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Seeing the invisible—Air vortices around a splashing drop

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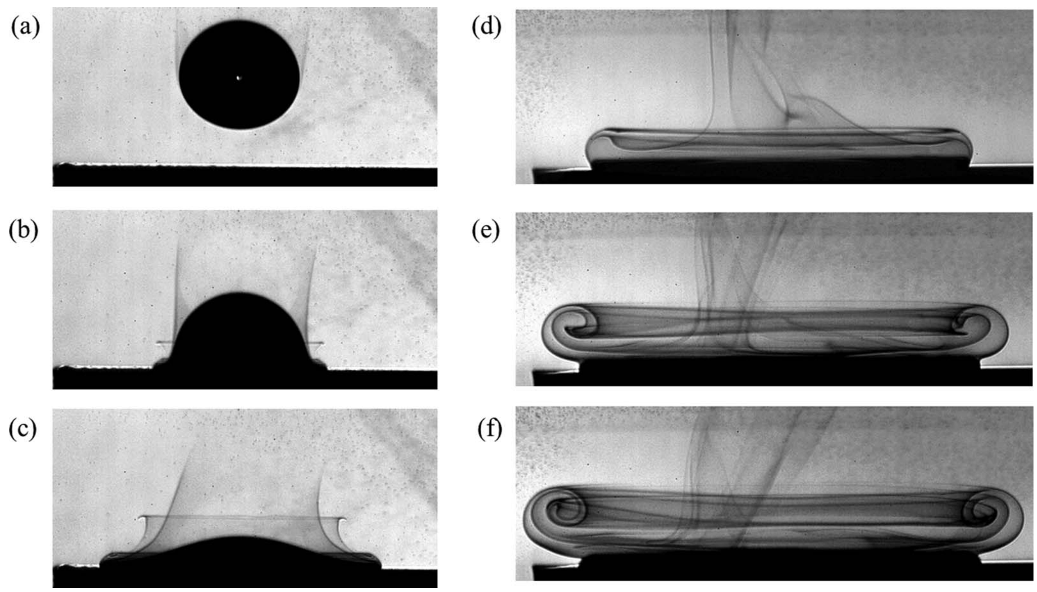

FIG. 1. Evolution of the airflow generated from the impact of a 2.8 mm drop of silicone oil ($\nu = 20$ mm^2/s, $\gamma = 20.6 \times 10^{-3}$ N/m) on a rough dry substrate with root-mean-square roughness $R_{rms} \approx 1$ μm. The time after impact for each frame is (a) -0.25 ms, (b) $+0.25$ ms, (c) 0.75 ms, (d) 1.75 ms, (e) 3.25 ms, and (f) 4.25 ms. (a) Just before impact, the drop creates a flow of air in its wake. (b) and (c) Immediately after impact, the air from the region below the drop is deflected into a crown. Spreading of the liquid induces the formation of a vortex ring that is bound to the drop edge. (d)–(f) At later times, the vortex detaches and curls into an elegant roll.

Seeing the invisible—Air vortices around a splashing drop

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A drop impacting a solid surface with sufficient velocity will splash and emit many small droplets. Surprisingly, however, removing the ambient air suppresses splashing completely so that at low pressure the drop spreads out smoothly on the substrate.[1] There are several distinct splashing regimes that are characterized by different behavior and different dependence on fluid and impact parameters. This includes regimes separated by the velocity[1] and viscosity[2,3] of the drops and on the roughness of the substrate surface.[4] Nonetheless, decreasing the air pressure suppresses splashing in all regimes.[1–4]

The mechanism by which the surrounding gas allows a drop to splash has still not been determined. For example, it has been recently shown that there is no air beneath a slightly viscous spreading drop that could cause the splash.[5] Thus the question to be addressed is: Where does the air matter?

In order to gain insight into this question, we visualize the airflow above a rapidly spreading drop after it has hit a glass substrate impacting at $u_0 = 3.8$ m/s in atmospheric pressure,

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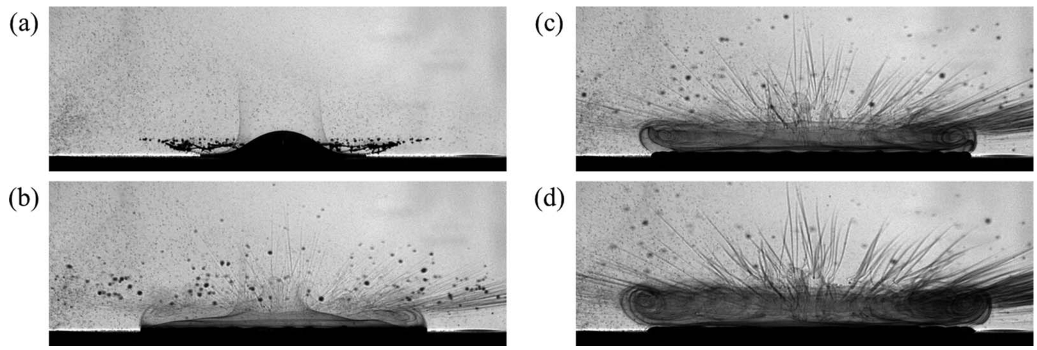

FIG. 2. The airflow created by a splash of a 2.5 mm water-ethanol drop ($\nu = 2.4$ mm^2/s, $\gamma = 27.0 \times 10^{-3}$ N/m) hitting a smooth dry substrate photographed at 0.55 ms (a), 2.05 ms (b), 3.55 ms (c), and 5.05 ms (d) after impact. The droplets ejected during the splash leave trails in their wake as they fly off. Simultaneously, the vortex ring generated by the spreading drop expands and curls into a toroidal structure similar to the shape seen in Figure 1.

$P = 101$ kPa. We use two types of drops: drops of silicone oil and drops of a water-ethanol mixture. We use Schlieren optics combined with high-speed video imaging as a tool to visualize changes in the refractive index of the surrounding air. By heating a layer of glycerol, which is placed on the side of the substrate away from the impact area, we can enhance the contrast in our images by creating a gradient of refractive index above the spreading liquid. We image the airflow above the spreading drop with a high-speed camera at 2000 frames/s.

Substrate roughness can completely suppress splashing.[4] We can use this effect to obtain an unobstructed view of the airflow caused by the spreading liquid without any perturbation of the air currents due to ejected droplets. Figure 1 shows the impact of a silicone oil drop onto rough glass. Upon impact, the liquid spreads out radially and induces flow in the surrounding air. As shown in Fig. 1(a), the drop induces airflow in its wake as it falls. Upon impact, the air below the drop is deflected upwards to form the air crown seen in Figs. 1(b) and 1(c). These panels also show the generation of a vortex ring above the outer edge of the spreading liquid. This vortex initially remains bound to the drop. At late times, the vortex detaches from the liquid and forms a beautiful toroidal vortex sheet that expands and curls up into a roll, as shown in Figs. 1(d)–1(f).

Because substrate roughness only disturbs the region below the spreading liquid, the airflow above the drop is not significantly affected. To demonstrate this, Figure 2 shows a time-series for the impact of a low-viscosity water-ethanol drop onto smooth glass. In this case, the drop splashes almost immediately after impact [Fig. 2(a)] and ejects many small droplets [Fig. 2(b)]. These droplets fly off leaving trails in their wake [Figs. 2(c) and 2(d)]. However, as in Figure 1, a vortex ring is also created by the spreading liquid and, at late times, detaches from the drop and curls up as it expands outwards.

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