Evaluation of Fiber Wettability Based on an Immerging Force Measurement

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ABSTRACT: This article provides a new approach to estimate the wettability of fibers based on the force analysis in immerging procedure. A fiber in horizontal is forced into and withdrawn from the liquid at a certain speed, and the force changes are detected simultaneously. The experimental results show that the force impulse can be found at fiber contacting with liquid and immersed into liquid, and its value depends on the wettability of the fiber. According to the force impulses of different fibers, the immerging behavior of the fibers can be obtained and categorized into four characteristics. Meanwhile, the wettability of the fibers can be evaluated with the wettability factor, w, derived from the fiber immerging curve, where w is the ratio of the force increment on fiber initially contacting with the liquid to the force increment on liquid surface closing with fiber immerging into the liquid, and with the contact angle, θ, calculated from the wettability factor ($\theta = \pi/(w+1)$) supposed that the fiber is a circular cross section. The pulling-out test for a fiber has also been conducted and the results are discussed briefly in this article. The force measurement indicates that the method can be used for various fibers with short length, or lower density than that of the liquid, or poor wettability.
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Key words: fiber; wettability; contact angle; force measurement; immerging

INTRODUCTION

Wetting behaviors of liquids to fibers are the fundamental of studying the actions of liquids to fibrous assemblies. The wettability of the fiber depends on its surface chemical nature and surface geometry, especially degree of roughness.[1–3] When liquid contacts fibers, at first, the liquid will spontaneously wet fibers or is forced to wet fibers, and then the liquid will move along the surface of fibers. For the fiber with positive wettability, the fiber absorbs the liquid strongly and the fiber–liquid contact points move quickly at the same time as the fiber contacts with the liquid. For the fiber with negative wettability, the surface of the liquid will be sunken, and the surface energy and the contacted area will change when the fiber is immerged into the liquid. These changes are corresponding to the work done by the forces immerging the fiber into the liquid. So, it is possible to evaluate the wettability of the fiber based on the force change during the fiber immerging into the liquid.

Because textile fibers are relatively flexible and fine, it is difficult and even impossible to make the fiber straight and immerge into the liquid in right way or keeping its shape and to see the state of the exact contact point between fiber and liquid while forcing the fiber into the liquid. Few methods can be employed to this kind of measurements though there exist indeed several classical methods of which the shortages are introduced as follows. The purpose of this present article is to propose a new approach to evaluate the wettability of the fiber based on force analysis in immerging process, as well as the pulling-out process.

EVALUATION METHODS OF FIBER WETTABILITY

Wettability of fibers is usually evaluated by wetting forces measurements using the Wilhelmy technique,[4–7] the pendant-drop method to acquire the contact angle according to the shape of the liquid drop surrounding the fibers,[8] and the inserting method to acquire the contact angle.[1,9] There are also the other methods, such as the contact angle measurements by a reflected light beam,[10–12] the wetting force measurements by a liquid membrane method,[13] a sink-float technique to acquire the critical surface tension of the fibers,[12,14,15] and a dynamic contact angle measurement by a continuous immersion–emersion technique at a liquid-fiber boundary.[3] The most widely used and commercial methods are Wilhelmy wetting force measurement and the pendant-drop approach.

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The wetting force exerting on the fiber when the fiber in perpendicularis is immerged or pulled out from the liquid is measured in Wilhelmy method to calculate the contact angle, according to the relationships among the wetting force, the surface tension of the liquid, and the perimeter of the fiber and contact angle. It is suitable for the longer fibers with good wettability and higher density, which is larger than that of the liquid because the fiber with negative or poor wettability is not easy to enter into the liquid spontaneously and the fiber with lower density will be afloat on the surface of the liquid. For the pendant-drop method, the contact angle is acquired by analyzing the shape of liquid droplet deposited on the fiber by a micro-syringe. The contact angle from this method is relative to the surface shape of the contact point, and the method is poor repetitive for single-fiber measurement. It is difficult to measure the contact angle of a fiber with higher than 90° because the liquid droplet cannot stand still or steadily on the fiber.

The inserting method takes the angle between the fiber axis and the liquid surface at the one side as the contact angle while the contact point is in the horizontal surface of the liquid at another side. It is also difficult to get the contact angle because the interface is a complex curvature surface, and the contact point will move with the turning of the inserted fiber.

The liquid membrane method can be used to analyze the effect of finishing or the surfactants to the filaments. It checks the force changes along the filaments by moving the liquid membrane formed around the filaments to get the contact angles. The principle of the method is the same as that of the Wilhelmy wetting force measurement.

The sink-float method takes the surface tension of the liquid as the critical surface tension of the fiber when half of the fiber samples float on the liquid and half of the fiber samples sink in the liquid. When the critical surface tension of the fiber is higher than that of the liquid, the fiber will be wetted thoroughly and sink into the liquid, if not the case, the fiber will float on the surface of the liquid. This method needs the operators to estimate beforehand the possible value of the critical surface tensions of the fibers and to prepare a series of no polar liquids with different but close surface tensions. It is not easy and laborsome.

From the earlier, we know that the different methods are suitable to different usages and different type fibers. For the fibers with the contact angle higher than 90° and density lower than that of the liquid, it is difficult to evaluate their negative wettability. But the measurement of the poor wettability of the fibers is important for the fibrous materials used for antifiltering and resisting liquids entering. This paper develops another method to evaluate the wettability of the fibers described as follows: the wettability of the fibers is appraised by analyzing the force-displacement curve during the process of putting the fibers in horizontal into the liquids.

TABLE I
The Specimen Specification of the Multifilament Yarns

Sample no.		Type[a]	Fineness/filament number	Shape of cross section
Extracted	Unextracted			
1a	1b	DTY	8.33tex/48f	Circular
2a	2b	FDY	5.56tex/36f	Circular
3a	3b	DTY	8.33tex/48f	Cross
4a	4b	FDY	5.56tex/36f	Triangle

[a] DTY is the short for drawn texturing yarn and FDY is fully-drawn yarn.

EXPERIMENTAL

Samples and wetting liquids

A series of polyester multifilament yarns with different fineness and cross-sectional shapes were chosen and their specifications are listed in Table I. The samples were divided into two sorts, one is extracted with Soxhlet and the other is not extracted as a control. The extracted fibers were the extracted oils on the surface for 3 h by acetone, rinsed in distilled water, and then dried in the oven. All specimens were conditioned at 65% RH and 23°C for 12 h before being tested.

Heptane with low surface energy can wet almost all of the fibers. Some literatures took the contact angle of heptane to the polyester fibers and cotton fibers as zero.[7,16] In this article, the distilled water and heptane are chosen as wetting liquids. The surface tension of distilled water is 72.75 dyn/cm and that of heptane is 22.10 dyn/cm at 23°C, and so heptane is easier to wet fiber samples than distilled water.

Testing apparatus and testing methods

The testing apparatus is shown in Figure 1. The fiber frame is made of pure silver with 1.2 cm wide. This means that the length of the fiber being tested is enough to a little longer than 1.2 cm. The fiber was glued horizontally on the fiber frame by celloidin, and the two excessive ends of the fibers were cut. The silver fiber frame was hung on the Instron® force sensor with the precision of 0.1 mg and the fiber is 1 mm above the liquid surface. The sensor was calibrated to zero to eliminate the effects of the gravity of the fiber frame and the fiber. Then, the fiber was immerged into the liquid at the velocity of 2 mm/min. After 2 min when the sample was immersed totally into the liquid, the fiber frame was pulled out from the liquid at the same shift speed until the liquid membrane attached on the fiber broke out. The computer

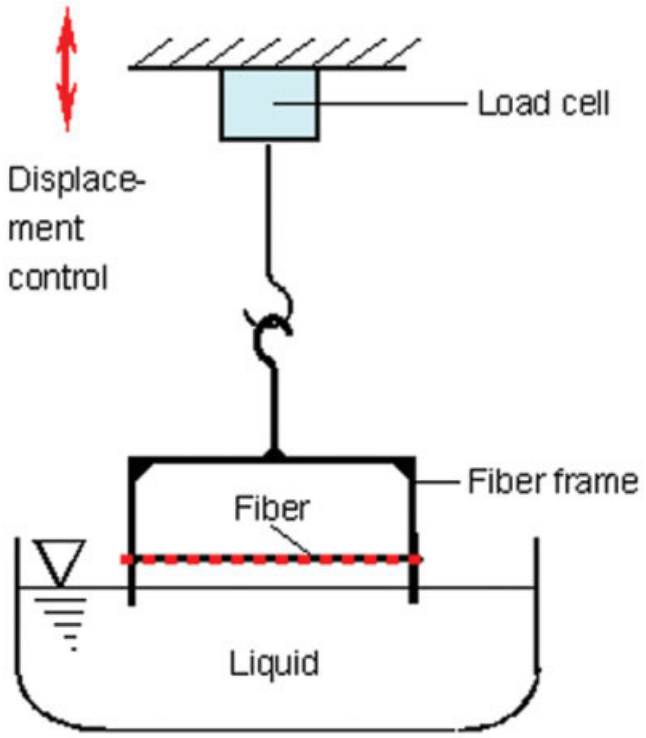

Figure 1 Schematic illustration of the testing apparatus. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

recorded the force-time curve to illustrate the wetting behavior of the fiber. The immersion step was controlled in 2 min and the pulling-out step was finished in 4 min for each sample.

As the wettability of fibers relies on the history of fiber wetting,[7,16] the wettability of the fiber in the second wetting is different from that in the first doing because the surface status of the immerged fiber has been changed. Therefore, a two continuous wetting tests for the same specimen and the same wetting liquid were done.

RESULTS AND DISCUSSION

Typical immerging and pulling-out curve

The schematic illustration of fiber positions and the typical immerging and pulling-out curve are both shown in Figures 2(a) and 2(b), respectively. Before t_1, from position O to position E records the fiber immerging process. The fiber frame is moved down just prior to the fiber–liquid contact at position O. At position O, we calibrate the detected force to zero. The force decreases with the fiber frame moving down but changing a little. We attribute it to the buoyancy increasing with the frame immersed. At position A, the fiber contacts with the liquid. The sharp force-impulse from point A to point B is mostly due to the liquid soaked to the fiber during which the fiber–air interface is displaced by the fiber–liquid interface. The subsequent linear decrease of the force from point B to point C is caused by the increase of the buoyancy of the fiber and the fiber frame, but the buoyant force on the fiber is dominant. While the fiber is immersed totally into the liquid, another sharp force impulse from point C to point D occurs from the closing of the separated liquid surface. The fiber frame continues to enter into the liquid from position D to position I, and the force at point D should be lower than that of the initial point A in theoretical because of the buoyancy of the frame and the fiber. The force should slightly decrease linearly from position D to position I due to the buoyancy of the frame. However, the little increase of the force, as shown in Figure 2(b), may come from the fiber soaking and the wicking on the frame.

After t_1, the pulling-out from position I to position H records the withdrawing process of the frame from the liquid. The slow increase of the force from position I to J1 is the contribution of the buoyancy decrease of the frame. The fiber starts being pulled out from the liquid at position J1, and the approximate linear force-increase is observed from point J1 to point J2. It indicates that the liquid surface close to the fiber is rising and the liquid membrane connected the fiber to the liquid is forming. With the pulling out, the force still increases from point J2 to point P gradually, and then decreases from point P to point P′ within a short range

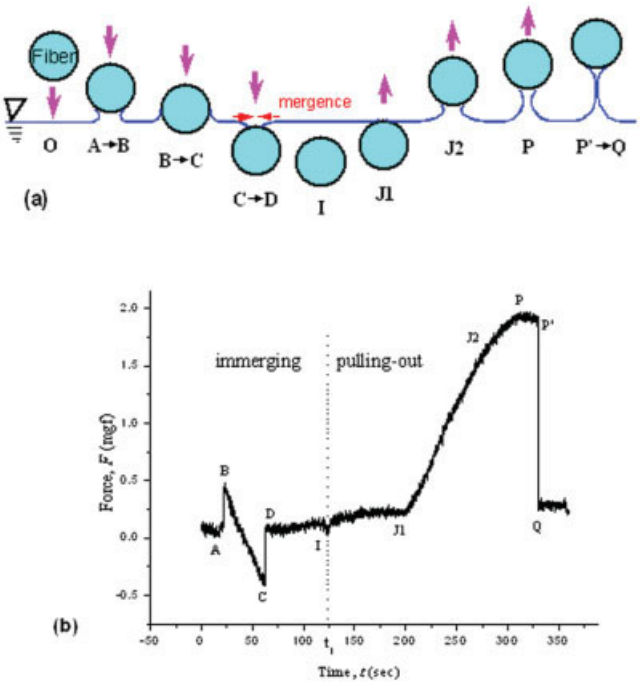

Figure 2 The process of immerging into and pulling-out from distilled water for the unextracted sample (no. 2b): (a) schematic illustration of the contact action between fiber and liquid and (b) typical immersion and pulling-out curve. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

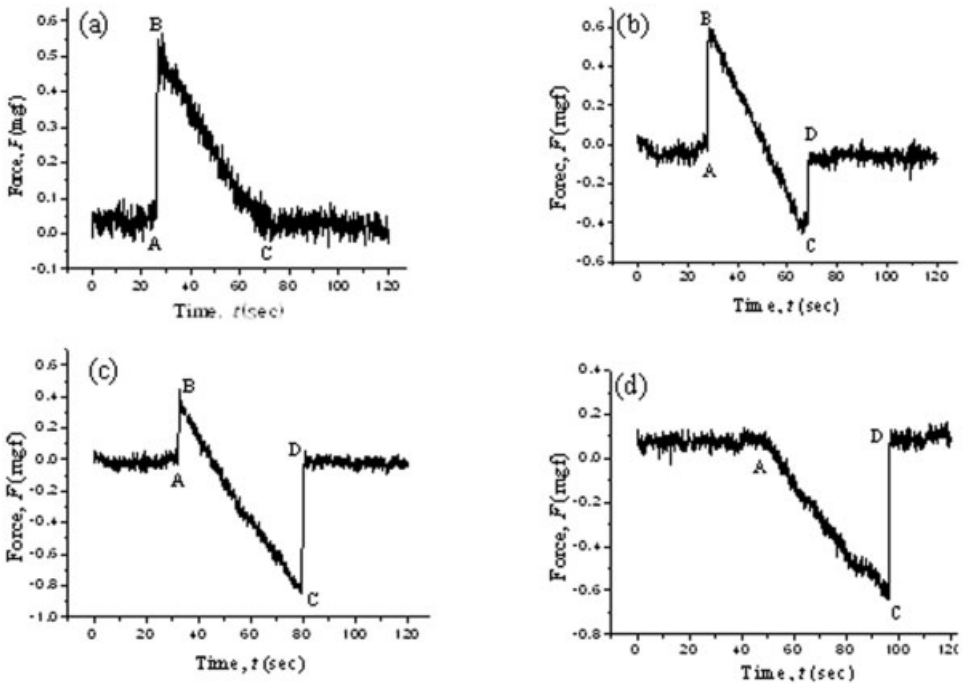

Figure 3 The four typical curves during the immerging process.

near to point P because the liquid membrane breaks from the fiber at different time. In fact, if the liquid membrane breaks out from the fiber at the same time, point P and point P′ should be one point. Lastly, the force drop from point P′ to point Q happens as the liquid membrane breaks completely.

For the immerging process from zero to t_1, i.e., point A–point D, four typical immerging behaviors for different liquids and fibers are observed and shown in Figure 3.

The force change from point C to point D is zero or near to zero, $F_{CD} = 0$, as shown in Figure 3(a). In experimental, all the fibers immerged into heptane appear this kind of behavior, that is, when fibers contact with heptane initially, the force increases sharply, then linearly decreases gradually until the fiber is immersed into the liquid. As aforementioned, heptane can wet polyester fiber thoroughly, and the contact angle between them can be considered as zero. The shape of the measured curve verifies the conclusion.

The force change from point A to point B is higher than that from point C to point D, i.e., $F_{AB} > F_{CD}$, as shown in Figure 3(b). Most of extracted fibers into distilled water show this sort of immerging curves. This kind of behavior indicates that the fiber is positive wetting. The contact angle, θ, should be $0° < \theta < 90°$. For the most second immersions of the samples, the force increment, F_{AB}, increases, whereas the force increment, F_{CD}, decreases at the second immersion. It indicates that the fiber becomes more easily wetted in the second time than in the first immersion by using the same liquid. The reason is that the fiber surface has been cleaned since the first immersion and becomes easier to contact with the liquid, that is just like the relationship between advanced (θ_A) and withdrawn (θ_W) contact angles, i.e., $\theta_A > \theta_W$, where the advanced contact angle is equal to that in first immersion, and the withdrawn contact angle approximates to that in the second contact. Therefore, a higher F_{AB} means a lower contact angle and more adsorbed liquid at the momentarily wicking. As the same, a lower F_{CD} because of the same fiber implies a lower contact angle and easier mergence while the fiber disappears into the liquid. It can also be proved from the results listed in Table II and Table III and from the fact that the higher the F_{AB}, the lower the F_{CD}.

The force change from point A to point B is lower than that from point C to point D, i.e., $F_{AB} > F_{CD}$, as shown in Figure 3(c). In the experiments, most of unextracted polyester fibers is the kind of immerging behavior in its first immersion into the distilled water. The typical curve is that the force increases suddenly when the fiber contacts with the liquid, then, decreases linearly, finally, increases sharply when the departed liquid surface is closed. The force-time curve indicates that the fiber is negative wetting during the immersion. The contact angle, θ, should be $90° < \theta < 180°$.

The force change from point A to point B is zero or near to zero, $F_{AB} = 0$, as shown in Figure 3(d). The phenomenon occurs only in the immersion of the unextracted no. 1 sample and no.3 sample into the distilled water for the first time. When the fiber contacts with the liquid, the force decreases because the liquid

TABLE II
Experimental Results of Different Polyester Fibers in Heptane and Distilled Water for First Wetting

	Heptane					Distilled water				
No.	F_{AB} (mgf)	F_{CD} (mgf)	w	θ (°)	F_{GH} (mgf)	F_{AB} (mgf)	F_{CD} (mgf)	w	θ (°)	F_{GH} (mgf)
1a	0.40	0	∞	0	0.67	0.31	0.24	1.29	78.6	1.06
2a	0.21	0	∞	0	0.62	0.31	0.24	1.29	78.6	1.06
3a	0.41	0	∞	0	0.64	0.34	0.23	1.48	72.6	1.02
4a	0.27	0	∞	0	0.65	0.47	0.32	1.47	72.8	1.06
1b	0.40	0	∞	0	0.67	0	0.73	0	180	1.05
2b	0.24	0	∞	0	0.64	0.30	0.39	0.77	101.7	1.04
3b	0.41	0	∞	0	0.63	0.09	0.84	0.11	162.1	1.11
4b	0.26	0	∞	0	0.64	0.23	0.78	0.29	139.5	1.06

surface deforms and is detached slowly. When the detached surface is closed, the force impulse occurs. The immerging behavior indicates that the fiber cannot be wetting, and the contact angle should be 180° or near to 180°.

Theoretical analysis

There are three steps from the fiber contacting with the liquid to the fiber immersing into the liquid thoroughly.

The first step is that the fiber initially contacts with the liquid, which is shown in from point O to point A of Figure 2(a) for $\theta < 90°$ and in (a) and (b) of Figure 4 for $90° < \theta < 180°$, respectively. The nature of the process is that the liquid adheres spontaneously to the surface of the fiber; thus, a liquid–air interface and a solid–air interface disappear, while a solid–liquid interface appears simultaneously. If the contact angle is lower than 180°, the liquid adheres to the fiber when the fiber is in the field of liquid molecule gravitation even without contacting with the liquid shown in Figure 2(a). This is why the first force impulse takes place. As the contact angle is equal to 180°, the liquid adheres to the fiber until the fiber contacts with the liquid shown in Figure 4(b), which corresponds to the zero force of F_{AB}.

The second step is mainly wetting, shown in Figure 2(a) from point A to point C for $\theta < 90°$ and Figures 4(b)–4(d) for $90° < \theta < 180°$. During the immerging process, the contact points between the fiber and the liquid move along the surface of the fiber, that means the solid–air interface and the liquid–air interface are displaced continuously by the solid–liquid interface. And the relative position of the contact point and the shape of liquid surface changes continuously. It can be found that there is the climb of the contact point on $\theta < 90°$ owing to wicking action, while there exist both the movement of the contact point and the deformation of the liquid surface for $90° < \theta < 180°$. At first, the contact points locate above the liquid surface, then horizontally with the liquid surface, and finally, below the liquid surface until the liquid surface closes with fiber immerging. The immerging steps are illustrated both in Figure 2(a) and in Figures 4(b), 4(c), and 4(d), respectively. At the same time, the force acted on the fiber by the liquid surface tension and its direction change continuously. It is very interesting and worth further discussing.

The third step is the separated liquid surface closing, shown in from point C to point I in Figure 2(a) and in Figure 4 from (d) to (e). The solid–air interface disappears, but the solid–liquid interface forms and the liquid–air interface reforms. When the contact an-

TABLE III
Experimental Results of Different Polyester Filaments in Heptane and Distilled Water for Second Wetting

	Heptane					Distilled water				
No.	F_{AB} (mgf)	F_{CD} (mgf)	w	θ (°)	F_{GH} (mgf)	F_{AB} (mgf)	F_{CD} (mgf)	w	θ (°)	F_{GH} (mgf)
1a	0.50	0	∞	0	0.67	0.50	0.30	1.67	67.4	1.02
2a	0.25	0	∞	0	0.62	0.38	0.27	1.41	74.7	1.07
3a	0.42	0	∞	0	0.64	0.35	0.23	1.52	71.4	1.08
4a	0.28	0	∞	0	0.67	0.50	0.31	1.61	68.9	1.05
1b	0.50	0	∞	0	0.69	0.38	0.35	1.09	86.1	1.07
2b	0.26	0	∞	0	0.64	0.28	0.36	0.77	101.7	1.09
3b	0.43	0	∞	0	0.62	0.38	0.61	0.62	111.1	1.11
4b	0.30	0	∞	0	0.72	0.25	0.65	0.38	130.4	1.06

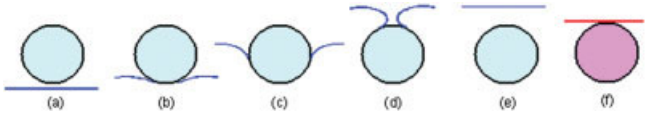

Figure 4 Schematic illustration of the relationship of fiber and liquid surface during three steps. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

gle is higher than zero, the liquid surface will not be close until the top of the fiber entering into the liquid to some distance, as shown in Figures 2(a) and 4(d), which results in the force increasing sharply. For the contact angle zero, the liquid surface will be close at the same time as the fiber top edge enters into the liquid totally shown in Figure 4(f).

According to the earlier analysis, supposing that the fiber is with circular cross section, the contact interface between the fiber and the liquid will be a column face when the fiber is horizontally forced into the liquid. Because the contact angle, $\boldsymbol{\theta}$, at fiber surface is the constant for a fiber, the effective wetting force acted on the fiber, which is the perpendicular component of the liquid surface tension, $\gamma^{\perp}$, will change with the contact point moving along the fiber surface, see Figure 5.

According to the scheme of Figure 5, the relationship between the contact point and the liquid surface during the movement of the contact point E can be found because point E and the contact angle, $\boldsymbol{\theta}$, de-

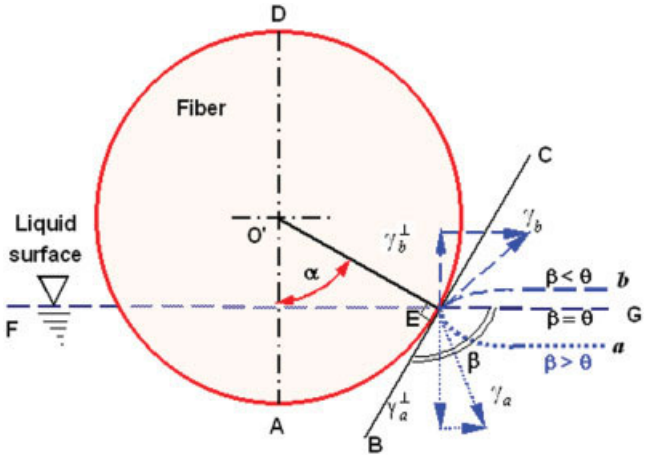

Figure 5 Schematic illustration of relationship between the contact point and the liquid surface, where point E is the contact point and shifts with the liquid advancing and withdrawing while the fiber immerging and pulling-out, respectively; point A is the initial contact point; point D is the final contact point when the liquid surface closes; and point O′ is the circle center of the fiber cross section; line BC is the tangent line at point E and line FG is the horizontal line via point E; α is the angle between line O′A and line O′E; β is the angle between the tangent line, CD, and the horizontal line, FG, at Point E. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

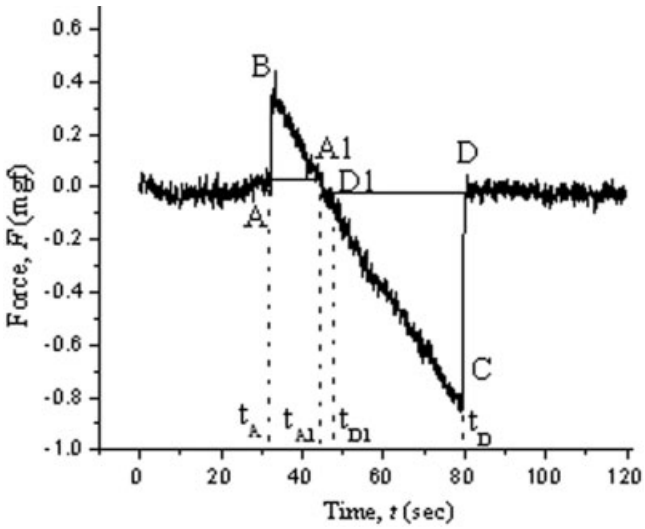

Figure 6 Schematic illustration of force analysis to experimental curve: $F_{A1} = \bar{F}_A$ at F_{A1}; $F_{D1} = \bar{F}_D$ at F_{D1}.

pend on the wettability of the immerged fiber. Obviously, the horizontal plane, i.e., line FG, and $\boldsymbol{\theta}$ are unchanged and what the changing item is the angle of β in this measuring system. In theory, there must be a contact point to let β equal to $\boldsymbol{\theta}$; thus, the contact angle of the fiber can be found.

If $\beta > \theta$, the contact point E locates above the liquid surface, i.e., line $\boldsymbol{a}$ so that the perpendicular component of the liquid surface tension, $\gamma_a^{\perp}$, directs downwards. If $\beta = \theta$, the contact point E is in the horizontal liquid surface, i.e., line **FG**, and the perpendicular component of the liquid surface tension is zero. And if $\beta < \theta$, the contact point E locates below the liquid surface, i.e., line $\boldsymbol{b}$ that the perpendicular component of the liquid surface tension, $\gamma_b^{\perp}$, directs upwards, that is the liquid surface tension will force the fiber to move up. Therefore, there will always exist a position at which the perpendicular component of the liquid surface tension is equal to zero during the immerging process of the fiber.

Calculation of wettability

In Figure 6, ignoring buoyancy, and let the value of the force at point A1 equal to that at point A. At that time, angle β at the point, E, is equal to the contact angle, $\boldsymbol{\theta}$.

As shown in Figure 5, with the contact point moving, angle β will decrease from 180° to 0° in geometric. Correspondingly to Figure 6, the shorter the time to reach point E at which $\boldsymbol{\beta = \theta}$ is, the larger the contact angle θ is, and the lower the wettability of the fiber is.

According to Figure 6, the wetting factor, w, is supposed to evaluate the wettability of the liquid to the fiber, which is $w = F_{AB}/F_{CD}$.

If t_T is the total time from the fiber initially contacting the liquid, t_A, to the last closing, t_D, of the separated liquid surface, the total radian for the contact point E moving from point A to point D is equal to π; thus, the time, t_T, can be measured.

$$t_T = t_D - t_A \quad (1)$$

Point E moves along the surface of the fiber, and the angle, α, increases and the angle, β, decreases. While $\beta = \theta$, we can obtain eq. (2).

$$\theta = \beta = \pi - \alpha = \pi - (t_{A1} - t_A) \cdot \pi / t_T \quad (2)$$

Because

$$w = \frac{F_{AB}}{F_{CD}} = \frac{t_{A1} - t_A}{t_D - t_{D1}} \quad (3)$$

where t_A, t_{A1}, t_{D1}, and t_D are shown in Figure 6, and if ignoring the buoyancy effect of the fiber, we have:

$$t_D - t_{D1} = t_T - (t_{A1} - t_A) \quad (4)$$

Combine eqs. (2), (3), and (4) together, the relationship between wettability and contact angle of the fiber with a circular cross section is:

$$\theta = \pi/(w + 1) \quad (5)$$

On the basis of the earlier analysis, the theoretical values of the contact angle are discussed in the following according to the wetting factor.

1. $F_{CD} = 0$, $w \to \infty$, $\theta = 0°$. The wettability of the liquid to the fiber is the best. The liquid can wet the fiber liquidly and spread on the surface of the fiber.
2. $F_{AB} > F_{CD}$, $0 < w < \infty$, $0° < \theta < 90°$. The wettability of the liquid to the fiber is the better. The bigger the value of w, the smaller the contact angle and better the wettability of the liquid to the fiber.
3. $F_{AB} = F_{CD,}$ $w = 1$, $\theta = 90°$. It means the wetting of the liquid to the fiber is zero, and is so-called the critical value of fiber wettability, neither wicking nor repelling.
4. $F_{AB} < F_{CD}$, $0 < w < 1$, $90° < \theta < 180°$. The wetting of the liquid to the fiber is negative. The smaller the value of w, the bigger the contact angle and the higher the negative wettability of the liquid to the fiber.
5. $F_{AB} = 0$, $w = 0$, $\theta = 180°$. The liquid cannot wet the fiber and the fiber must be forced into the liquid.

Obviously, the higher the value of w, the smaller the contact angle and better the wettability of the liquid to the fiber. On the basis of ignoring the buoyancy effect for the fiber with circle section, the contact angle is the function of the wetting factor, $\theta = \pi/(w+1)$. For the fiber with irregular cross section, the theoretical calculation of the contact angle may be not correct.

Effect of the fineness and shapes of fiber

Experimental results of polyester fibers with different fineness and shapes of cross section in heptane and in distilled water for the first wetting are shown in Table II and for the second wetting in Table III. The relative forces at point P, namely the force difference between point P and point Q, in heptane are all the same for various filament yarns with different fineness and cross-sectional shapes. They are also similar during the first wetting and the second wetting. Obviously, the force of stretching the liquid membrane depends only on the length of the fiber–liquid interface and the cohesive energy of the liquid. The relative forces at point P in distilled water are higher than those in heptane. The higher forces come from the higher interface tension between water and the fiber.

Comparing the data in Table II and Table III, during the continuous second immerging process, we can find that for the same fiber and same liquid, the initial immerging force, F_{AB}, increases and the closing immerging force, F_{CD}, decreases, especially for the sample no. 1b and sample no. 3b. Correspondingly, the contact angle is larger and the wetting factor is smaller in the first wetting than those in the second wetting. So, it is obvious that the force impulse during immerging is corresponding to the wettability of the fibers. The experimental results support the theoretical analysis mentioned earlier.

The fineness of fibers obviously affects the value of immerging force but little to the wettability according to the experimental results. The result is identical with the theoretical analysis. In Table II, the fibers with the same fineness such as sample no. 1 and sample no. 3, or sample no. 2 and sample no. 4 have the same or similar force changes during AB and CD steps and the same values of w in heptane. In the distilled water, the force impulses for the extracted fibers at AB and CD steps are a little different, but the values of w and contact angle for the filament yarns are close to each other. Theoretically, the contact angle is constant for the same fiber and the same liquid. The difference of the contact angle of the extracted polyester fibers comes from the difference of the cross-sectional shape because the theoretical estimation of the contact angle is based on the circular fibers. In the distilled water, the initial immerging force, F_{AB}, looks bigger among the samples with the same fineness such as unextracted sample no. 1 and unextracted sample no. 3.

Moreover, the difference of the surface oil on the polyester filament yarns may also influence the measurement.

For sample no. 1b and sample no. 3b, the value of F_{AB} is zero and near to zero, see in Table II and Table III, respectively, which is very different from the other samples in the distilled water. The distilled water cannot wet the fiber thoroughly, and so the value of F_{CD} is high. The measured data indicate that there is a low wettability for the polyester fibers, and the water cannot wet the filaments as a whole, so that the effect of fiber fineness is weakened.

The shape of the cross section of the fiber (Table I), which differs from fiber fineness, has a little effect to the force changes but affects the wettability, as shown in Table II and Table III. The fibers with the same fineness but the different cross sections such as sample no. 1 and sample no. 3 in heptane, or sample no. 2 and sample no. 4 in heptane, have similar force increments. The fibers with the same cross sections but the different fineness such as sample no. 1 and sample no. 2 have larger difference in force impulse values. So, for the immerging force impulses, the effect of the cross-sectional shapes is smaller than that of the fineness. However, the wetting factors, w, and the theoretical contact angles, θ, are different for the extracted fibers in the distilled water. Consequently, the difference of the cross shapes of the samples is the important factor to affect the wettability evaluation of fibers.

CONCLUSIONS

The wetting factor, w, acquired by the new method and the testing apparatus developed by authors can be used to evaluate the wettability of the liquid to the fiber quantitatively. The advantages of this measuring approach lie in the follows: (1) it is suitable for the single fiber and the fiber bundles with different length and different fineness, but most of the other methods can only be used for long and stiff fibers; (2) it is suitable for the measurement of fiber wettability, even for the fiber with very poor wettability; and (3) for the fiber with the density lower than that of the liquid. The theoretical analysis indicates that the contact angle can be derived from the immerging force curve and is the function of the wetting factor, w, for the fiber with circle cross section. The experimental results verify that the wettability of fibers can be characterized sensitively and accurately for very fine and flexible fibers by using the method.

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