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ABSTRACT

The flow dynamics of a thin viscous film down on a fiber is associated with a variety of industrial applications. In this paper, we experimentally investigate the flow behaviors of a thin film falling on differently shaped fibers. For a spiral fiber, flow behaviors show three typical flow regimes as the cylindrical fiber, which indicates the isolated regime, Rayleigh–Plateau regime, and convective regime. However, the transition process of various fiber shapes is distinctively different. Unlike the cylindrical fiber, flow on a spiral fiber exhibits a wider range of flow rate in the Rayleigh–Plateau regime, which is helpful for the precise control of flow patterns in a relatively stable regime. We further quantitatively investigate three important characteristic parameters of flow dynamics of a spiral fiber, i.e., bead velocity, thickness, and spacing. Results reveal that a thin film on a spiral fiber has a higher bead velocity, larger bead thickness, and larger bead spacing. Our findings provide important insights for understanding flow dynamics of a thin viscous film down on shaped fibers, which may also inspire coating flow control methods in various applications.

Thin liquid film flowing down vertical fibers is a typical unstable flow problem, and it breaks into liquid beads or drops due to the Rayleigh–Plateau instability. The rich dynamics of a thin viscous film down on a fiber is widely used in various industrial applications such as coating technology, heat exchangers, and vapor absorption. Among these applications, controlling the flow behaviors in a regular wave pattern is highly demanding. For example, controlling the coating flow with constant speed and constant spacing is an effective strategy for coating and photocuring the periodic wave pattern on a fiber. Therefore, it is of great importance to understand the flow dynamics of a thin viscous film down on a fiber.

When a liquid film falls down a vertical fiber, the gravity-driven flow exhibits complex interfacial dynamics, including the droplet formation and traveling wave patterns. The flow behavior was first demonstrated by Quéré, who investigated the film rupture characteristics and drop formation in both thick-film and thin-film systems. Kliakhandler et al. observed three typical flow regimes with increasing flow rates: (a) the isolated droplet regime, where widely spaced traveling beads are separated by small droplets, (b) the Rayleigh–Plateau regime, where a traveling wave propagates with constant speed and spacing, and (c) the convective regime, where faster and larger falling droplets are occasional collision. For the traveling wave behaviors, Duprat et al. used spatiotemporal diagrams to illustrate the absolute and convective instabilities, where the spatial growth is emphasized. Other experimental results show that the flow dynamics in such systems are mainly influenced by the flow rate, fiber diameter, and other fluid properties, e.g., the viscosity and surface tension. In addition, Sadeghpour et al. found that the nozzle geometry also changes the flow dynamics, where the liquid bead thickness, spacing, and velocity are used to characterize its dynamics.

The viscous film coating a fiber has been intensively studied in recent years. For a thin film coating flow, simple models based on the long-wave assumption were utilized to investigate the linear and nonlinear dynamics. It has been demonstrated that the flow is unstable due to the azimuthal curvature. Liu and Ding proposed a domain mapping method to solve the Navier–Stokes equations directly, by which the exact steady traveling wave solutions of a thick liquid film are explored. Recently, the effects of applied physical fields on coating flows have been extensively considered. For example, flow with thermocapillary effects, subject to electric fields, rotation fields, and disjoining pressure fields, has proven to be an effective approach to control the stability and dynamics of coating flows. The results showed that applied physical fields may trigger film breakup into droplets due to the enhancement of absolute instability.
Previous experimental and theoretical studies all focused on the cylindrical fiber, and the considered system is axial symmetry, whereas the radial and wall effects are always neglected. Consequently, the effects of fiber properties (porous media or slippery walls) are not quantified. However, these effects are proved to be of equal importance as other factors in the literature. Ding and Liu\textsuperscript{25} numerically studied the viscous film down on the porous fiber, which results in a more unstable behavior than that on the solid impermeable fiber. By increasing the permeability of the porous medium, the instability is enhanced. In addition, the instabilities in the spin coating of thin polymer films over porous substrates have also been studied.\textsuperscript{26} More importantly, fiber properties of the slippery wall\textsuperscript{27} were also investigated. Unlike the no-slip boundary, the slip effects strongly promote droplet formation and enhance the size and speed of droplets for thin film flows, leading to different dynamic behaviors. Sathyananth et al. investigated dip coating flows over porous solid substrates and identified regimes of thin liquid films, where they verified that the coating thickness is a function of the rescaled capillary number.\textsuperscript{28} These conclusions verify that fiber properties indeed influence the flow dynamics. Therefore, it is necessary to further investigate the dynamic behaviors of a thin viscous film down on the spiral fibers, which differ from other shapes. This implies that the spiral structure is essential in determining the flow dynamics of the liquid film, especially in the Rayleigh–Plateau regime. By considering key dynamic factors in this process, we propose the spatiotemporal diagram to evaluate the bead speed. We further quantitatively demonstrate that the spiral shape of fibers affects the flow dynamics, which results in the variation of characteristic parameters such as the liquid bead thickness and spacing. Our results are beneficial to enrich the fundamental mechanisms of thin viscous film flows, as well as applications involving the manipulation of electrospinning jets, which are used for producing fibers of solid materials by electrifying a liquid jet.\textsuperscript{29,30} Thus, different regimes of instability could be found based on the flow rate of liquid into the spinneret nozzle and liquid surface tension and viscosity.

We investigate the behavior of liquid films down on different types of fibers, as shown schematically in Fig. 1. Silicone oil v500 (density $\rho = 960\, \text{kg/m}^3$, viscosity $\mu = 500\, \text{mPa}\cdot\text{s}$, and surface tension $\sigma = 21\, \text{mN/m at 25}^\circ\text{C}$) is used as the working fluid. The viscous oil is extruded through a copper nozzle ($D_0 = 1\, \text{mm}$), and the flow is generated by a syringe pump (Longer Pump, China). The flow rate $Q$ is controlled from 0.1 to 25 ml/h. Sliver fibers with various shapes are fixed in the center of the nozzle, and then the liquid is guided along the fiber to form a thin film. The cross section of each shaped fiber is cylindrical, square, or spiral (the pitch is 4.4 mm), where their equivalent diameter is the same ($D = 0.5 \, \text{mm}$), as plotted at the right bottom in Fig. 1. To obtain the fully developed flow and stable state behavior, a fiber with 1.2 m length is used, and the observation position is 0.4 m away from the nozzle. We observe the attracting liquid film for several minutes in a constant flow rate, which ensures that the flow behaviors are not changed by the pump fluctuations. The dynamic behaviors of the liquid film caused by the Rayleigh–Plateau instability are recorded with a high-definition camera (LBAS-U350) at 25 frames/second. The axisymmetric flow morphology of liquid films, including the liquid bead thickness, spacing, and velocity, is analyzed by the image processing method. In addition, the spatiotemporal diagram for determining the flow dynamics is achieved by means of MATLAB software.

To characterize the parameters of the liquid film morphology, a border detection method based on the bilateral filtering algorithm and the Canny operator is proposed, as presented in the literature.\textsuperscript{24} We extract the contour of the liquid film (in the Cartesian coordinate system) and convert the pixel value into height based on the scale, as illustrated in Fig. 2. The height minus the fiber radius is equal to film thickness. Then, the liquid bead thickness $D_b$ is defined by the film thickness at the maximum curvature location, and the bead spacing $S_b$ is the average distance between two adjacent peaks. The bead velocity $V_b$ is determined by the variations of peaks at different times. From Fig. 2, we measure the film thickness ranging from 0.16 to 0.78 mm. According to the volume conservation, we integrate that the average thickness of liquid films is 0.49 mm, which is comparable to the fiber’s radius. The uncertainties in the measurement method due to the single-pixel scaling and the selection of the contour are estimated to be $\pm 0.04\, \text{mm}$.

Dynamic behaviors of shaped fibers on distinct flow regimes are first investigated. Three typical flow regimes formed by viscous liquid down on the spiral fibers are presented in Fig. 3. At a low flow rate, the liquid film ruptures to form equally spaced isolated droplets and propagates at a constant speed, called regime I. Note that several smaller droplets are derived in the back region between the big isolated droplets with regular sequences. Upon increasing the flow to a moderate rate, the Rayleigh–Plateau regime appears with closely bead spacing,
regarded as regime II, which is a relatively stable regime. At a high flow rate, droplet coalescence and breakup occur continuously, giving rise to convective instability behavior as regime III. Unlike the first two regimes with well-defined frequency characteristics, regime III exhibits growing wave behavior and results in time-dependent spacing and faster falling speed. The resulting flow regimes for the spiral and square fibers are consistent with the cylindrical fiber in the literature. To elucidate the underlying mechanisms of the flow regimes transition, we define a Bond number, which denotes the relative importance of the gravitational effect over the surface tension effects. Here, \( \text{Bo} = \frac{\rho g D_f^2}{\sigma} \), where \( g \) is the gravitational acceleration and \( l_{\text{eff}} \) is the effective length. For the cylindrical, square, and spiral fibers, the effective length is \( D_f/2 \), \( \sqrt{2D_f^2}/2 \) and \( \sqrt{2\pi(D_f/4)^2}/\pi \), respectively. Thus, for square, cylindrical, and spiral fibers, the Bond number is 0.055, 0.028, and 0.0045, respectively. The flow rate is also defined as a dimensionless quantity, \( Q = Q/(\pi D_f^2) \). Then, we plot the flow regimes using Bo and nondimensional flow rate. Figure 4 shows the phase diagram results for differently shaped fibers. Results reveal that the above-mentioned typical flow regimes are transiting in the same way. As the flow rate increases, the isolated regime arises first, then becomes the Rayleigh–Plateau regime, and ultimately manifests the convective regime. Interestingly, we find that the critical nondimensional flow rate of the transition process for the three shaped fibers is significantly different. For fibers with cylindrical cross sections, the critical point is from regime I to regime II and regime III, and the critical nondimensional flow rates are 0.013 and 0.056, respectively. While for a square fiber, the critical value is 0.013 and 0.053. However, the spiral fiber has a wider range of flow rate to keep the flow behavior under stable conditions in regime II. From regime I to regime II, the critical nondimensional flow rate is nearly 0.04, which is three times higher than the other shapes. When it turns into an unstable convective regime, the nondimensional flow rate needs to reach at 0.135, which fully retards the transition. This is due to the different sectional areas for different cross-sectional shapes. Although the equivalent diameter is identical, the sectional area plays a significant role in the
flow dynamics. A smaller sectional area like spiral fibers leads to a retardation of the transition regions when the flow rate increases. This indicates that the effect of the fiber shape plays a role in flow dynamics and provides important insights into precisely controlling the flow patterns.

To further study the effect of fiber shapes, we propose to use the spatiotemporal diagrams of the three shaped fibers to determine the flow dynamics, as illustrated in Fig. 5. The extracted film-thickness variations with time at a given position, typically 0.4 m, are presented. Each light line represents the spatiotemporal trajectory of the liquid bead, and the bead velocity is determined by the line slope. Here, we focus on a relatively stable regime to analyze the flow dynamics; thus, the nondimensional flow rate of 0.053 is selected. Under this specific flow rate, the liquid film on all the three shaped fibers is stable in the Rayleigh–Plateau regime. We find that the light stripes are parallel and spatially uniform for all the three kinds of fibers, which indicate that the propagations of three shaped fibers have a constant velocity and spacing. When the bead velocity of differently shaped fibers is compared, the velocity of the spiral fiber is significantly higher than that of the cylindrical and square fibers. The underlying mechanism can be attributed to the additive helical flow near the spiral wall, which increases the relative velocity. This implies that the spiral structure is significant in speeding up the gravity-driven flow of the liquid film.

To quantitatively describe the bead velocity variation and its dynamics, we measure the bead velocity at differing nondimensional flow rates for the three kinds of shaped fibers, as shown in Fig. 6. As the velocity variation induced by the droplet coalescence is quite different in the convective regime, the velocity in regime III is not given in this paper. Figure 6 clearly shows that the bead velocity increases with the nondimensional flow rate in regime I for all the three shaped fibers. The reason can be illustrated by the phenomenon that a big isolated droplet swallows up the smaller droplets in the back region, so that the droplet becomes bigger and faster. When the flow transmits to regime II, the velocity slightly changes as the nondimensional flow rate increases. More importantly, the bead velocity down on the spiral fiber is the highest and then followed by square fibers and cylindrical fibers. These results confirm our previous observations from the spatiotemporal diagrams.
The flow dynamics are also characterized by the liquid bead thickness and bead spacing. To elucidate the relationship between the bead thickness and nondimensional flow rate, we measure the bead thickness on differently shaped fibers before it changes to the convective regime, as shown in Fig. 7. We repeated each case at least five times under the same condition and then used these measurements of the bead thickness to compute the standard deviation. We observe that the spiral fiber has a greater bead thickness in regimes I and II, while coating flow on square and cylindrical fibers always show similar dynamic behaviors. We notice that in each of the regimes, the bead thickness remains almost constant. The difference is that in regime I at a lower nondimensional flow rate, the thickness is larger than that in a higher nondimensional flow rate of regime II. Thus, we can demonstrate that when the flow exhibits either isolated or Rayleigh–Plateau behavior, the flow instability could keep the bead morphology stable in a wide range of flow rate.

Figure 8 shows the relationship between the bead spacing and nondimensional flow rate for differently shaped fibers. It is found that the bead spacing decreases exponentially with the increase in the nondimensional flow rate for all the three kinds of fibers. When the nondimensional flow rate increases and bead thickness is constant, the bead spacing may decrease according to the mass conservation. Note that at a given nondimensional flow rate, the bead spacing on spiral fibers is larger, which indicates that the spiral fiber plays a significant role in terms of determining the propagating cycle. In the critical transition region from regime I to regime II, the bead spacing of square, cylindrical, and spiral fibers are 22.27, 24.98, and 19.27 mm, respectively. While for the transition from regime II to regime III, the bead spacing is nearly the same, being around 4.87 mm. These results reveal that different fiber shapes have little effect on the bead spacing from a relative regular state to the convective state but will slightly change the bead spacing from the isolated regime to the Rayleigh–Plateau regime.

In this paper, we study the influence of fiber shapes on the flow dynamics of the thin viscous film falling down a vertical fiber. The cross sections of cylindrical, square, and spiral are systematically investigated. For the spiral fiber, the flow behaviors show three typical flow regimes, i.e., the isolated, Rayleigh–Plateau, and convective regimes. However, the transition process is significantly different, which implies that the spiral structure plays an important role in determining the flow dynamics of the liquid film. Flow on the spiral fiber exhibits a wider range of the flow rate in the Rayleigh–Plateau regime. This helps one to control the flow pattern in a relatively stable regime, which is one of the challenges in coating technology. By considering key dynamic factors in this process, we propose to use the spatiotemporal diagrams to evaluate the bead speed. It shows that the bead velocity on the spiral fiber is significantly higher than that on the cylindrical and square fibers. We further investigate the effects of spiral fibers in a quantitative way, focusing on the three characteristic parameters of flow dynamics, velocity, bead thickness, and spacing. Results reveal that a thin film on spiral fibers has a higher bead velocity, larger bead thickness, and larger bead spacing. Our findings provide the missing pieces of the fundamental understanding of thin viscous films down on the shaped fiber and have important potential applications involving the manipulation of coating flow and electrospinning jets.

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AUTHOR DECLARATIONS
Conflict of Interest
The authors have no conflicts to disclose.

DATA AVAILABILITY
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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