

Enhanced slipperiness through rapid drop motion on liquid-infused surfaces

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Introducing a lubricant layer between a fluid and a solid substrate endows slippery liquid-infused surfaces (SLISs) with excellent interfacial properties, such as a low sliding angle, repellency toward various liquids, icephobicity, and self-healing capability. Previous studies found that the friction force of a sliding drop on SLISs obeys the Landau-Levich-Derjaguin (LLD) theory, i.e., $F_\eta \sim Ca^{2/3}$, with Ca being the capillary number. In this paper, however, our experiments show that this scaling law holds only at low capillary numbers. We find a distinct decrease in the scaling exponent as the drop accelerates: In the rapid sliding regime, SLISs demonstrate even greater slipperiness than that predicted by the LLD theory. Numerical simulations reveal that this unexpected behavior originates from the incompletely developed state of the back meniscus, while the influence of the front meniscus is insignificant. Compared with the prediction of the Bretherton model, the back meniscus possesses a shorter shear length and a thicker shear layer, therefore reducing friction and enhancing surface slipperiness. An analytical solution is derived to describe the incompletely developed meniscus. This work offers insights into the abnormal frictional behavior when the capillary number of a moving drop exceeds 4×10^{-3} .

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I. INTRODUCTION

The strong hysteresis caused by the contact-line pinning between droplets and solid surfaces has driven considerable interest in developing surface with exceptional liquid repellency [1–3]. Typically, frictional hysteresis originates from chemical or physical defects on solid surfaces [4]. The mobility of drops can be enhanced either by smoothing the surfaces or by introducing a thin lubricating layer. Compared to perfecting the surface, a more feasible strategy is the introduction of lubricants, such as a gas layer (Leidenfrost effect [5], superhydrophobic surfaces [6,7]) or an immiscible liquid layer [2,8]. However, methods relying on trapping a stable gas layer between drops and solids suffer from durability challenges [5,6,9,10]. Inspired by *Nepenthes* pitcher plants, an alternative approach has been proposed: impregnating a lubricating oil between the drops and the substrates [2,8,11]. These slippery liquid-infused surfaces (SLISs) have attracted significant attention due to their promising advantages, including the ability to repel various liquids [2,8,12], low hysteresis [2,3,8,13,14], self-healing capability [2,15], icephobicity [16–18], and high stability [19,20].

A fundamental aspect for the application of SLISs is to understand how drops shed down from such surfaces [15,21].

While the past decades have witnessed the success of the Landau-Levich-Derjaguin (LLD) theory in describing drop motion at small capillary numbers (Ca) [3,13,22–25], the equally important regime of large Ca remains unresolved. Here, we investigate drop motion on SLISs over a wide range of large Ca , from 10^{-3} to 1, through the combination of experimental, numerical, and theoretical approaches. We uncover a surprisingly more slippery regime characterized by a smaller scaling exponent when Ca exceeds 4×10^{-3} , in contrast to the LLD friction law applicable at Ca below this threshold. Our systematic experiments reveal that this enhanced slipperiness is accompanied by pronounced changes in the morphology of the back meniscus surrounding the drop. Interestingly, by considering the wetting ridge as two distinct menisci, the front and the back, we demonstrate through simulations that the contribution of the front meniscus to viscous friction is neglected, whereas the back meniscus exhibits an incomplete development state. Furthermore, our simulations reveal that, at large Ca , the back meniscus exhibits a shorter shear length and a larger shear thickness than predicted by the classical Bretherton model [26], thereby accounting for the observed more slippery regime. Finally, we introduce an extended Bretherton model that not only explains the altered meniscus morphology at large Ca ($Ca > 4 \times 10^{-3}$) but also provides a theoretical framework for exploring rapid drop motion on SLISs.

II. EXPERIMENTS

We adopt the methodology proposed by Keiser *et al.* [3,22] to investigate the motion of drops sliding down an inclined SLIS at a steady-state velocity v . Our experimental setup,

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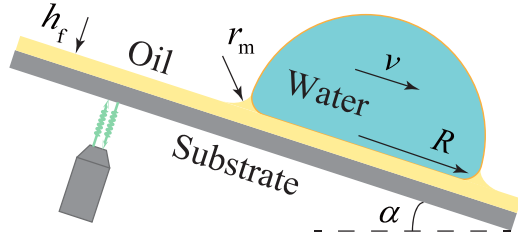


FIG. 1. Schematic of the experimental setup. A drop with contact radius R slides down a SLIS at velocity v . The tilt angle of the SLIS is denoted by α . The thickness of the lubricant film h_f along the trailing trajectory of the drop is measured using a reflection interference microscope, while the curvature radius of the meniscus r_m is determined from enlarged backlighting images.

illustrated in Fig. 1, measures the drop velocities at various tilt angles α of the SLISs using backlighting photography recorded with an industrial camera (IDS UI-3060 CP). Deionized water drops are gently deposited onto the SLISs, which are mounted on an angle-adjustable stage ($0^\circ < \alpha \leq 70^\circ$). These SLISs are fabricated by spin coating a uniform layer of silicone oil (DOW XIAMETER PMX-200, mass density $\rho_o = 963 \text{ kg/m}^3$, surface tension $\sigma_o = 20.3 \text{ mN/m}$, and kinematic viscosity $\nu_o = \eta_o/\rho_o = 50 \text{ cSt}$, 500 cSt, with η_o being the dynamic viscosity) onto a smooth silicon wafer coated with Glaco (SOFT 99) [3,23]. For film thickness measurements, the silicon wafer is replaced with a glass substrate. The lubricant thickness is controlled by varying the spin-coating speed. Previous studies have shown that the film thickness has a negligible influence on the average drop velocity [3,23]. The volume of the drop is independently varied within the range $5 \mu\text{L} \leq V_0 < 30 \mu\text{L}$. A representative chronophotograph capturing the motion of a sliding drop is presented in Fig. 2(a).

To characterize the friction force F_η acting on a drop sliding on the SLIS, we systematically investigate the dependence of the drop velocity v on the tilt angle α . This approach is motivated by the fact that F_η is directly related to v , and the drop achieves a steady velocity v when F_η balances the gravitational driving force, $F_g = mg \sin \alpha$ [3]. Here, m and g represent the drop mass and the gravitational acceleration, respectively. In Fig. 2(b), we plot v as a function of $\sin \alpha$ for various lubricant viscosity, η_o ; the dependence of v on drop volume V_0 is provided in Fig. S2 of the Supplemental Material [27]. Here, we focus on scenarios where the lubricant viscosity significantly exceeds that of the drop, so that dissipation occurs primarily within the lubricant oil [3,13]. The black dashed line in Fig. 2(b) represents the LLD prediction (i.e., $v \sim \sin^{3/2} \alpha$) reported in previous research [3,22,23,25], which matches our experimental data only below a critical tilt angle α_c . For $\alpha > \alpha_c$, the drop velocity increases more rapidly with increasing tilt angle, a trend that was also reported in Ref. [3]. However, in contrast to the previously proposed “tentative” scaling $v \sim \sin^3 \alpha$, we find a scaling relation of $v \sim \sin^{2.5} \alpha$, which agrees well with our subsequent analysis. Notably, for millimeter-scale drops, we find that α_c falls approximately within the range of 5° to 15° (varying with both drop volumes and lubricant viscosities), indicating that the LLD friction law applies only to a limited range of drop motion on tilted SLISs. Therefore, the relatively small

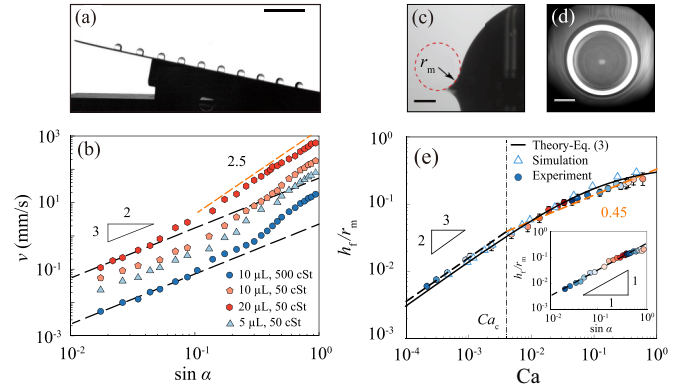


FIG. 2. Experimental results. (a) Representative chronophotograph showing the sliding of a $10 \mu\text{L}$ drop on an inclined SLIS at $\alpha = 10^\circ$. The time interval between successive drop positions is 2 s . (b) Dependence of drop velocity v on $\sin \alpha$. The black dashed line represents the LLD friction law, $v \sim \sin^{3/2} \alpha$. (c) Typical measurement used to determine the curvature radius r_m of the meniscus. (d) Interferential fringes obtained using illumination at a wavelength of 480 nm to measure the lubricant film thickness h_f at the tail of a $10 \mu\text{L}$ drop sliding on a SLIS spin-coated with 500 cSt silicone oil. (e) Dependence of h_f/r_m on Ca . The plot includes both experimental (circles) and numerical (triangles) results. The solid black curve represents predictions of the extended Bretherton model, i.e., Eq. (3). The black dashed line corresponds to the classical Bretherton prediction for small Ca [26], $h_f/r_m \sim \text{Ca}^{2/3}$, while the orange dashed line indicates the scaling $h_f/r_m \sim \text{Ca}^{0.45}$ at larger Ca . The inset demonstrates the approximately linear dependence of h_f/r_m on $\sin \alpha$, with a dashed line serving as a guide to the eye. Scale bars in panels (a), (c), and (d) represent 10 mm , $200 \mu\text{m}$, and 1 mm , respectively.

value of α_c , the distinct scaling relation we observe, and the lack of prior explanation regarding this unexpected enhanced slipperiness motivate us to conduct further investigations.

To uncover the physical origin of the observed change in the frictional behaviors (i.e., the scaling relation between F_η and Ca), it is imperative to investigate the dominant region of viscous dissipation (the *foot* of oil [22], the wetting ridge [13,25], or the meniscus [13,25]). To this end, using a modified fluorescence microscope (Nikon Ti2) and two high-speed cameras (Photron Fastcam Mini UX100 and Nova S20) equipped with filters (480 and 532 nm wavelengths), we systematically measure the curvature radius r_m of the oil-air meniscus [Fig. 2(c)] and the lubricant film thickness h_f at the tail of a $10 \mu\text{L}$ drop [Fig. 2(d)] sliding on a SLIS spin-coated with 500 cSt silicone oil on a glass substrate (Fig. 1).

As depicted in the inset of Fig. 2(e) in a log-log plot, the dependence of h_f/r_m on $\sin \alpha$ exhibits no pronounced variation. We therefore present h_f/r_m as a function of the capillary number $\text{Ca} = \eta_o v / \sigma_o$, which quantifies the dynamic shape of the meniscus behind the sliding drop. In comparison with the prediction of the Bretherton model for small Ca , $h_f/r_m \sim \text{Ca}^{2/3}$ [black dashed lines in Fig. 2(e)], we observe a clear transition in meniscus configuration at large Ca , where $h_f/r_m \sim \text{Ca}^{0.45}$. This transition coincides with the altered drop dynamics shown in Fig. 2(b). Since $v \sim \sin^{3/2} \alpha$ at small Ca and $v \sim \sin^{2.5} \alpha$ at large Ca , the overall scaling $h_f/r_m \sim \sin \alpha$ [inset of Fig. 2(e)] can be explained. These findings prompt us

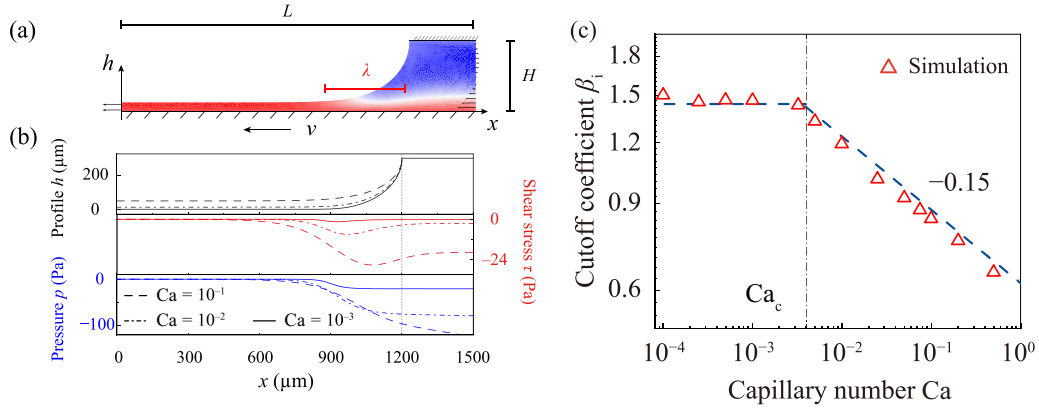


FIG. 3. (a) Numerical setup for the lubricant flow around a back meniscus, with the velocity field visualized by vectors and colors. λ represents the characteristic length of the dynamic meniscus. (b) Profiles of the lubricant-air interfaces (black curves), together with the distributions of shear stress (red curves) and pressure (blue curves) on the substrates for $Ca = 10^{-3}$, 10^{-2} , and 10^{-1} . (c) Dependence of the cutoff coefficient β_i on Ca . Red triangles represent simulation results, while dashed lines are guides to the eye.

to reexamine viscous dissipation originating from the meniscus region.

The meniscus is a prevalent phenomenon in a wide range of fluid interface systems [28–37] and has been thoroughly analyzed in the regime of small Ca based on lubrication approximation [29,31,32]. However, the behavior at large Ca remains challenging to investigate both theoretically and experimentally, due to the increased complexity of the system [26,38]. Therefore, we resort to numerical simulations to quantitatively examine the evolution of the meniscus and the associated friction.

III. NUMERICAL SIMULATIONS

Considering the significant difference in the length scales between the menisci and the drops in practical scenarios, our numerical simulations focus solely on the meniscus region, which is treated as a free-surface problem [38–40]. The computational domain is illustrated in Fig. 3(a), where we consider a steady two-dimensional (2D) flow of a lubricant forming a meniscus between two solid surfaces of length L , separated by a distance H (H has no significant impact on the results; see Fig. S3 of the Supplemental Material [27]). Moreover, we induce a steady 2D flow by imposing a constant lateral velocity v in the leftward direction. The left and right boundaries are set as outlet and inlet, respectively (more details of the simulation methodology are provided in Sec. S3 of the Supplemental Material [27]).

Leveraging our simulations, we investigate the detailed evolution of the meniscus. In Fig. 3(b), we compare the meniscus profiles (black curves) for three representative capillary numbers, $Ca = 10^{-3}$, 10^{-2} , and 10^{-1} , along with the corresponding distributions of shear stresses (red curves) and pressure profiles (blue curves) on the substrates. In all cases, the shear stress exhibits a pronounced localized region, which dominates the overall resistance and is commonly referred to as the dynamic meniscus [26]. We define the transverse length λ of this region, as indicated in Fig. 3(a), as the length of dynamic meniscus, which characterizes the viscous shear length scale [3]. Notably, the magnitude of λ displays qualitatively different scaling behavior for different values of Ca .

For small Ca (10^{-3}), along the outlet-to-inlet direction as depicted in Fig. 3(a), the shear stress gradually increases from nearly zero to a maximum value and then decreases back to nearly zero before approaching the lubricant-water-air contact line. Moreover, we observe two distinct regions of nearly constant pressure: the lubricant film near the outlet and the circular static meniscus near the contact line. Additionally, the dynamic meniscus acts as a transitional region connecting these two zones [see the solid blue curve in Fig. 3(b)]. In this regime, the entire meniscus is in a completely developed state. Previous studies revealed that the characteristic length of the dynamic meniscus follows the scaling law $\lambda \sim r_m Ca^{1/3}$ [31,32].

In contrast, for large Ca (e.g., 10^{-1}), along the outlet-to-inlet direction, the shear stress increases from nearly zero to a maximum value, but then decreases to a certain value at the contact line and remains constant up to the inlet. In this scenario, only one region of constant pressure exists, corresponding to the lubrication film near the outlet. This behavior indicates that the dynamic meniscus is cut off at the contact line, rather than developing to the static meniscus. Consequently, in contrast to the case of small Ca in which the meniscus is completely developed with two constant-pressure regions, the meniscus at larger Ca is incompletely developed, with its evolution interrupted by the contact line. Therefore, when calculating the viscous friction, the reduction in shear length λ due to contact-line truncation must be taken into account.

For both small and large values of Ca , the viscous friction F_η can be obtained by integrating the shear stress $F_\eta \approx 2\pi R \int_{-\infty}^{x_A} \tau(x) dx$, where x_A represents the location of the contact line along the x axis. By employing a characteristic shear stress τ_0 and a characteristic length λ_0 , the friction can be quantified by

$$F_\eta \approx 2\pi R \tau_0 \lambda_0 \int_{-\infty}^{\bar{x}_A} \bar{\tau}(\bar{x}) d\bar{x}, \quad (1)$$

where $\bar{\tau} = \tau/\tau_0$ and $\bar{x} = x/\lambda_0$. Here, $\bar{\tau}(\bar{x})$ is the dimensionless shear-stress distribution, which is independent of Ca . By analyzing the features of the shear stress distribution, it

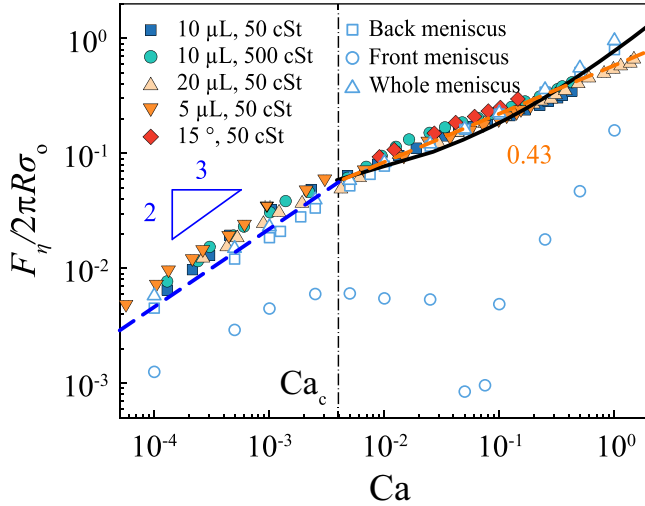


FIG. 4. Dependence of the nondimensional friction $F_\eta/2\pi R\sigma_o$ on Ca . Solid and hollow dots represent experimental and numerical results, respectively. The solid black curve represents the theoretical model [Eq. (4)]. The dashed lines represent the scale arguments [Eq. (2)] for small Ca (blue) and large Ca (orange).

has been shown that the characteristic shear stress τ_0 scales as $\tau_0 \sim \eta_0 v/h_f$, while the characteristic length λ_0 scales as $\lambda_0 \sim r_m Ca^{1/3}$ for small Ca and $\lambda_0 \sim r_m$ for large values of Ca , respectively (more details in Sec. S4 of the Supplemental Material [27]). In practical situations, the meniscus terminates at the lubricant-water-air contact line. Therefore, a *cutoff coefficient* $\beta_i = \int_{-\infty}^{x_A} \bar{\tau}(\bar{x}) d\bar{x}$ must be introduced (Fig. S4 of the Supplemental Material [27]) to consider the cutoff effect of the contact line on the shear length λ , or equivalently on the nondimensional integral in Eq. (1). For Ca smaller and larger than a critical value Ca_c , β_i scales approximately as Ca^0 and $Ca^{-0.15}$, respectively, as shown in Fig. 3(c). Consequently, the viscous friction F_η can be expressed as

$$F_\eta \sim 2\pi R \tau_0 \lambda_0 \beta_i = \begin{cases} 2\pi R \sigma_o Ca^{4/3} \frac{r_m}{h_f}, & Ca < Ca_c, \\ 2\pi R \sigma_o Ca^{0.85} \frac{r_m}{h_f}, & Ca > Ca_c. \end{cases} \quad (2)$$

Previous studies have proved that, for small Ca , the characteristic ratio of the back meniscus satisfies $h_f/r_m \sim Ca^{2/3}$ [3,22,23,25,26,31,32,41]. This scaling, which leads to $F_\eta \sim 2\pi R \sigma_o Ca^{2/3}$, is in good agreement with both the small- Ca data in Fig. 4 and previous theoretical work [3,14,15,22,23,25,26]. For large Ca , however, we temporarily adopt the experimental scaling $h_f \sim r_m Ca^{0.45}$ [orange dashed line in Fig. 2(e)], with further justification provided later. This yields a friction scaling $F_\eta \sim 2\pi R \sigma_o Ca^{0.4}$, which agrees well with the orange dashed line in Fig. 2(b). Verification of this scaling is straightforward, as the viscous friction F_η must balance the gravitational driving force F_g , i.e., $2\pi R \sigma_o Ca^{0.4} \sim mg \sin \alpha$. Since $Ca = \eta_0 v/\sigma_o$, this relation implies $v \sim \sin^{2.5} \alpha$.

Thus far, we have focused on the impact of the back meniscus of the wetting ridge on the motion of drops on SLISs. The role of the front meniscus, however, remains less clear. As illustrated in Fig. 4, we also investigate the friction associated with the front meniscus (see Sec. S5 of the Supplemental Material [27]) and compare it (hollow circles) with the back

meniscus (hollow squares). For small Ca , the friction from the front meniscus follows a trend similar to that of the back meniscus but with significantly smaller magnitudes, which agrees well with previous analyses [22,38]. However, for large Ca , the friction of the front meniscus unexpectedly decreases after exceeding a certain threshold Ca_{cf} and then increases. This behavior can be explained by the cutoff effect of the contact line on the front meniscus (Sec. S5 of the Supplemental Material [27]). In summary, within the Ca range explored in our experiments, the total meniscus friction is dominated by the contribution from the back meniscus. In the following section, we introduce an extended Bretherton model [12] to quantify the film thickness and further elucidate the friction behavior at large Ca .

IV. THEORY

In his analysis of long bubbles moving through a tube [26], based on the *lubrication approximation*, Bretherton proposed a classical relation for the film thickness, as $h_f/r_m \sim Ca^{2/3}$, for small Ca . This relation has been extensively validated and widely applied in the studies of menisci [28–37,42] and drop sliding on SLISs [3,22,23,25]. Significant efforts have also been devoted to extending this relation to the large- Ca regime. In particular, Klaseboer *et al.* [43] developed an extended Bretherton model that considers the influence of the film thickness h_f on the curvature radius r_m , which is analogous to the incompletely developed meniscus observed in our study. Therefore, we adopt the extended Bretherton model in the form

$$\frac{h_f}{r_m} = \frac{A(3Ca)^{2/3}}{1 + AB(3Ca)^{2/3}}, \quad (3)$$

where A and B are constants. They were previously determined through numerical calculations to be approximately $A \approx 0.643$ and $B \approx 2.79$ [36,43]. As shown by the solid black curve plotted in Fig. 2(e), the extended Bretherton model given by Eq. (3) exhibits excellent agreement with the observed meniscus feature h_f/r_m over the entire range from small Ca to large Ca .

Furthermore, using Eqs. (2) and (3), we obtain a theoretical expression for the viscous friction experienced by a rapid moving drop on the SLIS:

$$F_\eta \sim \frac{2\pi R \sigma_o Ca^{0.18}}{A} [1 + AB(3Ca)^{2/3}], \quad (4)$$

which demonstrates good agreement with both the experimental and numerical results, as shown by the solid black curve in Fig. 4. Fitting the data for Ca in the range $4 \times 10^{-3} \leq Ca \leq 0.5$, we can approximate the term $1 + AB(3Ca)^{2/3}$ by a power-law formula, $1 + AB(3Ca)^{2/3} \sim Ca^{0.25}$. Substituting this into Eqs. (3) and (4) yields the approximate scaling relations $h_f/r_m \sim Ca^{0.42}$ and $F_\eta \sim Ca^{0.43}$, respectively. Both of the scaling laws agree well with our experimental and numerical results, as illustrated in Figs. 2(e) and 4.

According to the above analysis, the physical meaning of Ca_c indicates the threshold at which the meniscus transitions from a completely developed to an incomplete developed state. This transition can be interpreted from two complementary perspectives, allowing Ca_c to be independently estimated

in two perspectives. First, the transition is expected to occur when the characteristic length λ_0 in the small-Ca regime, $\lambda_0 \approx 6.5r_m\text{Ca}^{1/3}$, becomes comparable to the meniscus curvature radius r_m . This condition, $6.5\text{Ca}^{1/3} \approx 1.0$, yields a critical capillary number $\text{Ca}_c \approx 3.64 \times 10^{-3}$. Second, the transition can be identified by the onset of the correction term in the extended Bretherton model, $1 + AB(3\text{Ca})^{2/3}$, becoming non-negligible. Taking $AB(3\text{Ca})^{2/3} \approx 0.1$ as the criterion gives a critical capillary number $\text{Ca}_c \approx 4.38 \times 10^{-3}$. Notably, the critical capillary number observed in our experiments, $\text{Ca}_c \approx 4 \times 10^{-3}$, exhibits a good agreement with the values predicted from both perspectives. This consistency is clearly illustrated by the dash-dotted lines in Fig. 2(e) and Fig. S4(b) of the Supplemental Material [27].

V. CONCLUSIONS

In summary, we have studied the drop motion on SLISs, with a particular focus on rapid sliding. We find that the friction experienced by fast-moving drops deviates from the conventional LLD power-law scaling. By combining experimental measurements with numerical simulations, we elucidate the origin of this unexpected behavior and show that it arises from the incompletely developed state of the back meniscus at large capillary numbers Ca. In contrast, the contribution of the front meniscus to the overall friction is negligible in this regime. The incompletely developed meniscus is characterized by a shorter effective shear length λ and a thicker shear layer h_f than those predicted by the classical Bretherton model, which together account for the enhanced slipperiness observed at high Ca. By introducing an extended Bretherton model, we provide a theoretical framework that captures both the meniscus thickness and the resulting friction in the larger-Ca regime.

Although the present study provides a comprehensive explanation for the modified frictional behavior of drops moving on smooth SLIS, this issue deserves further exploration beyond the surfaces considered here. For example, surface textures on the substrate of SLISs are known to significantly impact frictional scaling [22], an effect that lies beyond the scope of the current work and warrants further investigations.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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