

Ambient air pressure controls spray cloud formationAntoine Parrenin¹, Cees van Rijn, and Daniel Bonn^{1*}*Institute of Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, the Netherlands*(Received 13 July 2025; revised 31 October 2025; accepted 24 April 2026;
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We present an experimental study of sprays produced from microfabricated spray nozzles as a function of nozzle geometry, flow rate, and ambient pressure. Our findings reveal that spray cloud formation is driven by friction with the surrounding air, resulting in a conical structure whose spatial extent scales as the square root of time. We identify a critical pressure threshold below which the characteristic fanning out of spray clouds, attributed to the Kelvin-Helmholtz instability, fails to occur.

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Spray formation is a ubiquitous process with applications ranging from fuel injection in combustion engines [1,2] to pesticide deposition in agriculture [3]. While the transition from a coherent liquid jet [4–6] to a dispersed spray cloud [7–9] has been extensively studied [10–12], a complete understanding of spray cloud formation, structure, and spatiotemporal evolution has remained elusive [11,13–15]. In this Letter we provide a systematic characterization of spray cloud dynamics at different ambient air pressures. This allows us to show that the formation of spray clouds is driven by friction with the surrounding air, resulting in a structure whose front position scales as the square root of time [7,9] for a fully developed spray cloud. We identify a critical air pressure threshold below which the characteristic fanning out of spray clouds disappears. Systematically varying the ambient pressure in a pressure-controlled transparent vacuum chamber, we can analyze this threshold in terms of the Kelvin-Helmholtz instability, showing that there is a critical velocity difference between the spray and the air that is required for instability growth. The Kelvin-Helmholtz instability develops at the interface between two fluids moving at different velocities, where shear generates vorticity that amplifies small waves on the boundary. As the vorticity rolls up, these perturbations grow, leading to the characteristic wavelike motion and eventually to mixing and turbulence between the layers. While previous studies [16–18] showed how air density affects primary atomization and droplet formation, this Letter investigates the fundamentally different problem of spray cloud formation and collective propagation. These findings are especially relevant for predicting spray behavior in reduced pressure environments, such as propulsion systems operating at high altitudes, industrial processes in controlled environments, and even astrophysical phenomena such as cryovolcanism on icy moons [19]. Our study opens other ways for optimizing spray-based technologies and offers insights into natural spray phenomena.

Our experimental setup to investigate spray cloud formation and propagation consists of a high-pressure pump pushing water through a tailor-made microfabricated nozzle that produces a

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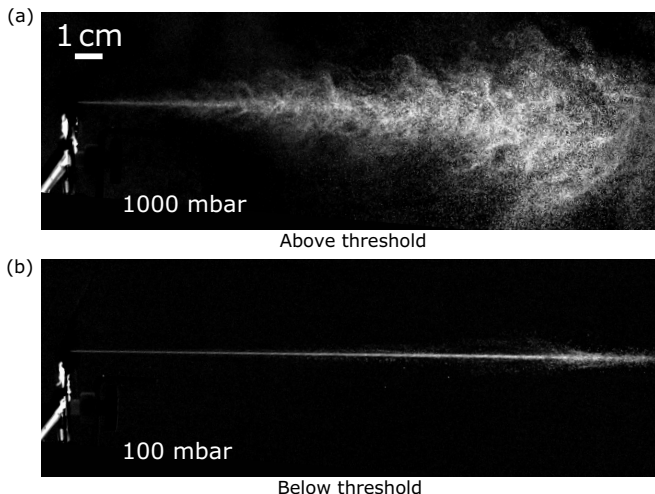


FIG. 1. Typical sprays generated by a nozzle with 24 holes of $4\ \mu\text{m}$ with a flow rate of $500\ \mu\text{L}/\text{min}$ at air pressures of (a) 1000 mbar and (b) 100 mbar, respectively, above and below the threshold value.

multitude of small liquid jets. The nozzles are made using semiconductor lithography techniques that allows to make very well controlled holes in a $2\text{-}\mu\text{m}$ -thin Si_3N_2 membrane; to make sprays we use multiple holes of fixed diameters (here, we focus mainly on nozzles with 24 or 120 holes of $4\ \mu\text{m}$, referred to as $24 \times 4\ \mu\text{m}$ and $120 \times 4\ \mu\text{m}$). We miniaturize the spray setup to be able to spray in a transparent vacuum chamber with inner dimensions $30 \times 30 \times 30\ \text{cm}^3$ in order to investigate the effects of air pressure on spray formation. A Phantom TMX 7510 high-speed camera records the spray at 2000–20 000 frames per second. Image analysis is performed using the “Reslice” method in IMAGEJ software, creating spatiotemporal maps of spray propagation. Particle image velocimetry (PIV) is employed to study droplet behavior within the spray cloud, using the droplets as tracer particles.

Our experiments at various air pressures reveal a surprising phenomenon: the complete disappearance of spray clouds at very low air pressures (Fig. 1). Below a certain pressure, the spray cloud does not develop and instead one observes a collection of jets. This threshold pressure depends on the nozzle configuration and flow rate. The transition is quite sharp, within 40 mbar of pressure one transitions from multiple individual jet behavior to the development of a full spray cloud. PIV analysis of the vorticity within the spray (Fig. 2) reveals that when the spray cloud is formed, it does so by vortices with a well-defined wavelength, that are on average antisymmetric with respect to the spray axis. This is suggestive of the presence of a Kelvin-Helmholtz instability that is well known to happen in the atmosphere when strong winds encounter clouds in stratified systems; something similar appears to happen here.

In fact, the threshold pressure for cloud formation can be understood through the Kelvin-Helmholtz instability mechanism, which requires a sufficient velocity difference between the spray cloud and the surrounding air [20]. In our case, as the air pressure decreases, the friction between the droplets and air diminishes, inhibiting the growth of the instability. Neglecting gravity for our small drops, Chandrasekhar [20] gives the critical velocity difference for the growth of the instability $|\Delta U|_{\min}$ as a function of the average density of the air-droplet mixture (ρ_1), the air density (ρ_2), the surface tension (γ), and the wave number of the disturbance (k):

$$|\Delta U|_{\min} = \sqrt{\frac{\rho_1 + \rho_2}{\rho_1 \rho_2}} \gamma k. \quad (1)$$

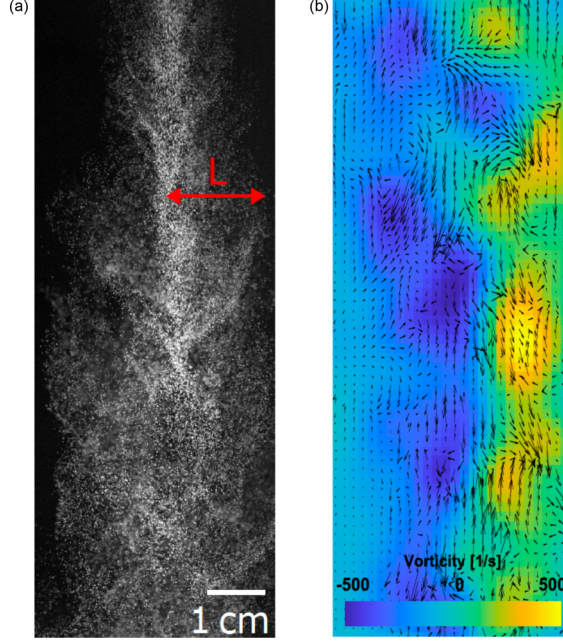


FIG. 2. (a) Snapshot from a video of a spray generated by a $24 \times 4 \mu\text{m}$ nozzle at $500 \mu\text{L}/\text{min}$ at a distance of 12 cm from the nozzle. Each white dot is a droplet. The radius of the cone is indicated. (b) Instant vorticity from the snapshot after removing the average speed. Arrows represent the motion of droplets where these arrows are located.

As ρ_2 (the air density) is a function of air pressure, this relationship implies that a lower air pressure results in a higher initial jet velocity required to form a spray cloud, which explains the observed transition to simple jets at low pressures. Specifically, the density of the spray as a mixture of water and air can be written as $\rho_1 = (\rho_w V_w + \rho_{\text{air}} V_{\text{air}})/V_{\text{tot}}$, with ρ_w , V_w , ρ_{air} , and V_{air} the density and volume of water and air, respectively. Then, replacing ρ_{air} by ρ_2 , V_w by $N\pi r_0^2 h$ with N the number of nozzle holes (h being the jet length), and r_0 the radius of these holes, and noting that $V_{\text{air}} = V_{\text{tot}} - V_w$, we obtain

$$\rho_1 = \rho_w N (r_0/R)^2 + \rho_2 [1 - N (r_0/R)^2]. \quad (2)$$

At room temperature, we can assume $\rho_2 \approx \rho_0 P/P_0$, with ρ_0 the air density at atmospheric pressure P_0 . Neglecting the effects of gravity, we find for the prefactor of Eq. (1),

$$\sqrt{\frac{\rho_1 + \rho_2}{\rho_1 \rho_2}} \approx \sqrt{\frac{\rho_w N \left(\frac{r_0}{R}\right)^2 + \rho_0 \frac{P}{P_0} \left[2 - N \left(\frac{r_0}{R}\right)^2\right]}{\rho_w N \left(\frac{r_0}{R}\right)^2 \rho_0 \frac{P}{P_0} + \left[1 - N \left(\frac{r_0}{R}\right)^2\right] \left(\rho_0 \frac{P}{P_0}\right)^2}}. \quad (3)$$

Figure 3 shows the measured threshold speeds versus the density ratio of Eq. (1), confirming the linear relationship and hence the occurrence of the Kelvin-Helmholtz (KH) instability.

The observed variation in the instability threshold with spray density (equivalent to the number of jets) can be explained by considering the momentum exchange between droplets and air within the spray cloud. As the spray emerges, the moving droplets entrain and accelerate surrounding air, which decreases their own speed. For denser sprays, more droplets are available to entrain the air, so the speed is less reduced than for a more sparse spray. This can be seen in Fig. 4, where droplets from a $120 \times 4 \mu\text{m}$ spray reach larger distances than the $24 \times 4 \mu\text{m}$ spray within a similar time.

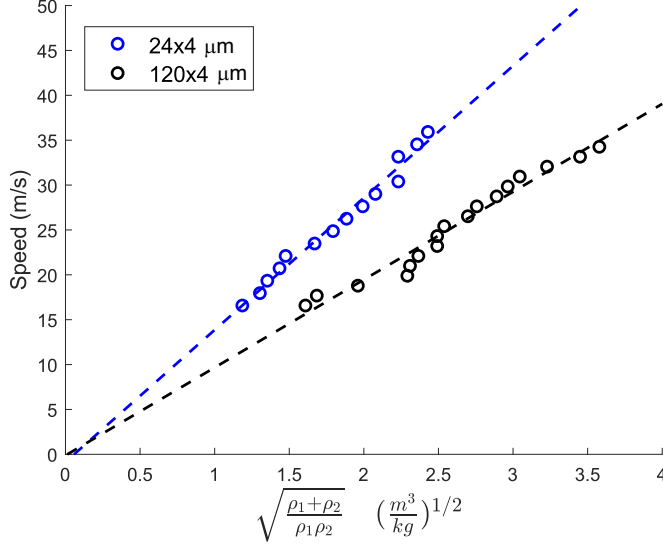


FIG. 3. Threshold speed vs $(\frac{\rho_1 + \rho_2}{\rho_1 \rho_2})^{1/2}$ for two different nozzles. Dashed lines are linear fits of the data.

Because the effective speed of the drops is smaller, one needs to impose a larger speed for the sparse jets to go unstable. It is difficult to systematically study the effect of hole size on the slope; $4 \mu\text{m}$ is the smallest size of nozzle available and larger jets are problematic because the vacuum chamber is too small to study this phenomenon at a larger scale. It is worthwhile noting that the atomization, as in the breakup of the jet into droplets, is not affected by the air pressure; it is given by the Rayleigh instability and indeed measurements of the jet breakup length [21] in our vacuum chamber show that it does not change with ambient pressure.

To estimate the effective surface tension γ of the spray cloud interface, we note that the wavelength of the Kelvin-Helmholtz perturbations should scale with the characteristic droplet spacing.

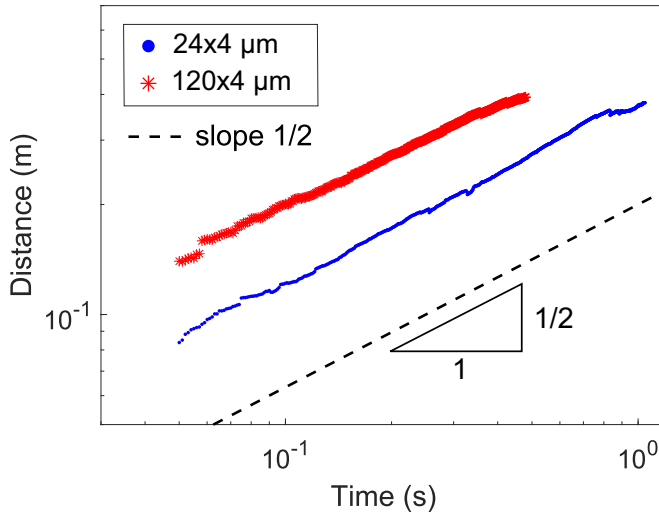


FIG. 4. Distance traveled by the front of the spray vs elapsed time for $24 \times 4 \mu\text{m}$ nozzle (blue) and $120 \times 4 \mu\text{m}$ nozzle (red). Dotted line is a power law with power $1/2$.

Taking $\lambda \approx 9R_0$ for Rayleigh breakup [20], where R_0 is the hole radius of the nozzle producing the jets, here $R_0 = 2 \mu\text{m}$, we obtain $\lambda \approx 18 \mu\text{m}$. The corresponding wave number is $k = 2\pi/\lambda \approx 3.5 \times 10^5 \text{ m}^{-1}$. From the observed slopes $\sqrt{\gamma k} \cdot \alpha \approx 13$ and ≈ 9 for the two configurations, and assuming that the air entrainment factor α varies moderately between the two sprays, we estimate the effective surface tension to be $\gamma \approx 5 \times 10^{-4} \text{ N/m}$. This value is approximately 140 times smaller than the surface tension of pure water ($\sim 72 \times 10^{-3} \text{ N/m}$), which is physically reasonable for a dispersed spray cloud interface. The diffuse, multiphase nature of the spray-air boundary makes it far more compliant and easily deformed by airflow compared to a sharp liquid-gas interface, thus explaining the dramatically reduced effective surface tension.

The Kelvin-Helmholtz instability threshold is dimensionally equivalent to a density-weighted Weber number and can be rewritten in terms of effective density, yielding a modified Weber number $We_{\text{eff}} = \frac{\rho_{\text{eff}} U^2 L}{\sigma}$ for the instability threshold, where the length scale is $L \sim 1/k$.

To account for the shape of the spray cloud, we note that the conservation of momentum flux predicts that the spray front propagates as $l \propto t^{1/2}$ [7,9], and given that $U = \frac{ds}{dt}$, we obtain $U \propto t^{-1/2} \propto 1/s$. Then, using the fact that the KH instability grows as $L \propto Ut$ [22] we obtain a spray shape with a constant opening angle: the cone radius r is proportional to the distance of the spray front from the nozzle s .

Tracking the wave-front propagation as a function of time, we find that its scaling with time indeed follows the expected 1/2 power-law relationship [9] for fully developed spray cones (i.e., at high air pressure), as shown in Fig. 4. When lowering the pressure, this scaling changes from $s \propto t^{1/2}$ at high pressures to $s \propto t$ at low pressures below the threshold leading to the instability, independently of initial flow rate. This shows that if no air friction is present, the jets travel at constant speed, and the fanning out behavior is due to air friction. This is shown for a $24 \times 4 \mu\text{m}$ nozzle in Fig. 5. Our experiments thus reveal that spray front propagation is also affected by pressure, and that below the pressure threshold the power laws obtained from momentum diffusion in the boundary layer do not hold: they require the KH instability to develop. It is consequently the transition, not the initial slope, that distinguishes the two regimes: the early $s \propto t$ scaling reflects a universal ballistic phase before instability develops. The key diagnostic of cloud suppression is the *absence of transition* to $s \propto \sqrt{t}$ scaling.

The conical shape of the spray cloud with a constant angle implies a direct relationship between the propagation of the spray front and the scaling of droplet velocities within the cloud. If the position of the spray front grows as $s(t) \propto \sqrt{t}$, then the instantaneous velocity of the front is $v_{\text{front}}(t) = \frac{ds}{dt} \propto t^{-1/2}$. Since $s \propto \sqrt{t}$, or $t \propto s^2$. The velocity at position s then becomes $v(s) \propto 1/s$. Thus, the observed $1/d$ decay of droplet velocity with distance from the nozzle is a direct consequence of the $\sqrt{t}$ front propagation law.

Using PIV data we can also analyze the velocity of droplets within the fully developed spray (in the stationary regime). Figure 6 shows that the droplet velocity v at the center of the spray cloud indeed roughly scales with as the inverse of distance d from the nozzle, slowing down due to air drag. The speed of drops within the spray, turns out to be larger than than the penetration speed of the spray (depicted by the dashed line), but follows a similar power law, meaning that the behavior of the droplets is similar within the spray and the front. Thus, interestingly, while the propagation of droplets inside the spray follows a similar scaling with time as the spray front, these droplets travel at a higher velocity due to the air entrained within the spray cloud. This phenomenon highlights the complex interplay between individual droplet behavior and collective spray dynamics. This interplay results also from coalescence effects; Ref. [23] shows how the drop velocity and size vary with the distance from the nozzle: the drops slow down due to air drag, but also grow because of coalescence; the front dynamics sensitively depends on the drop size, as larger drops have more inertia and hence go farther.

Our experimental results provide results on the dynamics of spray cloud formation and propagation. The observed $t^{1/2}$ scaling of spray front propagation aligns with theoretical predictions for high-density sprays [7,9]. However, sprays below the instability threshold exhibit faster (linear

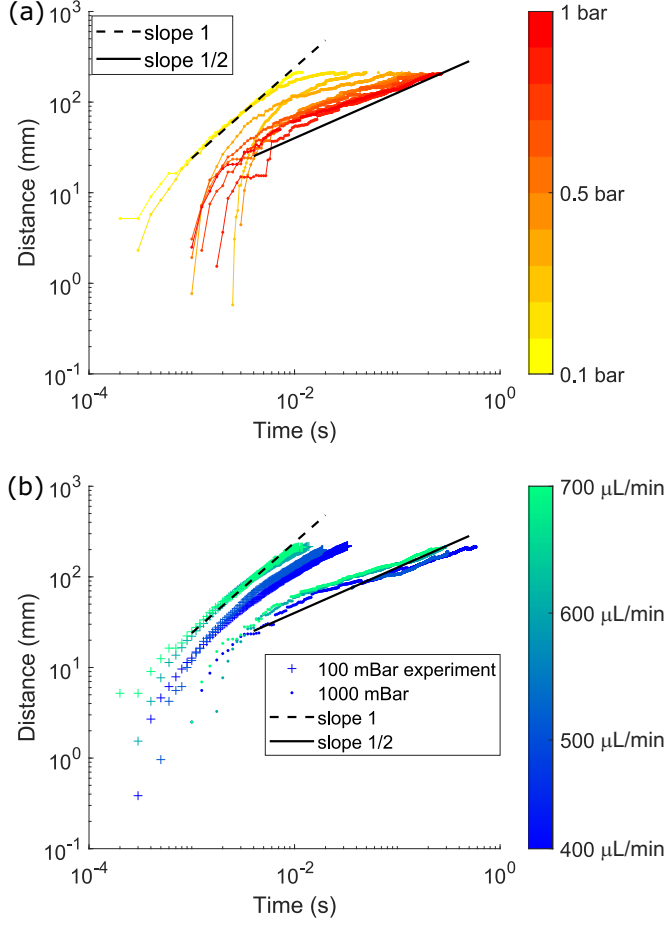


FIG. 5. (a) Distance traveled by the front of the spray cloud expelled from a $24 \times 4 \mu\text{m}$ nozzle at $700 \mu\text{L}/\text{min}$ as a function of time at various air pressures. (b) Distance traveled by the front of the spray cloud expelled from a $24 \times 4 \mu\text{m}$ nozzle at 100 and 1000 mbar air pressures and various flow rates as a function of time. Solid and dashed lines indicate power-law behaviors.

in t scaling), underlining the crucial role of air friction in spray dynamics. The constant angle of the spray cone, supported by our observations of Kelvin-Helmholtz instabilities, captures the dynamics of spray evolution, which is crucial for predicting spray behavior across scales and applications.

Our vacuum chamber experiments uncovered a critical pressure threshold for spray cloud formation. Below this threshold, the spray transitions from a conical cloud to separate jets, highlighting the essential role of air-droplet interactions in creating the collective spray cloud structure. This finding parallels the surprising suppression of drop splashing in low-pressure environments observed by Xu *et al.* [24], suggesting a fundamental connection between various multiphase fluid phenomena. Dombrowski and Hooper [16] studied sheet disintegration [17] from single-hole nozzles producing a liquid sheet across varying ambient densities and showed that the air pressure affects the drop size distribution. We have previously shown in Ref. [18] that the instability of such a sheet is indeed due to air drag, and so if one takes away the air it makes sense that the waves on the triangular sheet disappear and the sheet becomes flat [16]. This is however not equivalent to our system of parallel jets; there is still a sheet and even though the sheet has two edges, these are

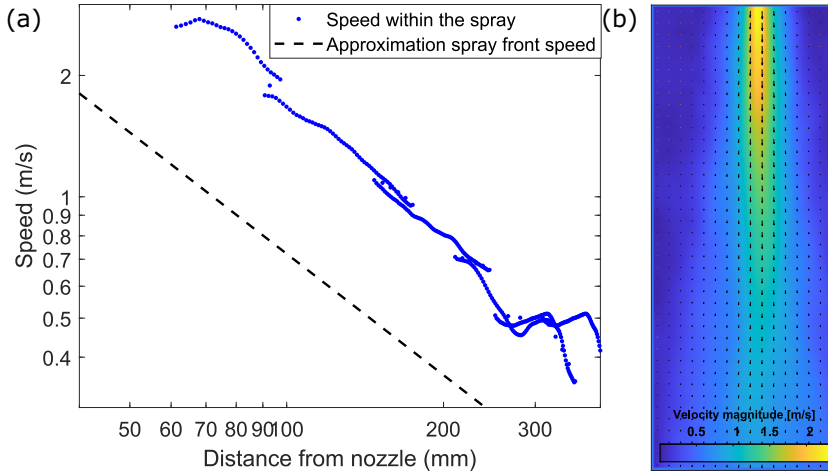


FIG. 6. (a) Droplet speed at the center of the spray vs distance from the nozzle, measured through PIV. Multiple experiments at different distances are concatenated in order to create a single curve. The black dashed line is a slope of -1 approximating the speed of the front of the spray from Fig. 4(a). (b) Average speed within the spray from PIV experiments in Fig. 2.

still very far from parallel jets and so do not have the same atomization mechanism. The present work examines spray *cloud* formation in a three-dimensional, axisymmetric geometry. Critically, we identify a *critical pressure threshold* for Kelvin-Helmholtz instability onset of the dispersed spray cloud.

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

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- [1] W. A. Sirignano, Fuel droplet vaporization and spray combustion theory, *Prog. Energy Combust. Sci.* **9**, 291 (1983).
 - [2] G. Faeth, Spray combustion phenomena, *Symp. (Int.) Combust.* **26**, 1593 (1996).
 - [3] A. H. Lefebvre and V. G. McDonell, *Atomization and Sprays* (CRC Press, Boca Raton, FL, 2017).
 - [4] S. Zaleski, J. Li, and S. Succi, Two-dimensional Navier-Stokes simulation of deformation and breakup of liquid patches, *Phys. Rev. Lett.* **75**, 244 (1995).
 - [5] P. Marmottant and E. Villermaux, On spray formation, *J. Fluid Mech.* **498**, 73 (2004).
 - [6] M. Gorokhovski and M. Herrmann, Modeling primary atomization, *Annu. Rev. Fluid Mech.* **40**, 343 (2008).
 - [7] S. S. Sazhin, G. Feng, and M. Heikal, A model for fuel spray penetration, *Fuel* **80**, 2171 (2001).
 - [8] S. Sazhin, *Droplets and Sprays* (Springer, London, 2014).
 - [9] L. Bourouiba, E. Dehandschoewercker, and J. W. Bush, Violent expiratory events: On coughing and sneezing, *J. Fluid Mech.* **745**, 537 (2014).
 - [10] G. Faeth, L.-P. Hsiang, and P.-K. Wu, Structure and breakup properties of sprays, *Int. J. Multiphase Flow* **21**, 99 (1995).
 - [11] E. Villermaux, Fragmentation, *Annu. Rev. Fluid Mech.* **39**, 419 (2007).
 - [12] N. Ashgriz, *Handbook of Atomization and Sprays: Theory and Applications* (Springer, New York, 2011).
 - [13] J. Eggers and E. Villermaux, Physics of liquid jets, *Rep. Prog. Phys.* **71**, 036601 (2008).

- [14] S. P. Lin and R. D. Reitz, Drop and spray formation from a liquid jet, [Annu. Rev. Fluid Mech. **30**, 85 \(1998\)](#).
- [15] D. R. Guidlenbecher, C. López-Rivera, and P. E. Sojka, Secondary atomization, [Exp. Fluids **46**, 371 \(2009\)](#).
- [16] N. Dombrowski and P. C. Hooper, The effect of ambient density on drop formation in sprays, [Chem. Eng. Sci. **17**, 291 \(1962\)](#).
- [17] H. B. Squire, Investigation of the instability of a moving liquid film, [Br. J. Appl. Phys. **4**, 167 \(1953\)](#).
- [18] S. Kooij, R. Sijs, M. M. Denn, E. Villermaux, and D. Bonn, What determines the drop size in sprays? [Phys. Rev. X **8**, 031019 \(2018\)](#).
- [19] C. C. Porco, P. Helfenstein, P. Thomas, A. Ingersoll, J. Wisdom, R. West, G. Neukum, T. Denk, R. Wagner, T. Roatsch, *et al.*, Cassini observes the active south pole of Enceladus, [Science **311**, 1393 \(2006\)](#).
- [20] S. Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability* (Dover, New York, 2013).
- [21] S. Kooij, D. T. A. Jordan, C. J. M. van Rijn, N. M. Ribe, and D. Bonn, What determines the breakup length of a jet? [Phys. Rev. Lett. **135**, 214001 \(2025\)](#).
- [22] J. Hoepffner, R. Blumenthal, and S. Zaleski, Self-similar wave produced by local perturbation of the Kelvin-Helmholtz shear-layer instability, [Phys. Rev. Lett. **106**, 104502 \(2011\)](#).
- [23] A. Parrenin, S. Kooij, C. J. M. van Rijn, and D. Bonn, Effect of coalescence on the propagation of water droplets from a jet, [Phys. Fluids **36**, 103323 \(2024\)](#).
- [24] L. Xu, W. W. Zhang, and S. R. Nagel, Drop splashing on a dry smooth surface, [Phys. Rev. Lett. **94**, 184505 \(2005\)](#).