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Measurement of Dynamic Contact Angle of Yarn for Evaluation of Fabric Comfort Performance

Cheol-Jae Hong*

Abstract : Testing device was newly designed and built to measure the dynamic contact angle. The measurement was made using microscope interfaced with computerized image analysis system while the dynamic condition being controlled using Instron^{R}. As specimens for the experiment, two different types of fibers, i.e., hydrophilic and hydrophobic, were prepared. In case of hydrophilic fiber, the increase of twist level gave the increase of contact angle. However, in hydrophobic yarn the increase of twist level gave the decrease of contact angle. When saline was used as a testing liquid, the increase of the concentration gave the increase of contact angle. The results rationalized clearly on the basis of known concepts could be used in designing fabric structure for the improvement of comfort performance.

Key word : contact angle, fabric comfort, porosity, surface roughness, yarn twist

1. Introduction

The objective of the research is to measure the apparent contact angle of multi-filament yarns twisted at different levels in the dynamic condition prior to further study on comfort performances such as absorbency, moisture transfer, and their related heat transfer in the fabrics. The contact angle, defined at the common liquid-solid-vapor interface, has been used to characterize the surface properties of material. When the contact angle of the yarn is below 90°, the fabric has hydrophilic property with absorbing liquid at the interstitial space between yarns. On the other hand, when the contact angle of yarn is above 90°, the fabric has hydrophobic property with repelling liquid.

Two different types of contact angles, i.e., advancing and receding ones are employed to evaluate wetting properties [2, 10]. Advancing contact angle is measured in the condition that liquid initially contacts with the dry surface of material. Advancing contact angle has been used to evaluate fabric's wetting transport properties. Otherwise, receding contact angle is measured in the condition that liquid is retracted after its being initially applied on the surface. Since the receding contact angle is measured at a partially wetted yarn surface, it could be used for an evaluation of fabric's liquid retention or dryness properties.

The testing methods could be mainly classified into two different categories. One is to measure the contact angle in the static condition and the other in the dynamic condition. For the static measurement, sessile drop method has been widely used. The method is to measure the contact angle in the equilibrium state after a given amount of liquid is dropped on the surface of material. In this, however, liquid drop amount should be precisely controlled to a small one because the gravitational force has a significant effect on the measured value [5, 8-9]. In addition, the method has difficulties in application to linear textile

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*Dept. of Textile Engineering, Soongsil University, Seoul, Korea

materials such as fiber and yarn because the surfaces are too narrow to drop and keep the liquid on them. To facilitate the measurement in linear material, the testing method was developed that is to stand the material up vertically and then forcibly immerse it into two immiscible liquids [9]. The measurement is made after a small amount of upper liquid attached on the specimen surface becomes stabilized in the position of down liquid. However, in practice, according to a material type and immersion speed condition, the liquid amount attached on the surface becomes irregular that also causes to change the values of contact angle due to the gravitational effect. To overcome these, tilting test method was developed [1]. The method that is convenient for the measurement in solid planar materials needs to design and build a separate specimen holder for the further application to linear flexible fiber or yarn. However, it has many difficulties in operating the holder while focusing on the image with microscope.

Compared to the static testing methods, the dynamic methods are more useful in the measurement in linear flexible fibrous materials [2, 6, 10-13]. Yarn has a large amount of interstitial spaces between fibers. In the experiment, according as time elapses, yarn continues to imbibe liquid through the interstitial space due to the capillary action. It causes to partially wet the surface of yarn and continues to change the contact angle during the testing. Thus, for the time dependent linear fibrous structure, it is highly recommended that the measurement of contact angle be made in the dynamic condition. One of dynamic methods is to measure the wetting force of specimen with a micro-balance while the specimen being immersed into liquid at a given controlled speed [2, 10]. After the measurement of wetting force, the contact angel is indirectly calculated based on the Wilhelmy principle. For the correct calculation, the perimeter at the end position of specimen that is initially contacted with liquid during testing should be precisely determined. In a porous yarn, therefore, cutting for the preparation of specimen should be carefully made without damaging the original shape. Even though the preparation of specimen is perfectly made, the free end of specimen hardly maintains its vertical stand at moment of the initial contact with liquid because of the buoyance effect. In this an irregular contact with liquid could give a wrong value in calculation of contact angle.

In order to solve the problems, in this research the contact angle was measured directly in dynamic condition. Yarn was fixed on a specially designed specimen holder to immerse it into liquid reservoir regardless of a buoyance effect. Instron^{R} to which the specimen holder is attached controls the immersion speed. Digital camera was mount on the microscope and interfaced with computer. The method has an advantage of considerably saving time and labor because of easy scanning and analysis of the image on the computer. For the testing, two different type of yarns were prepared, one is hydrophilic, and the other is hydrophobic. Twist levels were imparted differently to the yarns. As testing fluid, salines of different concentrations were used. The measured contact angles were rationalized on the basis of the concepts known from the following theoretical review. The analysis of contact angles in the twisted yarns would provide an useful information in designing fabric structure for improvement of the comfort performance such as absorbency, moisture transfer, and their related heat transfer.

2. Theoretical Review

The concept of the contact angle gives an indication of the potential of wettability of surface. When liquid completely contacts with a smooth homogeneous nonporous surface of solid, true contact angle θ is given by the Young's force balance equation as follows:

$$\cos\theta = \frac{\gamma_{sa} - \gamma_{ls}}{\gamma_{la}} \qquad (1)$$

where γ_{sa}, γ_{ls}, and γ_{la} are the surface tensions at the interface of solid-air, liquid-solid, and liquid-air, respectively.

However, theoretical approach based on Young's equation suffers from certain limitations due to the several ideal assumptions involved. In most of materials, the surfaces are rather locally irregular. Wenzel developed the relation between the macroscopic roughness of a solid surface and the contact angle [14]. He introduced the roughness factor, Φ, (defined as the ratio of the true area of the solid to the apparent area) into Young's equation, and gave its relation to the apparent contact angle, θ'=, as follows:

$$\Phi = \frac{\cos\theta'}{\cos\theta} \qquad (2)$$

in which θ is the true contact angle defined by the Young's equation.

Most surfaces have a value of roughness factor above 1. Equation (2) has been used in predicting the wettability of different types of surfaces of different roughness values. When true contact angle θ below 90° that represents hydrophilic material, then Equation (2) indicate $\theta' < \theta$. This means that wettability in hydrophilic material increases with the roughness. When θ above 90° that represents hydrophobic material, it indicates $\theta' > \theta$. This means that repellency effect in hydrophobic material increases with the roughness. However, Wenzel's equation has a limitation in application to highly rough or porous textile materials because of its assumption that liquid should adhere closely with the solid surface without forming air gaps at the interface. When pores exist at the interface, contact angle behaves in a very different manner unlike that from the Wenzel's equation. Cassie and Baxter expanded the Wenzel's equation in a more general fashion to apply to porous structure [3]. When porous surface is comprised of two portions, i.e., f_1 of solid-liquid interface and f_2 of liquid-air interface, the apparent contact angle θ' on the porous surface was derived as follows:

$$\cos\theta' = f_1\cos\theta - f_2 \qquad (3)$$

Equation (3) shows that in a loose textile structure, liquid in large portion of liquid-air interface (f_2) tends to lie in a spherical form due to liquid's surface tension, which results in an increase of the contact angle and water repellency. However, in the dense structure, large portion of solid-liquid interface (f_1) gives an increase of wetting force, which results in a decrease of apparent contact angle. If there are no pores on the interface between solid material and liquid, f_1 becomes the roughness factor shown in Wenzel equation (2), with f_2 being zero.

In this research, the contact angles of twisted multi-filament yarns were investigated as a function of the twist level. As twist levels are imparted differently to the yarn, the roughness factor and pore structure will be also changed differently. It would affect the contact angles and its related comfort performance in fabric. Testing device was designed and built to measure the contact angle in the dynamic condition. The results obtained were rationalized in detail on the basis of above known concepts.

3. Experimental

In this study we used rayon, nylon, polyester (PET), and polypropylene (PP) filaments. The fineness of filament is 3 denier. Yarns were prepared to be 390 denier/130 filaments. The yarns were purified by using soxhlet extraction with tetra-chloride carbon for 24 hours. The yarns purified were twisted to 10, 15, 20, and 25 twist per inch (t.p.i.) by using twister machine.

The apparatus and analysis system for the measurement of contact angle in the yarns were schematically illustrated in Figure 1. The yarn were attached firmly with glue on the specimen holder made of steel wire to prevent a change in twist level during the experiment. Specimen holder was mounted on Instron® to control the immersion speed of the yarn into liquid reservoir. The image of liquid-solid-air interface at the yarn was captured by using microscope attached with computerized digital camera. Advanced contact angle was measured while specimen is immersing into liquid reservoir. On the other hand, receding contact angle was measured while specimen being retracting from liquid reservoir after the measurement of advancing contact angle. Liquid used is saline of different concentrations, 0, 5, and 10%.

4. Result and Discussion

When contact angles were measured in the static condition, yarns continues to imbibe liquid through interstitial spaces between fibers due to the capillary action, which results in partially wetting the surface and continuously changing the value of contact angle during the test. Thus, in this research, we measured the contact angle in the dynamic condition to relatively evaluate contact angle between specimen. When the contact angles were measured at various controlled immersion speeds, an increase of immersion speed led to an

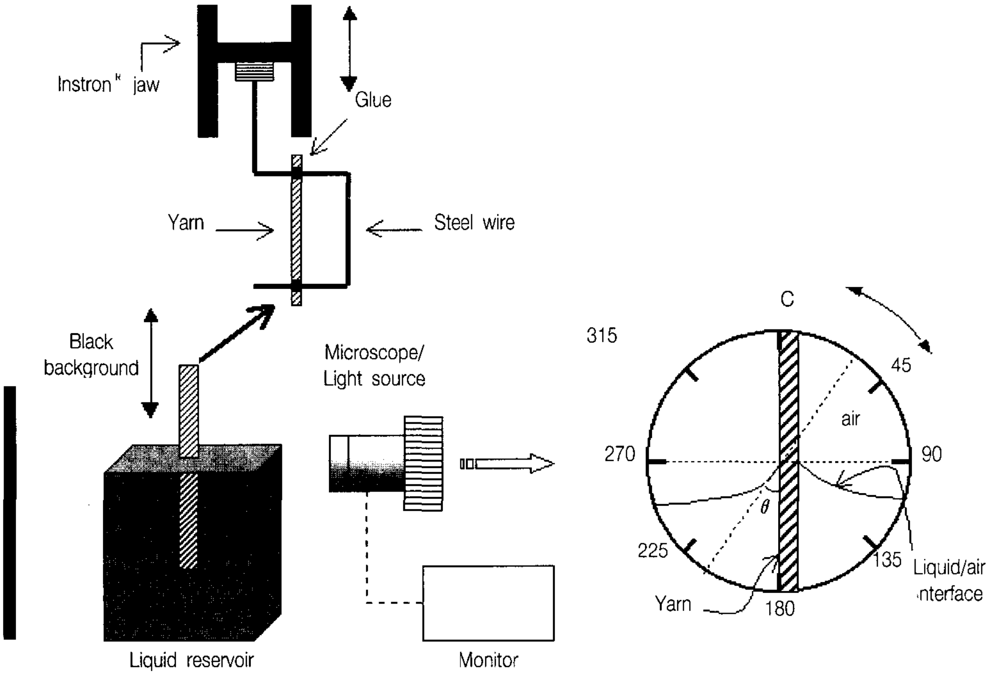


Fig. 1. Equipment of measuring dynamic contact angle.

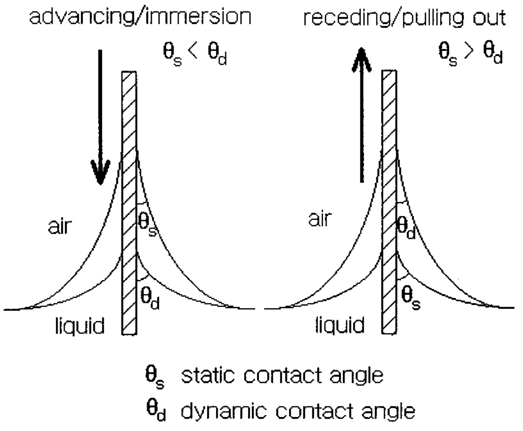


Fig. 2. static and dynamic contact angles according to specimen moving condition.

increases of advancing contact angle but a decrease of receding contact angle because of a viscous drag force at the yarn surface (Figure 2). For the relative evaluation, the immersion speed was controlled to 0.02 mm/sec.

Contact angles of yarns containing different fibers were shown in Figure 3. Contact angle was highest for polypropylene and increases as one goes to rayon, nylon, finally to polyester. The results could be expected from the polarities in molecular structures that are the groups of -OH for rayon, -NHCO- for nylon, and -O- for polyester. In the fibers containing the polar groups, i.e., rayon, nylon, and polyester, the advancing contact angles of yarns all appeared to be below 90° while the contact angle in non-polar polypropylene being above 90°. In all specimens, receding contact angle were lower than advancing contact angles. This is because partially wetted yarn surface during the receding has the increased surface energy, which resulted in the decrease of contact angle as known from Young's equation (1).

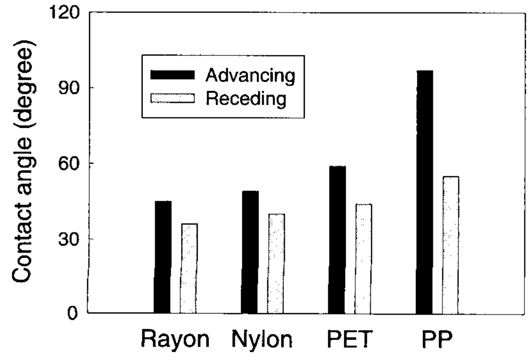


Fig. 3. Contact angle against yarn type (20 t.p.i., water)

Highly twist has been introduced to yarn to provide a cool feeling for summer. The effect of twist level on the contact angle was examined and the results obtained could give an information for the evaluation of wetting or evaporation transport related to a cool feeling. Results of contact angle measured at different twist levels were shown in Figures 4-a and 4-b. In fibers containing polar

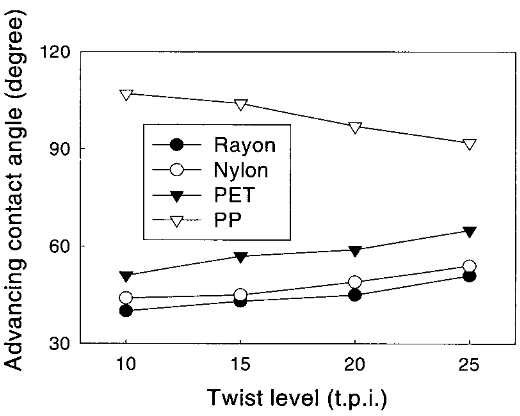


Fig. 4-a. Advancing contact angle against twist level (water)

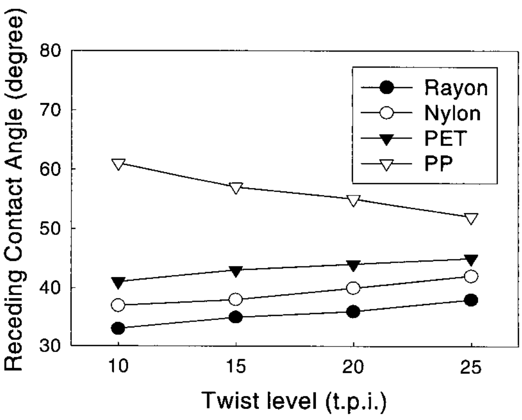
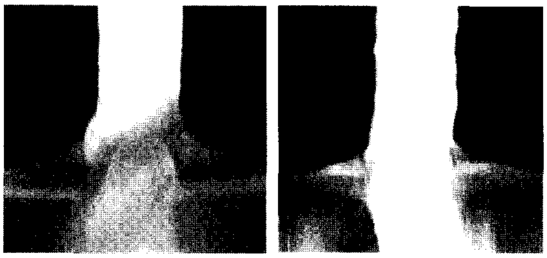
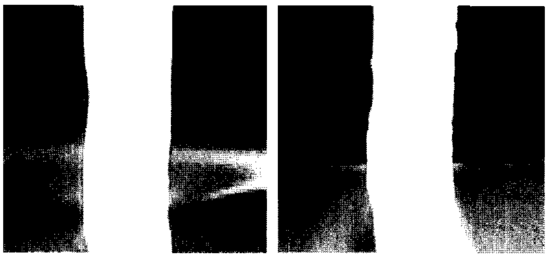


Fig. 4-b. Receding contact angle against twist level (water)

group, i.e., rayon, nylon, and polyester, the increase of twist level gave the increase of the contact angle. An increase of twist level is expected to give an increase of the surface roughness. In this, the contact angle in the yarns containing polar group should have decreased with the increase of the twist level, based on Wenzel's model (2). However, the opposite results appeared. This result could be rationalized on the basis of Cassie and Baxter's model (3). An increase of twist level would lead to an decrease of the interstitial space and thus, the absorption rate due to the capillary action at the space. In this, there would exit air gaps on the liquid-solid interface not being completely saturated with liquid. Therefore, in hydrophilic yarns, the increase of the air portion with twist level could result in the increase of contact angle. However, in hydrophobic polypropylene fiber the increase of twist level gave the decrease of contact angle. In case of hydrophobic polypropylene, water cannot be spontaneously absorbed into the interstitial space between fibers. The water at the air portion in the interstitial space has tendency to minimize its surface that causes to increase the contact angle. Thus, the increase of twist level gave the decrease of air portion that resulted in the decrease of the contact angle based on the Cassie and Baxter's model (3). Figure 5 shows the photographs of rayon and polypropylene at different twist levels, typically selected for representing hydrophilic and hydrophilic yarns.



(a) Rayon 10 t.p.i. (b) Rayon 25 t.p.i.



(a) PP 10 t.p.i. (b) PP 25 t.p.i.

Fig. 5. Photographs of contact angle at different twist levels in rayon and PP yarns (water)

Saline has been used as a testing fluid. Figure 6 shows the effect of the concentration on contact angle. The increase of the concentration in saline led to the increase of contact angles in hydrophilic fibers. This is because sodium chloride ions in the solution forms a screen on the electrolyte group in hydrophilic fiber. The screen effect hinders solution in further penetrating into fiber network that results in a decrease of the affinity of solution with the fiber [4]. The increase of the concentration in saline gave the increase of the liquid surface energy which also contributes to the increase of contact angle as known from the Young's model (1) [7].

5. Conclusion

We measured the contact angles of twisted multi-filament yarns in the dynamic condition. Device was newly designed and built to facilitate this measurement. As specimen, hydrophilic and hydrophobic yarns were prepared because most of fibers belong to one of them. For a relative evaluation of the effect of structural factors on the contact angles, the testing was made at the constant immersion rate. The result obtained could be summarized as follows. Physical and chemical properties of the constituent fiber in yarn have a significant effect on contact angles. Salines as a testing fluid also affects the contact angle. In this

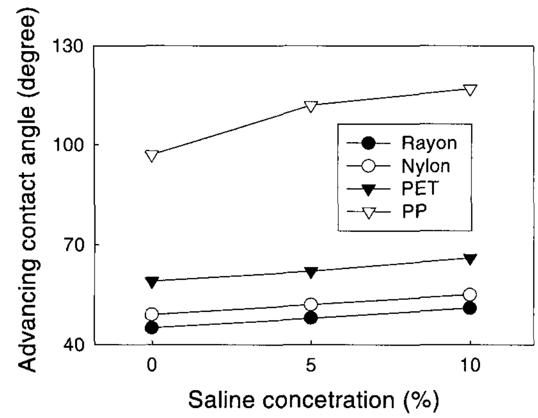


Fig. 6-a. Advancing contact angle against saline concentration (20 t.p.i.)

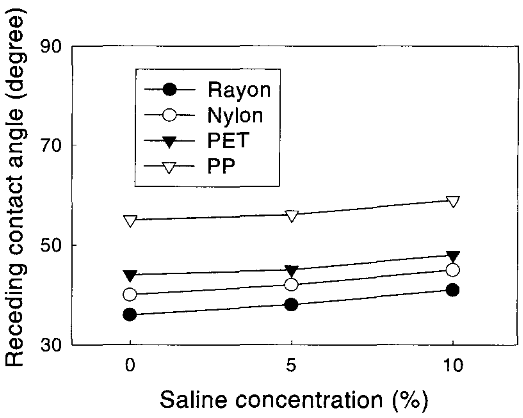


Fig. 6-b. Receding contact angle against saline concentration (20 t.p.i.)

research, we focused on elucidating the effect of twist level on the contact angles in different types of yarns. In hydrophilic fibers, the contact angles increases with the twist level. On the other hand, in hydrophobic fibers, as the twist level increases, the contact angle decreases. The results could be clearly rationalized on the basis of the known concepts. The methodologies and results could give an information in designing fabric structure for improvement of the comfort performance related with absorbency, water repellency, evaporation, heat transfer, and etc.

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