Dynamical wetting transition of a stretched liquid bridge

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AFFILIATIONS

ABSTRACT

The liquid bridge is an important model problem in printing processes. We report the experimental results of stretching a highly viscous liquid bridge between two parallel plates. Depending on the stretching speed, a thin liquid bridge exhibits two representative flow regimes. At low stretching speeds, the liquid bridge deforms in a quasi-static manner and no liquid films are observed. When the stretching speed exceeds a critical value, the contact line fails to follow the retracting meniscus, resulting in the deposition of liquid films on the plate. The entrained film is characterized by an annular rim that retracts and grows by collecting the liquid in the film. It is found that the velocity of the receding contact line is weakly decreasing, and the growth of the rim is characterized by a width of \( \frac{w_{\text{rim}}}{C_2} \approx C_1^{1/2} t^{1/2} \), where the capillary number \( C_a \) is defined by the stretching velocity and \( t \) is the time. The film may not be fully absorbed into the bulk of the liquid bridge before its eventual breakup at high stretching speeds, leading to variations in the liquid transfer ratio of the two plates.

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I. INTRODUCTION

A liquid bridge is a liquid that is held between two solid plates by surface tension forces. This phenomenon has been observed in several biological behaviors, such as the feeding mechanism of shorebirds and the lapping of animals. Liquid bridges have gained significant importance and attention in recent decades due to their relevance to a wide range of practical applications, including printing, porous-media flow, oil recovery, and rheological measurements. Extensive investigations have been conducted on the equilibrium shape and stability of a static axisymmetric liquid bridge between two disks or rods in industrial applications, both theoretically and experimentally, in the absence or presence of gravity.

The dynamic process of liquid bridges is more complicated due to the presence of deforming surfaces and moving contact lines. In the context of printing, of importance is the amount of liquid transferred between two adjacent substrates, which may be flat or contain cavities. The system can be modeled as a liquid bridge subject to a combination of stretching, shear, and rotation. The resulting motion of the liquid bridge is essentially three-dimensional and significantly asymmetric, making the problem challenging to solve. Dodds et al. conducted finite-element simulations of a liquid bridge under stretching combined with shear or rotation. They were able to produce the three-dimensional morphology of the liquid bridge by neglecting inertia and gravity. The study found the liquid transfer depends on the rotation and is insensitive to shear. Although contact lines are pinned in most calculations, a limited number of simulations with moving contact lines has shown that dynamic wetting plays a key role and can act as a potential strategy for adjusting the amount of transferred liquid. Campana and Carvalho investigated the stretching of liquid bridges between a plate and a trapezoidal cavity, with or without rotation. For simplicity, the problem was modeled as a two-dimensional system. They found the volume of liquid transferred from the cavity depends strongly on the plate motion as well as the moving contact lines. Since the dynamics of the liquid bridge is complicated for a general motion of the driving plate, it is simpler yet instructive to consider the situations with pure shear or stretching.

The shear of a liquid bridge can be implemented by imposing a pressure gradient or a relative motion between the confining substrates. Dimitrakopoulos and Higdon employed the boundary integral method to study the deformation of a liquid bridge subject to shear flow induced by a pressure gradient. They found that the shape of the contact line is influenced by the contact angle hysteresis and the capillary number. Wiklund et al. used a lattice Boltzmann numerical method to study the shear dynamics of two-dimensional capillary bridges between parallel plates, focusing on the dependency of shear resistance on the flow. Winkels et al. and Wu et al. carried out experiments to investigate the shear of a three-dimensional liquid bridge. At high shear rates, the shear can cause the formation of a...
cornered contact line and the emission of tiny droplets. This phenomenon is known as the dynamical wetting transition and has also been observed in sliding drops. Wang and McCarthy conducted an experimental study on the shear distortion and breakup of liquid bridges. They found that sessile droplets can be deposited on the plates, which are characterized by hydrophilic spots. Shear has also been used as an effective strategy to remove liquids from a cavity, as demonstrated in the experiment of Yin and Kumar. They discovered that the amount of the liquid entrained in the cavity after the liquid bridge breaks follows a power law dependence on the shear rate.

More extensive investigations have been devoted to the dynamics of liquid bridges under stretching. In this situation, the liquid bridge usually admits an axisymmetric geometry and can be conveniently handled. Early experiments of Chadov and Yakhnin showed that more liquid was transferred to the more wettable substrate at low stretching rates, while approximately the same amount of liquids was deposited on the substrates at sufficiently high rates, even though the wettability of the substrates was significantly different. These results demonstrate the important role of moving contact lines in the dynamics of the liquid bridges, which was also demonstrated by Kang et al. through detailed measurements. Using numerical simulations, Dods et al. showed that the contact line was effectively pinned at high stretching rates, leading to symmetric breakup. They further reported that inertia tended to shift the breakup point away from the less wettable plate, thus playing a competing effect with wettability. Qian et al. showed experimentally and numerically that the stretching of a liquid bridge can be regarded as a two-stage process. In particular, the liquid bridge suffered an instability before its pinch-off, leading to a rapid retraction of the contact line. Zhang et al. studied the dynamic stretching of a liquid bridge between two disks with fixed contact lines, using both experimental and numerical methods, and quantitatively probed the effect of physical and geometrical parameters on breakup characteristics. The setup for stretching of a thin liquid bridge is usually referred to as a tilted Hele-Shaw cell, which has also received much attention in the literature. The stretching can be realized by specifying a stretching velocity, a driving force, or an acceleration. The liquid bridge exhibits a fingering instability at high stretching rates, which is usually accompanied by the presence of a residual liquid film on the substrates. While the fingering instability is well investigated, less is known about the dynamics of the entrained film.

So far, investigations of the stretching process mainly concerned the cases in which the height and radius of the initial liquid bridge were comparable or the thin liquid bridges in the presence of fingering instabilities. In this work, we experimentally investigate the stretching process of a highly viscous liquid bridge between two parallel plates, focusing on the situation of thin liquid bridges, in which the height is much less than the radius. We will demonstrate that liquid films can be entrained on the substrates when the stretching rate is beyond a threshold but remains low to avoid the fingering instability. This phenomenon, known as dynamical wetting transition, has received significant attention in recent years. We perform a detailed analysis of the dynamics of the entrained film, which will be shown to affect the morphology of the liquid bridge and the liquid transfer ratio after the breakup.

II. EXPERIMENTAL SETUP

The experimental setup is shown schematically in Fig. 1. To generate a liquid bridge, a drop of silicone oil of volume \( V_0 = 13.6 \pm 0.2 \mu L \) was deposited onto the lower plate using a syringe. The silicone oil has a viscosity of \( \mu = 488.5 \) cP, a density of \( \rho = 971 \) kg m\(^{-3}\), and a surface tension of \( \sigma = 0.0211 \) N m\(^{-1}\) and was produced by Clearco. The volume of the liquid drop was fixed in our experiments and was measured with a high precision balance. The variation of the volume during each experiment was less than 1%, confirming the low evaporation of the liquid. The upper plate remained fixed and the lower plate was moved vertically using a high performance linear motor stage (IMS-LM from Newport). Both plates had a size of \( 75 \times 50 \times 0.5 \) mm\(^2\); in order to avoid contact line pinning, they were coated with a fluoropolymer (EGC-1700 from 3M), on which silicone oil has a static contact angle of \( \theta_c = 40.0 \pm 1.1^\circ \). The receding contact angle is approximately \( 36^\circ \) and is more relevant to the stretching problem. Initially, the lower plate together with the drop moved toward the upper plate at a sufficiently low speed. The drop then touched the upper plate to form a liquid bridge, which was subsequently squeezed until the required diameter or thickness was reached. The liquid bridge was stretched by moving the lower plate downward at a constant velocity \( U \). This process was recorded until the two plates were separated enough such that the liquid bridge broke up.

The entire experiment was conducted at a controlled room temperature of \( 23 \pm 0.1^\circ C \). Two cameras were used to capture the stretching process from both the side and top views. The side view of the liquid bridge was recorded using a Blackmagic URSA Mini 4.6k CCD camera equipped with a lens (2\( \times \times 20 \times \times \)). The field of the camera can reach up to \( 4608 \times 2592 \) pixels, with a spatial resolution of \( 0.278 - 2.78 \) \( \mu \)m pixel. This allows for the accurate capture of the shape of the liquid bridge, the width of the liquid film, and the position of the contact line. The top view of the liquid bridge was recorded using an AX-200 mini-camera. The images were analyzed using a Photron FASTCAM Viewer and MATLAB after the experiment. To enhance the image contrast, two light sources were positioned at an appropriate distance to produce a distinct and uniform background throughout the imaged area.

For the parameters of present interest, one can estimate that the Reynolds number is sufficiently small due to the high viscosity of the liquid such that inertia effect can be safely neglected. There are two independent parameters that can be adjusted in our experiment, namely the stretching velocity and the initial radius of the liquid bridge. They can be expressed in a dimensionless form using the capillary number \( Ca = \mu U/\gamma \) and the initial aspect ratio \( \lambda = R_0/H_0 \).
where $R_0$ and $H_0$ denote the radius of the initial contact surface and the initial height of the liquid bridge, respectively. In the present work, $\text{Ca}$ is varied by changing the stretching velocity $U$, and we focus on liquid bridges that are initially thin, i.e., $\lambda \gg 1$. In all experiments, the height of the bridge is much less than the capillary length before the stretching, but can exceed it when the plates are well separated. Therefore, gravity can be neglected, and the liquid bridge is symmetric up and down in the early stage. Gravity becomes important in the late stage, leading to asymmetric shapes of the liquid bridge.

### III. RESULTS AND DISCUSSION

#### A. Flow regimes

By varying $\text{Ca}$ and $\lambda$, two different stretching processes can be observed. Figure 2 shows the instantaneous side views of the evolution of the surface morphologies for $\lambda = 11$ and two representative values of $\text{Ca}$. Starting from the same initial configurations, the liquid bridges are stretched at different rates and eventually break up into two sessile droplets. A close examination of the early stages of stretching shows that liquid films are entrained at $\text{Ca} = 1.866 \times 10^{-2}$, while no films are observed at $\text{Ca} = 6.22 \times 10^{-4}$. For convenience, the stretching process in the absence and presence of the entrained films is referred to as regime I and II, respectively. The evolution of the liquid bridge in regime I is similar to that observed in previous experiments, except that a more viscous liquid is used in our work. In the following, we focus on regime II, which has not been well investigated before. In addition to the film deposition, the stretching rate also affects the location of breakup and the liquid transfer ratio, which will be discussed later.

More information about the interface structures in regime II can be gained by examining the side and top views simultaneously, as illustrated in Fig. 3 for $\lambda = 23$ and $\text{Ca} = 3.11 \times 10^{-3}$. It is seen from the top view that the liquid bridges evolve in an axisymmetric manner. The contact line can be clearly identified and maintains a perfect circular shape. The black rings in the top view represent the footprint of the meniscus, with the inner radius of the ring equal to the minimum radius of the liquid bridge. Once a liquid film is entrained, the outer edge of the black ring defines an apparent contact line, where the
meniscus intersects the liquid film. Our results show that the film is immediately entrained when the liquid bridge begins to extend. As the liquid bridge is stretched, both the contact line and the meniscus retract, and a competition between them can be observed. In the early stages of stretching, the retraction speed of the meniscus and the apparent contact line is greater than the real contact line, resulting in an increase in the area covered by the film. As the liquid bridge continues to deform, the speed of the apparent contact line decreases continuously, and the receding contact line tends to catch up with the meniscus. Depending on the flow parameters, the entrained film may or may not be absorbed into the bulk of the liquid bridge before the breakup. From the top view images, it can be seen that the retraction of the film is characterized by a well-defined annular rim, whose thickness is larger than the flat region of the film. The rim grows in size by collecting the liquid in the film, a scenario also observed in the drying of a film with a hole.\(^{36}\)

**B. Critical capillary number between regimes I and II**

The deposition of liquid films at high stretching rates is reminiscent of the dynamical wetting transition encountered in forced dewetting, such as dip coating of a plate\(^{33,49}\) and gas–liquid displacement in a capillary tube.\(^{46,51}\) In these problems, there is a critical capillary number \(\text{Ca}_{b,c}\) in the stretching of liquid bridges, a parametric study was performed. Figure 4(a) shows a phase diagram in the \((\lambda, \text{Ca}_b)\)-plane, where the two flow regimes are marked by different symbols. The boundary between the two flow regimes is represented by the dashed line, which shows that the critical capillary number \(\text{Ca}_b\) decreases monotonically with \(\lambda\).

In forced dewetting, a more relevant parameter is the relative velocity between the meniscus and the substrate. We have measured the initial retraction velocity of the meniscus by using the top view images. This speed is also the maximum speed of the meniscus and can be used to define a new capillary number \(\text{Ca}_b\). Note that we have assumed that different points of the meniscus move at the same speed, which is reasonable since the bridge is thin at the early stage. A phase diagram in the \((\lambda, \text{Ca}_b)\)-plane is shown in Fig. 4(b). It is interesting to note that the boundary between the two flow regimes is simply a horizontal line. The corresponding critical velocity of the meniscus is \(\text{Ca}_{b,c} = 8.7 \times 10^{-3}\), independent of the aspect ratio \(\lambda\). This is not surprising since it is expected that the macroscopic geometry has only a logarithmic effect on the critical velocity of the wetting transition,\(^{35,52}\) which cannot be detected for the parameters considered.

Based on the constant velocity of the meniscus at the onset of film deposition, an approximate analytical expression for \(\text{Ca}_b\) can be derived. For thin liquid bridges, we can neglect the detailed geometry of the meniscus and write the liquid volume as

\[V(t) = \pi R^2(t) H(t),\]

where \(R(t)\) and \(H(t)\) denote the radius of the contact line and the height of the liquid bridge, respectively. Differentiating with respect to time yields

\[2R(t)H(t) + UR(t) = 0,\]

noting that \(U \equiv H'(t)\). Applying this relation at \(t = 0\), we have

\[\text{Ca}_b = \frac{2\text{Ca}_{b,c}}{\lambda},\]

which is plotted as the solid line in Fig. 4(a). This relation captures the boundary between the two flow regimes when \(\lambda > 7\). The deviation from the numerical solution becomes significant for smaller values of \(\lambda\), where the liquid bridge cannot be approximated as a thin cylinder and the morphology of the meniscus should be taken into account.

**C. Diameter of the liquid bridge**

A further comparison of regimes I and II is made by examining the variation of the diameter of the liquid bridge. For convenience, all the lengths are scaled by \(V_0^{1/3}\) in the following. In Fig. 5, the minimum diameter of the liquid bridge, \(D_{\text{min}}\), is plotted as a function of height \(H\) for \(\lambda = 18\). We have chosen three representative stretching rates, i.e., \(\text{Ca}_b = 0.155 \times 10^{-3}\) for regime I and \(\text{Ca}_b = 3.110 \times 10^{-3}\) and \(4.354 \times 10^{-3}\) for regime II. The adoption of \(H\) rather than \(t\) as the horizontal coordinate is appropriate because the geometry of liquid bridges of the same height can be conveniently compared, as in Fig. 2.
In all cases, the minimum diameters decrease monotonically from their initial value to zero, where breakup occurs. During most of the stretching process, the meniscus is expected to retract in a quasi-static manner since $Ca/C_2^1$, except near the final breakup, where $D_{min}$ decreases rapidly. At the early times, the liquid bridge is thin, and a similar analysis based on mass conservation yields

$$D_{min} \approx 2/\sqrt{\pi H},$$

(2)

where the liquid in the entrained film has been neglected in regime II. This relationship is confirmed in Fig. 5 for all values of $Ca$.

For a fixed $H$, the minimum diameter in regime II is slightly smaller than that in regime I. This is obviously due to the mass loss of the bridge associated with the entrained film. Strictly speaking, the amount of entrained liquid should depend on the stretching rate; however, the resulting difference in $D_{min}$ for the two values of $Ca$ in regime II is too small to be observed in Fig. 5. Different shrinkage behaviors can be observed close to the breakup. As mentioned earlier, the entrained film may or may not be completely absorbed into the liquid bridge before breakup (see Figs. 2 and 3). At $Ca = 3.110 \times 10^{-3}$, the film is fully absorbed, and the subsequent evolution of the liquid bridge behaves as in regime I. Consequently, the data of $D_{min}$ at $Ca = 3.110 \times 10^{-3}$ (red circles) overlap the results of $Ca = 0.155 \times 10^{-3}$ (green squares), yielding the same height for breakup. In contrast, the film is not fully absorbed, and the breakup occurs at a smaller bridge height when $Ca = 4.354 \times 10^{-3}$.

D. Liquid film

The instantaneous morphology of the entrained film is shown schematically in Fig. 6. The film is characterized by a dewetting rim near the real contact line and connects to the meniscus at the apparent contact line. Both the real and apparent contact lines shrink during the stretching, and the competition between them determines the lifetime of the entrained film. The dewetting of a flat film induced by initializing a dry spot was investigated experimentally by Redon et al. who reported a constant velocity of the contact line. The present film dewetting also exhibits a constant velocity, although here the contact line shrinks, while in the other problem, it expands along with the dry spot. In both cases, the width of the rim is much less than the radius of the contact line such that the axisymmetric dewetting can be modeled as a two-dimensional process. In the framework of the lubrication theory, Snoeijer and Eggers presented an analytical expression for the dewetting velocity of a two-dimensional liquid film. In the dimensionless form, the corresponding capillary number, $Ca_f$, depends primarily on the contact angle and is insensitive to other parameters including the film thickness and the rim size, which have only a logarithmic contribution. For the present stretching problem, we have measured the dewetting speed of the entrained film in regime II. In Fig. 7, the dewetting speed expressed using $Ca_f$ is plotted as a function of time for representative values of $\lambda$ and $Ca$. Hereafter, time is scaled by $\mu V_0^{1/2}/\eta$.

The results are consistent with previous experiments and theory of film dewetting. First, $Ca_f$ is independent of $\lambda$ and $Ca$, indicating that the dewetting is a local process of the film. Second, a careful examination shows that the dewetting speed exhibits a slow decrease with time, which is predicted by the theory of Snoeijer and Eggers. This is attributed to the variations in the macroscopic geometry of the film,
e.g., the growth of the rim size. Third, it is found that the dewetting speed is systematically below the critical speed of the meniscus \( \dot{C}a_{k,\ell} \), which is given by the dashed line [see also Fig. 4(b)]. The discrepancy between the dewetting speed of the entrained film and the critical speed of the meniscus for wetting transition has also been observed in dip coating a solid cylinder\(^5\) and gas–liquid displacement in a capillary tube.\(^4,5\)

The amount of time the film can exist is determined by the movement of the real and apparent contact lines. In Fig. 8(a), the diameters of the two contact lines are plotted as a function of time. The film is immediately entrained when the stretching is imposed at \( t = 0 \); correspondingly, the two diameters begin to differ. Once the film is generated, the diameter of the real contact line decreases linearly since the dewetting speed is approximately constant. In contrast, the retraction of the apparent contact line exhibits a decelerating behavior. The film disappears when the two contact lines meet once again at \( t = T \). Given the constant contact line speed, \( T \) also measures the distance traveled by the contact line before the film disappears. Figure 8(b) shows the variation of \( T \) as a function of \( C a \) for \( \lambda = 17 \) and 23. The film can be sustained for a longer period of time at larger values of \( C a \) and \( \lambda \), and a saturation of \( T \) can be observed when \( C a \) is sufficiently large. At smaller values of \( C a \), the meniscus and the apparent contact line retreat at a lower speed and are more easily caught up by the real contact line. Therefore, the film is absorbed into the liquid bridge in less time. An increase in \( \lambda \) corresponds to a higher speed of the meniscus and a larger radius of the contact line at the beginning, which delays the disappearance of the film.

Figure 9(a) shows the temporal variation of the rim width, \( w_{rim} \), which is defined in Fig. 6 and can be measured in the top-view images. We have fixed \( \lambda = 23 \) and taken four representative values of \( C a \). It can be seen that \( w_{rim} \) grows with time as the liquid in the film is continuously collected into the rim. A larger rim can be generated at a higher \( C a \) because a thicker film is entrained and thus more liquid can be collected. This argument can be further refined to give a scaling law for the rim width. Given a constant speed of dewetting, the cross sectional area of the rim is approximately written as \( h_f C a t \). Here, we have treated the rim as a two-dimensional structure, and \( h_f \) is the thickness of the thin film (see Fig. 6). Accordingly, the width of the rim is estimated as

\[
\frac{w_{rim}}{C a^{1/3}} = \frac{C a^{1/3}}{C a^{1/3}} \frac{h_f}{C a^{1/3}} = \frac{h_f}{C a^{1/3}}
\]

FIG. 8. (a) Variation of the diameters of the real and apparent contact line at \( C a = 3.110 \times 10^{-3} \) and \( \lambda = 23 \) (regime II). The instant they meet defines the duration of the entrained film, \( T \). (b) Variation of \( T \) as a function of \( C a \) for \( \lambda = 17 \) and 23.

FIG. 9. Variation of (a) the width of the rim, \( w_{rim} \), and (b) \( w_{rim}/C a^{1/3} \) as a function of \( t \) at \( \lambda = 23 \). Note that logarithmic coordinates are used in (b).
finally, $hf$

The data in Fig. 9(a) are reproduced in Fig. 9(b), which shows $Ca$ was repeated five times. Figure 10 shows the effect of the capillary after and before the experiment, respectively. Each set of experiments total mass of the liquid bridge, measured using high-precision balance defined as the ratio of the mass of liquid left on the top surface to the $Ca$

Furthermore, in analogy to the Landau–Levich–Derjaguin theory, $hf$ depends on the velocity of the meniscus, which is proportional to the stretching velocity. Therefore, we have $hf \sim Ca^{2/3}$ and, finally, $w_{\text{rim}} \sim Ca^{1/3}t^{1/2}$. The data in Fig. 9(a) are reproduced in Fig. 9(b), which shows $hf/Ca^{1/3}$ as a function of $t$. We can see that the experimental results follow Eq. (4) well and a satisfactory collapse of the data is obtained.

E. Liquid transfer ratio

Another point of interest is the liquid transfer ratio $\Phi$, which is defined as the ratio of the mass of liquid left on the top surface to the total mass of the liquid bridge, measured using high-precision balance after and before the experiment, respectively. Each set of experiments was repeated five times. Figure 10 shows the effect of the capillary number $Ca$ on $\Phi$ at $\lambda = 23$. When $Ca$ is small, including all of regime I and part of regime II, the liquid transfer ratio hardly varies with $Ca$. In regime I, the morphology of the liquid bridge evolves quasi-statically and is insensitive to the stretching rate, leading to a liquid transfer ratio of $\Phi = 0.27$. This value is significantly different from 0.5, obviously due to the asymmetry induced by gravity. The film entrainment in regime II renders the stretching unsteady, but the liquid film can retract into the liquid bridge at small $Ca$, as illustrated in Fig. 3. Consequently, the history of film deposition is lost; the subsequent stretching becomes quasi-static as in regime I, leading to the same value of $\Phi$. If $Ca$ is increased, a liquid film is still observed on the upper plate when the liquid bridge breaks up, although the film on the lower substrate disappears, similar to the case shown as the right row in Fig. 2. Consequently, more liquid is left on the upper substrate, corresponding to an increase in the transfer ratio. If $Ca$ is sufficiently large, it is possible for the liquid films to be present on both plates before breakup, and a saturation of $\Phi$ is observed.

IV. CONCLUSION

We have performed experimental investigations on the stretching of thin liquid bridges with moving contact lines. The deformation of the liquid bridge is primarily governed by the balance between capillary and viscous forces due to the high viscosity of the employed liquid. At low stretching rates, the liquid bridge evolves in a quasi-static manner, similar to previous experimental work. When the stretching rates are large, we found that the stretching can give rise to a dynamical wetting transition with liquid film entrained on the substrates. The critical condition for wetting transition is accompanied by a constant retraction speed of the meniscus, $C_{\text{th}}$, or a threshold of $Ca$ that depends on the initial aspect ratio $\lambda$. The mass conservation condition gives a relation between these two critical values, i.e., Eq. (1) when $\lambda \gg 1$.

The stretching process in regime II is characterized by the competition between the retraction of the liquid bridge and the entrained film. The retraction speed of the entrained film is independent of $Ca$ and $\lambda$ and shows a weak decrease with time, consistent with the theory of Snoeijer and Eggers. $w_{\text{rim}}/Ca^{1/3}$,o that depends on $Ca$

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The time period of the entrained film increases with $Ca$ and $\lambda$. The film can be completely absorbed by the liquid bridge before its breakup when $Ca$ is small. In contrast, the meniscus retreats rapidly at large $Ca$, and the entrained film remains on the substrate at the moment of breakup. Consequently, the entrained films play the role of the liquid transfer ratio, which has a constant value at low stretching rates and grows with increasing $Ca$.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Zhenghao Shao: Data curation (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – original draft (equal). Peng Gao: Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Project administration (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

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