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Flow and Drop Transport Along Liquid-Infused Surfaces

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Abstract

Liquid-infused surfaces (LISs) are composite solid–liquid surfaces with remarkable features such as liquid repellency, self-healing, and the suppression of fouling. This review focuses on the fluid mechanics on LISs, that is, the interaction of surfaces with a flow field and the behavior of drops on such surfaces. LISs can be characterized by an effective slip length that is closely related to their drag reduction property, which makes them suitable for several applications, especially for turbulent flows. Drag reduction, however, is compromised by failure mechanisms such as the drainage of lubricant from surface textures. The flow field can also sculpt the lubricant layer in a coupled self-organization process. For drops, the lubricant reduces drop pinning and increases drop mobility, but also results in a wetting ridge and the associated concept of an apparent contact angle. Design of LIS wettability and topography can induce low-friction drop motion, and drops can dynamically shape the lubricant ridges and film thickness.

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1. INTRODUCTION

Biomimetic surfaces imitate the intriguing functionalities of surfaces found in nature. Superhydrophobic surfaces (SHSs) form an important class of biomimetic surfaces, inspired by, for example, the surface morphology of the leaves of the lotus plant (*Nelumbo nucifera*). Lotus leaves are water repellent and suppress the adhesion of particles (Barthlott & Neinhuis 1997), properties that are desirable in many technological applications. Apart from such effects found in nature, SHSs offer additional functionalities that are of interest in certain application areas. For example, they reduce drag in liquid flows (Rothstein 2010) and increase the efficiency of condensation processes (Boreyko & Chen 2009). However, their broad application is hampered by their lack of robustness. For example, when the pressure in a liquid flow exceeds a certain threshold value, a wetting transition is triggered in which an SHS loses many of its favorable properties (Bormashenko 2010, Lafuma & Quéré 2003, Quéré 2008).

Liquid-infused surfaces (LISs) form another class of biomimetic surfaces inspired by plants, specifically pitcher plants of the genus *Nepenthes*. These carnivorous plants have a pitcher in which they trap insects, which glide down into the pitcher by aquaplaning on an LIS (Bohn & Federle 2004). More than 15 years ago, researchers recognized that infusing a micro- or nanostructured solid surface with a low-surface tension liquid may result in a slippery composite solid-liquid surface (Quéré 2005). The infused liquid, acting as a lubricant, is immiscible with the liquids contacting the surface. Wong et al. (2011) established artificial LISs with ultraslippery features similar to those of the pitcher plant (see also Lafuma & Quéré 2011).

In particular, the self-healing properties of LISs (Wong et al. 2011) offer the promise of more robust properties in applications in comparison to SHSs. Here, “self-healing” refers to the fact that local perturbations or defects in the surface structure are repaired or compensated for by capillary suction; in other words, the lubricant automatically fills voids or dry spots on the surface. By contrast, on an SHS the transition from the initial Cassie state to the Wenzel state is very difficult to revert (Bormashenko 2010, Lafuma & Quéré 2003, Quéré 2008). Several promising applications of LISs have already been demonstrated. For example, LISs have great potential to suppress ice formation (Kreder et al. 2016, Latthe et al. 2019) and fouling of surfaces (Epstein et al. 2012, Xiao et al. 2013a), to enhance condensation heat transfer (Xiao et al. 2013b), and to provide stimuli-responsive functions (Lou et al. 2020), in addition to their use in medical applications (Howell et al. 2018). Generally, the research area of LISs has expanded dramatically over the past few years and includes methods for fabricating LISs with different morphologies, where the large variety of infusing liquids, surface topographies, and surface chemistries offers a vast design space. For further details, we refer the reader to several recent reviews (Chen et al. 2020, Huang & Guo 2019, Peppou-Chapman et al. 2020, Solomon et al. 2017, Villegas et al. 2019).

This review focuses on the fluid mechanics on LISs, that is, the interaction of surfaces with a flow field and the behavior of drops on such surfaces. Such aspects of fluid mechanics form the foundations of several applications of LISs, for example, drag reduction or enhancement of water vapor condensation (Anand et al. 2012).

The article is structured as follows. Section 2 gives a brief account of the morphology of LISs, specifically their composition and structural features, and introduces some of the fundamental concepts needed in subsequent sections. Section 3 addresses the interaction of LISs with a flow field, that is, single-phase flow. The focus is on the drag forces exerted by LISs and on the structure formation due to the flow that induces a redistribution of lubricant. Section 4 deals with drops on LISs, specifically with static wetting and drop motion. We pay special attention to the question of how far conventional concepts of wetting can be translated to wetting on LISs and to the origin of the frictional force experienced by drops translating along LISs.

2. MORPHOLOGY OF LIQUID-INFUSED SURFACES

Just as for SHSs, the design of LISs is inspired by nature, for instance, by pitcher plants of the genus *Nepenthes*. These carnivorous plants have a pitcher in which they trap insects (Bohn & Federle 2004). Insects on the upper rim of the pitcher, the peristome, glide down along the slippery surface and fall into the pitcher, where they are digested by enzymes.

The reason why the peristome surface is so slippery lies in sophisticated microstructures and a design principle that challenge the most advanced concepts from micro- and nanotechnology (Chen et al. 2016). The peristome surface becomes slippery via infusion with an aqueous liquid, for example, with nectar secreted by the plant or with rainwater. Insects glide down by aquaplaning on this LIS (Bohn & Federle 2004). The infusion of liquid into such surface structures is unidirectional and very fast (Chen et al. 2016).

Only about 10 years ago, scientists designed artificial LISs capable of matching the slippery surface performance of the peristome of the pitcher plant. Lafuma & Quéré (2011) reported microstructured surfaces where the trapped fluid was oil rather than air; these represented a new class of materials that are hemi-liquid and hemi-solid. Two qualitatively different wetting states were observed: one where the drops float on the mixed substrate, leading to low-contact angle hysteresis, and one where the drops sink and can pin on the solid defects, significantly increasing the contact angle hysteresis. Independently, Wong et al. (2011) studied both periodic and random oil-infused textures with a focus on the slippery state, where a drop is separated from the solid by a continuous thin film of oil. They termed the corresponding surfaces slippery liquid-infused porous surfaces (SLIPS). Specifically, these authors showed that such LISs can easily shed both aqueous and oil drops and that defects in the surface are self-healed by capillary suction. After these first demonstrations of artificial LISs, extensive research efforts were devoted to studying the properties of LISs and formulation of new surface designs.

The wetting morphologies of LISs can be inferred by considering the sum of the total interfacial energies among the solid, the infusing liquid, and the surrounding gas. For brevity, below we refer to the infusing liquid as the lubricant and the second liquid wetting the LIS as water. For concreteness, we imagine a surface topography consisting of structures with vertical walls and flat tops, such as a square array of posts of square cross section (width a) and height b , with an edge-to-edge spacing between neighboring posts of b . To decide whether or not the lubricant infuses the surface texture, we need to compare the interfacial energy of the infused state with that of a dry surface (Smith et al. 2013). The wetting morphology will also be influenced by the presence of water, for example, in the form of a drop. In the regions not covered by water, apart from a dry surface (configuration A), there are two other morphologies with lubricant infusing the textures (**Figure 1**). In the first, the tops of the elevations remain dry (configuration B); in the second, they are covered with lubricant (configuration C). Turning our attention first to the scenario where only lubricant is present, we can formulate the comparison between the interfacial energies of the different morphologies in terms of the microscopic contact angle $\theta_{LS(G)}$ between the lubricant (L), the solid surface (S), and the surrounding gas (G). The wetting morphologies are governed by a critical contact angle, $\cos \theta_c = (1 - \phi)/(r - \phi)$, which determines whether imbibition occurs (Bico et al. 2001). In this expression, r is the ratio of the total surface area of the dry surface and the projected surface area, and ϕ is the area fraction of the flat tops. For the example of a square array of posts, we obtain $r = 1 + 4ab/(a + b)^2$ and $\phi = a^2/(a + b)^2$. Expressed by the critical contact angle, the minimization of the total interfacial energy yields the following wetting morphologies (Smith et al. 2013): configuration A if $\theta_{LS(G)} > \theta_c$, configuration B if $0 < \theta_{LS(G)} < \theta_c$, and configuration C if $\theta_{LS(G)} = 0$.

The inclusion of a second liquid (water) complicates the picture. Depending on the specific values of the interfacial energy between solid and water, between lubricant and water, and between

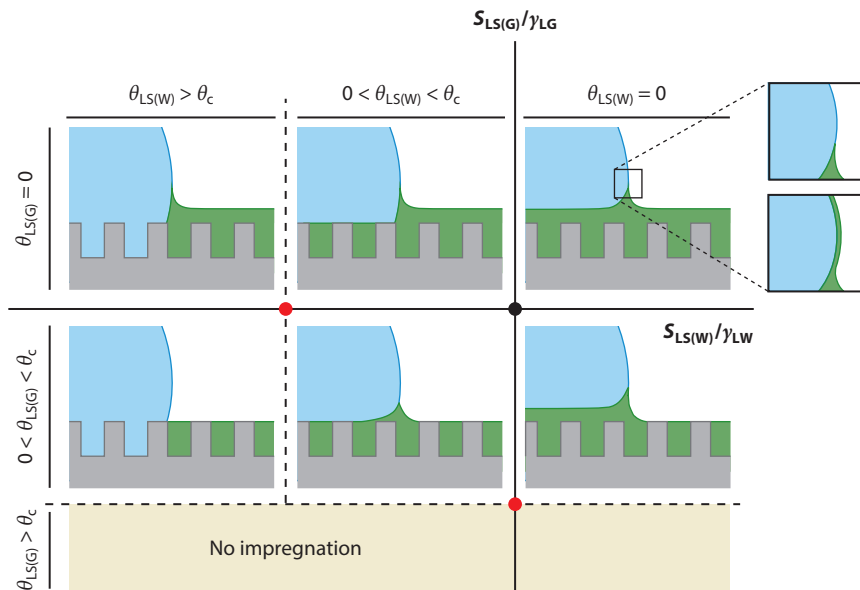


Figure 1

Map showing the possible wetting morphologies when a drop wets a liquid-infused surface (LIS). The x and y axes measure the dimensionless spreading coefficients $S_{LS(W)}/\gamma_{LW}$ and $S_{LS(G)}/\gamma_{LG}$, respectively, defined as $S_{ij(k)} = \gamma_{jk} - \gamma_{ij} - \gamma_{ik}$, where γ_{ij} denotes interfacial tension between materials i and j —here, gas (G), lubricant (L), solid surface (S), or water (W). The spreading coefficients can be translated into contact angles, as shown. The black dot represents the origin of the coordinate system. The red dots mark points that are a distance of $(r - 1)/(r - \phi)$ away from the origin, where r is the ratio of the total surface area of the dry surface and the projected surface area and ϕ is the area fraction of the flat tops. LISs exist everywhere above the dashed horizontal line. Below that line, the state of lowest energy is a dry surface. Each of the six different wetting morphologies depicted comes in two different versions, depending on whether or not the lubricant cloaks the water surface. Cloaking requires a positive spreading coefficient of lubricant on water. Figure adapted with permission from Smith et al. (2013); copyright 2013 Royal Society of Chemistry.

water and gas, the presence of water can change the wetting morphology of the lubricant-infused surface. It is possible that water either displaces the lubricant from the surface texture or displaces the lubricant film covering the tops of the elevations. **Figure 1** shows a map of the possible wetting morphologies for a water drop sitting on an LIS (Smith et al. 2013). Apart from the value of $\theta_{LS(G)}$, the configurations depend on the microscopic contact angle of the lubricant on the solid surrounded by water, $\theta_{LS(W)}$. The map is spanned by two spreading coefficients, $S_{LS(G)}$ and $S_{LS(W)}$, defined as $S_{ij(k)} = \gamma_{jk} - \gamma_{ij} - \gamma_{ik}$, where γ denotes interfacial tension and the subscripts i, j , and k refer to different materials.

Many of the favorable properties of LISs are connected to the existence of a thin lubricant film separating the water phase from the solid, which means that the liquids are usually chosen such that $\theta_{LS(W)} = 0$ or, equivalently, $S_{LS(W)} > 0$. Daniel et al. (2017) observed that this condition alone does not guarantee a stable lubricant film under a static drop. The reason is that for films as thin as the range of forces between the molecules in a fluid, the energetics of a configuration of different fluids can no longer be modeled solely on the basis of interfacial tensions. In that case, for van der Waals interactions the disjoining pressure $\Pi(b) = A/(6\pi b^3)$ needs to be considered; here, b is the lubricant film thickness and A is the Hamaker constant (Daniel et al. 2017). In order to obtain a stable lubricant film between the water phase and the solid, apart from $S_{LS(W)} > 0$, a positive

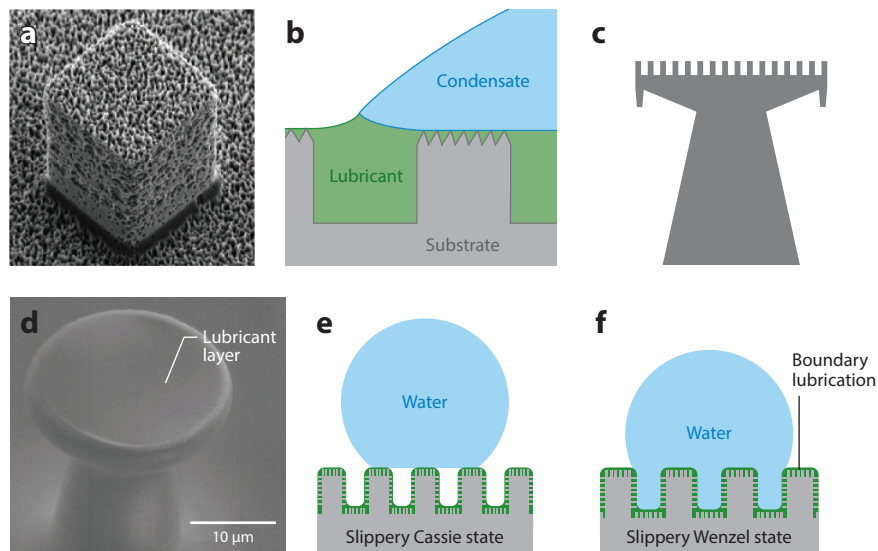


Figure 2

Hierarchical liquid-infused surfaces. (a) Single micropost with etched nanograss structures. (b) Schematic of a drop on liquid-infused nanograss microstructures. (c) Schematic of a doubly reentrant micropillar. (d) Scanning electron microscope image of such a pillar with a lubricant coating. (e, f) Schematics showing a drop on conformally coated microstructures in (e) a slippery Cassie and (f) a slippery Wenzel state. Panels *a* and *b* adapted with permission from Anand et al. (2012); copyright 2012 American Chemical Society. Panels *c* and *d* adapted with permission from Dong et al. (2018). Panels *e* and *f* adapted with permission from Dai et al. (2015); copyright 2015 American Chemical Society.

Hamaker constant is required. In a dynamic situation, for example, when a drop moves along an LIS, the lubricant film underneath the water phase is no longer governed by a static force balance but by hydrodynamic effects, which are discussed below in Section 4.

The key to many applications of LISs involving drops is to construct surfaces that minimize pinning. Toward this end, micrometer-scale LIS textures can have an additional, typically nanolength, scale of roughness that retains lubricant and ensures that drops never directly contact the solid tops of the texture. Examples include nanograss on microposts (Anand et al. 2012) (**Figure 2a,b**) and superhydrophobic nanoparticles on microscale textures (Guan et al. 2017, Keiser et al. 2017). These all follow the principle of hierarchical surfaces (Kim et al. 2013, Smith et al. 2013) and provide lubricant coatings following the underlying microscale texture shape. Such ideas have been implemented to create doubly reentrant micropillars with lubricant-infused tops (Dong et al. 2018) (**Figure 2c,d**). The corresponding surfaces can support drops in an ultraslippery Cassie state or a slippery Wenzel state (Dai et al. 2015) (**Figure 2e,f**). This idea of a conformal lubricant layer following the topography of an underlying solid structure can be reconceptualized as a shaped liquid surface (Launay et al. 2020). On the other extreme are flat surfaces, without any texture, impregnated with a thin liquid film. Eifert et al. (2014) showed that when using a lubricant with a positive spreading coefficient, such surfaces can display properties very similar to those of textured LISs.

Designing LISs with sophisticated morphologies and extended functionalities is a current research trend. For example, textured surfaces exposing patterns of two different infusing liquids have recently been reported (Paulssen et al. 2018). On such surfaces, drops can be guided either along defined tracks or according to size (Paulssen et al. 2019). Furthermore, stimuli-responsive

LISs have been reported; these allow the static and dynamic wetting properties of the surface to be adapted in response to external stimuli (Lou et al. 2020).

3. SINGLE-PHASE FLOW ALONG LIQUID-INFUSED SURFACES

3.1. Effective Slip Length of Liquid-Infused Surfaces

Although viscous dissipation in the gas phase enclosed in the indentations of the surface can usually be neglected for an SHS, the effect of the lubricant plays a key role in the drag force experienced by a liquid flowing along an LIS. It is customary to characterize the drag by an effective slip length β_{eff} , defined via

$$u|_{y=0} = \beta_{\text{eff}} \left. \frac{\partial u}{\partial y} \right|_{y=0}, \quad 1.$$

where x is the flow direction at the surface, y is the coordinate normal to the surface, and u is the flow velocity magnitude. By convention, the surface is located at $y = 0$. Specifically, Equation 1 refers to a scenario where, at a distance y_0 away from the surface (large compared with the typical scale of the surface features), the flow field looks like a Couette flow. Extrapolating this flow field to the plane of the surface yields a nonvanishing flow velocity at $y = 0$ from which the effective slip length can be calculated using Equation 1. Importantly, this equation does not refer to the (usually quite complex) actual flow field but rather to the Couette flow as defined above. The effective slip length needs to be distinguished from the intrinsic slip length of a liquid on a flat solid surface, which is often on the order of nanometers. For example, measurements of the intrinsic slip length of water on hydrophilic surfaces yield values below 10 nm (Lei et al. 2016).

Assuming a vanishing intrinsic slip length, on an SHS the interface at the surface is composed of solid–liquid patches with vanishing slip and gas–liquid patches with vanishing shear stress. The liquid–liquid patches on an LIS form the analog of the gas–liquid patches on an SHS. The shear stress on these patches does not vanish but rather depends on the viscosity of the lubricant and on the flow pattern inside the surface indentations. For these reasons, it is very difficult to obtain closed-form mathematical expressions for the effective slip length. The fact that the lubricant will be displaced from the indentations, as discussed in Section 3.2, introduces further complications. Below, we discuss the ideal case of a flat liquid–liquid interface.

Hocking (1976) made an early attempt to study the influence of the flow inside the indentations of a surface, specifically transverse flow over an array of infinitely thin parallel plates. Hocking’s study assumed two immiscible fluids of identical viscosity. We use the terms “transverse” and “longitudinal” to refer to flow normal to and along the orientation of surface corrugations, respectively. An important distinction has to be made concerning the connectivity of the space in which the lubricant is confined. For surfaces with grooves, this space is usually disconnected; in other words, the lubricant flow within a specific groove is not coupled to the flow inside the other grooves. By contrast, for a surface with pillars, this space can be viewed as a porous medium with connected pores, and results obtained for flow inside porous media can be applied. Along these lines, Ybert et al. (2007) suggested an expression for the effective slip length of a surface with pillars and found good agreement with finite-element calculations. Busse et al. (2013) considered the extreme case of this scenario, namely a situation in which the volume fraction of the pillars is so small that they can be neglected in comparison to the lubricant-filled domain.

Generally, one can assign a local slip length value to a specific point at the liquid–liquid interface when replacing the model velocity field of Equation 1 (Couette flow) by the local flow field at this point. Note that LISs cannot be modeled simply by averaging the slip length over the liquid–liquid interface, working with this average value, and assigning a vanishing slip length to

the solid–liquid interface patches. It needs to be taken into account that the local slip length values at the liquid–liquid interface depend on the angle between the flow velocity and the orientation of the surface structures (Nizkaya et al. 2014). For surfaces with parallel grooves, Schönecker et al. (2014) provided closed-form analytical expressions for the effective slip length in the case of longitudinal and transverse flow at low Reynolds numbers. These expressions are valid for arbitrary viscosity ratios of the two liquids and for arbitrary values of the parameters characterizing the surface geometry.

Experimental studies of slip on LISs are rather scarce. An early study by Solomon et al. (2014) used a cone-and-plate rheometer to determine the effective slip length of a microstructured surface with an array of posts. The results are roughly consistent with the predictions of Ybert et al. (2007). In particular, Solomon et al. (2014) found that the slip length increases as the viscosity ratio between the working fluid and the lubricant increases. The slip length of an unstructured surface completely wetted by a thin silicone oil was determined on the basis of colloidal probe atomic force microscopy (Scarratt et al. 2020). The results indicated that there could be a nonzero slip length at the interface between the two immiscible liquids, a sucrose solution and silicone oil as lubricant. Slip at liquid–liquid interfaces could add to the drag reduction properties of LISs.

Research in SHSs has shown that the adsorption of surfactants at the gas–liquid interface has a substantial impact on the effective slip length. This effect was suggested by McHale et al. (2010, 2011), who were motivated by the adsorption of surfactants or impurities on a bubble that rigidified the gas–liquid interface and thereby rendered the interface immobile. Subsequent experiments demonstrated that Marangoni stresses due to small gradients in the surface concentration of contaminants can substantially reduce the effective slip length of SHSs (Peaudecerf et al. 2017, Song et al. 2018), and theoretical/numerical models that provide insights into the underlying mechanisms have been developed (Baier & Hardt 2021, Landel et al. 2020). These physical principles extend beyond gas–liquid interfaces to liquid–fluid interfaces more generally, suggesting that similar effects due to adsorbed surfactants or impurities will occur on LISs. To date, however, the drag increase on LISs with surfactant, contaminated, or particle-laden interfaces has not been studied to any significant degree.

3.2. Drainage, Stability, and Structure Formation of the Lubricant Under Shear

Compared with SHSs, LISs possess self-healing properties, which means that when the lubricant becomes locally displaced from a surface, capillary forces will replenish the liquid and (approximately) restore the original structure of the surface. However, this desirable feature comes at a cost: It is much easier to displace the lubricant by exerting shear forces on the surface than to displace the gas from the indentations of an SHS. The reason is that liquids have a much higher dynamic viscosity than do gases. The higher level of viscous stress makes it easier to deform a fluid interface, which is the prerequisite for displacing the lubricant.

Wexler et al. (2015b) conducted a prototypical study of the shear-driven failure of LISs, using a microfluidic flow cell with streamwise parallel grooves at the bottom, filled with silicone oil stained with a green fluorescent dye (**Figure 3a**). The fluorescent silicone oil filled 50 parallel grooves (**Figure 3b**). When a threshold flow rate was exceeded, drainage of silicone oil was observed (**Figure 3c**) up to a point where a steady-state configuration was reached. **Figure 3d** shows the structure of the grooves. Wexler et al. (2015b) formulated a theoretical model for the steady-state length L_∞ that compares favorably with experimental data. This model was later extended to account for the viscosity ratio between the working fluid and the lubricant (Liu et al. 2016). The drainage of grooves can cause so-called overflow cascades, in which the lubricant displaced from the grooves forms bulges that merge and form drops that cover the LIS (Jacobi et al. 2015).

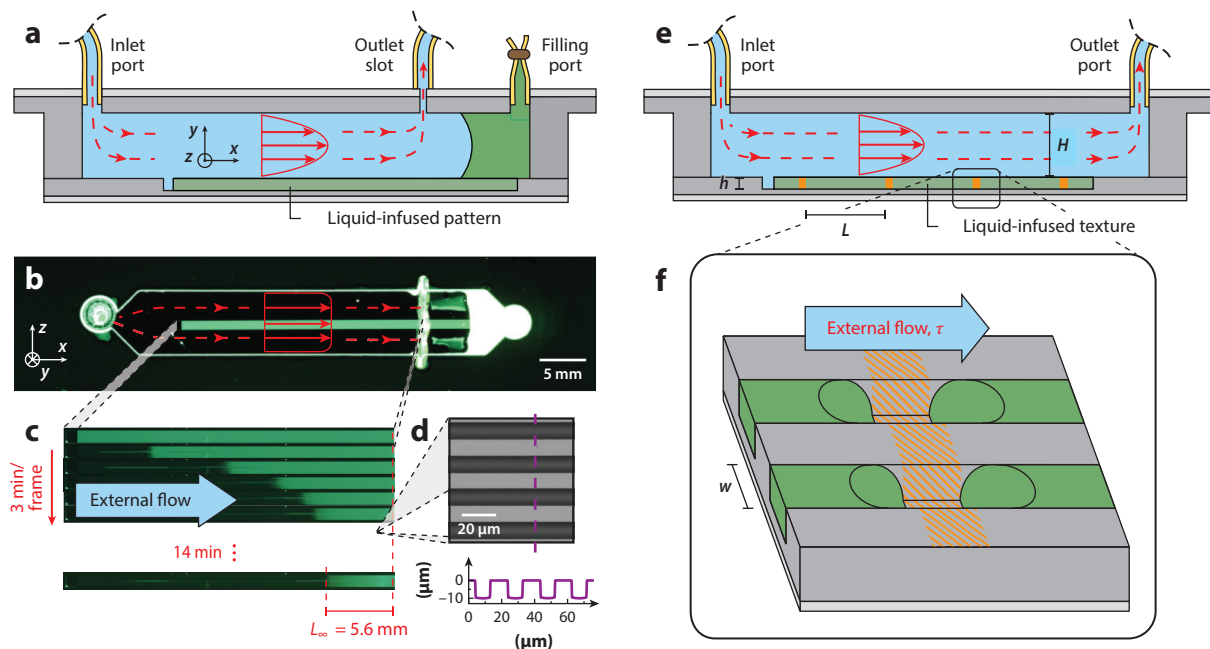


Figure 3

Shear-driven failure of liquid-infused surfaces with parallel grooves together with a solution that prevents drainage of the grooves. (a) Schematic of a flow cell with liquid-infused grooves at the bottom. (b) Top view in which the green fluorescence of the grooves becomes visible. (c) Time-lapse images showing drainage of the grooves until a steady-state filling length L_{∞} is reached. (d) Structure of the grooves in top view and in a schematic cross section. (e) Schematic of a flow cell with liquid-infused grooves and hydrophilic stripes (orange) orthogonal to the grooves. (f) Schematic showing a section of the bottom wall, indicating the distribution of lubricant inside the grooves. Panels a–d adapted with permission from Wexler et al. (2015b); copyright 2015 American Physical Society. Panels e and f adapted with permission from Wexler et al. (2015a); copyright 2015 American Chemical Society.

A suitable means to prevent drainage of grooves is to create liquid-infused regions that have an extension smaller than L_{∞} , which has been achieved by patterning a periodic array of hydrophilic stripes orthogonal to the grooves (Wexler et al. 2015a) (**Figure 3e,f**). These stripes are preferentially wetted by the working fluid rather than by the lubricant. The lubricant inside a groove then forms disconnected volumes separated by hydrophilic stripes (**Figure 3f**). In cases where the lubricant is almost completely drained from a groove without stripes, the hydrophilic stripes ensure that the liquid is largely retained inside the grooves (Wexler et al. 2015a).

While the drainage of the lubricant has been intensively studied for the case of longitudinal flow over parallel grooves, studies of shear-induced failure for other surface textures or flow configurations appear to be scarce. Some computational fluid dynamics studies on the stability of the liquid–liquid interface for the case of transverse flow over parallel grooves have been performed, yielding a stability map in terms of capillary number and viscosity ratio (Ge et al. 2018).

The (partial) drainage of lubricant by shear flow is one example of a more general phenomenon: The flow pattern inside the working fluid sculpts the distribution of the lubricant, which, in turn, influences the flow in the working fluid. Flow patterns can spontaneously form by self-organization in systems that exhibit hydrodynamic instabilities. Two classical examples of such instabilities are the Bénard–Marangoni instability (Davis 1987, Schatz & Neitzel 2001) and the Faraday instability (Miles & Henderson 1990). The Bénard–Marangoni instability has been studied for cases where the liquid layer is separated from the solid surface by a thin lubrication film

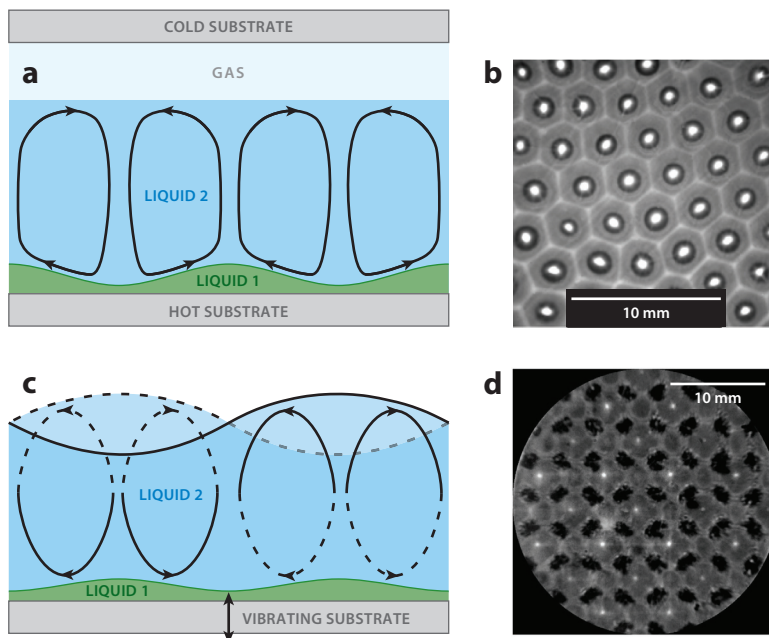


Figure 4

Sculpting of lubrication films by self-organized cellular flow patterns. (a) Schematic of the Bénard–Marangoni instability on a lubrication film. The solid lines indicate the streamlines of the flow. (b) Top view of a hexagonal array of flow cells as observed experimentally. At the center of each hexagonal convection cell is a bright spot caused by a bulge of the lubrication film, induced by shear forces due to the flow in each cell. Panel *b* adapted with permission from Nejati et al. (2015). (c) Schematic of the Faraday instability on a lubrication film. The solid lines indicate the streamlines of the flow at two different points in time separated by half the oscillation period of the Faraday waves. The solid (*dashed*) streamlines correspond to the surface deformation indicated by the solid (*dashed*) line. (d) Square array of flow cells as observed experimentally. Shown is a superposition of two snapshots, the light reflections from the surface of the upper layer (two nested square arrays of bright spots) and an image showing the lubrication layer. In the latter, the dark regions are those in which the lubrication film is thinned by shear forces. Panel *d* adapted with permission from Zhao et al. (2019).

(Nejati et al. 2015). **Figure 4a** shows a schematic of the corresponding experimental setup. The presence of the thin lubrication film shifts the marginal stability point of the upper liquid to lower values of the critical Marangoni number. Furthermore, the flow pattern in the convection cells (**Figure 4a**) sculpts the lubrication film, as shown in **Figure 4b**. There is a one-to-one correspondence between the pattern of convection cells and the deformation pattern of the lubrication film. Similar sculpting of a thin lubrication film under a thicker liquid layer is observed in the self-organization process via the Faraday instability (Zhao et al. 2019). **Figure 4c** depicts the corresponding experimental setup. The system of two superposed liquids sits on a horizontal harmonically vibrating surface. Similar to the case of the Bénard–Marangoni instability, the lubrication film shifts the point of marginal stability. Although the flow velocity in the upper layer is virtually reversed (**Figure 4c**) each half-period, remarkably, a steady-state deformation in the lubrication layer builds up (**Figure 4d**). This nonlinear response of the system can be qualitatively explained by the nonlinearities due to the liquid–liquid interface. **Figure 4d** shows a superposition of two snapshots, the light reflections from the surface of the upper layer and an image showing the lubrication layer, demonstrating that there is a one-to-one correspondence between the deformation pattern of the upper liquid layer and that of the lubrication layer.

3.3. Drag in Turbulent Flow

In many industrial applications, turbulent flows occur. During the past decade SHSs have been studied in this context as candidate structures for hydrodynamic drag reduction (Golovin et al. 2016). Turbulent flow poses significant challenges to SHSs. For example, pressure fluctuations can induce the Cassie-to-Wenzel wetting transition, which is difficult to reverse (Manukyan et al. 2011, Papadopoulos et al. 2013, Rofman et al. 2020). In comparison, LISs are significantly more robust owing to their self-healing properties.

Rosenberg et al. (2016) experimentally confirmed some basic features of LISs concerning drag reduction in turbulent flow compared with SHSs. They used a Taylor–Couette apparatus to measure the drag reduction factor. As expected, the achievable drag reduction depends on the viscosity ratio between the working fluid and the lubricant. LISs were found to perform better than SHSs, which suffered from a partial transition between the Cassie–Baxter and the Wenzel state. A subsequent study measured a drag reduction of up to 35% using an LIS in a Taylor–Couette apparatus (van Buren & Smits 2017).

Conceptually, the relevance of the effective slip length discussed in Section 3.1 is, a priori, unclear for turbulent flow over LISs. The reason is that β_{eff} is a useful concept only on a scale significantly larger than the characteristic feature size of the LIS, which needs to be compared with the viscous length scale of the turbulent flow, given by $\nu(\rho/\tau_w)^{1/2}$, where ν is the kinematic viscosity, ρ is the density, and τ_w is the wall shear stress. When the viscous length scale is smaller than β_{eff} , the usual assumption underlying most models for the effective slip length, namely Stokes flow in the boundary region, breaks down. Therefore, it is useful to define a dimensionless effective slip length via

$$\beta_{\text{eff}}^+ = \frac{\beta_{\text{eff}} \tau_w^{1/2}}{\nu \rho^{1/2}} \quad 2.$$

and to keep in mind that there will be a threshold value of β_{eff}^+ above which the slip length derived from Stokes flow ceases to be a useful concept with regard to turbulent flow. In comparison to the predictions by Schönecker et al. (2014), numerical simulations reported by Fu et al. (2017) indicate that this threshold value is approximately five for lubricant-filled longitudinal grooves.

Direct numerical simulations of turbulent flow over LISs have been performed for several different surface topographies, including the standard textures of parallel grooves (Arenas et al. 2019, Chang et al. 2019, Fu et al. 2017) and arrays of posts (Arenas et al. 2019). Some of the results significantly deviate from the predictions for Stokes flow along LISs. **Figure 5a** shows drag reduction due to a textured surface relative to a smooth, flat surface (Arenas et al. 2019) as a function of the viscosity ratio N between the working fluid and the lubricant. Arenas et al. (2019) considered turbulent flow between two parallel plates (one of them being textured and liquid infused), with a flat, undeformable liquid–liquid interface.

At least two aspects of these results defy intuition gained from Stokes flow. First, the drag reduction can be negative, meaning that the drag of an LIS is larger than that of a flat no-slip surface. Second, even at $N \approx 1$ a significant drag reduction may be achieved. This observation is counter-intuitive, because for $N = 1$ the flow configuration is similar to single-phase flow over a textured surface. For single-phase flow, numerical computations performed for surfaces decorated with staggered cubes, for example, suggest that the drag increases for configurations comparable to the one with a higher liquid–liquid area fraction shown in **Figure 5a** (Leonardi & Castro 2010). Qualitatively, the drag reduction of LISs for $N \approx 1$ can be explained by considering the time-averaged secondary flow above a textured surface. **Figure 5b** depicts the corresponding streamlines for single-phase flow along longitudinal grooves (Arenas et al. 2019). The figure shows that the

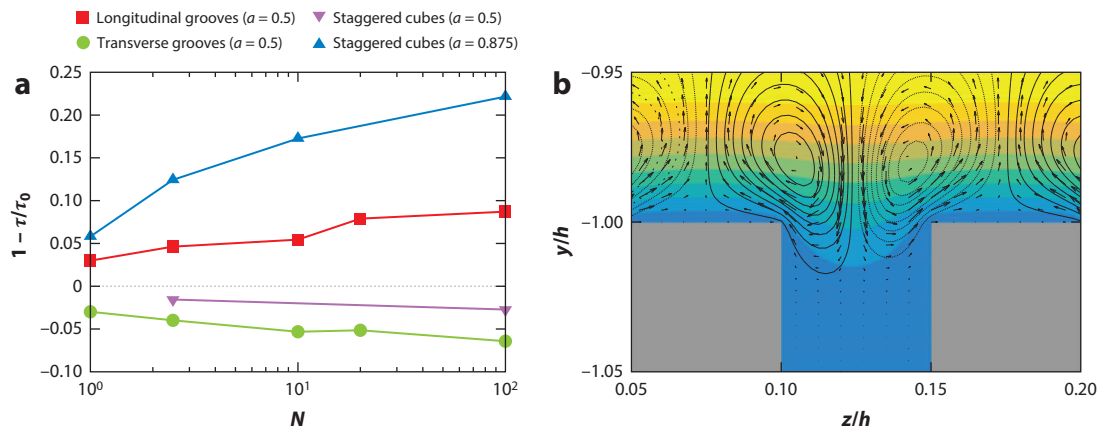


Figure 5

(a) Drag reduction of different liquid-infused surfaces in turbulent flow as a function of viscosity ratio (N), where a denotes the liquid–liquid area fraction. (b) Streamlines of the time-averaged secondary flow field over a surface indentation for longitudinal grooves in the case of single-phase flow. The color map represents the time-averaged streamwise velocity. The different curves represent different surface textures. The y - z plane is normal to the flow direction, and h represents half the height of the simulation domain extending between two parallel surfaces, one of which is the liquid-infused surface. Figure adapted with permission from Arenas et al. (2019).

secondary flow penetrates into the grooves. By contrast, the liquid–liquid interface of LISs tends to damp the wall-normal fluctuations and to keep the streamwise secondary vortices above the cavities, reducing momentum transfer inside the cavities and resulting in drag reduction.

4. DROPS ON LIQUID-INFUSED SURFACES

4.1. Static Wetting

A drop on an LIS has a wetting ridge (**Figure 6**), which complicates the concept of a contact angle. There can be a solid three-phase contact line where the substrate, drop, and lubricant (i.e., infusing liquid) meet; a liquid three-phase contact line at the top of the wetting ridge where gas, drop, and lubricant meet; both types; or none at all, depending on the interfacial tensions (Schellenberger et al. 2015). For a completely submerged texture there is no solid three-phase contact line, while for a cloaked drop there is no liquid three-phase contact line. Nonetheless, one can define an apparent contact angle, θ_{app} , at the inflection point in the profile of the drop at the top of the wetting ridge (Guan et al. 2015). There are also three Neumann angles, θ_D , θ_G , and θ_L , referring to drop, gas, and lubricant, respectively, which are related to the interfacial tensions by $\gamma_{LD}/\sin\theta_G = \gamma_{DG}/\sin\theta_L = \gamma_{LG}/\sin\theta_D$. When the spreading coefficient is positive, $S_{LD(G)} > 0$, a thin layer of lubricant can spread over the droplet–gas interface cloaking the droplet, so that the droplet–gas interfacial tension, γ_{DG} , is replaced by $(\gamma_{LD} + \gamma_{LG})$.

Semprebon et al. (2017) considered the apparent contact angle for a drop with wetting ridges controlled by the film and drop Laplace pressures, ΔP_{LG} and ΔP_{DG} , related to lubricant and drop volumes, respectively, and they derived a closed-form equation for θ_{app} . We interpret their results using an effective interfacial tension, $\gamma_{[LIS]f}$, between the LIS and an immiscible fluid, f . Considering an LIS to be composed of a solid surface fraction ϕ_s and an infused liquid surface fraction $(1 - \phi_s)$, we define a Cassie–Baxter combination $\gamma_{[LIS]f} = \phi_s \gamma_{sf} + (1 - \phi_s) \gamma_{Lf}$, where γ_{sf} and γ_{Lf} are the solid–fluid and liquid–fluid interfacial tensions; f can be gas/air/vapor (G), water/a drop (D), or lubricant/an infusing liquid (L) (see also Sadullah et al. 2020a). The definition

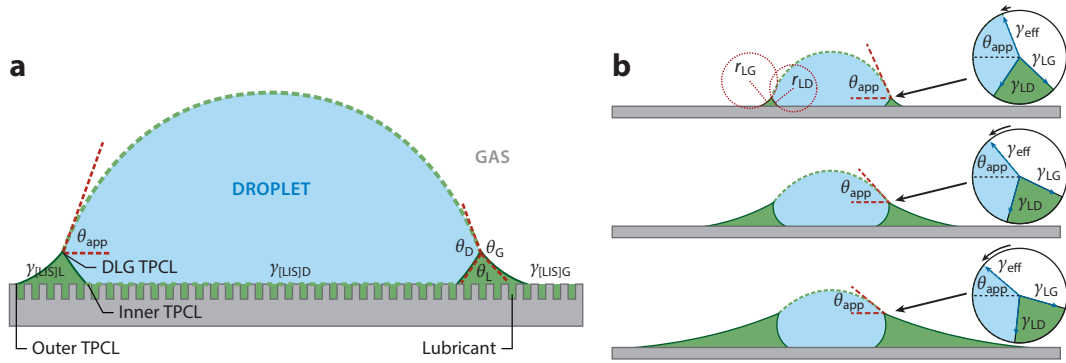


Figure 6

A drop on a liquid-infused surface (LIS). (a) The apparent contact angle (θ_{app}) defined at the drop (D)/lubricant (L)/gas (G) three-phase contact line (TPCL) and associated Neumann angles. The dashed drop outline shows possible cloaking by the lubricant (i.e., infusing liquid). The three-phase contact lines (DLG TPCL, inner TPCL, and outer TPCL) do not exist if the lubricant cloaks the drop or wets the solid surface structure in the presence of the gas or drop, respectively. The interfacial tension between materials i and j is denoted γ_{ij} . (b) The wetting ridge height and rotation of the Neumann triangle increase with lubricant film pressure relative to the drop, thus reducing θ_{app} . Here γ_{eff} is γ_{DG} or $(\gamma_{LD} + \gamma_{LG})$ for a noncloaked or cloaked drop, respectively. Figure adapted from Sempere et al. (2017).

of $\gamma_{[LIS]f}$ can also be generalized to Cassie–Baxter–Wenzel combinations of the two interfacial tensions, giving rise to different surface fraction and roughness parameters for the LIS interface with different fluids. When $\phi_s = 0$, the surface has a continuous lubricant film in contact with a fluid f , even when there is an underlying texture. In the limit of a vanishingly small wetting ridge, which for most LISs corresponds to a lubricant pressure that is large and negative compared with the Laplace pressure in the water drop (i.e., $-\Delta P_{DG}/\Delta P_{LG} \rightarrow 0$), the apparent contact angle θ_{app}^S is

$$\cos \theta_{app}^S = \frac{\gamma_{[LIS]G} - \gamma_{[LIS]D}}{\gamma_{eff}}. \quad 3.$$

Here $\gamma_{eff} = \gamma_{DG}$ or $\gamma_{eff} = (\gamma_{LD} + \gamma_{LG})$ for a noncloaked or cloaked drop, respectively.

Equation 3 can also be derived from interfacial force balance or by minimizing surface free energy changes at the drop periphery (Kreder et al. 2018, McHale et al. 2019). The limit of a smooth solid surface, $\phi_s \rightarrow 1$, yields Young’s law, $\cos \theta_{app}^S \rightarrow \cos \theta_{DS(G)} = (\gamma_{SG} - \gamma_{SD})/\gamma_{DG}$, which defines the contact angle of a drop on the solid in gas, $\theta_{DS(G)}$. The limit of a continuous thin liquid layer, $\phi_s \rightarrow 0$, yields a liquid form of Young’s law, $\cos \theta_{app}^S \rightarrow \cos \theta_{DL(G)} = (\gamma_{LG} - \gamma_{LD})/\gamma_{eff}$, which does not involve interfacial tensions linked to the underlying solid texture and defines a drop contact angle on the lubricant in gas, $\theta_{DL(G)}$. In this limit, one can study drop behavior on an ideal ultrasmooth hysteresis-free solid surface (e.g., McCarthy et al. 2019, Ruiz-Gutiérrez et al. 2017, Wells et al. 2018). Using Cassie–Baxter weighted combinations of a drop wetting the solid and lubricant components of the texture, Equation 3 yields $\cos \theta_{app}^S = \phi_s \cos \theta_{DS(G)} + (1 - \phi_s) \cos \theta_{DL(G)}$.

Based on the work of Sempere et al. (2017), for small $-\Delta P_{DG}/\Delta P_{LG}$ the apparent contact angle can be computed from

$$\frac{\gamma_{[LIS]D} - \gamma_{[LIS]L} - \gamma_{LD} \cos(\theta_{app} - \theta_D)}{\gamma_{[LIS]G} - \gamma_{[LIS]L} + \gamma_{LG} \cos(\theta_{app} + \theta_G)} = 1 - \alpha \left(\frac{\Delta P_{DG}}{\Delta P_{LG}} \right), \quad 4.$$

where $\alpha = 1/2$ for an axially symmetric droplet (Sempere et al. 2021). In contrast to Young’s law, the apparent contact angle of a drop on an LIS depends on the material constants and the size of the wetting ridge relative to the size of the drop. Increasing $-\Delta P_{DG}/\Delta P_{LG}$ increases the ridge

height around a drop and rotates the Neumann triangle, thereby decreasing the apparent contact angle (**Figure 6b**). Experimentally, the ratio of pressures can be determined from the lubricant–vapor and lubricant–drop interface curvatures and interfacial tensions. Equation 4 yields the linear correction to the vanishing ridge height solution:

$$\cos\theta_{\text{app}} = \cos\theta_{\text{app}}^S - \frac{\alpha\Lambda}{\gamma_{\text{DG}}} \left(\frac{\Delta P_{\text{DG}}}{\Delta P_{\text{LG}}} \right), \text{ with } \Lambda = \gamma_{\text{LG}} \cos(\theta_{\text{app}}^S + \theta_{\text{G}}) + \gamma_{\text{[LIS]G}} - \gamma_{\text{[LIS]L}}.$$

Physically, the rotation angle is the ratio of ridge height to drop base radius (Semprebbon et al. 2021). Similar concepts of contact line ridges and rotation of the Neumann triangle apply to drops on liquid films on flat surfaces (Tress et al. 2017) and soft solid substrates (Karpitschka et al. 2015, 2016; for a review of soft wetting, see Andreotti & Snoeijer 2020, Bico et al. 2018).

4.2. Onset of Drop Motion

Setting a drop into motion involves concepts of static and kinetic friction analogous to those for solids (Gao et al. 2018). On a smooth solid surface, the work done in moving a drop forward by wetting a new surface of width w and length Δl at its front and dewetting at its rear is $\gamma_{\text{DG}}(\cos\theta_{\text{R}} - \cos\theta_{\text{A}})w\Delta l$, where θ_{A} and θ_{R} are the advancing and receding contact angles, respectively (Furmidge 1962). The resultant pinning force, $F_{\text{p}} = \gamma_{\text{DG}}(\cos\theta_{\text{R}} - \cos\theta_{\text{A}})w$, can be approximated as $F_{\text{p}} = -w\gamma_{\text{DG}}\sin\theta_{\text{S}}\Delta\theta_{\text{CAH}}$, where $\Delta\theta_{\text{CAH}} = \theta_{\text{A}} - \theta_{\text{R}}$ and θ_{S} is the static contact angle (Barrio-Zhang et al. 2020). For an LIS, we have $F_{\text{p}} = -\Delta\theta_{\text{CAH}}F_{\text{N}}/\pi$, where the normal capillary force is $F_{\text{N}} = \pi w\gamma_{\text{eff}}\sin\theta_{\text{app}}$, which is reminiscent of Amonton’s first two laws of solid friction but with a coefficient of static friction $\mu_{\text{s}} = \Delta\theta_{\text{CAH}}/\pi$. By analogy, the coefficient of kinetic friction is proportional to the difference between the front and rear contact angles of a moving drop.

Simulations of drop depinning using a post model suggest there are two types of processes on an LIS (Sadullah et al. 2020b). Lubricant at the rear of each ridge at the front and back of a drop bridges to the next post [i.e., $\theta_{\text{L[LIS](f)}} = 0$, where the contact angle for a lubricant on an LIS in the presence of a fluid (f = drop or gas) is defined as $\cos\theta_{\text{L[LIS](f)}} = (\gamma_{\text{[LIS]f}} - \gamma_{\text{[LIS]L}})/\gamma_{\text{Lf}}$]. At the front of these ridges, lubricant detaches from the top of a post and slides when the contact angle satisfies $\cos\theta_{\text{L[LIS](f)}} = \Phi_{\text{S}}\cos\theta_{\text{L[LIS](f)}} + (1 - \Phi_{\text{S}})$, where Φ_{S} is the line (rather than area) average of the solid surface fraction. This yields a net pinning force per unit length $f_{\text{p}} = \Phi_{\text{S}}[\gamma_{\text{LD}}(1 - \cos\theta_{\text{L[LIS](D)}}) + \gamma_{\text{LG}}(1 - \cos\theta_{\text{L[LIS](G)}})]$ that is independent of the interfacial tension between the drop and the gas. As a result, one can define advancing and receding contact angles for a drop and predict a sliding angle (Sadullah et al. 2020b, Semprebbon et al. 2017).

LISs allow the design of slippery surfaces with low–contact angle hysteresis and low apparent contact angles while retaining a large drop footprint. For example, Luo et al. (2017) have shown that momentum can be transferred to a drop from a surface acoustic wave to actuate low friction motion while maintaining a large contact area for sensing. Because liquid adhesion of a drop to a surface depends on the receding contact angle, the combination ($\theta_{\text{R}} \approx \theta_{\text{app}}$, $\Delta\theta_{\text{CAH}}$) defines how easily a drop can be moved along a surface (shear hydrophobicity) and removed perpendicularly from the surface (tensile hydrophobicity) (Gao & McCarthy 2008, Tao et al. 2020). Thus, an inverted LIS may easily shed a hanging drop through motion along its surface but still retain the drop adhesively despite gravity (Eifert et al. 2014, Launay et al. 2020). Surfaces can be viewed as more or less wettable according to the contact angle of a drop on a solid, $\theta_{\text{DS(G)}}$, or the contact angle of a drop on the lubricant, $\theta_{\text{DL(G)}}$. When a drop rests on the top of a post-type model textured surface with gaps between the posts filled either by a lubricant or by a gas, the apparent contact angle can be described by a Cassie–Baxter equation: $\cos\theta_{\text{app}}^S = \phi_{\text{top}}\cos\theta_{\text{top}} + (1 - \phi_{\text{top}})\cos\theta_{\text{infill}}$.

When the tops of the posts do not have a conformal lubricant coating and the drop is in direct contact with the underlying solid, we have $\phi_{\text{top}} = \phi_{\text{S}}$. However, when the tops of the posts have a

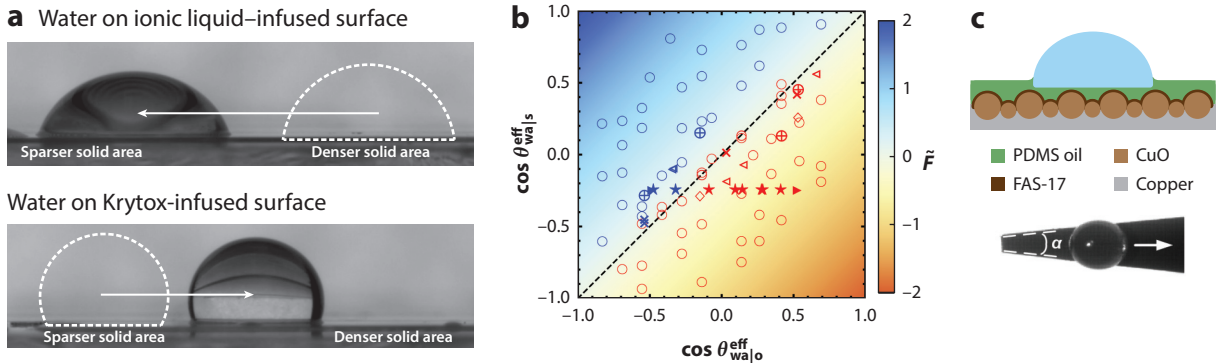


Figure 7

Drop motion driven by wetting. (a) Lubricant-determined bidirectional driving forces on topographical solid gradient liquid-infused surfaces (LISs). (b) Simulation and experimental data for sign dependence of wetting forces (Sadullah et al. 2020a). Here $\theta_{wal}^{\text{eff}}$ and $\theta_{wa|o}^{\text{eff}}$ are the drop apparent contact angle on a smooth solid surface in air and on a lubricant surface, respectively. The data points were obtained from simulations and experiments, in which the droplets were observed to move to the solid majority (blue) or the lubricant majority (red) surfaces. The other symbols are from simulations of different types of model surfaces. Panels a and b adapted from Sadullah et al. 2020a. (c) Motion on shape gradient LISs. Panel c adapted with permission from Zheng et al. (2017); copyright 2017 American Chemical Society. Abbreviations: PDMS, polydimethylsiloxane; FAS, fluoroalkylsilane.

lubricant conformal coating of thickness ε preventing direct contact by the drop, we have instead $\phi_{\text{top}} = \phi_s + 2\varepsilon$. Thus, self-propelled drop motion on conformally coated lithographic rails whose width narrows along their length and where the gaps contain air is toward the direction with a greater fraction of tops of the rails (Launay et al. 2020). In contrast, drop motion on a surface composed of gradient-width rails that have no lubricant on their tops but do have lubricant in their gaps can be in either direction, depending on the sign of $[\cos \theta_{\text{DS(G)}} - \cos \theta_{\text{DL(G)}}]$ (Sadullah et al. 2020a) (**Figure 7a,b**). In all cases, motion is toward the area with greater wettability. Similar concepts apply to other forms of self-propelled drop and bubble motion on structures with wetting gradients and lubricants, such as condensing drops on slippery asymmetric bumps (Park et al. 2016), drops on liquid-filled wedge textures (Zheng et al. 2017) (**Figure 7c**), and bubble transport (Zhang et al. 2018).

A Wenzel equation for slippery conformally coated surfaces can be written as $\cos \theta_{\text{app}}^S = r_W \cos \theta_L$, where r_W is the Wenzel roughness at the drop periphery. Slippery Wenzel states with microgrooves have been used for nucleation and directional transport of water drops (Dai et al. 2015). We also envision more complex combinations of roughness and surface fractions with conformal coatings modeled through a series of transformations, $\theta_s \rightarrow \theta_L \rightarrow \theta_W \rightarrow \theta_{\text{CB}}$, where the first transformation is the conformal lubricant coating and the second and third introduce local Wenzel roughness and solid/lubricant Cassie–Baxter surface fractions (Shirtcliffe et al. 2010). Beyond roughness and topography, apparent contact angles on LISs can be used more widely in wetting problems such as electrowetting (Brabcova et al. 2017, Hao et al. 2014, McHale et al. 2019).

4.3. Drop Dynamics

Studies of the mobility of drops on LISs have typically used tilted substrates and related the velocity of drop motion U to the body force F . Due to the presence of four phases (drop, gas, lubricant, and solid), there is a wide variety of sources of viscous dissipation, including in the drop, lubricant film, and wetting ridge (**Figure 8a**). Moreover, drop motion can dynamically shape the ridge and film thickness (**Figure 8b**). To understand viscous dissipation, one must consider the viscosities of the drop and lubricant, the height and density of the physical texture (assumed

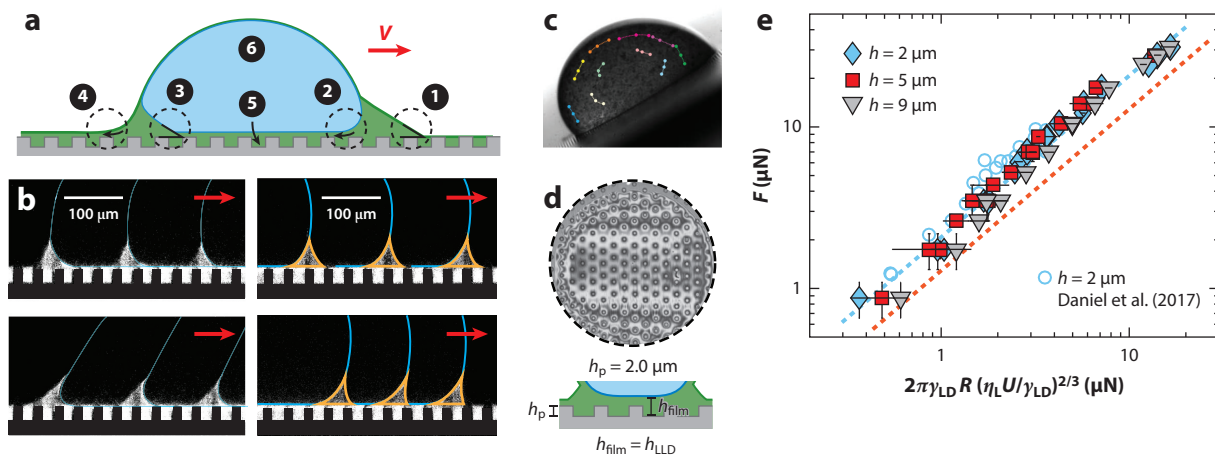


Figure 8

Drop friction. (a) Six dynamical regions for a drop moving on a liquid-infused surface. (b) Images of the rear foot (*left column*) and front foot (*right column*) of moving drops at low (*top row*) and high (*bottom row*) velocities. Panel a and right column of panel b adapted with permission from Keiser et al. (2020); copyright 2020 American Physical Society. Left column of panel b adapted with permission from Keiser (2018), with images acquired in collaboration with P. Baumli and A. Kaltbeitzel. (c) Trajectories of particles relative to a water drop, revealing drop rolling. Panel c adapted with permission from Smith et al. (2013); copyright 2013 Royal Society of Chemistry. (d) White-light interferometry of the film below an oleoplaning drop. Panel d adapted with permission from Daniel et al. (2017); copyright 2017 Nature Publishing Group. (e) Landau-Levich-induced transition between two regimes of friction, both obeying a $2/3$ power law, at high capillary number. Panel e adapted with permission from Keiser (2018) and Keiser et al. (2020), copyright 2020 American Physical Society. Abbreviation: LLD, Landau–Levich–Derjaguin.

here to be pillars), the lubricant film thickness, and the shape of the wetting ridge, including any dynamic effects. Experiments have reported different regimes depending on the drop–lubricant viscosity ratio and capillary number. For viscous drops compared to the lubricant viscosity, drop velocity follows a Stokes-type law, scaling linearly with force and inversely with drop viscosity. For nonviscous drops, regimes include velocity scaling linearly with force and inversely with lubricant viscosity, nonlinearly with a $3/2$ power law and texture dependence, and (at the highest capillary numbers) a cubic power law independent of texture density, as discussed below. Drops have been observed to undergo rolling (**Figure 8c**), and modeling suggests they may undergo a combination of rolling and sliding (Sadullah et al. 2020). However, while the transition from rolling to roll-slip motion of drops on SHSs (Backholm et al. 2020) has been studied experimentally, such studies appear to be lacking for LISs.

Smith et al. (2013) measured drop-shedding velocities on tilted liquid-infused nanograsstopped micropost surfaces. By matching the shear stress at the drop–lubricant interface they deduced an interfacial velocity U_i , scaling as $U_i/U \sim [1 + (\eta_L h_{CM})/(\eta_D d)]^{-1}$, where h_{CM} is the drop center of mass and d is the lubricant film thickness. They predicted that the low-viscosity drops ($\eta_D < \eta_L$) would follow a rolling motion consistent with the observed trajectories of particles added to the drops. They also estimated the rate of viscous dissipation in the bulk drop, lubricant film, and wetting ridge and concluded that dissipation from the wetting ridge dominated. Importantly, the resulting scaling of drop velocity inversely proportional to lubricant viscosity was consistent with their data (also confirmed by Eifert et al. 2014). The predicted velocity–force scaling was Stokes-like ($U \sim F/\eta_L$), but published data deviate from linearity at higher tilt angles.

Using thin-film interference, Daniel et al. (2017) probed the dynamical states of lubricant films at a resolution down to a few nanometers. This approach revealed oleoplaning on continuous films of lubricant for drops moving on micropost-textured LISs that, under static conditions, had

completely or partially wetted tops. The film thickness b increased with velocity and followed a Landau–Levich–Derjaguin (LLD) scaling as $b \sim RCa^{2/3}$ (e.g., Seiwert et al. 2011), where R is the drop radius and the capillary number Ca is equal to $\eta_L U / \gamma_{LD}$, provided that it is larger than the height of the microposts, b_p . Using a cantilever force sensor, Daniel et al. measured velocity–force relationships and fitted their data to $U \sim F^{3/2}$ and $U \sim F$ for films with $b = b_{LLD}$ and $b_{LLD} = b_p$, respectively. They described the functional form of these relations by using an LLD mechanism (Daniel et al. 2017, 2018). In their model, the dissipation in the rear corner of the front ridge is determined by a deformation over a distance $l \sim RCa^{1/3}$, leading to a lubricant film thickness of $b_{LLD} \sim RCa^{2/3}$, with $Ca = \eta_L U / \gamma_{LD}$. Because force is the viscous stress $\eta_L U / b_{LLD}$ integrated over the transition region area $2\pi Rl$, the velocity and lubricant viscosity scale as $U \propto F^{3/2} / \eta_L$ provided that $b_{LLD} > b_p$. In these experiments, the lubricant is more viscous than the drop ($\eta_D < \eta_L$), and the drop rolls while oleoplaning (**Figure 8d**). Similarly to Smith et al. (2013), Daniel et al. found that viscous dissipation occurs in the ridge, but they modeled it as occurring at the rear of the ridge in a small dynamically shaped transition region whose height and extent depend on the drop velocity. Subsequent research developed these ideas and determined the impact on the thickness of the cloaking of the drop and depletion of lubricant as the ridge grows (Kreder et al. 2018).

Keiser et al. (2017) studied drop shedding on tilted pillar–based microtextures, with and without a hydrophobic nanoparticle coating, with both large and small drop–lubricant viscosity ratios and with modest slip ($U_i/U < 0.1$). Their data and analysis suggested that the viscosity ratio determines a crossover between a bulk drop–dominated dissipation regime and a lubricant ridge–dominated dissipation regime. When $\eta_L < \eta_D$, the dissipation for a millimeter-size drop was Stokes-like, with a linear velocity–force relationship, and was inversely proportional to drop viscosity: $U \sim (F/\eta_D)$. In the opposite limit, for $\eta_L > \eta_D$, dissipation was modeled as dependent on texture density, and it occurred mainly in a dynamically shaped ridge with a dynamic contact angle at its front corner. Taking into account both Tanner’s law for the dynamic contact angle, $U \sim (\gamma_{LG}\theta^3)/\eta_L$, and the scaling of the wedge friction that occurs over the pillar tops, $\sim(\phi_s R \eta_L U)/\theta$, yields a velocity–force relationship that retains Smith et al.’s (2013) inverse scaling with lubricant viscosity but has a 3/2 power law: $U \sim F^{3/2} / (\eta_L \gamma_{LG}^{1/2} R^{3/2} \phi_s)$. At higher driving forces, and hence higher capillary numbers, Keiser et al. observed a transition to a texture-density independent cubic law regime, $U \sim F^3 / \eta_L$, which they tentatively interpreted as a self-lubrication effect due to a fully dynamic meniscus. This self-lubrication effect was assumed to occur across a dynamic meniscus of unknown size, r_{men} , and to create a thick lubricant film obeying an LLD thickness scaling, $b_{LLD} \sim r_{men}(\eta_L U / \gamma_{LD})^{2/3}$. However, at these higher velocities, there is insufficient detail on the existence and shape of any dynamic meniscus or the nature of the lubricant film, and not enough data to provide any clarity about a scaling law (Keiser 2018).

Lattice Boltzmann simulations have reproduced the crossover (at around $\eta_D \sim 2\eta_L$) between the bulk drop–dominated and ridge–dominated energy dissipation regimes (Sadullah et al. 2018). These simulations, focused on partial wetting liquids, also highlighted the relative importance of contact line pinning and viscous dissipation and the role of the lubricant contact angle in determining the aspect ratio of the ridge. For large apparent contact angles, contact line pinning dominates and drops on more-wetting lubricants move faster, whereas for small apparent contact angles, viscous friction in the ridge dominates and drops on less-wetting lubricants move faster. Sharma et al. (2019) have reported a reduction in the velocity of drops on LISs with reducing apparent contact angles as a result of reducing interfacial tension by use of ethanol–water mixtures.

Researchers have also suggested that the 3/2 power law is universal for drops whose viscosity is less than the lubricant film viscosity and can fit the entire data set presented by Daniel et al. (2017), that is, for films with both $b = b_{LLD}$ and $b = b_p$ (Keiser et al. 2020). We note that a 3/2 power law can also be fitted to the data presented by Smith et al. (2013). Keiser et al.’s interpretation identifies

dissipation mechanisms in the front and rear corners within the dynamically shaped wetting ridges (regions 1 and 3 and regions 2 and 4 in **Figure 8a**). The dissipation in the front corners of the two ridges is determined by a dynamic contact angle (**Figure 8b**) and thus has a velocity scaling inversely in lubricant viscosity: $U \sim F^{3/2}/(\eta_L \gamma_{L,f}^{1/2} R^{3/2} \phi_s)$, where $\gamma_{L,f}$ is γ_{LG} or γ_{LD} for the front or rear ridge, respectively (Keiser et al. 2017, 2020). This means that drop friction from these two front corners is always present and tuned according to the choice of solid surface fraction (e.g., pillar density in a microtexture). The dissipation from the rear corners is determined by an LLD coating mechanism with a deformation of the rear of the foot of each ridge over a distance $l \sim RCa^{1/3}$, leading to a lubricant film thickness $b_{LLD} \sim RCa^{2/3}$, where either $Ca = \eta_L U/\gamma_{LD}$ (region 2 in **Figure 8a**) or $Ca = \eta_L U/\gamma_{LG}$ (region 4). The dissipation results in a lubricant scaling in each region of $U \propto F^{3/2}/\eta_L$ with prefactors $1/(\gamma_{LD}^{1/2} R^{3/2})$ and $1/(\gamma_{LG}^{1/2} R^{3/2})$ for the rear corners of the front and rear ridges, respectively. Here, an LLD film is expected to form on a micropost texture only when the pillar height b is less than b_{LLD} or, equivalently, the drop velocity exceeds $U^* \sim (\gamma_{L,f}/\eta_L)(b/R)^{3/2}$. Otherwise, there is no LLD film and the friction in regions 2 and 4 is negligible compared with that in regions 1 and 3. Thus, dissipation at the front of the ridges always occurs, whereas at the rear of the ridges, dissipation can be switched on and off by varying the pillar height b_p or drop velocity U while the scaling remains $U \propto F^{3/2}/\eta_L$ (**Figure 8e**). The drop speed threshold, for a given pillar height, at which the LLD film is established depends on texture density, but thereafter the resulting friction is independent of texture density.

Keiser et al. (2020) experimentally confirmed the suggested universality of the scaling laws on LISs for confined drops in a Hele–Shaw cell, where a lubrication film exists between the drop and the impregnated textured walls. However, the different modes of drop motion (for example, rolling/sliding) on LISs, and the influence of surfactants, do not appear to have been studied in a similar way as for the case of Hele–Shaw cells (e.g., Hodges et al. 2004, Huerre et al. 2015, Keiser et al. 2018, Reichert et al. 2018).

SUMMARY POINTS

1. Owing to their robustness and self-healing properties, liquid-infused surfaces (LISs) represent a promising alternative to superhydrophobic surfaces (SHSs) for applications involving either single-phase flow or droplet transport along surfaces. However, shear-induced failure is an important effect limiting the usefulness of an LIS interacting with a flow field. Special measures can be taken to suppress shear-induced failure.
2. A key quantity characterizing LISs is the effective slip length, which, in contrast to SHSs, depends on the flow field in the fluid-filled indentations of the surface. Slippery LISs can reduce drag even under turbulent conditions.
3. Flow fields interacting with LISs can sculpt the lubricant layer, which in turn affects the flow field and drop motion.
4. Drops on LISs have a wetting ridge and an apparent contact angle, which for vanishingly thin lubricants obeys a liquid form of Young's law. For increasing ridge height, this contact angle decreases by rotation of a Neumann triangle.
5. Friction for drops moving on LISs depends on the viscosity ratio and properties of the physical texture. For viscous drops, dissipation occurs in the drop and the drop velocity obeys $U \sim F/\eta_D$. For nonviscous drops, dissipation occurs in dynamically shaped wetting ridges and the drop velocity obeys power laws $U \sim F^m/\eta_L$.

FUTURE ISSUES

1. The widespread use of LISs could be promoted by a better understanding of shear-induced failure and by developing surface designs that allow this failure mechanism to be suppressed.
2. Sculpting of the lubricant layer holds promise for creating surface structures by self-organization and for the control of flow fields via their interaction with the surface.
3. How will the performance of LISs concerning drag reduction and drop dynamics change when surfactants or impurities adsorb at the interfaces between the gas, lubricant, and primary liquid?
4. Textured surfaces with two or more different lubricants and stimuli-responsive LISs could broaden the range of applications involving flow and drop transport along LISs.
5. For motion of nonviscous drops (relative to lubricant viscosity), what is the mechanism and nature for deviation from a universal $U \sim F^{3/2}$ power law at higher capillary numbers?

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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