorption performance.

Fabric water absorption testing typically involves measuring the fabric's ability to absorb moisture under specific conditions. The testing parameters may include the following aspects:

Water Absorption Rate: Measures the speed at which the fabric absorbs moisture within a certain period.

Water Absorption Capacity: Measures the total amount of water absorbed by the fabric within a specific timeframe.

Performance Change After Water Absorption: Tests the changes in fabric parameters such as strength, stiffness, elongation, etc., after absorbing water.

Liquid Penetration Resistance: Measures the fabric's resistance to liquid penetration, commonly used for evaluating waterproof fabrics.

Drying Time: Measures the time required for the fabric to completely dry after absorbing water.

Yarn Water Absorption Performance Testing primarily focuses on the water absorption capabilities of the yarn itself. This type of testing typically involves the following aspects:

Water Absorption: Measures the yarn's ability to absorb water, including parameters such as water absorption height, absorption rate, and absorption quantity.

Mechanical Property Change After Water Absorption: Tests the changes in mechanical properties of the yarn after absorbing water, including strength, elasticity, and whether any swelling occurs.

2.1 Wicking measurement method for fabric

Here, we mainly discuss three common methods for measuring the absorbency of fabrics: Byreck method, drip method and thermocouple method.

Byreck Method: This is a commonly used laboratory testing method that assesses the absorbency of fabrics by measuring their ability to absorb moisture. In this method, the fabric sample under test is typically placed under specific conditions, such as controlled humidity and temperature. The amount of water absorbed by the fabric within a specific time frame is then measured to determine its absorbency.

Drip Method: This method is a relatively simple way to measure absorbency. In this approach, water droplets are dripped onto the fabric surface, and the absorption behavior of the fabric is observed. If the fabric has good absorbency, the water droplets will be quickly absorbed into the fabric. This method allows for a rapid preliminary assessment of fabric absorbency, making it especially suitable for quick screening purposes.

Thermocouple Method: This method relies on temperature changes to measure absorbency. A thermocouple is inserted into the fabric, and moisture is applied to the fabric. As moisture is absorbed, the fabric's temperature changes, which the thermocouple detects. By measuring the magnitude and rate of temperature changes, information about the fabric's absorbency performance can be obtained. This method is commonly used to study fabric absorbency under different conditions.

The choice of these methods depends on specific testing requirements and experimental conditions. Different methods can provide varying levels of absorbency information, helping researchers and manufacturers gain a better understanding of the fabric's performance characteristics.

2.1.1 Byreck method

In this testing method, the fabric sample to be tested is first placed in a water tank. During the testing process, there are two main measurement methods: one is to record the fabric's water absorption height, and the other is to record the specific amount of water absorbed by the fabric.

Firstly, when aiming to measure the fabric's water absorption height, one can directly capture videos or take photos using a camera to observe the state of water droplet penetration into the fabric. To facilitate observation, ink, dye, or other visible color solutions are often added to the water tank, making the depth of water droplet penetration more apparent. This method visually demonstrates the fabric's absorbency; fabrics with high absorbency allow water to quickly penetrate and spread, resulting in a larger water absorption height.

To measure the fabric's water absorption quantity, there are two approaches. One method involves measuring the decrease in the mass of water in the tank during the testing process. As the fabric absorbs water, the water level in the tank decreases. By measuring this decrease in mass, the specific weight of water absorbed by the fabric can be calculated. The other method entails measuring the increase in the fabric's mass due to water absorption. The fabric's mass is weighed before and after the test, and the difference between the two measurements indicates the increase in mass caused by water absorption.

Additionally, in certain research and experiments, neutron radiography techniques can be employed to gain a deeper understanding of the distribution of moisture inside the fabric. This technique can penetrate the fabric, capturing the movement and distribution of water within the fabric, and providing more detailed information about its absorbency.

In summary, through these detailed testing methods, we can comprehensively understand the fabric's absorbency, providing a scientific basis for selecting suitable materials for different application situations.

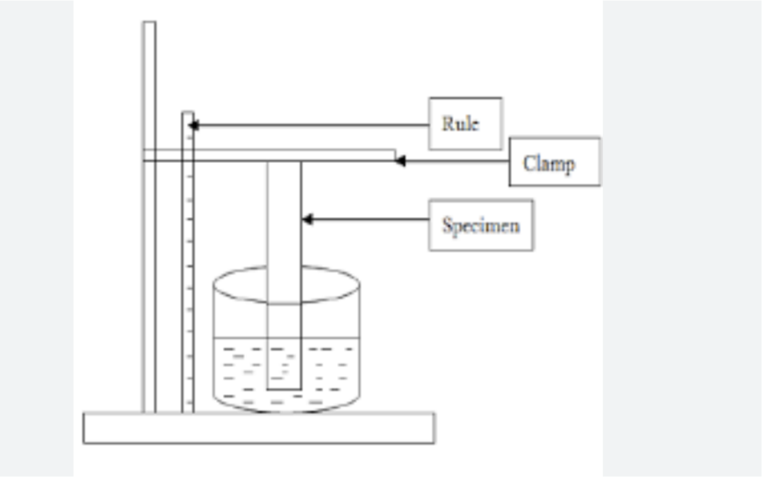


Figure 2.1 Diagrammatic representation of the fabric wicking test apparatus [1]

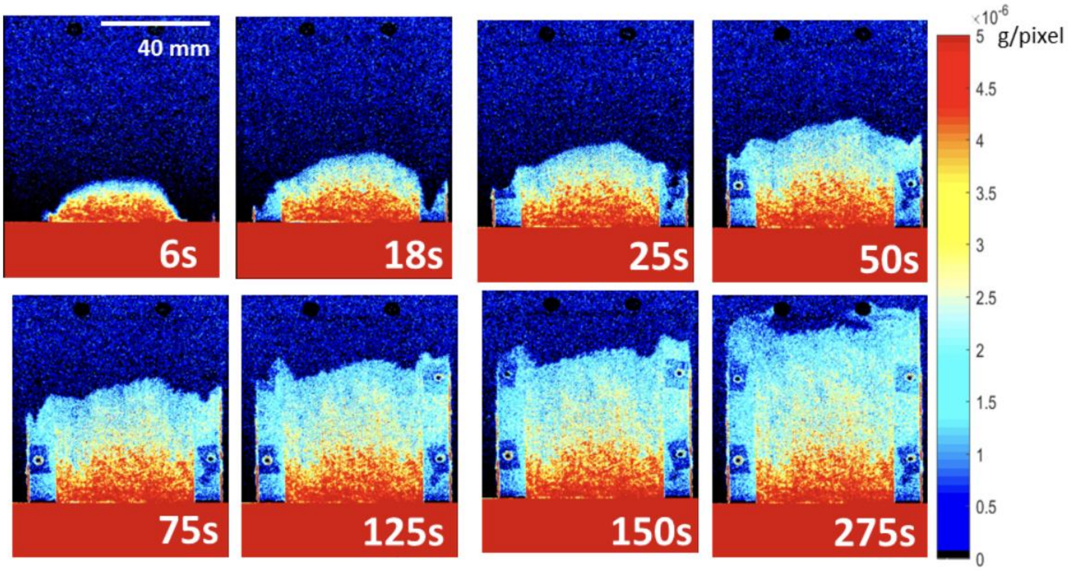


Figure 2.2 Dynamic Wicking Process in Textiles [2]

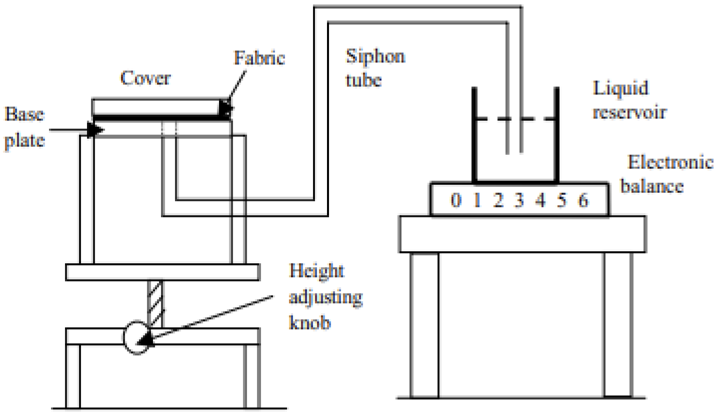


Figure2.3 Use electronic balance to record the wicking progress [3]

2.1.2 Drip method

To elaborate, in this method, a fixed-sized water droplet is dropped onto the fabric, which has been previously fixed onto a flat surface. The process involves carefully measuring the area covered by the water droplet as it forms on the fabric. By monitoring the changes in this area over time, the fabric's absorbency can effectively characterized.

This approach provides valuable insights into the fabric's ability to absorb moisture. A larger area covered by the water droplet signifies that the fabric absorbed the water more effectively, indicating higher absorbency. On the other hand, a smaller area suggests lower absorbency, indicating that the fabric repels or does not readily absorb the water droplet.

By quantifying the water droplet's area on the fabric surface and observing how it changes, researchers and fabric developers can gain a precise understanding of the fabric's absorbent properties. This information is crucial in various industries, such as textiles, where selecting the right fabric for specific applications, such as sportswear or medical textiles, relies heavily on its absorbency characteristics.

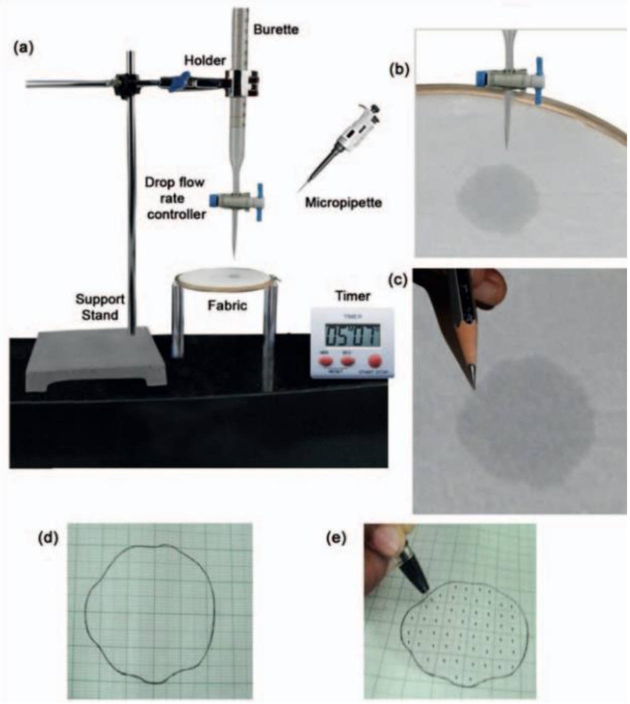


Figure 2.4 use the drip method get the wicking progress [4]

2.1.3 Sensor method

Connecting temperature and humidity sensors to fabrics is a common application, especially in the textile, clothing, and smart home industries. By embedding sensors into the fabric, real-time monitoring and measurement of fabric moisture absorption can be achieved. The purpose of this design is to enable sensors to detect the presence of moisture in the fabric after it absorbs water, thus providing information about the fabric's humidity.

First, it is necessary to choose sensors suitable for measuring temperature and humidity. Common types of temperature and humidity sensors include resistive humidity sensors and capacitive humidity sensors, which can measure the humidity in the air. Additionally, special sensors like moisture-absorbing sensors can be chosen. These sensors are designed to directly measure the surface humidity of fabrics.

Once the sensors are selected, they are embedded into the fabric. This can be achieved by sewing or adhering the sensor probes (typically small chips) to the fabric's surface or inside layers. Careful consideration is given to the sensor placement to ensure it accurately reflects the overall humidity of the fabric. The sensors are connected to the corresponding data acquisition system or processor. This connection can be established using wires or wireless communication technology. The data collected by the sensors (temperature and humidity values) are transmitted to the data acquisition system, where they can be processed and analyzed.

The collected data can be interpreted as the humidity level of the fabric. When the fabric absorbs water, the humidity sensor detects an increase in humidity signals. This data can be used to monitor the fabric's moisture absorption performance or be applied in smart textile products, such as smart sportswear, intelligent bedding, and so on. In these applications, corresponding responses can be triggered based on the sensor data, such as alerting users to change bed sheets or clothing with higher humidity levels.

In summary, connecting temperature and humidity sensors to fabrics can provide real-time humidity information for various applications, helping people better understand and manage the moisture absorption performance of fabrics.

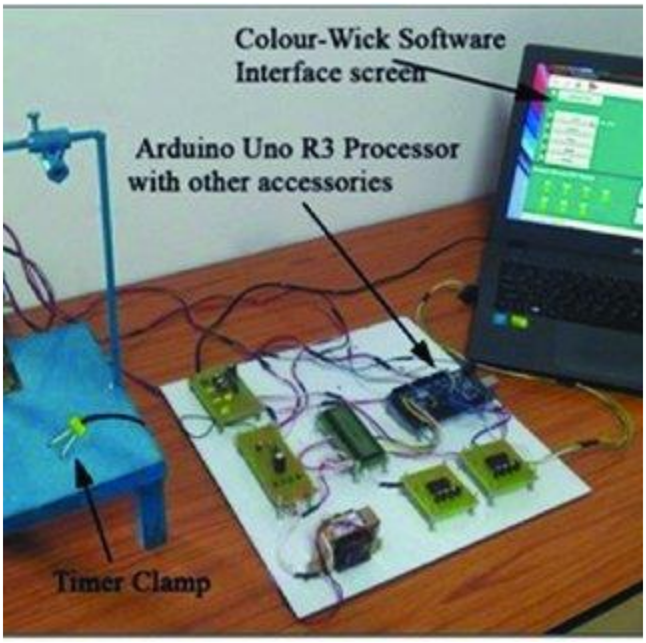


Figure 2.5 use the sensor get the wicking progress [5]

2.2Wicking measurement method for yarn

2.2.1 Resistance change method

The experimental setup of N. Ansari is illustrated in the diagram: the sensor is fixed at one end of the yarn, and the other end is secured at a specific position on a water cup container. As the yarn absorbs water, its resistance value changes. When the yarn is dry, the resistance value is relatively high; whereas, when the yarn absorbs water, the electrical conductivity of the moisture reduces the resistance value. This change in resistance can be recorded by the sensor.

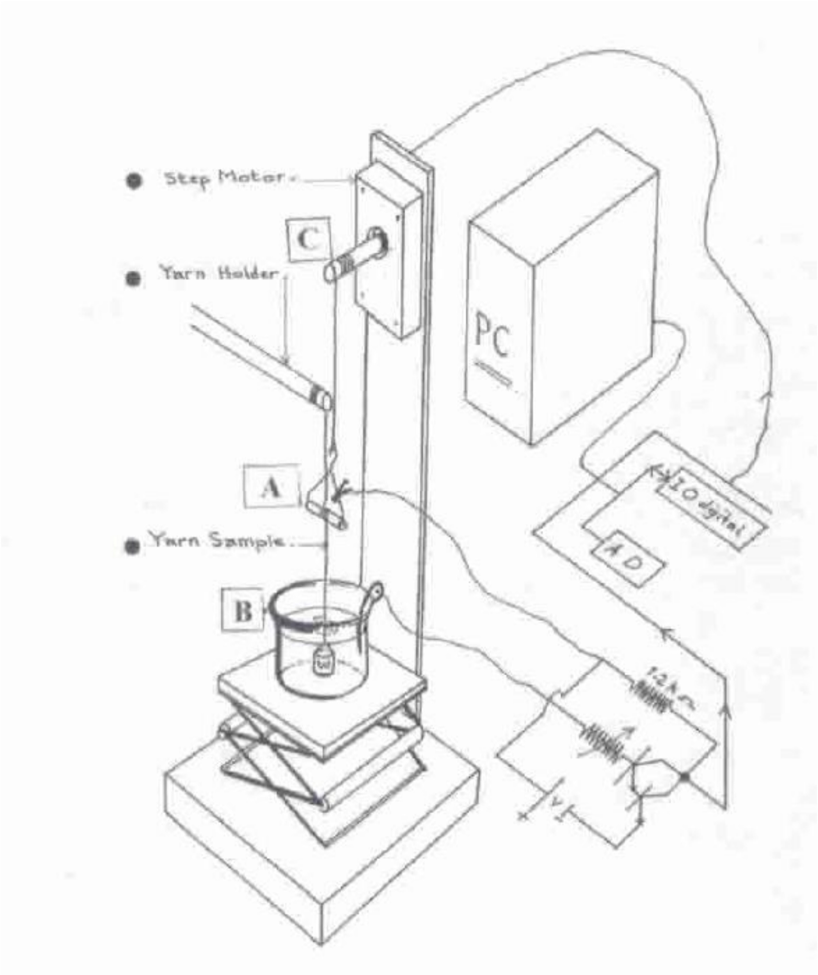


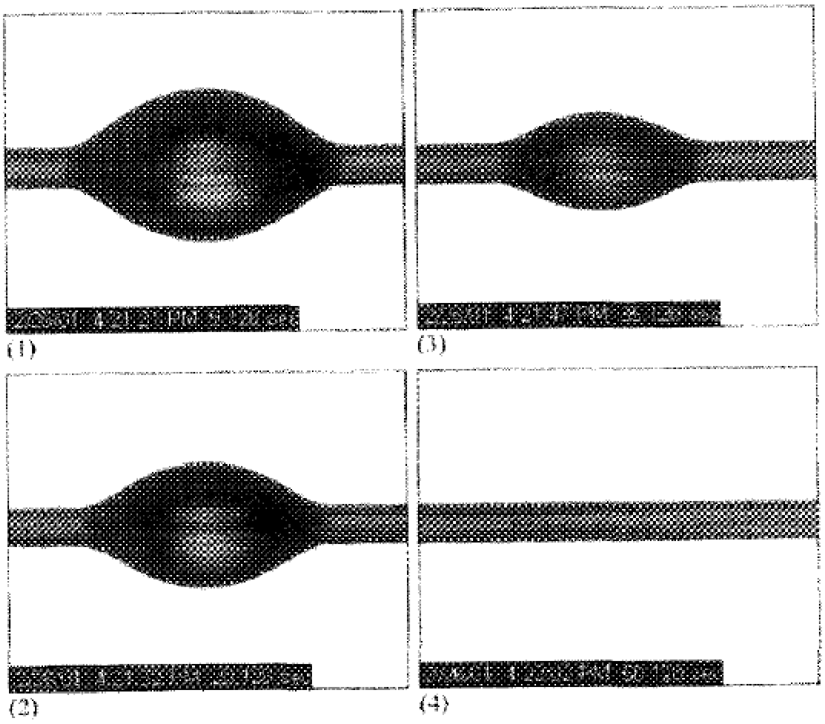
Figure 2.6 Equipment for use voltage change get the wicking of yarn[6]

2.2.2 The droplet monitoring method

In this method, a droplet of water is first placed onto the yarn. Upon contact, the moisture permeates the fiber structure of the yarn. Using a microscope, we can magnify and observe the movement of moisture on the yarn.

On the yarn, moisture diffuses and gets absorbed between the fibers. This process can be clearly observed under the microscope. The movement path, speed, and distribution of moisture within the yarn structure can all be observed and recorded. As moisture is absorbed, the yarn fibers may expand and become looser, and these structural changes can also be observed under the microscope.

Through this method, we can gain a detailed understanding of the propagation and absorption process of moisture within the yarn. This information is crucial for understanding yarn's water absorption properties, fiber structural characteristics, and the design and production of textiles. Moreover, this experimental method is widely used in studying the waterproofing capabilities and absorption rates of textiles.



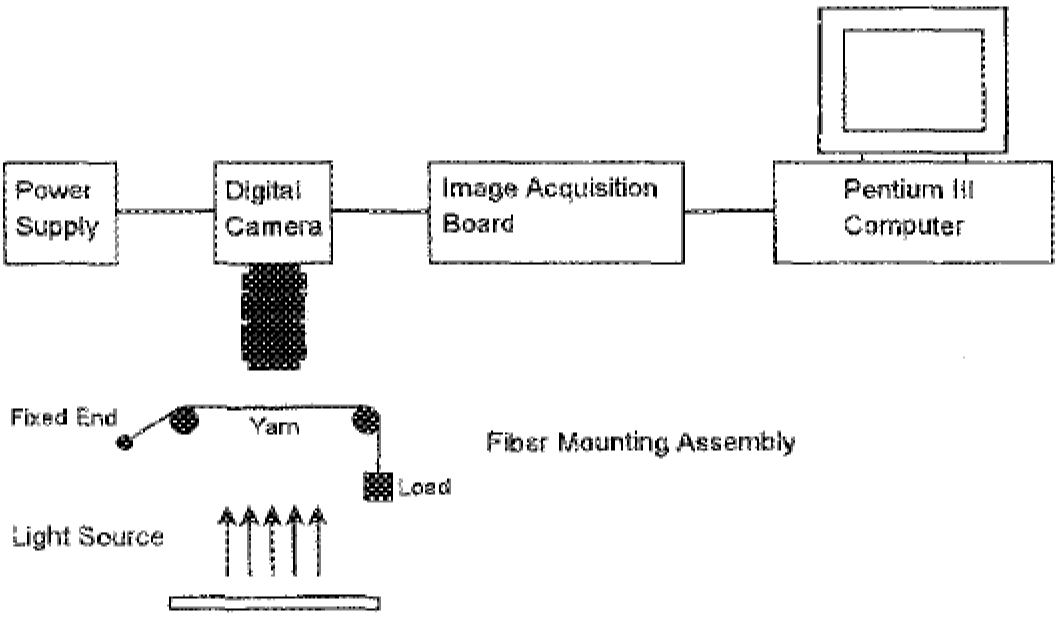


Figure2.7 Drop a liquid on the yarn [7]

2.2.3 Byreck method

In investigating the water absorption results of yarn under different tensions and twist levels, one end of a sample is clamped using a clip, while a certain tension is applied to the other end of the sample. Simultaneously, by controlling the height of the lifting platform, the height of the water tank is adjusted. For yarn that has undergone changes in twist, the experimenter clamps the tail end of the yarn to apply the required twist. With this setup, researchers can observe and study the relationship between yarn twist and tension.（(AB Nyoni 2006)

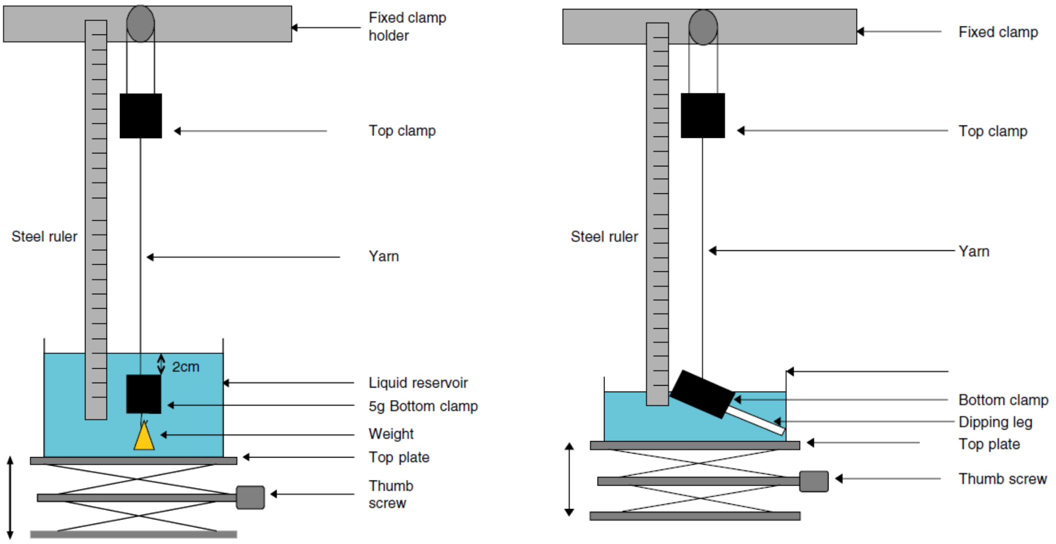


Figure 2.8 Static loading test equipment arrangement [8]

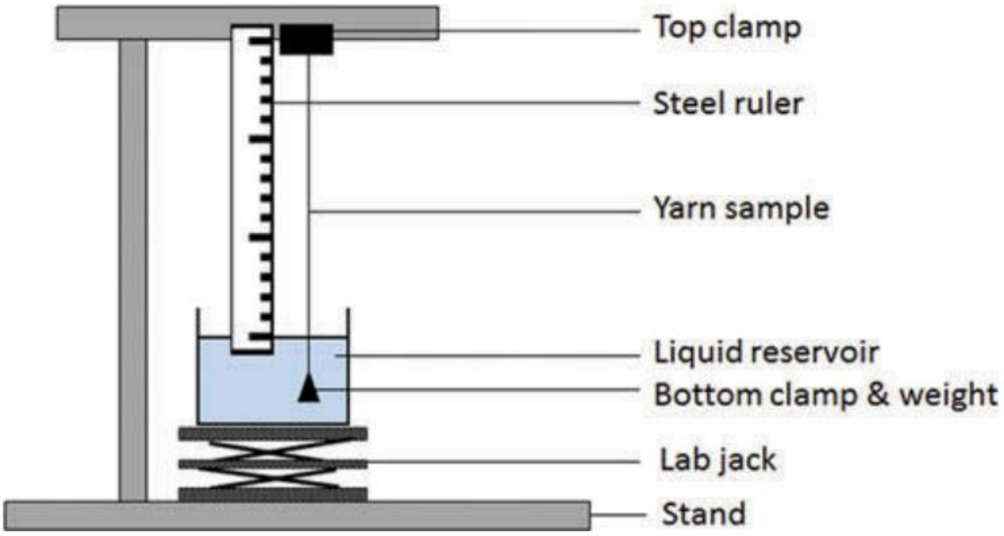


Figure 2.9 Equipment for the Byreck method [9]

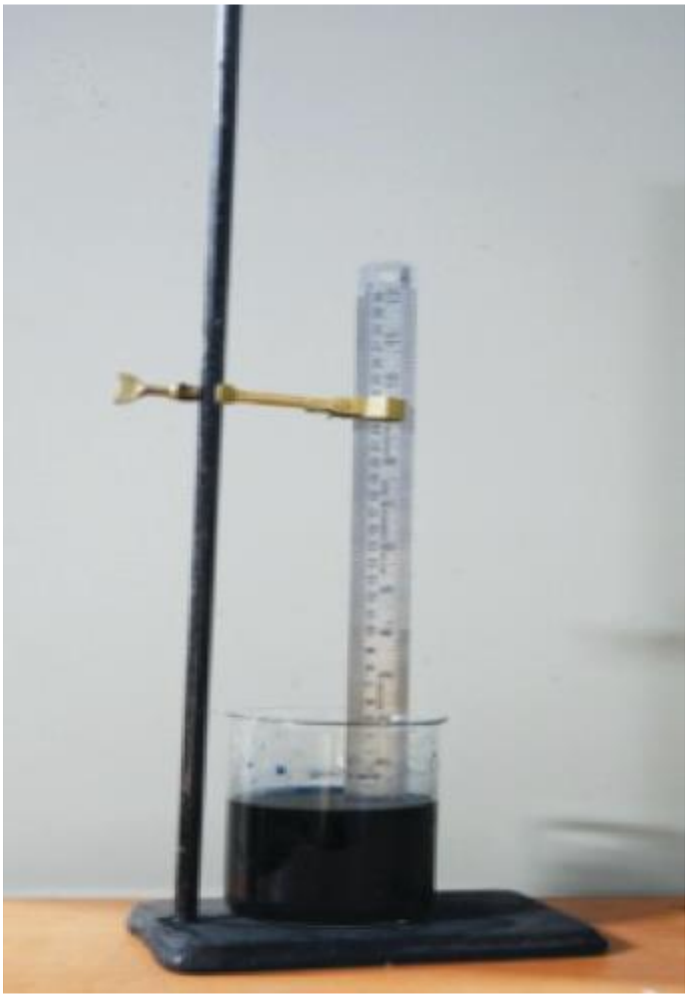


Figure 2.10 Equipment for the Byreck method [10]

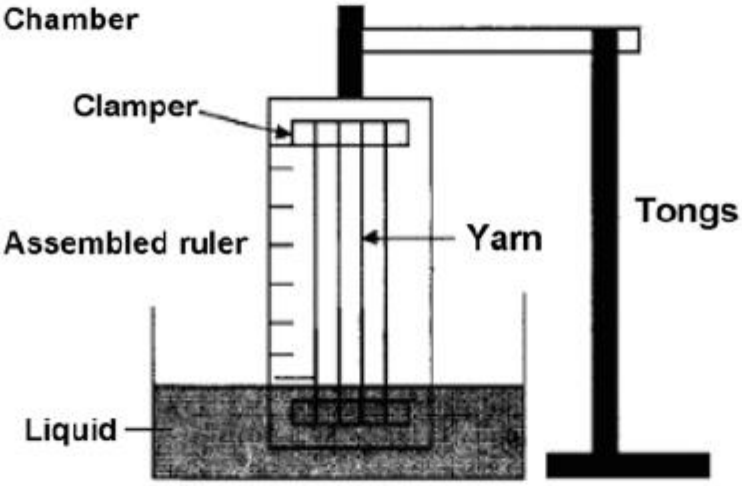


Figure 2.11 Equipment for the Byreck method [11]

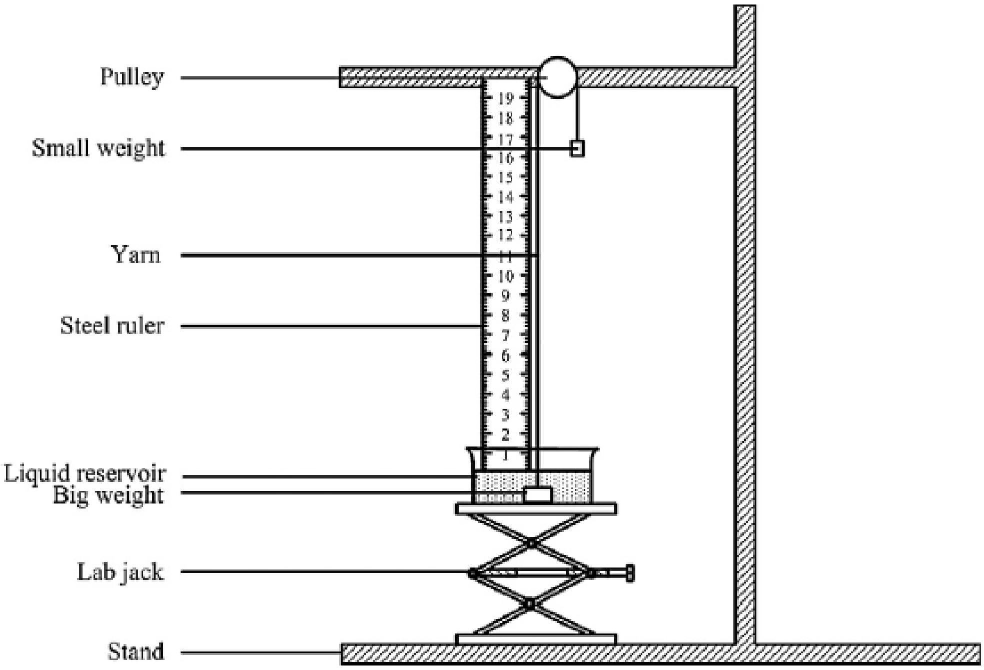


Figure 2.12 Equipment for the Byreck method [12]

2.2.4 The sweat gland simulation method

A new method was employed in designing yarn and evaluating the water absorption properties of intersecting yarns. This method involves using a needle to simulate the rate at which sweat glands perspire and transport water onto individual yarns of the fabric. This approach simulates the distribution and perspiration speed of sweat on fabrics when the body is in motion or perspiring.

Typically, the water absorption performance of fabrics is crucial for sportswear, outdoor gear, and everyday wear. To better understand the fabric's water absorption under different conditions, researchers used this simulated method to assess the yarn's moisture absorption rate. By using a needle to control the input speed of moisture, different levels of human perspiration during activities can be simulated, providing a more accurate evaluation of the fabric's performance.

The advantage of this method lies in its ability to provide quantitative data for designing various types of yarns and fabrics. It assists manufacturers in selecting suitable materials and processes, ensuring the final product meets the required standards for water absorption. Additionally, it offers a more precise and reliable testing method in the field of textile research, promoting the development of new materials and technologies.

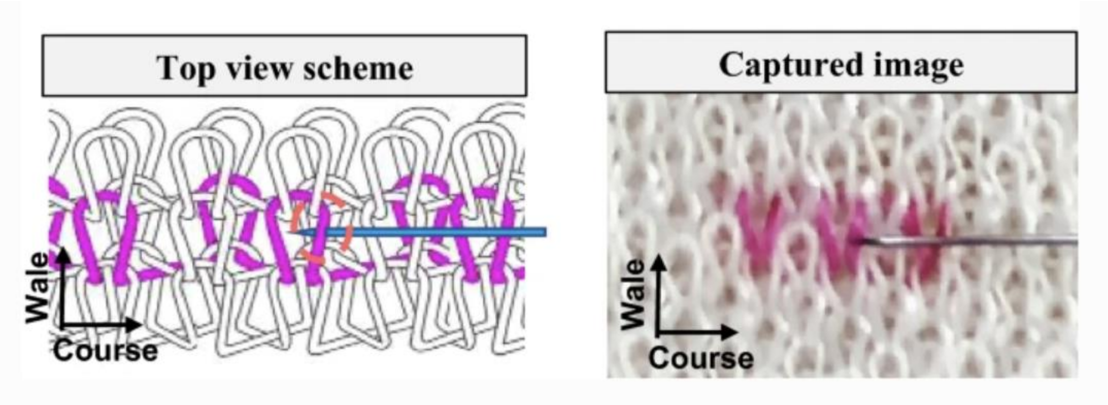
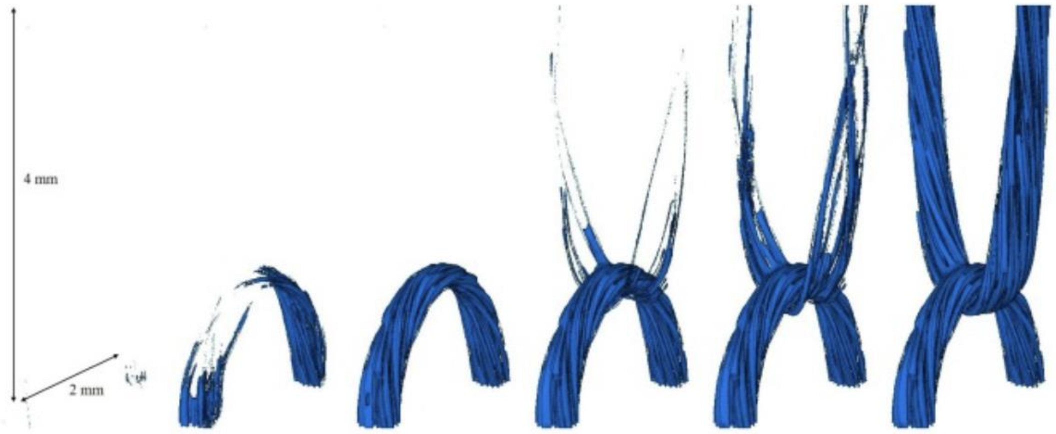


Figure 2.13 Equipment for the sweat simulation [13]

2.2.5 Time-resolved synchrotron tomographic microscopy method

R. Fischer utilized time-resolved synchrotron tomographic microscopy, an advanced experimental technique, to investigate the distribution and evolution of water within interlacing yarns during the wicking process. This technology provides exceptionally high spatial and temporal resolution, enabling researchers to observe and document the propagation and distribution of moisture within the yarn.

In this study, Fischer focused on the changes in moisture configuration, specifically within the interlaced structure of the yarn, as it absorbed water. The research offers valuable insights into yarn's water absorption properties, fabric structure, and absorption rates. By observing the evolution of moisture within different yarn structures, researchers can gain a better understanding of fabric behavior during the wicking process. This knowledge holds significant importance for the textile manufacturing industry and material research and development. The application of this technology has also propelled advancements in the field of textile science, fostering high-quality research and innovation.



(a) 20.4 s (b) 24.4 s (c) 40.4 s (d) 64.8 s (e) 75.6 s (f) 144.4 s

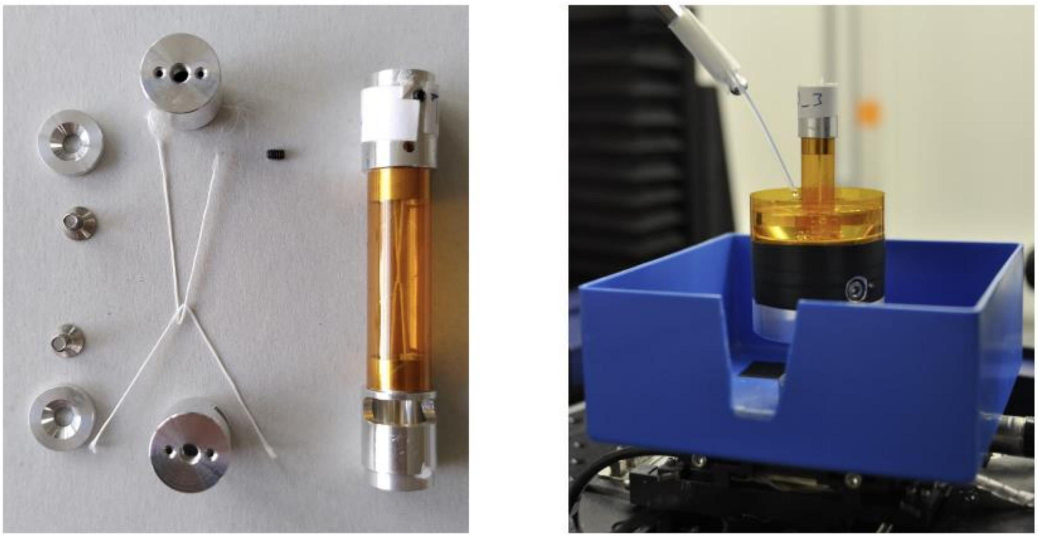


Figure 2.14 Equipment for the simulation of interlaced yarn [14]

Reference

1. M. Yanılmaz and F. Kalaoğlu, Textile Research Journal, 82, 820 (2012).

2. M. Parada, P. Vontobel, R. M. Rossi, D. Derome, and J. Carmeliet, Transport in Porous Media, 119, 611 (2017).

3. B. Das, A. Das, V. K. Kothari, R. Fangueiro, and M. d. Araújo, Journal of the Textile Institute, 100, 588 (2009).

4. D. Raja, G. Ramakrishnan, V. R. Babu, M. Senthilkumar, and M. B. Sampath, Journal of Industrial Textiles, 43, 366 (2012).

5. S. Chinnadurai, D. Raja, S. Priyalatha, S. S. Suresh, and C. Prakash, Journal of Natural Fibers, 19, 3837 (2020).

6. N. Ansari, The Journal of The Textile Institute, 91, 1 (2000).

7. X. Chen, K. G. Kornev, Y. K. Kamath, and A. V. Neimark, Textile research journal, 71, 862 (2001).

8. A. B. Nyoni and D. Brook, Journal of the Textile Institute, 97, 119 (2006).

9. Q. Li, J. J. Wang, and C. J. Hurren, Journal of Natural Fibers, 14, 400 (2016).

10. P. Mallick and S. S. De, Journal of Natural Fibers, 19, 5297 (2021).

11. N. Wang, A. Zha, and J. Wang, Fibers and Polymers, 9, 97 (2008).

12. T. Liu, K. F. Choi, and Y. Li, J Colloid Interface Sci, 318, 134 (2008).

13. H.-s. Kim, S. Michielsen, and E. DenHartog, Journal of Materials Science, 55, 7816 (2020).

14. R. Fischer, C. M. Schleputz, R. M. Rossi, D. Derome, and J. Carmeliet, J Colloid Interface Sci, 626, 416 (2022).

Chapter 3

Discuss the effect of void area and cocoons area of silk yarn on wicking

Chapter 3 Discuss the effect of void area and cocoons area of silk yarn on wicking

3.1 Introduction

Wetting and wicking is ubiquitous phenomenon in nature and industry. In nature, botanists believe that transpiration (the movement of moisture from roots to xylem capillaries to leaves) occurs through a passive wicking mechanism. In industry, the yarn structure can drastically change the wicking properties of fabric [1] and influence comfort [2].

Many studies on water transport in the textile are available [3]. Further, many researchers have studied the water absorption status of fabrics and then compared the yarn properties of fabrics to infer the effect of fibers on water absorption. Das (2013) [4], for example, studied the interaction effects of variables (i.e., linear densities, the proportion of shrinkable acrylic fiber, and twist levels) on the moisture vapor transmission rate of fabrics. Ruksana et al. [5] [6] [7] [8] explored cotton fabric's wicking behavior and the swell ratios of cotton yarn and fiber. Researchers have also directly explored the characteristics of fibers and water absorption of single yarn. Rader et al. [9] studied the effects of viscosity and surface tension of the liquid, contact angle relationships, air permeability, wettability, and geometry of yarn and yarn-liquid system. Sengupta (1985) et al. [10] [11] [12] also compared the wicking ability between the open-end spun yarn and ring-spun yarn with varying twist levels. Twisted filament yarn shows a lower wicking rate than a yarn without a twist. Almoughni et al. [13] [14] [15] [16] used mathematical models and simulation software to simulate liquid water flow through yarns. Besides, Kamath et al. [17] [18] studied water absorption in the horizontal direction.

Three types of methods are used in studying wicking property. The first [11] [17] uses weight variation measurement by a Wilhelmy balance during capillary wicking. The second [8] [11] [9] sets liquid-sensitive sensors along with the yarns. The last one [8] [19] [20] [21] uses a camera to observe and measure the capillary flow of a colored liquid. These methods were used to measure water transport on fiber, yarn, and fabric in one direction.

Until now, to our best knowledge, no equipment can measure water absorption in the warp and weft way at the same time. However, the wicking phenomena of interlaced points is the crucial point for the study of the wicking for yarn. Researchers focused on the relationship between fiber and yarn or yarn and fabric in all of these studies. As previously discussed, the fabric is constructed with interlaced yarn. In this study, we choose silk yarn.

However, obtaining the water absorption or function of the final material, such as fabric, generally needs to be determined after the fabric is made. Fabric manufacturer requires human resources and material resources, which does not meet SDGs standards. Computer technology is relatively advanced. In the future, it will be valuable to predict the water transport performance of the final fabric with the help of CAD instead of measurement after manufacturing. Woven fabric is a network which is structured by warp and weft yarn. The fabric weave parameters, such as yarn parameters, weave density, weave diagram, determine the network. Water transport in fabric occurs on yarns, both interlaced and non-interlaced. For the non-interlaced, the water transport property is determined by the yarn properties. For the interlaced, the water transport is influenced by the yarn character and weave parameters. In order to explore the water transport mechanism in fabric, it is necessary to focus on the network, especially on the interlacing points. In our previous study [20], the experimental equipment for measuring interlaced yarn was settled, discussing the effect of twist and interlaced angles on the water transport of interlaced cotton yarn. Silk is one of the most widely and popularly used fibers because of its favorable characteristics, dimensional stability, and regular inter-channel for moisture transportation. In order to investigate the wicking performance of interlacing silk yarn for further prediction, this study explored the effect, e.g., fiber numbers, void area, etc., of water transport on silk yarn. Moreover, the wicking performance was evaluated for the interlaced yarns, and the relationship between the single silk and interlaced silk yarn was discussed.

3.2 Experimental details

3.2.1 Test apparatus

Figure 1 shows the apparatus in our experiment [20], including single yarn in the vertical direction and interlaced yarns measurements. The single yarn measurement was to evaluate the vertical wicking length, referring to the Byreck method of JIS L1096, while interlaced yarn measurements were used to investigate the cross conditions of yarn in vertical and horizontal directions, such as in woven fabric. The two conditions are recorded as a single and interlaced yarn during this study. The wicking length of the single yarn is defined as **S**, the wicking length of the interlaced vertical yarn in the warp direction is described as **WP**, the interlace horizontal yarn in the weft direction is defined as **WT**.

For the single yarn measurement, the water surface was set to be 5 mm below the measure origin. F1 was the pretension of warp yarn obtained based on JIS L 1095 [22] testing methods for spun yarns. According to JIS L 1095, pretension for different fineness of yarns is different, as shown in Table 1. When water moves to the measure origin, the wicking phenomenon was pictured. We took one shot every 10 seconds. The whole wicking procedure contains 600 s.

Table3. 1. Pretention of each samples in warp and weft directions

	A	B	C	D	E	F
F1(g)	2.4	4.7	7.03	8.78	10.53	14
F2(g)	0.14	0.14	0.16	0.18	0.18	0.2

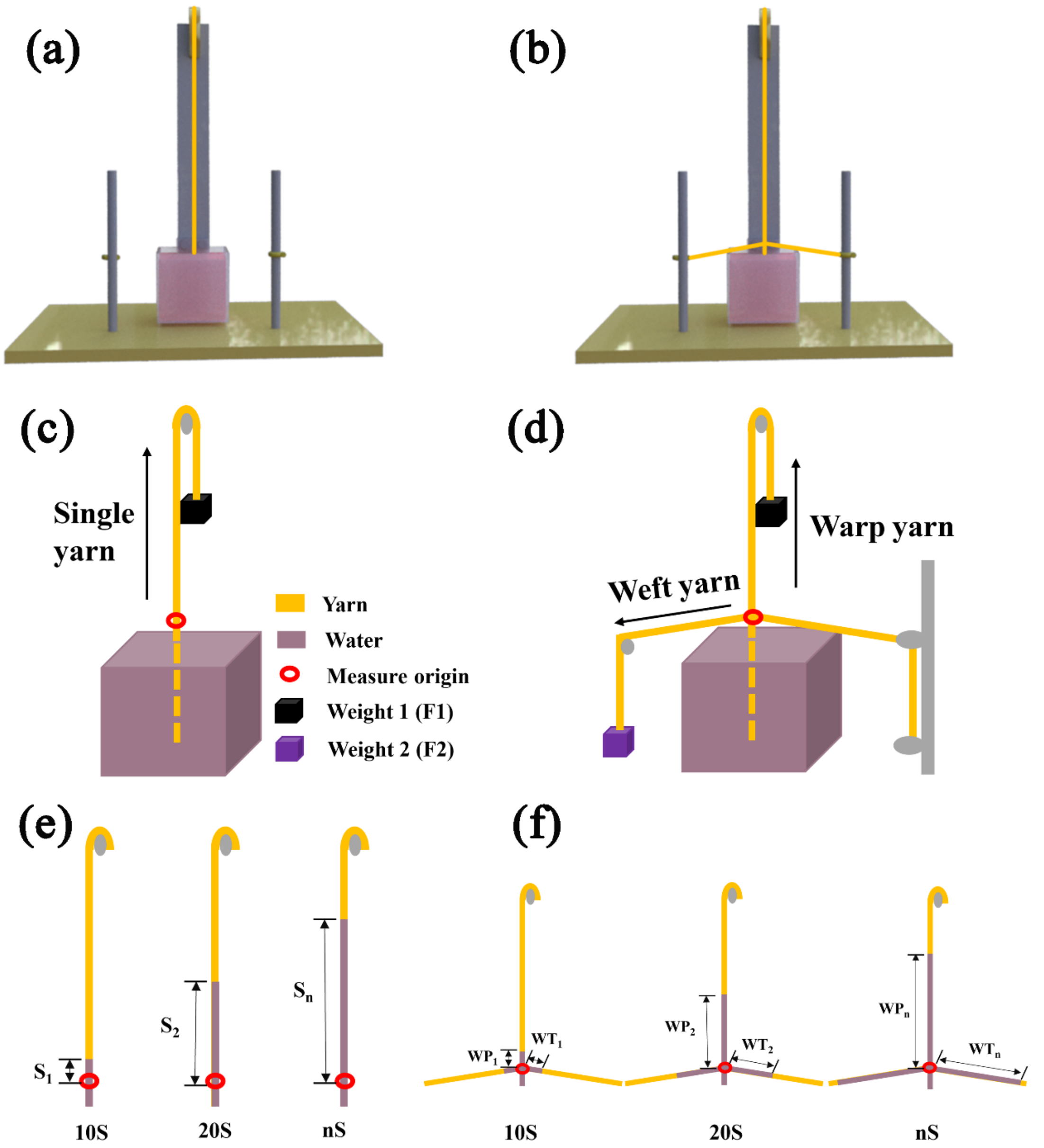


Figure 3.1. Details of the apparatus: (a) 3D front view of the equipment for single yarn; (b) 3D front view of the equipment for interlaced yarn; (c) 2D device display diagram for single yarn; (d) 2D device display diagram for interlaced yarn; (e) the wicking length of single yarn; (f) the wicking length of interlaced yarn.

For the interlaced yarns measurement, when the warp and weft yarn was interlaced, the interlacing angle was set as 120°, which is near the actual interweaving situation of woven fabrics. As is shown in Figure 1(d), the weft wrapped the warp yarn, and the weft yarn form the interlacing angle. The same tension (F1) is added onto the **WP**, which is the same as pointed in the single yarn measurement. Meanwhile, **WT** was set in the horizontal direction to wind around **WP**, with a wind angle (defined as interlacing angle) of 120^o. Tension F2 (Table 1) was added to the **WT**, which was the minimum that sets weft yarn wrapped around the weft yarn and keeps the warp yarn straight. Photography was taken when water moves to the exact measure origin. All experiments were conducted on 23 ± 2 ^{o}C, 50 ± 5 % RH.

3.2.2 Test samples

Six different deniers of degummed silk yarns were purchased and used without further treatment. The samples are defined as **A**, **B**, **C**, **D**, **E**, and **F**. Yarn parameters, such as diameter, twist, and twist angle were measured (detailed information is shown in Table 2). Each sample was used for single and interlaced yarn measurement.

Table 3.2. Specification of Silk Yarn

Yarn Samples	Denier	Diameter (μm)	Twist (Turns/m)	Twist Angle (º)
A	84	150	180	10.4
B	168	526	230	13.3
C	252	308	200	17.1
D	315	469	150	12.6
E	378	639	150	15.0
F	504	547	90	14.9

3.3 Results and discussion

3.3.1 Effect of wicking length of single yarn

The total water transport distance after 10 min is summarized in Figure 2, which shows that wicking length increases with time. The wicking curves are similar for all the samples here. At the initial stage the wicking length increases dramatically. After that, the wicking continued with decreased wicking speed, and finally, the wicking tended to be saturated. In this experiment, sample **A** has the lowest water absorption height, followed by **B**, **C**, **D**, and **E**. Sample **F** has the highest water absorption height. Sample **A** reached the water-absorption saturation state first, at about 120 s, sample **F** reached the water-absorption saturation state at about 420 s.

Researchers use different techniques to analyze liquid flow. Here, we analyzed the effect of material and liquid properties on the wicking phenomenon. The wicking process has also been described by structural information such as porosity, size, pore distribution, etc. Many researchers use an equation to describe the water transport in fabric, such as the Lucas–Washburn equation[3], as shown below:

$$L = \sqrt{\frac{R * \gamma * cos\,\theta}{2 * \eta} * t^{0.5}}\ . \qquad (1)$$

According to Eq. (1), we can see that, for the same material silk, the main influencing factors of the water absorption height (L) are decided by the radius of the pore (R), along with other factors, including surface tension of the liquid (γ), contact angle (θ), and viscosity of a liquid (η), which remain unchanged. Thus, we need to analyze which factors of silk yarn can affect the actual effective water absorption radius. The radius r in the formula is not the actual radius of the silk yarn. The radius described by the formula(1) refers to the cylindrical capillary effect radius, but for the yarn, the yarn is not a cylinder, and the capillary radius (R) of the yarn should be the approximate radius of the void between the fibers in the yarn.

According to Figure 3, the cross section of the silk yarn (sample **B**) is composed of silk fibers and the distributed irregularly void in the yarn. The void can absorb the water, as demonstrated by the capillary effect. After degumming, silk fibers are hydrophilic and can absorb water. In this study, the water absorption is conducted by the hydrophilic silk fibers and capillary phenomenon caused by the void between fibers. However, after adding the twist and tension, the void area will be changed. The area of the void is decided by the tension, twist, and fiber number of the silk yarn. Figure 4(a) shows the relationship between fiber area and wicking length. Herein, with the increase of fiber area, the wicking length was found to be increased. The correlation coefficient is 0.96, shown a high correlation. The relationship between void area and wicking length is shown in Figure 4(b). Increasing the void area can increase the wicking length linearly.

On the other hand, the void area was also influenced by the yarn structure, such as the yarn twist in this study. According to the results of correlation analysis, the void area had a low negative correlation to the twist. For a comparatively weak twist, the higher one of yarn increased the transport route. As a result, the appeared wicking length was lower. Further, the twist angle demonstrated a weak relationship with the wicking height. In this experiment, twist angle and wicking length also demonstrated a weak relationship. The correlation coefficient between the wicking height and the diameter is very low, and the diameter is the 2D performance of the cross area. We can use the void and fiber areas to replace the diameter as an index. It can be concluded that the wicking performance on single silk yarn was affected by the fiber area and void area, which was summarized as silk yarn fineness.

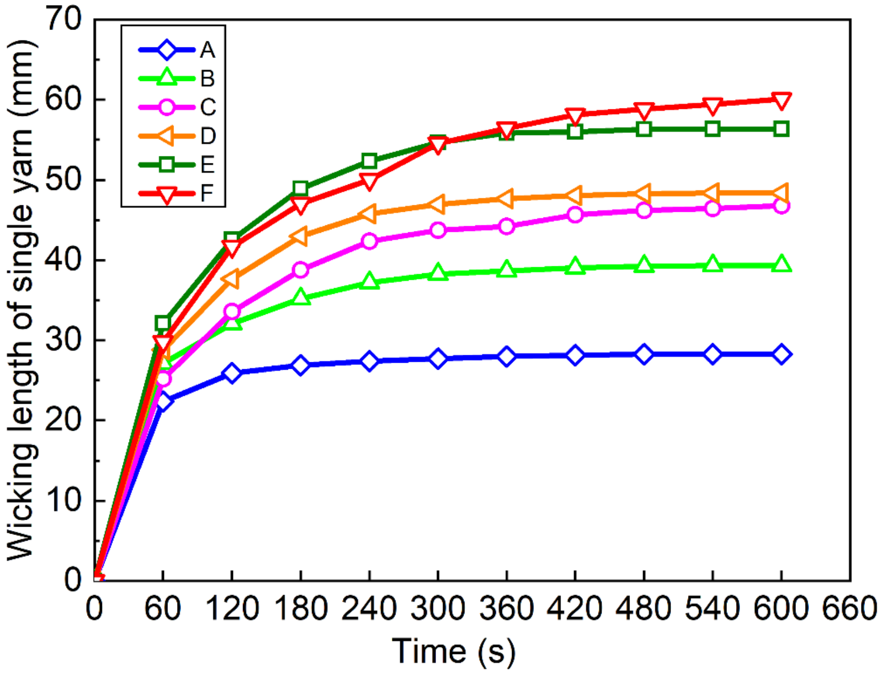


Figure 3.2. Wicking length of single yarn (from 0~600s).

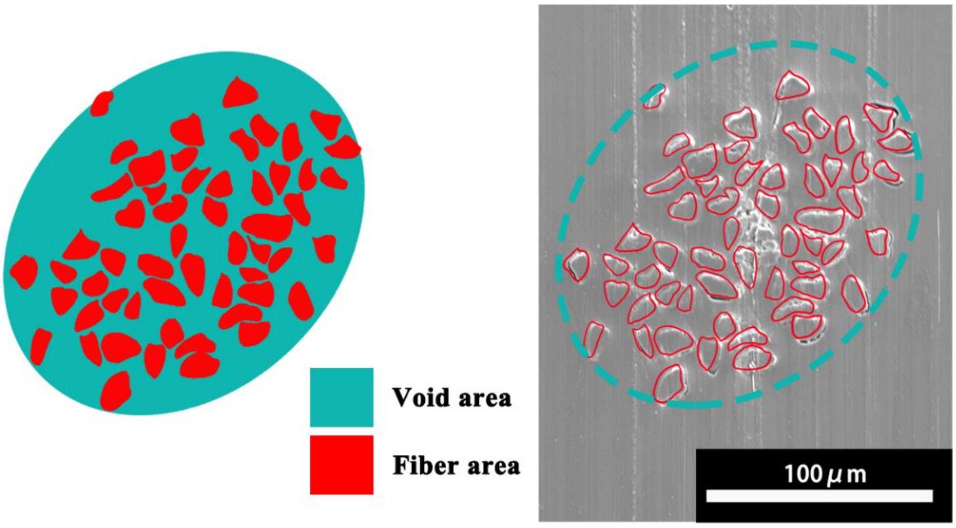


Figure3. 3. Cross area of silk yarn (sample **B**): (a) illustration for the silk yarn; (b) SEM image for silk yarn.

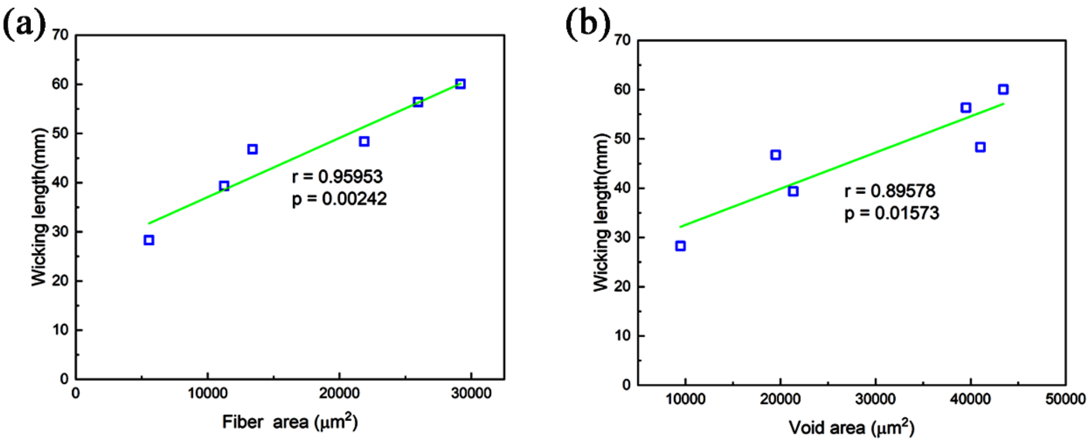


Figure3.4. Relationship analyze: (a) correlation between fiber area and wicking length; (b) correlation between void space and wicking length. (r: a correlation coefficient from -1 to 1; p is the probability between 0 and 1).

3.3.2 Wicking length of interlaced silk yarns

When the two yarns are crossed, it will affect the water absorption compared with the original single fiber. In this study, we only discuss the cross of silk yarns on different parameters. The above six different silk yarns were used to investigate the influence of interlacing on water transport between yarns.

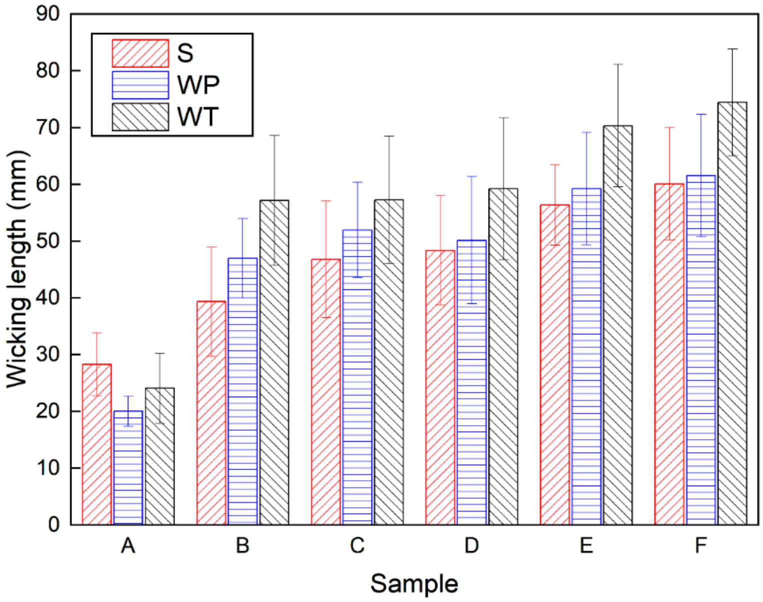


Figure 3.5. Wicking length of silk yarn (at 10 min, **S** is the wicking length of single yarn, **WP** is the wicking length of warp yarn, **WT** is the wicking length of weft yarn).

The total water transport distance after 10 min is summarized in Figure3.5. A significant difference between different samples can be found. As claimed in the above paragraph, to the single yarn, the wicking length of samples **F** was larger than in samples **E**, **D**, **C**, **B**, and **A**. Similar to the single yarn, results of the interlaced yarns show the trend that increases the yarn fineness can increase the wicking length of interlaced yarns, in both vertical and horizontal directions. It is interesting to note that **WT** is higher than **WP**, for the reason of the gravitational force, which hinders the moving speed and length of the liquid in the warp direction.

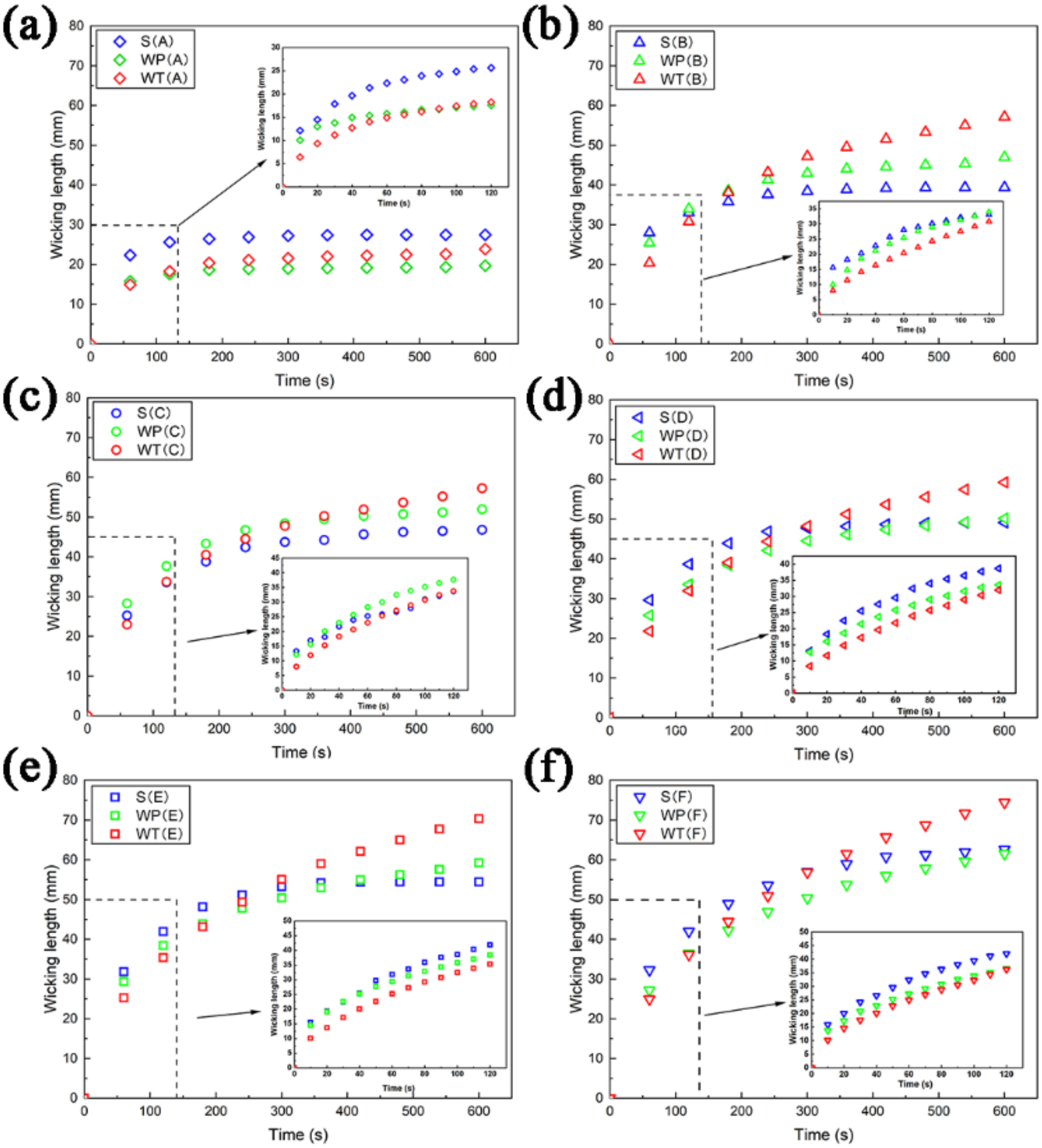


Figure3. 6. Wicking length of single yarn during 600 s: (a) water transport for sample **A**; (b) water transport for sample **B**; (c) water transport for sample **C**; (d) water transport for sample **D**; (e) water transport for sample **E**; (f) Water transport for sample **F**. Inset shows the detail at the first 120 s.

Results of water transport distance versus time of samples **A**, **B**, **C**, **D**, **E**, and **F** are shown in Figure 3.6, respectively. The results also show that, regardless of interlacing, the distance of water transport increases in the process of time. Generally, in the initial stage of all samples, the water transport speed is relatively high. As time increases, the speed gradually decreases until the yarn is saturated with water and stops absorbing water. This is because, at first, the upward capillary force is more significant than the downward gravity of the liquid. As the liquid rises, the gravity gradually increases, and the speed slows. When the gravity and capillary force reach a balance, the wicking ends.

In addition, for the same yarn, as shown in the inset, the initial speed of single yarn water transport is the highest, followed by the warp and weft directions. This is because, in the interlaced state, the water of the warp direction silk yarn will transport to the weft direction of silk yarn. The initial moving speed **WP** is less than **S**. In addition, it takes a specific time for the moisture to move from the silk yarn in the warp direction to the silk yarn in the weft direction, so the initial speed of **WT** is smaller than **WP**.

Figure 3.7 summarizes the speed of the six samples, including single yarn, **WP**, and **WT**. No matter for **S**, **WP**, or **WT**, the initial speed of sample **A** is the lowest. This means that the initial speed of interlaced yarns is affected by the single yarn performance.

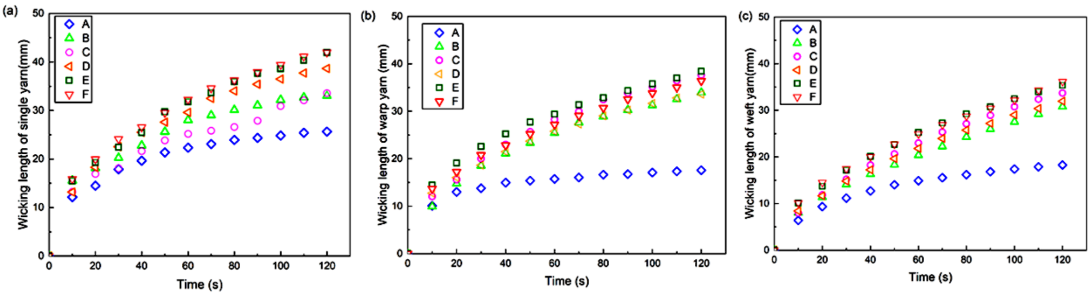


Figure 3.7. Wicking length of six samples at the first 120 s: (a) Initial water transport for all the samples in single yarn; (b) initial water transport for all the samples in the warp direction; (c) initial water transport for all the sample in the weft direction.

The relationship among **S**, **WT**, and **WP** is shown in Figure 3.8. Figure 3.8(a) shows that, at 600 s, **S** and **WP** show the dominant positive correlation and correlation coefficient up to 0.93804 and the correlation coefficient of the **S** and **WT** shows the same trend. Figure 3.8(b) shows the relationship between **S** and **WP** at every 10 sec. The correlation coefficient between them is 0.94, and the **S** and **WT** also are as high as 0.94. This result shows it is reasonable to use the wicking height of single yarn to predict that of the interlaced yarn, which can make it possible to predict the wicking height of fabrics, including woven and knit fabrics, via measurement of single yarn.

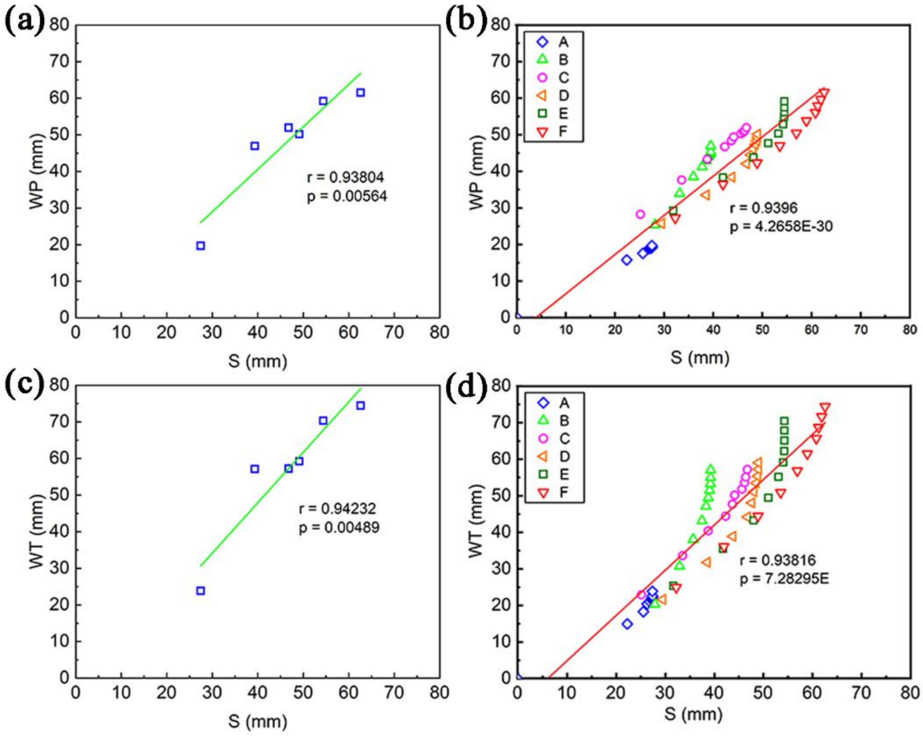


Figure 3.8. Correlation analysis: (a) relationship of wicking length of 10 min between the single yarn and warp direction; (b) relationship between wicking length of the whole procedure of single yarn and warp direction; (c) relationship of wicking length of 10 min between the single yarn and weft direction; (d) relationship between wicking length of wicking length of the whole procedure of single yarn and weft direction. (r: a correlation coefficient from -1 to 1; p is the probability between 0 and 1)

3.4 Conclusion

The purpose of this study is to investigate the relationship between single silk yarn and interlaced yarns to create fundamental preparation for establishing a network wicking model in the future. Six kinds of silk yarn with different fineness were studied on the wicking property, clarifying the effect of fiber area and void area on the wicking length. Moreover, we investigated the effect of interlacing on water transport.

The results show that the void and fiber areas of the silk yarn are important factors in influencing the wicking length of single yarn. The wicking length of the silk yarn shows the same trend with the increase of void and filament areas. Further, the effect of the interlacing condition of the silk yarns was discussed. To the interlaced situation, the initial speed of single yarn water transport is the highest, followed by the warp direction and the weft direction. Furthermore, the wicking length of **S** shows a high relationship with **WP** and **WT**, which can be used to predict the wicking length of interlaced yarns based on that of the single yarn.

This is a preliminary study for investigating the mechanism of water transport in textile. Now that computer technology is relatively advanced, we can try to predict the final fabric by simulating the water absorption properties of the network composed by yarn in CAD.

Reference

1. Das B, Das A, Kothari VK, et al. MOISTURE TRANSMISSION THROUGH TEXTILES. *AUTEX Research Journal* 2007; 7: 23.
2. Patnaik A, Rengasamy RS, Kothari VK, et al. Wetting and wicking in fibrous materials. *Textile Progress* 2006; 38: 1–105.
3. Zhu C, Takatera M. Effects of hydrophobic yarns on liquid migration in woven fabrics. *Textile Research Journal* 2015; 85: 479–486.
4. Das A, Yadaw SS. Study on moisture vapor transmission characteristics of woven fabrics from cotton-acrylic bulked yarns. *Journal of the Textile Institute* 2013; 104: 322–329.
5. Baby R, Michielsen S, Wu J. Effects of yarn size and blood drop size on wicking and bloodstains in textiles. *Journal of Forensic Sciences*. Epub ahead of print 2021. DOI: 10.1111/1556-4029.14702.
6. Benltoufa S, Fayala F, Nasrallah S Ben. Determination of yarn and fiber diameters after swelling using a capillary rise method. *Journal of the Textile Institute* 2012; 103: 517–522.
7. Mhetre S, Parachuru R. The effect of fabric structure and yarn-to-yarn liquid migration on liquid transport in fabrics. *Journal of the Textile Institute* 2010; 101: 621–626.
8. Öztürk MK, Nergis B, Candan C. A study of wicking properties of cotton-acrylic yarns and knitted fabrics. *Textile Research Journal* 2011; 81: 324–328.
9. Rader CA, Schwartz AM. The Migration of Liquids in Textile Assemblies. *Textile Research Journal* 1962; 32: 140–153.
10. Sengupta AK, Sreenivasa Murthy H V. Wicking in Ring-Spun Vis-a-Vis Rotor-Spun Yarns. *Indian Journal of Textile Research* 1985; 10: 155–157.
11. Ansari N, Kish MH. The wicking of water in yarn as measured by an electrical resistance technique. *Journal of the Textile Institute* 2000; 91: 410–419.
12. Taylor P, Nyoni AB, Brook D, et al. Wicking mechanisms in yarns — the key to fabric wicking performance Wicking mechanisms in yarns – the key to fabric wicking performance. 2010; 37–41.
13. Almoughni H, Gong H. Capillary flow of liquid water through yarns: A theoretical model. *Textile Research Journal* 2015; 85: 722–732.

14. Datta Roy M, Chattopadhyay R, Sinha SK. Wicking Performance of Profiled Fibre Part A: Assessment of Yarn. *Journal of The Institution of Engineers (India): Series E* 2017; 98: 155–163.

15. Charpentier JB, Brändle de Motta JC, Ménard T. Capillary phenomena in assemblies of parallel cylindrical fibers: From statics to dynamics. *International Journal of Multiphase Flow* 2020; 129: 103304.

16. Mao N, Ye J, Quan Z, et al. Tree-like structure driven water transfer in 1D fiber assemblies for Functional Moisture-Wicking Fabrics. *Materials and Design* 2020; 186: 108305.

17. Kamath YK, Hornby SB, Weigmann HD, et al. Wicking of Spin Finishes and Related Liquids into Continuous Filament Yarns. *Textile Research Journal* 1994; 64: 33–40.

18. Patnaik A, Rengasamy RS, Kothari VK, et al. Wetting and Wicking in Fibrous Materials. *Textile Progress* 2006; 38: 1–105.

19. Ravandi SAH, Dabirian F, Sanatgar RH. Capillary rise investigation of core-spun nanofiber yarn. *Industria Textila* 2011; 62: 59–63.

20. Zhu C, Tada H, Shi J, et al. Water transport on interlaced yarns. *Textile Research Journal* 2019; 89: 5198–5208.

21. Li Q, Wang JJ, Hurren CJ. A Study on Wicking in Natural Staple Yarns. *Journal of Natural Fibers* 2017; 14: 400–409.

22. JIS L 1095, JIS handbook: Testing methods for spun yarn[J]., Japanese Standards Association, Tokyo(2010).

Chapter 4

Discuss the effect twist and thickness of silk yarn on wicking

Chapter 4 Discuss the effect twist and thickness of silk yarn on wicking

4.1 Introduction

With the improvement in the quality of life, people pay more attention to the various properties of clothing materials when choosing clothes. For example, the elasticity[24], strength, breathability[2], softness, moisture retention, and moisture[25] absorption of the materials for pursuing a higher quality of life. During these properties, suitable moisture absorption performance of cloth fabric can make people feel more comfortable when wearing, due to the timely adsorption of sweat from the body, and regulate body temperature. In research related to moisture absorption of materials[26], this property is mainly expressed as the spontaneous flow of liquid in the yarn or fabric, and this surface infiltration phenomenon caused by the surface tension[27] of the liquid is also called wicking.

The water absorption of fabric consists mainly of the absorption of water from fibers, yarns[28-30], and fabrics[11, 31]. In experiments exploring the wicking of fabric studies usually focus on characterizing the wicking properties of fabric in terms of the water content of the fabric, the wicking height of the fabric (vertical water absorption)[32], or the wicking length of the fabric (horizontal water absorption)[33]. There are three main experimental methods, the first one[34] is to use electronic scales to obtain the change in mass of the fabric or the water bath. The second one[20, 35] is to obtain the state of water movement in the fabric by video or photo. The third one [11, 36] is to use the sensor to monitor the wicking of the fabric. Besides, in studying the water absorption properties of fabrics, some researchers also investigate the different water absorption properties of fabrics on the front and back sides. Some researchers [36] also investigate the water absorption properties of fabrics with different fabric structures by studying the water absorption properties between yarns on the fabric.

A bundle of fibers is twisted into the yarn, and the yarns are woven or knitted in different combinations to form the fabric. Yarn water absorption testing can be divided into two main categories, finite drip and infinite sinks[17]. The finite drip is where a fixed-size droplet of water is dropped on the yarn to see how the droplet moves or wraps on the yarn. An infinite sink is where one end of the yarn is fixed and the other end is placed in the sink, and the water absorption of the yarn is obtained by observing the height of the water movement on the yarn or by characterizing the resistance of the yarn. With the development of technology, some researchers use Fast X-ray tomographic microscopy instead of cameras to observe and record the wicking process of yarns. In addition to the study of yarn water absorption, some researchers also investigate the effect of yarn structure and other factors on yarn water absorption. A.B. Nyoni[37] studied the effect of twist and applied tension on the wicking of nylon, and proposed the unsaturated, saturated, and dry zones of yarn absorption. Robert Fischer[21] used X-ray tomographic microscopy to study core suction flow in interwoven yarn contact with similar properties to knitting stitches. In the same year, Robert Fischer[17] also revealed the specific pore space and pore network structure of yarns.

With the development of artificial intelligence and advances in areas such as information technology intelligence, emerging concepts such as Virtual fashion[38] have attracted widespread attention. When selecting clothes virtually, people not only pay attention to the style and other aspects but also pay great attention to the comfort of clothing, especially sweat absorption and other properties. Sweat absorption[39] mainly includes the absorption of liquid sweat, etc., and this involves the sweat absorption mechanism of fabrics, which are composed of yarns. However, the prediction of sweat (water) absorption of yarns is still subject to some limitations, researchers have mainly focused on the study of water absorption of nylon[17], cotton[20], polyester [40], etc. There are still some issues that need to be further discussed in the study of water absorption of natural filament silk yarns. Therefore, this study aims to investigate the water absorption properties of silk yarns. Before this, we explored the effect of cotton twist[41] on the water migration of interlaced yarns, as well as the effect of different interlacing angles on the transport distance of weft yarns. Following this, the absorption behavior of silk yarns in both vertical and horizontal directions was explored[42]. It was found that the absorption behavior of silk yarns was found to increase in the first initial stage and decreased with time until the yarns were saturated. The length of wicking in the vertical direction suggests that the fiber and void regions in the silk yarn have an important influence on water transport. In addition, the wicking relationship between single and interlaced yarns was discussed. However, further discussion on the effect of silk yarn parameters on water absorption is needed. Therefore, more silk yarns were added to this article, mainly focusing on the effects of twist and thickness on water absorption. Through these studies, it is hoped that more innovations and improvements can be brought about for future virtual garment design and actual wear.

4.2 Experimental details

4.2.1 Test apparatus

Based on the JIS L1096, the single yarn apparatus was to evaluate the vertical wicking length of the silk yarn. Fig. 1 shows the equipment in our experiment, including the apparatus of the silk yarn in the vertical direction. The apparatus was placed on a tabletop, water was poured into a square transparent container (6×6×6 cm), and the capillary phenomena of the silk yarn were recorded with a camera. We set the surface of the water (6 cm above the ground of the container) as the starting point of the recording (measure origin), and the total duration lasted 10 minutes.

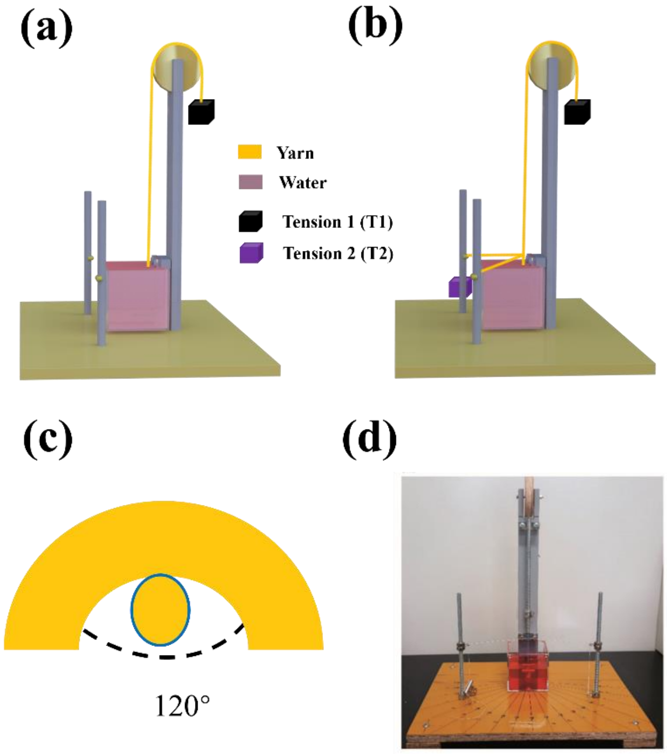


Figure 4.1 (a) Device of single yarn; (b) Device of interlaced yarn; (c) Interlaced point enlargement; (d) Actual picture of the device.

For the single yarn measurement, the water surface was set to be the measured origin. T1 was the pretension of warp yarn obtained based on JIS L 1095 testing methods for spun yarns.

According to JIS L 1095, the pretension for the different fineness of yarns is different, as shown in Table 1. When water moves to the measured origin, the wicking phenomenon is captured by the video camera. All experiments were conducted at 23±2°C, 50±5% RH.

For the interlaced yarn measurement, as shown in Figure 4.1(b), the weft yarn (WT) set in the horizontal direction, wrapped the warp yarn (WP) in the vertical direction. The angle formed by the WP at the WT (defined as the interlacing angle) is 120°, near the interweaving situation of woven fabrics. By the way the interlaced point is 5mm above the water surface. The same tension (T1) is added onto the WP, which is the same as in the single yarn measurement. Meanwhile, Tension 2 (T2) was added onto the WT which is minimum to keep the warp yarn straight. Videos were taken when the water moved to the exact measure origin. All experiments were conducted at 23±2°C, 50±5% RH.

4.2.2 Test samples

Thirteen different kinds of degummed silk yarns were used in this experiment. The yarn parameters, such as denier, twist are shown in Table4.1. Each sample was purchased and used without further treatment. In order to express the comparison and illustration easily, we use Yaaa/bbb to name the sample, aaa means the fineness of the yarn, and bbb means the twist of the yarn.

Table4. 1. The parameters of the silk.

	Sample parameter			Experiment parameter	
	Fineness (Denier)	Yarn composition	Twist(Turns/m)	T1(g)	T2(g)
Y168/230	168	Single twist	230	4.79	0.14
Y168/350	168	Single twist	350	4.79	0.14
Y168/650	168	Ply twist	650	4.79	0.14
Y252/200	252	Single twist	200	7.17	0.16
Y252/350	252	Ply twist	350	7.17	0.16
Y252/650	252	Ply twist	650	7.17	0.16
Y315/150	315	Single twist	150	8.95	0.18
Y378/150	378	Single twist	150	10.74	0.19
Y504/90	504	Single twist	90	14.30	0.20
Y630/90	630	Single twist	90	17.88	0.20
Y336/550	336	Ply twist	550	9.55	0.18
Y420/550	420	Ply twist	550	10.93	0.20
Y504/550	504	Ply twist	550	14.31	0.20

4.3 Characterization of yarn capillary parameters

The distance $h(t)$ of liquid traveled in a given time t in a porous medium can be calculated as[17, 20, 43, 44],

$$h(t) = \frac{a}{b}\left[1 + W\left(-e^{-1-\frac{b^2 t}{a}}\right)\right] \tag{1}$$

$$a = \frac{4\sigma K \cos\theta}{D\phi\mu}$$

$$b = \frac{\rho K g \sin\psi}{\phi\mu}$$

where $W(\cdot)$ is the Lambert function, σ is the surface tension of the liquid, μ is the dynamic viscosity of the liquid, θ is the contact angle, ρ is the density of the liquid, g is the acceleration due to gravity, D is the capillary diameter, ϕ is the porosity of the medium, K is the permeability of the porous medium, and ψ is the angle of porous medium with respect to the horizontal liquid plane.

Further the maximum distance travelled by liquid can be calculated as [20, 45],

$$h_{max} = h_{t\to\infty} = \frac{4\sigma\cos\theta}{D\rho g \sin\psi} \tag{2}$$

It must be noted that parameters K and D are related to the structure assembly of the porous medium. For example, in the case of yarns, the liquid transports through the capillaries formed between the fibers. Hence, the characterization of the capillary formed with the yarn cross-section becomes a critical component to understanding the wicking behavior of the yarns. Thus, the capillary diameter D in Eq.1 represents the hydraulic diameter, which represents the mean capillary diameter formed within the fibers within the yarn body.

4.4 Results and discussion

4.4.1 Results of the single yarn

In order to discuss the effect of yarn fineness on the water-absorbent property of yarn, Fig.4.2(a) shows the water-absorbent heights of several groups of silks with the same number of twists and different fineness after 10 minutes. The result can be divided into 5 groups, each group of yarn has the same twist. According to the figure, when the twist is the same, the yarn with a higher fineness has a higher wicking height. Take samples Y504/90 and Y630/90 as an example, the twist of Y504/90 and Y630/90 are the same and both of them are 90 turns/m, the fineness of Y504/90 yarn is 504 Denier, and the fineness of Y630/90 yarn is 630 Denier, in the case of the same twist, the final wicking height of Y630/90 is higher. Taking samplesY336/550, Y420/550, and Y504/550 as an example, the twist of all three samples is 550 Denier, and the yarn finesses are 336, 420, and 504, Denier, respectively, and the water-absorbing height increases with the fineness of the yarn.

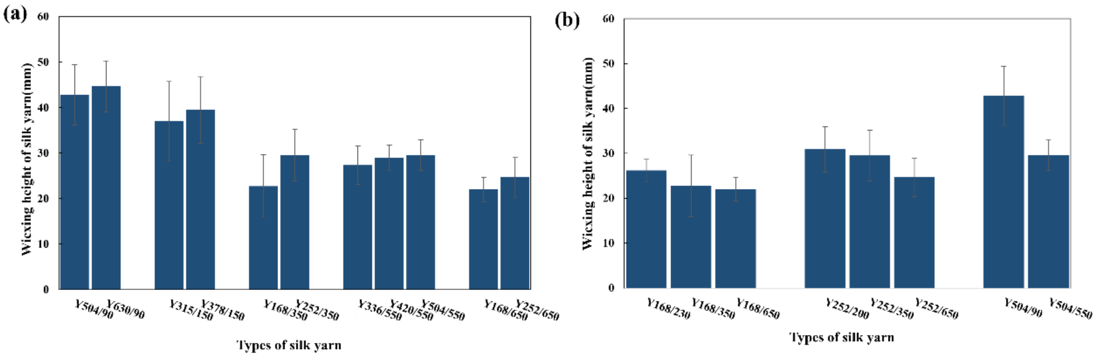


Figure 4. 2. Wicking length in silk yarn samples, groups based on (a) the same twist and arranged with increasing fineness and (b) the same yarn fineness and arranged with increasing twist.

The main reason why the wicking height of silk yarns is positively correlated with their fineness when the twist is the same is the effect of surface area. A thicker silk yarn has a larger surface area compared to a finer yarn because it contains more fiber filaments. Fig. 3 shows the yarn cross section of the above mentioned Y336/550, Y420/550, and Y504/550 samples, by ImageJ we calculated the fiber area for each sample, the total fiber area of Y336/550, Y420/550, Y504/550 is

21161.39, 27399.26 and 32232.48 μm^2 respectively. The more fibers there are, the more voids will be formed from fiber to fiber.

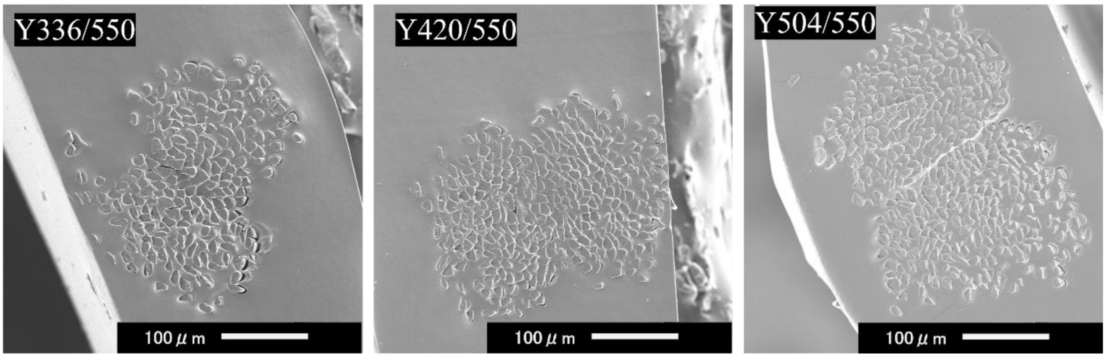


Figure 4.3. The cross-section photo of Y336/550, Y420/550, Y504/550.

When silk is degummed, the sericin on its surface is removed, which exposes the fibroin in the silk. Fibroin is the main component of silk and has good hydrophilicity, so silk can absorb water after degumming. In addition the thicker the silk yarn the higher the number of monofilaments contained inside, this is due to the fact that yarn thickness is associated with the diameter of the monofilaments. Silk fibers are twisted together to form the yarn. The thicker the yarn, the more monofilaments it contains, so that there are more inter-monofilament spaces within the yarn. These inter-monofilament spaces can trigger the capillary effect because silk fibers are inherently hydrophilic and absorb water better. The capillary effect is a phenomenon in which a liquid rises along the tiny pores. In addition to the surface area, the thicker the silk fiber, the more monofilaments it contains, and the capillary effect triggered by the inter-monofilament spaces will be stronger, a phenomenon that has been mentioned in previous papers.

In order to discuss the effect of yarn twist on the water absorption properties of yarns, Fig. 2b shows the wicking height of single silk yarns for 10 minutes. The result can be divided into 3 groups, each group of yarn has the same fineness. The yarn fineness of Y168/230, Y168/350, and Y168/650 were 168 Denier and the twists were 230, 350, and 650 turns/m respectively (Fig. 4), and the wicking height decreased with the increase of twist, and the same trend was observed easily in the other two groups.

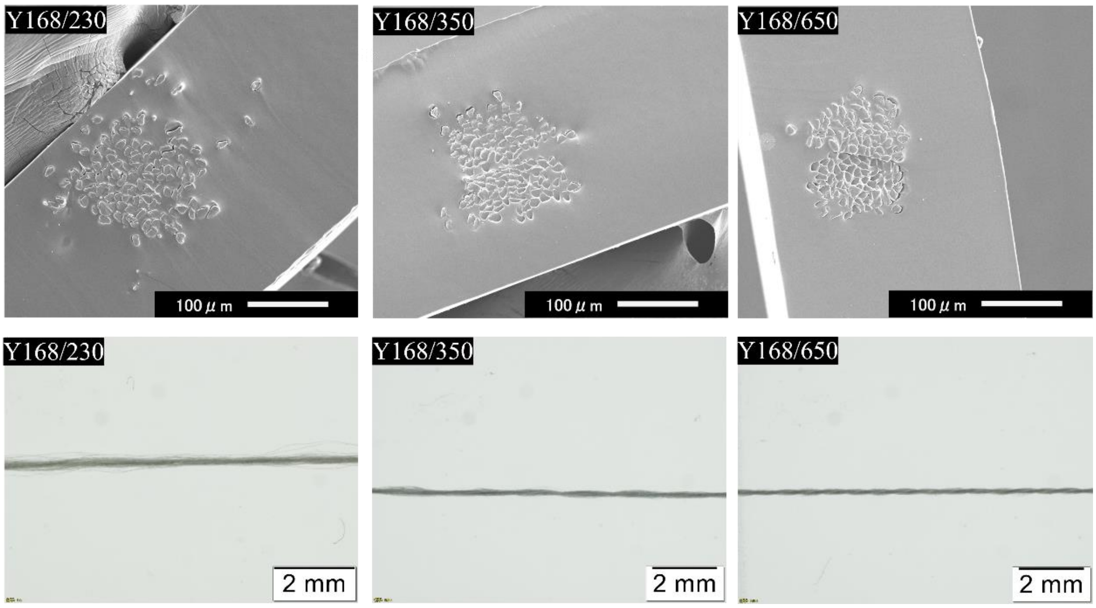


Figure 4.4. The cross section of SEM images for Y168/230, Y168/350, Y168/650 (upper); Digital microscope images of longitudinal direction for Y168/230, Y168/350, Y168/650(under).

For the twisted silk yarn, the twist added on the fibers can form the capillary channels for wicking, With the increase of the twist, the wicking radius will decreaced and the final wicking height will increased (twist wicking). However, too much twist will block the wicking channels, and the wicking height will decrease with the increased in this situation. As in highly twisted yarns, the increase in twisting leads to a decrease in diameter (the radii of Y168/230 and Y168/650 are 159.7±4.7 μm, 139.0±6.7 μm), resulting in a displacement of the filaments as the inward transverse pressure on the inner outer layers forces them closer to the dense structure. This slow migration occurs in the yarn structure, which changes the density of the yarn, which leads to disruptions in the continuity, length, and direction of the capillaries. According to the previous study[15], the best twist of the filament yarn to form the wicking radius is around 100~300 turns/m. In our study, with the increase of twist, the wicking height decreased with the same trend. Moreover, in the experiment, the wicking height was evaluated by the apparent water absorption height, which showed a lower result than the actual height.

4.4.2 Theoretical approach

To characterize the hydraulic flow in single yarns Eq. 1 and Eq. 2. were used to calculate the permeability and capillary hydraulic diameter. Fig. 4.5 (A-N) shows a comparison of experimental results and best theoretical fits according to Fries and Dryer’s proposed model. In general, the model fits well with the experimental data, which indicates that the concept proposed by Fries and Dryer can be applied to modeling the wicking behavior of yarns. While From Eq. 1, it is clear that the maximum wicking length is dependent on the hydraulic diameter and independent of the permeability of the fibrous media, the experimental results in Fig. 5 (O) show that these two parameters are not completely independent for silk yarns. In general, with the increase in hydraulic diameter, the flow permeability also increases (Fig. 5).

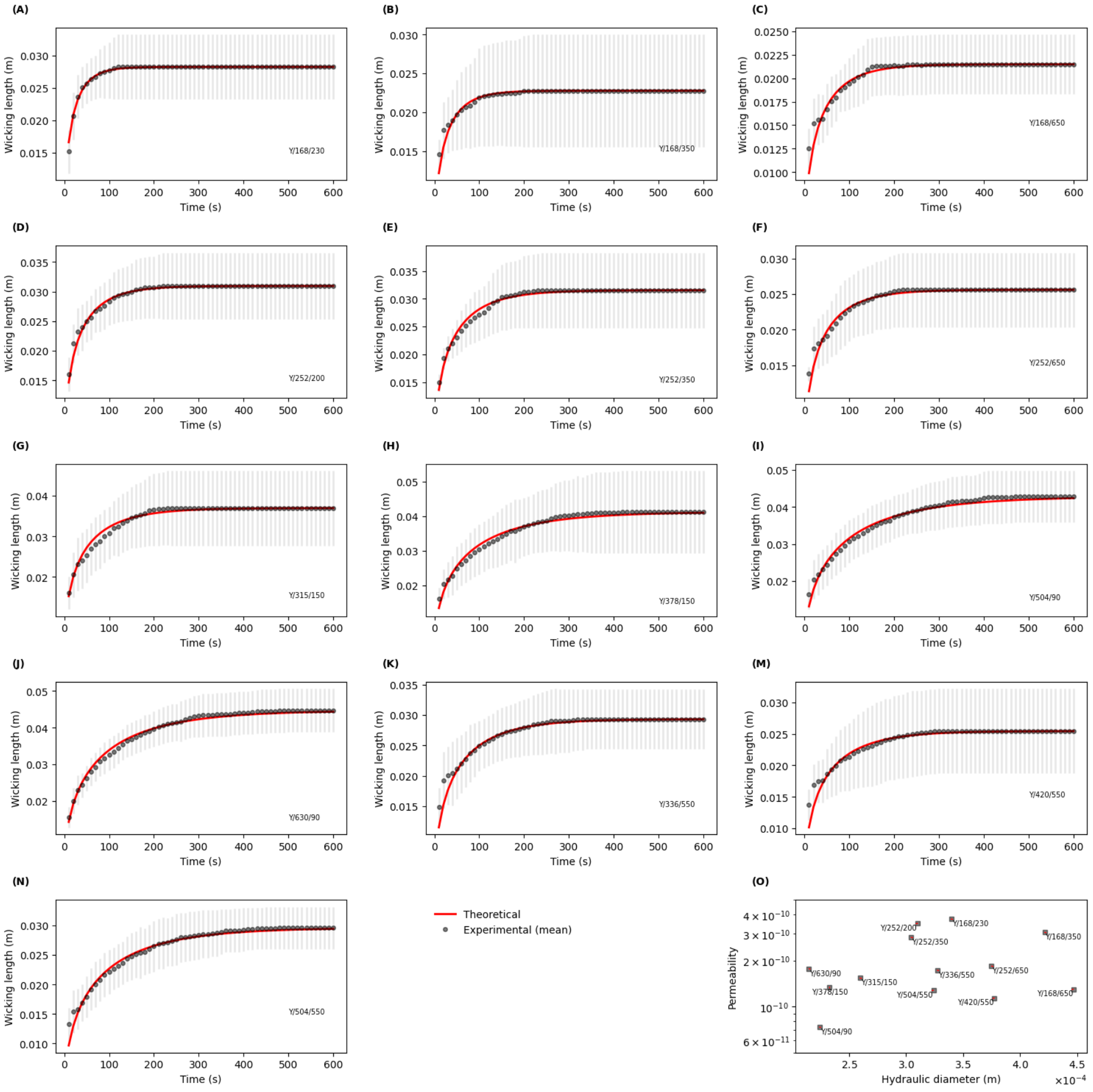


Figure 4.5. Comparison of results for experimental data and theoretical fit of Fries and Dryer

model for yarn samples (A)Y168/230, (B)Y168/350, (C)Y168/650, (D)Y252/200, (E)Y252/350, (F)Y252/650, (G)Y315/150, (H)Y378/150, (I)Y504/90, (J)Y630/90, (H)Y336/550, (I)Y420/550, (J)Y504/550, (O) best fit values of hydraulic diameter and permeability for yarn samples.

4.4.3 Results of the interlaced yarn

Fig. 4.6a shows the wicking heights of interlaced yarn, where S is the wicking height of the single yarn, WP is the wicking height in the vertical direction of the interlaced yarn, and WT is the wicking length in the horizontal direction of the interlaced yarn. Herein, WT is the average of the absorbent lengths of the left and right sides in the horizontal direction. The general trend of wicking on interlaced yarn is consistent with the trend of single yarn. All the yarns showed WT is higher than S and WP, which is due to the effect of gravity due to water in the vertical direction. Fig.4.6b also shows high correlation between S and WP with the correlation coefficient as 0.96, from which it can be found that the wicking height of the single yarn and WP show a very high correlation, and the wicking height of WP can also be predicted by the wicking height of single yarn (S).

In addition, Fig.4.6c demonstrates the correlation between S and WT, shown the correlation coefficient as 0.96, which means that the wicking height of WT can also be predicted based on the wicking height of a single yarn. Moreover, the correlation coefficient between WP and WT is 0.90 (Fig. 6d), indicating a high correlation between the interlaced WP and WT.

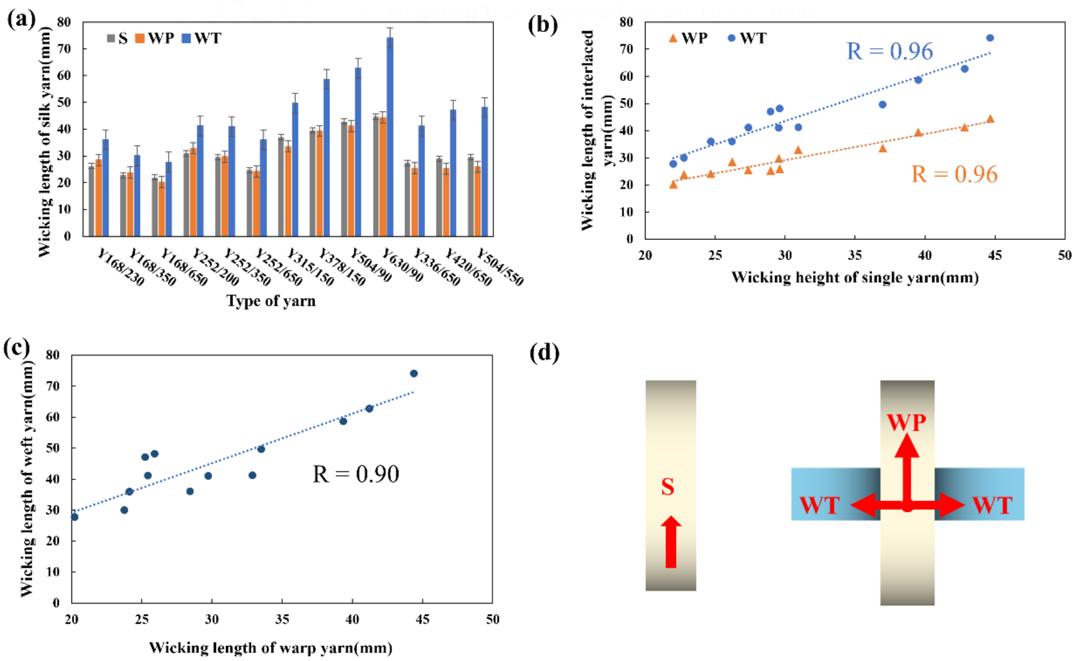


Figure 4.6. (a) Wicking length of silk yarn for S, WP, and WT; (b) Correlation of wicking length between S and WP, as well as S and WT; (c) Correlation of wicking length between WP and WT; (d) Schematic view of the single yarn and interlaced yarn.

Fig. 4.7 shows the wicking height in the interwoven state of sample Y168/230. In the initial stage (Fig. 7a), it can be found that the wicking height of WP is higher than that of WT. The initial movement of water in the yarn is in the vertical direction, and due to the direction of yarn alignment, etc., water is transported more rapidly in the vertical direction. In addition, since water in the horizontal direction is transported past the intersection point, moisture will be transported preferentially in the vertical direction before the water fills the interlaced point.

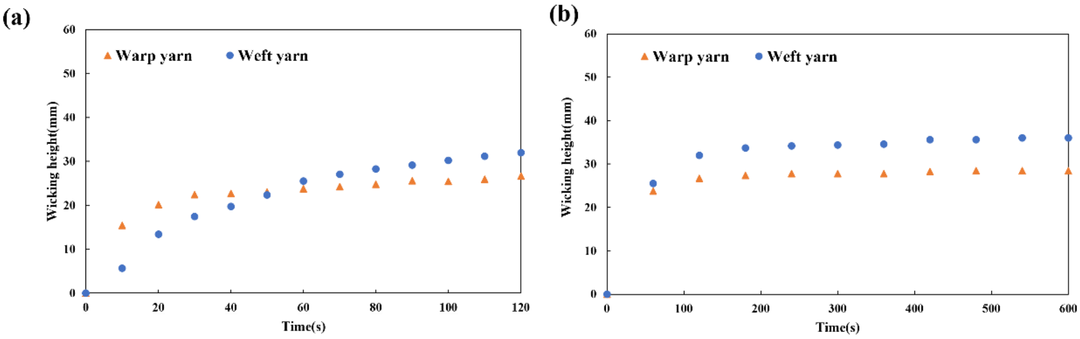


Figure 4.7. Wicking height of interlaced silk yarn (a)Wicking length of Y168/230 over the first 120 s (b)Wicking length of Y168/230 over 600 s.

In order to investigate the wicking time on the interlaced area, water moving to the interlaced point has been analyzed properly. We set the initial recording point as O, to the interlaced point, as is shown in Figure 8a, point X is the point water went to the interlaced point, point Z is the water passed the interlaced point in the vertical direction, and point Y is the water passed the interlaced point in the horizontal direction, while started to went to weft yarn.

Fig. 4.8b shows the time taken for water from point O to move to points X, Y, and Z, respectively. The trend for water to reach point X and point Z is consistent and short, but the time for water to move in the horizontal direction is longer and more variable. As mentioned earlier, the initial direction of movement of the water in the yarn is vertical, and because of the direction of yarn alignment, etc., water will be transported more rapidly in the vertical direction. Since water in the horizontal direction is transported past the intersections, moisture will be transported preferentially in the vertical direction before the water fills the interlaced point.

The time of water moving to point Z shows a positive correlation with the twist (Fig. 4.8c). The longer it takes for moisture to pass through the crossing point when the twist is higher. This result shows the same trend with the single yarn we talked before. When all the yarn character are the nearly the same, with the twist increasing, the channel for the wicking become smaller or even destroyed. In this situation, the capillary effect occurs in the silk yarn is more weaker, and the transmission of moisture between the yarns will be decreased correspondly.

Besides, the time of water moving to point Y shows a high negative correlation with the interlaced area, shown in Fig.4.8d. That is, when the contact area is larger, the time required for migration to the interwoven yarns is smaller. When the point of contact between two yarns is larger, the capillary effect between the crossing points is stronger, this is what causes moisture to take less time to migrate from one yarn to the other through the crossing points. When two yarns cross, tiny voids, and tiny pores form between them. The silk yarn itself is hydrophilic and it absorbs moisture very well. When the contact area between the yarn crossings increases, so that more capillary effect occurs, moisture moves along the surface of the yarn towards the crossings, then through the crossings, and eventually into the other yarn. As a result of the enhanced capillary effect, the rate of transport of moisture between the yarns is increased, so that it takes less time to migrate from one yarn through the intersection point to the other. This phenomenon is very important in the textile process because it can affect the wetting and water absorption properties of the yarn, which has an impact on the dyeing, processing, and weaving processes.

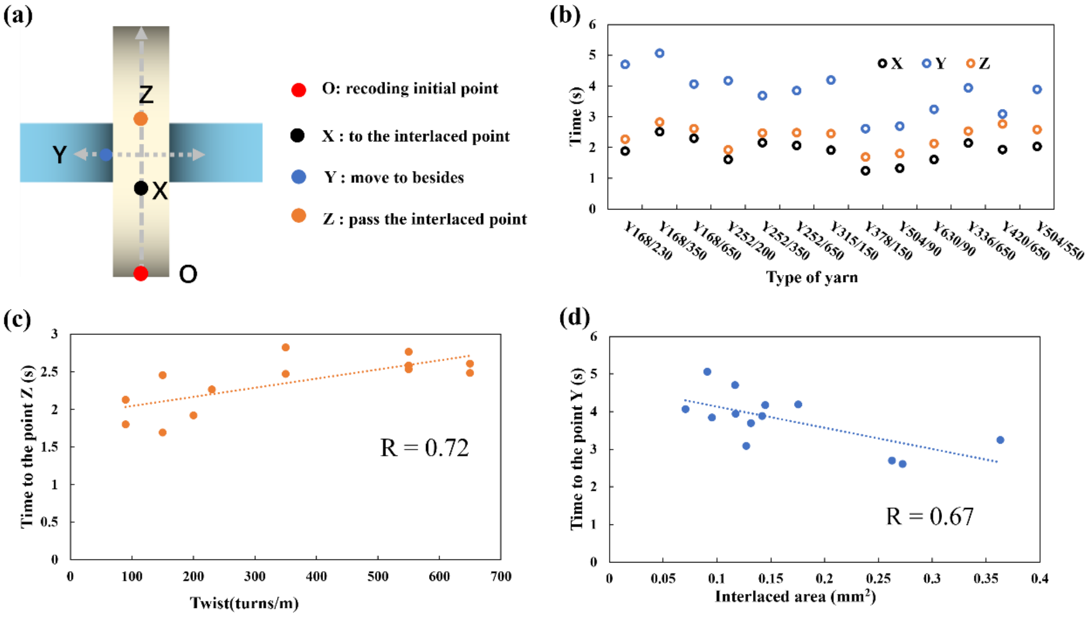


Figure 4.8. The water moving time to X, Y, and Z point, the relationship between twist and time to point C, the relationship between interlaced area and time to point B, the diagram of points X, Y, Z.

4.5 conclusion

The purpose of this study is to investigate the effect of yarn character on the wicking of the silk yarn so as to make the fundamental preparation for the prediction of the wicking of fabric in the future. 13 kinds of silk yarns with different fineness were studied on the wicking property, clarified the effect of twist and fineness on the wicking length. Moreover, we investigated the effect of interlacing on water transport.

The results show that the twist and finesse of the silk yarn are the important factors influencing the wicking length of a single yarn. The wicking length of the silk yarn shows the same trend with the finesse of the silk yarn. Besides, the effect of the interlacing condition of the silk yarns was discussed. In the interlaced situation, the initial speed of WP is higher than WT, while the wicking length of the weft direction(10 mins) is higher than the warp direction. Furthermore, there is a strong correlation between the wicking length of S, WP and WT. This relationship can be utilized as a predictive tool to estimate the wicking length of interlaced yarns based on the wicking length of individual single yarns.The time for moisture reaching the interlaced point and moving from warp yarn to weft yarn shows a certain relationship with interlaced point area.

This preliminary study aims to explore the water transport mechanism in silk yarns. With the advancement of computer technology, future research can focus on predicting the final fabric by simulating the water absorption properties of the interlaced yarn network using Computer-Aided Design (CAD) tools.

Reference

1. T. Naoe, S. Hasegawa, A. Bucheeri, and M. Futakawa, *Journal of nuclear science and technology*, **45**, 1233 (2008).
2. Z. Zhang, G. Wang, W. Gu, Y. Zhao, S. Tang, and G. Ji, *J Colloid Interface Sci*, **605**, 193 (2022).
3. H. A. Eren, E. K. Çeven, G. Günaydın, M. S. Güler, and E. Akdemir, in "III International conference Contemporary trends and innovations in the textile industry"Ed.^Eds.), Year of Converence.
4. Q. Zhuang, S. Harlock, and D. Brook, *Textile Research Journal*, **72**, 727 (2002).
5. A. Tarbuk, S. Flinčec-Grgac, and T. Dekanić, *Advanced technologies*, **8**, 5 (2019).
6. N. C. Brown, H. T. Pruett, D. S. Bolanos, C. Jackson, B. Beatson, S. P. Magleby, and L. L. Howell, *Wearable Technologies*, **3**, e6 (2022).
7. J. D. Sousa, *Applied Ergonomics*, **45**, 1447 (2014).
8. G. Zhu, J. Militký, Y. Wang, B. V. Sundarlal, and D. Křemenáková, *Fibres & Textiles in Eastern Europe*, (2015).
9. C.-J. Hong and J. B. Kim, *Fibers and Polymers*, **8**, 218 (2007).
10. M. Yanılmaz and F. Kalaoğlu, *Textile Research Journal*, **82**, 820 (2012).
11. B. Kumar and A. Das, *Fibers and Polymers*, **15**, 625 (2014).
12. M. Lei, Y. Li, Y. Liu, Y. Ma, L. Cheng, and Y. Hu, *Polymers (Basel)*, **12** (2020).
13. N. Ansari, *The Journal of The Textile Institute*, **91**, 1 (2000).
14. Q. Li, J. J. Wang, and C. J. Hurren, *Journal of Natural Fibers*, **14**, 400 (2016).
15. N. Wang, A. Zha, and J. Wang, *Fibers and Polymers*, **9**, 97 (2008).
16. T. Liu, K. F. Choi, and Y. Li, *J Colloid Interface Sci*, **318**, 134 (2008).
17. A. B. Nyoni and D. Brook, *Journal of the Textile Institute*, **97**, 119 (2006).
18. M. K. Öztürk, B. Nergis, and C. Candan, *Textile Research Journal*, **81**, 324 (2010).
19. H.-s. Kim, S. Michielsen, and E. DenHartog, *Journal of Materials Science*, **55**, 7816 (2020).
20. P. Mallick and S. S. De, *Journal of Natural Fibers*, **19**, 5297 (2021).
21. R. Fischer, C. M. Schleputz, J. Zhao, P. Boillat, D. Hegemann, R. M. Rossi, D. Derome, and J. Carmeliet, *J Colloid Interface Sci*, **625**, 1 (2022).
22. Y. Zhang, H. Wang, C. Zhang, and Y. Chen, *Journal of Materials Science*, **42**, 8035 (2007).
23. T. Stuart, R. D. McCall, H. S. Sharma, and G. Lyons, *Carbohydr Polym*, **123**, 359 (2015).
24. B. Yang, *Comput Intell Neurosci*, **2022**, 5745457 (2022).
25. Y. Su, Y. Fan, G. Liu, M. Tian, and J. Li, *Sustainability*, **15** (2023).
26. C. Ge, D. Xu, H. Du, Z. Chen, J. Chen, Z. Shen, W. Xu, Q. Zhang, and J. Fang, *Advanced Fiber Materials*, **5**, 791 (2022).
27. S. Popinet, *Annual Review of Fluid Mechanics*, **50**, 49 (2018).
28. Y. Li, J. Fan, S. Zhang, Z. Xia, L. Wang, and Y. Liu, *Fibers and Polymers*, **24**, 759 (2023).
29. F. Hajiani, A. A. Ghareaghaji, A. A. A. Jeddi, S. H. Amirshahi, and F. Mazaheri, *Fibers and Polymers*, **15**, 1966 (2014).
30. M. S. M. Jad, S. A. H. Ravandi, H. Tavanai, and R. H. Sanatgar, *Fibers and Polymers*, **12**, 801 (2011).
31. R. Bagherzadeh, M. Gorji, M. Latifi, P. Payvandy, and L. X. Kong, *Fibers and Polymers*, **13**, 529 (2012).
32. N. Asfand and V. Daukantienė, *Journal of Industrial Textiles*, **53** (2023).

33. A. Karthik, J. D. James D, V. Vijayan, Z. Ahmad, S. Rajkumar, S. Sharma, K. P. Sharma, R. Singh, C. Li, and S. M. Eldin, *Journal of Materials Research and Technology*, **24**, 8429 (2023).
34. B. Das, A. Das, V. K. Kothari, R. Fanguiero, and M. de Araújo, *Fibers and Polymers*, **9**, 225 (2008).
35. R. Kumari, G. Mishra, R. S. Rengasamy, and R. Chattopadhyay, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **665** (2023).
36. C. Zhu and M. Takatera, *Textile Research Journal*, **85**, 479 (2014).
37. R. Fischer, C. M. Schleputz, R. M. Rossi, D. Derome, and J. Carmeliet, *J Colloid Interface Sci*, **626**, 416 (2022).
38. *Frontiers in Educational Research*, **6** (2023).
39. Z. Dong, M. Ge, Y. Ding, H. Cong, G. Zhao, and P. Ma, *ACS Applied Polymer Materials*, **5**, 7497 (2023).
40. A. Patnaik, R. S. Rengasamy, V. K. Kothari, and A. Ghosh, *Textile Progress*, **38**, 1 (2006).
41. C. Zhu, H. Tada, J. Shi, J. Yan, and H. Morikawa, *Textile Research Journal*, **89**, 5198 (2019).
42. J. Yan, C. Zhu, J. Shi, and H. Morikawa, *Textile Research Journal*, **92**, 3808 (2022).
43. N. Fries and M. Dreyer, *J Colloid Interface Sci*, **320**, 259 (2008).
44. V. Kumar, P. V. Kameswara Rao, and A. Rawal, *Journal of Power Sources*, **341**, 19 (2017).
45. A. Rawal, P. V. K. Rao, V. Kumar, S. Sharma, S. Shukla, D. Sebők, I. Szenti, and A. Kukovecz, *Journal of Energy Storage*, **21**, 505 (2019).

Chapter 5
Conclusion

Chapter 5 Conclusion

In the fields of textiles and apparel, "wicking" (moisture absorption capability) is a highly significant performance characteristic. Wicking ability of the yarn refers to the water absorption ability of the yarn to transmit moisture. This feature plays a crucial role in the comfort, insulation, and athletic performance of textiles.

The exploration of yarn's water absorption capabilities holds paramount significance in the field of textiles. By delving into the moisture absorption properties of yarn, we can gain a deeper understanding of the overall performance of fabrics, which is pivotal in the design and manufacturing processes of textiles. Yarn constitutes the fundamental building block of fabrics, and its water absorption properties directly impact the overall water absorption capacity of the fabric.

Understanding the moisture absorption properties of different yarns enables us to predict the fabric's water absorption characteristics, allowing the selection of appropriate yarns for various textile applications. Different sectors have diverse requirements concerning the moisture absorption capabilities of textiles. In-depth knowledge of yarn's water absorption properties facilitates the customization of fabrics according to specific needs, meeting the demands of various fields. The comprehensive study of yarn's water absorption characteristics not only provides essential insights for predicting and designing fabric performance but also plays a proactive role in various aspects of the textile industry, propelling the industry towards continuous advancement.

This paper introduces a new experimental setup capable of simultaneously measuring the water absorption properties of individual and intersecting yarns. For individual yarns, one end of the yarn is secured in a water tank, while the other end is connected to a pulley system and subjected to tension. A miniature water pump adds water to the tank, and the yarn's absorption process is recorded using a camera. For intersecting yarns, two columns are used to control the ends of the horizontal yarn, which is crossed at a desired angle with a vertical yarn. Water is added to the tank using a miniature water pump, and the yarn's absorption process is captured by a camera.

In this research, we find that the void and fiber areas of the silk yarn are important factors in influencing the wicking length of single yarn. The wicking length of the silk yarn shows the same trend with the increase of void and filament areas. Further, the effect of the interlacing condition of the silk yarns was discussed. To the interlaced situation, the initial speed of single yarn water transport is the highest, followed by the warp direction and the weft direction. Furthermore, the wicking length of **S** shows a high relationship with **WP** and **WT**, which can be used to predict the wicking length of interlaced yarns based on that of the single yarn.

The twist and finesse of the silk yarn are also the important factors influencing the wicking length of a single yarn. The wicking length of the silk yarn shows the same trend with the finesse of the silk yarn. Besides, the effect of the interlacing condition of the silk yarns was discussed. In the interlaced situation, the initial speed of WP is higher than WT, while the wicking length of the weft direction(10 mins) is higher than the warp direction. Furthermore, there is a strong correlation between the wicking length of S, WP and WT. This relationship can be utilized as a predictive tool to estimate the wicking length of interlaced yarns based on the wicking length of individual single yarns. The time for moisture reaching the interlaced point and moving from warp yarn to weft yarn shows a certain relationship with interlaced point area.

To the different humidity, it was observed that in the case of silk yarn, increasing the twist reduces the impact of humidity on water absorption height for fine yarn, whereas for coarse yarn, increasing the twist intensifies the impact of humidity on water absorption height. Further in-depth research is needed, specifically by refining the parameters of the yarn, to explore these findings in more detail.

The significance of fundamental physics research lies in its ability to provide us with opportunities to deeply understand natural phenomena and principles. The study of water absorption, although it might seem tedious on the surface due to the extensive experiments and data analysis involved, holds profound implications for our daily lives and technological advancement. While research in water absorption demands patience and perseverance, it holds crucial importance for our everyday life, health, and environmental sustainability. With more people actively engaging in this field, driving fundamental physics research forward, it will bring forth numerous benefits for our society and technological progress.

Published papers

Jiawei Yan, Vijay Kumar, Tianshuo Gao, Jian Shi, Icksoo Kim, Hideaki Morikawa, Chunhong Zhu. The Wicking Performance of Interlaced Silk Yarn Focusing on Yarn Parameters[J]. Fibers and Polymers, 2024: 1-9.

Jiawei Yan, Chunhong Zhu, Jian Shi, Hideaki Morikawa Effect of silk yarn parameters on the liquid transport considering yarn interlacing[J]. Textile Research Journal, 2022, 92(19-20): 3808-3815.

Chunhong Zhu, Haruka Tada, Jian Shi, **Jiawei Yan**, Hideaki Morikawa. Water transport on interlaced yarns[J]. Textile Research Journal, 2019, 89(23-24): 5198-5208.

Yao Xiao, Gan Zhenzeng, Erying Dong, **Jiawei Yan**, Wanwan Liu, Guangyu Zhang. Construction and characterization of hyperbranched polymer stabilized Se nanoparticles and its application on the antibacterial finishing of viscose nonwoven fabric[J]. Journal of Applied Polymer Science, 2023, 140(8): e53500.

Yao Xiao, Zhenzheng Gan, Erying Dong, **Jiawei Yan**, Wanwan Liu, Guangyu Zhang. Synthesis and Characterization of Antibacterial Viscose Nonwoven Fabric by the Cooperative Action of Se Nanoparticles and Amino Hyperbranched Polymer[J]. 2021.

Guangyu Zhang, Yao Xiao, Qitao Yin, **Jiawei Yan**, Chuanfeng Zang, Huiyun Zhang. In situ synthesis of silver nanoparticles on amino-grafted polyacrylonitrile fiber and its antibacterial activity[J]. Nanoscale Research Letters, 2021, 16: 1-9.

Guangyu Zhang, Ran Cheng, **Jiawei Yan**, Yao Xiao, Chuanfeng Zang, Yu Zhang. Photodegradation property and antimicrobial activity of zinc oxide nanorod-coated polypropylene nonwoven fabric[J]. Polymer Testing, 2021, 100: 107235.

Guangyu Zhang, Yao Xiao, **Jiawei Yan**, Wei Zhang. Fabrication of ZnO nanoparticle-coated calcium alginate nonwoven fabric by ion exchange method based on amino hyperbranched polymer[J]. Materials Letters, 2020, 270: 127624.

Guangyu Zhang, Yao Xiao, **Jiawei Yan**, Ningwei Xie, Rong Liu, Yu Zhang. Ultraviolet light-degradation behavior and antibacterial activity of polypropylene/ZnO nanoparticles fibers[J]. Polymers, 2019, 11(11): 1841.

Guangyu Zhang, Dao Wang, **Jiawei Yan**, Yao Xiao, Wenyan Gu, Chuanfeng Zang. Study on the photocatalytic and antibacterial properties of TiO2 nanoparticles-coated cotton fabrics[J]. Materials, 2019, 12(12): 2010.

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