

Electrostatics slows down the breakup of liquid bridges on solid surfaces

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We experimentally study the breakup of water-glycerol liquid bridges on nonconductive surfaces and find that spontaneous charge deposition at the receding contact line, slide electrification, can have a substantial influence. Compared to bridge breakup on conductive surfaces, electrostatic forces slow down the dynamics during, and cause spontaneous motion of satellite drops after the bridge breakup. We present a model for electrostatic contact line dissipation that aligns with our experimental observations. Our findings demonstrate that slide electrification plays an important role in dewetting beyond drop-related scenarios.

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I. INTRODUCTION

The breakup of capillary liquid bridges between two parallel surfaces, referred to as *free liquid bridges*, has been studied for several decades [1–7] and has important implications for printing processes such as offset and inkjet printing [8,9]. In free liquid bridges, the dynamic breakup behavior is governed by the balance of three forces: the capillary force, which drives the dynamics, as well as viscous and inertial forces, which oppose the capillary force. It can be subdivided into three regimes: viscous, viscous-inertial, and inertial, depending on which is the main contribution opposing the driving force. In the viscous-inertial regime, viscous and inertial forces are of similar magnitude [10]. Scaling relations and similarity solutions have been derived for all three regimes [2,5,7]. In contrast, the breakup of capillary liquid bridges on solid surfaces, *wetting liquid bridges*, has remained obscure to some degree. For example, wetting liquid bridges form on surfaces with nonuniform wettability and are especially important for applications like multilayer inkjet printing, as is used in the production of electronic circuits, fuel cells, and solar panels [9]. Upon evaporation, wetting liquid bridges become unstable [11–13] and break up [14]. In contrast to free liquid bridges, wetting liquid bridges are not axisymmetric but are bounded by a three-phase contact line. This introduces contact line forces as an additional contribution governing the breakup dynamics. For low-viscosity wetting liquid bridges, the breakup is governed by a balance of capillary and inertial forces [15]. However, at higher viscosities, as commonly found in the above-mentioned applications, contact line friction often dominates [16]. Consequently, the solid substrate properties have a substantial impact on the breakup of viscous wetting liquid bridges.

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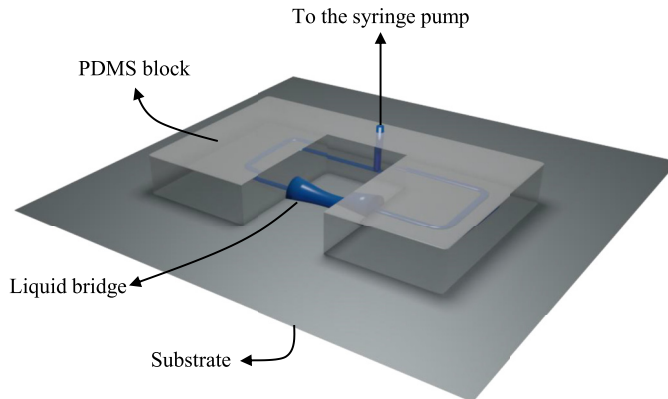


FIG. 1. Schematic representation of the experimental setup with the microfluidic components.

In dynamic wetting, viscous dissipation [17,18], molecular processes at the contact line [19,20], surface roughness, heterogeneities, defects [21], elastic deformation [22], and adaptation [23] can lead to forces hindering the motion of the contact line. Recent work on sliding and impacting drops shows that in addition to these, electrostatic phenomena contribute to the forces acting on sliding and impacting drops [24–30]. This is due to an effect called slide electrification, i.e., the spontaneous deposition of charges by moving contact lines.

Here, we experimentally study the breakup of viscous wetting liquid bridges on conductive and nonconductive substrates and find that the breakup is significantly slower on nonconductive substrates. We systematically trace the effect back to slide electrification. The additional contact line dissipation due to electrostatic effects aligns with slide electrification theory. Our work suggests that the effects of slide electrification not only concern drops on surfaces, but are generally important in wetting processes with receding contact lines.

II. EXPERIMENTS

The experimental setup, procedure, liquids, and substrates used in this study are similar to those in our previous study. For more details, the reader is referred to [16]. However, a brief summary of the methodology is provided here. To form and break up a liquid bridge on a solid surface, a microfluidic setup, schematically depicted in Fig. 1, is used. The corresponding polydimethylsiloxane (PDMS) structure is fabricated using a soft lithography protocol. It consists of two channels with semicircular cross sections, each having a diameter of 0.5 mm. The PDMS block is placed on a substrate, and liquid is pumped through the channels by a syringe pump (KDS Legato 200) to form the liquid bridge on the substrate in the gap between the channels. Subsequently, the same syringe pump is used to withdraw the liquid and reduce the volume of the liquid bridge, leading it to an unstable configuration where it breaks up. The evolution of the liquid bridge is recorded using a high-speed camera (Photron FASTCAM SA-1.1) coupled with a Navitar 12 $\times$ macro objective, resulting in a pixel size of around 1.57 μm in the recorded images. An in-house MATLAB script is used to determine the minimum width of the capillary bridge and the corresponding velocity from the recorded images. Although the theoretical resolution limit for length determination is approximately 6 μm , in practice we encountered difficulties resolving length scales below about 8 μm . Therefore, data in this regime should be interpreted with caution. It should be noted that our analysis of the breakup dynamics is conducted well outside this regime; nevertheless, we report the full dataset for completeness. Owing to the limited temporal resolution, the exact breakup time cannot be determined precisely. Therefore, in analogy with [15], the breakup is assumed to occur $\Delta t/2$ before the first recorded frame in which the liquid bridge appears broken, where Δt denotes

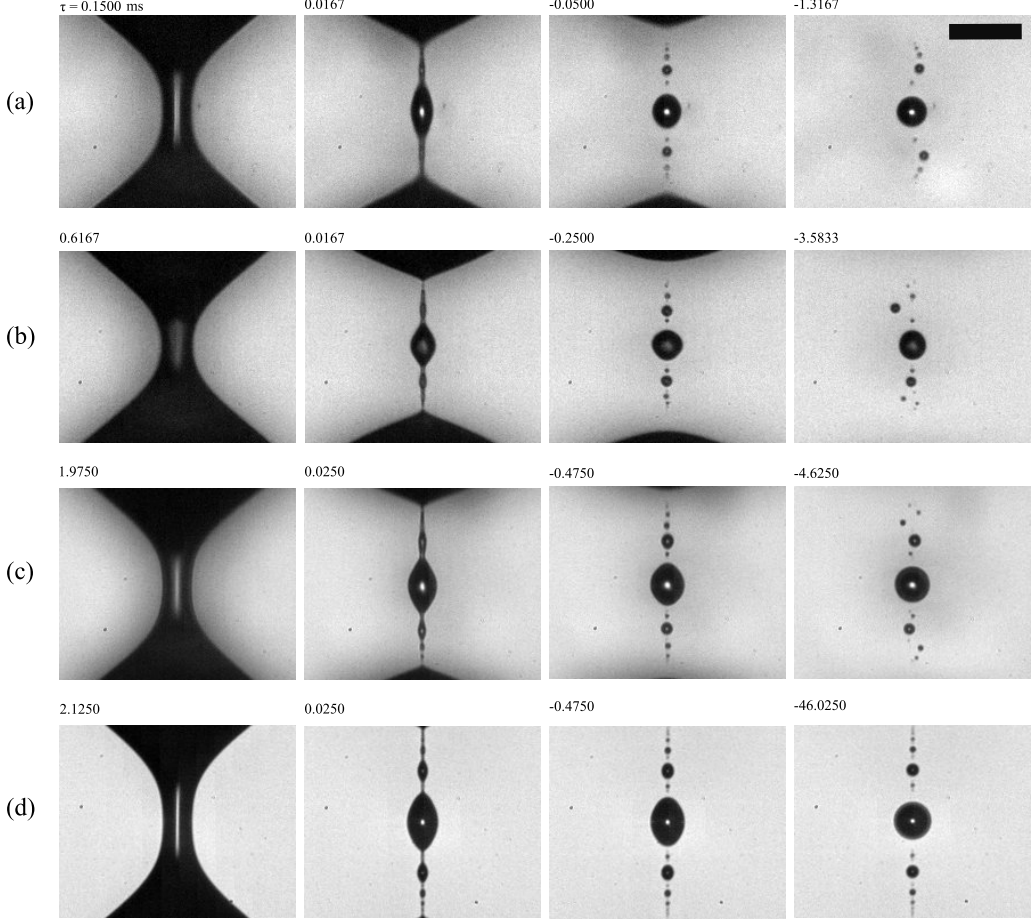


FIG. 2. Snapshots of the time evolution of liquid bridges. τ is the time before breakup and the scale bar represents $100 \mu\text{m}$. On a nongrounded, dielectric glass substrate, liquids of (a) 30%, (b) 50%, and (c) 70% glycerol content exhibit spontaneous and apparently erratic motion of satellite droplets. (d) Satellite droplet motion is suppressed for a 70% liquid on a grounded, conductive substrate.

the time interval between consecutive frames. The time before breakup is defined as $\tau = t_b - t$, with t_b being the breakup time. Consequently, $\tau = -\Delta t/2$ for the first frame showing a broken bridge, while $\tau = \Delta t/2$ for the last frame in which the bridge remains intact. As a result, the uncertainty associated with the determination of t_b leads to an uncertainty Δt in τ [the horizontal error bars in Fig. 3(a)]. Silicon wafers (CZ-Si wafer, 4 in. diameter, thickness $500 \pm 50 \mu\text{m}$; Microchemicals GmbH, Germany) coated with thin layers of chromium (15 nm) and gold (50 nm) using the E-beam method (Balzers BAK 600) are chosen as the conductive substrates. Glass slides (soda lime, $76 \times 52 \text{ mm}$, thickness 1 mm; Paul Marienfeld GmbH, Germany) are used as the nonconductive substrates. The relaxation time of surface charges on soda lime glass due to the presence of free ions is of the order of 2–4 s [28,31,32], which is much longer than the duration of the bridge breakup process. A PDMS pseudobrush coating with a thickness of approximately 3 nm, similar to [33], is applied to the surfaces, resulting in advancing and receding water contact angles of $108.4 \pm 1.6^\circ$ and $95.5 \pm 1.0^\circ$ on the glass substrate, and $110.2 \pm 0.8^\circ$ and $97.2 \pm 1.4^\circ$ on the gold substrate [Supplemental Material (SM) [34] S1 including Ref. [35]].

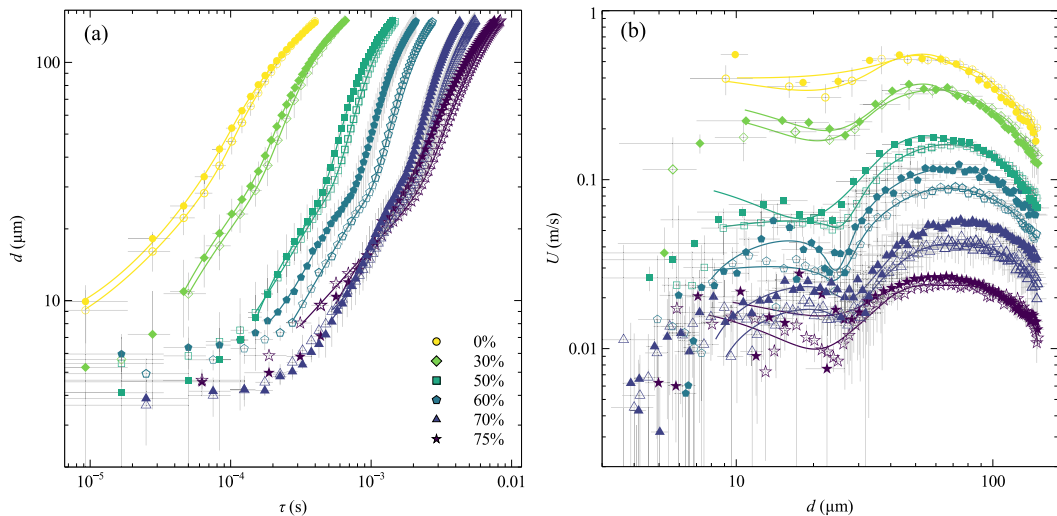


FIG. 3. Electrostatic influence on the breakup dynamics of liquid bridges with glycerol contents between 0% and 70%. Filled symbols mark nongrounded dielectric substrates, and empty symbols grounded conductive substrates. The symbols represent measurements and the solid lines are B-spline fits to the data to indicate the trends. (a) Minimum width of the liquid bridge d vs time before breakup τ . (b) Contact line velocity U at the minimum width vs d from the same data as in (a). The error bars indicate the standard deviation of at least four experiments.

Within the accuracy of the measurement, the contact angles are the same for the two substrates. Atomic force microscopy (AFM) scans reveal that the root-mean-square roughness for both substrates is between 0.4 and 0.6 nm. Water (purified using a Milli-Q device; specific resistance 18.2 M Ω cm at 25 $^{\circ}\text{C}$) and glycerol (>99.5%; Sigma-Aldrich, Germany) mixtures are used as the working liquids, with glycerol contents ranging from 0% to 75% by weight, corresponding to viscosities of 1–46 mPa s. Throughout this article, we will refer to the liquids by their glycerol percentage (mass of glycerol/mass of the solution $\times 100$).

III. RESULTS AND DISCUSSION

A. Satellite droplet motion

During the breakup of liquid bridges on surfaces, a chain of satellite droplets forms at the symmetry plane [15,16]. When performing experiments with the 0% liquid (viscosity of 1.0 mPa s) on nonconductive glass substrates (we will call this the *nongrounded case*), we observe that after the bridge breakup, these satellite droplets spontaneously move along the surface, achieving a configuration that breaks the symmetry (see Supplemental Material Video [34]). The motion is much slower than the bridge breakup and covers distances of 10–90 μm in 1–20 ms, yielding average satellite droplet velocities of 0.1–5 mm/s. The final distribution of satellite droplets appears largely random. However, the length scales and velocities of the droplet motion are reproducible. This behavior is not observed in the breakup of viscous wetting liquid bridges on conductive silicon wafers [16].

To rule out inertial forces as a cause for this motion, we increase the viscosity of the liquid bridge by increasing the glycerol content. This reduces the characteristic velocity of the breakup and thus the inertial forces possibly acting on the satellite droplets. Figures 2(a)–2(c) show the breakup process for the 30%–70% liquids, with viscosities in the range 2.5–23.7 mPa s. While the overall timescales of the breakup process increase substantially, the satellite droplets travel about the same distance before reaching their final configuration. The scattering of droplet

morphologies is similar to that between repeated experiments with the same set of parameters. At these low droplet velocities below 1 mm/s, contact angle hysteresis governs the contact line forces [36]. Surface tension does not vary substantially for different glycerol contents [37]. Consequently, if inertial forces were responsible for the droplet motion, we would expect a less pronounced motion at higher viscosities and, correspondingly, lower velocities.

We repeat these experiments on grounded conductive substrates (*grounded case*) with the same surface properties, where slide electrification is suppressed [25]. Figure 2(d) shows an experiment under the same conditions as Fig. 2(c), but for the grounded case. The grounded substrate completely suppresses the satellite droplet motion, even when recording the dynamics over a much longer time period [compare the timestamps in the rightmost panels of Figs. 2(c) and 2(d)]. We conclude that the satellite droplet motion during liquid bridge breakup on nonconductive substrates is caused by electrostatic effects.

B. Slide electrification

When drops slide along dielectric, nonconductive hydrophobic substrates, they leave behind a (usually negative) surface charge along their path. Due to charge conservation, the drops acquire an opposite net charge [32,38,39]. This effect, called slide electrification, is caused by charge separation at the receding contact line [28,29]. At the solid-liquid interface, an electric double layer is present, comprising a physically or chemically bound layer of surface charge and a diffuse layer of countercharge of thickness $\lambda \approx 1\text{--}1000$ nm. The thickness of the diffuse layer in equilibrium is called Debye length. It is an inherent property of an electrolyte solution and scales inversely with the square root of the ion concentration c_0 [40],

$$\lambda = \sqrt{\frac{\varepsilon_r \varepsilon_0 R T}{2 z^2 F^2 c_0}}, \quad (1)$$

where ε_r is the liquid's dielectric constant, ε_0 the vacuum permittivity, R the universal gas constant, T the temperature, z the ion valence, and F the Faraday constant. When the surface is dewetted at the receding contact line, a part of the bound surface charge from the electric double layer stays on the dewetted surface and leaves the liquid while its countercharge remains in the liquid. The deposited surface charge decreases with decreasing receding contact angle, with increasing dewetting velocity, and with increasing electrostatic potential in the liquid due to accumulated counterions [29,39]. Charge separation occurs even when the liquid is grounded [28,29,41].

The dewetted surface charge interacts electrostatically with the liquid. Li *et al.* [25] recently showed that these electrostatic interactions cause a previously overlooked contribution to contact angle hysteresis, as they decrease the receding contact angle. Microscopically, the effect is caused by Maxwell stresses near the contact line. Macroscopically it can be attributed to an increase in solid surface energy γ_s due to the presence of charges and their mutual electrostatic repulsion. By considering the work required to bring a point charge from infinity to a surface with a surface charge density σ , it has been shown that the increase in solid surface energy scales like (see Supplemental Material of Ref. [25])

$$\Delta \gamma_s = \gamma_s^{\text{eff}} - \gamma_s = \frac{\sigma^2 w}{2 \varepsilon_0 (1 + \varepsilon_s)}, \quad (2)$$

with the substrate's dielectric constant ε_s . The length scale w depends on the contact line width, the total distance moved by the contact line, as well as the thickness of the dielectric substrate [24,25]. In the present case of the breakup of capillary liquid bridges, all of these length scales are on the order of 1 mm. As more surface charges are deposited by the receding contact line, the wettability of the dewetted surface increases. Drops tend to move towards areas of higher wettability, which is commonly utilized in microfluidic drop transport via electrowetting [42] and can even lead to drop movement against gravity along a surface charge gradient [43].

This helps explaining the satellite droplet motion in our experiments. As the liquid bridge breaks up, its receding contact line deposits surface charge, leading to a charged area of the same length scale as the initial liquid bridge. Because the dynamic contact angle and the dewetting velocity both vary during the breakup process, the deposited surface charge is not uniform. After the breakup, the satellite droplets spontaneously move due to electrostatic interactions with the charged surface and other drops, yielding the seemingly random morphologies seen in Figs. 2(a)–2(c).

C. Electrostatic influence on breakup dynamics

Under the assumption that the breaking liquid bridge deposits a surface charge density σ on a nongrounded substrate, the resulting increase in surface energy, Eq. (2), should also influence the breakup process itself. In this section, we systematically study the influence of electrostatics on the breakup dynamics of viscous wetting liquid bridges. To this end, we keep all experimental parameters the same and only vary the substrate between grounded and nongrounded. Note that the other surface properties including contact angles are dictated by the coating and do not vary between grounded and nongrounded substrates. By analyzing the difference between grounded and nongrounded substrates with otherwise identical parameters, we can identify the influence of electrostatics. A similar technique has been applied in [24,25] with sliding drops.

Figure 3(a) shows the minimum lateral width d of the wetting liquid bridge against the time until breakup τ . Figure 3(b) shows the contact line velocity U at the position of minimum width against the minimum width d . Filled symbols represent the grounded case and empty symbols the nongrounded case, respectively. The velocities throughout the breakup process vary across $1\frac{1}{2}$ orders of magnitude between the liquids of different glycerol content. When looking at the individual pairs of grounded and nongrounded cases in Fig. 3(b) at the time of maximum velocity, there is little difference for pure water (yellow circles). For 30% glycerol, the nongrounded case shows roughly 8% lower velocities. This difference increases with the glycerol content up to a content of 70%, amounting to about 33%. For the 75% liquid, the effect again declines. The high-speed images of Fig. S2 in the SM [34] give a clear visual representation of the differences in breakup velocity.

Next, we define a quantitative measure for the electrostatic effects. In the breakup of viscous wetting liquid bridges, the main contribution opposing the capillary force is contact line friction. The total dissipation (dissipated energy per unit time) at the receding contact line scales like [16]

$$D_{\text{tot}} = k_{\text{tot}} U^2 L, \quad (3)$$

where k_{tot} is a friction factor (in $\text{kg m}^{-1} \text{s}^{-1}$), U is the contact line velocity, and L is the length of the contact line. To compare the grounded (G) and nongrounded (NG) cases, we estimate the relative change in contact line dissipation based on the quadratic dependency on the contact line velocity as

$$\Delta \tilde{D}_{\text{tot}} = \frac{U_{\text{G}}^2 - U_{\text{NG}}^2}{U_{\text{G}}^2}. \quad (4)$$

As characteristic velocities for each experiment, we choose the respective maxima of the B-splines in Fig. 3(b). The highest relative difference of 41% in contact line dissipation between the grounded and nongrounded cases is reached for a glycerol content of 70%. It decreases to 3.3% for pure water. To confirm that the additional contact line dissipation is caused by slide electrification, we take a look at slide electrification theory.

D. Parametric trends in slide electrification

A contact line receding on a dielectric substrate generally deposits a part of the surface charge within the electric double layer. The surface charge density that exists in chemical equilibrium in the electric double layer is given by the Grahame equation, here in its linearized form [29,39]

$$\sigma = \frac{\varepsilon_r \varepsilon_0 \zeta}{\lambda_{\text{eff}}}, \quad (5)$$

where ζ is the surface potential of the solid-liquid interface. Far from the contact line, the effective screening length λ_{eff} is equal to the Debye length and the equilibrium surface charge density is $\sigma_0 = \varepsilon_r \varepsilon_0 \zeta / \lambda$. Near the contact line, where charges are dewetted, the effective screening length λ_{eff} can generally deviate from the Debye length [29,44,45]. For a constant surface potential, the surface charge density in the electric double layer, and correspondingly the deposited surface charge density, decrease with an increasing effective screening length λ_{eff} .

The effective screening length at the receding contact line and thus the deposited surface charge density depend on the dewetting velocity. At the receding contact line, the hydrodynamic flow away from the surface can expand the diffuse layer and increase the effective screening length to (see Ref. [46])

$$\lambda_{\text{eff}} = \lambda \frac{\sqrt{\text{Pe}^2 + 4} + \text{Pe}}{2}, \quad (6)$$

where the Péclet number $\text{Pe} = U\lambda/D$, with “ D ” being the diffusion coefficient, is a nondimensional measure for the dewetting velocity and expresses the relative importance of advection over ion diffusion [29]. At low Péclet numbers $\ll 1$, the flow has no influence, the diffuse layer does not expand, and the deposited surface charge density approaches that of quasistatic contact line movement. At higher Péclet numbers > 1 , the effective screening length increases to $\lambda_{\text{eff}} \approx \lambda \text{Pe}$ and the deposited surface charge density decreases. The ratio

$$\frac{\sigma}{\sigma_0} = \frac{2}{\sqrt{\text{Pe}^2 + 4} + \text{Pe}} \quad (7)$$

indicates the amount of deposited surface charge density compared to a contact line receding with a negligible dewetting velocity [29].

The deposited charge causes an increase in solid surface energy, as given by Eq. (2), and results in electrostatic stresses pulling the contact line towards the dry substrate. When the contact line moves with dewetting velocity U against this force, the liquid experiences an electrostatic contact line dissipation

$$D_{\text{el}} \propto U \Delta \gamma_{\text{S}} L = U \frac{\sigma^2 w}{2\varepsilon_0(1 + \varepsilon_{\text{s}})} L. \quad (8)$$

To derive a scaling law for the electrostatic contact line dissipation, we concentrate on the dependence $\propto \sigma^2 U$. To nondimensionalize Eq. (8), we first divide by the nonvariable terms $wL/[2\varepsilon_0(1 + \varepsilon_{\text{s}})]$ multiplying $\sigma^2 U$. Next, we scale the surface charge density σ with the equilibrium surface charge density σ_0 , and the velocity U with D/λ . Expressing the nondimensional surface charge density through Eq. (7) and the nondimensional velocity through the Péclet number yields a general nondimensional scaling for the electrostatic contact line dissipation per unit length on nongrounded, dielectric substrates,

$$\tilde{D}_{\text{el}} = C \text{Pe} \frac{\sigma^2}{\sigma_0^2} = C \frac{4 \text{Pe}}{(\sqrt{\text{Pe}^2 + 4} + \text{Pe})^2}, \quad (9)$$

where C is an unknown constant. For grounded, conductive substrates, there is no charge separation, $\sigma = 0$, and $\tilde{D}_{\text{el}}$ vanishes. We note that, while electrostatic forces are conservative and not dissipative, they counteract contact line motion in the same manner as contact line dissipation. We thus use the established terminology. The physical dissipation of energy occurs when the deposited surface charge is neutralized, e.g., by conduction through the substrate or by free ions in the atmosphere [28,30].

Equation (9) predicts how electrostatic contact line dissipation depends on the dewetting velocity under the condition that the surface potential ζ , dielectric constant ε_r , and the Debye length λ remain unchanged. During our experiments, we decrease the characteristic breakup velocity by adding glycerol, which could potentially influence ζ , ε_r , and λ . In Sec. III E we show that adding glycerol

keeps these variables approximately constant across our experiments. Thus, Eqs. (7) and (9) can be used to predict trends in the deposited surface charge density and the corresponding electrostatic effects, respectively. Experimentally, we evaluate electrostatic contact line dissipation through the relative deviation between grounded and nongrounded cases $\Delta\tilde{D}_{\text{tot}}$, Eq. (4). As the deviation is caused by electrostatic effects, it should be well captured by $\tilde{D}_{\text{el}}$, Eq. (9). To quantitatively compare the relative change in contact line dissipation $\Delta\tilde{D}_{\text{tot}}$ from our experiments to the anticipated electrostatic contact line dissipation $\tilde{D}_{\text{el}}$, we need to quantify the Péclet numbers in the experiments.

E. Influence of glycerol content on charge separation

Changing the glycerol content between experiments can influence charge separation and the Péclet number in multiple ways. Characteristic breakup velocities are available from the measurements shown in Fig. 3(b) and vary by more than a factor of 10. Increasing the glycerol concentration increases the liquid viscosity and slows down the process. Yet, it also affects the other relevant parameters influencing the Péclet number and the effective screening length: the dielectric constant ϵ_r and the ion concentration c_0 , the surface potential ζ , as well as the ion diffusivity D . In the following, we analyze how the dielectric constant, ion concentration, surface potential, and ion diffusivity vary, and show that the overall difference between the mixtures is dominated by velocity changes.

1. Dielectric constant

Water and glycerol are both polar solvents with dielectric constants of $\epsilon_{\text{water}} = 78$ [47, p. 1004] and $\epsilon_{\text{glycerol}} = 41$ [48] at room temperature. The Debye length scales $\propto \sqrt{\epsilon_r}$, so the influence of the dielectric constant of pure glycerol compared to pure water yields a maximum decrease in Debye length of 27%. In our experiments, we are only going up to a glycerol content of 70% by weight in water and thus expect an even smaller variation. Even for a constant effective screening length, the higher dielectric constant of pure water would yield a slight increase in surface charge according to Eq. (5), opposite to the experimentally observed trend. Yet, these influences on the surface charge density by themselves are small compared to the influence due to velocity changes through the Péclet number.

2. Ion concentration

While we do not add any ions to the liquid, the autodissociation of water into protons and hydroxide ions leads to the presence of ions even in ultrapure water. The $\text{p}K_{\text{A}}$ of this reaction is 14 [49]. Glycerol is a propane molecule with one hydroxyl group attached to each carbon atom. In water, the hydroxyl groups of glycerol can dissociate and release protons. This reaction has a $\text{p}K_{\text{A}}$ of 14.4 [50], similar to the autodissociation constant of water. Because the highest glycerol content used in this study, 75% by weight, only amounts to 37 mol % of glycerol, we expect the glycerol to dissociate in the water. Thus, the ion concentrations of ultrapure water and our water-glycerol mixtures due to dissociation should not vary significantly. The theoretical Debye length of water due to autodissociation is $\lambda = 971$ nm.

Importantly, we conduct our experiments at ambient conditions in air. Vogel *et al.* [51] showed that in this case, the dissolution of atmospheric CO_2 in water is non-negligible and increases the ion concentration beyond that caused by pure dissociation. This causes a decrease in the Debye length. At ambient conditions, the solubility of CO_2 is ≈ 7 mol/kmol [52] in water and ≈ 2 mol/kmol [53] in pure glycerol. Accordingly, the ion concentration in water under atmospheric conditions can be expected to be slightly higher than in pure glycerol. This would yield a Debye length that is slightly higher in pure glycerol by a factor of ≈ 1.87 . Since our highest glycerol concentration is just 37 mol %, we assume that the change in ion concentration will be much lower than a factor of 2.

Overall, we conclude that the Debye length of the liquids used should not vary substantially with the glycerol content and use the value for water in contact with atmospheric CO_2 at $\text{pH} = 5.5$ [51], $\lambda \approx 170$ nm, for our estimations of the Péclet number and the changes in surface charge density.

3. Surface potential

The surface potential emerges from the physicochemical interaction of the surface with ions in the liquid. Surface potentials in mixtures of water and glycerol have, to the best of our knowledge, not been measured. The surface coating in contact with the liquid does not change in our experiments, and the liquid composition is dominated by the water content in all considered cases. Additionally, the proton concentration in the liquids is not expected to vary substantially between the different water-glycerol mixtures. Thus, we assume that the surface potential ζ stays roughly constant between experiments. The surface potential of PDMS weakly depends on the liquid's ionic strength and pH [54], both of which are essentially constant across our measurements.

4. Ion diffusivity

PDMS-coated glass surfaces acquire a negative charge during slide electrification with typical surface charge densities on the order of $-10 \mu\text{C}/\text{m}^2$ [24,28,55,56]. Thus, the only available counterions in our liquids are protons, which accumulate in the diffuse layer. The diffusion of protons in water is governed by the Grotthuss mechanism, a proton hopping mechanism yielding diffusivities much larger than conventional diffusion [57,58]. Due to the abundance of hydroxyl groups, the Grotthuss mechanism also dominates in pure glycerol [59]. Thus, despite the higher viscosity of glycerol compared to water, the diffusivity of protons is comparable between the two liquids.

F. Comparison of experiments with theoretical predictions

The above analysis has important implications. It indicates that using mixtures of glycerol and water enables slide electrification experiments with varying viscosity and Péclet numbers, while keeping all other parameters essentially constant.

We estimate the Péclet numbers in our experiments based on the properties of pure water at $\text{pH} = 5.5$. Using $D = 5 \times 10^{-9} \text{ m}^2/\text{s}$ [47] and the respective maximum velocities from the B-splines in Fig. 3(b), we find the Péclet numbers for the experiments with the different glycerol contents.

Figure 4 shows the experimental values of $\Delta\tilde{D}_{\text{tot}}$ [Eq. (4)] and the theoretical trend $\tilde{D}_{\text{el}}$ [Eq. (9)] for the electrostatic contact line dissipation over the Péclet number. Equation (9) is not expected to give absolute values but to accurately predict trends. We find that with $C = 1$ the experiments align well with the theoretical prediction. All data points fall within a 75% error of the predicted trend (shaded area).

Notably, Eq. (9) predicts a maximum electrostatic contact line friction at a Péclet number of $2/\sqrt{3} \approx 1.15$, corroborated by our experimental data. This prediction is not limited to the breakup of wetting liquid bridges but universally applies to dynamic wetting scenarios with slide electrification. In total, our analysis corroborates that slide electrification plays an important role in the breakup of wetting liquid bridges on nonconductive substrates.

IV. CONCLUSIONS

We have demonstrated that electrostatics affects the breakup of wetting liquid bridges on nonconductive substrates. During the breakup, the contact line can be slowed down by over 30% compared to grounded conductive substrates of the same wettability. After the breakup, satellite droplets spontaneously move along the surface for tens of micrometers before reaching seemingly random final positions. The electrostatic influence on bridge breakup increases with the liquid viscosity. We presented a model for electrostatic contact line dissipation that aligns well with our experiments. It predicts a universal maximum in electrostatic contact line friction at a Péclet number of $2/\sqrt{3} \approx 1.15$ that can be further probed in future experiments.

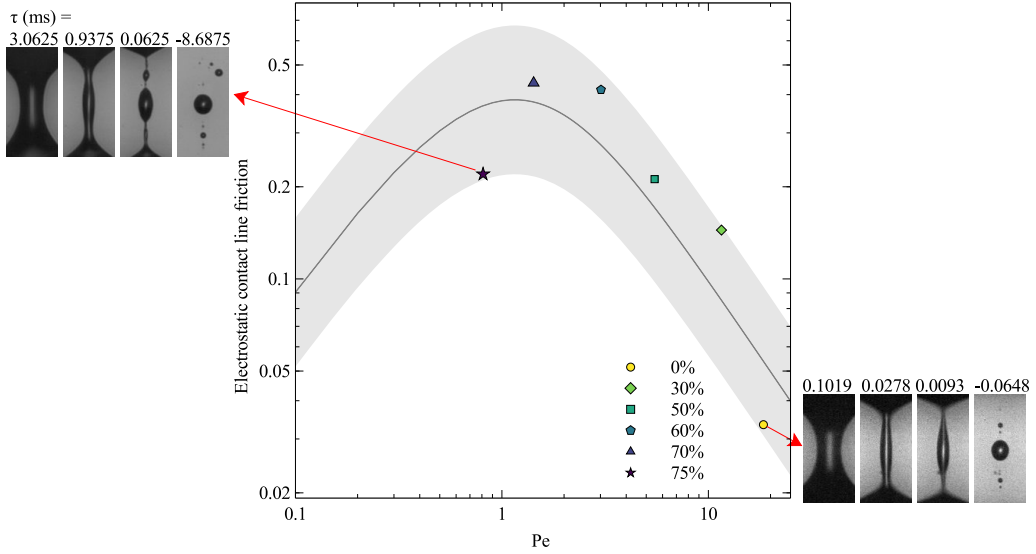


FIG. 4. Nondimensional electrostatic contact line dissipation over Péclet number. The symbols show the relative increase in contact line dissipation between experiments with grounded and nongrounded substrates, following Eq. (4). The line shows the theoretical trend predicted by Eq. (9). The shaded area indicates a $\leq 75\%$ deviation from the theoretical trend line.

Up to now, slide electrification effects have been identified for drops sliding along surfaces. Our findings indicate that the relevance of slide electrification goes beyond such scenarios and suggest that it is a common phenomenon occurring in dynamic wetting.

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S.J.F. devised, designed, conducted, and evaluated the experiments; A.D.R. developed the theoretical framework; S.J.F. and A.D.R. jointly developed the model, interpreted the results, and wrote the manuscript; and S.H. proposed and supervised the work.

DATA AVAILABILITY

The data that support the findings of this article are openly available [60].

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