Carole Planchette

Fundamental Fluid Mechanics for Sustainable Applications

The controlled manipulation of small liquid quantities offers, among others, possibilities to reduce material consumption, gain efficiency, and reduce unwanted pollution, … . Such attributes make it an essential step on the path to more sustainability. Yet, as simple as a droplet may look, it is subject to complex phenomena which need to be better understood in order to be rationally optimized.

As dimensions of liquid bodies come in the range of millimeters or below, the role of their interface becomes predominant. It is responsible for the shape of drops, for the instability of liquid jets, for the coalescence or rupture of bubbles, for the difficulties in producing sprays or applying a regular coating. As the interface becomes curved, it leads to a pressure jump, which, for instance, drives the ascension of coffee in a porous sugar cube, a well-known principle used in paper-based microfluidics. Depending on the systems at stake and the targeted purposes, the interfacial effects, also called capillarity, must be either minimized or enhanced. Yet, despite its apparent simplicity, the dynamics of capillary systems, i.e. drops, bubbles, jets, thin films … often remains very challenging to predict. This is partly due to the complexity of the momentum equation used in fluid mechanics. The difficulty, however, is enhanced by the presence of a liquid interface whose local curvature contributes to the pressure field which, in turn, influences the bulk flow, possibly leading to liquid fragmentation. This aspect makes the problem costly for numeric approaches: the interface must be well resolved, tracked and reconstructed, while questionable thresholds, often related to the mesh size, must be set to induce fragmentation. Thus, combining experiments and analytical modeling remains a method of choice for the study of these fascinating systems, a task which my group and I work on at the Institute of Fluid Mechanics and Heat Transfer. >

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has been working on the physics of droplets for more than 10 years. After her graduation in Paris, she worked for the Research Center for Pharmaceutical Engineering (RCPE, Graz) where she applied her knowledge to industrial processes. Since 2019, she has had a tenure-track position at the Institute of Fluid Mechanics and Heat Transfer of Graz University of Technology (TU Graz). With over 20 peer-reviewed publications in top-ranking journals, she is a recognized expert in capillary hydrodynamics.

Source: Privat

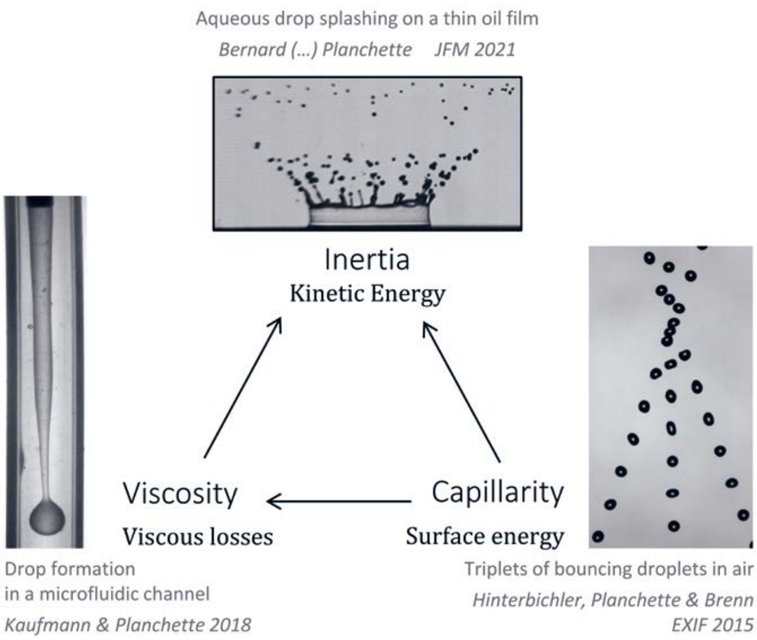

Figure 1:
Interplay between inertia, viscosity and capillarity and diversity in the phenomena in question.

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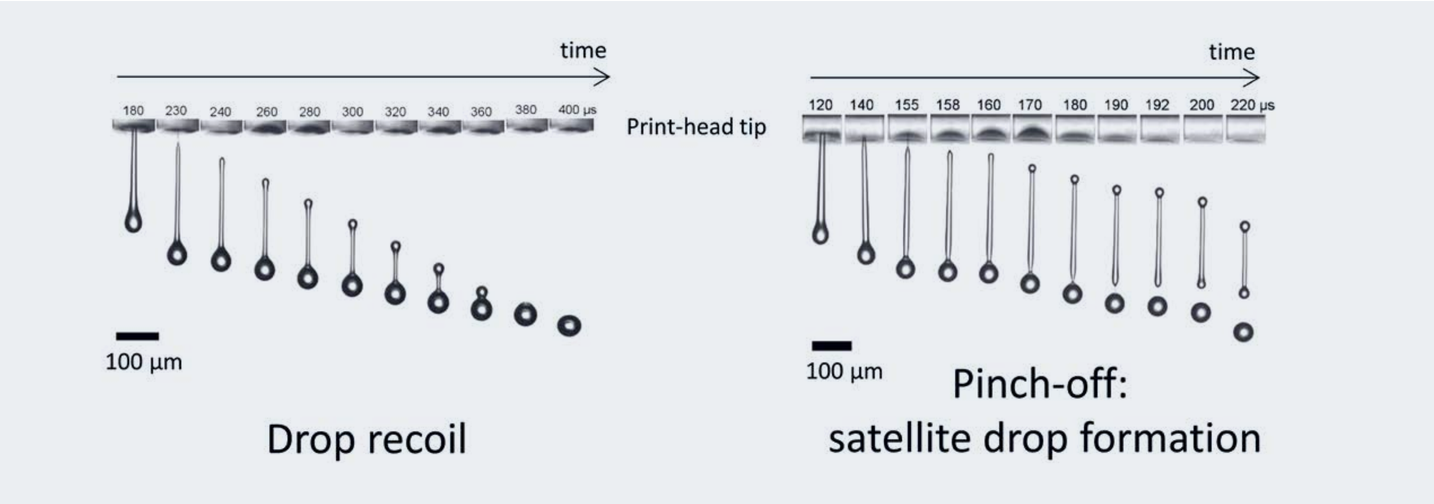


Figure 2: Droplets ejected from a piezo-based print-head. Left: recoil and right: pinch-off.

Source: Adapted from Phys. Rev. Fluids 4, 124004 (2019)

PRINCIPLE OF CAPILLARY HYDRODYNAMICS

In practice, our research deals with a variety of systems whose common point is the significant contribution of the liquid interface to their dynamics. Depending on the relative importance of inertia, viscous losses and capillarity, very different phenomena can be obtained, see Figure 1. When inertia dominates, as during drop impact on a liquid film, a splash gives rise to many small secondary droplets, a potential issue for coating applications. In some cases, drop formation is desired and may be driven by viscous shear, a principle exploited in some microfluidic chips. Finally, the systems can also be dominated by capillarity. This is the case in bouncing droplets, which can be observed during collisions in air or impacts on hot surfaces. Also known as the Leidenfrost effect, the latter makes spray cooling a poorly efficient process. Indeed, the sustainability of numerous industrial processes depends on the dynamics of capillary systems. Let me briefly present some concrete problems my group "capillary hydrodynamics and milli- micro- fluid mechanics" is currently working on.

APPLICATION TO INKJET PRINTING

In the last decades, printing has become one of the most popular additive manufacturing methods. Droplets of a few nanoliters can be accurately placed on various substrates for applications going beyond graphic arts, such as printing medicines and electronics. The possibility to print in three dimensions has raised further interest. Yet, as versatile as it seems, it remains challenging to formulate a functional ink whose properties are adapted to a print-head. The latter must be designed to overcome excessive viscous losses. Further, empirical tuning is required to find the appropriate printing parameters (pulse voltage, duration, shape). Empirically conducted, these adjustments cost much time and materials. Our expertise

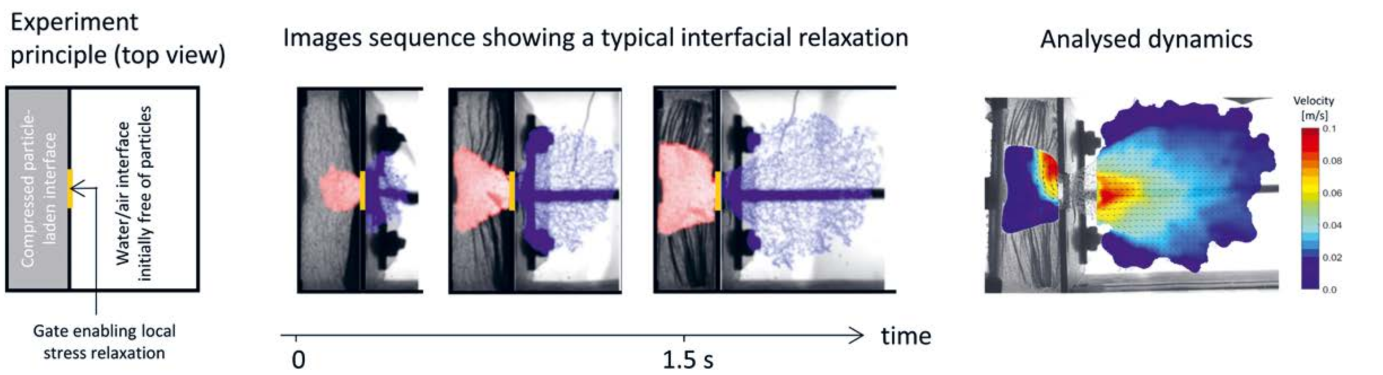


Figure 3: Left: experiment principle dedicated to the study of the self-healing properties of particle-laden interfaces. Center: images showing the relaxation of compressed interfaces upon local stress release triggered by the opening of a gate (yellow, 1 cm wide). The particles initially jammed (grey) are unjamming (red) and cover (blue) the interface area intially free of particle. Right: analysed dynamics.

Source: Adapted from Phys. Rev. E, 106. 034903 (2022).

in the dynamics of deformed drops has contributed to the rationalization of this crucial step. The emergence (or not) of unwanted satellite droplets, results from the competition of the capillary recoil of the droplet tail and its viscous pinch-off, see Figure 2. By modeling these processes, we have opened the route to a rational tuning of inkjet printing.

APPLICATION TO INTERFACE STABILIZATION

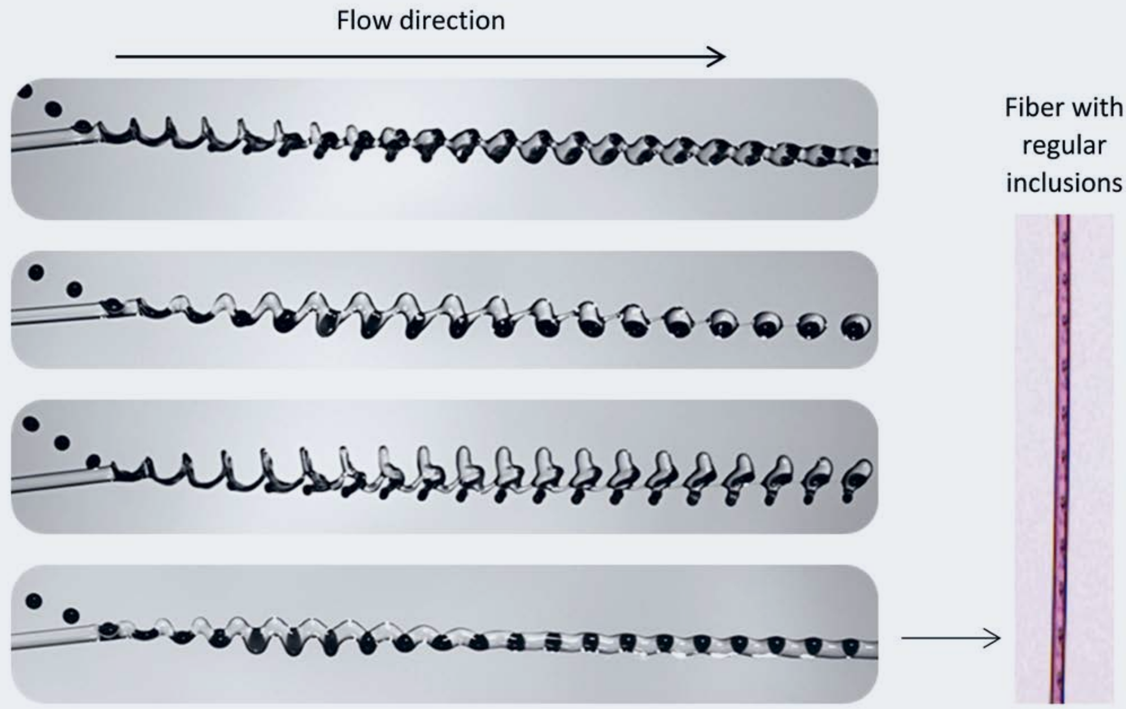
Whenever foams or emulsions come into play, it is essential to stabilize the interface of their individual bubbles or drops. These intrinsically unstable systems age and eventually reach phase separation, losing their applicability. This stabilization can be obtained using surfactants. These molecules, however, are rarely environmentally friendly, and recovering them from waste is difficult. Thus, in my group, we propose using microparticles which capillary adsorb at the interface, providing stabilization. The particles can be easily filtered, and the encapsulation of drops or bubbles is reversible. The mechanical properties of these interfaces remain poorly understood and constitute a bottleneck for their industrial usage. Our key expertise is to design dedicated experiments to fill this gap. Figure 3 shows the relaxation of a compressed particle-laden interface and illustrates its self-healing capacity.

APPLICATION FOR LIQUID ENCAPSULATION

Another important field of expertise of my group is in-air microfluidics for liquid encapsulation. In-air microfluidics consists in combining drop streams and jets in air to form regular liquid structures. The latter may then be hardened to produce capsules or fibers. This presents several advantages over classical chip-based technology. Thanks to the absence of a chip, there is no need for a continuous carrying phase, there is no risk of clogging, the throughput is increased (factor 10 to 100) and the energy needs are decreased (no viscous losses at the wall). Following this approach, we have obtained various types of liquid structures, see Figure 4. Successful on-the-fly solidification of the "drops-in-jet" structure produces remarkable fibers.

Figure 4: Four types of liquid structures produced with dyed glycerol solution (drops) and a silicon oil (jet, transparent). From top to bottom: fragmented-drops-in-jet, capsules, mixed fragmentation, and drops-in-jet with corresponding fiber (right). Drop diameter: 200µm; 0.1 ms between two consecutive drops.

Source: David Baumgartner



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