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Gallery of Fluid Motion

Rayleigh-Taylor instability in drop impact experiments

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Consider a drop of radius R_d and density ρ_d falling on a pool of a liquid of density ρ_p. The drop strikes the pool surface at a velocity v_d, which results in the formation of a transient crater of mean radius $R(t)$. Though easy to conduct, this experiment hosts a wealth of fluid dynamics phenomena, involving a variety of hydrodynamical instabilities. It is also of interest in geology and planetology, drop impacts being in some respects surprisingly good analogs of crater-forming planetary impacts [1]. In most previous studies, the drop is made of the same liquid as the pool (see, e.g., [2–4]). New phenomena appear when the drop and pool liquids have different densities.

Figure 1 shows two snapshots obtained from experiments involving a drop whose density is either equal to [$\rho_d/\rho_p = 1$, Fig. 1(a)] or higher than [$\rho_d/\rho_p = 1.8$, Fig. 1(b)] that of the pool. In the experiment with $\rho_d/\rho_p = 1.8$, the drop is made of a dense salt aqueous solution. We have also conducted a few experiments at $\rho_d/\rho_p = 0.8$ using ethanol in the drop. The experiments are characterized by similar values of a modified Froude number $\mathrm{Fr}^* = \rho_d v_d^2/\rho_p g R_d$ and Bond number $\mathrm{Bo} = \rho_d g R_d^2/\sigma$, where g is the acceleration of gravity and σ the surface tension. Here Fr^* is the parameter governing the maximum size of the crater. It can be interpreted as the ratio of the kinetic energy of the drop at impact (approximately $\rho_d R_d^3 v_d$) to its gravitational potential energy just before impact (approximately $\rho_d g R_d^4$). In addition, Bo is the ratio of buoyancy forces to interfacial tension at the air-liquid interface. The two snapshots show the crater at the time at which its size is maximum.

Though the density ratio ρ_d/ρ_p affects the shape of the crater and crown (Fig. 1), its most striking effect concerns the fate of the drop liquid. When $\rho_d/\rho_p = 1$, the liquid from the drop is observed to spread at the floor of the crater, forming a layer whose thickness decreases with time in response to crater expansion, the liquid from the drop being redistributed over an increasingly large surface area. A similar behavior is obtained when $\rho_d/\rho_p < 1$. The behavior is markedly different when $\rho_d/\rho_p > 1$. In this case the layer formed from the drop liquid develops mushroom-shaped structures penetrating radially into the water pool [Fig. 1(b)]. Figures 2(a) and 2(b) show snapshots from

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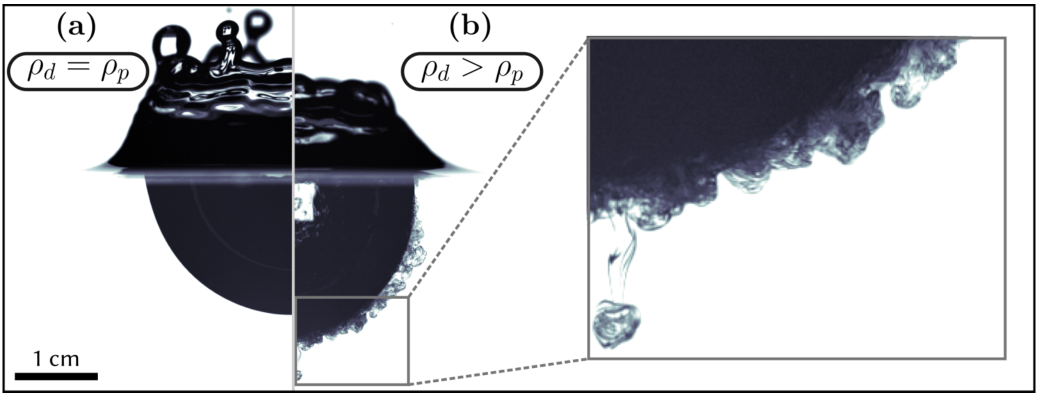

FIG. 1. Craters produced by the vertical impact of a drop onto a pool of water with (a) $\rho_d/\rho_p = 1$, $\mathrm{Fr}^* = 977$, and $\mathrm{Bo} = 0.96$ and (b) $\rho_d/\rho_p = 1.8$, $\mathrm{Fr}^* = 976$, and $\mathrm{Bo} = 1.34$. The original video is available online at https://doi.org/10.1103/APS.DFD.2020.GFM.V0019.

experiments using, respectively, direct visualization, with the drop liquid being dyed, and laser-induced fluorescence. Close inspection of these time sequences shows that the drop liquid first spreads over the crater floor to form a layer of approximately uniform thickness, before small-scale corrugations of the interface develop and gradually evolve into radially growing plumes. The fine-scale structure of the layer made of the drop liquid is reminiscent of mixing layers observed in Rayleigh-Taylor experiments in planar configurations (see, e.g., [5]). Measurements of the thickness of the mixing layer show that it first decreases with time before increasing until the crater reaches its maximum size.

These observations can be rationalized as follows. During crater opening, the rate at which the crater grows gradually decreases with time, which results in the deceleration of the boundary between the drop layer and the surrounding liquid. This situation is unstable with respect to Rayleigh-Taylor instability when the liquid in the layer is heavier than its surroundings. The deceleration $\dot{R} = dR/dt$ of the crater boundary can be estimated from conservation of energy (see, e.g., [2,3]). For a significant fraction of the crater opening phase, the energy balance is dominated by the kinetic energy of the flow surrounding the crater, which is approximately $\rho_p R^3 \dot{R}^2$. Equating this with the impact kinetic energy, which is approximately $\rho_d R_d^3 v_d^2$, and taking the derivative with respect to time gives $\ddot{R} \sim -g\,\mathrm{Fr}^*(R_d/R)^4$. When $\mathrm{Fr}^* \gg 1$, the deceleration can therefore be much larger than the acceleration of gravity. This explains why the dense liquid plumes grow radially

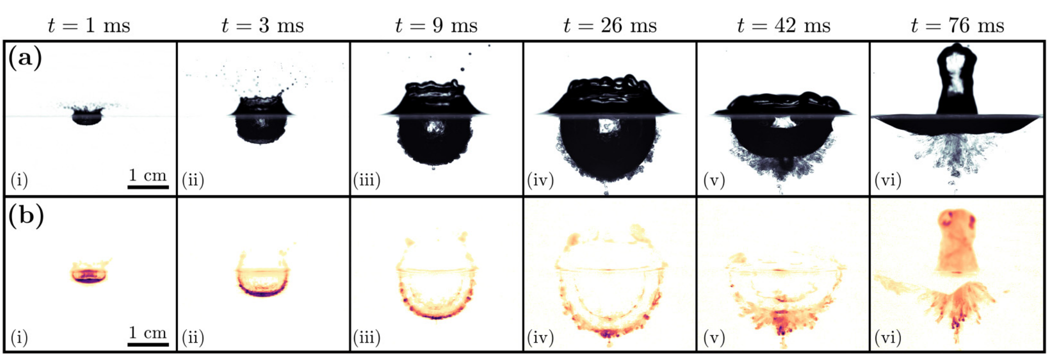

FIG. 2. Time sequences from experiments with $\rho_d/\rho_p = 1.8$ using (a) direct imaging with a dyed liquid drop at $\mathrm{Fr}^* = 976$ and $\mathrm{Bo} = 1.34$ and (b) laser-induced fluorescence at $\mathrm{Fr}^* = 1030$ and $\mathrm{Bo} = 1.25$.

outward rather than in the vertical direction. The nonmonotonic evolution of the mixing layer thickness results from a competition between the growth of the instability and the stretching of the layer associated with the expansion of the crater. The latter effect always dominates at early time, thus initially inducing a decrease of the layer thickness, but is overcome at later times if the density ratio is large enough.

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