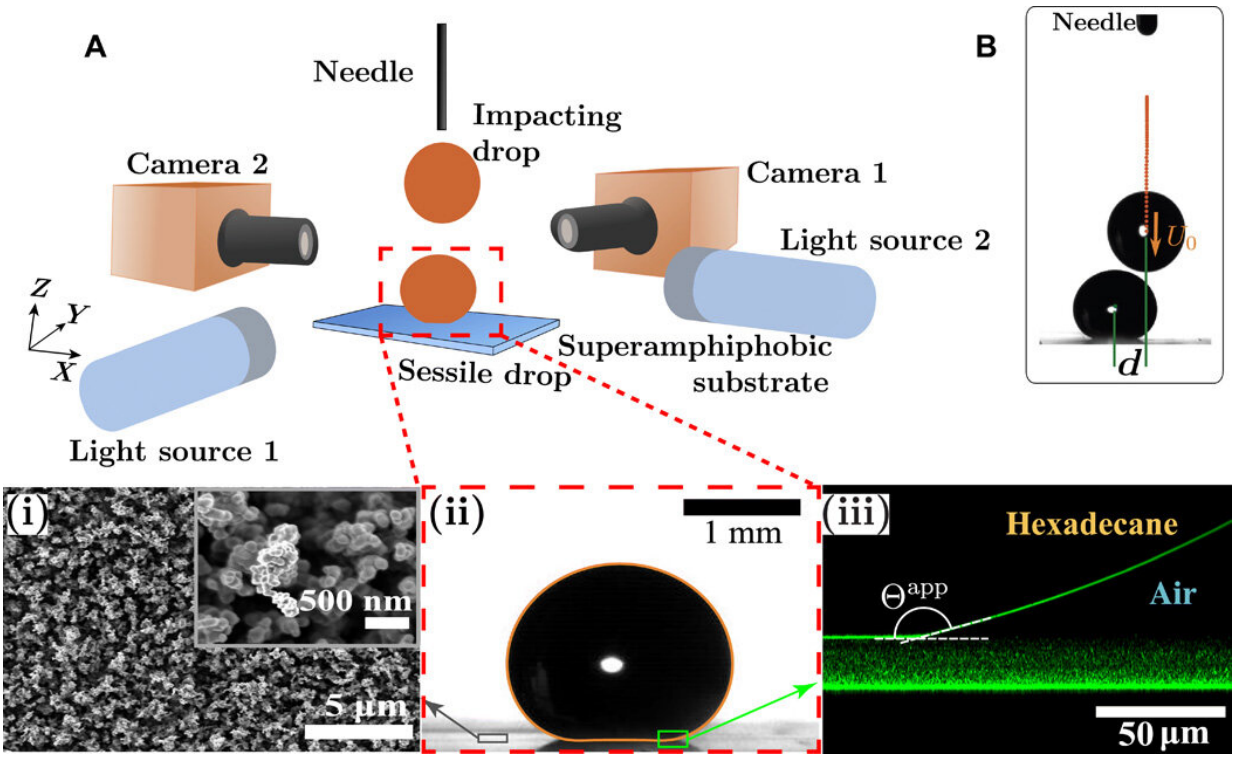
Lifting a sessile drop from a superamphiphobic surface using an impacting droplet

August 26 2020, by Thamarasee Jeewandara



Experimental approach and the sessile drop. (A) Sketch of the experimental setup for binary drop impact on superamphiphobic surfaces. The needle is fixed to set the impacting height in the Z direction and the relative distance between the sessile and impacting drops. The sessile drop is first centered along the YZ plane. Then, the impacting drop is dispensed from the needle while the impact is monitored with camera 2. Camera 1 is used to determine the relative positions of the drops in the X direction. The cameras and the light sources are aligned to observe the impact both in the XZ and YZ planes. Insets: (i) SEM image of a

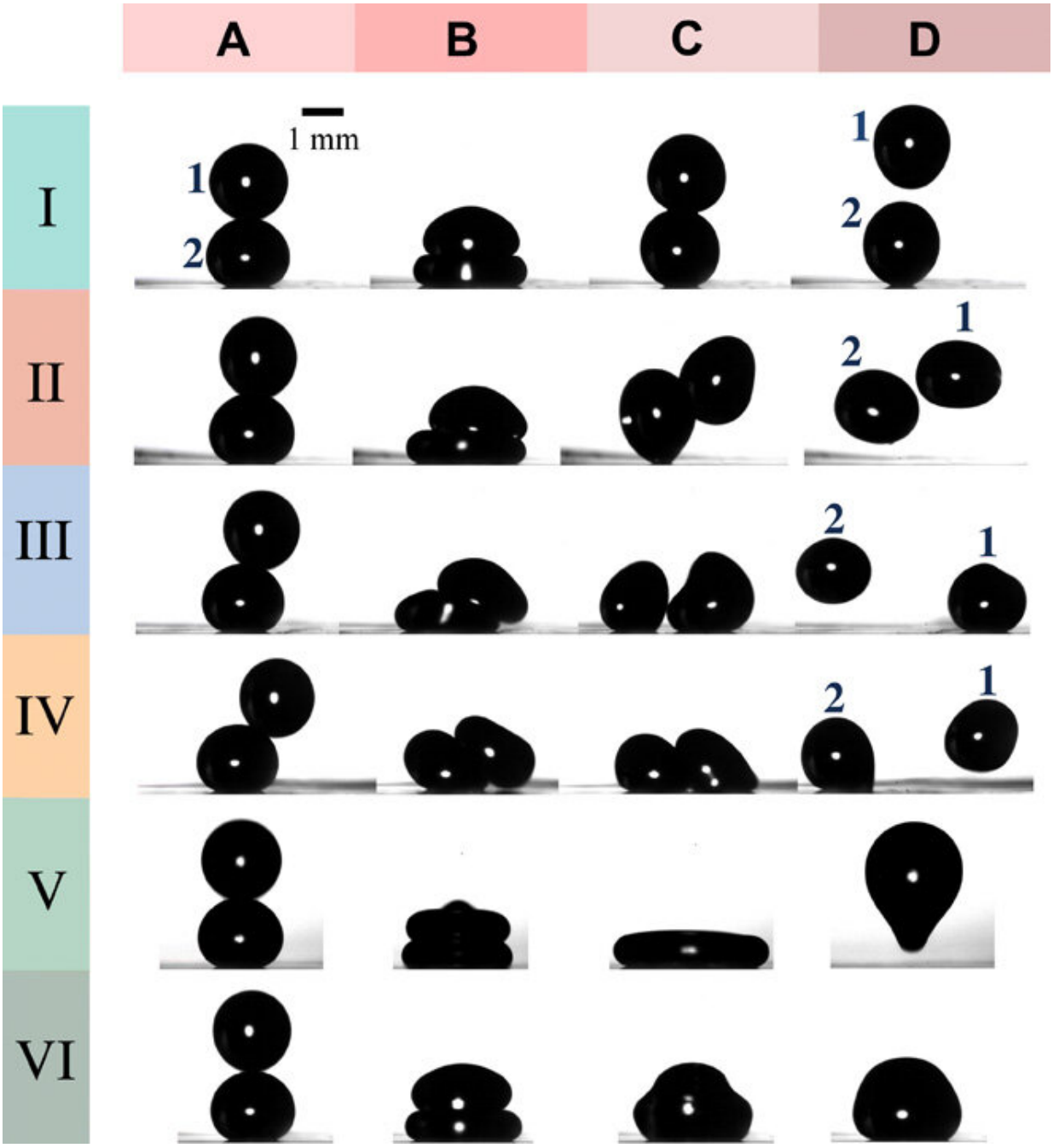
soot-templated surface at two magnifications. (ii) Hexadecane drop (V ≈ 3 μl) resting on the superamphiphobic surface. The orange contour is the solution of Eq. 1 for a corresponding Bond number Bo = 0.3. (iii) Confocal image showing a drop of hexadecane on the superamphiphobic surface. The image illustrates the apparent contact angle of the drop with the surface (Θapp ≈ 164°). The image is taken in reflection mode, i.e., no dye was added to the hexadecane. Reflection of light results from the differences between the refractive indices of hexadecane (1.43), air (1.0), and glass and silica (~1.46). The superamphiphobic layer consists mostly of air, and thus, its refractive index is close to 1. Therefore, the horizontal glass-superamphiphobic layer and the hexadecane-superamphiphobic layer interfaces are visible. The superamphiphobic layer itself is visible as a diffuse pattern, resulting from the reflection of light from the silica nanoparticles. (B) Image showing an off-center collision. The impact parameter is χ = d/(2R). Photo credit: Olinka Ramírez-Soto, Max Planck Institute for Polymer Research. Credit: Science Advances, doi: 10.1126/sciadv.aba4330

Colliding droplets are ubiquitous in everyday technologies such as combustion engines and sprays, and in natural processes such as raindrops and in cloud formation. The collision outcomes depend on the velocity of impact, degree of alignment, intrinsic properties of surface tension and a low-wetting surface. In a new report on *Science Advances*, Olinka Ramírez-Soto and a team of scientists in polymer research, fluid dynamics, chemical and materials engineering in Germany, Netherlands and the U.S. investigated the dynamics of an oil drop impacting an identical sessile droplet on a superamphiphobic surface. A superamphiphobic surface is analogous to superhydrophobicity (water repellence), although it can repel both polar and nonpolar liquids. Using numerical simulations, the team recreated rebound scenarios to quantify the velocity profiles, energy transfer and viscous dissipation in the experimental setup. This work showed the influence of impact velocity on rebound dynamics for oil drop-on-drop collisions on superamphiphobic surfaces.

Investigating drop-on-drop impact

When a liquid droplet impacts a sessile drop of an identical liquid, the intuitive expectation is for both drops to coalesce or combine. This process is common with rain and drops from a leaky faucet, but sometimes a thin layer of air between two drops can enable water drops to perfectly bounce from hydrophilic (water-loving) surfaces instead. In the 1800s, scientist and engineer Osborn Reynolds first recorded and credited the gliding motion of water droplets across a pool to this phenomenon. A vapor layer is similarly responsible for the Leidenfrost effect, where a drop hovers above a superheated surface.

Despite experimental characterization of impact dynamics, methods to quantitatively model the velocity fields and energy transfer are lacking. Studies on drop-on-drop impact on superamphiphobic surfaces are currently hampered by a limited number of techniques to design nonwetting surfaces. It is therefore important to understand what scenarios determine drop-on-drop impact of oil on a superamphiphobic surface and how energy is transferred between the drops. In this study, Ramírez-Soto et al. experimentally and numerically studied the dynamics of a low-surface-tension oil drop impacting a sessile liquid of similar composition resting on superamphiphobic surface. The team showed how the impacting oil droplet could lift the resting droplet off the surface without coalescing.



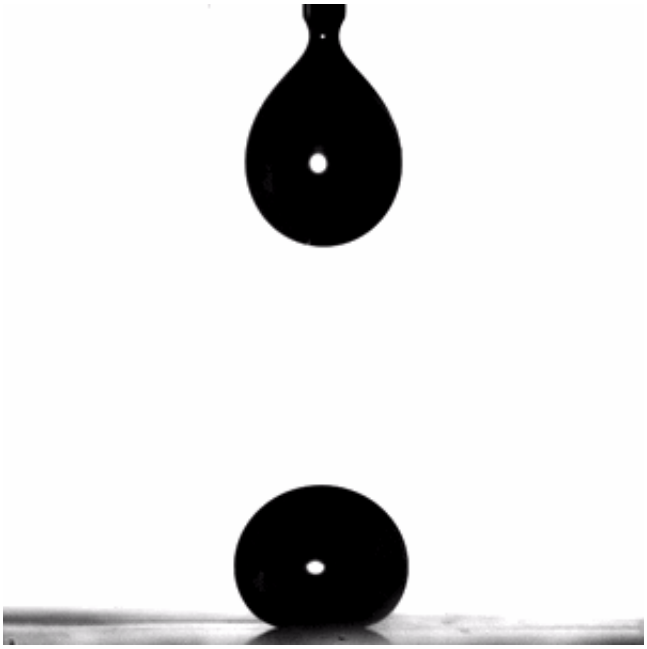
Snapshots of the impact dynamics. Note that the drop labels 1 and 2 are for the impacting and sessile drop, respectively. Six outcomes (cases I to VI) are observed when varying the impact parameter χ and the Weber number (We). The rows correspond to different impact parameter for I to IV. The columns show characteristic stages of the collision process. A, just at collision; B, sessile drop at maximum compression; C, droplet shape just before separation or

coalescence; D, final outcome of the impact. The height of the center of mass of the impacting, sessile, or coalesced drops is maximal. Volume of both drops is 3 μl. Case I: We = 1.30 and χ = 0.01, the time stamps for each frame are tA = 0 ms, tB = 8 ms, tC = 20 ms, and tD = 25 ms. Case II: We = 1.53, χ = 0.08; tA = 0 ms, tB = 8 ms, tC = 20 ms, and tD = 24 ms. Case III: We = 1.44, χ = 0.24; tA = 0 ms, tB = 8 ms, tC = 20 ms, and tD = 24 ms. Case IV: We = 1.48, χ = 0.52; tA = 0 ms, tB = 5.5 ms, tC = 7 ms, and tD = 21 ms. Case V: We = 5.84, χ = 0.08; tA = 0 ms, tB = 3.75 ms, tC = 8.5 ms, and tD = 25.5 ms. Case VI: We = 1.43, χ = 0.03; tA = 0 ms, tB = 7.5 ms, tC = 9 ms, and tD = 17 ms. Photo credit: Olinka Ramírez-Soto, Max Planck Institute for Polymer Research. Credit: Science Advances, doi: 10.1126/sciadv.aba4330

The experimental approach

The scientists conducted four rebound experiments without coalescence. In the first scenario, both drops rebound; in two other scenarios, the impacting drop rebounds while the sessile drop remains, and in the final scenario the sessile drop rebounds while the impacting drop remains surface bound. During the experiments, Ramírez-Soto et al. gently positioned a sessile oil drop on a superamphiphobic surface and impacted it with a second identical drop. They created the superamphiphobic surface using a 20 μm-thick layer of templated candle soot, which contained a porous network of carbon nanobeads. To increase the stability of the fragile network, they deposited a layer of silica on the porous nanostructures. They lowered the surface energy of the soot-templated surface through fluorination to produce a superamphiphobic surface that repelled water and most oils. The scientists used hexadecane as a model oil during the experiments due to a myriad of favorable properties including Newtonian behavior and recorded the angle of a drop of hexadecane using confocal microscopy. The study quantitatively compared the experimental and numerical data of the rebound dynamics. Ramírez-Soto et al. calculated and confirmed

the value of the shape of the drop using the Young-Laplace equation.

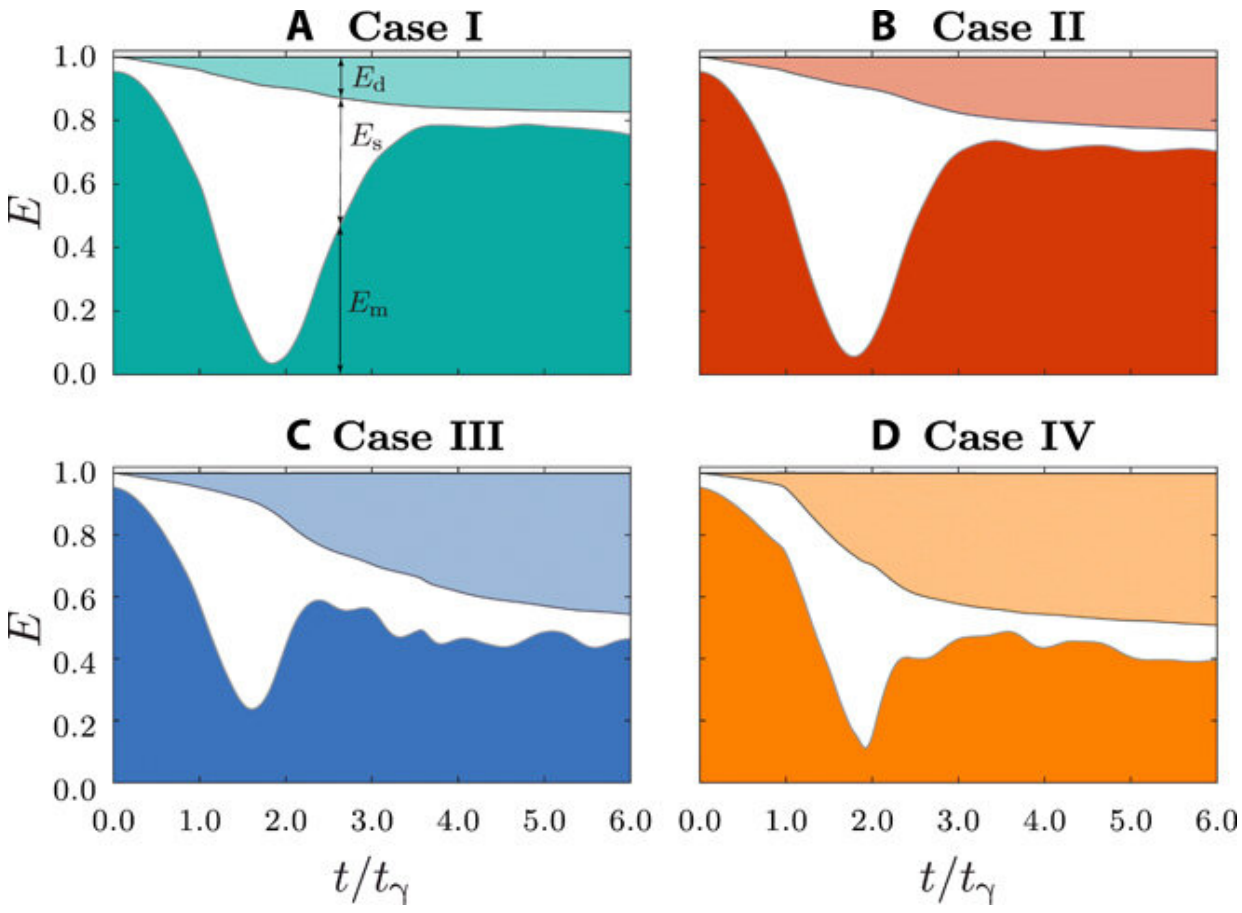


Experimental video of Case I for hexadecane drops: bouncing of impacting drop. (Weber number -

Experimental outcomes and numerical simulations.

The team observed six outcomes for impact dynamics. During impact, both drops deformed and spread radially to show axial compression, while the kinetic energy of the system transferred to the surface energies of both. When the drops began to retreat, the previously sessile drop transferred energy back to the impacting drop in the form of kinetic energy. After collision, the impacting drop bounced away, while the sessile drop stayed on the substrate. The scientists maintained a constant Weber number (*We* ~ 1.5) for all six observed cases; where the parameter typically characterized the atomizing quality of a spray or the resulting droplet size of emulsions. They then plotted the head-on

alignment (denoted X) and increased the Weber number for coalescence of drops in the experimental setup. They credited the outcome to the instability of the air layer between the drops as a result of direct contact under the experimental conditions.



Energy budget. The temporal variation of energy transfer elucidates different stages of the drop-on-drop impact process at We ~1. Initially, all the energy is stored as the mechanical energy of the impacting drop and surface energy of the sessile drop. Then, the mechanical energy of the system decreases and is transferred into the surface energy of the drops. This transfer is followed by a recovery stage where surface energy is transferred back into the mechanical energy of the system. A part of the energy is lost as viscous dissipation. This viscous dissipation considers the combined energy dissipated both in the liquid drops and the surrounding air. This calculation includes the air layers between

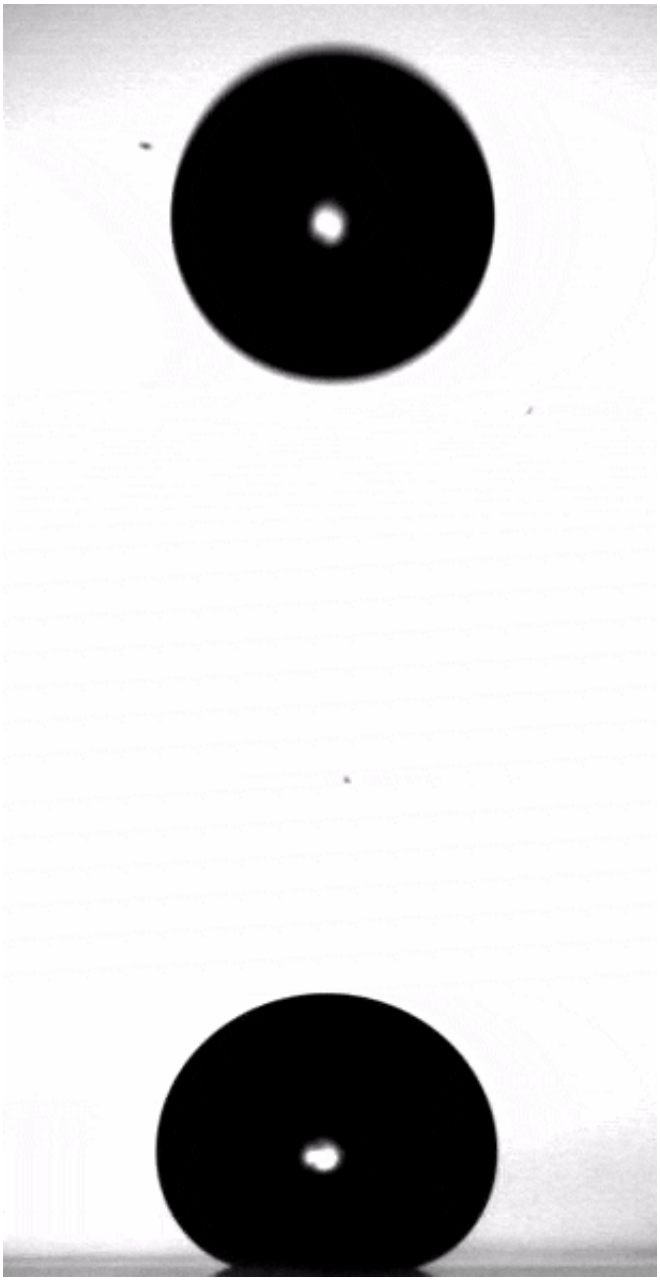
the drops and between the drops and the superamphiphobic substrate. During impact, the drops (A) case I: $\chi = 0$, (B) case II: $\chi = 0.08$, (C) case III: $\chi = 0.25$, and (D) case IV: $\chi = 0.625$. Em is the total mechanical energy of the system (Em = Ek + Ep), Es is the surface energy of the two drops, and Ed is the viscous dissipation in the system. Note that the total mechanical energy (Em) includes the energy of center of mass of the drops as well as the oscillation and rotational energies obtained in the reference frame that is translating with the center of mass of the individual drops. Credit: Science Advances, doi: 10.1126/sciadv.aba4330

Ramírez-Soto et al. then conducted direct numerical simulations (DNS) to illustrate the effect of the velocity fields and energy transfer between drops and compared the results with the experimental data. The team used the geometric volume of fluid (VOF) method and preserved a finite layer of air between the drops throughout the process to mimic experimental conditions to achieve noncoalescing droplets using simulations. The team ran the first four simulations and quantified the velocity vector fields for each case; the results will make it possible to quantitatively explore dynamics of the oil drop-on-drop collision process.

Energy budget

In all cases, the impacting drop contained energy as mechanical energy (in the form of kinetic and potential energy) and as surface energy of the sessile drop. The mechanical energy of the system then decreased and transferred into the surface energy of the combined droplets. A recovery step followed the transfer, in which surface energy transferred back into the mechanical energy of the system, while a part of the energy dissipated in the form of viscous dissipation. This process accounted for combined energy dissipated in the liquid drops and in to the surrounding air. The calculations also accounted the layer of air between drop-on-

drop contact as well as between drop-on-superamphiphobic substrate. The numerical simulations provided a quantitative description of impact dynamics, where a strong agreement existed between the drop boundaries and experimental mechanical energies.



Experimental video of Case V (five) for hexadecane drops: coalescence of drops and lift-off of coalesced drop. Credit: Science Advances, doi:

10.1126/sciadv.aba4330

In this way, Olinka Ramírez-Soto and colleagues combined systematic experiments and numerical simulations to predict and control the outcome of binary oil drop impacts on low-adhesion surfaces. The experimental and numeric one-on-one comparisons revealed the drop boundaries and center of mass mechanical energies, while illustrating the power of direct numerical simulations. The study highlighted how the alignment of droplet impact alone could be used to determine the recovered energy distribution between two drops after impact.

More information: Olinka Ramírez-Soto et al. Lifting a sessile oil drop from a superamphiphobic surface with an impacting one, *Science Advances* (2020). DOI: 10.1126/sciadv.aba4330

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