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Droplets 2021

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## Book of Abstracts

CRC 1194
Interaction between
Transport and
Wetting Processes

## Contents

# Plenary Lectures

# Nanobubbles explain the large slip observed on lubricant-infused surfaces

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Lubricant-infused surfaces, in which a liquid lubricant is trapped within surface roughness, hold promise to reduce the huge frictional drag that slows down the flow of fluids at microscales,(*1*) but their mechanism of action is not yet understood.(*2-4*) We show that infused Teflon wrinkled surfaces induce an effective slip length 50 times larger than expected based on the presence of the lubricant alone (b = 5 μm for the flow of water, equivalent to 12 ± 3% drag reduction). This effect is particularly striking as it occurs even in situations when the viscosity of the infused lubricant (silicone oil $\mu_o$ = 10 cSt and 5 cSt, hexadecane $\mu_o$ = 4 cSt) is several times higher than that of the flowing liquid (water, $\mu_w$ = 0.89 cSt). Crucially, the slip length is observed to increase with increasing air content in the water but is much higher than expected even in degassed and plain Milli-Q water.(*5*) Imaging directly the immersed interface using a mapping technique based on atomic force microscopy meniscus force measurements,(*6, 7*) we reveal that the mechanism responsible for this huge slip is the nucleation of surface nanobubbles, which can be unequivocally distinguished from the infused lubricant. The large magnitude of drag reduction is quantitatively explained with the height and distribution of surface nanobubbles, and by a numerical model of flow on these composite surfaces. The presence of nanobubbles on lubricant-infused surfaces, and not the lubricant alone, explains the large drag reduction reported so far.

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# Hydrodynamic quantum analogs

John Bush

Department of Mathematics, MIT, USA

In 2005, Yves Couder and Emmanuel Fort discovered that droplets walking on a vibrating fluid bath exhibit several features previously thought to be exclusive to the microscopic, quantum realm. These walking droplets propel themselves by virtue of a resonant interaction with their own wave field, and so represent the first macroscopic realization of a pilot-wave system of the form proposed for microscopic quantum dynamics by Louis de Broglie in the 1920s. New experimental and theoretical results allow us to rationalize the emergence of quantum-like behavior in this hydrodynamic pilot-wave system in a number of settings, and explore its potential and limitations as a quantum analog. A generalized pilot-wave framework is developed with a view to capturing additional quantum-like features inaccessible to the hydrodynamic system. A fledgling, trajectory-based description of quantum dynamics, informed by the hydrodynamic system, is proposed and explored.

# Charge-controlled wetting and electromechanical energy conversion

Frieder Mugele

Univ. Twente – Physics of Complex Fluids

Interfacial charges have a profound impact on wetting. They can change contact angles by several tens of degrees and even induce transitions from partial to complete wetting. Interfacial charges can change either by spontaneous physico-chemical processes at interfaces, or they can be tuned by applying voltages to external control electrodes. In both cases, an initial electric phenomenon gives rise to a mechanical response of the system. If, conversely, a drop is forced to mechanically move along or fall onto a surface in the presence of charges, part of the mechanical energy in the system can be converted into electrical electric energy by means of electrical induction and – using suitable external circuitry – can be harvested for other purposes.

In this lecture, I will discuss several examples to illustrate the coupling between electrical and wetting phenomena, starting from the electrically induced mechanical motion of droplets in electrowetting to the reverse harvesting of electric energy from falling drops. I will focus in particular on the conditions required to optimize the efficiency of the latter process. Next to the macroscopic response, some aspects of physico-chemical charge generation at solid-liquid interfaces will be discussed.

# Keynote Lectures

# Contact Angles and Droplet Motion on Slippery Surfaces

**Glen McHale**

*Institute for Multiscale Thermofluids, University of Edinburgh, UK.*

Wettability refers to the interfacial properties of a solid surface in contact with a liquid and determines the extent to which the surface repels a liquid or a liquid is able to form a film on the surface. It is often characterised by the contact angle of the liquid but, for solid surfaces, there is rarely a unique experimental value due to topographical and chemical heterogeneity causing contact line pinning. These properties of wettability and contact line pinning are important for droplet and liquid film processes such as printing, evaporation/condensation and icing/anti-icing and droplet microfluidics. The innovation of lubricant impregnated surfaces has provided pinning free surfaces with super-slippery properties to droplets [1,2], but these either have little or no contact with the underlying solid surface, thus complicating the concept of a contact angle [3]. Here I will outline key work of our group and collaborators in studying the wettability of slippery lubricant impregnated (liquid-infused) surfaces. I will consider how sessile droplets wet hemi solid-hemi liquid surfaces and how this leads to the concept of a generalized Young's law and a definition for the wettability of a liquid surface [4 ,5]. I will argue that hierarchical texturing, which creates a continuous lubricant surface conformal to the shape of a solid micro-texture, can be re-conceptualized as a "shaped-liquid" surface. Finally, I will demonstrate surfaces with gradient liquid wettability which generate low friction uni- and bi-directional self-propelled motion of droplets (Fig. 1) [6,7].

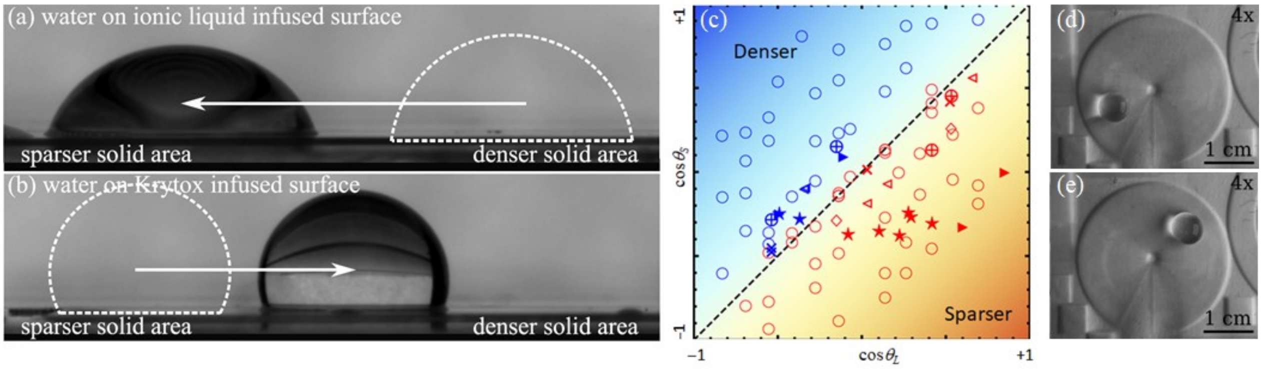

Figure 1. Bidirectional droplet motion on (a) ionic liquid and (b) Krytox infused gradient surfaces, and (c) experimental data and lattice-Boltzmann simulations. (d) and (e) circular motion on a shaped liquid surface.

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# Theory of bubble tips in strong viscous flows

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When a fluid interface is subjected to a strong viscous flow, it tends to develop near-conical ends with pointed tips so sharp, their radius of curvature is undetectable. In microfluidic applications, tips can be made to eject fine jets, from which micron-sized drops can be produced. Here we show theoretically that the opening angle of the conical interface varies on a logarithmic scale as function of the distance from the tip, owing to non-local coupling between the tip and the external flow. Using this insight we are able to show that the tip curvature grows like the exponential of the square of the strength of the external flow, and to calculate the universal shape of the interface near the tip. Our experiments confirm the scaling of the tip curvature as well as of the interface's universal shape. Our analytical technique, based on an integral over the surface, may also have far wider applications, for example treating problems with electric fields, such as electrosprays.

# Rolling of non-wetting droplets down a gently inclined plane

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In their pioneering 1991 paper, Mahadevan & Pomeau argued that small non-wetting drops roll, rather than slide, down gently inclined surfaces [1]. They showed that the rolling speed possesses an anomalous scaling with an inverse dependence upon drop size, in contrast with conventional modes of drop mobility. The Mahadevan-Pomeau scaling was corroborated by the experiments of Quéré and coworkers [2].

We go beyond scaling arguments, carrying out an asymptotic analysis of the hydrodynamic problem of a small non-wetting droplet rolling down a gently inclined plane [3]. The non-wetting assumption eliminates the familiar non-integrable stress singularity at the contact line, resulting in a purely hydrodynamic problem; the assumption of a small inclination angle $\alpha$ allows linearising the problem about the drop's stationary state; and the assumption that the drop is small, such that the Bond number B is small, facilitates a matched-asymptotics analysis where the drop domain is conceptually decomposed into an 'outer' drop-scale region, where the drop is nearly spherical and flows as a rigid body, and an 'inner' region near the flat-spot of the drop. The solution to the linearised flow problem in the flat-spot region is solved in terms of integral functions of the coordinates. The drop speed is then extracted in closed form by calculating the dissipation associated with that flow; in terms of the capillary number Ca associated with it, we find

$$\mathrm{Ca} \sim \frac{3\pi}{16}\sqrt{\frac{3}{2}} \times \frac{\alpha}{\sqrt{\mathrm{B}}}. \tag{1}$$

This is Mahadevan & Pomeau's celebrated scaling up to the prefactor $\approx 0.72$, which gives good agreement with the experiments of Quéré and coworkers. From our analysis we also extract closed-form expressions for the local asymptotic behaviour of the linearised flat-spot flow close to the circular contact line. We find that near the contact line the flow is mainly in the plane locally normal to the contact line; the flow in that plane is similar to the local solution proposed in Mahadevan & Pomeau for a 2D drop, up to the multiplicative factor $2\cos\theta$, $\theta$ being the azimuthal angle. This linkage breaks down only for $\theta \approx \pm\pi/2$, where the contact line propagates parallel to itself and the local flow is genuinely three-dimensional.

A peculiar property of the linearised flat-spot flow is that it simultaneously satisfies no-slip and no-shear on both the solid flat spot and the fluid interface in its vicinity. This observation illuminates a unique 'peeling' mechanism by which the contact line moves down the plane. It also suggests that our analysis may be robust to hydrodynamic slip on the solid substrate. The present work builds on an earlier analysis of the corresponding 2D problem [4].

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# Direct Numerical Simulation (DNS) of Drop Dynamics

by

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## Abstract

The numerical prediction of two-phase flows is generally difficult. Normally a lot of simplifications and assumptions have to be made. On the other hand, a lot of two-phase flow phenomena are present in our daily life and in a lot of technical processes. In many of these processes single droplets or interactions of droplets are of great interest (e.g. injection, interaction and evaporation of fuel droplets in a rocket or car engine or a gas turbine combustion chamber, clouds formation, rain droplets, air pollution, sprays in medical applications,…). The ITLR in Stuttgart has developed over the past 25 years a CFD code named FS3D (Free Surface 3D), which is able to predict droplet interactions, droplet evaporation as well as jet disintegration by using direct numerical simulation (DNS). The computational resources needed for this approach are high, so that the code is run normally on the supercomputer in Stuttgart. Grid sizes of several billion grid cells have been used already successfully.

For the numerical simulations of basic droplet processes, the in-house 3D-CFD program FS3D (Free Surface 3D) has been used. This code solves the Navier-Stokes equations for incompressible flows with free surfaces. The equations are solved without a model by Direct Numerical Simulation (DNS), which requires a high resolution of the computational domain to capture the small length scales of the multiphase flow. The governing equations are conservation of momentum, mass and energy. In two-phase flows additional information about the interface position between the disperse and continuous phase are needed. In FS3D a volume-tracking method, well known as the Volume-of-Fluid (VOF) method, is used. In the VOF-method an additional transport equation for the volume fraction $f$ (VOF variable) of the dispersed phase is solved. To ensure a sharp interface and to suppress numerical dissipation of the disperse phase in each step, the interface is reconstructed with the PLIC-method (Piecewise linear interface reconstruction computation). After the reconstruction of the interface, the disperse phase is transported on the basis of its reconstructed distribution. The spatial discretization is realized by a structured Finite Volume scheme on a staggered grid. In each phase the discretization is second-order-accurate. The program is fully parallelized and adapted to high speed computing.

In this presentation applications of FS3D for different droplet processes will be shown. The examples range from droplet-droplet, droplet-film, droplet-wall collisions, droplets with phase change to primary jet break-up.

# Droplet Dynamics in the Presence of Gas Nanofilms: Bouncing, Merging, Wetting & Levitation

**James E. Sprittles**[1], Mykyta V. Chubynsky[1], Indrajit Chakraborty[1], and Duncan A. Lockerby[2]

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Recent advances in experimental techniques have enabled remarkable discoveries and insight into how the dynamics of thin gas/vapour films can profoundly influence the behaviour of liquid droplets: drops impacting solids can "skate on a film of air" [1], so that they can "bounce off walls" [2,3]; reductions in ambient gas pressure can suppress splashing [4] and initiate the merging of colliding droplets [5]; and evaporating droplets can levitate on their own vapour film [7] (the Leidenfrost effect). Despite these advances, the precise physical mechanisms governing these phenomena remains a topic of debate. A theoretical approach would shed light on these issues, but due to the strongly multiscale nature of these processes brute force computation is infeasible. Furthermore, when films reach the scale of the mean free path in the gas (i.e. ~100nm) and below, new nanoscale physics appears that renders the classical Navier-Stokes paradigm inaccurate.

In this talk, I will overview our development of efficient computational models for the aforementioned droplet dynamics in the presence of gas nanofilms into which gas-kinetic, van der Waals and/or evaporative effects can be easily incorporated [8,9]. It will be shown that these models can reproduce experimental observations – for example, the threshold between bouncing and wetting for drop impact on a solid is reproduced to within 5%, whilst a model excluding either gas-kinetic or van der Waals effects ~170% off! These models will then be exploited to make new experimentally-verifiable predictions, such as how we expect drops to behave in reduced pressure environments. Finally, I will conclude with some exciting directions for future work.

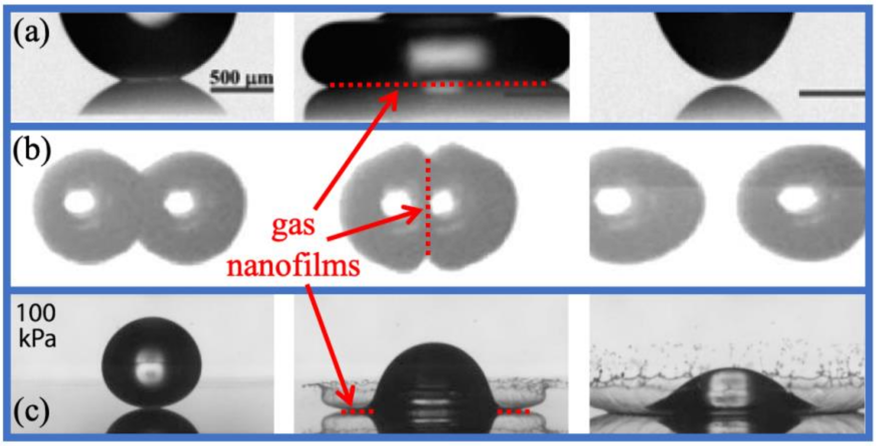

Figure 1. Drop bouncing off solid [2], drop-drop collisions [6] and splashing [4]

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# Modeling and computing heat flow for evolving films and drops on nanoscale

**Lou Kondic**[1], Ryan Allaire[1], and Linda J. Cummings[1]

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Modeling thermal effects and their influence on dynamics of thin films and drops is of relevance in a number of different setups, and on the lengthscales that range from nano to micro to macro. The common feature is that one needs to consider a complicated setup such that the dynamics of films and drops modifies the heat flow, which in turn influences the fluid dynamics due to temperature dependence of fluid material properties, such as surface tension and viscosity. Therefore, one needs to come up with a self-consistent approach that considers coupling of fluid and thermal effects.

Considering the outlined problem is complicated both from modeling and from computation point of view since it involves coupled heat and fluid flow in a time dependent domain. A significant simplification is however possible for thin films and/or drops: in such a case it is possible to reduce the problem to a simpler one by carrying out asymptotic analysis which is similar in spirit to the approach used for deriving well-known thin-film equation [1].

The outlined approach is illustrated by considering metal films of nanoscale thickness, exposed to external heating by nanosecond laser pulses: such pulses melt the film which then evolves and breaks up into droplets [2]. One unusual feature of this setup is that that the heating is volumetric due to the fact that the film thickness is comparable to thermal absorption length: therefore, not only heat conduction, but also heat absorption depends on the film thickness. Additional feature of this problem is that the film temperature depends on the film thickness in a non-monotonous manner, leading to, e.g., Marangoni effect which may be stabilizing or destabilizing for different films thicknesses, and even at different times. Figure 1 illustrates such a situation for a stationary flat film. For evolving, unstable films, thermal effects then play an important role in determining film evolution.

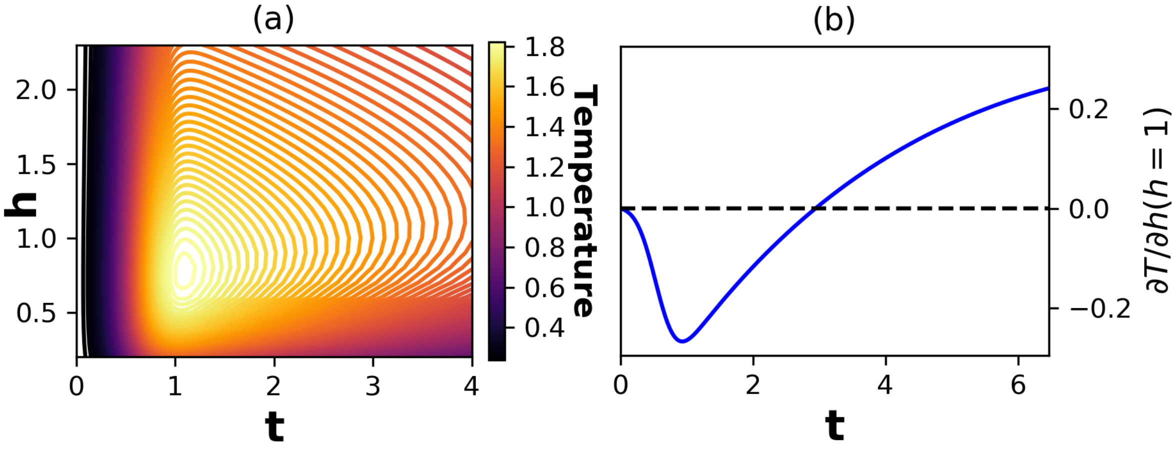

Figure 1: (a) Contour plot of average film temperature for a static flat film. (b) Rate of change of temperature with film thickness. From [1].

**Acknowledgement:** This work was supported by NSF Grant CBET-1604351 and DMS-1815613.

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# Electrokinetic transport in sub-nanometric droplet

Anne-Laure Biance

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As reported by Benjamin Franklin in 1774, when a droplet is deposited on a wetting substrate, it will spread until reaching a thickness of a few molecules.

We use here this property to experimentally investigate electrokinetic transport in ultra thin films of water on silica, with a tunable thickness below 1 nm.

After describing our experimental set-up, we will show that, in this regime, transport properties can not be predicted by standard continuous models anymore. We will then propose a new simple description, that we will compare with the experimental results we present here among others.

# Droplet Dynamics and its Implications during Dropwise Condensation on Engineered Surfaces

**Sameer Khandekar**[1]

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Heterogeneous condensation process is one of the most efficient ways of heat transfer in engineering systems, the ensuing heat transfer coefficients being orders of magnitude larger than single-phase convective paradigms. Such a phase-change process may result, under quasi-steady-state conditions, in either, (a) the formation of distinct droplet ensemble mode, (b) the formation of a continuous condensate film or, (c) a mixed mode paradigm having fuzzy overlapping characteristics of dropwise and filmwise modes occurring simultaneously. The heat transfer coefficient of dropwise mode is usually one order of magnitude higher than the other modes of condensation process. The preferred mode of condensation depends not only on the thermophysical properties of the fluid getting condensed, but also on the chemo-physical properties of the cold substrate [1, 2]. Deploying dropwise condensation process in advanced engineering systems involves not only an understanding of the fundamental thermo-fluidic transport behavior, but also the intrinsically coupled microscale issues associated with (i) droplet interaction with the substrate material (ii) droplet-droplet dynamical interaction during the growth process.

In this talk, we will try to understand dropwise condensation process at various length and time scales, from droplet nucleation to subsequent removal of drops by either sliding (on an inclined substrate) and/or falling-off from the condensing surface. Of particular interest is the interaction of growing droplets with each other, leading to coalescence, incipience of instability, and eventual removal of the condensed fluid. The interplay of inertia, surface tension and viscous forces in the droplet mass leads to complex interfacial dynamics, generating local shear stress capable of leaching and surface degradation [3]. Hence, sustainability of long term droplet condensation continues to pose challenges in contemporary times too. Advent of nano-technology, breakthroughs in thin film coating, physical and chemical texturing technologies, advanced manufacturing and superior experimental techniques has facilitated deeper probing and understanding of the process control parameters.

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# Functional droplet dynamics in the context of Covid 19

Saptarshi Basu

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Spread of COVID can be through respiratory droplets and fomites. In this talk I will provide a detailed exposition of how respiratory droplet dynamics can be mated with pandemic model to provide a first principle insights into infection spread rate. We will show through experiments using surrogate fluids, such models can be experimentally verified rigorously. Subsequently I will show how fomites form and how the virion are embedded in the crystal network using both contact free as well as sessile droplets. In the last part of the talk, I will highlight some unique pathways through which covid can spread namely eye procedures and surgeries. We will through through fluid dynamic approach, how droplets are created during eye procedures like tonometry, phaco surgeries to name a few. We will then summarize how safe these surgical procedures are in COVID19 pandemic.

# Which contact angle to measure? Status in academia and industry. An industry perspective.

Thomas Willers

KRÜSS GmbH

Proper interpretation of different types of contact angle measurement methods has been a source of constant research and debate for decades. On the one hand comprehensive, detailed scientific guidelines have been established, but on the other hand there are numerous standards and technical data sheets that do not even specify the type of contact angle to be assessed. KRÜSS is the world market leader in contact-angle measurement equipment, and at our laboratories in Charlotte, Shanghai, and Hamburg we complete hundreds of contact angle measurement projects annually for industry, academic customers and internal projects. Based on this experience, I want to review both the fundamentally more correct 'academic' and the sometimes more pragmatic 'industrial' methods of contact angle measurement. I also want to touch on the question "does success in optimizing industrial processes via 'wrong' contact angles prove these methods still to be 'right'? In addition, I will present high-speed recordings (~8.000 fps) of pendant drop and liquid-needle drop deposition processes and discuss these with respect to the effect of dynamic wetting pressure on the final contact angle. As an outlook and discussion point, I want to conclude with the currently still open key questions about contact angle measurements when used for industrial processes.

# Wetting and vapor dynamics under drops impacting on hot plates

**Kirsten Harth**[1, 2], S.-H. Lee[3], M. Rump[2], M. Kim[3], K. Fezzaa[4], M. A. J van Limbeek[2], J. H. Je[3] and D. Lohse[2,5]

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[3] *X-ray Imaging Center, Pohang University of Science and Technology, Pohang, Republic of Korea.*
[4] *X-ray Science Division, Advanced Photon Source, Argonne National Laboratory, Argonne, USA.*
[5] *Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany.*

Droplets impacting on hot targets are found in numerous technical or natural occasions. The outcomes of such impacts can be manifold, depending on liquid and substrate properties, as well as ambient conditions. In case the substrate is hot enough, the liquid will hover above a layer of its own vapor, which is known as the Leidenfrost effect. Under gently deposited droplets, this vapor layer typically has tens of micrometres thickness. However, during impact, the phenomenology becomes exceedingly complex, as heat transfer and fluid mechanics, phase change and wetting are complex. In particular, the vapor layer initially can become as thin as few tens of nanometers, non-discernable in side view imaging, even at high frame rates.

Techniques as total internal reflection imaging (e.g. [1]), interferometry or high-speed phase contrast X-ray imaging [2] allow to obtain information on contact locations and vapor layer profiles underneath the spreading and receding drop. These techniques allow to reveal the highly complex wetting dynamics underneath droplets impacting on hot plates, in particular in the temperature range in between the "static" Leidenfrost temperature for gently deposited drops and the threshold temperature for levitation of impacting drops. The individual contacts' dynamics grow exceedingly fast and localized with increasing temperature.

We analyse the contact and liquid-vapor interface dynamics from high-speed optical and X-ray imaging, with focus on oscillatory behaviour. Contact and rebound times on different substrates will be quantified [3], a significant residence time reduction slightly above the "static" Leidenfrost temperature is related to hole formation. The "dynamic" Leidenfrost temperature, i.e. the lowest temperature for contact-less rebound, is found to be considerably higher than expected from the literature. Last, we infer a simply measurable criterion for the detection of the "dynamic" Leidenfrost transition, of droplets at moderate impact velocities.

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# Effect of residual water on drying of suspensions in non-polar solvents

Steffen B. Fischer[1] and **Erin Koos**[1]

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Lateral accumulation and film defects during drying of hard particle coatings is a common problem, typically solved using polymeric additives and surface active ingredients, which require further processing of the dried film. Capillary suspensions with their tunable physical properties, devoid of polymers, offer new pathways in producing uniform and defect free particulate coatings [1]. We investigated the effect of small amounts of secondary liquid on the coating's drying behavior. Stress build-up and weight loss in a temperature and humidity controlled drying chamber were simultaneously measured [2]. Changes in the coating's reflectance and height profile over time were related with the weight loss and stress curve.

Capillary suspensions dry uniformly without defects. Lateral drying is inhibited by the high yield stress, causing the coating to shrink to an even height. The bridges between particles prevent air invasion and extend the constant drying period. The liquid in the lower layers is transported to the interface via corner flow within surface pores, leading to a partially dry layer near the substrate while the pores above are still saturated. Increasing the relative humidity enhances this effect, even for pure suspensions [3]. This change is driven by transport of the water through the bulk liquid to the bridges [4]. We show that capillary suspensions can be formed by mixing particles with partially saturated 1-alkanol (6–8 carbon atoms)/water solutions, without the need for a temperature induced phase separation. Moreover, we show this effect works with different particle sizes and geometries.

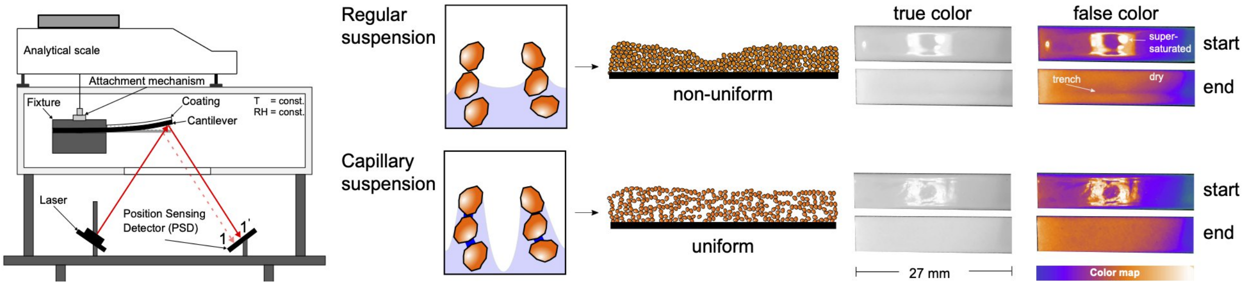

Fig.1. (left) Stress drying apparatus. (right) Schematic difference between regular and capillary suspensions with corresponding images of the films at the beginning and end of the drying experiments.

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# Oral Presentations

# Wetting and spreading of complex liquids over porous substrates

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There has been a substantial increase in the number of publications in the field of wetting and spreading since 2010. This increase in the rate of publications can be attributed to the broader application of wetting phenomena in new areas. These applications include interactions of complex liquids and surfaces. The interaction of complex liquids with complex surfaces occurs frequently not only in our daily lives but also in different technological applications. Many cosmetics such as skin-care creams and haircare products are formulated to be applied on skin and hair which are complex surfaces. Complex polymer/surfactant solutions (in the form of droplets or foams) interact with human hair during application of shampoos, conditioners or hair colorants. In all the above-mentioned examples, understanding the interaction between complex liquids and complex surfaces at interfaces at different nano, meso and macro length scales is essential in order to understand physical mechanisms, gain essential stored information, enhance product quality and functionality in multidisciplinary applications. In addition, the interaction condition of complex liquids with complex surfaces is very important because, for example in a number of situations, it can affect the kinetics of delivery of active substances from complex liquids to the target places inside the complex surfaces. In order to make a proper choice of the process parameters and improve the performance of the system, the properties of the complex liquids should be considered in connection with the properties of complex surfaces.

In this presentation, examples of such complex interactions will be presented. Kinetics of wetting and spreading of biological fluid (blood), surfactants, polymer solutions and their mixtures over various porous substrates will be presented.

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[2] P. Johnson, T. Routledge, A. Trybala, M. Vaccaro, V. Starov; Wetting and Spreading of Commercially Available Aqueous Surfactants on Porous Materials. *Colloids and Interfaces*, 2019, 3(1), 14;
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# Effect of relative humidity on the retraction dynamics of blood drop after impacting a solid substrate

**Houssine BENABDELHALIM**[1], David BRUTIN[1]

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Although the receding (retraction) of a drop after its impact on a solid substrate is an important phenomenon, it receives less attention than spreading. We investigate the retraction dynamics for a drop of whole human blood with impact velocities ranging from $1.3$ m.s$^{-1}$ to $4.5$ m.s$^{-1}$ on wooden floors that were either varnished or not. The effect of relative humidity and temperature are taken into account by carrying out extensive experiments under different surroundings conditions. For this purpose, we used human blood taken from the same healthy donor, with a hematocrit level of $42.8$ % $\pm$ $2.6$ %. Blood drops had the same volume and the same initial temperature 37 °C. The impact, spreading, splashing, and retraction of the blood drops are recorded through a high-speed camera.

The obtained results show that retraction is present on the varnished wooden floor (smooth substrate), in contrast to the unvarnished wooden floor (rough substrate). For the first one, the retraction occurred only at high relative humidities Fig. 1b and Fig. 2d, and it is more important at high impact velocities, hence with high kinetic energy. In Fig. 1 we can see that with the same impact velocity, the increase in relative humidity leads to an increase in the maximum diameter $D_{max}$. Bouzeid and David [1], in their study on the spreading of a blood drop, deposited gently on a glass substrate, showed that at high relative humidities, the drop spreads more than low relative humidities.

We will present our results on blood drop retraction after impact by discussing its dynamics and the influence of relative humidity.

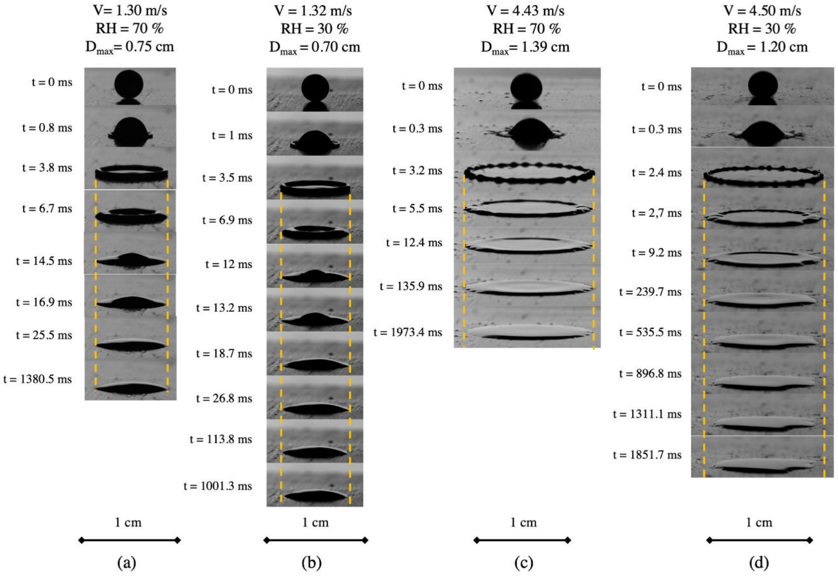

Figure 1: Image sequence showing blood drop impact under a temperature of 17 °C with the same initial diameter for two different humidities and impact velocity on varnished wooden floor.

[1] Bouzeid, W. and Brutin, D. Effect of relative humidity on the spreading dynamics of sessile drops of blood. Colloids Surfaces A: Physicochem. Eng. Aspects 456, 273–285 (2014).

# Dynamic arrest during the spreading of a yield stress fluid drop [1]

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[1] *Institut Lumière Matière, Université de Lyon 1 and CNRS, UMR5306, France*

When a liquid drop is gently deposited on a wetting solid surface, it spreads due to capillary forces until it reaches a thermodynamical equilibrium set by the relative surface energies of the system [2]. We investigate here experimentally the spreading ability of drops made of yield stress fluids (here Carbopol gels), which flow only if the applied stress is above a finite value. We observe that in this case, after a spreading phase, the motion stops and a well-defined contact angle can be measured. This contact angle depends on the rheological properties of the fluid and in particular on its yield stress $\sigma_y$, on the drop radius and on the hydrodynamic boundary condition at the surface which contrast strongly with what is obtained with simple fluids. These results are quantitatively compared to an analysis showing that, due to the yield stress of the fluid, a mechanical equilibrium is indeed reached which does not correspond to the thermodynamical equilibrium. This complex behaviour that is both liquid and solid and their wetting properties are important for many applications in various industries (food, cosmetics, building or 3D printing) [3,4].

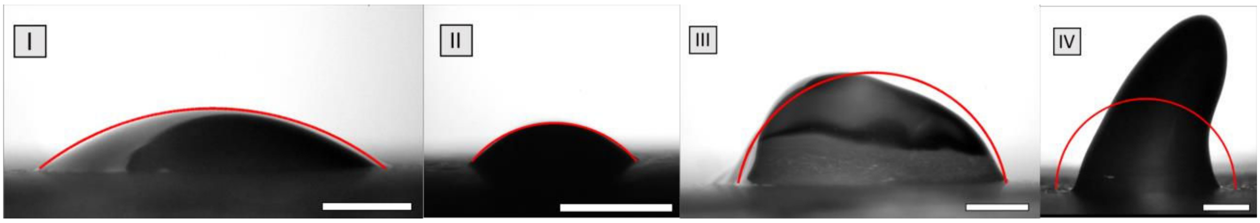

Figure 1. Pictures of drops of various yield stress fluids after spreading on rough surface: (I) Carbopol gel (ETD at 0.3%) with a yield stress $\sigma_y = 6$ Pa, (II) and (III) Carbopol gel (ETD at 2%) with $\sigma_y = 35$ Pa, (IV) Carbopol gel (U10 at 0.5%) with $\sigma_y = 85$ Pa. Fits of the drop shape assuming a spherical cap of a same volume as the drop, are plotted in red. Scale bar corresponds to 1 mm.

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# Getting into the skin of thin-skinned emulsion drops stressed by elasticity and capillarity

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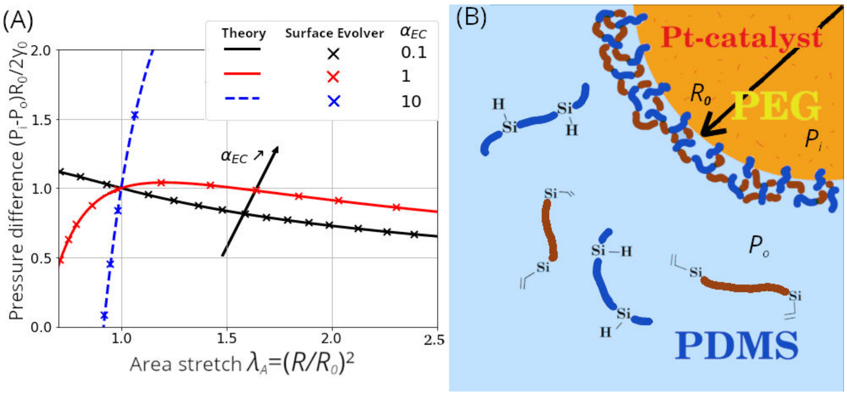
Simple fluid-fluid interfaces between the two immiscible phases at thermodynamic equilibrium are characterised by a well-defined interfacial tension creating capillary stresses captured by the Young-Laplace law. When these interfaces become more complex (for example, due to adsorption of interfacially active species) or when they go out of equilibrium, an extra-stress of mechanical origin may add up to the capillary stress, differing by its non-linearity and the existence of a reference state of zero stress. In the case of drops, an additional elastic stress modifies the pressure-deformation relation. In order to understand interfacial elasticity in its various manifestations, we investigate a modified Young-Laplace law to account for the elastic stress. This modified law predicts a transition from a pure capillary drop to a pure elastic one, characterised by a unique elastocapillary number $\alpha_{EC}$. We show first the effect of this transition on the existence and the evolution of deformation states of zero and maximal pressure difference (Fig. A). In a second step, we apply the model to a standard pendant drop geometry as can be found in capsule elastometry experiments[1]. In parallel, numerical simulations performed using the Surface Evolver software[2] are confronted to theoretical predictions by the elastic model. We show for the first time the usefulness of Surface Evolver to study elastic interfaces in non-trivial geometries, and the good precision of our simplified model for pressure-deformation predictions. At last, we propose an experimental model system where the elastocapillary transition can be tuned by activation/inhibition of a crosslinking reaction between two differently functionalised silicone polymer[3] (Fig. B). This systems opens the door to studying the impact of the elastocapillary transition on the packing properties of emulsion drops.



A) Surface Evolver simulations and theory of pressure-deformation relation for three different elastocapillary number α EC for a spherical drops. B) PEG-in-silicone system. Reactive silicone polymers crosslink at the interface through a platinum-catalysed hydrosillylation reaction.

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[2] K. Brakke, *Exp. Math.*, 1992
[3] A. Giustiniani *et al.*, *Soft Matter*, 2019

# Formation of liquid cratering from the impact of liquid marbles on rough solid substrates

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The fluid dynamic phenomena of bare droplets impact on solid substrates have been studied for more than one century.[1] However, studies on the impact of particle-armored droplets are rarely conducted. In this study, we report the formation of liquid cratering from the impact of particle-stabilized droplets (also named liquid marbles [2]) on rough solid substrates (Fig. 1a). The phenomenon is counterintuitive, as the Laplace pressure mismatch between the inner and outer radius of the toroidal structure makes the liquid cratering hydrodynamically unstable and should result in the formation of sessile droplets, which is not what we observe. Using high-speed imaging, we reveal liquid marbles with size $D_0$ impact solid substrates vertically and mirror closely that of bare droplets at the spreading stage in a short timescale. By characterizing the spreading of the marble on the rough solid substrate, a power-law scaling is observed for the normalized maximum spread $D_{max}$ in terms of the impact Weber number, $D_{max}/D_0 \sim We^{\alpha}$, with $\alpha \approx 1/3$ (Fig. 1b). A thin layer of air is entrapped beneath the impact marble, which is later compressed into a bubble. Other than forming lenticular sessile droplets with the bubble entrapped, a toroidal-shaped liquid cratering is formed when the liquid marble hits the substrate above a critical height. The liquid cratering forms when the advancing liquid film starts to retract. Capillary waves converge at the center and lead the entrapped bubble to burst and form a dry patch. Extensive experiments show that, with sufficient inertia, the liquid cratering formation is a material constant and does not depend on the impact velocity. The Ohnesorge number, $Oh = \eta/\sqrt{\rho\gamma D_0}$, is the dimensionless parameter to forecast its formation.

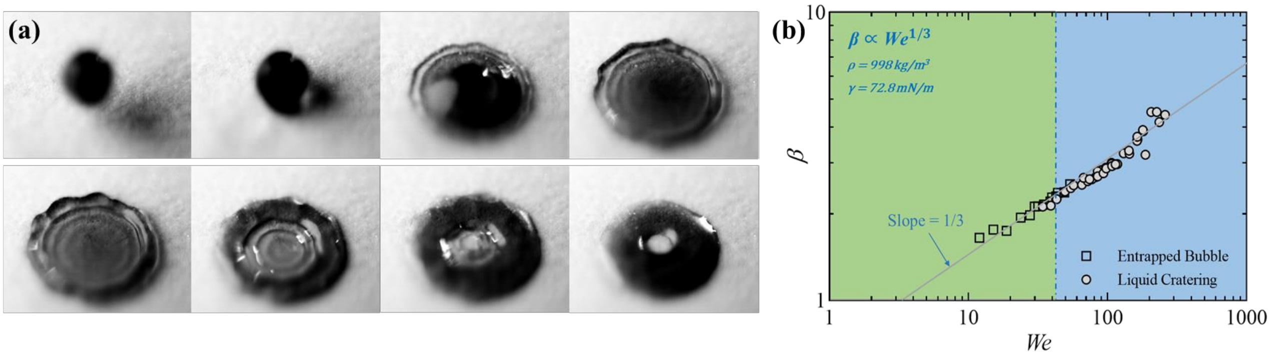

Figure 1. (a) Formation of the liquid cratering from the impact of a liquid marble on sandpaper substrate. (b) Spreading factor $\beta_{max} = D_{max}/D_0 \sim We^{1/3}$ for the impact of water marbles.

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# Drop Dynamics of non-Newtonian dairy solutions

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[2] *The MacDiarmid Institute for Advanced Materials and Nanotechnology, New Zealand*
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The dynamics of heated dairy droplets are of interest for production of powders by spray drying. During spray drying, drops may collide with each other [1] or with the stainless-steel walls of industrial spray dryers, leading to fouling. Dairy products with high solids content are also non-Newtonian [2]. Our understanding of non-Newtonian drop impacts remains underdeveloped relative to Newtonian drops, despite their wide relevance in industries such as coatings and food. Moreover, dairy droplets at elevated temperatures are of interest because they solidify from the crust inwards [3].

In this project, impacts of heated dairy droplets on stainless steel surfaces are experimentally studied using vertical drop impact (Fig.1) recorded via high-speed photography. The experiments were carried out under controlled temperature and humidity within an environmental chamber. The chamber temperature was adjusted ranging from 22°C to 200°C with a constant humidity. Reconstituted milk was used for consistent liquid preparation. The data obtained from image analysis of the recorded video was used to determine the effect of solids concentration and temperature variation on droplet spreading and drying. Initial results show that the droplet spreads more with decreasing solids concentration or increasing temperature.

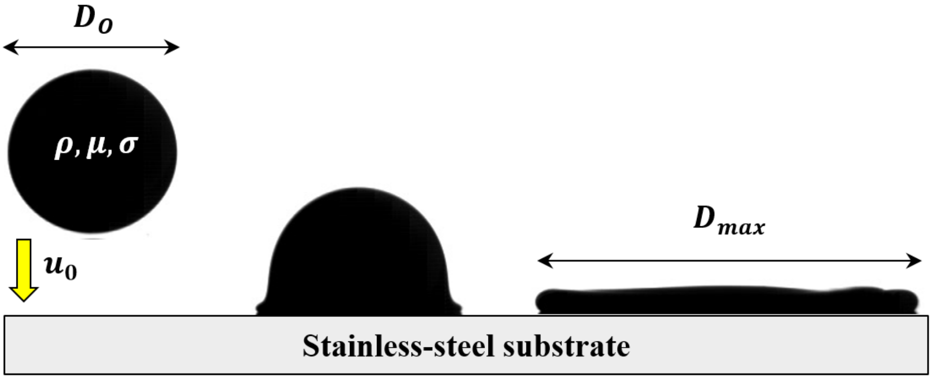

Figure 1. Photographs of a dairy solution droplet impacting on a surface with labelled experimental parameters.

[1] G. Finotello, R.F. Kooiman, J.T. Padding, K.A. Buist, A. Jongsma, F. Innings, J.A.M. Kuipers, The dynamics of milk droplet–droplet collisions, *Experiments in Fluids*, **59** (2018) 17.
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# Contact angle of EGaIn with interfacial oxide layer

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Gallium-based liquid metals (GBLMs) are attracting growing attention in various engineering fields thanks to their exclusive combined properties of fluidity and high electrical conductivity. GBLMs have an oxide skin in the atmosphere with nanometer thickness, and oxide skins causes unique interfacial behaviors. Although oxide skins are crucial for controlling the motions of GBLMs at a microscale, the interfacial physics of GBLMs has been little explored. We studied the contact angle of eutectic gallium-indium (EGaIn) with the oxide skin. We visualized the contact line motions of EGaIn in comparison of those of mercury and membrane-encapsulated water (see Fig. 1). The results show that while the equilibrium and receding contact angles of EGaIn cannot be defined, a specific advancing contact angle is observed. We develop a mathematical model for the advancing contact angle of EGaIn. The model captures the features of the wetting behavior of EGaIn, thus elucidating the physics behind the interfacial behaviors of EGaIn. Our study provides not only a theoretical framework for handling GBMLs but also new insights into the manufacturing techniques of GBLMs for various applications.

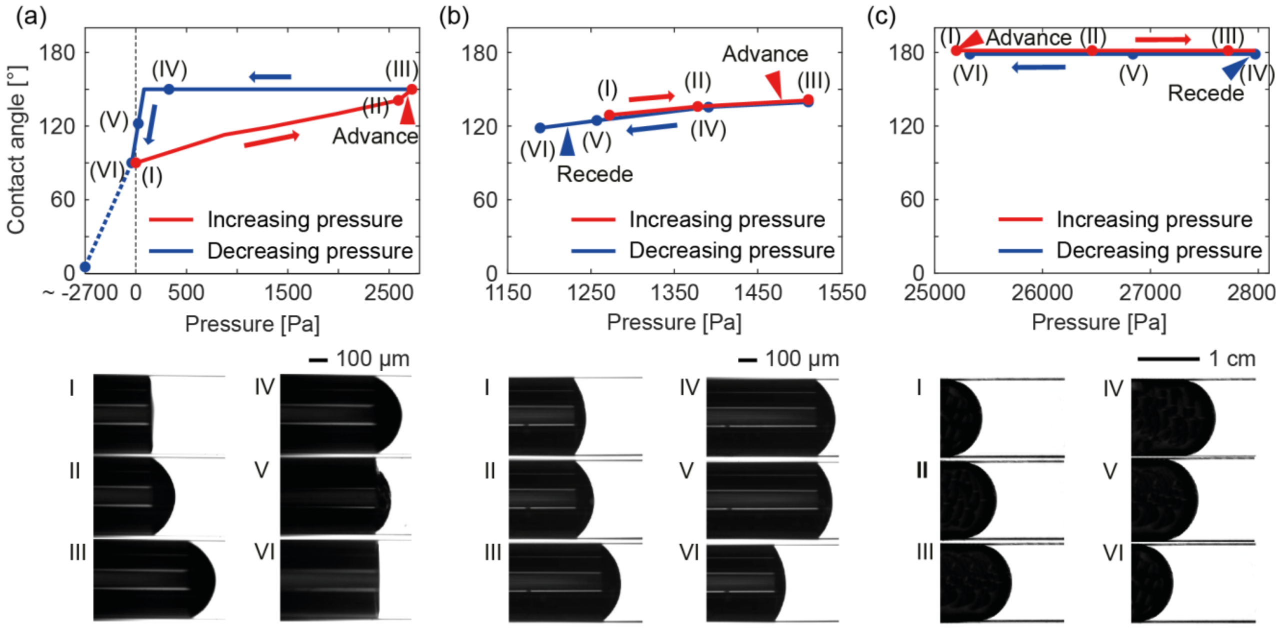

Figure 1. Comparative description of the contact line motions of (a) EGaIn, (b) mercury, and (c) membrane-encapsulated water.

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# Charging of impacting drops onto superhydrophobic surfaces

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Charge separation by drop impact plays an important role in the conversion of kinetic energy directly to electric energy [1, 2]. However, the lack of fundamental understanding hinders the improvement in the efficiency of generators using flowing liquids. Hence, identifying the main parameters involved in charge separation upon impact results crucial in the prediction, control and full comprehension of general contact electrification.

Here we present experiments and a complementary theoretical model of charging of water drops rebounding onto superhydrophobic surfaces. The proposed model is based on the theory of the electrification of sliding drops [3]. We reproducibly measure the drop charge using electric fields that horizontally deflects a drop after the impact. We study the influence in the charging process of parameters such as the impact speed, retracting motion of the contact line, drop size and contact area. Our findings evidence that contact area is the controlling parameter in charge separation. As a drop spread further on a surface, it enhances the charge deposition coming from a fraction of the Debye layer. This supports the idea of charge separation during the retraction phase and the charge deposition at the outer ring of the impact area.

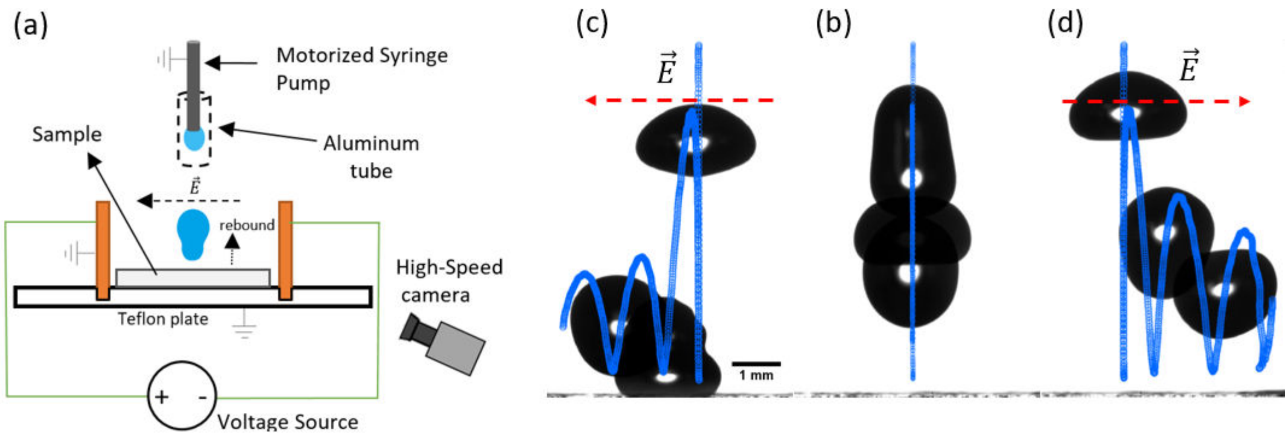

Figure 1. Schematic of the experimental setup (a). 4μL drop bouncing on a SN-FDTS surface in three cases: no electric field (b); electric field oriented from right to left (c); electric field oriented from left to right (d). The blue markers represent the movement of the center of mass of the drop.

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# Jet through Droplet: Influence of the liquid properties on the dynamics of a jet impacting a pendant droplet

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The impact of liquid droplets, jets and solid objects onto deep pools and thin liquid layers is well documented in the literature [1-3]. Research has mostly focused on the critical energy necessary for air entrainment into the pool, the collapse of the entrained air cavity and the subsequent formation of a Worthington jet. The air entrainment and cavity formation, can be explained by the sudden formation of a singular cusp at the jet-pool intersection, which breaks at increasing jet velocities, due to a decrease in the radius of curvature at its tip [4].

However, few studies have focused on sub-millimetric projectiles, situations where gravity can be neglected, or where the cavity dimensions are constrained. Here, we study the impact and traversing of thermocavitation jets on pendant liquid droplets with different properties, such as Newtonian and visco-elastic. In thermocavitation, a bubble is formed from the evaporation of a liquid inside a microfluidic channel generating a high-speed micro jet. When the jet impacts a droplet an expanding cavity is created, and, at a critical impact velocity, the jet traverses the droplet (Fig. 1). We predict the critical traversing velocity with two methods; with an energy balance analysis and by comparing the cavity Young-Laplace and dynamic pressures. We contrast the model predictions against experimental data, showing good agreement. Moreover, our results show that the dynamic surface tension and visco-elastic effects impose a limiting threshold for droplet traversing.

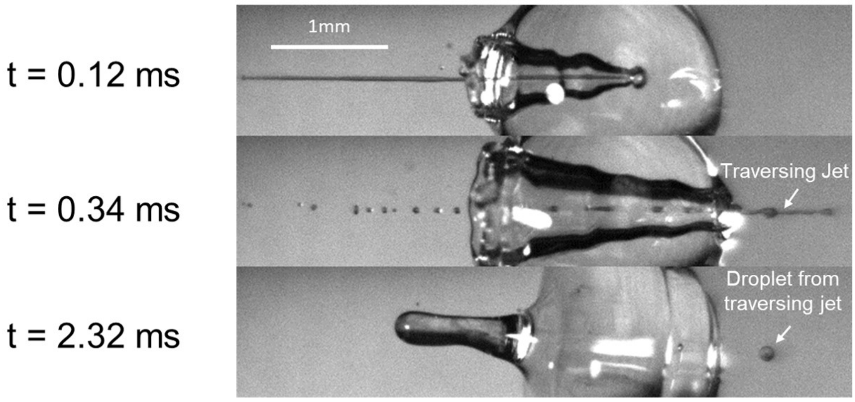

Figure 1: Snapshots of a liquid jet impacting and traversing a water droplet containing 0.1wt % of 100k molecular weight polyethylene oxide.

[1] AM Worthington, “A study of splashes”. Longmans, Green, and Company, 1908

[2] M Lee, RG Longoria and DE Wilson, Physics of Fluids **9** (1997), 540–550.

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# High-speed droplet impact onto deformable substrates

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The impact of a high-speed droplet onto a deformable substrate, such as a spring-supported plate [1] or an elastic membrane, is a highly nonlinear process, and understanding the fluid-structure interaction is important in many areas of nature and industry, including pesticide distribution and inkjet printing. Over the past decade, advances in experimental imaging techniques have invigorated the study of droplet impact [2], and insight into the physical mechanisms involved has been gained from the development of analytical and numerical models.

We present two modeling approaches for droplet impact onto deformable substrates: matched asymptotics and direct numerical simulations. The former uses inviscid Wagner theory to derive analytical expressions which approximate the behaviour of the droplet during the early stages of impact. The direct numerical simulations build on the open source volume-of-fluid code Basilisk, coupling the motion of the substrate to the velocity field of the fluid. We show that these methods are complementary, and how a combination of both can lead to a thorough understanding of the droplet impact across timescales.

Both methods demonstrate the strong influence that the substrate motion has on the dynamics of the droplet, such as through altering its internal pressure distribution (see Fig. 1 below). We also quantitatively show that the speed the droplet spreads across the substrate is notably decreased when the substrate is more compliant, which is consistent with experimental findings that splashing can be inhibited by impacting onto a soft substrate [2].

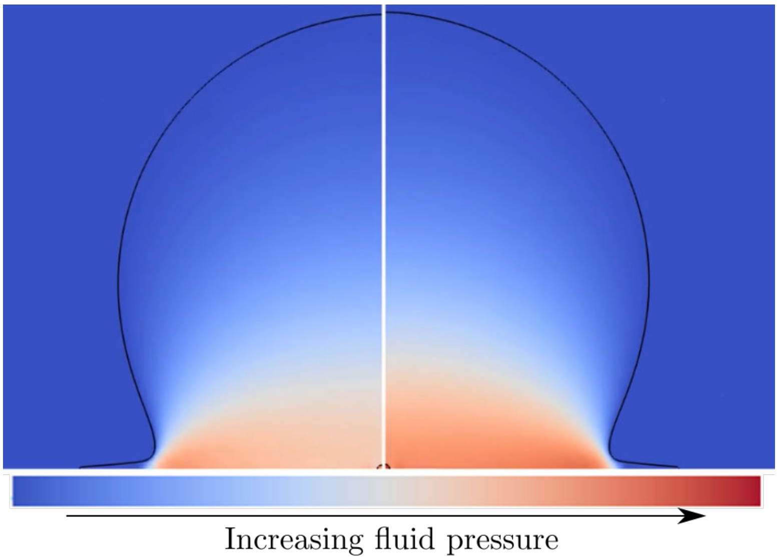

Figure 1: Snapshots of the direct numerical simulations, comparing the pressure distribution for droplet impact onto a stationary substrate (left) and a spring-supported plate (right).

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# Slippery hydrophobicity for liquid impact resistance

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[2] *Wellcome/EPSRC Centre for Interventional and Surgical Sciences, University College London, London, W1W 7TS, United Kingdom.*

Rough solid surfaces (protrusions, pores or pillars) minimize contact with liquid by creating a composite surface of air/infused immiscible liquids[1]. The capillary pressure of the rough surface perpetuates the presence of the immiscible layer at low speeds of impact but fails at high speeds. Under those conditions, liquid compressibility is significant, creating shock waves near the liquid-solid contact, also known as the water-hammer effect. Ensuing transient pressure peaks easily exceed the anti-wetting pressure of the rough surface, leading to a Wenzel like pinned state. A known strategy of reducing water-hammer pressure is to lower the sonic speed in the solid substrate[2], thus reducing impalement. This work experiments with transparent, multi-tiered flexible substrates[3] to further enhance impalement resistance. Liquid repellence is demonstrated for water as well as low-surface tension fluid. Mechano-chemical resistance, crucial for industrial applications, is also demonstrated here. This presentation will not only discuss the physics of impact but also scalable methods of producing durable, liquid repellent surfaces on a wide range of base materials.

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# Post-impact drop velocity in general multi-liquid systems

**Ben D. Fudge**[1], Radu Cimpeanu[2], and Alfonso A. Castrejón-Pita[1]

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2. *Mathematics Institute, University of Warwick, Coventry CV4 7AL, UK*

When a drop impacts onto a pool of another liquid, the common interface will move down at a well defined speed for at least the first few milliseconds. Simple mechanistic models and experiments with same the fluid used for the drop and the pool have predicted this speed to be half the impacting drop speed [1], a value which has been used in a variety of situations [2,3]. However, this is only one small part in a rich and intricate behaviour landscape. Many applications of interest, from inkjet printing to estimating environmental risks after oil spills, naturally include impingement events of fluids with (potentially vastly) different physical properties.

By using a combination of high-speed photography, high-resolution numerical simulations, and physical modelling we disentangle the different roles that physical fluid properties play in determining the true penetration velocity. These powerful techniques have resulted in a step change in terms of predictive capabilities, allowing us to show and explain how this penetration velocity can deviate strongly from the previously estimated half impact speed value, which we summarise through a simple and compact formula. Velocities between 10% and 90% of the reference initial drop velocity have been uncovered over a range of three orders of magnitude in density and viscosity ratios between the impacting drop and the pool.

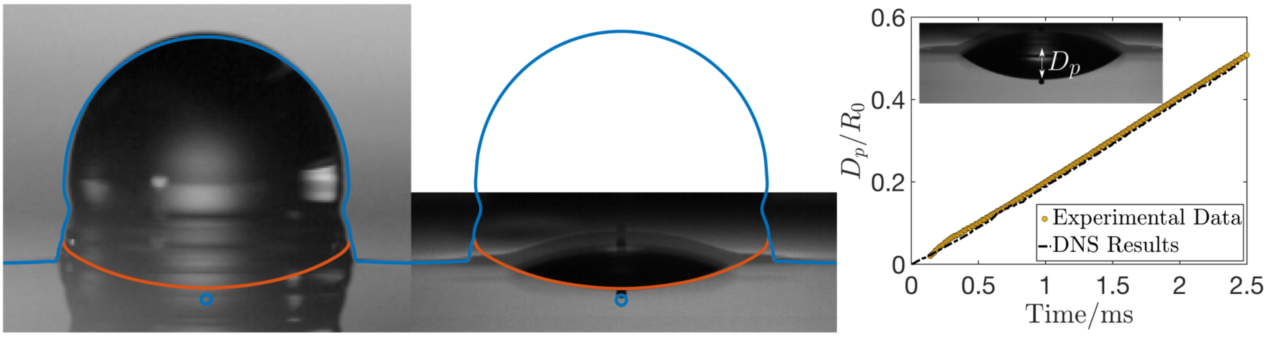

Figure 1: Comparisons between an experiment and direct numerical simulation for a 2.56 mm diameter drop of a 5 cP water-glycerol solution impacting onto an FC-40 pool with $\mathrm{Re}=274.1$, $\mathrm{We}=9.4$, $\mathrm{Fr}=3.2$. Left and Centre: view above pool and from underside of the pool surface respectively. Interface contours are extracted from the numerical data. Right: temporal evolution of the pool depth comparing experimental data (symbols) and simulation results (dashed line).

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[3] Z. Jian, M. A. Channa, A. Kherbeche, H. Chizari, S. T. Thoroddsen, and M.-J. Thoraval, To split or not to split: Dynamics of an air disk formed under a drop impacting on a pool, Physical Review Letters **124**, 184501 (2020).

# Stability of evaporating drops comprising binary mixtures

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[2] *Department of Chemical Engineering, Aristotle University of Thessaloniki, Greece*
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[4] *Department of Mechanical Engineering, Kyushu University, Japan*

The evaporation and spreading dynamics of a binary mixture sessile drop are complex due to the interplay of thermal and solutal Marangoni stresses alongside the hydrodynamic transport, evaporation, mass diffusion, capillary stress and surface tension of the drop. We investigate the stability of volatile bicomponent sessile drops with high wettability comprising ethanol-water deposited onto heated substrates (Figure 1) [1]. We obtain the transient base state using a one-sided model [1] under lubrication approximation before freezing the base state and introducing small disturbances to perform a quasi-steady-state linear stability analysis. The base state equations are derived assuming an ideal miscible mixture and the surface tension linearly depends on temperature and concentration. The stress singularity at the contact line is avoided by including a precursor film. We end up with an eigenvalue problem where the stability of the flow is determined from the real part of the eigenvalues. The stability equations for the binary system are solved to reveal the most dangerous unstable nodes. Our stability analysis shows that any evaporating sessile drop comprising a binary mixture is highly unstable and the results qualitatively agree with behaviour seen in experiments for ethanol-water. Our analysis further shows several competing modes for bicomponent drops and we are currently developing a transient growth analysis to understand the roles of these modes better.

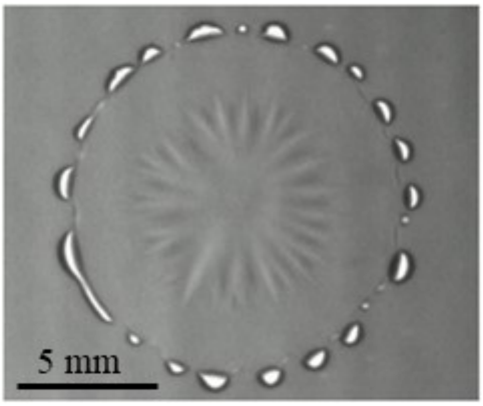

*Figure 1. Previous experimental results for an evaporating droplet comprising a binary mixture of ethanol and water from Williams et al. [1]. Instabilities at the contact line are shown.*

[1] A Williams, G Karapetsas, D. Mamalis, K Sefiane, O Matar, & P Valluri (2021) Spreading and retraction dynamics of sessile evaporating droplets comprising volatile binary mixtures. *Journal of Fluid Mechanics.* **907**, A22-1.

# A numerical study of a droplet spreading between Newtonian and viscoplastic stratified fluids

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The present study is focused on the numerical investigation of the dynamics of a droplet spreading between two stratified fluids with the bottom layer exhibiting a viscoplastic behavior. The stress deformation of the viscoplastic subphase is taken into account by utilizing the Herschel-Bulkley model. A computational model is developed based on the finite volume method and the volume of fluid method (VOF), which employs a volumetric phase fraction for each fluid phase. Sharpening of the interface is achieved by introducing an artificial compression term in the equation for each volume fraction. A continuum surface force model is used in order to account for the multiphase nature of the system. The interfacial tension coefficient decomposition method is used to handle the interface tension pairings between the different phases. The time and space discretization is performed by using second order accurate schemes. The present computational model is validated through comparisons with existing analytical and numerical solutions in the case of Newtonian liquids (see Fig. 1). Since there is no rigorous benchmark for three-phase viscoplastic fluid flows, the two-phase problem of a Newtonian bubble rising in a viscoplastic fluid was used as a reference to validate the present implementation of the Herschel- Bulkley model. The results of a thorough parametric study are presented and discussed, which include the impact of the rheological characteristics of the subphase, the layer depth and the effect of density and surface tension ratios between the three phases.

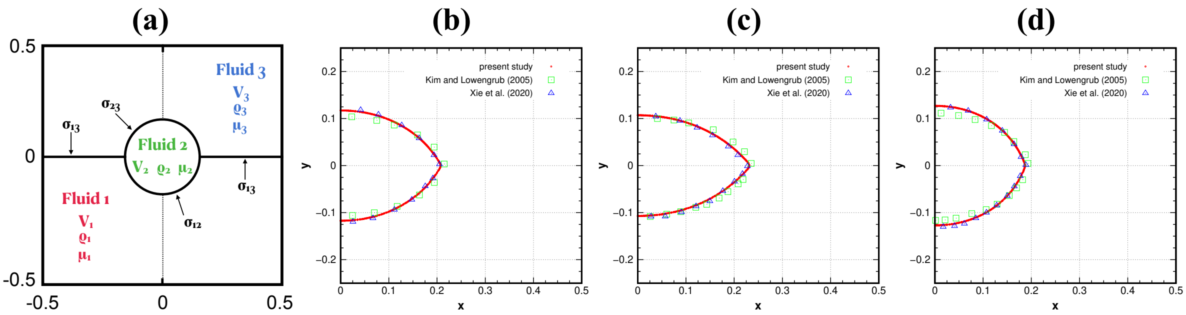

Figure 1: Geometry of the three-phase flow problem of a droplet spreading between two stratified fluids (a). Equilibrium shapes for three different cases with densities $\rho_1 = \rho_2 = \rho_3 = 1000\,\mathrm{kg\,m^{-3}}$, dynamic viscosities $\mu_1 = \mu_2 = \mu_3 = 1\,\mathrm{kg\,m^{-1}s^{-1}}$, and surface tension coefficients $\sigma_{12} = \sigma_{13} = \sigma_{23} = 2\,\mathrm{N\,m^{-1}}$ (b) $\sigma_{13} = 3.334\,\mathrm{N\,m^{-1}}$, $\sigma_{12} = \sigma_{23} = 1.556\,\mathrm{N\,m^{-1}}$ (c), and $\sigma_{13} = 1.112\,\mathrm{N\,m^{-1}}$, $\sigma_{12} = \sigma_{23} = 1.556\,\mathrm{N\,m^{-1}}$ (d). The present results are compared against the numerical results of Kim and Lowengrub [1] and Xie et al. [2].

*This project has received funding from the Hellenic Foundation for Research and Innovation (HFRI) and the General Secretariat for Research and Technology (GSRT), under grant agreement No 792.*

[1] J Kim and J Lowengrub, Interfaces and Free Boundaries **7** (2005), 435.

[2] Z Xie, D Pavlidis, P Salinas, C C Pain, and O K Matar, Int. J. Numer Meth Fluids (2020), 1.

# Superspreading – It seems like the mystery has been unraveled …

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Superspreading is an – also scientifically – fascinating phenomenon that was first observed about 30 years ago [1] with dilute solutions of trisiloxane surfactants on hydrophobic substrates (Figure 1C). Despite the work of many groups all over the world that have contributed significantly to the understanding of this phenomenon, the reasons why only some trisiloxane surfactants promote superspreading, whereas others of similar chemical structure behave more like ordinary surfactants, remained somewhat of a mystery for decades.

Equations and quantitative models that are in agreement with the kinetics of superspreading, but are not involving or even ignoring the chemical structure of the surfactants, cannot provide insight into the mode of action, i.e. an answer to the question how the superspreading surfactants are doing this (in contrast to the non-superspreading ones). One of the most frequently suspected driving forces is still the Marangoni effect, but it is hard to believe why a surface tension gradient should persist for about 60 s, which is the typical timescale for superspreading. Therefore, a "better" hypothesis has been proposed (Figure 1D-E), which is A) in agreement with basic thermodynamics and B) able to explain all phenomena encountered in the application of trisiloxane surfactants, including the known structure/property relationships [2]. Moreover, the proposed mode of action is in agreement with several experimental findings which are not related to wetting phenomena.

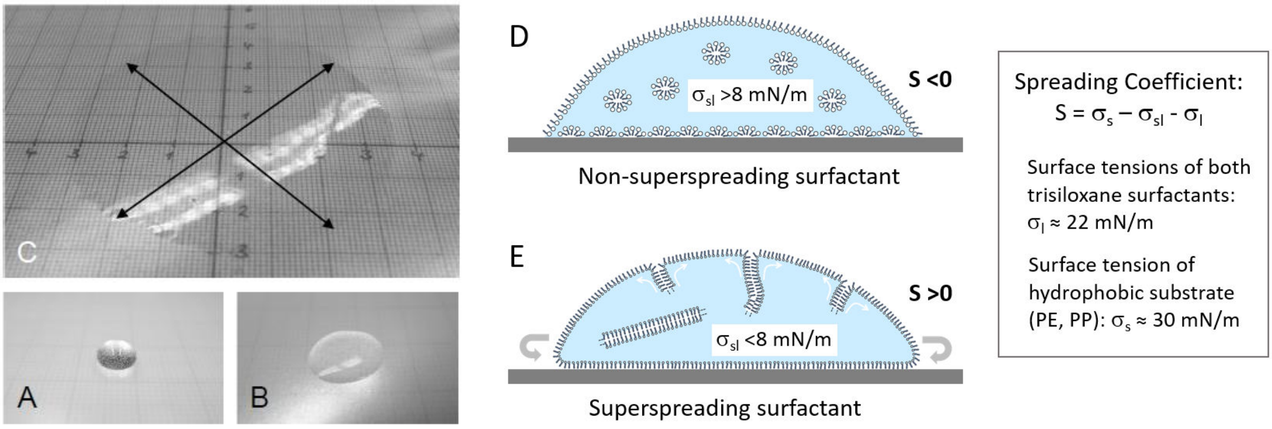

Figure 1. A-C): Photos taken 1 minute after placing a 50 µL droplet onto polypropylene film (with a cm scale underneath): Water (A); Non-superspreading trisiloxane surfactant (M(D'E10P2OH)M): 15 mm diameter (B); Superspreading trisiloxane surfactant (M(D'E6P3OH)M): 70 mm diameter (C); D-E: Proposed schematic situation using micelle-forming non-superspreading surfactants (D) and bilayer-forming superspreading surfactants (E).

[1] J. Venzmer, Curr. Opinion Colloid Interf. Sci. 16 (2011) 335-343.
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# Dynamics of wetting using Langevin's approach : a review

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Abstract:

The wetting of a solid by a liquid is such a familiar process that one would expect it to be well understood. A drop of liquid placed on a flat solid surface either spreads completely or, more often, comes to rest with its meniscus subtending a finite contact angle $\theta$ with the solid surface. But what is extremely frustrating about this apparently simple spreading process is that we cannot predict its dynamics from first principles. We have to perform an experiment and then use one theory or another to fit the data. Since these data usually cover a limited period of time or rate of spreading, perhaps just a few decades, it is not very surprising that all the fits are often acceptable, irrespective of the underlying model. In addition, all current theories have parameters that we cannot determine with sufficient accuracy *a priori* or independently verify.

Nevertheless, an understanding of the dynamics of wetting is of utmost importance to a wide range of key industrial processes, such as liquid coating, painting, oil recovery, crop protection and printing.

The basic idea is that the leading edge of the liquid will move under a driving force as already demonstrated by MD simulations. At the microscopic level however, the contact line position will be affected by way of individual molecular displacements between discrete interaction sites on the surface of the solid. Displacement of the contact line is thus the result of the collective thermal motion of the liquid atoms within the Three Phase Zone due to a capillary driving force which is precisely what Langevin equation can describe. In consequence, the contact line will constantly fluctuate about some mean position evolving with time, with corresponding microscopic changes in the local contact angle.

In this talk we will review how Langevin's approach has been used by several authors to study the dynamics of a moving contact line. We will see how this approach can be used to predict ( in some cases) the dynamics of wetting.

# A continuum model of nanodrop spreading

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For nanoscale flows, a question of both theoretical and practical importance is to what extent such flows can be described by continuum models. With this question in mind, we compare molecular dynamics (MD) simulations of a quasi-2D water nanodrop approach to and spreading on a solid surface [1] to a continuum model in which the flow inside the nanodrop obeys the usual Navier-Stokes equations and the interaction with the surface is modelled via normal and shear stress boundary conditions on the drop surface. The disjoining pressure contribution to the normal stress is derived from the interaction potential used in the MD simulations and shear stress corresponds to Navier slip with the slip length measured from an independent MD simulation. To take into account thermal fluctuations of the drop shape that, in particular, lead to off-axis initial contact between the drop and the solid, a random drop shape can be drawn from the equilibrium ensemble of shapes and used as the initial shape, or a shape from an MD simulation can be used to compare to that specific simulation run. At the same time, thermal fluctuations are not included in the equations or the boundary conditions. We find excellent agreement between the drop shape profiles obtained in MD and our continuum simulations at different stages of the spreading process (Fig. 1). An effect present in both our model and MD, but absent in classical simulations of wetting, is acceleration of the free surface of the drop towards the solid surface both before and after contact. Simulations with the continuum model are considerably faster than MD and can be used to study the relative significance of different effects (e.g., slip, van der Waals interactions, thermal fluctuations) that are difficult or impossible to vary independently in MD simulations.

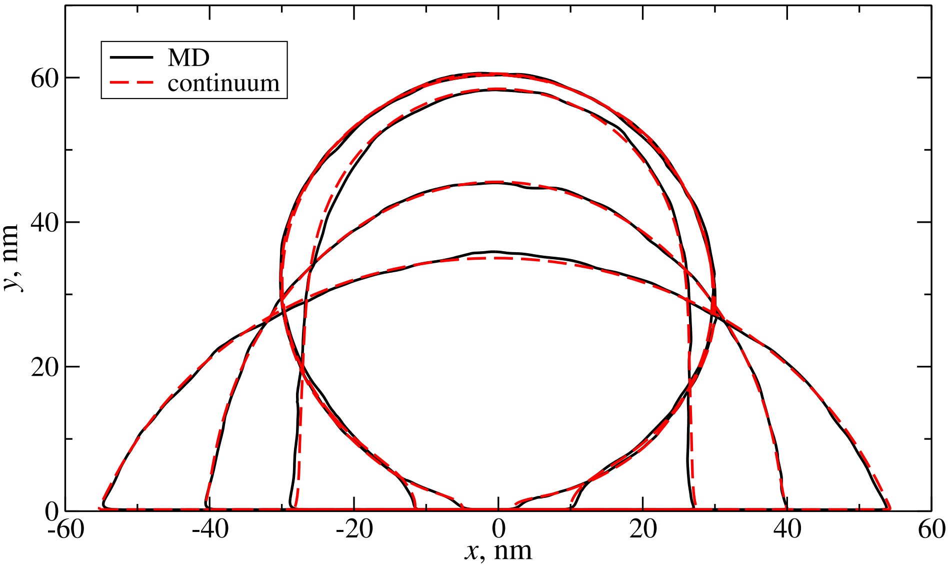

Figure 1: For a quasi-2D drop of radius 29.8 nm with the equilibrium contact angle of 63°, a comparison between MD and continuum drop shapes at 0.02, 0.1, 0.5, 1 and 2 ns after contact. Note slight asymmetry of the contact area with respect to $x = 0$ because of off-axis contact.

[1] See the talk by S. Perumanath *et al.* at this conference.

# Nanodroplets deform soft substrates: elasticity vs. capillarity

**Binyu Zhao**[1,2], Elmar Bonaccurso[3], Günter K. Auernhammer[1], and Longquan Chen[2]

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A liquid droplet sitting on soft substrates induces deformation of the substrates: a wetting ridge rises along the three-phase contact line and a dimple forms underneath the droplet. Whereas surface tension is usually associated with the spherical shapes of small droplets and bubbles, the tensile force at the surface of solids, known as surface stress, is responsible for surface instabilities of thin films and elastocapillary deformation of soft solids. Surface stress, as given by the Shuttleworth equation, is a coupling of elastic strain and surface free energy. However, the strain-induced increase in surface free energy is usually not considered in theoretical modelling.

In this study, we probe the three-dimensional interfacial configuration of soft substrates (with different shear moduli) deformed by nanodroplets (with different sizes). We show that the substrate deformation undergoes a transition from the substrate elasticity-dominated regime to the substrate capillarity-dominated regime with increasing a characteristic ratio $\gamma_\mathrm{S}/Gr$ (where $\gamma_\mathrm{S}$ and $G$ are the surface tension and shear modulus of the substrate and $r$ is the contact radius of the nanodroplet). In comparison to the theoretical models, our experimental results suggest that the Shuttleworth effect should be considered when $\gamma_\mathrm{S}/Gr \gtrsim 1$, i.e., when the droplets are sufficiently small and/or the substrates are sufficiently soft.

# High speeds of impacting micron-sized droplets suppress the splashing

**Yoshiyuki Tagawa**[1], Masashi Usawa[1] Yuta Fujita[1], Guillaume Riboux[2] and José Manuel Gordillo[2]

[1] *Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology*
[2] *Área de Mecánica de Fluidos, Departamento de Ingeniería Aeroespacial y Mecánica de Fluidos, Escuela Superior de Ingenieros, Universidad de Sevilla,*

We investigate the transition from spreading to splashing of droplets impacting onto a partially wetting smooth substrate at normal atmospheric conditions[1]. In our experiments, the radii $R$ of droplets is varied from millimeters to tens of microns. Remarkably our experimental results shown in Fig.1 reveal that splashing can be suppressed if the droplet impact speed is so high that $\mathrm{We}_\lambda = \rho V^2\lambda/\sigma > 0.5$ is satisfied, where $\sigma$, $\rho$, $V$, and $\lambda$ are the interfacial tension coefficient, the liquid density, the impact speed, and the mean free path of gas molecules, respectively. We propose a predictive theory that explains the spreading-splashing-spreading transition as the impact speed increases when the droplet radius is above a certain threshold value. For sufficiently large values of $V$, the thickness of the ejected lamella of impacting droplets $H_t$ becomes similar to (or smaller than) the mean free path of gas molecules $\lambda$. Under such conditions, the splash of the droplet is suppressed because the lift force that causes the liquid to dewet the solid surface is negligible. The transitions from both spreading to splashing and splashing to spreading are well predicted by previous theories [2][3] if the lift force is assumed to be zero when $\mathrm{We}_\lambda = \rho V^2\lambda/\sigma > 0.5$ as shown in Fig.1.

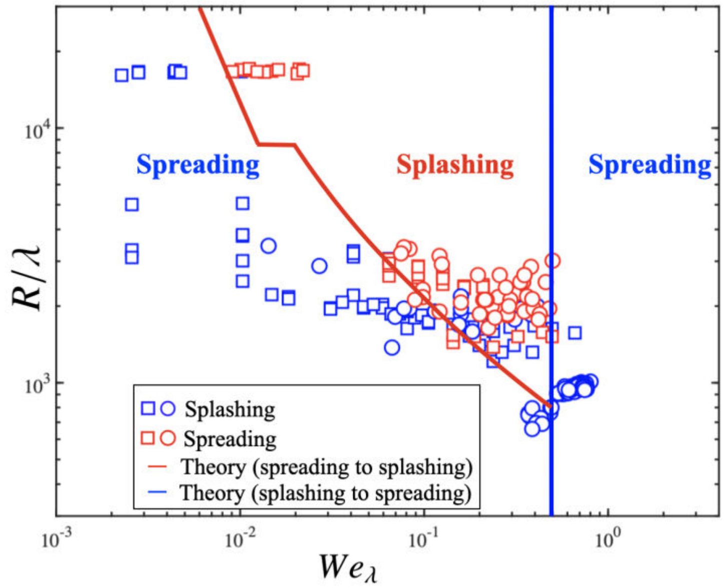

Figure 1. The experimental results of spreading and splashing droplets and the theoretical predictions of transitions in a $R/\lambda$-$\mathrm{We}_\lambda$ plane. The red and blue lines indicate the predicted spreading-splashing transition and splashing-spreading one, respectively.

[1] M. Usawa, Y. Fujita, Y. Tagawa, G. Riboux, and J.M. Gordillo, Large impact velocities suppress the splashing of micron-sized droplets, *Phys. Rev. Fluids*, **6** (2021) 023605.
[2] G. Riboux and J. M. Gordillo, Experiments of drops impacting a smooth solid surface: a model of the critical impact speed for drop splashing, *Phys. Rev. Lett.* **113** (2014) 024507.
[3] J. M. Gordillo and G. Riboux, A note on the aerodynamic splashing of droplets, *J. Fluid Mech.* **871** (2019) R3.

# Surfactant-laden Drop Bouncing

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Water drops impacting on a superhydrophobic surface undergo bouncing due to the inherent repellency of the substrate as well as the low viscosity and high surface tension of water drops. Richard *et. al.*[1] found that the time $\tau$ spent by the drop in contact with the substrate arises out of a balance between inertia and surface tension of the drop and scales as $\sqrt{m/\gamma}$ where $m$ and $\gamma$ represent the mass and the surface tension of the drop. We herein look at the influence of the presence of additives, specifically surfactants, on the drop bouncing capability.

The surface tension of the liquid reduces upon the addition of surfactant. Surprisingly, although pure liquids of low surface tension stick to the surface, surfactant-laden drops with similar surface tension still exhibit rebound. At a closer inspection, the effect of this reduced surface tension becomes explicit in the increase of the contact time of the drop. As studied previously by Mourougou-Candoni *et. al.*[2] and Aytouna *et. al.*[3]*,* the spreading of the drop happens so quickly that the surfactant molecules do not have enough time to diffuse to the surface in the spreading phase. The relevant surface property in this scenario is then the dynamic surface tension of the liquid, which differs from the equilibrium surface tension. As a consequence of this difference the result changes depending on the adsorption rate of the surfactants. While fast surfactants behave as a pure liquid at equilibrium, slow surfactants deviate from this behavior.

[1] Richard *et. al.*, *Nature* **417**, 811 (2002).
[2] Mourougou-Candoni *et. al.*, *J. Colloid Interface Sci.* **192**, 129 (1997).
[3] Aytouna *et. al.*, *Exp. Fluids* **48**, 49 (2010).

# Can face masks atomize cough droplets?

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[3] *Institute for Aerospace Studies, University of Toronto, Toronto, ON M3H 5T6, Canada.*

Face masks are known to provide resistance to the inhalation and exhalation of respiratory droplets, and their usage is crucial in preventing the transmission of COVID-19 or similar diseases. In this study, we observe that the impingement of a large-sized surrogate cough droplet (> 250 μm) on a single- or double-layer mask leads to atomization, while triple-layer masks effectively block them [1]. The droplet size considered here (> 250 μm) constitutes ~90% of the volume of droplets expelled during a single cough which directly relates to the number of pathogens contained in it. The primary experiments are conducted with de-ionized (DI) water droplets, while additional experiments with a surrogate respiratory fluid yield similar results. These droplets are ejected using a droplet dispenser (as shown in Fig. 1) at a velocity of 10 m/s (average velocity of a cough droplet). An existing theoretical understanding of the droplet penetration criteria is implemented, which determines the governing parameters to be the velocity at impact, the pore size, and the thickness of the mask. Thus penetration is found to be independent of the diameter of the impinging droplet for the size range considered in this study. The applicability of this criteria is experimentally verified by varying the impact velocity (from 2 to 10 m/s), the diameter of the impinging droplet (from 250 μm to 1.2 mm), and the pore size and thickness of the mask (single-, double-, and triple-layer). The size of the atomized droplets is characterized by probability distributions, and it is found that a majority of them are < 100 μm in diameter (~60% for single-layer, ~80% for double layer), which falls in the regime of aerosolization. Thus, this study advocates the use of triple-layer masks over single- or double-layer masks to prevent the atomization of cough droplets.

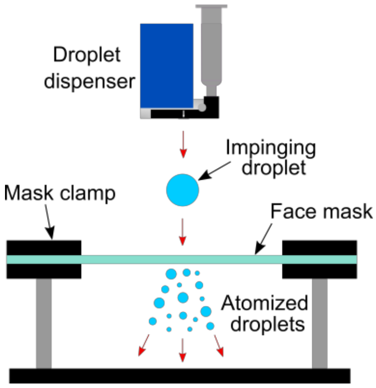

Figure 1. Atomization of a droplet impacting a face mask (single-, double-layer). Impact on triple-layer masks does not lead to atomization.

[1] S. Sharma, R. Pinto, A. Saha, S. Chaudhuri, S. Basu, On secondary atomization and blockage of surrogate cough droplets in single- and multilayer face masks. *Sci. Adv.* **7**, eabf0452 (2021).

# Non-coalescence of oscillating multiple compound droplets on coplanar EWOD platform

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Compound droplet, a liquid droplet in an immiscible oil shell, is employed for several lab-on-chip applications because of the advantages such as prevention of biofouling, contamination reduction, reduction in hysteresis, and lower evaporation rate[1]. Recently, Shubhi *et al.* demonstrated the non-coalescence of such oscillating sessile compound droplets by electrowetting[2]. The interaction of multiple compound droplets forms an oil bridge that drains with time, and coalescence of core droplets is observed. However, continuous modulation of oil bridge with the help of oscillating drops prevents drainage and helps in maintaining droplets without merging for a longer period of time. The reported study was only limited to the interaction of two compound droplets of the same size on a blank device (without patterning). Such electrowetting on dielectric (EWOD) devices needs wire insertion from the top to the core droplet. Thus, it is difficult to accurately position multiple droplets, limiting their scalability and practical applications[3]. In the present study, we explored the multiple compound droplets non-coalescence on a coplanar EWOD device. Coplanar interdigitated electrode (IDT) pattern for an EWOD device allows us to incorporate a greater number of compound droplets without any insertion of wire from the top. Besides multiple droplet non-coalescence, we also demonstrated the capability of such systems with different droplet volumes. We aim to use such systems in controlled and sequential mixing of drops for applications related to multi-step sequential chemical and biological processing. Controlled pattern and actuation allow the targeted droplets to coalesce or non-coalesce upon application of voltage, and the continuous oscillations of merged droplets also result in enhanced mixing of the reagents inside droplets.

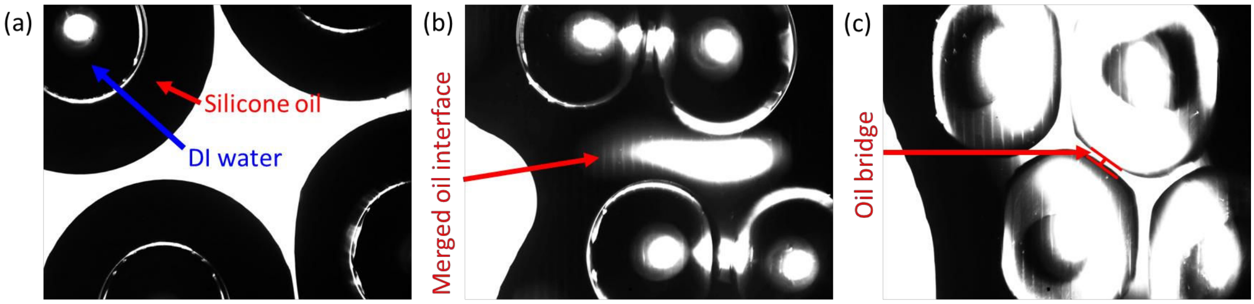

Figure 1. Compound droplets with DI water core and silicone oil shell (20 cst) with an equal volume of 5 µL oscillation on IDTs pattern on the glass wafer. (a) Before actuation (b) Droplets approaching towards each other with actuation ON (200V and 25 Hz) (c) Droplets interacting with each other showing non-coalescence behaviour among four droplets (Snapshot at maximum amplitude in a particular cycle).

## References:

[1] S. Bansal and P. Sen, *Langmuir*, 2017, **33**, 11047–11058.
[2] S. Bansal and P. Sen, *J. Colloid Interface Sci.*, 2018, **530**, 223–232.
[3] C. T. Burkhart, K. L. Maki and M. J. Schertzer, *Langmuir*, 2020, **36**, 8129–8136.

# Exploring a new dimension in high-speed liquid-liquid impact

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Droplet-liquid impacts are fundamental to a range of industrial applications such as spray cooling, fuel injection, pesticide spray distribution in the context of high precision agriculture and manufacturing applications such as inkjet printing and droplet-based 3D printing. The bulk of prior work on liquid impact problems focuses on axisymmetric, normal impacts due to the relative simplicity of experimental characterisation and visualisation, as well as reduced computational demands. In practice, however, non-axisymmetric impacts are far more common.

Building on the success of past comparisons in two-dimensional settings [1], we generalise the early time asymptotic theory to three dimensions and investigate its predictive capabilities, as well as range of validity. We use the open-source *Basilisk* package as the backbone of our implementation, taking advantage of its parallelisation features (alongside considerable computational resources) in order to unlock previously inaccessible general impact scenarios. We focus on the characterisation of meaningful morphological features such as the location of the turnover point and the root of the ejected sheet, the shape of the latter, as well as velocities therein. The later stages of the impact (including formation of secondary droplets) are then interrogated numerically over a range of impingement angles. We also outline further modelling avenues in order to improve the proposed methodology [2].

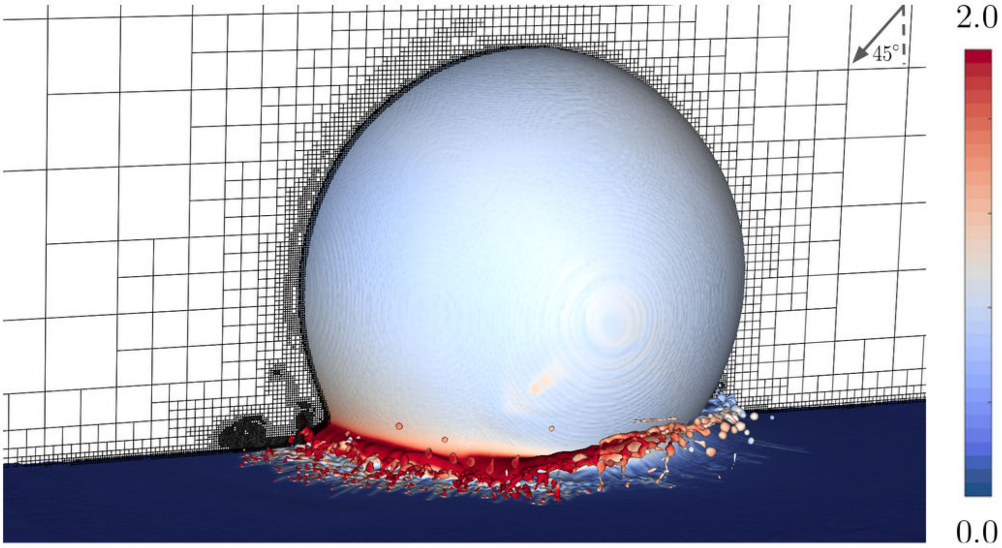

Figure 1: Direct numerical simulation of a water drop of diameter 1 mm impacting onto a deep liquid pool at a 45° angle of incidence with an initial velocity of 10 m/s. The liquid-liquid interfaces are coloured using the norm of the velocity field. The underlying (adaptive) volume-of-fluid discretisation is also highlighted.

[1] R. Cimpeanu and M. R. Moore, Early-time jet formation in liquid-liquid impact problems: theory and simulations, Journal of Fluid Mechanics **856** (2018), 764-796.

[2] M. R. Moore, R. Cimpeanu, H. Ockendon, J. R. Ockendon and J. M. Oliver, Boundary layers in Helmholtz flows, Journal of Fluid Mechanics **882** (2020), A19 1-20.

# Numerical Simulation of wetting on textured surfaces with Lattice Boltzmann Method

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The control of surface wetting is of prime interest in different application fields like super-hydrophobicity, anti-icing, low friction interfaces… Moreover, surface texturing is a good candidate to modify the conditions of liquid spreading. To complete experimental wetting tests, a numerical simulation code is developed. Due to its high level of parallelization and to its high ability with complex surface roughness, the Lattice Boltzmann Method is used. Simulations of the physical evolution of the contact angle and the triple line motion on both chemical and topographical textured surfaces are performed. LBM method with Bhatnagar-Gross-Krook (BGK) approximation coupled with multi-components and multi-phases interactions incorporated through the Shan-Chen pseudo-potential model is applied [1]. Shan-Chen interaction forces also allow the implementation of adhesion force component that depends on the fluid-solid adhesion potential. This latter was defined in order to respect the theoretical Young static contact angle as proposed by Martys-Chen and Sukop works [2-3]. Figure 1 presents the study of the hydrophilic to hydrophobic transition: for the advancing triple line, it is notable to observe that the triple line is stuck at the border between the hydrophilic and the hydrophobic domain. Unlike, in the case of the receding triple line, the hydrophilic to hydrophobic transition is associated to an abrupt variation of the contact angle value. Both of these behaviors are associated to a sticking and releasing effect of the triple line at the chemical transition, also observed in the case of topographical textured surfaces.

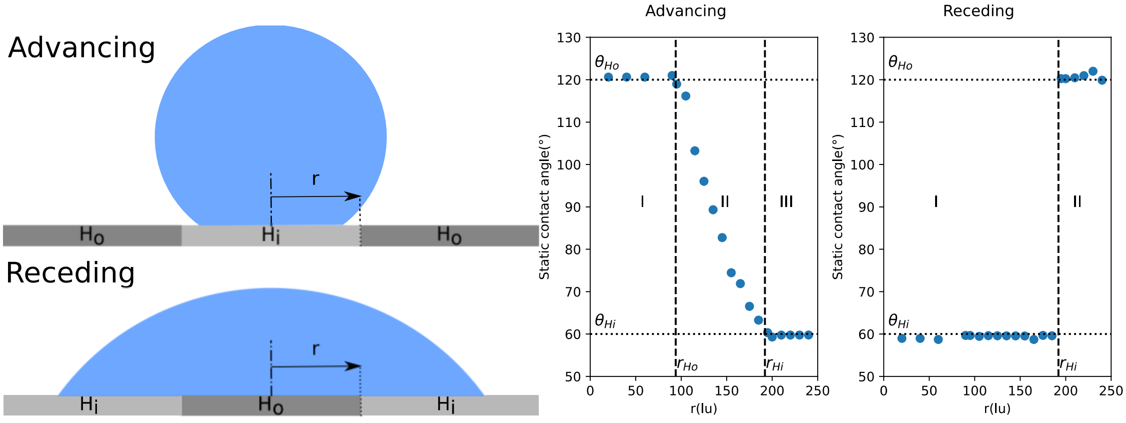

Figure 1. Initial state of the system for the study of a hydrophilic to hydrophobic transition for the advance and the receding of a triple line (left side) and corresponding static contact angle evolution as a function of the position (right side).

[1] L. Chen *et al.*, *Int. Jour. of Heat and Mass Transf.* (2014), 210-236.
[2] N. S. Martys and H. Chen, *Phys Rev E* **53** (1996), 743–750.
[3] M. C. Sukop and D. T. Thorne, Springer Publishing Company (2010)

# Numerical simulation of wetting dynamics on viscoelastic substrates

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The interaction of a viscoelastic substrate with liquid droplets is at small length scales dominated by surface tension forces. Understanding how these forces deform the solid is crucial for the design of new materials, structures, and fabrication techniques.

We present a first numerical model to simulate the interaction between two immiscible fluids and an incompressible viscoelastic solid. The fluid-fluid interface is represented by a phase-field function. The deforming elastic body is described by an additional phase-field [1] or a moving Finite-element grid [2]. Formulating all equations in an Eulerian frame of reference, we obtain a single momentum equation including the solid and both fluid materials.

In numerical tests we demonstrate that this novel method is robust and flexible, and we illustrate that material properties of the viscoelastic substrate can be continuously tuned from purely viscous to purely elastic. Finally, we present a comparison to experimental results and unravel the physics of the observed stick-slip phenomenon.

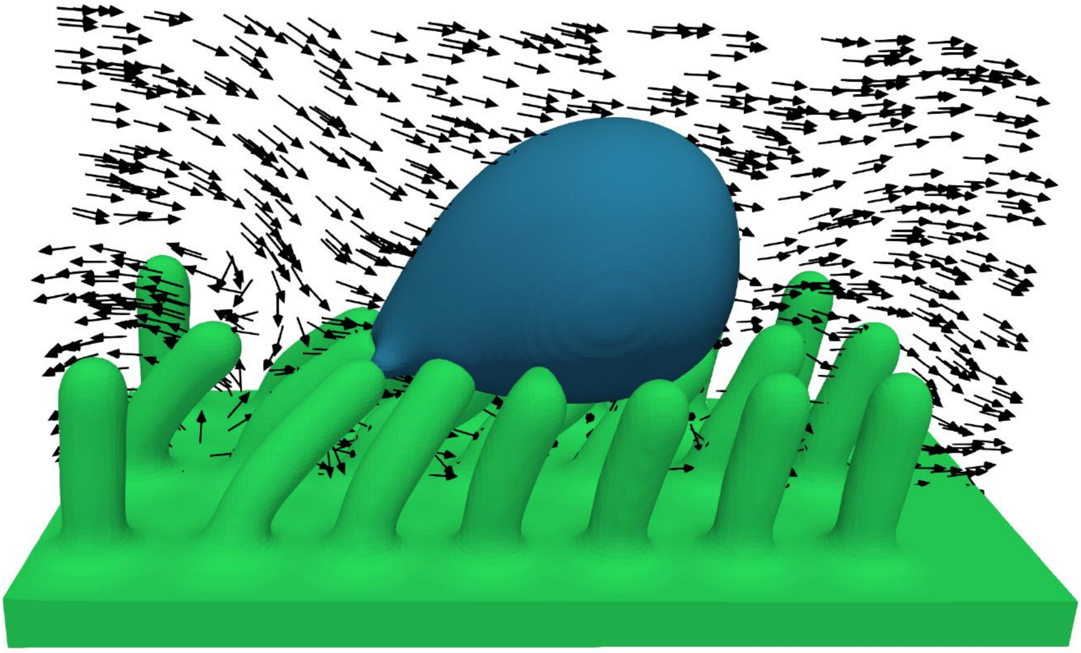

Figure 1. Numerical simulation of a liquid droplet (blue) rolling over a viscoelastic microstructured substrate (green) [1].

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# Contact-Angle Hysteresis and Contact-Line Friction on Slippery Liquid-like Surfaces

**Hernán Barrio-Zhang**[1], Élfego Ruiz-Gutierrez [1], Steven Armstrong[1], Glen McHale[1], Gary G. Wells[1] and Rodrigo Ledesma Aguilar [1]

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Contact-line pinning and dynamic friction are fundamental forces which oppose the motion of droplets on solid surfaces. Experience and intuition suggest that the relationship between contact-line pinning and dynamic friction is proportional. In this work, however, we show that this is not always the case and that Slippery Omniphobic Covalently Attached Liquid-like (SOCAL) surfaces have a remarkable combination of contact-angle hysteresis and contact-line friction properties[1] where the surface exhibits low pinning[2,3] but high dynamic friction against the motion of droplets. Volume change experiments at controlled temperature and humidity conditions show that droplets return to stable equilibrium state contact angle values that can be used to describe the static friction of the liquid-solid-gas interaction. Additionally, we use these results to compare to predictions made by the Cox-Voinov model and a contact-line model based on Molecular Kinetic Theory. Our results show that SOCAL surfaces exhibit low contact-angle hysteresis, 1°-5°, but have unexpectedly high dynamic friction driven by the contact line. This highlights the unique wettability of SOCAL surfaces and potential application for low-pinning, slow droplet shedding surfaces.

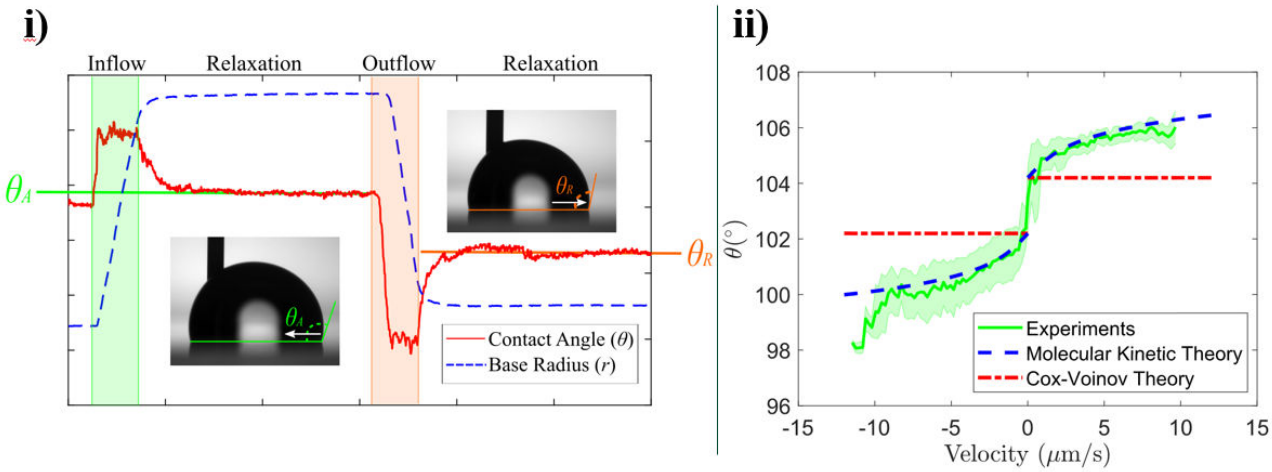

Figure 1. Relaxation and dynamics of the contact angle, i) The apparent contact angle relaxes to constant values and the difference between these values is identified as the contact-angle hysteresis. ii) Instantaneous measurements of the contact angle vs and contact-line velocity showing a significant agreement with the Molecular Kinetic Theory.

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# Wetting origins: how droplets meet surfaces

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We present evidence of a new mode of contact line motion during the initial stages of wetting of a solid by a liquid and theoretically quantify it. Our large-scale molecular dynamics (MD) simulations reveal that soon after the first contact, whose location is probabilistic as it is in the case of nanodroplet coalescence [1], the contact line advances as a result of interfacial molecules from the approaching liquid surface collectively jumping on to the solid wall (see Figs. 1a and 1b). In this 'thermal-vdW' regime, the dynamics is governed by the solid-liquid interaction and interfacial thermal fluctuations. This new mode of contact line evolution continues until a 'thermal length scale $l_T$' is achieved, which is dependent on the droplet size and the equilibrium contact angle between the wetting liquid and the substrate. The wetting dynamics thereafter cross over to a regime that is seemingly described by the classical molecular kinetic theory of dynamic wetting (MKT; see Figs. 1c and 1d) [2].

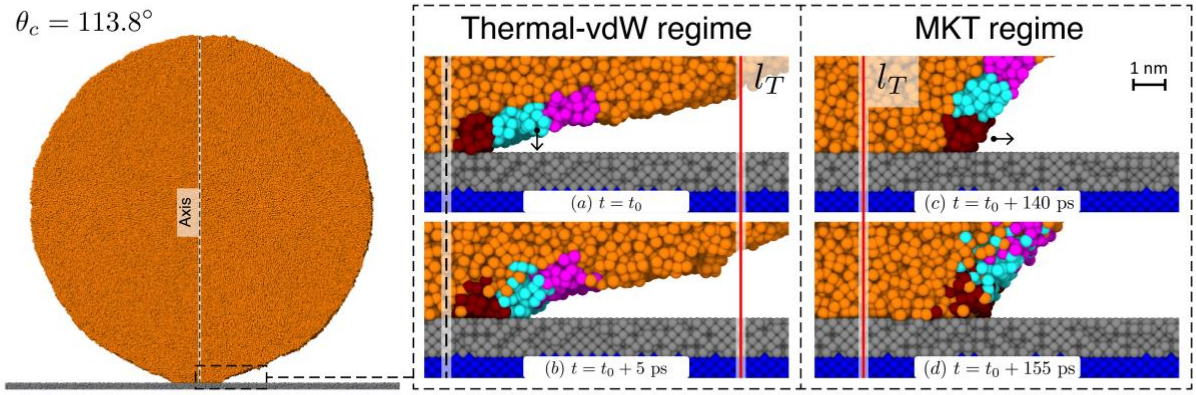

Figure 1. MD simulation snapshots showing how differently the contact line evolves in (a & b) the thermal-vdW regime and in (c & d) the MKT regime. Here, the radius of the quasi-2D droplet is 29.8 nm and $\theta_c = 113.8°$ is the equilibrium contact angle. In the thermal-vdW regime, the (cyan) interfacial molecules make collective transverse jumps across the gap between the droplet and the wall. In the MKT regime, the (brown) TPZ molecules jump laterally along the solid surface. Note that the molecules are re-coloured in (c).

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[2] T. Blake and J. Haynes, *J. Colloid Interface Sci.* **30**, 421 (1969).

# Wetting and Evaporation of Hygroscopic Drops

**Senthil Kumar Parimalanathan**[1], Alexey Rednikov[2], and Pierre Colinet[3]

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The wetting dynamics of a sessile droplet made of alcohol and water mixture has been observed to depend on the initial water mass fraction ($c_w$) and the ambient relative humidity (RH, water vapour only) [1]. The dependence is consolidated into one unique plot referred to as Map of Regimes (MOR) (Fig. 1). It has been found that the non-ideality (deviation from Raoult's law) of these binary mixtures together with a faster diffusivity of water vapour give rise to water depletion as a result of the evaporation process for certain region of the parameter space, in spite of the alcohol being more volatile. Surface tension being higher for water than for alcohol, much depends on whether we eventually have water enrichment or depletion, which processes go on more intensely near the contact line (due to a small volume-to-surface ratio and the evaporation singularity) and hence give rise to solutal Marangoni stresses intervening in the wetting dynamics (spreading or contraction, respectively).

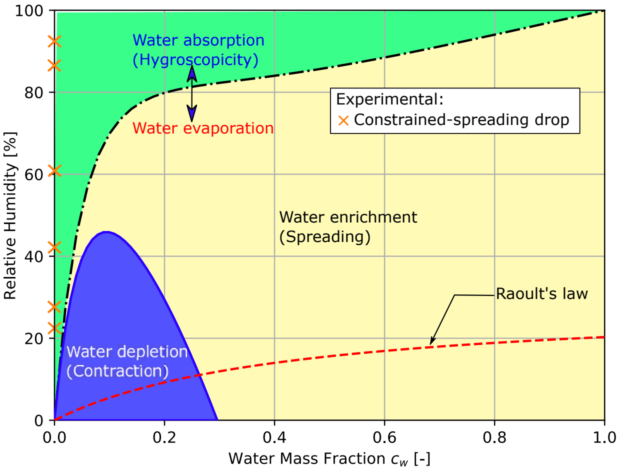

Figure 1: Map of Regime for IPA/Water solution

In the present talk, we shall be interested in the cases of initially pure alcohol drops, which start to absorb water from the ambient atmosphere (hygroscopicity), more intensely at the contact line, and which find themselves in a spreading regime as a consequence (cf. the crosses in the MOR diagram). We actually refer to it as a 'constrained-spreading' regime, meaning that more 'violent' spreading regimes (with contact-line instabilities) not considered here can be found when the drop consists of a mixture from the very beginning. We proceed by depositing pure IPA drops on a plasma-cleaned substrate inside a control cell where the humidity can be varied and maintained at the desired level. The drop shape, contact angle, and the instantaneous position of the contact line have been measured using a Mach-Zehnder interferometer. The drop shapes for different humidity conditions at t = 5 s after deposition are shown in Fig. 2. The radius, shape and evaporation rates are strongly affected by the ambient humidity for a pure IPA drop due to its hygroscopicity. We see that a flattened shape in the middle of the drop is attained faster for more humid conditions.However, the contact angles for all these cases approached a value in the range of 3° to 6° irrespective of the ambient humidity.

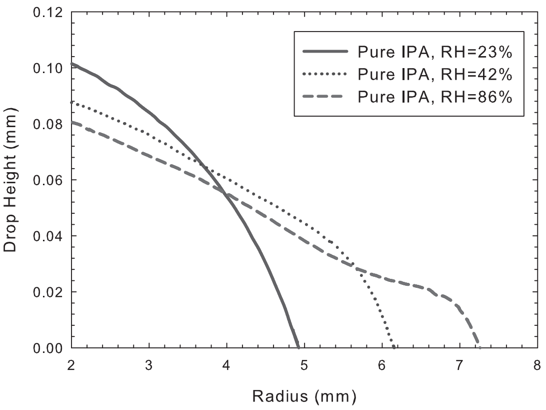

Figure 2: Drop shapes at t = 5 s after deposition

Acknowledgments: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 801505 as well as from ESA and BELSPO PRODEX (Evaporation and Heat Transfer), and from Fonds de la Recherche Scientifique-F.N.R.S.

[1] Parimalanathan, S. K. et al. , J. Colloid Interface Sci., **592** (2021), 319-328.

# Evaporation of a respiratory droplet and residual thin-film on impermeable and porous surfaces in the context of COVID-19

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The likelihood of survival of coronavirus on different surfaces has been analysed herein to demonstrate safety aspects of different materials and thereby mitigating the disease transmission through the fomite route. It was previously demonstrated that the aqueous phase of a respiratory droplet serves as a medium for survival of enveloped viruses such as coronavirus [1, 2]. Therefore, evaporation plays a major role in dictating the survival time. While the bulk droplet, depending on the surface character (wettability, roughness, porosity etc.), takes only a few seconds to evaporate from the surface, the thin liquid film which is left behind takes a significantly longer time to evaporate. The present study shows that the slowing down of evaporation in the latter case can be attributed to the disjoining pressure within the thin film, which drives the evaporation of the thin film. This notion, thus explains the recent findings on virus titer experiments [3] that why the cornavirus survives for days on surfaces. For porous surfaces, the evaporation of the residual thin-film is much fastrer, making them lesser susceptible to virus survival. The aforsaid faster evaporation is caused by droplet spreading due to horizontally oriented fibers and modification of effective solid-liquid interfacial area that leads to a higher disjoining-pressure within the thin-film. This explains why coronavirus survives longer on impermeable than porous surfaces [4]. Based upon the knowledge gained above, we design antiviral surfaces with varying wettability and texture. Details will be presented in the conference.

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[2] R Mittal, *J. Fluid. Mech.* **894** (2020), F2.
[3] R Bhardwaj and A Agrawal, Phys. Fluids. **32** (2020), 111706.
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# Droplet splashing on curved substrates

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It is well-known that the propensity for an impinging droplet on a solid substrate to splash is affected by the droplet fluid properties, pre-impact dynamics, the surrounding gas dynamics, and substrate wettability. Understanding the conditions under which splashing occurs is crucial in natural and industrial situations (e.g. coating and inkjet printing), usually to prevent the formation of smaller droplets with indiscriminate trajectories and unwanted aerosolisation of fluid. In nature and applications, high-speed droplets often impact concave or convex substrates and particles (such as in spray drying), but the influence of substrate geometry on droplet splashing is not well understood. Previous experimental studies for droplets impacting spheres have generally considered wet substrates, either by design or because droplets impinged continuously leaving behind a thin and variable film of fluid, with contradictory results regarding the influence of curvature on the splashing threshold.

Figure 1: Examples of various impact outcomes for droplets on spheres, from deposition to splashing. Sphere diameters of 5 mm–20 mm are shown. Times after impact $\{0.2, 0.6, 1.0, 0.4\}$ ms for each frame, respectively.

We present a high-speed imaging study of droplet impact onto curved substrates covering a wide range of Weber numbers, encompassing simple deposition through to corona splashing (see Fig. 1 for examples with a spherical substrate). The substrate was thoroughly dried between successive depositions. We consider a uniquely wide range of curved substrates, from spheres of radius $\mathcal{O}(1\,\mathrm{mm})$, through flat substrates, to concave lenses. Two high-speed cameras positioned perpendicularly simultaneously captured the impact dynamics, enabling the effect of droplet-sphere alignment to be studied, and axisymmetry ensured when desired. The precision of our experiments enables the transition between simple deposition and splashing to be precisely delineated across the range of curvatures considered. We also examine the spreading dynamics post-impact, using image processing to extract contact angles during spreading (amongst other quantities) and consider a mathematical treatment of our experimental results to make progress towards uncovering the fundamental mechanism of splashing on curved substrates.

# Drop impact on thin film: mixing, thickness variations and ejections

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Stalagmites of all shapes and sizes (Fig. 1 (a)) grow on the floor of caves by precipitation of calcium ions. These ions are found in the residual water film covering the top of the stalagmite, which is progressively drained away at the same time. Drops dripping from stalactites ensure the renewal of these ions and of the liquid film. Over short timescales, the distribution of calcium ions, which dictates subsequent stalagmite growth rate and morphology, is affected by the way drops impact this film.

The residual film thickness $\delta$ varies in time and space in response to both drop impacts and drainage. It is of the order of $[50, 500]$ $\mu$m thus $\delta/R \lesssim 0.2$, where $R \simeq 2.6$ mm is the drop radius [1]. Cave ceiling heights sometimes reach several tens of meters, yielding impacting drop velocities to range in $[1, 10]$ m/s. High velocity drop impacts on very thin, miscible films have been described in [2,3]. They are mostly characterized by i) prompt splash accompanied by a large amount of secondary droplet ejections before and during the jetting phase, ii) a crown inclined at a small angle with the horizontal, developing and fragmenting in a similar manner as on a dry wall, iii) a retraction phase (Fig. 1 (b)). The latter is not similar to that of impacts on a dry wall and does not yield the formation of a large Worthington jet as for drop impacts on a deep bath either.

The retraction phase is at the very heart of the film thickness variability post-impact. We investigate how this film thickness is affected, as well as how would ions be redistributed in the solution following the impact. We proceed by recording high-speed impacts on films of controlled thickness in a lab environment. By using two different colors for the drop and the film and applying a colorimetry technique (Fig. 1 (c)), we assess the mixing between the drop and the film. We also measure the film thickness $\delta$ right after impact in all points from the impact position up to the unperturbed free surface, and deduce how much liquid would be added following one impact. In a second time, we collect and take pictures of post-impact ejections in an area of radius 100 times larger than $R$ (Fig. 1 (b)). Based on the same technique, we evaluate which ejected proportion comes from either the drop or the film. We finally relate all these parameters to the various regimes observable in situ.

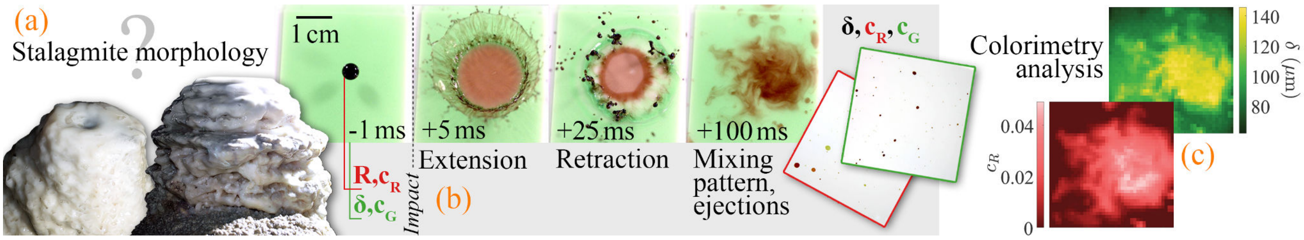

Figure 1: (a) Possible stalagmite shapes. (b) Time sequence of an impact showing the crown extension, the lamella retraction and the mixing pattern obtained ($R = 2.3$ mm, $\delta \simeq 100$ $\mu$m), along with two ejection patterns. (c) Measurements obtained for $\delta$ and the red dye concentration after impact, using colorimetry analysis.

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# Fragmentation of Acoustically Levitated Fuel Droplets using Nano-Femtosecond Laser Pulses

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[2]*Department of Physics, University of Gothenburg, Sweden*
[3]*NASA-Jet Propulsion Laboratory, California Institute of Technology, USA*

Liquid atomization plays a vital role in various engineering applications like internal combustion engines, agriculture sprays, spray drying, spray cooling, and spray painting. However, fundamental research on laser-induced single droplet atomization and evaporation is limited.The current study is an attempt to understand the droplet disintegration due to instability from laser heating. We focus on the breakup mechanism and fragmentation of single and multi-component fuel droplets (trapped in the air using an acoustic levitator) exposed to nanosecond [1] or femtosecond laser pulses [2]. The droplet sizes used are in the range of 0.5-1.6 mm in diameter, laser energies per pulse are 0.5-7 mJ for nanosecond and 1 mJ for femtosecond laser pulses. An IR camera is used to record the surface temperature of the droplet before the laser pulse impact. The three different breakup phenomena are observed during the laser–droplet interaction: Breakup through bubble generation, sheet formation, and prompt fragmentation (catastrophic breakup). Figure 1 shows the nanosecond- induced fragmentation of the water droplet for an initial droplet size of 1.2 mm. The droplet is getting stretched vertically and stable sheet is formed. The maximum expansion of the sheet is reached at $\Delta t = 0.36$ ms, afterwards it shrink due to the effect of surface tension. The small droplets and ligaments are emerged out from the circular edge of the sheet, subsequently these ligaments disintegrate into fine droplets called secondary atomization as observed from figure 1.The secondary droplet sizes and the number of droplets produced are deduced from image analysis where the Sauter Mean Diameter (SMD) is calculated for the different fuel droplets.

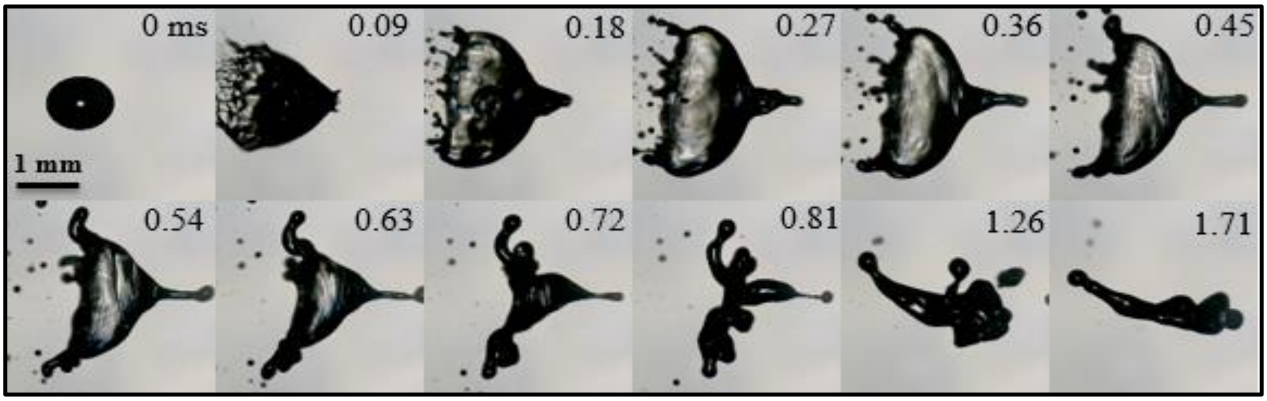

Figure 1. Nanosecond laser-induced fragmentation dynamics of water droplet: stable stretched liquid sheet at 2.5 mJ. Scale bar :1 mm.

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# Drops on Soluble Coatings - Experimental Investigation of the Influence of Substrate Thickness on Wetting and Surface Restructuring

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The wetting of polymer coatings with solvents is a complex physical process which is involved in many applications in cleaning, food and micro-manufacturing technology. In addition to the surface energies of the coating and the liquid, both the transport of dissolved coating molecules into the fluid and the transport of solvent molecules into the coating influence the wetting process. During the process sequence of wetting and subsequent evaporation of the solvent, a restructuring of the coating surface takes place, in which different surface topologies are formed depending on the combination of layer thickness and the dissolution rate of the polymer. In this work, the spreading process of the droplet after contact of the solvent with the coating, the evaporation of the droplet into an unsaturated atmosphere as well as the resulting surface structures are examined. In previous investigations, different molecular masses of the polymer (polystyrene) have been used to adjust the dissolution rate into the solvent (toluene) [1]. In the present work, both the layer thickness and the molecular mass of the polystyrene are varied to control the polymer dissolution rate.

The contribution shows wetting speeds, dynamic contact angles and surface topologies after evaporation. It is shown that the wetting of soluble coatings can be divided into two qualitatively different phases. In agreement with [1], the first, rapid expansion phase is independent of the solubility of the coating. The subsequent slow second spreading depends on both the thickness and the molecular mass of the substrate. This phase is responsible for about 60% of the total wetted area on thin (300 nm) coatings and decreases in significance with increasing coating thickness. The surface topography emerging after the complete evaporating of the drop depends both on the molecular mass and the coating thickness. Thick coatings lead to formation of high ring-shaped structures whereas thin coating lead to formation of irregular structures.

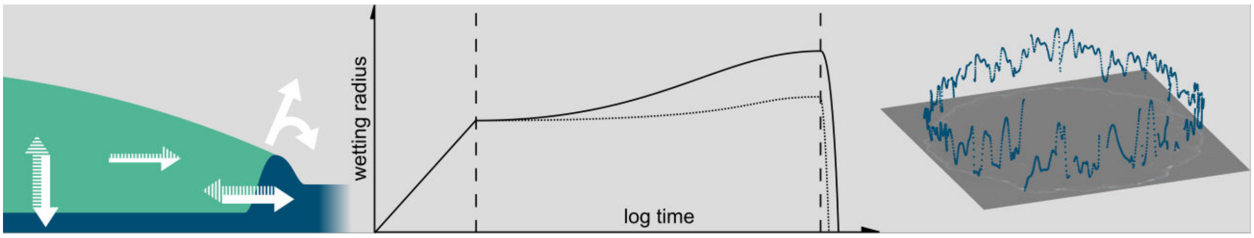

Figure 1. Left: Sketch of a solvent drop on a soluble coating showing mass transport routes of solvent (full white) and polymer (hatched); Middle: Semi-logarithmic sample plot of wetting radius over time of a solvent drop on a thin and a thick (dashed) coating; Right: Height profile of a structure left behind after solvent evaporation on a low molecular mass, thin (17.9 kg $\mathrm{mol}^{-1}$, 200 nm) coating

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# Imaging moving wetting ridges on liquid-infused surfaces

**Abhinav Naga**, William S. Y. Wong, Anke Kaltbeitzel, Azadeh Sharifi-Aghili, and Doris Vollmer

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Inspired by pitcher plants, liquid-infused surfaces can repel most liquids. Liquid-infused surfaces consist of a solid scaffold that is imbibed with a suitable lubricant. The liquid repellent nature of these surfaces is due to the lubricant, which effectively minimises pinning forces between the surface and the liquid to be repelled. Consequently, drops start moving as soon as the surface is slightly tilted (roll-off angle $< 5°$). However, a low roll-off angle does not imply high droplet mobility. Indeed, on liquid-infused surfaces drops move significantly more slowly than on superhydrophobic surfaces which have comparable roll-off angles.

When water drops move on a liquid-infused surface, they experience significant friction, which is predominantly due to the lubricant meniscus (or wetting ridge) surrounding the drop. Despite the crucial role of the wetting ridge in determining drop mobility and friction, microscopic visualisation of its evolution during motion is lacking. To image the wetting ridge continuously, we fixed a drop on a liquid-infused surface, directly above the objective lens of an inverted confocal microscope, and then moved the surface at controlled speeds (10 – 2000 µm/s). This setup allows us to monitor the geometry of the wetting ridge over 4 orders of magnitude in the capillary number ($10^{-6} < Ca < 10^{-2}$, where $Ca = \eta v/\gamma$, $\eta$: viscosity of the lubricant, $v$: speed, $\gamma$: drop-lubricant interfacial tension). During motion, the front side of the wetting ridge changes significantly, decreasing by up to 70% (at $Ca \approx 10^{-2}$) of its static size (Fig. 1). In contrast, changes in the rear side of the wetting ridge are much less pronounced. As a result, the wetting ridge becomes noticeably asymmetric during motion.

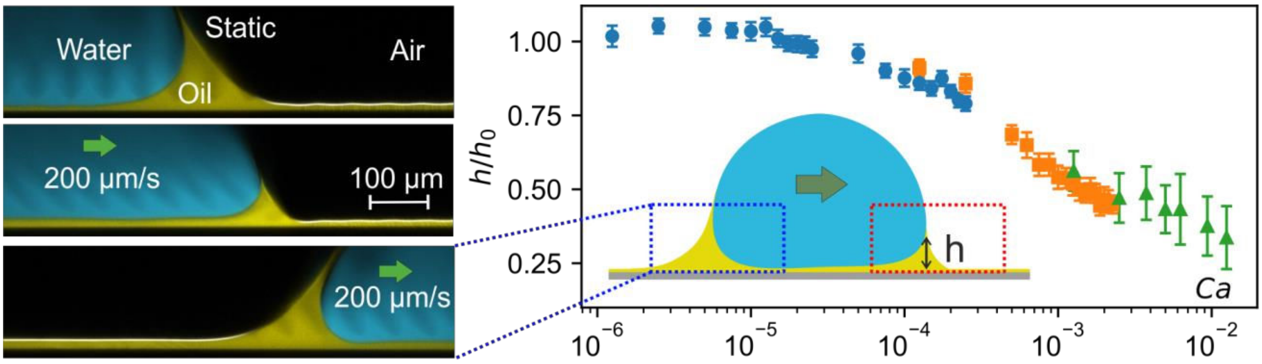

Figure 1. Left: Water drop moving on a liquid-infused surface. The height of the front side of the wetting ridge decreases with speed. Right: Normalised height of the front side of the wetting ridge. $h$ is the height during motion and $h_0$ is the height before motion. The blue, orange and green symbols correspond to liquid-infused surfaces containing lubricant of viscosities 10 cSt, 50 cSt and 500 cSt, respectively.

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# Dynamic wetting of droplets on vibrated complex surfaces

**Elise Contraires**[1,2,3], Li Fu[4], Mohammed Boussenna[1], Matthieu Guibert[5], Alain Le Bot[1] and Stéphane Benayoun[1]

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Droplet motion is of large interest in many application, form the rain droplet on windshields to fine positioning of droplets in 3D printing or self-cleaning of photovoltaic panels [1]. Although spontaneous motion can be achieved under certain conditions, the use of vibrations is mostly involved to increase droplet velocity and control. Indeed, the motion of droplets on vibrated surfaces has been the subject of several studies since 15 years.

Daniel *et al.* studied the motion of a droplet on a surface submitted to lateral vibration and determined the conditions to have a motion in terms of surface tension and contact angle [2]. The transition from a pinned to a mobile contact line in the case of a vertical motion was depicted by Noblin *et al.* and the transport of such vibrated droplets was studied by Holmes and Böhringer [3, 4].

A droplet submitted to vibration dissipates energy due to its deformation, in the droplet's volume as well as at the liquid-solid interface. This dissipation was the studied by Sharp and coworkers who discussed the influence of contact angle on the resonance frequency [5]. Very recently Xia and Steen focused on the dissipation due to an oscillating contact line [6].

Based on this solid framework, we propose to analyse the onset of motion of a droplet on a textured surface when submitted to lateral vibration. Several low-energy surfaces with different equilibrium contact angles and anisotropic and isotropic textures were employed, allowing us to modulate the real contact area between droplet and solid. High-level image analysis is used to extract the acceleration corresponding to the transition from fixed to mobile droplet. We interpret this acceleration in the light of the surface topography taking into account the nature of the contact, between suspended and impaled droplets.

In a second part, the phase-lag between the droplet and the substrate is analysed as a function of the topography as well. We demonstrate the effect of the real contact area of the droplet and make some interpretations of the dissipation source during the motion.

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# Fluid separation and network deformation in soft wetting of swollen elastomers

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When a water drop is deposited onto a soft adhesive solid, the water surface tension drives an out-of-plane deformation, leading to the emergence of a wetting ridge around the drop perimeter. The formation of the wetting ridge can be resisted by solid surface tension and the elasticity of the underlying substrate [1-3]. On the other hand, if a water drop is placed onto an immiscible fluid, like oil, both liquids deform until they adopt the appropriate contact angles and the force vectors are balanced. This kind of liquid-liquid contact line geometry is commonly observed in slippery, lubricant-infused porous surfaces (SLIPS) [4]. Although many efforts have focused on understanding the wetting of soft solids and of SLIPS, less attention has been given to swollen elastomers. Swollen elastomers are soft, crosslinked polymer networks that are infused with a compatible fluid. When a drop is placed onto a swollen elastomer, it is possible for both the swelling fluid to be pulled out and for the network to deform. However, it is unclear what determines when fluid is pulled out and how the solid network deforms to accommodate the interfacial energies. Although it has been demonstrated that free, uncrosslinked molecules can play a role in static and dynamic wetting and adhesion [5-9], the effects of swelling and mechanical properties have not been experimentally considered in soft wetting. Here [10], we employ confocal microscopy and dye selection to visualize the crosslinked polymer network and the swelling fluid separately during static wetting. The surfaces are made from silicone elastomers with controlled crosslinking and amounts of swelling using low molecular weight silicone fluid. We show that both the fluid separation and network deformation are governed by both the degree of crosslinking and the degree of swelling. It appears that the network wetting ridge height reaches a maximum as a function of increasing swelling for soft elastomers. We anticipate that examining the wetting ridge geometry will help in developing a unified theory for wetting on soft gels.

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[2] H. Liang, et al., *Langmuir.* **34** (2018), 7497.
[3] S. Karpitschka, et al., *Nature Communications.* **6** (2015), 7891.
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[9] Q. Xu, et al., *Physical Review Letters.* **125** (2020), 238002.
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# Title: Capillary Bridges on Liquid Infused Surfaces

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Inspired by pitcher plants, a novel class of functional surfaces, termed liquid infused surfaces (LIS), can be constructed by infusing rough or porous materials with a lubricant [1-3]. To date, many applications of LIS exploit the fact that, on LIS, liquids move easily parallel to the substrate. This "slippery" nature results in numerous advantageous properties, such as self-cleaning, enhanced heat transfer, antifouling, and anti-icing. Here, we focus instead on the adhesive properties of droplets when displaced perpendicularly to the substrate. To this end, we present numerical study of capillary bridges formed when a liquid droplet is placed in between two LIS [4].

Compared to the more commonly studied case of capillary briges between non-infused solid surfaces, liquid bridges on LIS can exhibit a wider range of morphologies due to the presence of the infusing lubricant, where the liquid droplet is directly in contact with two, one, or none of the LIS substrates. In addition, the capillary bridges may lose stability when compressed due to the envelopment of the droplet by the lubricant. We also characterize the capillary force, maximum separation, and effective spring force and find that they are influenced by the shape and size of the lubricant ridge. Importantly, these can be tuned to increase the effective capillary adhesion strength by manipulating the lubricant pressure, Neumann angle, and wetting contact angles. As such, LIS are not only "slippery" parallel to the surface, but they are also "sticky" perpendicular to the surface.

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# Dewetting of thin lubricating films under aqueous drops on slippery surfaces

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The stability of thin liquid films depends on various interfacial energies related to the system. Thin lubricating films of slippery surfaces, inspired by *Nepenthes* pitcher plants, show stable or unstable behavior depending on the surface energy of the underlying solid surface.[1] Here we present the dewetting of thin lubricating oil films of different thicknesses on hydrophilic solid surfaces underneath aqueous drops. The interaction between drop and substrate through film depends on spreading coefficient for micrometer thick films and intermolecular interactions for nanometer thick films.[2] As a result, the final dewetting morphologies of thin lubricating films underneath aqueous drops depend on the film thickness (Fig. 1). Hole growth during dewetting shows linear relation with time, which is similar to the conventional dewetting of films in the air for a no-slip system. Dewetting of lubricating films also affects the macroscopic wetting behavior of aqueous drops as their contact angle decreases with time, showing two regimes corresponding thinning and dewetting of the lubricating films.

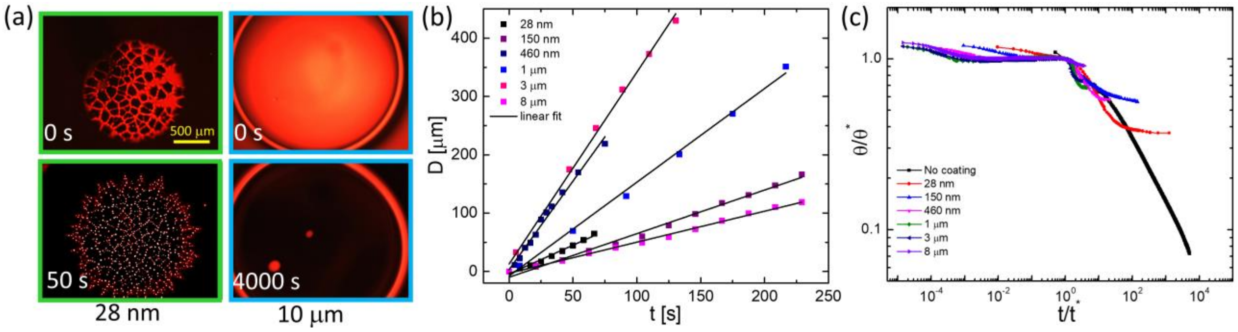

Figure 1. (a) Fluorescence optical images of initial and final morphologies of lubricating films of thickness 28 nm and 10 µm underneath aqueous drops; (b) dewetting distance (D) vs. time for different film thicknesses showing linear behavior; (c) apparent contact angle of aqueous drops with time showing the scaling behavior.

Lubricating films of slippery system also show reversible dewetting-rewetting transition by manipulating the interfacial energies via external electric field. Although on hydrophobic solid surface, thin lubricating films are stable under aqueous drops, they undergo dewetting due to additional electrostatic energy. Dewetted drops slowly coalesce to form uniform film when electric field is removed. Detailed investigation of the reversible dewetting-rewetting transition is discussed.

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[2] Dan Daniel, *Nat. Phys.* **13** (2017), 1020.

# Delayed lubricant depletion of liquid infused surfaces through nanostructure tuning

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[2] *Nanoengineered Systems Laboratory, Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, UK*
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[4] *Department of Chemistry, University College London, Torrington Place, London WC1E 7JE, UK*

Liquid infused surfaces (LIS) are an important class of repellent materials with slippery properties, which can better manage low surface tension fluids and are less susceptible to damage under physical stress as opposed to superhydrophobic materials.[1] LIS are also able to self-heal,[2] however these collective properties are only efficient as long as the lubricant remains infused, which has proved challenging.[3],[4] We hypothesised that, in comparison to a nanohole and nanopillar morphology, the 'hybrid' morphology of a hole within a nanopillar, namely a nanotube, would be able to retain lubricant more effectively; due to the lubricant reservoir within the tube, the greater 'roughness', and therefore greater thermodynamic stability of the lubricant film within the structure. Owing to recent fabrication advances in Spacer Defined Intrinsic Multiple Patterning (SDIMP),[5] we fabricated a 2x2 cm array of silicon nanotubes, and equivalent arrays of nanoholes, and nanopillars (pitch; 560 nm, height; 2 μm). After infusing the nanostructures (pre-rendered hydrophobic) with lubricant Krytox 1525, we probed the lubricant stability under dynamic conditions and correlated the degree of the lubricant film discontinuity to changes in the contact angle hysteresis. As a proof-of-concept, the so-called durability test, which involved consecutive deposition of droplets onto the surface amounting to 0.5l, revealed a 2-fold and 1.5-fold enhancement of lubricant retention in nanotubes, in comparison to nanopillars and nanoholes respectively; showing a clear trajectory for prolonging the lifetime of a slippery surface.

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# The unique attributes of droplets shaped by surface tension gradients on high energy surfaces

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On high energy surfaces, the free energy of the solid/air interface is higher than the sum of free energies of the liquid/air and liquid/solid interfaces. Thus, the canonical behavior for a liquid on a high energy surface is continual spreading, slowed by viscosity [1]. However, evaporation can give rise to solutal or thermal surface tension gradients that drive fluid flow (Fig. 1) [2] impacting the shape and dynamics of droplets. This flow can accelerate or even arrest spreading on completely wetting surfaces [3]. The resulting droplets have unique properties such as negligible contact angle hysteresis and negligible pinning even on geometrically and chemically imperfect substrates [4]. This enables such droplets to move in response to subtle gradients in height [4], humidity [5], pressure, temperature, volatile chemicals [5], and the presence of adjacent droplets and barriers [6]. This unique responsiveness enables creation of fluidic machines [5] and potential applications to the cleaning of high energy surfaces [7]. This talk will synthesize recent results on this topic and highlight unresolved questions and directions for future research.

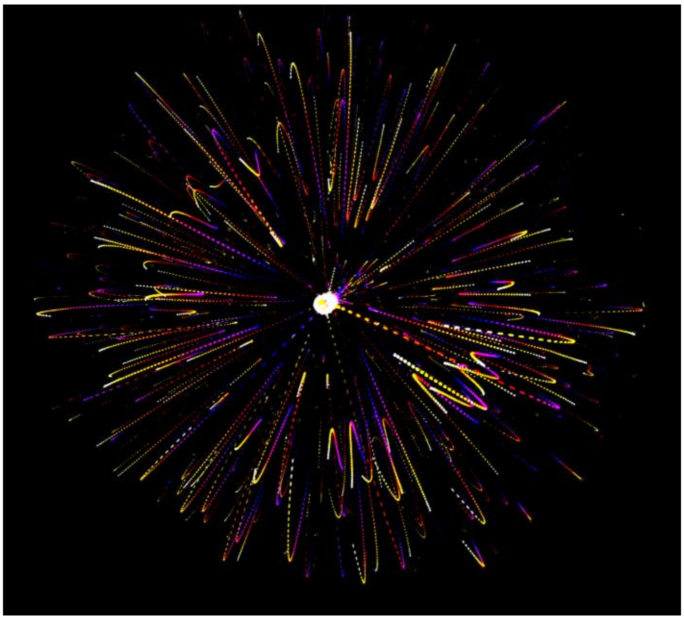

Figure 1. Typical toroidal flow pattern within a Marangoni contracted droplet, created by time lapse imaging. Droplet radius ~1 mm.

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# Thin film instability driven dimple mode of air film failure during drop impact on smooth surfaces

**Lige Zhang**[1], Tejaswi Soori[1], Arif Rokoni[1] and Ying Sun[1]

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Air film stability underneath a drop is crucial for drop contact dynamics upon impact. An unstable film leads to the drop contacting the surface and subsequent spreading or splashing. Apart from previously reported film and kink contact modes, here we present the experimental evidence for a dimple failure mode of an air film, driven by a thin film instability when a drop impacting onto an atomically smooth surface. The dimple failure occurs beyond the inertial-capillary time scale and is initiated when the dimple inverts at the drop's central axis. For the same impact Weber number, the dimple failure observed in low viscosity drops is absent at a higher viscosity, due to damping of capillary waves.

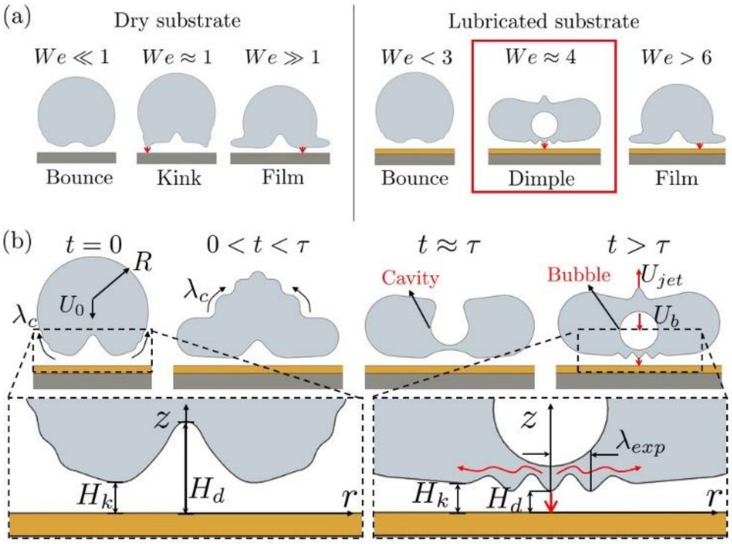

FIG. 1. (a) Schematics of contact modes for water drop impacting on dry and lubricated substrates [1–3], where the red arrows indicate the contact locations. The red-bordered panel corresponds to the dimpsle mode of the current study at $We \approx 4$. (b) Schematics of drop evolution undergoing dimple collapse at four different instances with respect to the inertial-capillary timescale, $\tau \equiv \sqrt{(\rho_l R^3/\gamma)}$. The spherical drop of radius, $R$, impacting at a velocity, $U_0$, deforms and creates an air film at $t = 0$. The maximum and minimum air film heights are at the center of the air dimple, $H_d$, and at maximum curvature kink, $H_k$, respectively, for $t \leq \tau$. Capillary wave of wavelength, $\lambda_c$, propagates along the drop surface during $t \leq \tau$. A representative wavelength, $\lambda_{exp}$, is the distance between two consecutive local minima in an air film profile at $t > \tau$, shown in (b). $z$ and $r$ are the axial and radial coordinates.

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# Production of submicron droplets via partial coalescence

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In 2009 it was shown that when a sufficiently strong electric field drives an aqueous drop towards an oil/aqueous interface, coalescence between the drop and the aqueous reservoir can be suppressed [1]. After contacting the reservoir, the drop gets repelled from the interface. In addition to that, there is a partial coalescence mode. When the salt concentration inside the aqueous phase falls below a critical value, it is possible that the daughter drop has a volume smaller than that of the original drop [2].

We utilize the principle of partial coalescence in an electric field to produce droplets with submicron diameters. We use a microfluidic chip with a silicone oil-filled main channel and two water-filled side channels, between which a DC electric field is applied. Under the influence of the electric field, a droplet reciprocates back and forth between the two interfaces. The conditions are chosen in such a way that the droplet undergoes partial coalescence at one of the oil/aqueous interfaces, c.f. Figure 1. As a result, a droplet experiences a specific volume loss in each cycle, and increasingly smaller droplets are observed with increasing number of cycles. That way, the droplet diameter can be reduced to values that are below the resolution limits of the microscope used to image the process. The smallest droplets that can still be detected in our experiments have a diameter of approximately 400 nm.

We have formulated a scaling relationship that describes the ratio between the droplet diameters before and after partial coalescence, whose predictions compare favorably with experiments. This ratio is given as a function of a dimensionless group representing the ratio between the electrostatic force and the capillary force.

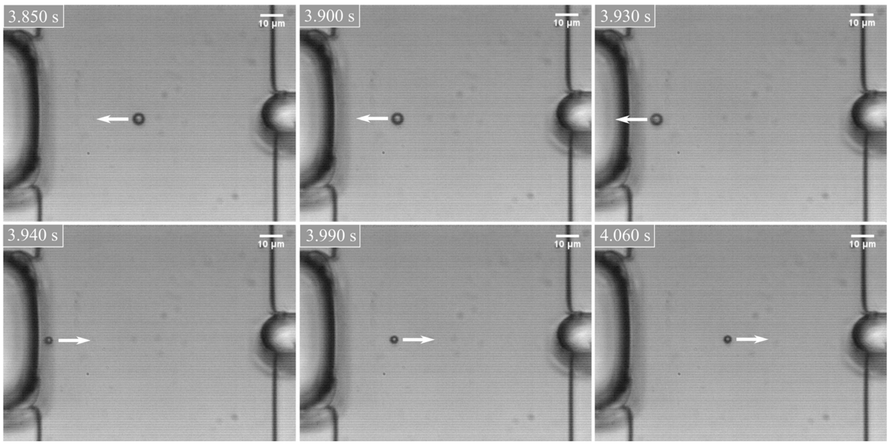

Figure 1. Partial coalescence of a droplet with ~5 µm diameter. Upon contact with the aqueous reservoir on the left, the droplet size gets significantly reduced.

[1] WD Ristenpart, JC Bird, A. Belmonte, F. Dollar, HA Stone, *Nature* **46** (2009), 377.

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# Jet break-up and drop oscillation in the presence of surfactants

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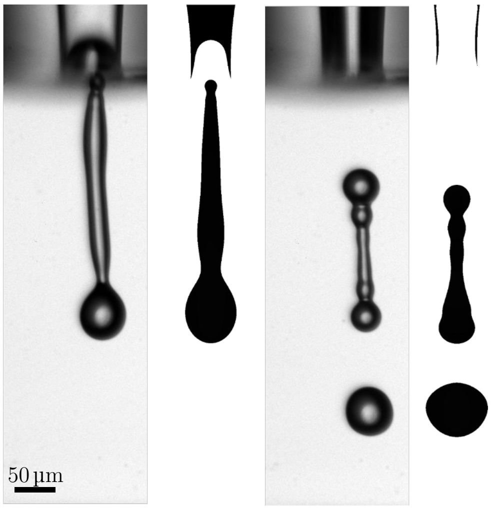
2. *School of Mathematics, University of Leeds*
3. *School of Computing, University of Leeds*

The effect of surfactants on jet break-up in drop-on-demand inkjet printing is considered. Surfactants are often added to aqueous inks in order to modify the surface tension. However, the time-scales for drop formation in inkjet printing are short compared to the time-scales of the surfactant diffusion resulting a non-uniform surfactant distribution along the interface leading to surface tension gradients and Marangoni stresses. We compare the jetting behaviour of solutions both with and without surfactants, using a combination of both experiments and numerical simulations. The numerical simulations were conducted using a modified version of the Lagrangian finite element developed by Antonopoulou et al. [1] by including the solution for the transport equation for the surfactants over the free surface. The predicted evolution of the free surface compared with high-speed video images of solutions of Triton-X 100 at 1 CMC jetted from an industrial inkjet print-head in figure 1.



(a) $t = 140$ µs (b) $t = 168$ µs

Figure 1: Comparison between simulations and experiments with water-Triton X-100 mixture

During the initial jetting phase, surfactants are transported to the head of the droplet leading to a depletion of surfactants in the trailing ligament. The lack of surfactants in the ligament means that the break-off of the ligament from the nozzle is unaffected by the presence of surfactants compared to that of a pure fluid. However, Marangoni forces delay (and in some circumstances prevent) the pinch-off off the main drop from the ligament. We also examine the effects of surfactants on the shape oscillations of the main drop. Paradoxically we find that while there is little change to the oscillation frequency, the presence of surfactants significantly increases the rate of decay due to the rigidification of the surface.

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# Title: Partial Coalescence of Liquid Metal Droplets in a Viscous Quiescent Fluid

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Partial coalescence is a phenomenon in which capillary instabilities break up a larger drople into a smaller one. This smaller, "daughter" droplet will be driven towards the interface by gravity and capillary forces causing a bouncing droplet which results in a cascade effect of progressively small daughter droplets until the Ohnesorge Number approaches ~1 and the cascade terminates with a full coalescence. Utilizing a room temperature liquid metal alloy composed of gallium, indium and tin, the high density and interfacial forces are sufficient to overcome dissipation from a viscous surrounding fluid resulting in an extended partial coalescence sequence up to 5 iterations. We observed the event using high speed videography measuring effects such as the droplet to daughter droplet ratio, droplet velocities, droplet bounce heights and coefficients of restitution for the bouncing event. Using an existing model form our group [1], which was refined to include buoyancy effects, the bounce height was measured and modelled as a validation for the velocity model. Two methods were introduced to estimate the hydrodynamic drag on the traveling droplet: the first utilizes the Stokes model for drag to moderate success while the second utilizes a model from Beard [2] and an RK4 numerical integration to predict the droplet velocity and position as functions of time. Additionally, the coefficient of restitution was determined from the model using a shooting method technique in tandem with measured data to find a coefficient of restitution value of A = 0.29 +/- 0.06. This continues in a quiescent viscous fluid to the sub-micron scale and was facilitated by the material properties of the liquid metal including the high density, moderate viscosity, and particularly high interfacial tension. Fig 1 illustrates the process from start to generation of the daughter drop.

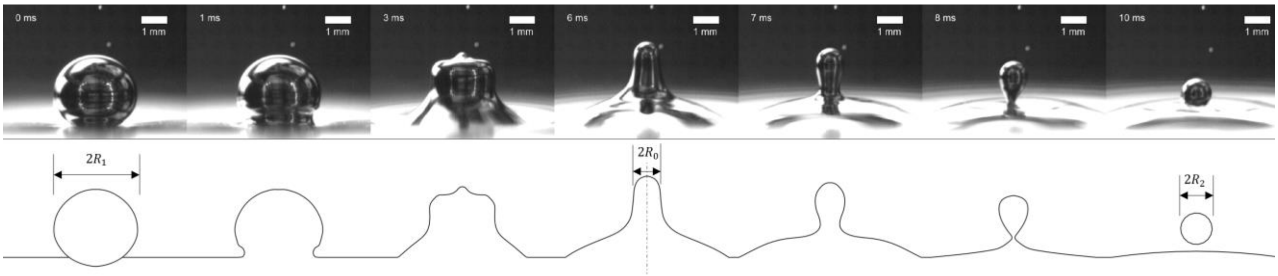

Fig 1. Partial coalescence sequence of liquid metal droplet. A capillary wave originating from the free surface results in a cylindrical shaped structure. Capillary force work to pinch off the droplet while exerting a downward force on the droplet along with gravity. These forces impart an initial downward velocity which will cause the droplet to bounce on the interface.

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# Dynamics of Fluid Transport on (Super)biphilic Surfaces: the Role of Asymmetry

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[1] *Tel-Aviv University, School of Mechanical Engineering, Ramat Aviv, 69978, Tel- Aviv, Israel*

Biphilic surfaces, with both hydrophilic and hydrophobic features, are ubiquitous in nature. Some are evolutionary designed, such as in the case of the Namib Desert beetle, in order to concentrate water droplets on specific spots on the beetle's back. In other cases, biphilicity is the result of defects or hydrophilic contaminations on hydrophobic surfaces. In both cases, the hydrophilic areas are mostly round or randomly shaped. Therefore, the role of the biphilic patches' shape, directionality, size and distribution in fluid transport and dynamics is not well established. In addition, the asymmetry of patches' design is especially important for directional transport, needed in applications such as water collection or removal from the surface. As opposed to homogenous or uniform surfaces, condensation and transport dynamics of water and other liquids on biphilic surfaces are fundamentally different. This is a result of significant confinement of droplets and strong adhesion forces due to hysteresis. In addition, the area fraction of the hydrophilic patches, and their asymmetry, govern collective effects and mutual influence of adjacent droplets.

In this work, droplet nucleation, growth, and directional transport are studied over several time and length scales on asymmetric (super)biphilic surfaces, using a custom made environmental chamber with regulated temperature (5- 50° C) and humidity (10- 85% RH). Isosceles triangular hydrophilic patches range in size between few millimetres (water capillary length), down to a few dozen microns, in a superhydrophobic matrix. Their shape varies in length of the side-to-base ratio (l/w) between 2.1 and 3.7. As a result, the Laplace pressure gradient within condensed growing droplets increases, forcing droplets to accumulate at the base of the hydrophilic triangles. Using image analysis and detailed statistics, we identify several phases starting from the early nucleation through growth and roll-off, differing by the dynamics of the water directional transport, and depending on the hydrophilic patches design. We quantify the amount of water collected on the surface, depending on the energy landscape, surface orientation and tilting angle, and compare the performance of synthetic regular surfaces to biphilic surfaces in nature, used for fog and due harvesting.

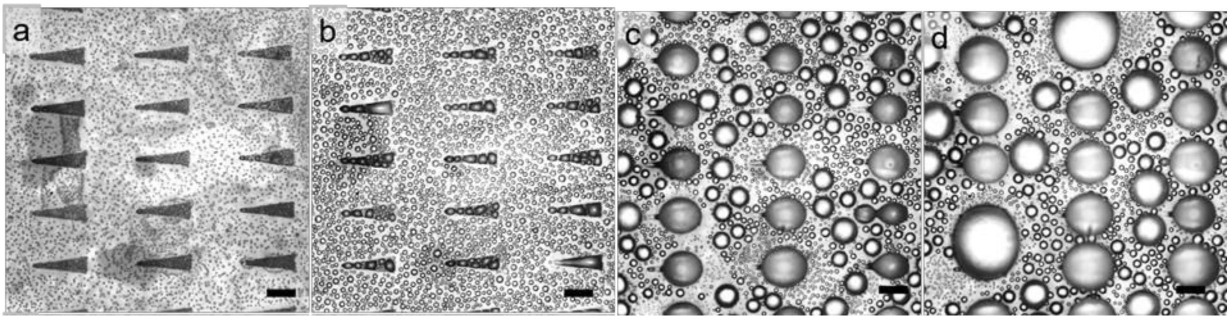

Figure 1. Condensation, growth and transport of water droplets on inclined (Super)biphilic surfaces with hydrophilic isosceles triangles.

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[2] Pinchasik et al., ACS Nano, 10, 10627–10630 (2016)

# Quantifying surface wetting properties using droplet probe AFM

**Dan Daniel**[1], Yunita Florida[1], Chee Leng Lay[1], Xue Qi Koh[1], Anqi Sng[1], and Nikodem Tomczak[1]

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Surface wettability has a huge influence on its functional properties. For example, to minimize smudging, surfaces should be able to repel oil droplets. To quantify surface wettability, the most common approach is to measure the contact angles of a liquid droplet on the surface (Fig. 1a, b). While well-established and relatively easy to perform, contact angle measurements are crude and imprecise; moreover, they cannot spatially resolve surface heterogeneities that can contribute to surface fouling. To address these shortcomings, we report on using an Atomic Force Microscopy (AFM) technique to quantitatively measure the interaction forces between a micro-droplet and a surface with piconewton force resolution (Fig. 1c-f). We show how our technique can be used to spatially map topographical and chemical heterogeneities with micron resolution.

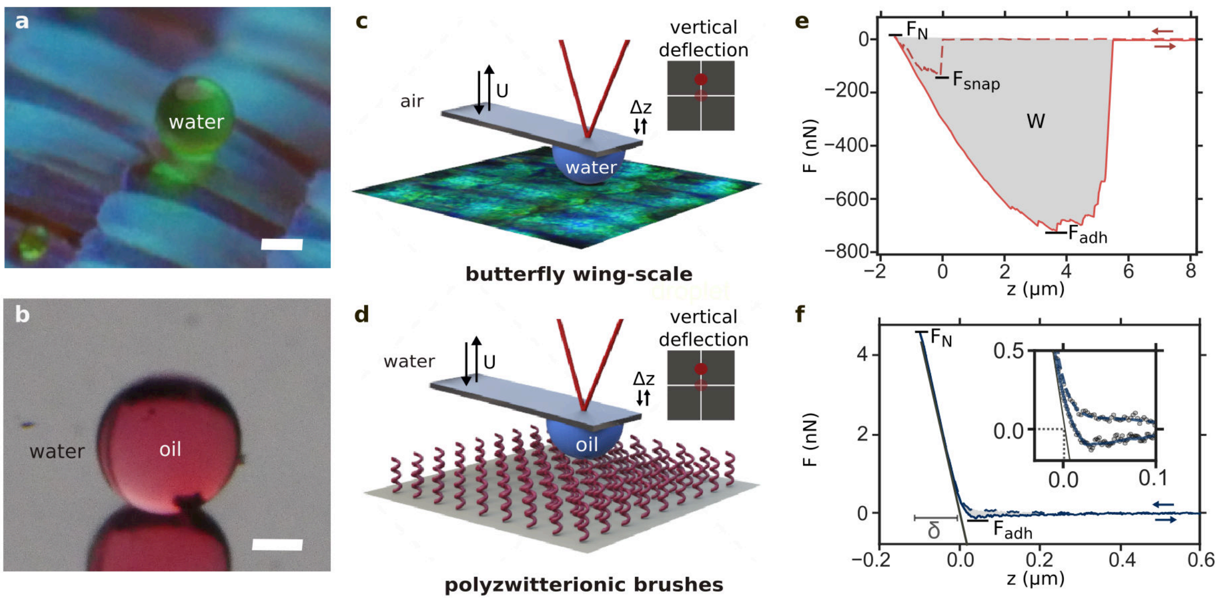

Figure 1: (a, b) Water and oil droplets remain spherical on butterfly wing-scales and zwitterionic pSBMA brush surface (under water), respectively. Scale bars are 50 $\mu$m. (c, d) Droplet probe AFM can be used to quantify the repellency of the two surfaces. (e, f) Force spectroscopy results for a 30-$\mu$m-sized water droplet and 40-$\mu$m-sized oil droplets moving at $U$=10 $\mu$m s$^{-1}$, respectively.

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[3] D Daniel, SS Goh, TN Truong, XQ Koh and N Tomczak, Adv. Mater. Interfaces **8(2)** 2021

# Visualizing and quantifying wettability alteration by silica nanofluids

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2. *Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), 2 Fusionopolis Way, Innovis, Singapore 138634*
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5. *Department of Geoscience and Petroleum, Norwegian University of Science and Technology (NTNU), S.P. Andersens veg 15a, Trondheim, Norway, 7031*

An aqueous suspension of silica nanoparticles or nanofluid can alter the wettability of surfaces, specifically by making them hydrophilic and oil-repellent under water. Wettability alteration by nanofluids have important technological applications, including for enhanced oil recovery and heat transfer processes. A common way to characterize the wettability alteration is by measuring the contact angles of an oil droplet with and without nanoparticles. While easy to perform, contact angle measurements do not fully capture the wettability changes to the surface. Here, we employed several complementary techniques, such as cryo-scanning electron microscopy, confocal fluorescence and reflection interference contrast microscopy and droplet probe atomic force Microscopy (AFM), to visualize and quantify the wettability alterations by fumed silica nanoparticles. We found that nanoparticles adsorbed onto glass surfaces to form a porous layer with hierarchical micro- and nano-structures. The porous layer is able to trap a thin water film, which reduces contact between the oil droplet and the solid substrate. As a result, even a small addition of nanoparticles (0.1 wt%) lowers the adhesion force for a 20-$\mu$m-sized oil droplet by more than 400 times from 210±10 nN to 0.5±0.3 nN as measured using droplet probe AFM.

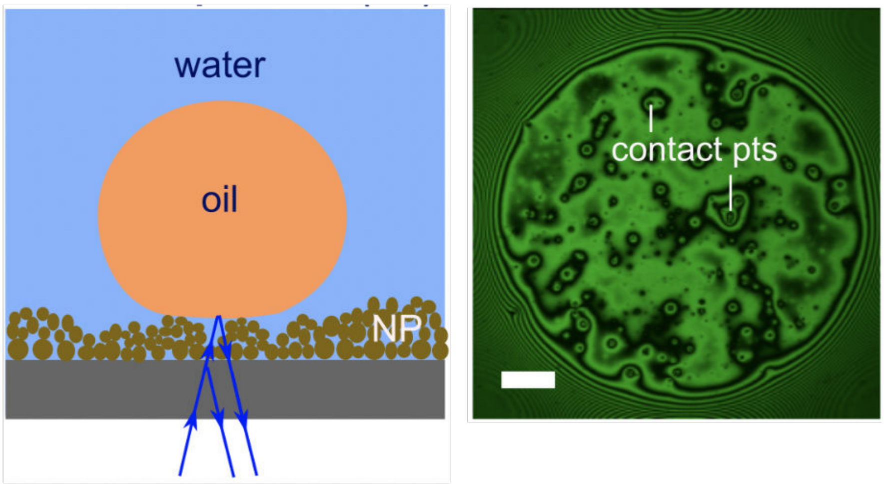

Figure 1: (a) Schematic of wettability alteration by nanoparticles (NP) resulting in underwater superoleophobicity. (b) Reflection Interference Contrast Micrograph showing thin water film stabilized by NP beneath the oil droplet.

# Nonlinear shape oscillations of inviscid liquid droplets

**S. Akbari**[1], D. Plümacher[1], D. Zrnić[2], G. Brenn[2], M. Smuda[1], F. Kummer[1], Y. Wang[1], M. Oberlack[1]

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[2] *Institute of Fluid Mechanics and Heat Transfer, Graz University of Technology, A-8010 Graz, Austria*

Nonlinear shape oscillations of inviscid liquid drops are studied analytically and numerically. Drop shapes are treated as axisymmetric, and the ambient medium as dynamically inert. The first analytical study follows the normal-mode concept with the weakly nonlinear method, expanding the flow field variables with respect to a small deformation parameter [1]. The initial drop shape is given by a Legendre polynomial, and the surface is at rest. The basis of the weakly nonlinear analysis (WNLT) is an expansion of the flow field variables and the drop surface shape with respect to a deformation parameter. Introducing the expansions into the equations of motion reveals terms of quantities with a given power of the deformation parameter, revealing equations for the various contributions of different orders to the flow field properties. The equations, which involve the influence from the solutions of the respective lower orders, are solved successively, together with the related boundary conditions. For the two-lobed initial deformation mode the results show that the trend of the drop to spend more time in the prolate than in the oblate state during one oscillation period is a second-order effect. The analytical results agree remarkably well with the classical work [2]. In contrast to the excess time, the decrease of the oscillation frequency with increasing initial deformation amplitude is found to be a third-order effect for the initially two-lobed deformation.

In a second investigation [3], a potential flow inside the droplet is assumed and the viscosity is considered only at the droplet surface induced by the jump condition of momentum. The unified transformed method by Fokas [4] is employed to transform the free boundary value problem formulated on a time-dependent domain into a nonlinear system of integro-differential equations defined on a time-independent unit sphere surface. This geometrically nonlinear theory (GNT) governs the general droplet oscillation with arbitrarily large deviations from the spherical shape. In an ongoing numerical study [5], the governing equations obtained in [3] are solved for arbitrarily large drop deformations. By means of the Galerkin method we decompose the unknowns into Legendre polynomials to obtain a series of ordinary differential equations for the time-dependent coefficients. They are solved by Newton's method for arbitrary initial droplet shapes defined by the Legendre polynomials. Fully nonlinear dynamic effects with arbitrarily large drop deformations are investigated. This includes the dependence of the oscillation frequency and the asymmetric time expenditure in the prolate and the oblate states during one oscillation period. Results from the two methods agree remarkably well.

[1] D. Zrnić and G. Bren, J. Fluid Mech. (2021) under review.
[2] Tsamopoulos, J.A. and Brown, R.A., J. Fluid Mech., 127, (1983), pp. 519-537.
[3] Pluemacher, D., Oberlack, M., Wang, Y., Smuda, M., Phys. Fluids 32, (2020).
[4] Fokas, A.S. Proc. R. Soc. London, Ser. A 453, (1997), pp. 1411-1443
[5] Akbari, S., Numerical simulation of droplet oscillation with arbitrarily large deformations, Master thesis (2021).

# Sessile volatile drop evaporation under microgravity

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The evaporation of sessile drops of various volatile and non-volatile liquids, and their internal flow patterns with or without instabilities have been the subject of many investigations. The current experiment is a preparatory one for a space experiment planned to be installed in the European Drawer Rack 2 (EDR-2) of the International Space Station (ISS), to investigate drop evaporation in weightlessness. In this work, we concentrate on preliminary experimental results for the evaporation of hydrofluoroether (HFE-7100) sessile drops in a sounding rocket that has been performed in the frame of the MASER-14 Sounding Rocket Campaign, providing the science team with the opportunity to test the module and perform the experiment in microgravity for six consecutive minutes. The focus is on the evaporation rate, experimentally observed thermo-capillary instabilities, and the depinning process. The experimental results provide evidence for the relationship between thermo-capillary instabilities and the measured critical height of the sessile drop interface. There is also evidence of the effects of microgravity and Earth conditions on the sessile drop evaporation rate, and the shape of the sessile drop interface and its influence on the de-pinning process.

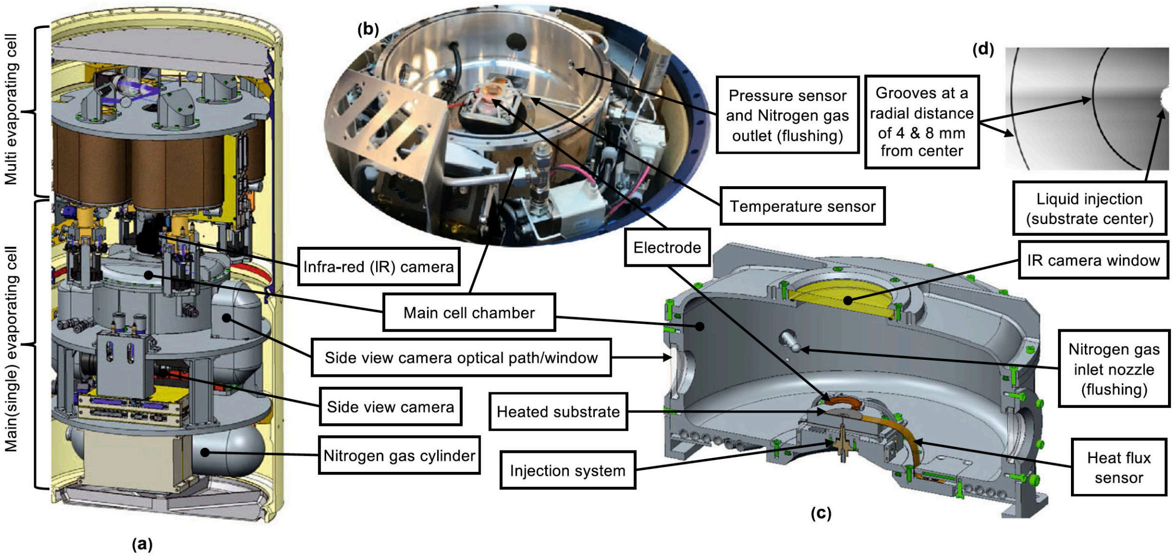

Figure 1. Overview of the ARLES experimental setup. a Experiment module on-board the MASER 14 rocket, divided into two parts: the main evaporating and multi-evaporating cells. b, c Main evaporating cell (MEC) with a detailed schematic. d Platinum layered surface crystal silicon wafer substrate (top view) with grooves. Images a, b, and c are credited to the European Space Agency (ESA) and Swedish Space Corporation (SSC).

[1] S. Kumar et al., NPJ Microgravity, **6**:37 (2020).

# Title: Leidenfrost droplet evaporation dynamics: from puddles to spherical caps

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Author list: **Suryansh Gupta**, Nagesh D. Patil

Leidenfrost effect is usually, characterized by, a liquid water droplet levitating on its self-sustaining vapor film, over a heated solid surface maintained notably above the boiling point of the liquid. We study the Leidenfrost droplet evaporation dynamics considering the droplet size effects with its diameter larger than the capillary length (in case of a puddle) and smaller than the capillary length (in case of a spherical cap). When the large-sized droplet (puddle) is deposited on a solid surface having slight concavity, a distinctive behavior is observed. In such cases, initially it is seen that there is a co-existence of both nucleate and film boiling regimes, localized at the central and peripheral regions, respectively. Due to nucleate boiling, there is a periodic generation and collapse of the bubble at the center. Consequently, it causes droplet deformation that leads to transient oscillations with interesting liquid-gas interfacial shapes (Fig. 1). But, as the droplet size reduces further due to continuous evaporation, it transits into an ellipsoidal shape with periodically alternating major and minor axes (Fig. 1b), whose oscillating frequency increases with droplet size reduction. Finally, towards the end, there is film boiling and the droplet assumes a spherical cap shape, levitating on the vapor film in a quasi-static state until, complete evaporation. Therefore, it can be inferred that there exists a complex interplay primarily between surface tension and gravity force, whose magnitudes are dependant upon the droplet size that changes over its lifetime. In the study, we utilize high-speed videography and infra-red thermography to investigate the time evolution of the droplet dynamics. Experiments have been performed to establish the critical size of the droplet that distinguishes various regimes i.e from simultaneous nucleate and film boiling initially, to only film boiling at a later stage. Also, an attempt has been made to understand the underlying physics associated with the oscillatory behavior.

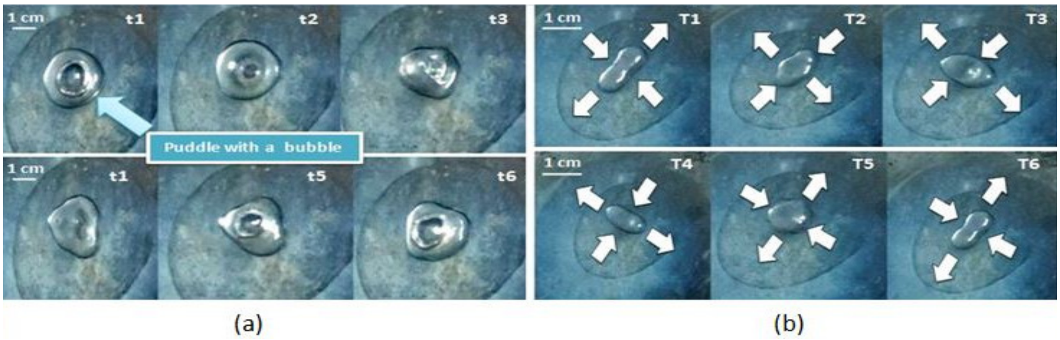

Figure 1. High-speed visualization images of an evaporating droplet characterized by, (a) the co-existence of both nucleate and film boiling (t1 to t6) (b) with transient droplet shapes evolution (T1 to T6). In part b, arrows indicate the direction of contact line motion.

1] M Zeuner, K Schwark, C Hanisch, and M Ziese, *Eur. J. Phys.* **40** (2019) 065101.

# Boundary conditions for dynamic wetting - A mathematical analysis

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The moving contact line paradox discussed in the famous paper by Huh and Scriven [1] has lead to an extensive scientific discussion about singularities in continuum mechanical models of dynamic wetting in the framework of the two-phase Navier–Stokes equations. Since the no-slip condition introduces a non-integrable and therefore unphysical singularity into the model, various models to relax the singularity have been proposed. Many of the relaxation mechanisms still retain a weak (integrable) singularity, while other approaches look for completely regular solutions with finite curvature and pressure at the moving contact line. In particular, the model introduced recently in [2] aims for regular solutions through modified boundary conditions.

The present work [3-5] applies the mathematical tool of compatibility analysis to continuum models of dynamic wetting. The basic idea is that the boundary conditions have to be compatible at the contact line to allow for regular solutions. Remarkably, the compatibility analysis allows to compute explicit expressions for the pressure and the curvature locally at the contact line for regular solutions to the model of Lukyanov and Pryer [2]. We show that the boundary conditions at the contact line are compatible for the latter model if the rate of mass transfer to the surface phases is non-zero. On the other hand, one can show that there are choices of the model parameters such that the mass transfer rate vanishes and no regular solution exists.

[1] C. Huh, L. E. Scriven, Hydrodynamic model of steady movement of a solid/liquid/fluid contact line. Journal of Colloid and Interface Science **35** (1971), 85–101, DOI:10.1016/0021-9797(71)90188-3.

[2] A. V. Lukyanov, T. Pryer, Hydrodynamics of Moving Contact Lines: Macroscopic versus Microscopic, Langmuir **33** (2017), 8582–8590, DOI:10.1021/acs.langmuir.7b02409.

[3] M. Fricke, M. Köhne, and D. Bothe. A kinematic evolution equation for the dynamic contact angle and some consequences. Physica D: Nonlinear Phenomena **394** (2019), 26–43, DOI:10.1016/j.physd.2019.01.008.

[4] M. Fricke, D. Bothe, Boundary conditions for dynamic wetting - A mathematical analysis. The European Physical Journal Special Topics **229** (2020), 1849–1865, DOI:10.1140/epjst/e2020-900249-7.

[5] M. Fricke. Mathematical modeling and Volume-of-Fluid based simulation of dynamic wetting, PhD thesis, TU Darmstadt (2021), DOI:10.12921/tuprints-00014274.

# Modelling of Bubble Growth and Diffusion in a Combusting Metal Droplet

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Numerous applications are interested in the use of combusting metal powders such as explosives, propellants, pyrotechnics, and bio-agent defeat. Optimising the performance of these reactions is of great interest to many of these fields. Particles of such powders have been observed to explode during combustion, yielding new surface areas and potentially enhancing the burn rate of the powder. It is thought that better understanding this process will help to design more optimised powders with greater benefits. Following the work of Wainwright et al. (2019), this project investigates the bubble growth within combusting metal droplets and compares the data from experimental recordings with solutions of a mathematical model. This model is developed from the Navier-Stokes equations in spherical coordinates and by applying assumptions and substituting expressions of mass continuity is simplified to coupled first order ordinary differential equations. These simplifications allow the equations to be solved using `ode45` in MATLAB to obtain a plot of the bubble radius over time. In addition, the diffusion equation was coupled with the bubble growth ODE to obtain plots of concentration in the liquid phase. Figure 1 shows the resulting plot of bubble radius with data points from a microexplosion event for different expression of nitrogen moles in the bubble.

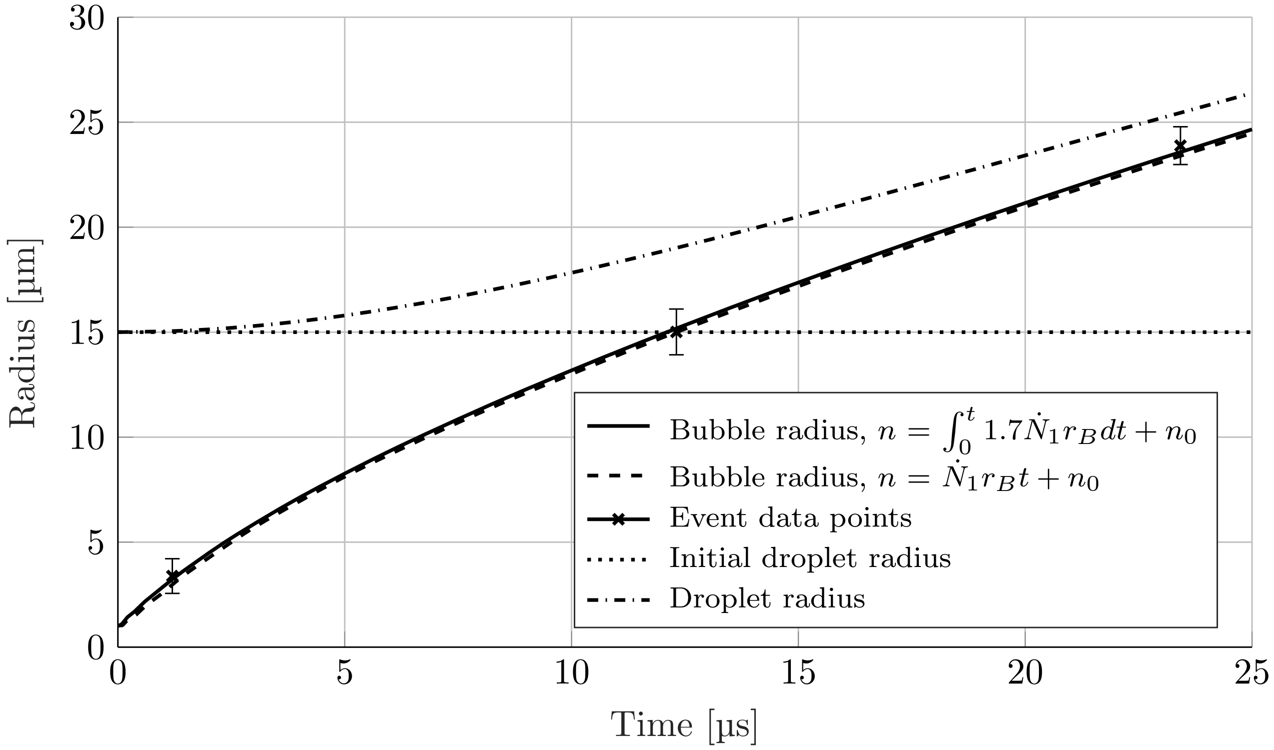

Figure 1: Plot of bubble radius over time for $\dot{N}_1 = 1.12 \times 10^{-3}$ mol m$^{-1}$ s to fit data from Event 1.

[1] Elliot R. Wainwright, Shashank V. Lakshman, Andrew F.T. Leong, Alex H. Kinsey,John D. Gibbins, Shane Q. Arlington, Tao Sun, Kamel Fezzaa, Todd C. Hufnagel,and Timothy P. Weihs. Viewing internal bubbling and microexplosions in com-busting metal particles via x-ray phase contrast imaging. *Combustion and Flame*, 199:194–203, (2019)

# Picolitre Pancakes

**Colin D. Bain**[1], Lisong Yang[1], Amir A. Pahlavan[2], Howard A. Stone[2]

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The prediction and the control of the fate of a droplet landing on a solid, for example, mitigating coffee-ring effect (CRE), are of importance in agriculture sprays, spray coating, inkjet printing and fabrication of (opto)electrical and biological devices. For a volatile liquid, after the dissipation of the inertia from the droplet impact, wetting and evaporation are strongly coupled leading to contact line (CL) expansion immediately followed by CL retraction until the droplet vanishes. This moving CL and the evaporative singularity at the CL make the local solution of heat and mass transfer difficult. The understanding of the drying dynamics of sessile droplets is therefore challenging and has attracted widespread interest in scientific community. This talk describes two types of experiment involving inkjet-scale (picolitre) droplets of binary mixtures of volatile liquids: (i) mixtures of two alcohols; (ii) pure alcohols in a humid environment.

Surface tension gives small droplets their spherical shape to minimize the interfacial energy at equilibrium. In mixtures of liquids with different surface tensions, Marangoni effects can compete with capillary flow and lead to shape changes. In a binary mixture of isopropanol (IPA) and 2-butanol, we report enhanced spreading and formation of pancake shapes over a range of compositions. A theoretical model, which couples the capillary and solutal Marangoni stresses, the evaporative flux and vapour-phase diffusion, is in quantitative agreement with experiment (Figure 1). There is a threshold concentration of the more volatile component above which the spreading switches from a spherical cap to a pancake, which can be understood in terms of dimensionless quantities governing the fluid flow. We characterise the scaling behaviour of the drying process and observe a new regime where the contact line retracts with a 1/5th scaling exponent in contrast to the ½ scaling observed for pure liquids.

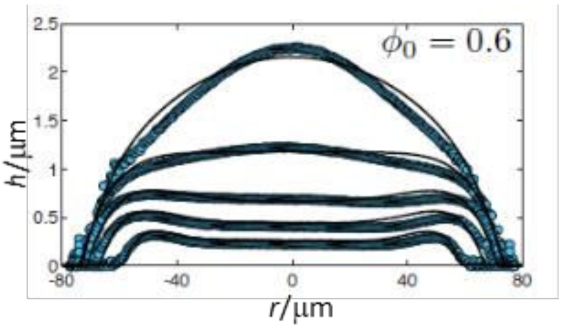

Figure 1. Droplet profile (symbols) and theoretical calculation (solid line) for evaporation of a 60 v% IPA / 40 v% 2-butanol droplet at various times.

A pure droplet of an alcohol (IPA) deposited in a moist environment evolves into a binary droplet during drying due to condensation of water. These droplets show a range of behaviour including Marangoni-enhanced spreading, pancake formation and rim instabilities.

Acknowledgement: CDB thanks the EPSRC under grant EP/N025245/1 for supporting this work.

# Evaporation Dynamics of 2D Droplet Arrays

**Fouzia. F. Ouali**, Andrew M. J. Edwards, David J. Fairhurst, Joseph Kilbride, Carl V. Brown and Pierre Le Minter

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The evaporation dynamics of interacting multiple droplets on a substrate is of great importance in a wide range of applications such as inkjet printing and spray coating. Droplet interaction can be either via vapour or substrate, with vapour-mediated interaction being believed to be dominant. Each droplet experiences an increased vapour concentration in the presence of its neighbours, which in turn, reduces its overall evaporation rate [1]. Current measurement techniques of evaporation rates of two-dimensional (2D) multiple droplet arrays are limited to top-down imaging and mass balance analysis, and therefore provide limited measurements of the contribution of individual droplets to the global dynamics of the array. In this work, we report how individual evaporation flux of each droplet within a pinned 2D array can simultaneously be determined from Mach-Zehnder interferometric measurements. We validate the principle and accuracy of the technique on isolated droplets, which shows an excellent agreement with conventional goniometric measurement methods. We then apply our technique to ordered and randomised 2D droplet arrays to enable a direct measurement of the evaporation rate of each droplet and its variation with position within the array (See Fig. 1). We compare our experimental measurements of the average evaporative flux to the recent theoretical analysis of Wray *et al.*[2] finding excellent agreement between experiments and theory. The technique can be applied to a variety of arrays including high density and polydisperse arrays.

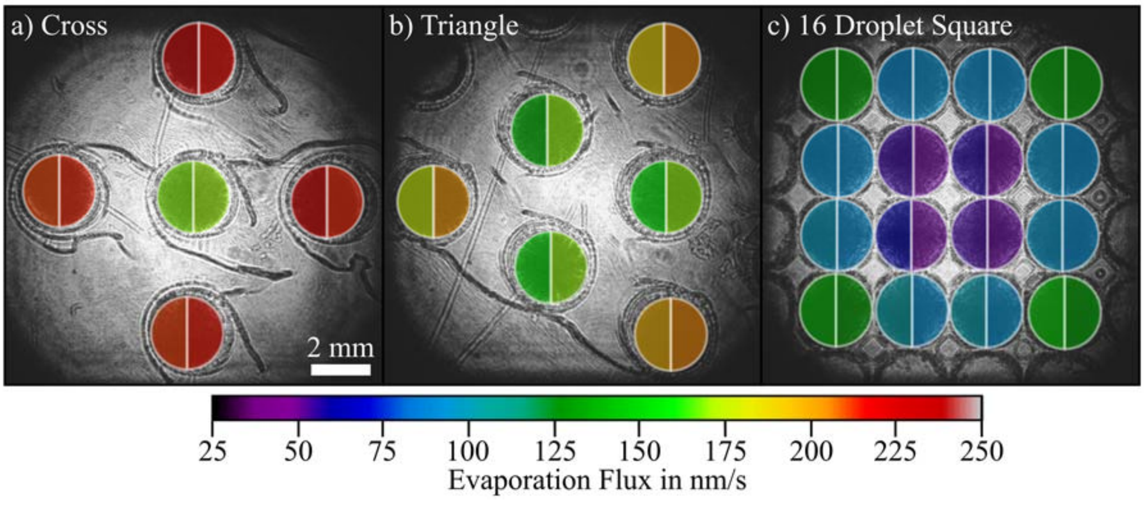

Figure 1. Three different 2D arrays of droplets, colour coded to illustrate the variation of evaporative flux with position. In each droplet, the left semicircle shows the measured time-averaged evaporation flux and the right semicircle shows the predicted average evaporation flux obtained from *Wray et al*'s theory.[2]

[1] O Carrier, N Shahidzadeh-Bonn, R Zargar, M Aytouna, M Habibi, J Eggers, D Bonn, *J. Fluid Mech.* **798** (2016) 774.
[2] AW Wray, BR Duffy, SK Wilson, *J. Fluid Mech.* **884** (2020) A45.

# Freezing of a nanofluid droplet: from pointy tip to flat plateau

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[1] *Shanghai Key Laboratory of Multiphase Flow and Heat Transfer in Power Engineering, School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, P. R. China*
[2] *Key Laboratory of Icing and Anti/De-icing, China Aerodynamics Research and Development Center, Mianyang Sichuan 621000, P. R. China*
[3] *School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore*
[4] *MOE Key Laboratory of Power Machinery and Engineering, School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai 200240, P. R. China*

Understanding the dynamics during freezing of nanofluid droplets is of importance from both fundamental and practical viewpoints. It is known that a universal pointy tip is formed on the top of a frozen water droplet due to the expansion of water upon freezing as shown in Fig.1 (a). Here we report that the formation of a pointy tip is broken down due to the presence of nanoparticles. Instead, the top of a frozen nanofluid droplet exhibits a flat plateau shape as shown in Fig.1(b), and such plateau becomes larger at higher particle concentrations. We show that the phenomenon of such shape changes in freezing nanofluid droplets is universal, independent of contact angle, droplet volume, particle size and particle material. We also propose an analytical model to attribute the plateau formation to a capillary driven compensating flow due to segregated particles moving along the freezing interface.

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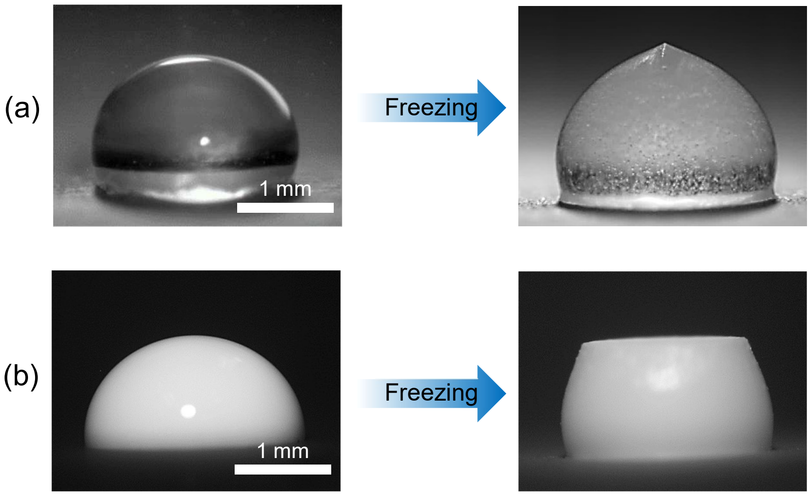

Figure 1. Shape change when freezing a deionized water droplet (a) and a nanofluid droplet (b)

# Non-Leidenfrost levitation of a droplet over liquid surface

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We consider droplets of a volatile liquid (water or alcohol) placed above a bath filled with hot liquid. We examine silicone oils of different viscosity as the lower liquid. The bath is heated from sides or below and kept at the temperature below or close to the droplet's boiling temperature. We observe the levitation of the millimetric droplets. We present a mathematical model estimating the levitation time and discuss different ways of the end of the levitation.

We perform experiments releasing droplets over the free surface of the hot liquid surface. If there is a convective flow inside the bath, the droplet of water or alcohol is likely to stay above the surface for a long time (about 1 minute for alcohol, 10 minutes for water), a thin air gap separates two liquids. The size of the droplets gradually decreases. The levitation is not possible if the lower liquid is too viscous or not heated enough to exhibit thermal convection. The droplet evaporation is also crucial; droplets of non-volatile liquids (silicone oils, glycerol) do not levitate for a long time but sink within 10-20 seconds without sufficient change of their size. Visualisations of the process by aluminium powder in the bath and by a thermocamera show that the droplet finds its location over the coolest part of the bath surface, where the convective flows along the surface converge.

Our model [1] considers convective flow inside the bath and the air. The problem for the droplet's capillary equilibrium gives the radius of the air gap between the droplet and the bath. With an estimation of the bath and air velocity due to convection, we find the thickness of the air gap. To describe the droplet's temperature and the evaporation rate, we introduce two fitting parameters that correspond to the average height of the droplet over the bath surface (about a droplet radius) and the ratio between the convective and diffusive rate of the vapour transport from the droplet surface. These parameters allow a good enough prediction of the evaporation rate; the theoretical dependence fits our data, and the data from [2], which the model used there does not describe. The model [2] applies the classical Leidenfrost levitation mechanism to an underlying liquid surface and predicts singularity if the bath temperature equals the droplet's boiling temperature.

The total duration of the levitation depends on the evaporation rate and on the way levitation ends. The droplet placed over the relatively hot surface (above 70° C for water droplets) moves along the surface and usually sinks before it becomes tiny. The typical radius is about half of the initial one and is still in the order of millimetres. If the surface is cooler (about 50° C), the droplet reaches a tiny radius (order of magnitude smaller than the initial one). In this case, the levitation of the water droplets lasts about an hour. The probability of the hour-long levitation depends on the bath liquid's viscosity: it is more probable to observe the effect with 20 cSt oil than with 5 cSt one. Meanwhile, an increase in the oil viscosity increases the number of droplets that sink immediately after release. We associate this effect with the stability of the convective patterns in the bath and the margin of the droplet levitation stability and analyse the statistics of the droplet levitation time to confirm this conclusion.

[1] E. Mogilevskiy, Phys. Fluids **32** (2020), 012114.

[2] L. Maquet et al., Phys. Rev. Fluids **1** (2016), 053902.

# Numerical analysis of shock-focusing phenomena during shock-bubble interaction

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1. *Technical University of Munich, Department of Mechanical Engineering, Chair of Aerodynamics and Fluid Mechanics, Boltzmannstraße 15, 85748 Garching, Germany*

Shock-bubble interactions are a generic configuration to study the more general case of shock-accelerated inhomogeneous flows. These are of fundamental importance for many technical applications such as supersonic combustion engines or the fragmentation of kidney stones by shock waves [1]. Depending on the fluid properties, the external flow field, and whether the gas inhomogeneity has a spherical or cylindrical shape, the macroscopic characteristics of the shock-bubble interaction vary drastically.

We analyze numerical simulation results of cylindrical- and spherical-shaped heavy gases interacting with a shock wave in ambient air. Our numerical solver [2] discretizes the compressible Navier-Stokes equations with a finite volume approach and low-dissipation, high-order WENO schemes. The interface dynamics are described by a level-set based sharp-interface model with conservative interface interaction.

In Fig. 1 the flow field and shape of the gas inhomogeneity at an intermediate stage is shown for three different gases. All three configurations show similar evolution at the upstream side of the interface and an outward-directed jet at the downstream side. The gas with the highest speed of sound initially forms an inward-directed mushroom-like jet on the focus axis. This event reduces the final outward-directed jet in length and strength compared to gases with lower speed of sound (middle and right). We observe a non-monotonic relation between jet size and the bubble-ambient impedance ratio, predominantly caused by shock-focusing phenomena. Furthermore, baroclinic processes generate instabilities and vortices at the bubble surface.

Cylindrical and spherical arrangements show significant differences in jet formation and peak values. Peak values of pressure and density are a magnitude lower for cylindrical setups and jet formation is drastically reduced or even suppressed.

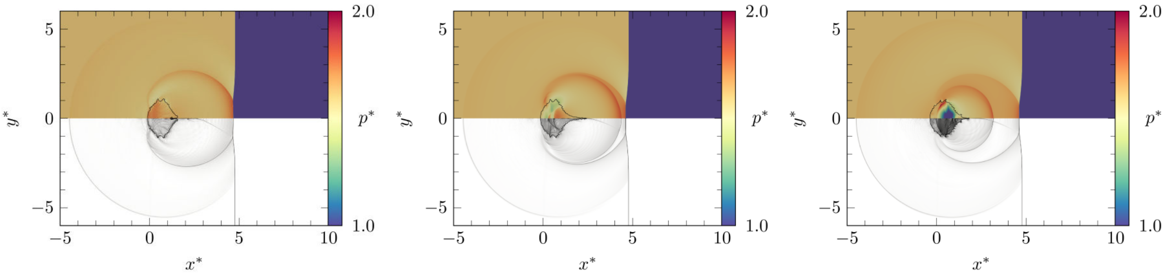

Figure 1: The intermediate-stage flow field of an axisymmetric simulation of the interaction of a shock wave with Kr (left), $R_{22}$ (middle), and $SF_6$ (right) bubble. The upper half of the images show the non-dimensional pressure field, and the lower half numerical schlieren.

[1] Ranjan, D., Oakley, J., & Bonazza, R. (2011). Shock-bubble interactions. Annual Review of Fluid Mechanics, 43, 117-140.

[2] Hoppe, N., Adami, S., & Adams, N. A. (2020). A modular massively parallel computing environment for three-dimensional multiresolution simulations of compressible flows. arXiv preprint arXiv:2012.04385.

# Micro-Droplet Trampolining on Smooth Substrate at Reduced Pressure

**Gaoyuan Wang**[1], Ruina Xu[1], and Peixue Jiang[1,*]

[1] *Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Beijing Key Laboratory for CO2 Utilization and Reduction Technology, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China*

Spontaneous trampolining of liquid droplets either on heated smooth substrate at atmospheric pressure[1] or on micro-structured substrate during reducing pressure process[2] have been discovered and investigated in recent years. The size of droplet is a key factor for droplet trampolining. Compared to millimetre-sized droplets, micro-scale droplets are much realistic in industry applications such as spray cooling and their intrinsic behaviours are different from millimetre droplets, i.e. more violent evaporation and surface tension dominance. Here we found that by downsizing the droplets to micro-scale, a significant droplet trampolining and self-propelling mode could appear on heated smooth surface at reduced pressure. The strengthened droplet trampolining was resulted from the over pressure beneath the micro droplets and the relatively large surface-to-mass ratio of micro-droplets. The mechanism of this phenomenon was analysed theoretically. A phase diagram of micro-droplets impingement on heated substrate at reduced pressures and the trend of velocity ratio of rebounding in the rebound regime are presented for better understanding of this phenomenon.

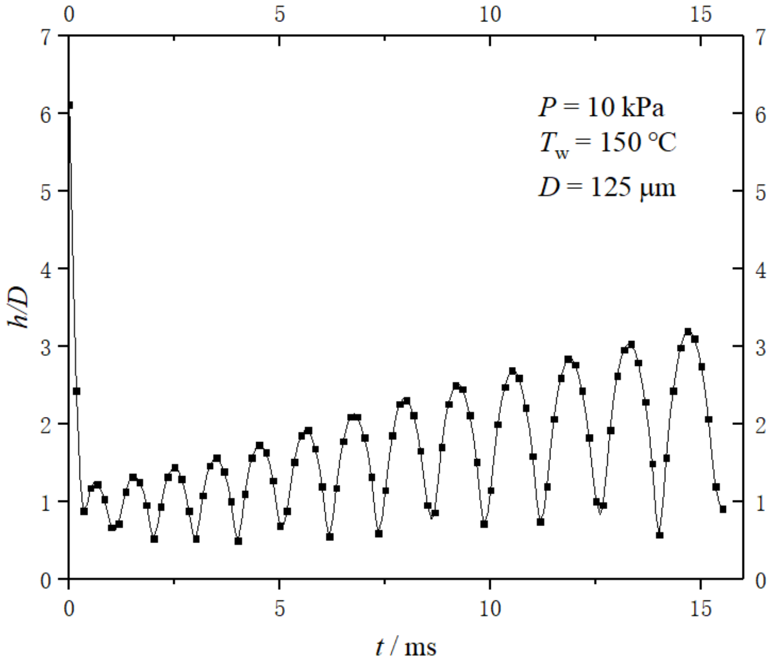

Figure 1. Variation of droplet $h/D$ during spontaneous trampolining where $h$ is droplet height, $D$ is droplet diameter. Chamber pressure is 10 kPa, substrate temperature is 150 °C, droplet diameter is 125 μm.

[1] G Graeber, et al, *Nat. Commun.*. **12** (2021), 1727.
[2] T M Schutzius, et al, *Nature.* **527** (2015), 82-85.

# Walking, Climbing, and Shooting: Complex Dynamics in Drops on Vibrated Substrates

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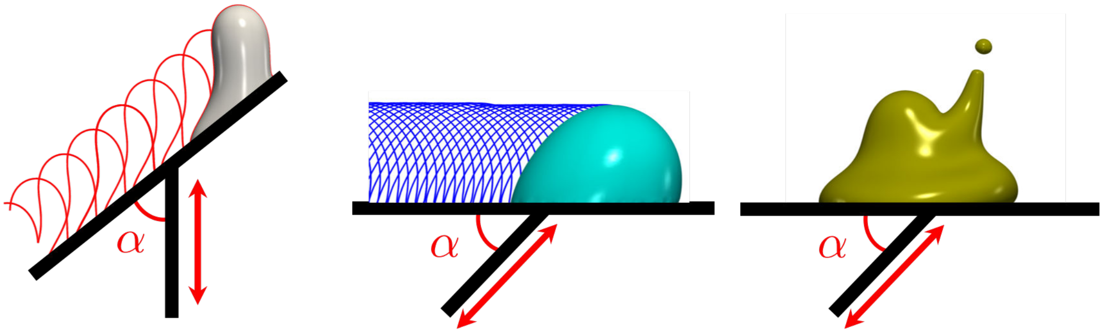
[2] *Department of Mechanical and System Design Engineering, Hongik University, Seoul 04066, Republic of Korea*

[3] *Université Paris Saclay, Centre National de la Recherche Scientifique (CNRS), Laboratoire Interdisciplinaire des Sciences du Numérique (LISN), 91400 Orsay, France*

We use direct numerical simulations (DNS) to study the phenomena observed in the work of Brunet et al., Phys. Rev. Lett., Vol. 99, 144501, (2007). Here a drop can climb up an inclined surface when it is subjected to a vertical oscillation in the presence of a gravity. In this talk, we present a detailed study of these climbing phenomena using DNS with a generalized Navier boundary condition in the context of a front-tracking-based multiphase method. Further detailed numerical simulations in the context of vibrated droplet are extended to different vibration configurations (horizontal, vertical, and oblique) in order to explain how these climbing phenomena occur leading to regimes characterised by droplet `walking', `bursting', and `shooting'.



(a) (b) (c)

Figure 1. Different configurations of droplet vibration on substrate leading to (a) walking, (b) climbing, and (c) shooting phenomena.

[1] P. Brunet, J. Eggers, and R. D. Deegan, Vibration-Induced Climbing of Drops. Phys. Rev. Lett., Vol. 99, 144501, (2007)

# Impinging spray on superhydrophobic meshes

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Impinging liquids on leaky substrates – such as mesh substrates – would result in the formation of many small droplets from the ligament fragmentation [1, 2].Though this strategy has been widely used for spray production, the underlying mechanics is not well understood and the spray characteristics need more characterizations. Here, we report an investigation on the spray formation in impinging water droplets on superhydrophobic meshes (Fig. 1a). In general, we identified two types of liquid sprays, which occur at different stages of droplet impact. The first type takes place in the recoiling stage as a result of the development, propagation and oscillation of a capillary wave, which leads to the formation and subsequent collapse of an air cavity (Fig. 1b). The onset of the spray is determined by the competetion between the collapse-induced dynamic pressure and the capillary pressure. The size of the mesh area below which liquid spray forms is almost identical to the size of the upward jet accompanying with the cavity collapse. The other type of spray is triggered by the hydrodynamic pressure of the impinging droplet in the spreading stage (Fig. 1c & 1d), and thus it happens at much higher impact velocity (Fig. 1e). The size of the spray area was found to increase with the Weber number according to a power law of $\sim We^{1/2}$ first, and then reach a maximum value and keep nearly constant. Simple scaling arguements were performed to explain these findings. Moreover, we also analyzed the size distrution of the impinging spray on superhydrophobic meshes, and relevant mechanism has been recovered.

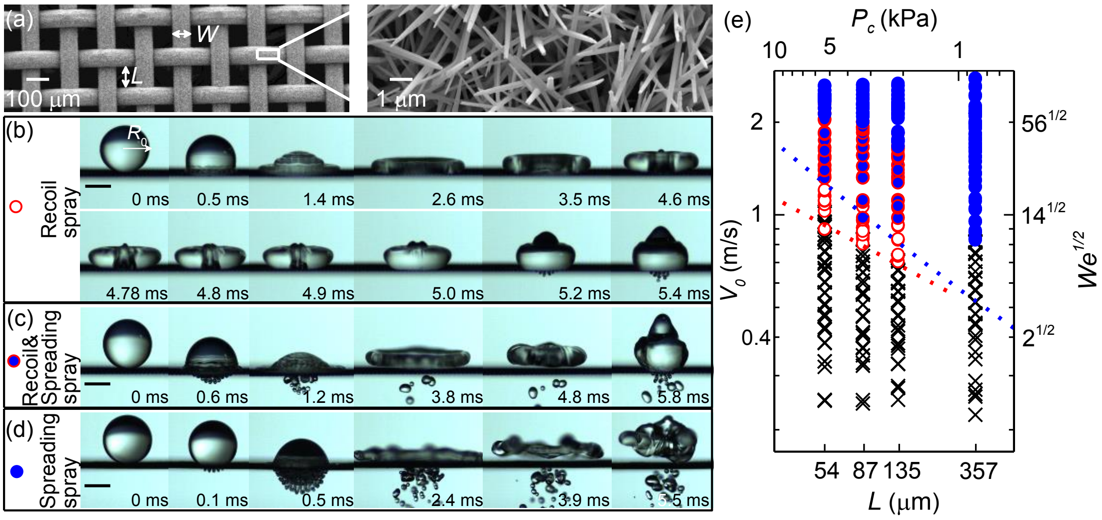

Figure 1. (a) SEM images of a superhydrophobic mesh with pore length $L = 87\ \mu m$. (b-d) Sequential images of impinging sprays on the superhydrophobic mesh with $L = 87\ \mu m$. The scale bar is always 1.0 mm. (e) Spray formation diagram as a function of the impact velocity, the Weber number and the mesh pore length.

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# Experimental and numerical investigation of the inner and outer flow structure of an adhering droplet in shear flow

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The removal of droplets on surfaces by an (air-) flow is relevant, e.g. for cleaning processes or to prevent corrosion or damage of electronical devices. Although, several investigations have been performed to find (empirical) laws for the critical velocity [1, 2], still the condition for droplet movement is not fully understood. This combined numerical and experimental study provides new insight into the flow phenomenon of adhering droplets in shear flow. The rotational flow structure inside the droplet as well as the flow reversal for higher Reynolds numbers observed by PIV measurements [3] are confirmed by CFD calculations. Concerning the outer flow, separation takes place at the droplet contour and backflow zone in the wake of the droplet is detected. Again, CFD confirms experimental results in this case performed by laser-doppler profile sensor [4]. The location of flow separation and size of the corresponding recirculation region strongly depends on Reynolds number and is correlated to the inner flow structure. Therefore, the flow structures differ from those of rigid hemispherical structures. Additionally, the oscillation of the droplet interferes with the surrounding flow. The Strouhal numbers (St = 0.03) are in the range of typical values of an aeroelastic self-excitation ("galloping"). Hence, it may be assumed that this phenomenon may also affects the force balance of adhering droplets in shear flow.

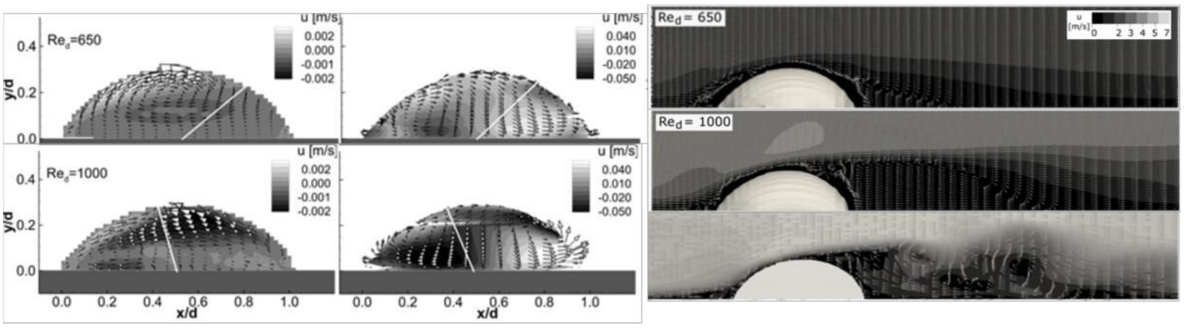

Figure 1, flow structures of an oscillating adhering 20 µl-droplet in shear flow; left: inner flow structure as found by PIV and CFD; right: average and instantaneous velocity distribution of the outer flow (CFD result)

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# A parallelized initialization algorithm for triangulated surfaces immersed in arbitrary unstructured meshes for VOF and level-set methods

**Dirk Gründing**[1], Tobias Tolle[1], Dieter Bothe,[1] and Tomislav Marić[1]

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When simulating multiphase flows, initial conditions for the spatial distribution of the various phase volumes are required. For example, when a liquid is in contact with a possibly inhomogeneously coated surface, even the stationary interface can form highly complex shapes. While experimental measurements such as 3D-scans or numerical descriptions such as surface meshes typically provide triangulated surfaces, this data has to be transformed to be used in phase-indicator-based simulation approaches as illustrated, see Figure 1 left. We present a novel algorithm that provides phase indicators and level set fields from triangulated surfaces for arbitrarily unstructured background meshes. Specifically, this approach can be used to provide initial data for all methods that are based on representing the phases with phase-indicator functions such as level-set methods, volume of fluid methods such as Basilisk, interFoam, FS3D (see Figure 1), and phase-field methods.

The method geometrically computes signed distances near the triangulated fluid interface, while the inside/outside information is propagated throughout the solution domain by an approximate solution of a Laplace equation. Volume fractions are computed with second-order convergence using signed distances, either via geometrical intersections or by a polynomial approximation. Adaptive tetrahedral decomposition of polyhedral cells and its subsequent local refinement ensures a high level of absolute accuracy [1]. Experimental comparisons demonstrate, that accurate initial conditions are essential to correctly predict the behavior of the liquid-gas system, see the experimental comparison in Figure 1.

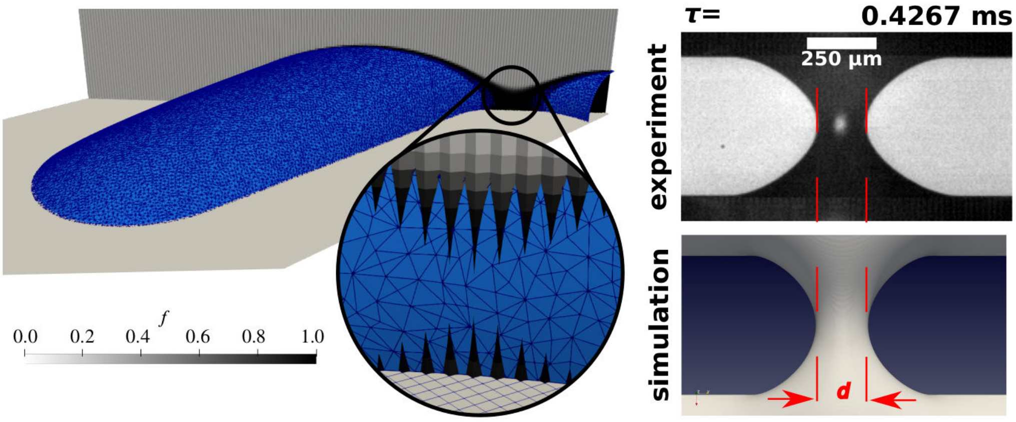

Figure 1: Left: intersection of a triangulated surface with a background mesh and resulting distribution of the phase indicator $f$. Right: Comparison between simulation of an evaporation driven drop-breakup on a surface and experiments [2].

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# Optimal Control of Droplets with Contact Angles

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In many droplet-based microfluidic processes and applications, the precise shape and position of droplets or other curved interfaces over time play a significant role for the performance of the device. Examples include optical applications where curved interfaces act as flexible lenses with continuous refraction power ranges and devices where the shape of the dropet influences the heat and mass that is exchanged with the solid surface and the surrounding fluid phase. However, these applications rarely involve model-based optimization strategies to calculate designs, trajectories or even actively adjust the position and shape of drops in a mathematically optimal way.

In this talk, we discuss and demonstrate the (openloop) optimal control of both the shape and position of a droplet which slides along an inclined surface. As a tribute to the influential paper by Chaudhury & Whitesides [1] we illustrate our results by letting a water droplet run uphill in an optimal way (Fig. 1). The contact angle between the solid surface, the surrounding gas, and the liquid drop serves as the control variable. By using several control patches the contact angles are allowed to vary discretely in space and time. The dynamics of the drop are described by the complex and accurate Cahn−Hilliard−Navier−Stokes equations. Furthermore, we briefly discuss our results on the existence of solutions and state first order optimality conditions to the optimal control problem.

This talk is based on our recently published papers [2,3]. We anticipate our demonstration to be the starting point for more sophisticated optimal design and control concepts involving curved interfaces and drops.

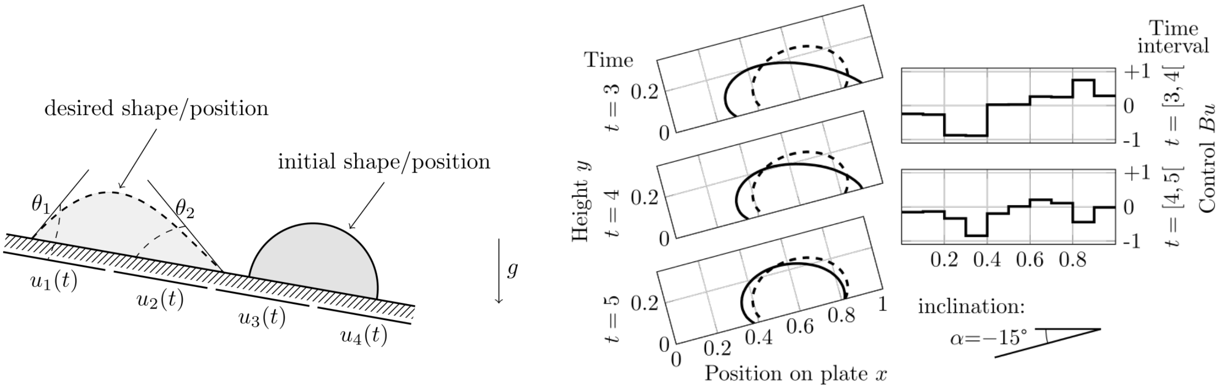

Figure 1: Setting of the control problem (left) and an extract of the resulting sequence of the drop (right) and the optimal contact angles (far right). Copyright by SIAM.

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# A high-order numerical method for wetting, dewetting and heat transfer

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The motivation for our work is an experiment, where a superheated wall is dragged out of a liquid reservoir. This setup is a central experiment in the Collaborative Research Center 1194 at TU Darmstadt. For small ratios of dewetting velocity to wall superheat, evaporation occurs mainly in the vicinity of the three-phase contact line (Fig. 1, left). If the dewetting velocity is raised the so called microlayer evaporation can be observed experimentally[1]. This is characterized by the formation of an eponymous microlayer of liquid at the moving, superheated wall in which evaporation occurs (Fig. 1, right). In our talk we present a high order numerical method for the simulation of such wetting/dewetting phenomena, subject to mass transfer at the liquid-vapor interface.

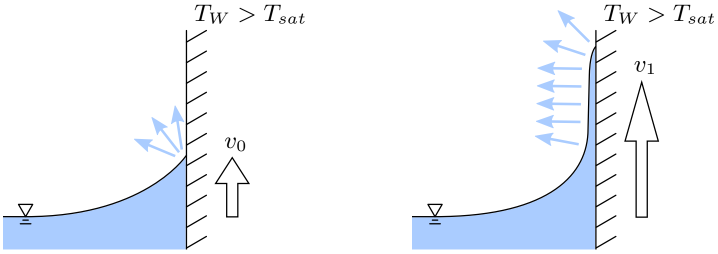

Figure 1: A superheated wall (wall temperature $T_W$ greater than saturation temperature $T_{sat}$) is dragged out of a liquid reservoir. The upper part is filled with the vapor of the liquid. Depending on wall speed ($v_1 > v_0$) and superheat evaporation (blue arrows) occurs in a contact line region (left) or a microlayer (right).

We are going to present a high order eXtended Discontinuous Galerkin (XDG) method for solving the two-phase Navier-Stokes equations coupled to the heat equation. The usage of XDG, also known as cut-cell or unfitted DG, allows, together with a level set based interface capturing technique, for a sharp representation of the liquid-vapor interface. One key advantage of our method is the ability to directly capture jumps/kinks in the solution at the interface. Furthermore we are able to obtain a subgrid accurate representation of the interface. On the boundaries intersecting the interface we employ a Generalized Navier Boundary (GNB) condition, to model the motion of the three-phase contact line[2].

In our talk we will present the aforementioned method, as well as our results for the problem presented in Figure 1. By comparing our numerical to the experimental results, we will discuss the validity and limitations of our method.

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# Fine detection of contaminants by measuring the tip angle of frozen water drops

**François Boulogne**[1], Anniina Salonen[1]

1. *Université Paris-Saclay, CNRS, Laboratoire de Physique des Solides, 91405, Orsay, France.*

The freezing of water drops is known to form a singular tip, an observation that recently gained an important interest in the community [1]. Marìn *et al.* measured systematically the tip angle for various freezing temperatures and drop aspect ratios, and they concluded that the angle of the tip is universal against these parameters [2].

In this presentation, we will show the effect of the presence of solutes at low concentrations on the final frozen drop morphologies [3]. As a comprehensive study on the variety of water solute would have been unrealistic, we choose an example of salt, polymer and surfactant, respectively. Our measurements reveal that traces of these solutes lead to a measurable variation of the tip angle. In particular, we show that the tip angle is more sensitive than conductivity or surface tension measurements. In addition, we will present recent results with silica suspensions. These allow us to probe the physical mechanism of the phenomenon, as the particle interactions can be finely tuned.

Measurements on tap water give a tip angle nearly 3° larger on average compared to pure water. Although the tip angle cannot directly reveal the nature of solutes, we believe that these findings can be used for a quick quality assessment of water purity with an optical device, which could be fully automatized. As the tip angles have a certain distribution, a quality assessment protocol would require to perform a statistical analysis of the sample. These results also indicate the significance of the water purity in freezing studies such as noticed on icicles with salt [4].

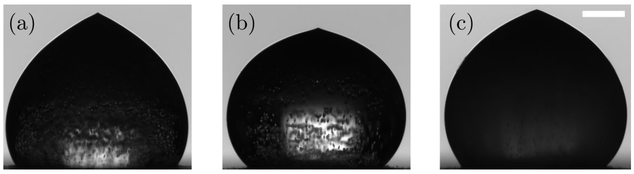

Figure 1: Images of frozen drops of surfactant solutions (TTAB) at (a) 1.0×10−4CMC, (b) 1.0×10−2CMC, and (c) 1.0 CMC. The tip angle varies non-monotonically with the concentration from 120° to 150°. These pictures also indicate a change of the ice transparency with concentration.

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# Evolution of and deposition from an evaporating annular droplet

**L. M. Mills**[1], H.-M. D'Ambrosio[1], S. K. Wilson[1], B. R. Duffy[1], A. W. Wray[1], and K. Sefiane[2]

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For obvious reasons, the vast majority of previous work on evaporating sessile droplets has focussed on the case of an axisymmetric droplet with a circular contact line. However, not only is the evaporation of an annular droplet of intrinsic scientific interest in its own right, but it also arises in a number of practical and industrial contexts, such as the evaporation of a droplet in a well (see, for example, D'Ambrosio *et al.*[1]). More generally, the evaporation of, and deposits from, droplets with non-circular contact lines, such as those studied by Saenz *et al.*[2], and multiple droplets, such as those studied by Wray *et al.*[3], have been the subject of considerable recent interest.

In the present work we formulate and analyse a mathematical model for the diffusion-limited evaporation of a sessile annular droplet. Exact, approximate, asymptotic and numerical solutions of the problem for the concentration of vapour in the atmosphere are described, and used to determine the local, and hence the global, evaporative flux from the droplet (shown in Fig. 1(a) and (b), respectively). The evolution (see, for example, Fig. 1(c)), and hence the lifetime, of annular droplets in various modes of evaporation, as well as the nature of the deposit left behind on the substrate after a droplet with pinned contact lines containing suspended particles has entirely evaporated, are all described and analysed.

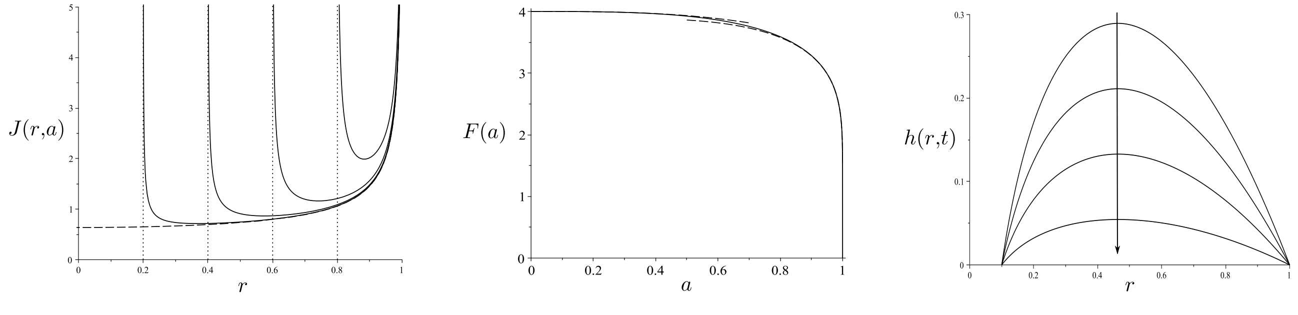

Figure 1: Plots of (a) the scaled local evaporative flux $J(r, a)$ from an annular droplet as a function of radial coordinate $r$ for various values of the scaled inner radius $a$, (b) the scaled global flux $F(a)$ from the droplet as a function of the scaled inner radius $a$, together with the asymptotic solutions for $F$ in the limits $a \to 0^+$ and $a \to 1^-$ (shown with dashed lines), and (c) snapshots of the scaled free surface $z = h(r, t)$ of a droplet with pinned contact lines at equally spaced times, where the arrow indicates the direction of increasing $t$.

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# MRI and localised spectroscopy of sessile droplets

**Jonas Kind**[1] and Christina Thiele[1]

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The evaporation of small sessile droplets plays a major role, e.g. in the formation of coffee stains[1] or in offset printing[2]. In most cases, it is not the evaporation of a pure substance that is of interest for such processes, but rather that of complex fluids such as mixtures or suspensions. In addition, the complexity of the surface also plays a corresponding role in the wetting and evaporation of the liquid droplets. In order to understand the complex interplay of fluid composition, surface properties and mass and energy fluxes, a variety of experimental methods and modelling approaches are currently being tested. An important building block for a comprehensive understanding of the interactions is, for example, the measurement of time- and location-dependent concentration profiles in evaporating droplets of complex fluids. Nuclear magnetic resonance offers the possibility to measure compositions of liquid mixtures without calibration. As shown in previous investigations, NMR can be used to image small liquid droplets and analyse the composition of sessile droplets.[3,4,5] Using localized spectroscopy, the composition can be investigated in a location- and time-dependent manner. Here, we present results on various liquid/liquid mixtures on hydrophobic surfaces. We use Point RRESolved Spectroscopy (PRESS)[6] to examine the local composition of sessile droplets composed of 1-butanol/1-hexanol or water/dimethylsulfoxide (DMSO) on hydrophobic Perfluorodecyltrichlorosilane (PFDTS) surfaces during evaporation. From these experiments the composition of the droplets can be monitored over the evaporation time (Figure 1).

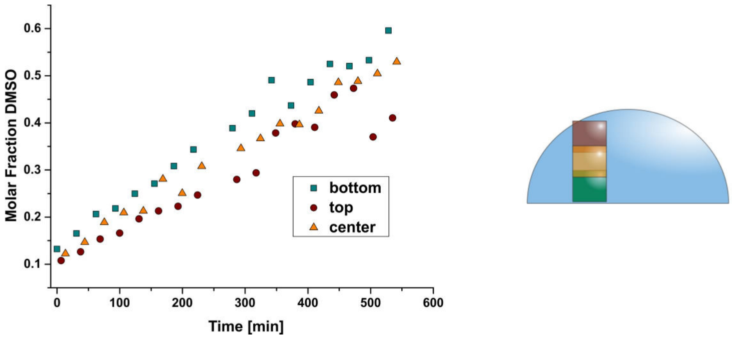

Figure 1. (left) Molar ratio of DMSO in a sessile droplet on a PFDTS surface vs. evaporation time for three different positions within the droplet. Molar ratios are calculated from relative signal integral of water and DMSO. (right) sketch of voxelpositions within the droplet.

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# Evaporation of colloidal drops on inclined surfaces

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Drop evaporation is ubiquitous phenomenon in everyday lives. Most research focused on drops evaporating on horizontal surfaces in spite the numerous encounters in our daily lives with drops on inclined surfaces (e.g. windshield of cars, photovoltaic arrays). Only few studies have focused on the relationship between inclination angle and evaporation rate with contradicting findings [1,2].

Here, we show how inclination affects the evaporation kinetics of colloidal drops as can be evidenced in Fig. 1. Inclination leads to the elongation of the shape (Fig. 1a), and the appearance of an initial spreading period dependent on the degree of inclination due to the action of gravity, along with extended drop lifetimes due to larger part of the drop evaporating at a higher angle (Fig. 1c,d). In turn, this leads to the unexpected, elongated deposit patterns with more particles accumulated at the receding side of the drop and less to the advancing front (Fig. 1b).

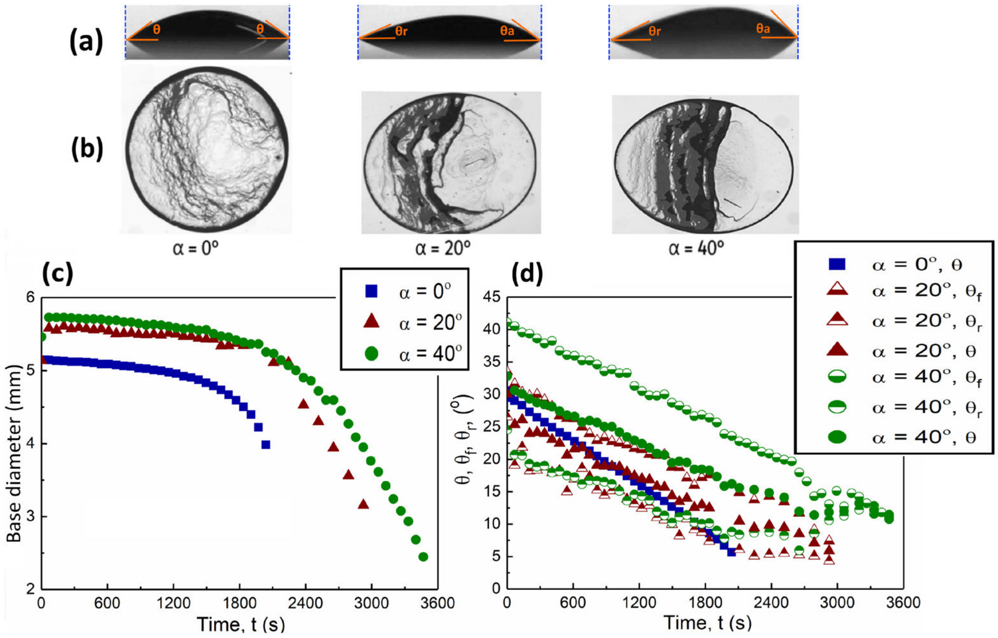

Figure 1. (a) Snapshot of a colloidal drop evaporating at 0°, 20° and 40° inclination with mean contact angle, θ, receding contact angle, $\theta_r$, and advancing contact angle, $\theta_a$. (b) Corresponding deposit patterns. Temporal evolution of (c) base diameter and (d) contact angles.

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# Title: Water-Based Electric Nanogenerator for Environmental Mechanical Energy Harvesting

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When water (including a water droplet) contacts a specific solid surface, it will either generate static surface tribo-charge or lead to electrostatic induction. In some circumstances, these both occur. By properly using the water/solid contact electrification or/and the interaction between water and a (pre-charged) hydrophobic surface, the mechanical energy contained in the movements of water (including a water droplet) can be converted into electricity. Water-based electric nanogenerator was invented based on this idea. In this presentation, I will present two kinds of recently developed water-based electric nanogenerators: the water droplet-based electric nanogenerator [1-3] and the water-tube-based triboelectric nanogenerator [4]. The water droplet-based electric nanogenerator is designed for droplet energy harvesting[1-3, 5]. The water-tube-based electric nanogenerator that encapsulates water into a small tube is designed for harvesting various environmental mechanical energies, including ocean waves and body movements [4]. I will discuss both the working mechanisms[1, 4] and the related applications[4, 5] of these two kinds of water-based electric nanogenerators.

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# Robust droplet-based generator with stable and high surface charge density under various harsh environments using a slippery surface

**Song Yuxin**[1], Xu Wanghuai[1], Liu Yuan[2] and Wang Zuankai[1]

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Recently, a myriad of energy harvesting devices has been designed in response to the impending energy crisis originating from the increasing electricity demand of mankind in powering a wide range of advanced applications ranging from implantable medical micro-device[1] to large-scale real-time environmental monitoring[2]. Particularly, the invention of droplet-based generator (DEG) that efficiently converts ambient kinetic energy of water droplets to electricity has invoked a paradigm-shift in the field of water energy harvest[3-5]. However, such devices have are limited to the rapidly deterioration of electrical performance due to the fast degradation of the physiochemical properties of interfacial materials under harsh environments[6]. In this regard, here we report the design of a slippery lubricant-impregnated porous surface (SLIPS) based DEG, referred to as SLIPS-DEG, exhibits the stable and high electrical performance in a wide spectrum of harsh working conditions including low temperature, high humidity, seawater, and even caustic acid-base, respectively. Specifically, SLIPS-DEG owes its surface charge stability to an immaculate lubricant layer that allows for almost complete prevention from the ubiquitous ion absorption effect in different harsh environments. We envision that SLIPS-DEG would inform a breakthrough to the practical application of water energy harvest technology.

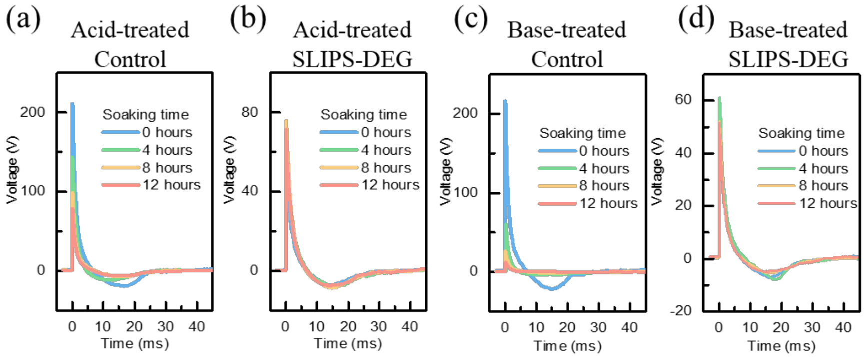

Figure 1. Electrical performance of SLIPS-DEG before and after acid or base soaking. (a and b) Time evolution of test samples' output voltage e in 12 hours' acid soaking. (c and b) Time evolution of test samples' output voltage in 12 hours' base soaking.

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# Spray deposition and the dynamic surface tension of drops at millisecond time scales

Hanne Hoffman[1,*], **Rick Sijs**[1,*], Thijs de Goede[1], and Daniel Bonn[1]

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* *Both authors contributed equally to this paper*

Droplets of complex fluids impacting on a surface are key to a wide range of applications such as spray deposition and inkjet printing. Yet, a full understanding of how they spread and retract is still lacking. One of the main complications is that surfactants are often added to improve spreading and coverage of aqueous solutions, resulting in variations of the surface tension at time scales beyond the reach of conventional dynamic surface tension measurement methods. Here we study the impact dynamics of aqueous surfactant solutions on hydrophobic surfaces at millisecond time scales. We found that the spreading and retraction of droplets cannot be adequately described by parameters associated with longer time scales. We infer the dynamic surface tension in the first milliseconds after impact from the spreading dynamics of droplets. 'Slow' surfactants that take a lot of time to reach newly created droplet surface, only slightly decrease or even increase the surface tension. 'Fast' surfactants, on the other hand, allow efficient wetting of aqueous solutions on hydrophobic surfaces. Our findings provide access to the parameter space that is most relevant to the process of droplet impact, and hence determines the overall success of drop deposition by spraying.

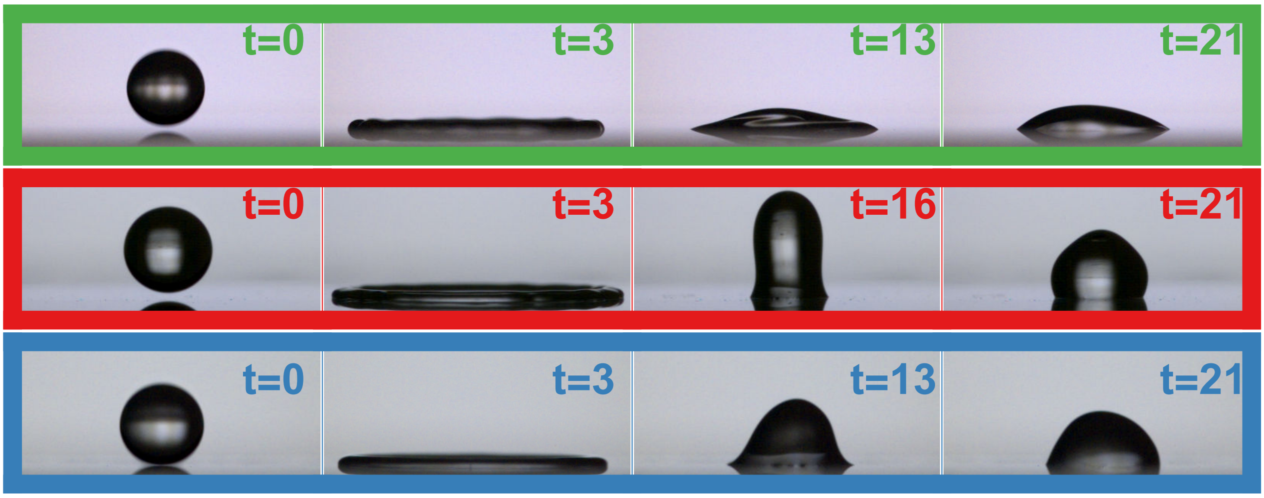

Figure 1. Droplet spreading and retraction. Snapshots of typical droplet spreading for water (in blue), slow surfactant solution (0.1 CMC; in red) and fast surfactant (0.1 CMC; in green) impacting at a speed of 1.9 m/s. Timestamps are in ms. Maximum spreading is reached at 3 ms, equilibrium around 21 ms. Conventional surface tension measurement techniques do not reach these time scales.

# Title: The elastic Rayleigh drop

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Bioprinting technologies rely on the formation of soft gel drops for printing tissue scaffolds and the dynamics of these drops can affect the process. A model is developed to describe the oscillations of a spherical gel drop with finite shear modulus, whose interface is held by surface tension. The governing elastodynamic equations are derived and a solution is constructed using displacement potentials decomposed into a spherical harmonic basis. The resulting nonlinear characteristic equation depends upon two dimensionless numbers, elastocapillary and compressibility, and admits two types of solutions, (i) spheroidal (or shape change) modes and (ii) torsional (rotational) modes. The torsional modes are unaffected by capillarity, whereas the frequency of shape oscillations depend upon both the elastocapillary and compressibility numbers. Two asymptotic dispersion relationships are derived and the limiting cases of the inviscid Rayleigh drop [1] and elastic globe are recovered. For a fixed polar wavenumber, there exists an infinity of radial modes that each transition from an elasticity wave to a capillary wave upon increasing the elastocapillary number. At the transition, there is a qualitative change in the deformation field and a set of recirculation vortices develop at the free surface. Two special modes that concern volume oscillations and translational motion are characterized. A new instability is documented that reflects the balance between surface tension and compressibility effects due to the elasticity of the drop.

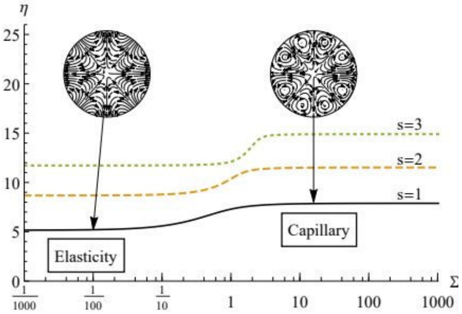

Figure 1. Transition of natural frequencies $\eta$ for a fixed polar mode ($l = 4$). As elastocapillarity number $\Sigma$ increases, flow field within the drop is changed.

**Acknowledgement**: This study was supported by NSF Grant CBET-1750208.

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# Electric forces and stresses on evaporating sessile droplets in microgravity

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When a sessile droplet is subjected to an electrostatic field (e.g. placed inside a plane capacitor), the droplet shape changes very clearly. A comprehensive understanding of the role played by electric forces can clarify important implications linked to the droplet evaporation process, and open the way to new applications. The action of electric stresses manifests itself especially at the vapour-liquid interface, due to the sharp change of electric permittivity. This work aims to extend to droplets the stresses and forces analysis formerly performed on bubbles ([1],[2]). Experiments of evaporating droplets of HFE-7100 in microgravity were considered.
Using the methods described by [1] it is possible to estimate the overall vertical electric force acting on the droplet. Moreover, once the local interface curvature is determined, the electric stress difference across the interface can be evaluated experimentally from the extended capillary equation. The experimental values of electric force and stress were compared with the ones calculated solving Maxwell's equations using COMSOL; the results are shown in Figure 1.

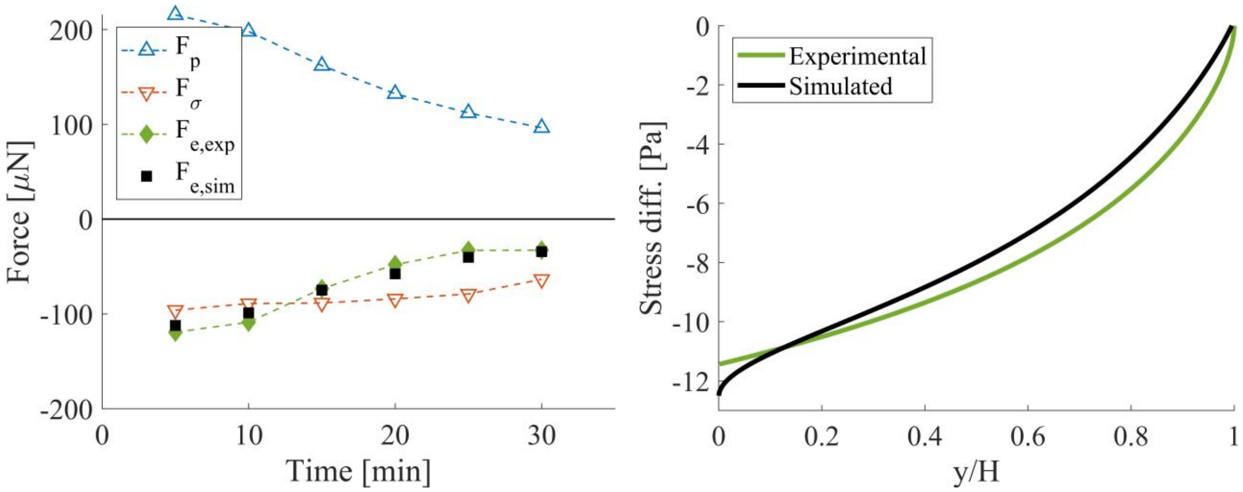

Figure 1. Left: vertical force balance vs time of the droplet (forces are overpressure force ($F_p$), surface tension ($F_\sigma$), electric force from the balance ($F_{e,exp}$), and from COMSOL ($F_{e,sim}$). Right: electric stress vs difference dimensionless height: comparison between experimentally and COMSOL calculated values.

The vertical electric force calculated matches well the data. Also the computed electric stresses are in good agreement with the measured ones, meaning that even during evaporation the interface balance can be considered quasi-static. Remarkably, since the relaxation time of HFE-7100 at 25°C is about 0.006 s [3], the fluid was considered as a conducting one in the calculations. On the contrary, imposing dielectric boundary conditions lead to a mismatch with experimental data.

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# Numerical modelling of instabilities in volatile sessile drops in weightlessness

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Our work is dedicated mainly for the validation of our model for microgravity conditions via comparison with experiments for the evaporation of HFE-7100 sessile drops in Maser-14 sounding rocket and ethanol in the parabolic flight experiment. After the validation we propose the analytical model for pinned sessile drop of ethanol on heated substrate under microgravity condition. Then we understand the role of Marangoni effect that influence the dynamic inside the domain via Marangoni convection and secondary Marangoni instabilities. In parallel we study the effect of the different substrate temperature, contact radius and ambient pressure on the evaporation rate, interface temperature, velocity field, instabilities pattern. Then with above cases we define the relation for critical Marangoni number for transition from Marangoni convection to secondary Marangoni instabilities through critical aspect ratio. Next, we use our model to apply on HFE7100 evaporation microgravity to find the critical thermal Marangoni (and critical height) for transition from Marangoni convection to secondary Marangoni instabilities to help future rocket experiment.

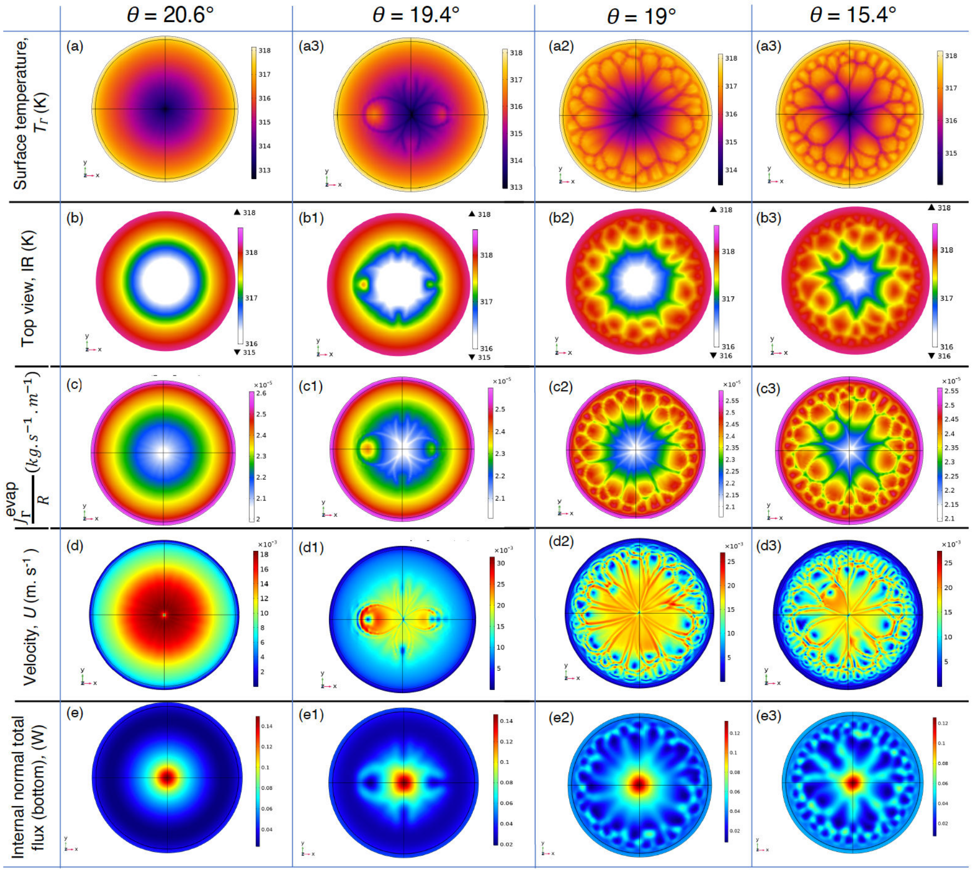

Figure 1. Ethanol sessile drops Interface with surface temperature, IR temperature , local evaporation rate distribution, velocity and internal normal total flux (at substrate) at the substrate temperature Tsub = 318.15K, pressure (p = 0.835 bar) and radius R = 2mm.

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# How viscosity influences the outcome of collisions between liquid droplets and another immiscible liquid jet

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## Abstract

We experimentally investigate collisions between a regular stream of droplets and a continuous liquid jet. Currently, extensive studies on drop impacts mainly focus on drop collisions, while investigations of drop-jet collisions, which are of interest for in-air microfluidics, remain limited [1,2]. In the present study, we focus on the influence of the viscosity of both the drop and the jet liquid. The drops are made of aqueous glycerol solutions whose viscosity ranges between 1.3 and 17.1mPas while the jet is of silicon oil, its viscosity varying between 1.4 and 19.1mPas. In total, six different totally wetting liquid pairs are investigated, where only the viscosity ratio $\lambda = \mu_{drop}/\mu_{jet}$ is varied in the range $0.25 < \lambda < 4$. The results indicate that, varying the relative impact velocity and the drop spacing, four main collision outcomes occur: drops-in-jet (Fig. 1), fragmented drops-in-jet, capsule stream, and mixed fragmentation.

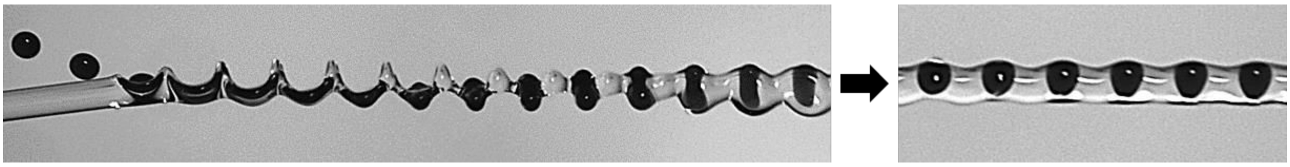

Fig. 1: Picture of the drops-in-jet regime obtained for a droplet Weber number $We_d$=101 and a spatial normalized jet period $L_j/D_j$=1.85. The drop liquid (aqueous glycerol solution 5.1mPas) is darkly dyed, while the jet liquid (silicon oil 19.1mPas) remains transparent.

The transition between drops-in-jet and fragmented drops-in-jet can be attributed to the fragmentation of the drops only, the jet remaining continuous in both regimes. Whatever the outcome, we show that the maximum extension of the drop inside the jet depends on the impact velocity and the drop viscosity only, similarly to drop extension observed for drop impacts on a solid wall [3,4]. A scaling law combining the drop Reynolds and Weber numbers is proposed that predicts very well the maximum drop extension. Drop fragmentation takes place during drop recoil according to the end-pinching mechanism proposed by Stone et al. [5]. Thus, increasing the drop viscosity stabilizes the drop and favours drops-in-jet while the jet liquid viscosity has no effect on the drop fragmentation.

The transition between drops-in-jet and capsule stream corresponds to the fragmentation of the jet only. We attribute this fragmentation to an excessive stretching of the jet sections found between two consecutive drop impacts. An analogy with the stretching separation observed for binary drop collisions can be made [6]. It explains why increasing the jet liquid viscosity stabilizes the jet and favours drops-in-jet whereas changing the drop liquid viscosity has no effect on this transition.

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# Final stage of sessile droplet evaporation: thin liquid droplet

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Although sessile liquid droplet evaporation are well investigated, the reports concerning the final stage of droplet evaporation are scarce. Comprehensive exploration of nano- and pico- liter sized thin droplet requires a high spatial resolution technique [1].

We adopt an Image Analyzing Interference technique, which is capable do measure film thickness of the order tens of nanometers to microns over the relatively large area with curved regions depending on the resolution of the optical system. The example will be an evaporating droplet on smooth glass surface with coating or uncoated one [1]. Interference patterns were obtained using an optical microscope with a monochrome camera. The system provides a resolution of 1.1 μm/pixel with a 10x lens and 100 nm/pixel with 100x. Coherent light was used. The reflection of light from the liquid-gas and liquid-solid interfaces forms interference fringes, Fig. 1. To calculate the film thickness, the light refractive indices were used for glass, for water, for air. The approach differs from the classical interference method where only the peaks are used for construction. We use the wave function itself, which allows you to obtain and approximate data at each pixel. And then using the refractive indexes of each media the film thickness at each point can be obtained. And the slope, curvature and contact angle can be found out. Droplet profiles with an angle of less than 5 degrees have been restored (Fig. 1). Using video registration one can obtain evolution in time of the meniscus region. The liquid thickness in the transitional region and droplet profiles of the order of 40 nm are measured. And applying the integration procedure of the rotation figure, the volume and surface area can be obtained [1], which made it possible to calculate the evaporation rate and intensity, which is important for applied problems.

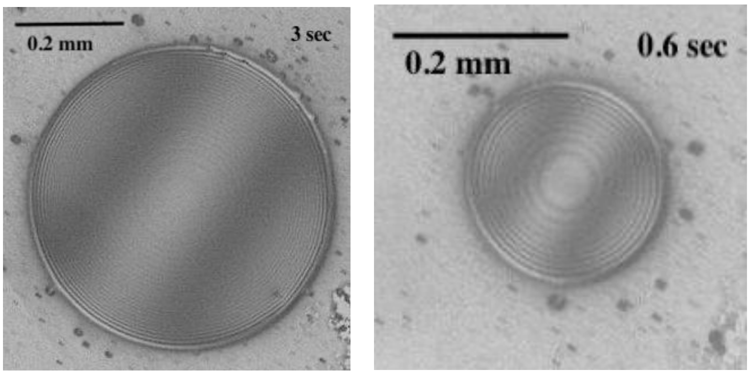

Figure 1. Interference pictures of thin droplet.

The work was financially supported by the Russian Science Foundation (project No. 20-19-00722).

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# Quantifying vapour field around evaporating sessile drops using background-oriented schlieren technique

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Despite the extensive progress in the studies of the evaporation of isolated sessile drops for the past decades, little is understood about how they evaporate in a group, which is rather relevant to actual applications such as printing, nanofabrication, cooling and bioassays. Recent theoretical analysis has concerned the evaporation of a pair of thin drops adjacent each other, revealing the so-called "shielding effect" due to the interaction between the drops [1]. However, to the best of our knowledge, no accurate and direct quantitative characterisation of vapour diffusion in such systems has been made, which could assist in a more detailed description of the competitive evaporation. In this contribution, we develop a technique capable of visualising vapour concentration fields around evaporating drops based on the background-oriented schlieren (BOS) principle [2]. Our BOS setup (Fig. 1 (a)) comprises of a background window with random dot patterns backlit by an LED, a substrate (Si-wafers) on which drops of acetone evaporate, and a visual camera focused on the background. In the course of drop evaporation, the background image is distorted by the variation of refractive index of the vapour phase due to its density gradient caused by the evaporation. The distorted image is then analysed using a cross-correlation algorithm to obtain a density field map. Acetone is used in the present study by virtue of a sufficient refractive-index contrast of the vapour with air. A relative vapour concentration profile obtained by our preliminary test for a single drop is presented in Fig. 1 (b) which shows a qualitative agreement with the prediction by a diffusion-limited model [3]. Having verified the applicability of this technique, further quantitative investigation on the evaporation of multiple drops has been undertaken.

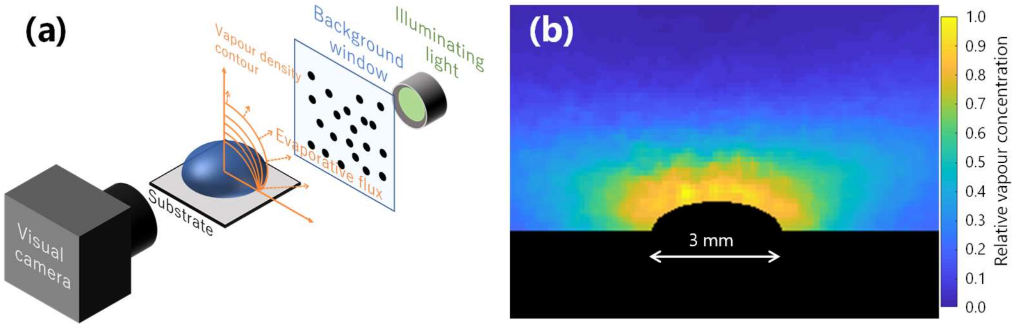

*Figure 1. (a) Brief schematic of the BOS setup. (b) Relative vepour concentration profile around an evaporating acetone drop.*

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# On explosive boiling of Leidenfrost drops

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[2] *Department of Chemical Engineering, University of California, Santa Barbara, USA*
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The gasification of multicomponent drops is relevant in various energy-related technologies. An interesting phenomenon associated with this process is the self-induced explosion of the drop, which promotes drop atomization. Here, we study a unique explosive gasification process of a suspension (solid-liquid) droplet and a tri-component (liquid-liquid) droplet in a levitated Leidenfrost state. The suspension droplet consists of ethanol and microparticles. As the droplet evaporates, microparticles accumulate at the droplet-air interface and form a particle shell, resulting in reduced evaporation rate and contact with the substrate [1]. For the tri-component droplet consisting of water, ethanol, and oil (ouzo), the evaporation process is even richer (shown in figure 1). The preferential evaporation of the most volatile component, ethanol, triggers nucleation of the oil micro-droplets in the remaining drop, and finally leads to the drop explosion [2]. These two phenomena illustrate the rich evaporation dynamics of Leidenfrost drops.

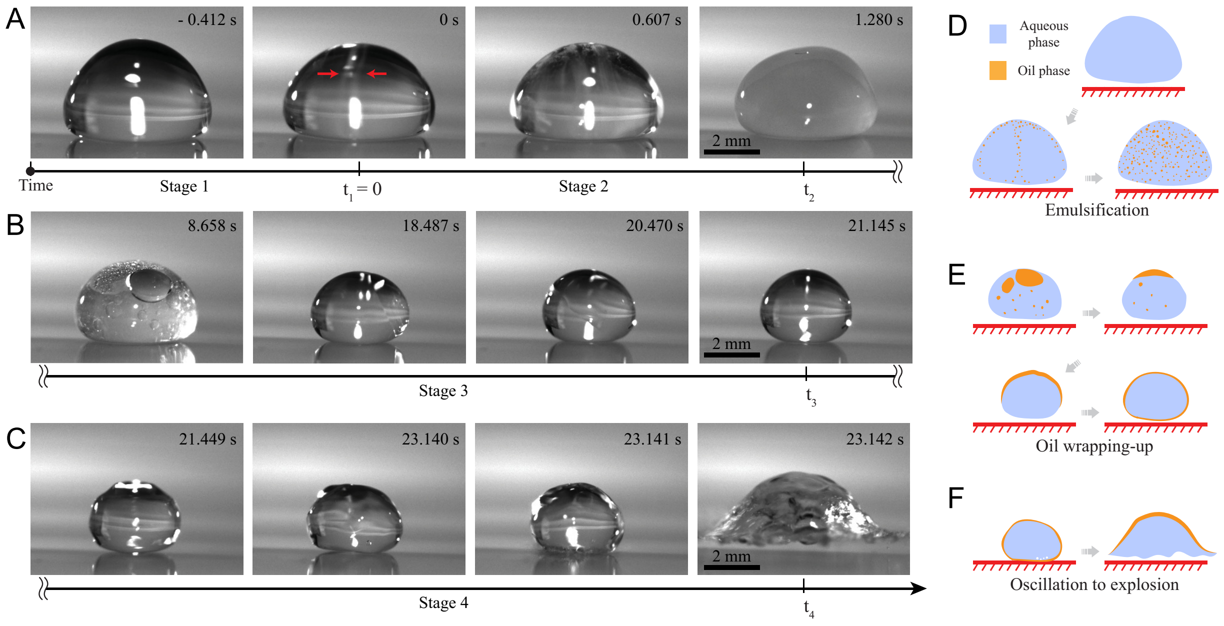

Figure 1. The entire boiling process of an ouzo drop initially in the Leidenfrost state.

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# Dynamics of respiratory saliva droplets

**Avshalom Offner**[1] and Jacques Vanneste[1]

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Over the past year we have all become alert to keeping a safe distance from one another, so as to avoid inhalation of droplets that possibly contain the SARS-CoV-2 (Covid-19) virus, with a rule-of-thumb of $2\,\mathrm{m}$ distance. While this general guidance has been criticised (see e.g. [1]), the rule yet largely remains in place, reflecting a void in the understanding of the dynamics of carrier droplets, i.e. the distance and time they travel before ceasing to be hazardous. Generally, this time is reached by either complete vaporisation of the saliva carrier droplet, or by the droplet landing on a surface – typically falling to the ground. However, the presence of salts and proteins in human saliva prevent the complete droplet vaporisation, leaving droplets of radius $R \approx R_0/5$ in air with 50% relative humidity [2], where $R_0$ is the exhaled droplet initial radius. Considering the droplet size distribution of human breath, speech, or cough to be in the range $R_0 \sim 0.1 - 100\ \mu$m [3], a droplet terminal velocity $v_t \propto (R_0/5)^2$ can be extremely small, suggesting that droplets can stay aloft for long times and be carried with the air flow. In the present work, we study the dynamics of saliva droplets by modelling the evolution of a single, representative droplet as it travels through air.

Our theoretical model is governed by a set of ordinary differential equations (ODEs) for the droplet position, velocity, radius and temperature, reflecting the conservation of momentum (Maxey-Riley model [4]), mass and energy, respectively. Since the Reynolds number of small droplets satisfies $Re \ll 1$, the ODEs for the radius and temperature can be decoupled from the others, allowing analytic approximations to be derived for the terminal droplet radius as well as for the time until this radius is reached. In order to numerically solve the full system of ODEs, a model for the air velocity is required. Attempting to provide sensible estimates on the droplet airborne time before touching the ground, we simplify the model by considering a one-dimensional problem (aligned with gravity), in which an indoor vertical air velocity is described using an Ornstein–Uhlenbeck process.

The model results suggest that SARS-CoV-2 droplets can stay aloft for up to several hours. Droplets typically shrink to their terminal radius in about 10 seconds, during which they may fall a considerable distance depending on their initial size. Having reached their terminal radius, droplets are almost fully entrained with the air flow. Air velocity fluctuations result in non-negligible probability of droplets rising above their original height. In practice, this means that people within indoor spaces may inhale infectious droplets by passing through a location previously occupied by a person carrying the virus. These results may assist in shaping and adjusting social-distancing guidelines, as well as affect regulation on the allowed number of people within indoor spaces.

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# High-Time Resolution Measurements of Droplet Evaporation Kinetics and Particle Crystallisation Imaging

**D. A. Hardy**[1], J. S. Walker[1], P. Lemaitre[2] and J. P. Reid[1]

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Powder production by spray drying is used in a variety of industries including the food and pharmaceutical industries. It is a ubiquitous technique as it is controllable, continuous produces consistent particle quality and is applicable to heat-sensitive compounds.[1]

Droplet-drying processes impact on the final dry particle morphology. This, in turn, determines the aerodynamic and transport properties of the dry particles. One way to understand the effect of evaporation rate on final morphology is to use a Péclet number, which compares the evaporation rate to the rate of diffusion of a solute within the droplet.[2] A Péclet number above one indicates that evaporation rate is dominant and surface enrichment occurs, and droplets have a propensity to form a skin or crust. For a Péclet number less than one the rate of diffusion is dominant, and homogeneity is maintained.[3]

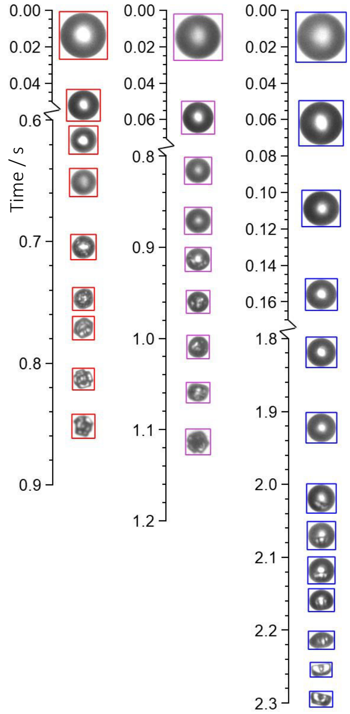

Figure 1. Morphological evolution of sodium chloride solution droplets evaporating in varying relative humidity 20% (red), 30% (purple) and 40% (blue).

This work describes a new Falling Droplet Column (FDC), capable of analysing in detail the entire evaporative lifetime of droplets, with a sub-microsecond temporal resolution. The instrument operates by establishing a chain of uniform falling droplets within a temperature and humidity-controlled environment. Stroboscopic imaging of droplets enables direct measurement of droplet diameter and calculation of aerodynamic diameter by measuring droplet settling velocity. High time-resolution is achieved using a delay generator between droplet dispensing and image capture. Dry particles are deposited at the bottom of the FDC and imaged using SEM. This allows study of evaporative dynamics with comparison against final morphologies.

In this talk we will compare evaporative profiles and resulting morphologies produced in a range of conditions for different inorganic salts. We will explore the specific crystallisation events through detailed imaging of aerosol droplets such as in Figure 1.

This work is supported by the IRSN (grant S100100-101) and the EPSRC (grant EP/N025245/1)

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# Reciprocating thermocapillary motion of liquid plug in a capillary tube - A numerical study

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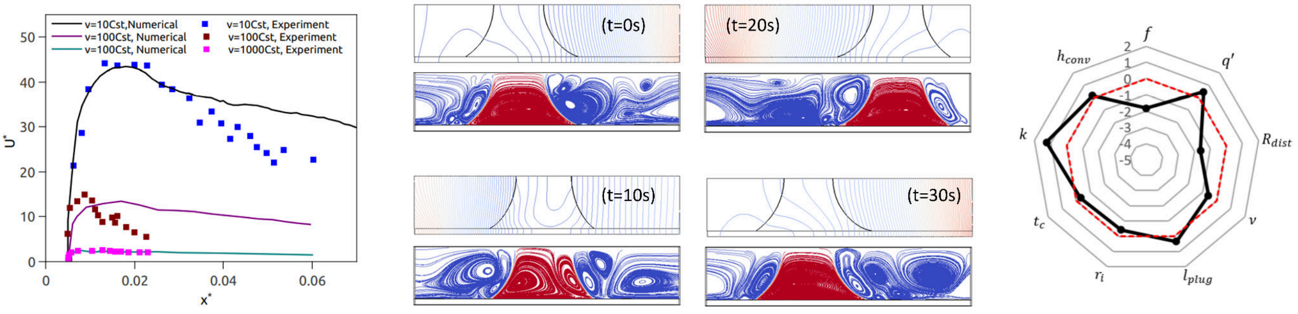
Droplet-based microfluidics is proposed as an alternative to continuous-flow microfluidics due to the advantage of having reduced reagent volumes and high throughput experiments [1]. The droplet enclosed in a solid surface in systems such as capillary tubes or microchannels is one of the droplet configurations studied for these applications. The droplets are referred to as liquid plugs if their length is larger than the channel/tube width and forms two menisci. The motion of these liquid plugs enables many microfluidic operations, and in this work, we considered the thermocapillary phenomenon as an actuation mechanism where the temperature dependence of surface tension generates the driving force required for droplet motion. Here, to actuate the droplet, the temperature of a meniscus is increased, reducing its surface tension, and the resulting capillary pressure difference drives the droplet away from the heater. Apart from motion, mixing is another essential microfluidic operation, and to enhance it in a liquid plug actuated by thermocapillary means, Jiao et al.[2] proposed to reciprocate the droplet between two periodically operated heaters. However, the resulting flow structures, influential parameters and their impacts on reciprocating motion are not thoroughly investigated. To develop an understanding, we modelled the liquid plug's motion using an OpenFOAM-based in-house solver. The solver is validated with the work of Nguyen et al. [3] studying the motion of the plug (Fig. 1a) and is used to explore the influential parameters and their impact on the reciprocating motion of the plug (Fig. 1b). The parametric study revealed that the change in switching frequency affects the reciprocating motion the most, whereas the change in convective heat transfer coefficient affects the least. Additionally, the revealed sensitivity (Fig. 1c) of other influential parameters can guide the design of a capillary tube-based microfluidic system employing reciprocating motion.



(a) (b) (c)

Figure 1: (a) Validation of motion of plug with experiments of Nguyen et al. [3] (b) Isotherm contour and stream line at various stages of reciprocating motion of plug between two heaters which are periodically switched with a frequency of 0.025Hz from start of the switching cycle. (c) Sensitivity of different parameters on reciprocating motion of the plug.

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# Interactions between a microfluidic droplet and a membrane

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In droplet microfluidics, a carrier flow conveys sub-nanoliter droplets through a network of microfluidic channels. Droplet trafficking can be controlled in real-time, e.g. through dielectrophoretic forces [1] or thanks to pneumatic microvalves. The latter are thin elastomer membranes that locally replace one of the channel walls [2]. When the membranes are pressurised from the outside, they partially obstruct the channel and increase the corresponding hydraulic resistance. In 2016, Jeong *et al.* [3] proposed a fully addressable droplet array in which each droplet is immobilised at a controlled spot thanks to pneumatic valves. This array can be seen as a microscopic, automated and reusable alternative to the 96-well plate.

In this work, we investigate many possible interactions between a microfluidic droplet and an elastomer membrane. If the membrane is pressurised, the droplet may either stop in front of it or pass under it. It may also split in several droplets with some passing while others are still stopped. The transitions between these regimes are rationalised in terms of a balance between capillary and shear forces. When the membrane is not pressurised, the droplet may also stop below and deform the latter, in an attempt to decrease its interfacial energy (Figure 1). This regime involves a coupling of capillary, elastic and shear forces. We provide simple and generic theoretical models to rationalise our experimental data.

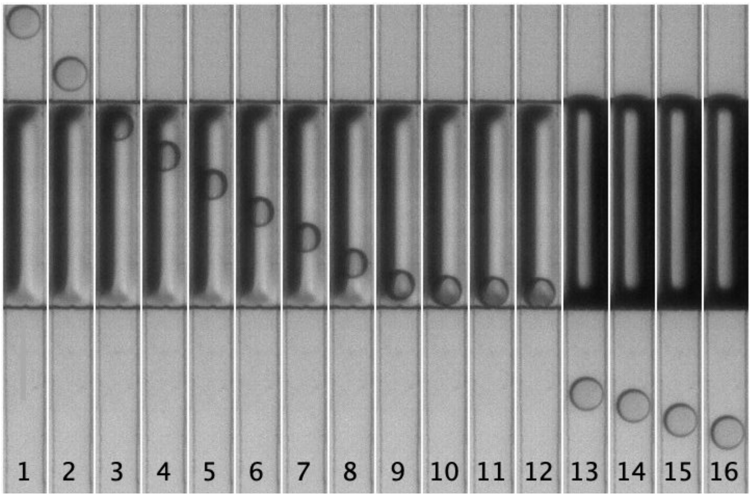

Figure 1. (a) Top view of a droplet moving in a microfluidic channel of width 100 µm and height 30 µm. Successive snapshots are taken every 50 ms. In snapshots 9-12, the droplet is trapped by a non-pressurised membrane of length 600 µm which covers the channel. The droplet is released as soon as the membrane is pressurised (from snapshot 13).

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# Surface acoustic wave driven droplet coalescence in a microwell

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[2] *Micro/Nanophysics Research Laboratory, School of Engineering, Royal Melbourne Institute of Technology (RMIT University) Australia.*

The **presenting author** is in bold.

Microwell structures are extensively used to perform various biochemical assays [1]. Herein, we present the coalescence of droplets in a two-phase system in a microwell (Fig. 1a) using surface acoustic waves (SAWs). We bond a PDMS microwell onto a piezoelectric substrate (lithium niobate) in front of an interdigitated transducer (IDT) as shown in Fig. 1a and 1b. The microwell structure, together with its uniform exposure to the SAWs emanating from the IDT, generate a pair of counter-rotating vortices as depicted in Fig. 1c in the continuous phase liquid. The vortical flows carry droplets to the trapping zone where they come in contact to result in their coalescence (Fig. 1d). From the experiments, we affirm that droplet−droplet interface contact is established via the formation of a liquid bridge, whose neck radius grows linearly in time in the former viscous regime and proportionally with the square root of time in the later inertial regime (Fig. 1e). Further, we study the effect of the input SAW power on the film drainage time and delineate the coalescence and non-coalescence regimes to obtain a basis for the onset of coalescence (Fig. 1f). We anticipate that the outcome of the present study will find applications in the development of individually addressable microwell platforms for a variety of biochemical assays.

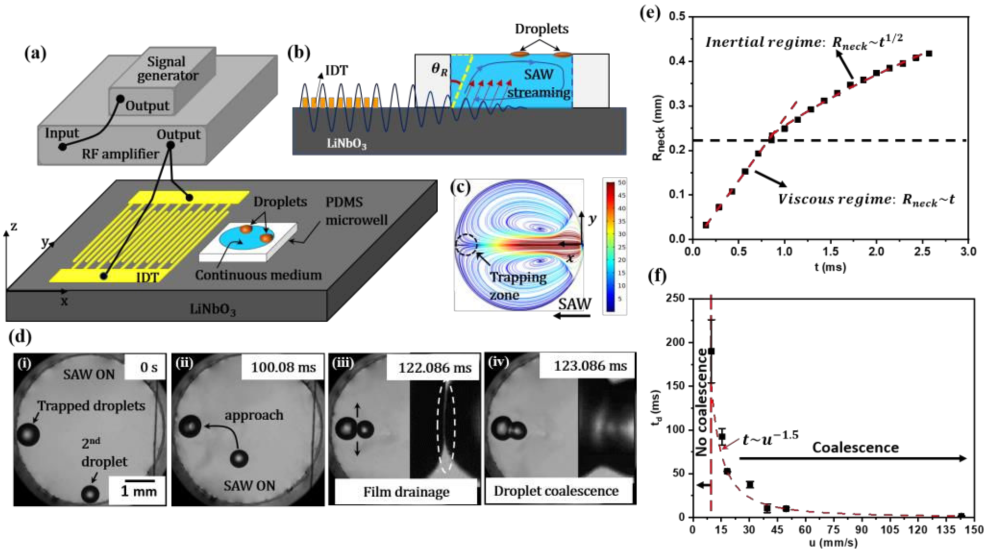

Figure 1. (a, b) Schematics of the experimental setup, (c) formation of vortices and trapping of droplets in the microwell, (d) time-lapse images of the droplet coalescence, (e) temporal growth of the liquid bridge radius, and (f) effect of the input SAW power on film drainage time.

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# Self-templating assembly of soft microparticles into complex tessellations

Fabio Grillo[1], **Miguel Angel Fernandez-Rodriguez**[1,2], Maria-Nefeli Antonopoulou[1], Dominic Gerber[1] and Lucio Isa[1]

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The self-assembly of soft microgels at liquid-liquid interfaces is usually constrained to hexagonal compact monolayers due to isotropic interactions. Sequential depositions of monolayers of microgels with different sizes, e.g. big and small microgels, can already be used to produce a variety of 2D binary colloidal alloys on solid substrates [1]. In this work, we take advantage of the soft nature of microgels, allowing for sequential depositions of the same microgel. In this way, we produced Archimedean and non-regular tessellations where the first monolayer retains the hexagonal structure and acts as a template for the particles of the second monolayer [2]. By varying the packing fraction of the two monolayers, we obtain low-coordinated structures: rectangular and honeycomb lattices, and rhomboidal, hexagonal and herringbone superlattices encoding non-regular tessellations. Molecular dynamics simulations confirm that these structures are thermodynamically stable and develop from short-range repulsive interactions, making them easy to predict (Fig. 1).

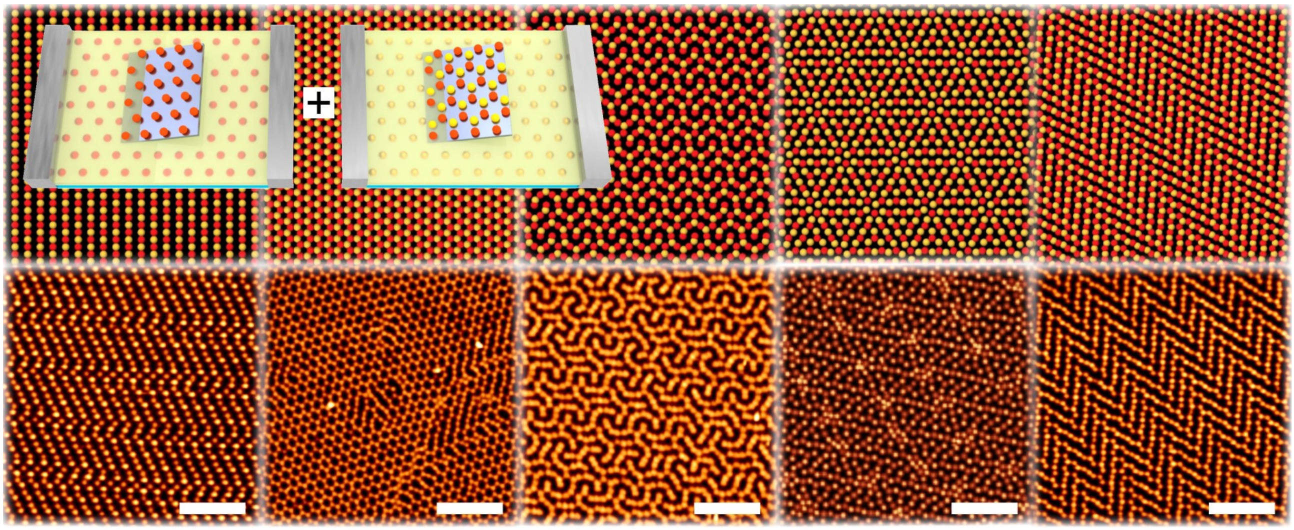

Figure 1. Rectangular lattices, Honeycombs, Interlocking-S structures, Hexagonal superlattices, and Herringbone superlattices. Top row: Simulation snapshots. Bottom row: AFM images (scale bar: 5 μm) of the corresponding experimental structures. Inset: schematic of the sequential depositions.

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**Acknowledgement:** Swiss National Science Foundation Grant PP00P2-172913/1, Juan de la Cierva Programme 2018 - Incorporation Grants (IJC2018-035946-I), and MAT2017-82182-R.

# Frost Formation and Growth on Lubricated Surfaces: Challenges and Solutions

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2. *Department of Mathematical Sciences and Center for Applied Mathematics and Statistics, New Jersey Institute of Technology, Newark, New Jersey, United States*

Frost forms in nature and technology where it can become detrimental (slip hazard, blocking or deforming surfaces, black frost, etc.). This calls for anti-frosting strategies such as new materials which aim for passive frost and ice reduction on surfaces. While icing on surfaces is commonly studied by localized nucleation mechanisms, the formation of frost is more complicated: Formation of condensate droplets, freezing, and frost front propagation are multi-physical processes on multiple time and length scales. Lubricant impregnated surfaces are known for improved anti-icing properties. They experience lower ice drop adhesion and allegedly delayed surface frost formation. We show that frost formation can induce immensely strong capillary forces that could result in surface damage, lubricant depletion and the loss of anti-icing properties. Laser scanning confocal microscopy enables us to monitor the dynamic lubricant migration during condensation frosting on micro-structured surfaces. We present a quantitative model of the lubricant migration, utilizing lubrication theory. By understanding the fundamental mechanisms of frost formation on lubricant impregnated surfaces, we find new routes for anti-icing materials which we explore and present.

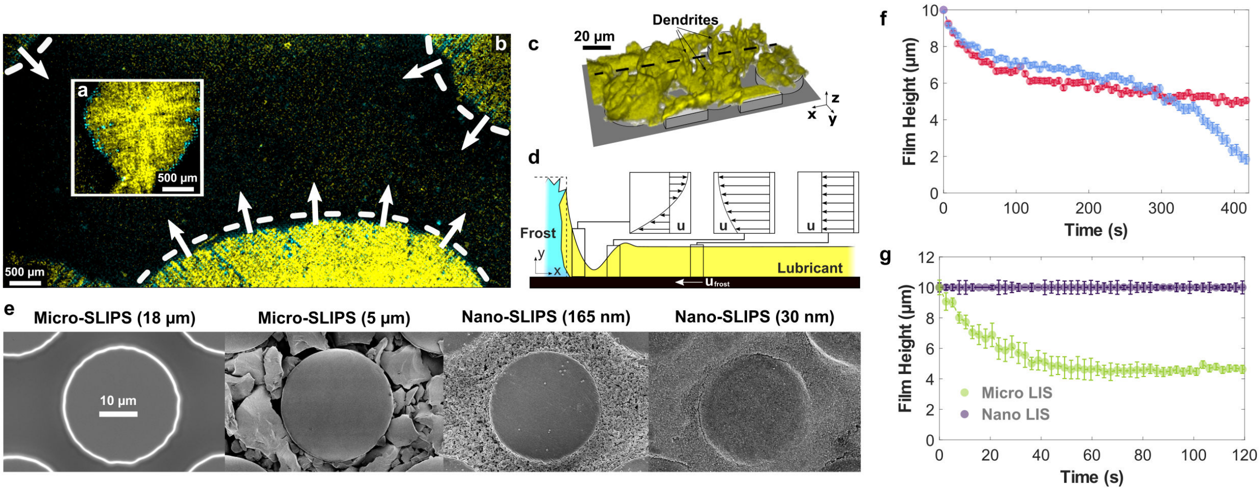

Figure 1: Condensation frosting on lubricated surfaces. a) Mesoscopical top view micrograph of frost patch formation and b) propagation. Lubricant is yellow. c) Three dimensional confocal micrograph of lubricant covered frost forest. d) Lubricant flows in interaction with frost. Flow profiles were obtained by thin-film approximation. e) Scanning electron microscope image of differing interstitial spacing (18 $\mu$m to 30 nm) of surface scaffold. f) Average lubricant height in between micropillars. Condensation reliably cause depletion ($t < 100$ s); frost may (red) or may not (blue) depletes lubricant, depending on field of view. g) Small interstitial spacing (purple) retain lubricant better than larger ones (green).

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# Influence of substrate temperature on spreading, imbibition and evaporation of drops on substrates with nanofiber coatings

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Heat transfer and hydrodynamics during drop impact or deposition strongly depend on the wetting properties of the pair substrate/fluid and on the substrate temperature. Experimental investigations have shown that the heat transfer resulting from drop impact can be enhanced using nanostructured coatings of the wall surface [1]. It has been suggested that the heat transfer enhancement results from imbibition of liquid into the porous coating, leading to enlargement of the wetted area compared to smooth substrates and consequently to increasing of evaporation rate. Furthermore, phenomena limiting the drop spreading, such as bouncing and splashing, are suppressed.

In this work, the influence of substrate temperature and nanofiber coating thickness on the kinetics of spreading, imbibition and evaporation of deposited pure water and pure ethanol drops is studied.

The substrates are manufactured from infrared-transparent calcium fluoride and coated with submicrometer CrN and Cr layers. The substrate can be heated by electric current through the chromium layer. Nanofiber mats are manufactured by electrospinning on top of the chromium layer. The dynamics of the initial drop spreading and subsequent wetting are captured by a high-speed camera in a side view, whereas the imbibition is observed by a camera in a top view. Simultaneously, the temperature distribution at the interface substrate/coating is captured with an infrared camera underneath the substrate and used for determination of the radius of the cooled area (Fig. 1). In this way, the relationship between the liquid spreading and imbibition, from one side, and heat transfer, from the other side, is described.

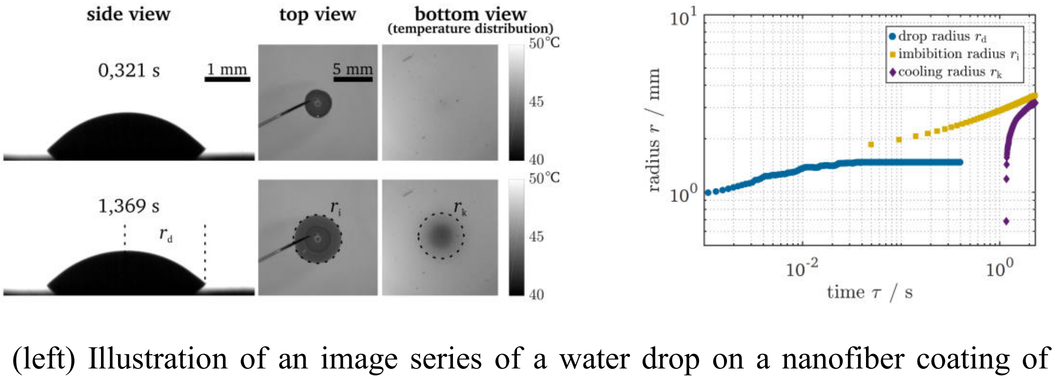

Figure 1. (left) Illustration of an image series of a water drop on a nanofiber coating of 20 µm thickness and an initial temperature of 46 °C. (right) Drop radius, imbibition radius and radius of the cooled area plotted over time.

ACKNOWLEDGEMENTS: Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) -- Project-ID 265191195 -- SFB 1194.

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# Evaporation of binary mixtures on structured surfaces

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Studying and understanding the fundamentals and underlying complex phenomena during droplets evaporation is paramount to a wide variety of everyday applications such as inkjet printing, spray cooling and medical and biological technologies[1]. In this work, we experimentally investigate wetting and evaporative behaviours of pure water, pure ethanol and their binary mixtures droplets on intrinsically hydrophobic micro-structured surfaces with different spacing between pillars. The initial wetting regime is a function of the fluid and the pillar spacing conditioning subsequent evolution of the droplet contact angle and contact radius. Three evaporative regimes have been revealed: pinning, stick-slip, and mixed-mode, which are consistent with the literature, while a further mixed stick-slip mode is additionally noticed. The extent of these evaporative regimes are a function of ethanol initial concentration and spacing between pillars, which are quantified in this work. For example, lower ethanol concentrations on pillars with small spacing have a longer initial pinning time. However, as ethanol initial concentration increases along with larger spacing between pillars, a shorter initial pinning time has been observed. Investigating the initial pinning time and the other evaporation modes can lead to a better understanding of choosing the proper structure combined with the correct binary mixture concentration to be specifically tailored to industrial, medical and biomedical applications.

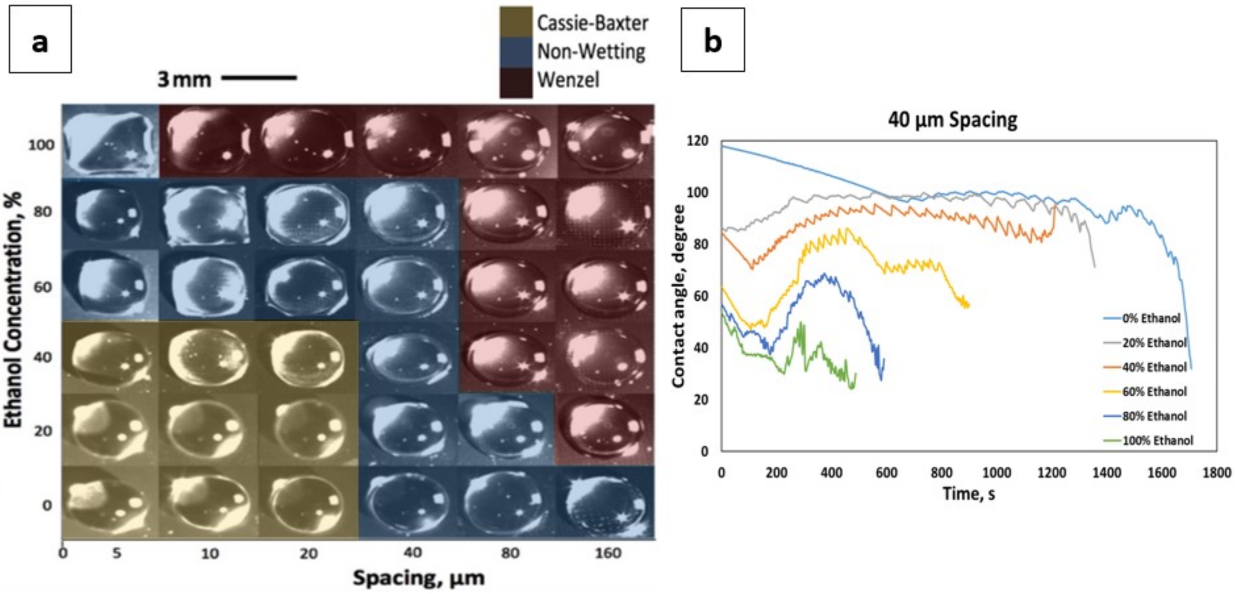

Figure 1. (a) Initial wetting shapes of pure water, pure ethanol and their binary mixtures, %, on microstructured surfaces with different spacing, *s* (µm). (b) Evolution of the contact angle, degree, versus time, *s*, on 40 µm spacing.

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# Functional and Structured Particles by Inkjet Printing of Emulsions

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Emulsion solvent evaporation is a method for generating microparticles from solutions of polymers in volatile organic solvents dispersed in an aqueous medium. In this talk, we will show how this technique can be combined with microfluidics and inkjet printing to produce monolayers of uniformly sized particle that can self-assemble into hexagonally ordered arrays (Fig. 1).[1]

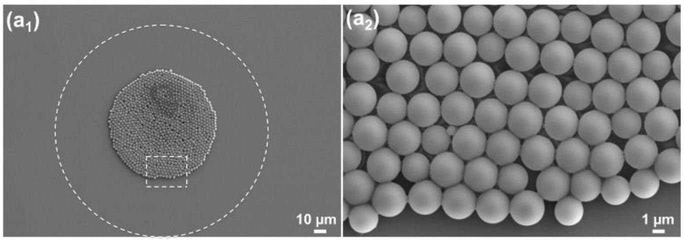

Figure 1. SEM image of a deposit with a monolayer of polystyrene particles from emulsions (O, 66.5 mg mL$^{-1}$ PS/DCM; W, 1.0 mg mL$^{-1}$ SDS/water). 80-µm nozzle, 6-µm oil drops, plasma-treated glass substrate.

We further show that microcapsules can be created if the volatile organic contains a shell-forming polymer and a core-forming fluid that is a poor solvent for the polymer. This method is demonstrated for microcapsules with various shell-forming polymers (polystyrene, poly(methylmethacrylate) and poly(L-lactide)) and core-forming poor solvents (hexadecane and a 4-heptanone/sunflower oil mixture). Here dichloromethane (DCM) is used as good solvent for the polymer and PVA as the emulsifier. Cargoes such as fluorescent dyes (Nile Red and tetracyanoquinodimethane) or active ingredients (e.g., the fungicide tebuconazole) can be encapsulated. The conditions for the successful formation of microcapsules are discussed

The emulsion solvent evaporation method is not limited to polymers. We show that inkjet printing of monodisperse emulsions containing silica nanoparticles produces hierarchically structured porous materials (Figure 2).

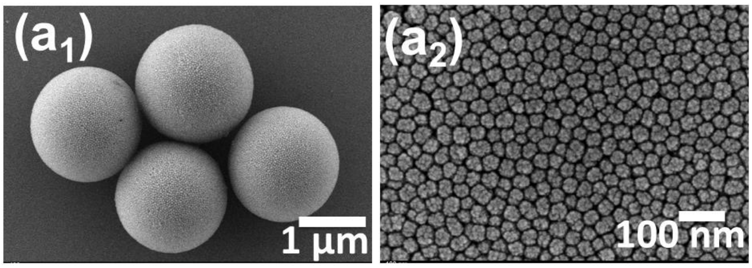

Figure 2. SEM image of 1-µm spheres composed of 50-nm silica nanoparticles.

Acknowledgement: YW thanks the China Scholarship Council and Durham University for support.

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# Drop impact dynamics onto a deep liquid pool: Influence of free surface topology

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When a liquid drop impacts a deep flat pool comprising of the same liquid, the following dynamics can manifest themselves through different phenomena: the coalescence with the pool liquid, the thick jet (short or long), the thin jet or the thin/thick jets with bubble entrapment [1] depending on its impact parameters and pool-surrounding liquid properties, typically represented by Weber Number ($We = \rho u_d^2 D/\sigma$) and Froude Number ($Fr = u_d^2/gD$). Droplet impact at $We = 252$ and $Fr = 220$ leads to a W-shaped cavity formation followed by a long thick Rayleigh jet emerging upon its collapse which further fragments into a single secondary droplet [1]. However, the outcome of the impact varies, depending on the initial surface topology. In the present numerical study, the initial pool surface is modelled as a spatial axisymmetric wave, a topology commonly generated by the prior drop impact or by perturbations due to vertical vibrations or by winds, formulated by the zeroth-order Bessel Function of the first kind as done by Farsoiya et al. [2]. While serving the impact point of the drop on the surface as the trough of the topological wave, a gradual transition in the impact regime from the thick Rayleigh jet to the slender jet is observed upon incrementing the surface wave parameters-amplitude and wave number. The range of these parameters was taken that to mimic the order of the capillary perturbations due to the wind. The impact on the surfaces with a relatively smaller magnitude of the wave parameters showed a similar result as the long thick jet regime of the flat surface involving a W-shaped cavity during retraction. As for the thin jet regimes of a flat surface, the cavity attains a V-shape before retracting. However, unlike the flat surfaces, the cavity is noted to be at its maximum depth while having a nearly hemispherical shape for highly slender jets. This indicates that the cavity retraction has initiated at comparatively earlier stages after the impact and is noted to be relatively faster, attributed to the greater hydrostatic pressure below the cavity base. During the jet evolution, a transition from capillary-driven instability to the inertia-capillary driven instability is observed, complemented by an almost consistent increase in the maximum intact jet height with the maximum of about $3$ times that of the flat surface with the same impacting conditions. The secondary droplets' characteristics serve as a prevalent factor for the air-water mass exchange. The number of secondary drops pinched off the jet reached the maximum of $10$ and their cumulative volume having a maximum of $1.74$ times the initial impacting droplet volume compared to $0.27$ times of the flat surface. The detailed study will include a comprehensive parametric and physical understanding of the underlying dynamics.

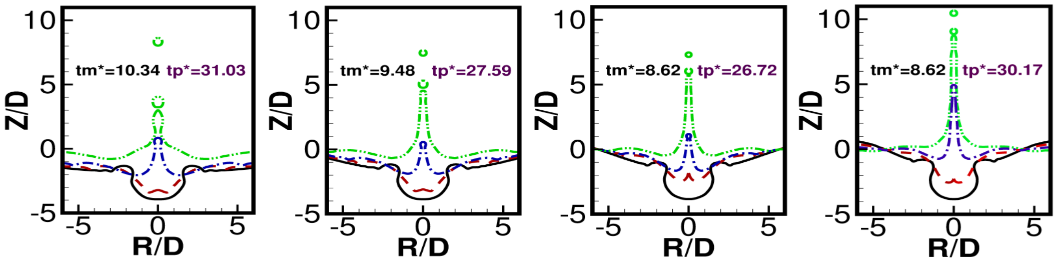

Figure 1: Contours at different evolution stages for initial surfaces having amplitude twice the droplet diameter and wavenumbers increasing along the row from $55\,m^{-1}$ to $190\,m^{-1}$ at equal intervals.

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# Effect of surface properties on the impact behaviour of supercooled microdroplets in a high-speed airflow

**Alexandre Laroche**[1], Alexandre Cuco[1], Norbert Karpen[1], Vittorio Vercillo[1], and Elmar Bonaccurso[1]

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The current model for predicting impalement of water droplets impacting onto textured surfaces does not match observations for impacting supercooled microdroplets at high speed. A study by Deng et al.[1]revealed that a pressure balance calculation could predict the wetting state of an impacting droplet as either fully non-wetted, partially wetted, or fully wetted. That model was however inconsistent with the experimental study of Vercillo et al.[2] who measured the ice adhesion strength on surfaces of varying topography, and where ice was formed by impacting supercooled water droplets. The ice adhesion strength was expected to correlate with the predicted wetting state of droplets after impact. To better understand supercooled microdroplet impalement, and to validate the hypothesis that droplet impalement is directly related to ice adhesion strength, we investigate here the impact behaviour of microdroplets in an airflow onto surfaces of varying topography and wettability (laser-patterned titanium, and polyurethane aircraft paint). The setup used to generate the airflow and the droplets is shown in Figure 1A, along with the target (Figure 1B), and the camera placement (Figure 1C). Our results show that supercooled droplets follow the same spreading ratio scaling laws as room-temperature droplets such as those presented by Visser et al.,[3] who showed the transition between viscous-dominated and surface tension-dominated droplet impact regimes for micro-scale droplets at speeds up to 100 m $s^{-1}$ onto a glass target.

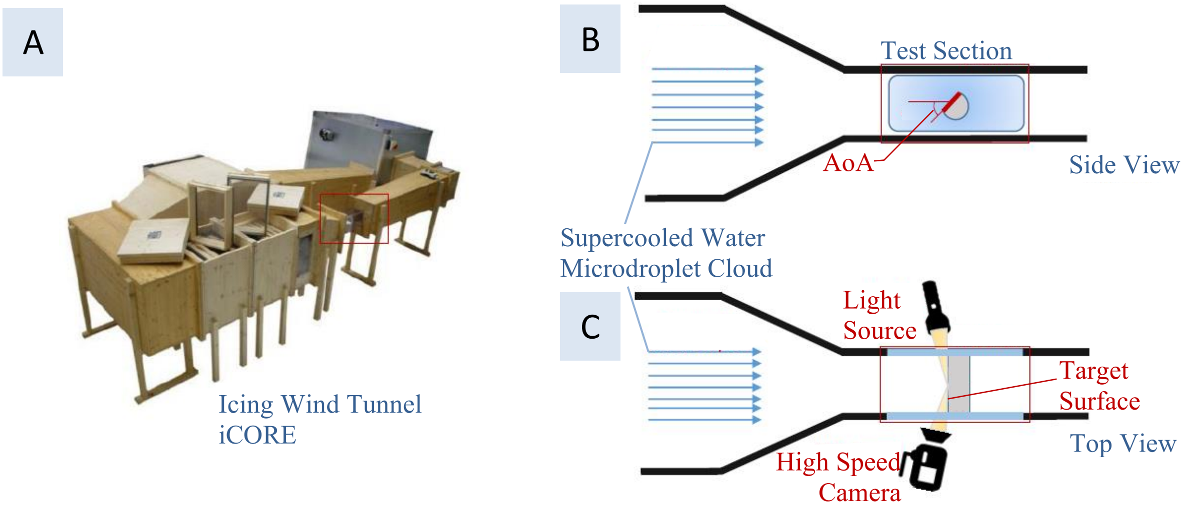

Figure 1. Experimental setup used for studying the impact behaviour of supercooled water droplets onto various surfaces, showing (A) the icing wind tunnel with test section encircled by a red rectangle, (B) a schematic side view of the test section showing the sample holder and angle of attack (AoA), and (C) a schematic top view of the test section showing relative camera and light source placements.

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# The influence of droplets on electrohydrodynamic instabilities

**Sebastian Dehe**[1] and Steffen Hardt[1]

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A fluidic interface disintegrates when sufficiently strong electric fields are applied, leading to electrohydrodynamic (EHD) tip streaming. For example, when a pin electrode is placed above a liquid-liquid interface, a conical cusp forms and emits charged droplets from the tip towards the electrode. In Fig. 1a, we show an example of this well-known Taylor cone. In Fig. 1b, we show an alternative interface deformation mode that can be observed in liquid-liquid systems. Here, the interface is repelled by the electrode, forms a dimple, and additional cone-like structures emerge from the rim. We illuminate the underlying mechanism behind these alternative deformation modes both experimentally and numerically, and demonstrate that the presence of droplets triggers the dimple at the interface.

We characterize the underlying mechanism by replacing the pin electrode by a hollow metallic needle with a prescribed electrolyte volume flow. This submerged electrospray injects droplets of an aqueous KCl solution with varying ion concentrations into silicone oils of varying viscosities. We measure both the electric current as well as the interface deformation and investigate the system response to variations of the ion concentration, viscosity, applied voltage and the volume flow rate. The electric current and interface deflection depend strongly on the voltage between needle and lower liquid, and reach a limiting value with increasing viscosity and ion concentration.

Additionally, we use a finite element solver to compute the electric field, flow velocity and interface deformation, and model the current transported through the oil phase by droplets as an advection-diffusion process. After calibrating the model by particle tracking velocimetry data, we are able to reproduce the experimentally observed interface deformation. Furthermore, we identify the experimentally observed limits at high concentrations and viscosities as a space-charge effect. In total, we highlight the importance of charged droplets for the complex dynamic modes observed when a liquid-liquid interface is exposed to a local electric field.

We acknowledge funding from the German Research Foundation (DFG, Grant No. HA 2696/45-1).

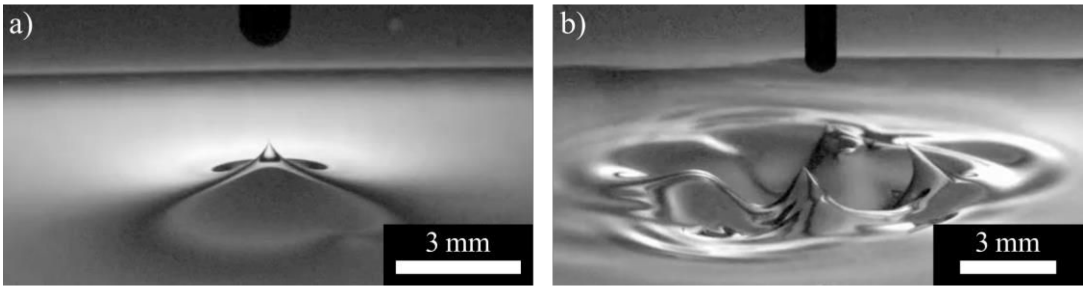

Figure 1. Disintegration of a liquid-liquid interface induced by a pin electrode as a Taylor cone (a) and as a surface dimple with additional cones emerging at the rim (b). The upper liquid is a dielectric and the lower liquid a conducting aqueous KCl-solution in contact with the ground electrode.

# Adaptive Wetting of Polydimethylsiloxane

**William S. Y. Wong,** Lukas Hauer, Abhinav Naga, Anke Kaltbeitzel, Philipp Baumli, Rüdiger Berger, Maria D‘Acunzi, Doris Vollmer and Hans-Jürgen Butt

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The contact angles of a drop depends on its contact line velocity. Typically, velocity dependent contact angles are modelled using molecular kinetic or hydrodynamic theory. On polydimethylsiloxane (PDMS) and other soft polymers, these theories do not describe dynamic contact angles adequately. Here, we test if spontaneous changes in surface chemistry during wetting, so-termed wetting adaptation, can explain the velocity dependence of contact angles. Therefore, we measured advancing and receding contact angles of sessile water drops on cross-linked PDMS as a function of contact line velocity. Our results show that wetting adaptation theory provides a quantitative description of dynamic advancing contact angles. Experiments indicate that PDMS adapts to the presence of water by an enrichment of free oligomers at the interface. This work sheds new light on soft elastomeric materials, highlighting how wetting contact can induce lubrication which alters effective interfacial energies and dynamic contact angles.

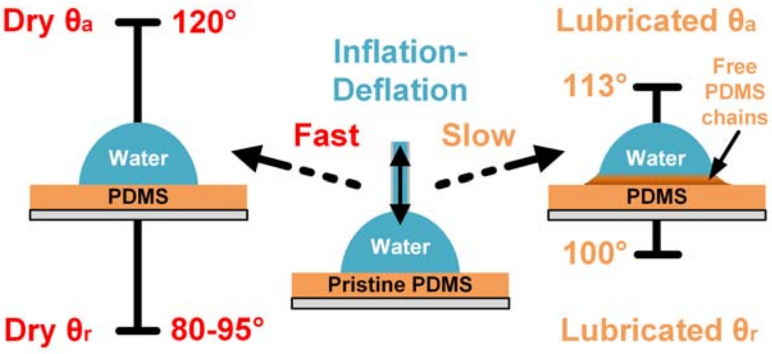

Figure 1. Sketch of dependence of the contact angle of pristine PDMS on the inflation/deflation rate. At high inflation/deflation rates, the advancing (θa) / receding (θr) contact angles resemble those on PDMS not containing free oligomers (dry). At low inflation/deflation rates, the advancing/receding contact angles resemble those on lubricated PDMS (free PDMS chains are not to scale).

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# Spatio- topological regulation of multiscale dendritic patterns in respiratory droplets using vapor mediated interactions

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The droplets ejected from an infected host during the expiratory event can get deposited as fomites on everyday use surfaces. These fomites can be a precursor for disease transmission. The final precipitation pattern strongly depends on the flow field within the droplet and crystallization dynamics. Dendritic and cruciform-shaped crystals are formed aftermath the evaporation of respiratory droplets on the glass surface. We show that by modulating the flow field within these sessile respiratory droplets using vapor-mediated interaction, we can control the crystallization dynamics and induce spatio-topological regulation in the final dendritic patterns in the crystals. The introduction of a pendant ethanol droplet near the droplet's vicinity creates an asymmetric ethanol vapor gradient around the sessile drop. The differential adsorption of ethanol vapor on the surface of the saline droplet gives rise to a spatial surface tension gradient. This, in turn, enhances the internal convection [by $\sim O\ (10^2–10^3)$] within the droplet. Preferential transfer of solutes in the droplet results in targeted contact line de-pinning, morphological control of dendrites' size, control of directionality of dendrites, and suppression of cruciform shaped crystals. One can also control the spatial location of the nucleation sites, thus, the occurrence and growth of dendrites. The bacteria/virus emulating nanoparticles get preferentially segregated in the final pattern. The methodology can have ramifications in disease detection. Controlling the crystallization also has various other potential applications starting from water purification to portable diagnostics, fouling, and scaling, particularly in cases that require the separation of unwarranted solutes from solvents.

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# Particle encapsulation in aqueous ferrofluid droplets and sorting of non-empty droplets from empty droplets using a magnetic field

**Utsab Banerjee**[1], Sachin Kumar Jain[1], and Ashis Kumar Sen[1]

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Encapsulation of particles inside droplets is a stochastic process that follows a Poisson distribution [1]. We report encapsulation of microparticles in aqueous ferrofluid droplets in a primary continuous phase (CP) and sorting of particle encapsulated droplets (PED) from empty droplets (ED) at the interface of continuous phase (CP) in coflow with a second continuous phase ($CP_2$) using a magnetic field [2] as shown in the schematic Fig. 1a and 1b. It is found that the size contrast between the PED and ED depends on the flow regime – squeezing, dripping, or jetting, which in turn is governed by the ratio of the discrete phase to continuous phase capillary numbers, $\mathrm{Ca_r} = \mathrm{Ca_{DP}}/\mathrm{Ca_{CP}}$ as shown in Fig. 1c and 1d. The difference between the volume fractions of ferrofluid in the PED and ED, $\Delta\alpha_{\mathrm{PED}} = (\alpha_{\mathrm{ED}} - \alpha_{\mathrm{PED}})$, where $\alpha_{\mathrm{PED}} = (\mathrm{D}_{\mathrm{PED}}^3 - \mathrm{d}_{\mathrm{P}}^3)/\mathrm{D}_{\mathrm{PED}}^3$ is the effective volume fraction of ferrofluid in the PED, and $\alpha_{\mathrm{ED}} = 1$ since the empty droplets do not contain any particles is utilized for sorting, and is also found to depend on the ratio of the capillary numbers, $\mathrm{Ca_r}$. The difference $\Delta\alpha_{\mathrm{PED}}$ is found to be significant in the jetting regime, suggesting that the jetting regime is suitable for encapsulation and sorting. The sorting criterion is represented in terms of a parameter ξ, which is a function of the ratios of the magnetic force to the interfacial force experienced by the PED and ED and is shown in Fig. 1e. The experimental images of sorting of PED and ED in case of beads and cells are shown in Fig. 1f and 1g respectively. Our study revealed that sorting is possible only when $\xi < 0$, which corresponds to $\Delta\alpha_{\mathrm{PED}} > 0.25$, where $\xi = (1 - \kappa_{\mathrm{PED}})(1 - \kappa_{\mathrm{ED}})$ and $\kappa = {}^{\mathrm{F_m}}/_{\mathrm{F_i}}$.

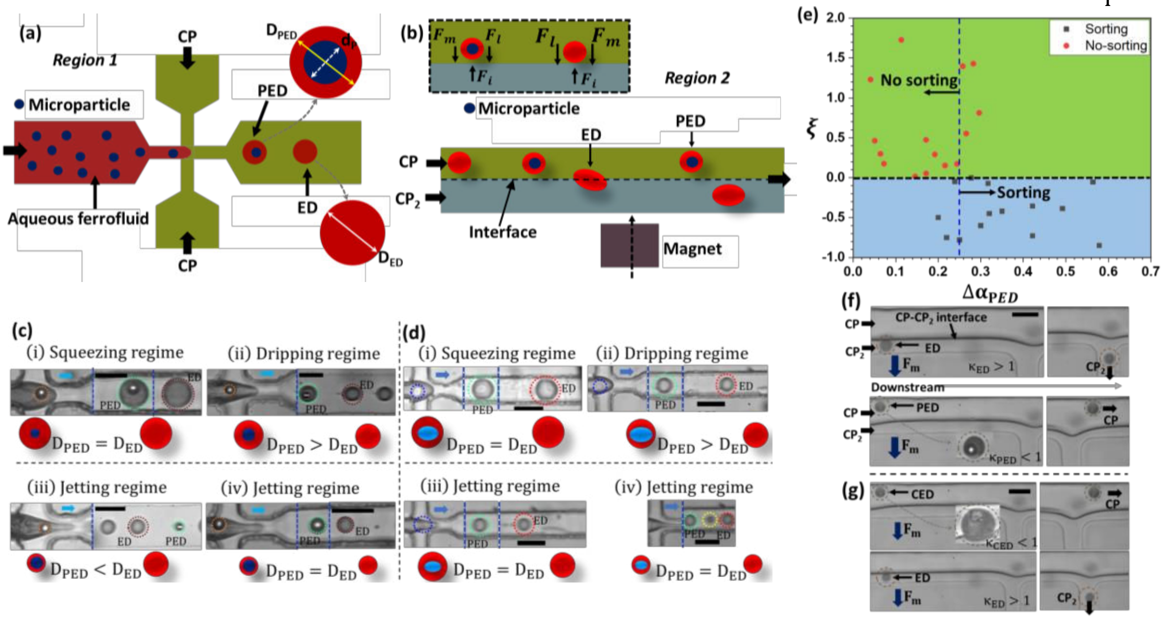

Figure 1: (a), (b) Schematic showing encapsulation and sorting of PED and ED, (c), (d) Experimental images of beads and cells inside ferrofluid droplets respectively, (e) Regime of sorting and non-sorting, (f), (g) Images of sorting of bead and cell encapsulated droplets and empty droplets respectively, scale bar represents 50 μm.

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# Humidity effect and phase-separation in evaporating binary mixture drops

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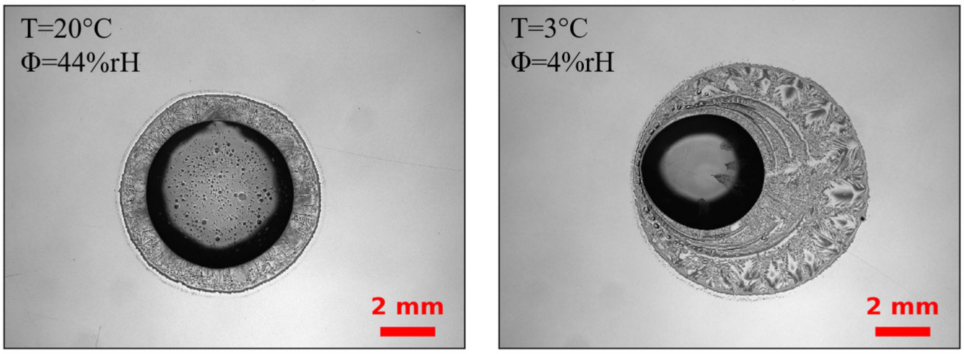
At room temperature, certain binary solutions are completely miscible for all mixture compositions. However, when the temperature is reduced below the critical solution temperature (CST), a miscibility gap is reached, resulting in liquid-liquid phase separation. Such phenomena are vital in many bio-medical, pharmaceutical, and polymer processing applications [1]. Analysis of such systems in an evaporating sessile droplet configuration is very attractive due to its minuscule size and quick response to the composition and temperature variations, as well as due to the numerous applications. For this purpose, a mixture of hexane and Diethylene Glycol Monoethyl Ether (DGME) has been chosen. The variation of CST with the DGME mole-fraction for such mixture combinations is readily known [2]. This binary mixture is easy to handle since it is stable for a wide range of temperatures, e.g. the highest temperature at which phase separation occurs is 7°C for DGME mole fraction ($c_{DGME}$) = 0.3. In experiments, drops were deposited on a silicon wafer substrate and visualized using a contrast imaging technique. The substrate could be maintained at different temperature levels using a recirculating cooler. It was surprising to see some features similar to the phase separation even at ambient conditions (20°C), in spite of the mentioned CST limit of 7°C, as shown in Fig. 1(a). It was conjectured that this effect could be due to the water absorption/adsorption by DGME from ambient in view of the hygroscopicity of DGME (the ambient relative humidity RH was 44%), which presumably led to a CST rise for the resulting ternary system. This motivated a series of experiments in a controlled-humidity chamber at a nearly zero humidity, under which conditions a behaviour compatible with the expected CST at 7°C was indeed observed e.g. as shown in Fig. 1(b). The study was eventually undertaken at various temperature, humidities and DGME concentrations in order to clarify such phase separation phenomenon in an evaporating sessile drop.



(a) (b)

Figure 1: Instantaneous images of the evaporating droplet with $c_{DGME} = 0.3$.

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# Evaporating drops on fiber: how the fiber influences their lifetime?

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Evaporation is ubiquitous in natural phenomena such as sea spray dynamics or animals perspiration. This phase transition also plays a major role in many industrial processes like coating, spray cooling or powder production. Moreover, understanding the drying of facial mask could provide new insights into limiting the spread of Covid-19. The evaporation dynamics depends strongly of the geometry of the liquid, which is related to its surface tension and the substrate wetting properties and also to the substrate thermal properties [1]. While evaporation of spherical and sessile droplets have been widely investigated for the last century, studies of evaporation in other geometries remain scarce. Among the different substrates, fibrous materials are known to provide a rich liquid organisation and evaporating dynamics [2].

Here we investigate experimentally the evaporation of a drop deposited on a fiber. Our measurements reveal that the fiber can have a significant effect on the drop lifetime depending on both the nature of the liquid and the fiber material. We attribute this difference to the thermal properties of the substrate (Fig. 1). We propose an analytical model to predict this lifetime for diffusion-limited and forced-convective evaporation by taking into account evaporation cooling effects and thermal conductivity of the fiber. This model provides a dimensionless parameter to evaluate the significance of the substrate conductivity on the drop lifetime. Our model is validated by comparison to our experiments for which the liquid and the fiber material are systematically varied.

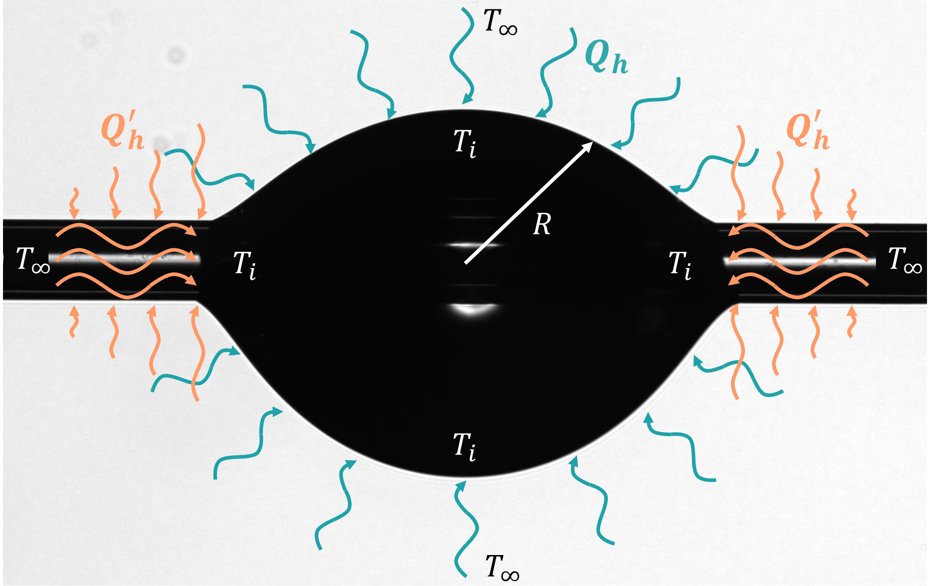

Figure 1: Schematic representation of a droplet deposited on a fiber and of the thermal fluxes exchanged between air, liquid and solid during the droplet evaporation.

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# Droplet splashing of nanofluids: an experimental study

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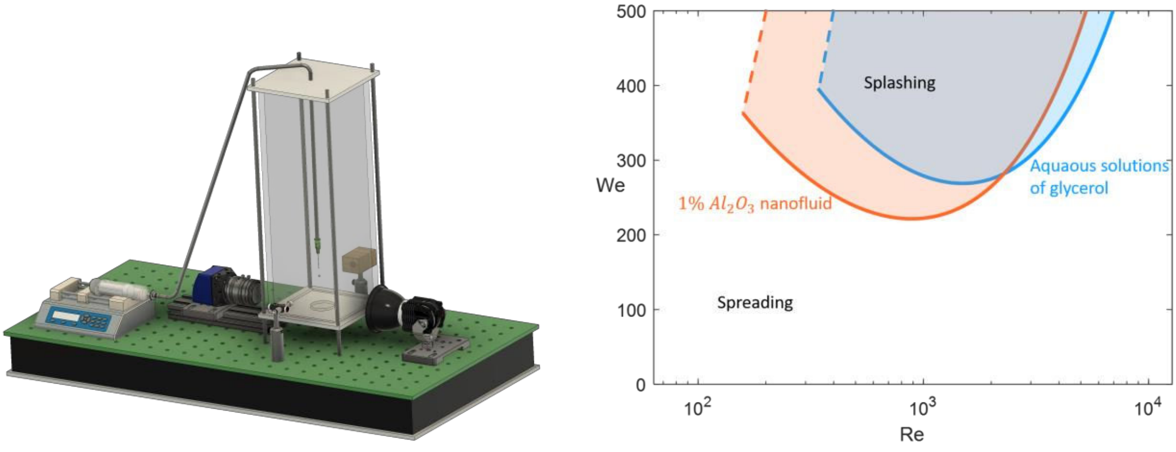
Cooling by impinging droplets has been the subject of several studies for decades and still is, and, in the last few years, the potential heat transfer enhancement obtained thanks to nanofluids' use has received increased interest. Indeed, the use of high thermal conductivity fluids, such as nanofluids, is considered today as a possible way to strongly enhance this heat transfer process [1]. Nevertheless, those new generation coolants do not only alter the thermal properties of the base fluid, but also modify the rheological properties and dynamic behaviour during the impact. In this research, the influence of nanofluids on droplet splashing conditions is studied. Almohammadi et al. [2] observe a change of the splashing curve on the Weber-Reynold map due to surface wettability. In our research we have investigated how this splashing curve is affected by the presence of nanoparticles in the bulk fluid. We have performed experimental campaigns using the set-up presented in Fig 1a. Droplets with diameter ranging from 2 to 3 mm and composed by a bulk of aqueous solutions of glycerol are dropped from a needle on a sapphire plate. Images of the droplet-surface interaction are recorded to distinguish spreading from splashing (prompt and corona). We will show that the correlation proposed in [2] is accurate and that the addition of $Al_2O_3$ nanoparticles (1% mass concentration in the example reported in Fig 1.b) causes a significant difference. We will present a modified correlation which takes into account the impact of nanoparticle concentration and phenomenologically describe how the droplet-surface dynamics is modified.



(a) (b)

Fig.1. (a) Experimental setup composed of a high-speed camera and LED for illumination. The droplets are generated with a syringe pump. (b) The difference between the splashing regions of nanofluids and the corresponding base fluid is given in a We-Re map. The blue curve and area are corresponding to the fluid without nanoparticles and the orange curve and area represent the splashing region of the nanofluid.

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# Arrested evaporation kinetics and electro-hydrodynamics of saline sessile droplets under applied electric field

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The article experimentally examines and theoretically establishes the influence of electric field on the evaporation kinetics of sessile droplets. The anomalous behavior of reduction in the evaporation kinetics of conducting saline aqueous solution droplets due to presence of transverse, varying electric field stimulus is observed and reported in this article. The evaporation rates is found to be enhanced with presence of salt but reduced directly with increase in the strength of electric field (voltage) for different salt concentrations on hydrophilic surface. The classical vapor diffusion driven evaporation model is found to be incapable in predicting the modulated evaporation rates. The surface tension variations with electric field is also not able to predict the change in the altered physics. Accordingly, the particle image velocimetry studies were performed to obtain the internal hydrodynamics in presence of altering electric field. The presence of electric field is observed to arrest the internal circulations inside the evaporating droplet and circulation velocity is found to be reduced directly with electric field. A scaled analytical model is proposed based on the internal advection mechanisms to quantify the role of internal electrohydrodynamics, electro-thermal and electro- solutal effects on the droplet internal circulations. The theoretically predicted velocities are in good agreement with the experimental values. The present study has many industrial [1] as well as bio-medical applications.

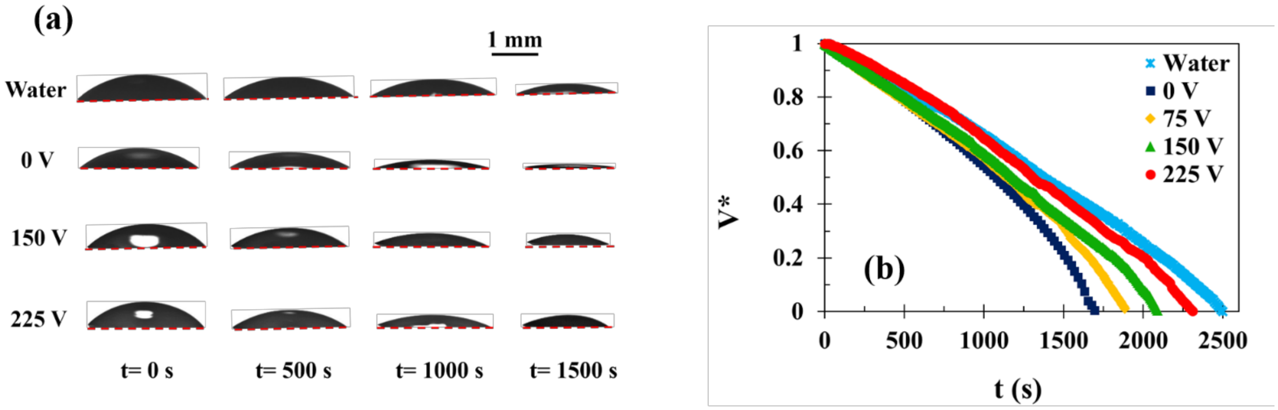

Figure 1. (a) Time evolution array of evaporating DI water and NaI salt based 0.1 M solution droplets at different electric field strengths. (b) Transient variation in the non-dimensional volume V* of DI water and 0.1 M NaI salt based droplets at different strengths of electric field.

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# Crystallization from evaporating droplets: Salt creeping and self-lifting crystals

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The formation of salt crystals by evaporation of aqueous solutions is a process that is ubiquitous in both industry and everyday life. The phase change between dissolved salt and crystals happens within the solution because of solvent evaporation. I will show that crystallization patterns of evaporating of water drops containing very common salts such as NaCl can be surprisingly different from the formation of a single salt grain. I will present our results on the mechanism of salt creeping, where ‘trees’ of stacked salt crystals can travel over large distances. This is a major problem for the conservation of artworks and buildings, as well as for outdoor electronics and soil sodification. I will also show how the wetting properties of the emerging crystal can affect its growth, and even make crystals ‘self-lifting’: they push themselves away from a substrate they do not want to be in contact with. This may be a first step to the development of self-cleaning surfaces.

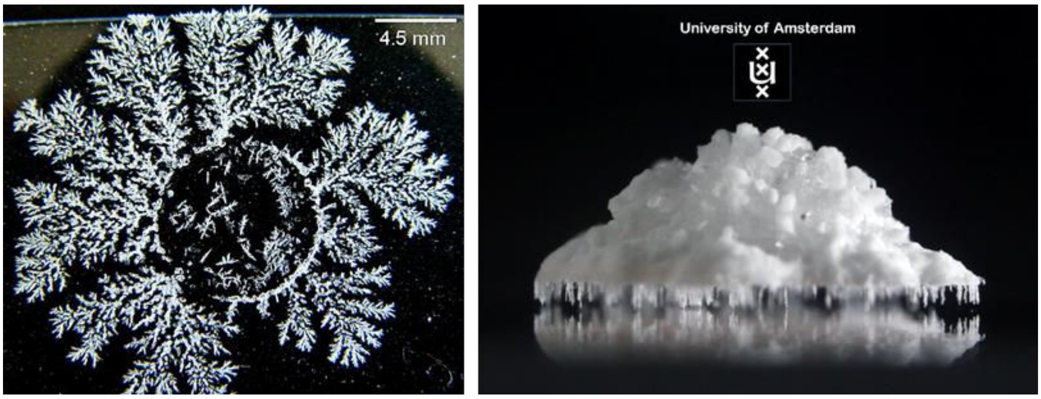

Figure 1. Salt creeping beyond the contact line (left) and self-lifting crystals (right) from evaporating droplets [1,2].

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# Droplet-impact-induced liquid film dewetting on superhydrophobic surfaces

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The spontaneous breakup and withdrawal of liquid films from substrates, also known as dewetting, is a daily phenomenon with practical importances in applications such as ink-jet printing,self-cleaning and anti-icing.[1] To better utilize the dewetting of liquid film, understanding its mechanisms is essential. From previous studies, the process of dewetting involves nucleation and growth of dry regions, where the former is the process of gas-liquid-solid interface replacing liquid-solid interface, and the latter is the competetion between gravity and surface tension. Generally, it is difficult to control the dewetting of liquid film due to its complexity. Here, we report a controlled liquid film dewetting process on a superhydrophobic surface. In our experiments, a droplet drops from a certain height and then impacts onto a liquid film with a finite thickness, pushing away the liquid under the impact site and creating a cavity. The cavity expands and leaves a residual film at the bottom which is much smaller than the initial thickness of the liquid film. With the expansion of the cavity, the residual film becomes thinner and finally breaks up, leading to the appearence of a dry hole on the liquid film on the microstructured superhydrophobic surface.[2] The dry hole surpassing a critical value will continue to grow and cause permanent dewetting on the superhydrophobic surface; otherwise, it will collapse and disappear within a certain period of time. [3] Our results show that, the dewetting effect will be strengthened with larger droplet impacting speed, thinner liquid film, and rougher surface structures. We expect that our work will not only deepen the understanding of dewetting physics, but also promote related engineering applications.

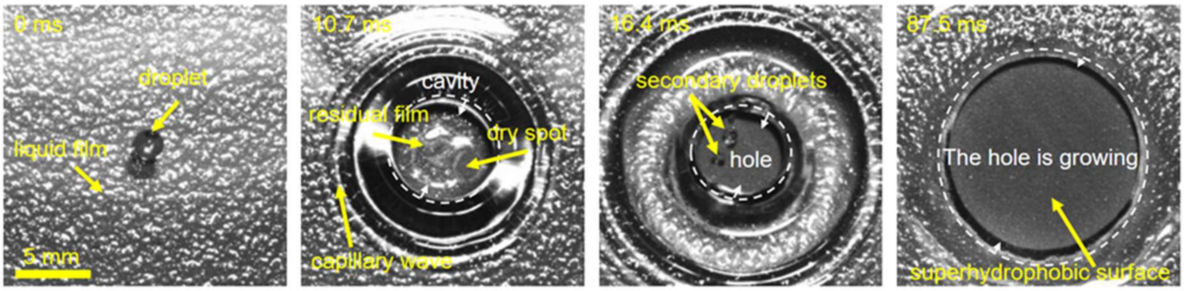

Figure 1. Dewetting process of a liquid film induced by droplet impacting on superhydrophobic surfaces

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# Droplet impact dynamics on hydrophobic and slippery liquid-infused porous surfaces controlled by propagating surface acoustic waves

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Controlling droplet impact on different solid surfaces is an essential topic in developing diverse types of engineering surfaces. Slippery liquid infused porous surfaces (SLIPs) has recently been used in self-cleaning and lab-on-a-chip devices surfaces. Up to date, research has focused on controlling the droplet impact on such surfaces using passive methods with modification of the oil layer thickness. However, a major problem with passive control methods is the lack of on-demand control over the impact dynamics.

This paper introduces a new method to actively control the droplet impact on SLIPs surfaces using surface acoustic wave (SAW) technology. To do that, we designed and fabricated SLIPs on ZnO/Al thin film SAW devices. Different scenarios of droplet impact on the surfaces were experimentally investigated. The effect of SAW amplitude and oil layer thickness on the impact dynamics was analysed, and the droplet impact's mechanisms were explored.

Our experimental results showed that by applying a SAW wave, the droplets' spreading and retractions are altered, leading to a change in droplet impact regime. We demonstrated that droplet deposition on the surface after the impact could be effectively prevented using SAWs. Furthermore, the droplet contact time was reduced up to 30% by applying SAWs. Our results also showed that oil thickness of ~8µm is the optimum one to reduce the droplet impact time by SAWs. Our work offers the opportunity to use SAWs with SLIPs to reduce the contact time and alter the droplet rebound angle. The new paradigm introduced in this study opens a wealth of possibilities in applications such as self-cleaning, anti-icing and anti-erosion.

# How do chemical patterns affect equilibrium droplet shapes?

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Droplet wetting on chemically patterned surfaces is ubiquitous in nature and industrial applications. Due to anisotropic wetting morphologies, neither the Young's law nor the classic Cassie-Baxter model is sufficient to describe the equilibrium droplet configurations. Here, we analytically scrutinize the equilibrium shapes of droplets on diverse chemically patterned surfaces by using an energy landscape method and a proposed modified Cassie-Baxter model, which are both corroborated through phase-field simulations. The well consistency between the analytical models and phase-field simulations reveals the capability and the justifiability of the proposed approaches. Moreover, by utilizing the analytical models combined with phase-field simulations, we have found out that the number of equilibrated droplets and the equilibrium shapes of droplets are dependent on the droplet sizes, contact angles, and the ratios of the hydrophilic area to the hydrophobic area. The number of equilibrium shapes of droplets on chemically patterned surfaces increases with the droplet volume. While for a fixed volume, the decrease in the average contact angle engenders more equilibrium shapes of droplets. The average contact angles can be controlled by changing either the intrinsic contact angles on the hydrophilic and hydrophobic areas or the area ratio of these two components. Our findings open a promising avenue for applications of droplet manipulation and the design of functional surfaces.

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# Dynamic dewetting from complex liquid film shapes

**Carl V. Brown**[1], Andrew M. J. Edwards[1], Élfego Ruiz-Gutiérrez[2], Michael I. Newton[1],
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The wetting and dewetting properties of liquids on solid surfaces are fundamental in processes such as drying, coating, and lubrication. Dewetting of retracting thin liquid films have previously been investigated predominantly around growing dry areas after bursting the liquid film [1,2]. We have demonstrated dielectrophoresis control of surface wettability to create a liquid film of prescribed initial shape on a normally non-wetting surface [3]. The ability to release the film on demand and initiate dewetting revealed that dewetting involves an initial dynamic regime where a liquid rim recedes at constant speed and constant dynamic contact angle, followed by a relatively short exponential relaxation of a spherical cap shape [3]. Here, we show dielectrophoresis control over the static and dynamic wettability of a surface can be used to create various liquid film shapes, including disk, square, rectangle [4], stripe, and ring (Fig. 1). In the ring geometry the coalescence of the liquid rims around the expanding inner diameter and around the retracting outer ring diameter creates an unstable toroidal liquid filament. We demonstrate control over the instability pathways via the initial film shape and volume and show the selection of breakup mode via slip-controlled liquid retraction.

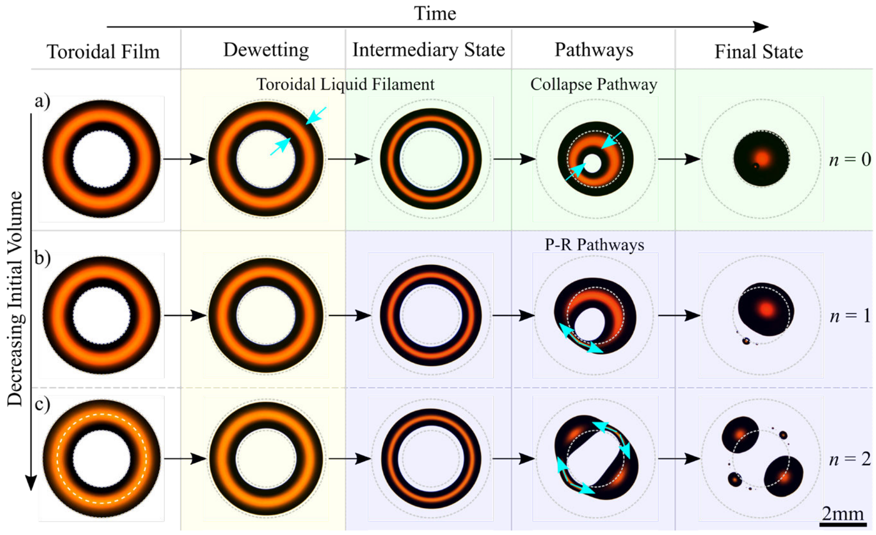

Figure 1. Experimental images of the dewetting and resulting pathways for liquid films of different initial volumes in a ring-shaped geometry.

This work was kindly supported by the U.K. EPSRC (grants EP/R042276/1 and EP/R036837/1).

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# Onset of droplet motion induced by superposition of shear flow and surface vibration

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Adhesive droplets play an important role in a large number of technical applications, whether in the operating circuit of a machine or in electronic components. Depending on the application desired or undesired droplet movement can be initiated in different ways. In addition to an incident flow, vibration as well as different surface structures can initiate the movement of a droplet. Numerous studies focus on the investigation of individually acting forces when investigating droplet dynamics. Several investigations have been performed to find (empirical) laws for the critical velocity for the onset of droplet motion [1, 2] or to analyse the droplet movement due to a surface vibration [3, 4]. However, in many applications these influences occur in a superimposed manner. We report on current research which investigates the superposition of an incident flow with simultaneously acting vibration excitation.

The experimental setup, consisting of a plexiglass channel with movable wall and an electromagnetic vibration exciter, allows a defined alignment of the vibration excitation relative to the flow channel. Within the scope of the experiments, the influence of a vibration excitation acting in the horizontal as well as in the vertical plane are considered.

Water droplets of different volumes (7.8 – 39.9 µl) are excited with different frequencies covering a range between 0.75 and 4 × $f_1$with $f_1$ being the first natural frequency of the droplet. In addition, the excitation acceleration is varied (25 – 100 m/s$^2$).

The data obtained indicates that the critical velocity for the onset of motion of an adherent droplet can be reduced compared to the pure channel flow case. The reduction rate is a function of the frequency of the superimposed oscillatory excitation. An influence of the direction of excitation of the surface vibration can be observed. A significant decrease of the critical velocity is found for an excitation in the range of the first natural frequency, in case the vibration excitation takes place in the horizontal plane. In contrast, if the vibration excitation is in the vertical plane, the droplet can be detached with the lowest channel flow velocity when excited with the second natural frequency. In both cases, increasing the excitation acceleration leads to a further decrease in the critical velocity.

Furthermore, a relationship can be shown between the deflection of the droplet (or the contact angle difference) and the decrease in the critical velocity. If the contact angle difference of the droplet excited by a vibrational excitation is maximum, the critical detachment velocity is minimum.

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# Ultra-thin Robust and Thermally Conductive Vertical Graphene Lubricant-infused Surface for Continuous Dropwise Condensation

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Lubricant-infused surfaces (LIS) have attracted considerable research interest in recent years due to their slipperiness, enabling dropwise condensation of water and other fluids of lower surface tension. The continuous shedding of nucleated droplets prevents a condensate film formation, which would otherwise result in a significant thermal resistance, and thus condensation efficiency is enhanced.

However, securing the lubricant presence for a reasonable amount of time during condensation requires surface micro- and nanostructuring. Usually, the lubricant is infused into such structures, which are typically on the order of 1 μm, resulting in a lubricant layer of a similar thickness. Unfortunately, commonly used lubricants have low thermal conductivity (~ 0.1 W $m^{-1}$ $K^{-1}$) and the thermally insulative lubricant layer inevitably limits the heat transfer improvement brought by dropwise condensation.

In this work we introduce a thermally conductive nanoscaffold composed of vertically grown graphene sheets in place of traditional surface micro- and nanostructures. A forest of vertical graphene with a height of 70 nm is used to retain the infused lubricant (Fig. 1). This thin layer imposes minimal thermal resistance with an order-of-magnitude decrease compared to state-of-the-art lubricant-infused CuO nanoblades, resulting in a two-fold improvement in heat transfer coefficients of steam condensation at 50 mbar over CuO-based LIS. The nanoscaffold is found to retain the lubricant for at least 7 hours of condensation, despite its low thickness. The lubricant consumed is half of that of CuO nanostructures as well. The findings suggest our material to be a strong candidate in terms of its heat transfer performance, durability, and scalability.

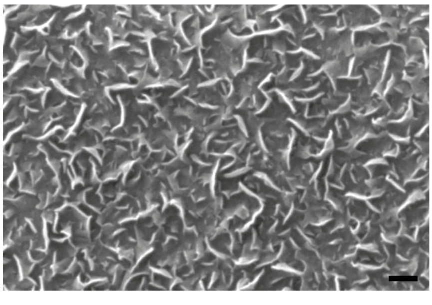

Figure 1. Scanning electron micrograph for a vertical graphene nanoscaffold within which a lubricant can be infused. The graphene sheets have a height of 70 nm. Scale bar: 100 nm.

# How wettability can optimize heat transfer for electronic systems.

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Abstract: It is well known that a heterogeneous surface will significantly affect condensation and boiling characteristics. In this study we compare the effect of different patch sizes in order to design heterogeneous surfaces for a single-loop heat transfer pipe, typical of that used to cool an electronic system. Keeping constant the surface ratio between hydrophobic and hydrophilic surfaces, we prove that different patch sizes change the correlation between the heat fluxes of the condenser and the evaporator , opening a route for possible optimization of this technology. This is true not only in terms of temperature and pressure, but also in terms of heat fluxes for which we observe significant changes. One of the most remarkable results is that the surface we have designed and which works best does so for all gravity conditions. This nicely illustrates the importance of the geometry of the patches in optimizing the performance of a thermal loop.

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# Droplet stabilization by Thermal Marangoni

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Volatile single-component liquids can exhibit non-zero apparent contact angles, even on completely wetting surfaces. The typical mechanism proposed to explain this angle involves evaporation, capillarity, and viscous dissipation, with faster evaporation rates leading to higher contact angles. [1,2]. Droplet evaporation can also cause a non-uniform temperature distribution and hence surface tension gradients that result in thermal Marangoni flow. Numerous studies have focused on induced thermal Marangoni flow within single-component droplets on partially wetting substrates and indicate that the induced flows can be towards or away from the center of the droplet depending on contact angle, thermal conductivities of the liquid and solid, and substrate thickness [3,4]. Recently it was shown that for fast enough evaporation both evaporation-driven stabilization and Marangoni flow are important in establishing the droplet shape on completely wetting surfaces [5].

Here, we investigate how substrate properties alone can influence Marangoni flow and impact the apparent contact angle for single component droplets on completely wetting surfaces. We observed that for sufficiently thin substrates, faster evaporation leads to a lower apparent contact angle, opposing the prediction from evaporation-driven stabilization, Figure 1. To determine whether internal flows were consistent with putative Marangoni contraction, we added and imaged fluorescent tracer particles in the droplets. We found the magnitude of the flow was faster with thinner substrates, consistent in direction and trend with a potential Marangoni contraction mechanism. Moreover, we derive the droplet temperature distribution and use it as part of a criteria to show that thermal Marangoni contraction plays a significant role in establishing droplet shape on thin substrates.

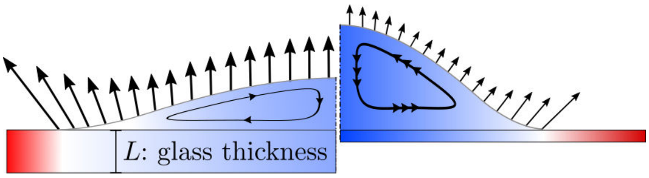

Figure 1: Schematic showing evaporation of a droplet on thinner glass generating a larger temperature gradient that induces a stronger thermal Marangoni flow and a higher apparent contact angle despite slower evaporation.

[1] L. Hocking, Physics of Fluids 7, 2950 (1995).

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# Evaporation of levitated droplets under radiative heating measured with Whispering Gallery Modes

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Models of radiative heating of droplets commonly consider static droplets since the radiation is much faster than the droplet's movement [1]. In this work, this approximation remains valid for long times since we have employed an optical trap to both heat and hold the droplet. The trap consisted of two focused, counter-propagating beams with which stable trapping of water droplets was achieved from radii of $\simeq$5 $\mu$m down to full evaporation. During the evaporation process, the droplets flicker because of Whispering Gallery Mode (WGM) resonances that occur every change in circumference of $\Delta c \simeq \lambda/n$ [2]. The stability range from $\mu$m to nm has allowed us to observe a WGM spectrum reaching down to the lowest order resonances (Fig. 1**A**). Since the circumference change between resonances is constant, the period between resonances contains high-resolution information of the droplet's evaporation rate.

At first, the droplets are in thermal equilibrium with the air around them, but when they fall into the trap they are suddenly heated by the laser. A possible analogy of this experiment is a cloud droplet in the shadow that is suddenly exposed to sunshine. Fig. 1**B** shows how the resonances' period initially can be approximated by an exponential function (green fit). After about 6 seconds, however, the period instead shows a linear decay (magenta line).

In this work we will present the use of WGM spectra to study the evaporation rate of sub-$\mu$m droplets and discuss possible mechanisms for the change from exponential to linear decay rate. Furthermore, the trap used here is stable over a large range of laser powers and the droplets were trapped in a vacuum chamber. Hence, it will be shown how detailed studies of the evaporation rate of sub-µm droplets, at a variety of heating and pressure conditions can be carried out.

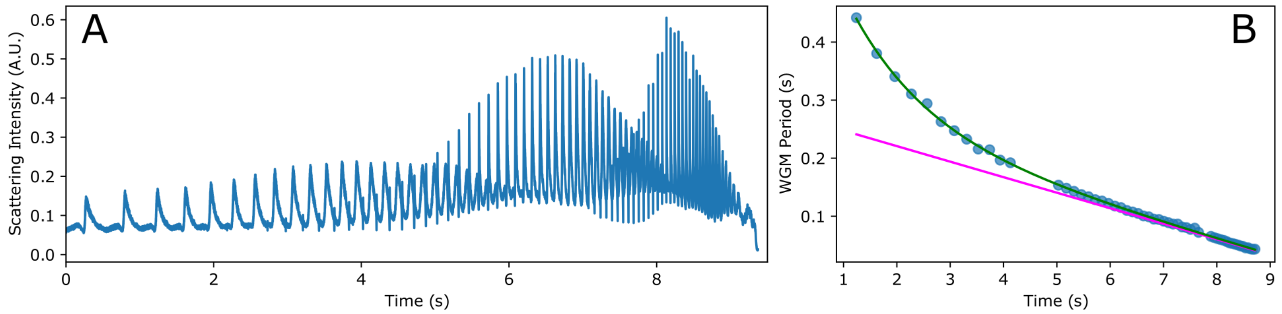

Figure 1: Accelerated evaporation of an optically trapped droplet. **A** WGM spectrum. A series of sharp resonances occur during the evaporation of a levitated droplet. **B** Period between every two consecutive resonances at the time they appear. Initially the WGM period decays exponentially (green fit). At about 6 seconds, however, the decay changes to a linear behaviour (magenta line).

[1] Sergei S. Sazhin, Advanced models of fuel droplet heating and evaporation, Progress in Energy and Combustion Science, **32** (2006).

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# Evaporative self-assembly of soft colloids in pendant and sessile drops: The formation of depletion zones

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We report the role of the orientation of the substrate on the evaporative self-assembly of soft colloids. In particular, we present a comparative study of the microstructure of the deposits of soft colloidal drops dried in sessile and pendant geometry. Aqueous dispersions of surface active soft microgel particles of Poly(N-isopropylacrylamide) (p-NIPAM) having a hydrodynamic diameter of about 650 nm (at 25°C) are used. A uniform monolayer deposit is achieved via the evaporative self-assembly route by simply tuning the concentration of microgels in the sessile drop to monolayer concentration ($C_{ML}$)[1,2]. Identical dried patterns consisting of uniform monolayer deposits are obtained by drying small pendant and sessile drops (volume $\sim 1\mu$L). In contrast, when the concentration of soft colloids is reduced to $C_{ML}/2$, the final deposits are dramatically different for the two geometries. A monolayer coffee-ring forms in the sessile case whereas, for the pendant drop geometry, a region depleted of colloids (the depletion zone) appears prominently near the three phase contact line as shown in Fig.1. The depletion zone widens further with increasing drop volume. The formation of the so-called depletion zone is accounted for by considering a surface tension gradient that sets up across the air-water interface of the drop during the evaporation[3]. The presence of larger depletion zones in pendant drops is reconciled by considering the gravitational forces, that opposes the formation of depletion zone in the sessile drops whereas it is favourable in the pendant case. The time evolution of depletion zone and its dependence on the particle concentration will be presented in detail.

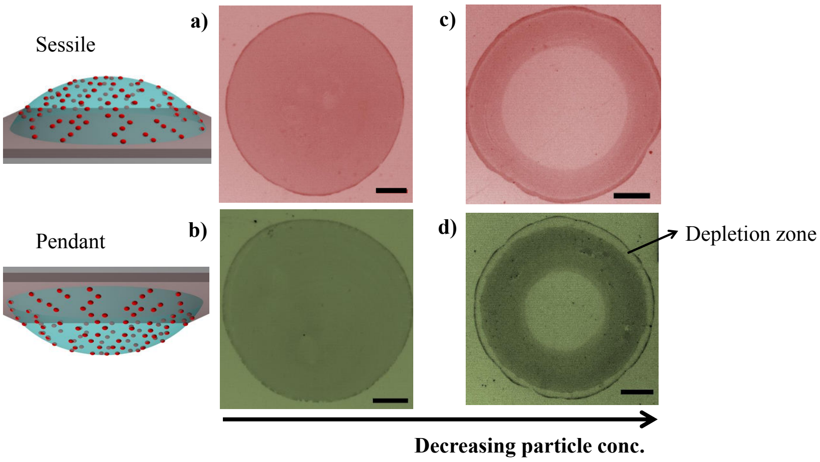

Figure 1: At the monolayer concentration ($C_{ML}$), particles are uniformly distributed irrespective of substrate orientation (a) and (b), implying that particles cover the entire interfacial area. Below monolayer concentration ($C_{ML}/2$), contrasting stains are observed for sessile and pendant drops (c) and (d). Scale bars: 0.5 mm.

[1] M Mayarani *et al.* Nanoscale **9** (2017), 18798.

[2] M Jose *et al.* Physical Chemistry Chemical Physics (2021) DOI: 10.1039/d1cp00440a.

[3] M Mayarani *et al.* Soft Matter **15** (2019), 4170.

# Contact-line deposits from multiple evaporating droplets

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Building on the recent theoretical work of Wray *et al.*[1] concerning the competitive diffusion-limited evaporation of multiple thin sessile droplets in proximity to each other, we obtain theoretical predictions for the spatially non-uniform densities of the contact-line deposits (often referred to as "coffee stains" or "ring stains") left on the substrate after droplets containing dispersed solid particles have completely evaporated. Neighbouring droplets interact via their vapour fields, which results in a spatially non-uniform "shielding" effect. We give predictions for the deposits from a pair of identical droplets, which show that the deposit is reduced the most where the droplets are closest together, and demonstrate excellent quantitative agreement with experimental results of Pradhan and Panigrahi [2]. We also give corresponding predictions for a triplet of identical droplets arranged in an equilateral triangle (see Fig. 1), which show that the effect of shielding on the deposit is more subtle in this case.

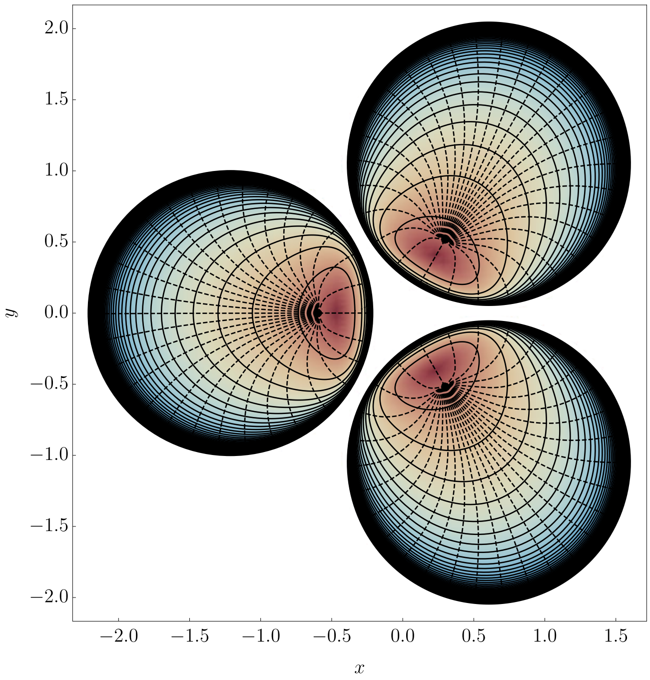

Figure 1: Contours of the local evaporative fluxes (solid curves) and the resulting streamlines of the depth-averaged flows (dashed curves) for a triplet of identical droplets of unit radius with their centres a distance 2.1 apart.

[1] A W Wray, B R Duffy, S K Wilson, *J. Fluid Mech.* **884** (2020) A45.

[2] T K Pradhan, P K Panigrahi, *Coll. Surf. A* **482** (2015) 562.

# The effect of spatial variation of the evaporative flux on the deposition from an evaporating droplet

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The deposition from an evaporating sessile droplet has been the subject of extensive investigation in recent years, particularly regarding the ring deposit that often forms near the contact line (the "coffee-ring") [1]. Of key interest in many industrial applications, such as inkjet printing, is the ability to control the shape of the deposit. We investigate the effect of spatial variation of the evaporative flux on the deposition from a pinned evaporating droplet. We consider a one-parameter family of evaporative fluxes with exponent $n$ (see Fig. 1), which includes diffusion-limited and spatially-uniform fluxes, as well as fluxes with a maximum at the centre of the droplet, as special cases. For a thin axisymmetric droplet we determine the resulting flow due to the evaporation, the evolution of the concentration of particles within the droplet, and the evolution of the mass of deposit on the substrate. We also numerically investigate the particle paths within the droplet (see Fig. 2), to examine the role of the free surface in deposition. Three qualitatively different deposit types are observed depending upon the parameter $n$, namely, ring deposits, paraboloidal deposits and deposits at the centre of the droplet.

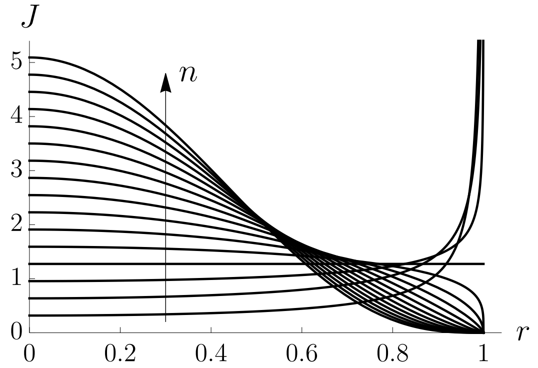

Figure 1: Plot of the evaporative flux $J$ for $n = -3/4, -1/2, \ldots, 4$. The arrow indicates the direction of increasing $n$.

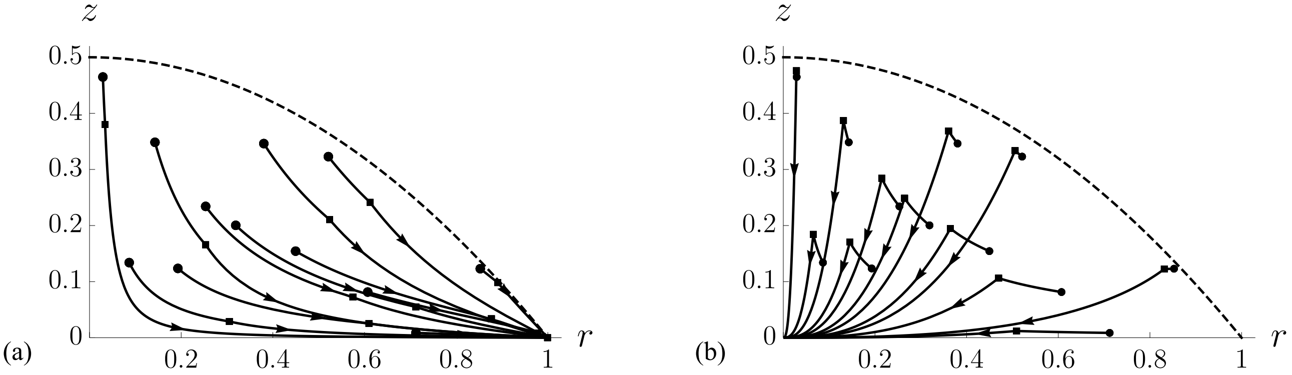

Figure 2: Representative particle paths for (a) $n = -1/2$ and (b) $n = 2$. The dots and squares correspond to the initial position of each particle and the point at which a particle meets the free surface of the droplet, respectively. The dashed lines correspond to the profile of the initial free surface of the droplet.

[1] R. Deegan, O. Bakajin, T. Dupont, G. Huber, S. Nagel, and T. Witten. Physical Review E, **62**(1):756–765, 2000.

# Mass transport in a drying drop of a charged colloidal dispersion: new insights using Mach–Zehnder interferometry

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3. *Current affiliation: CNRS, LFCR, UMR 5150, Univ. Pau & Pays Adour, 64600 Anglet, France.*

In the present work, we use Mach–Zehnder interferometry to thoroughly investigate the drying dynamics of a 2D confined drop of a charged colloidal dispersion [1]. This technique makes it possible to measure the colloid concentration field during the drying of the drop at a high accuracy (about 0.5%) and with a high temporal and spatial resolution (about 1 frame/s and 5 $\mu$m/pixel), see Fig. 1(Left). These features allow us to probe mass transport of the charged dispersion in this out-of-equilibrium situation. In particular, our experiments provide the evidence that mass transport within the drop can be described by a purely diffusive process for some range of parameters for which the buoyancy-driven convection is negligible. We are then able to extract from these experiments the collective diffusion coefficient of the dispersion $D(\varphi)$ over a wide concentration range $\varphi = 0.24 - 0.5$, i.e. from the liquid dispersed state to the solid glass regime, with a high accuracy. The measured values of $D(\varphi) = 5 - 12D_0$ are significantly larger than the simple estimate $D_0$ given by the Stokes–Einstein relation, see Fig. 1(Right), thus highlighting the important role played by the colloidal interactions in such dispersions.

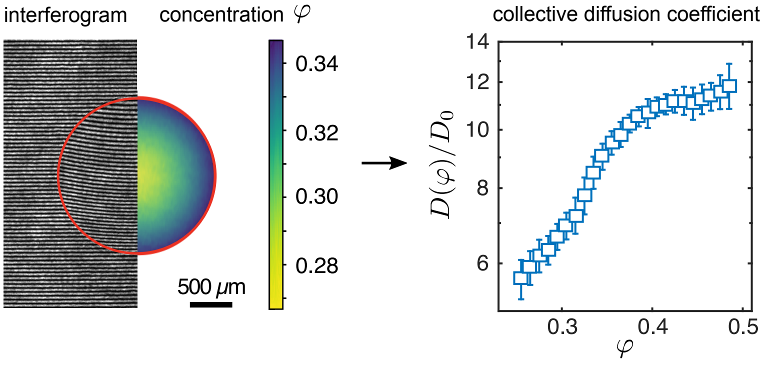

Figure 1: (Left) Colloid concentration field within a drying confined drop measured from a pattern of interference fringe. (Right) Normalized collective diffusion coefficient of the Ludox AS dispersion estimated from our experiments.

[1] B Sobac, S Dehaeck, A. Bouchaudy and J-B Salmon, Soft Matter **16** (2020), 8213.

# Role of polarizability on interfacial tension and surface energy

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*"A liquid spread completely if it is less polarizable than solid [1]."* In accordance with this theory, for equilibrium configuration of drop on a solid surface, numerous arguments are established stating that extend of interactions between polar–polar, polar–non-polar and non-polar–non-polar components of surface tension or energy dictate the final equilibrium contact angle [2]. In this work, the similar hypothesis is verified for the liquid-fluid interface. As depicted in Fig. 1 (A), we critically investigate the impact of the polarizability of the surrounding saturated vapour phase on the equilibrium surface tension ($\gamma_{eq}$) measurement. For extremely volatile liquid drops, where such measurements are always erroneous, we developed a standard protocol to obtain $\gamma_{eq}$. A wide range of liquid-vapour combinations, polar-polar, polar-nonpolar and nonpolar-nonpolar, are studied and it was noticed that apart from these interactions, the influence of molecular weight of both the phases (drop and surrounding saturated vapour) cannot be ignored as shown in Fig. 1 (B). If either phase is purely non-polar, it is observed that the liquid drop interface becomes active only if the molecular weight of vapour is lower than the drop phase. Being an anomalous liquid, water does not follow this observation therefore a study is underway to further investigate this behaviour.

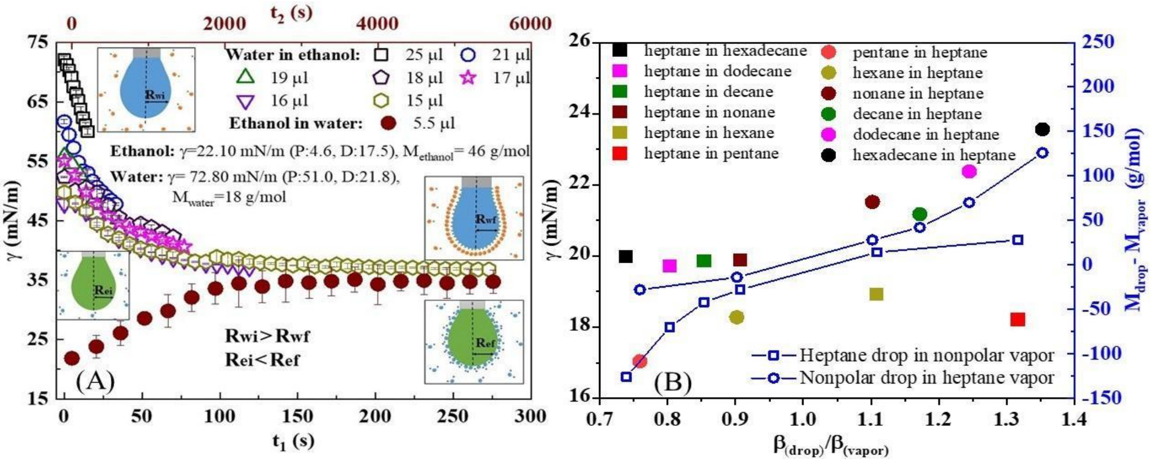

Figure 1. (A) Attainment of equilibrium surface tension in saturated vapour for polar-polar liquid-fluid interface: water drop in saturated ethanol vapour (decrement from 72.10±0.64 to 36.81±0.57 mN/m, open symbols and corresponding time $t_1$) and ethanol drop in saturated water vapour (increment from 21.85±0.30 to 34.73±1.98 mN/m, solid symbols and corresponding time $t_2$) (B) Role of non-polarizability along with the molecular weight for non-polar – non-polar liquid-fluid interface: solid symbols suggest that the increase in non-polar component of either drop or vapour increases the surface tension where as empty symbol represents the dependency on the molecular weight of drop and medium phase.

[1] de Gennes, Pierre-Gilles, Françoise Brochard-Wyart, and David Quéré. "Capillarity and wetting phenomena: drops, bubbles, pearls, waves", Springer Science & Business Media, 2013.
[2] Jin, Ming, Frank Thomsen, Thomas Skrivanek, and Thomas Willers. *"Why Test Inks Cannot Tell the Whole Truth about Surface Free Energy of Solids."* Advances in Contact Angle, Wettability and Adhesion 2 (2015): 419-438.

# Thermally regulated water drop self-propulsion using Laplace pressure manipulation

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Capillary movement of a water drop in a millimetric channel is ubiquitous in nature and many industrial applications, including capillary lubrication and water-oil separation. A common way to generate such movement is to manipulate the Laplace pressure along the water drop, similar to the feeding process of shorebirds. They move a water drop (containing prey) from the tip of their beak to their mouth by repeatedly opening and closing the beak in a tweezering fashion [1]. Utilizing the same concept, we introduced a mechanism to move a water drop along a channel, which is controlled solely by a change in temperature. The water drop in our system is bounded by a bimetallic strip on one side and an acrylic surface on the other. The fixed end of the bimetallic strip is attached to a Peltier element, whose temperature is controlled by a fast responsive PID controller. As the temperature of the bimetallic strip changes, it bends towards or away from the fixed acrylic surface. Consequently, the drop experiences different heights along itself, which translates into a Laplace pressure gradient. For a combination of a hydrophilic bimetallic strip and the acrylic surface, the induced Laplace pressure gradient causes capillary movement of the water drop from the fixed end of the strip towards its free end. For a hydrophobic combination, however, the water drop moves in the opposite direction (*i.e.*, from the free end to the fixed end). Here, we will explain the capillary movement mechanism in detail *via* a thermal analysis that prescribes the bending profile of the bimetallic strip due to its temperature change, which subsequently translates into the Laplace pressure gradient along the drop. We propose that this thermally driven drop manipulation can be used as a passive actuation system for uses in thermal management and lab-on-a-chip applications.

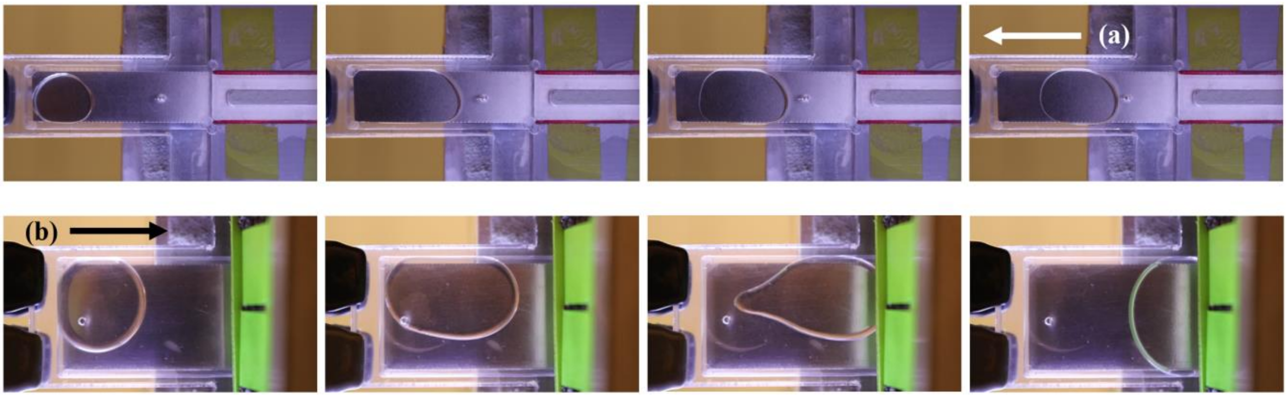

Figure 1. (a) For a hydrophilic surface, the water drop moves from the fixed end to the free end as a result of a Laplace pressure gradient imposed by the bending of a bimetallic strip. (b) For a hydrophobic case, the water drop moves from the free end to the fixed end (opposite direction) using the same actuation mechanism.

[1] M Prakash, D Quere, JWM Bush, *Science.* **320** (2008), 931.

# Capillary dynamics of four-phase contact point while drop merging on hard and soft substrates

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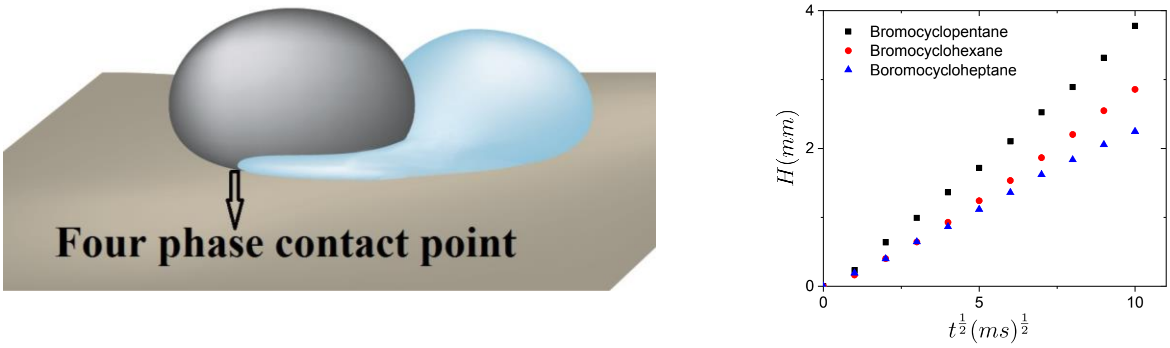
A four-phase contact point, e.g., in merging of immiscible drops, is the point where the liquid-liquid interface advances along the contact line of one drop. The dynamics of drop merging involve various driving and dissipating forces in the dynamics of the four-phase contact point. The viscous friction, i.e. the flow field, within liquids is influenced by the different boundary conditions on the different interfaces (liquid-gas, liquid-liquid, and liquid-solid). Additionally, Marangoni stresses between the two liquids plays role. Effectively, these effects lead to a capillary force acting on the four-phase contact point. In total, the situation resembles the capillary flow in open V-shaped groove. The important difference is that, in classical problem, the grooves are made out of two solid walls, but in the present case one of the "walls" is liquid (Fig.1 (a)). We investigate a range of liquids with different combination of physical properties (viscosity ratio, surface and interfacial tensions). The results show a good qualitative agreement for different liquids between the experimental results and classical Washburn equation ($h \sim \sqrt{t}$), which h is the capillary filled length by the second drop (Fig.1 (b)). Also, by applying PDMS pseudo-brushes on glass substrate, we investigate the effect of softness. These pseudo-brushes leads to higher mobility on the surface and higher velocity of four-phase contact point.



a b

Fig. 1: a: Schematic of capillary rise problem of four-phase contact point during drop merging process. b: Sample results for pairs of water with bromocyclopentane, bromocyclohexane and bromocycloheptane.

# Analysis of a Binary Sessile Droplet Evolution through Machine Learning Algorithms

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Analysis of binary or multi-component droplet evolution, being a crucial part of numerous industries, is challenging for both experimental and numerical methods. We introduce a new method to analyze such interfacial fluid mechanics problem. A binary droplet evolution is investigated through data-driven regression and classification algorithms to capture and predict the environmental conditions, regime of droplet, diameter, and contact angle evolution. The model is trained by experimental measurements of methanol droplet evolving under different environmental humidity levels and substrate temperatures. Higher levels of humidity demonstrate increased interfacial tension and contact angle due to higher amount of water uptake. Different classifiers are used to detect the regime of droplet evolution through point-by-point analysis of droplet profile where decision tree show better performance compared to Naïve Bayes. Regression techniques are utilized for predicting surrounding humidity and time evolution of diameter and contact angle. The results show promising performance for the cases of droplet evolution under unseen conditions. The present approach has great potential in establishing new avenues for analyzing complex physics of multi-component droplet evolution and advancing medical diagnostics.

# Manipulating Programmable Droplets with Vapor Point-Sources

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The manipulation and control of evaporating droplets are important for phenomena as diverse as printing, thin-film deposition and self-assembly [1]. Typical approaches to perform such tasks rely on controlling the intrinsic physical, chemical and/or geometrical properties of the droplet and its environment at the onset of the evaporation process. Here, I will show a novel experimental technique to generate recirculating Marangoni flows within the droplet during evaporation. In particular, the deterministic emergence and real-time control of these flows can be achieved within an evaporating droplet by relying on an external point source of vapor positioned near the droplet's free interface. Depending on the droplet's initial composition, these flows can be either used to control in-situ deposition of materials when the droplet is sessile [2] or, alternatively, they can be used to induce continuous 2D manipulation of a moving droplet for applications in printing, materials deposition and for controllable reactions [3].

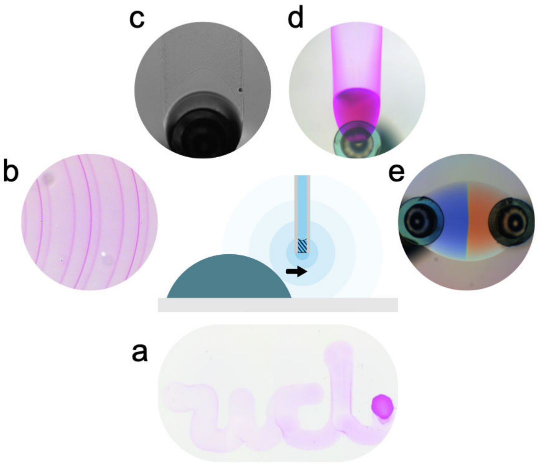

Figure 1. Examples of applications of programmable droplets under a vapour source. (Center) Sketch of a binary droplet moving under the effect of a localised vapor source. (a-e) Examples of applications, including (a,b,d) printing, (c) molecular alignment and (e) chemical reactors.

[1] R. Malinowski, I.P. Parkin and G. Volpe, *Chem. Soc. Rev.* **49** (2020), 7879.
[2] R. Malinowski, I.P. Parkin and G. Volpe, *J. Phys. Chem. Lett.* **9** (2018), 659.
[3] R. Malinowski, I.P. Parkin and G. Volpe, *Sci. Adv.* **6** (2020), eaba3636.

# Continuous Dropwise Condensation in Stagnation Flow Conditions

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Condensation is a very complicated subject to fully unveil as it constitutes a complex interplay of momentum, heat and species transport and interfacial physics. Drop-wise condensation (DWC) adds more layers of complexity by introducing droplet dynamics and the two-way interaction with droplets surrounding. The scientific community were up for the challenge and have been studying ways of promoting DWC over film-wise condensation (FWC). DWC has been shown repeatedly for about a century to possess around an order of magnitude improved heat transfer rates. Additionally, it has been shown that DWC is limited by the maximum size of droplets a surface sustains. Since this realization, promoting DWC has been greatly steered towards developing stable hydrophobic coating techniques. Here, we show using high speed microscopy that aerodynamic drag due to jet impingement provides excellent means of tuning the maximum droplet size without the need of hydrophobic surfaces. To demonstrate the effectiveness of our technique, we perform condensation experiments on a wide range of contact angle and contact angle hysteresis surfaces. Droplets as low as 20 $\mu$m in radius were shed with this technique surpassing the traditional gravity-assisted shedding mechanism by 80 folds. This translates to an improvement of nearly 150% in heat transfer rates. We also show that by our current technique, the effect of NCG can be greatly alleviated. An improvement by at least six folds in mass transfer compactness factor compared to state-of-the-art dehumidification technology was possible.

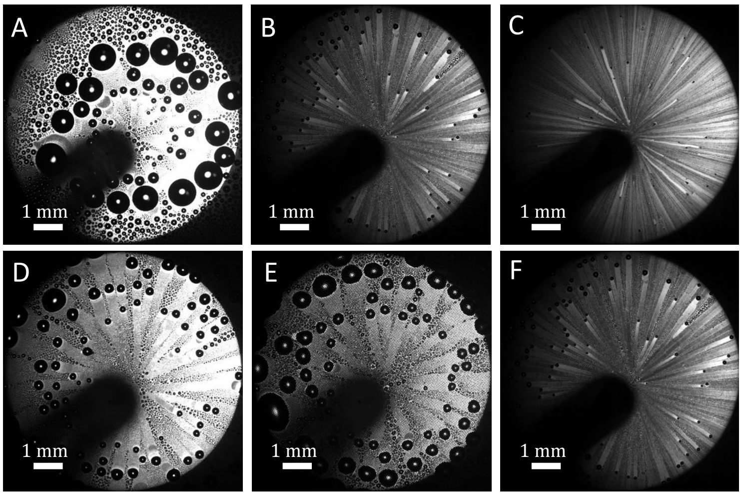

Figure 1: Selected images depicting the maximum droplet being shed under the effect of jet impingement. For the same surface and temperature difference, the effect of jet's Reynolds number is shown at **A.** $Re_j$ = 1200, **B.** $Re_j$ = 1200, and **C.** $Re_j$ = 1200. For the same jet Reynolds number and temperature difference, the effect of surface wettability is shown for **D.** Hydrophilic surface ($\theta_A$ / $\theta_R$ = $85^o/72^o$), **E.** Hydrophilic micro-structured surface ($\theta_A$ / $\theta_R$ = $70^o/50^o$), and **F.** Hydrophobic surface ($\theta_A$ / $\theta_R$ = $107^o/103^o$).

# Coarsening droplet: hydrophilic slippery surface enabled coarsening effect for rapid water harvesting

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Water harvesting through the condensation of vapor in the air has the potential to alleviate water scarcity in arid regions around the globe. When water vapor is condensed on a cooled surface, tiny water droplets act as thermal barriers. Thus, they must be removed rapidly for efficient water harvesting. Passive technologies for droplet removal rely on in-site growth and direct contact of densely distributed droplets. However, it is challenging to remove submicrometer droplets that lead to a large area of water coverage and poor water harvesting. Here, we present a coarsening effect to rapidly remove water droplets with diameters < 20 mm from the hydrophilic slippery liquid-infused porous surface (SLIPS). Such a passive droplet movement rapidly reduces the number of droplets below 20 μm and simultaneously increases the number of droplets with diameters above 150 μm. Due to the coarsening effect, a slightly thicker lubricant with a larger conductive thermal resistance can provide a higher heat transfer performance than a thinner one. We quantitatively study the driving and drag forces to enhance the rapid droplet size evolution. The self-propelled coarsening effect enables rapid droplet removal regardless of surface orientations, showing a promising approach compared to those on PEGylated hydrophilic surface, hydrophobic SLIPS, and superhydrophobic surface in water harvesting.

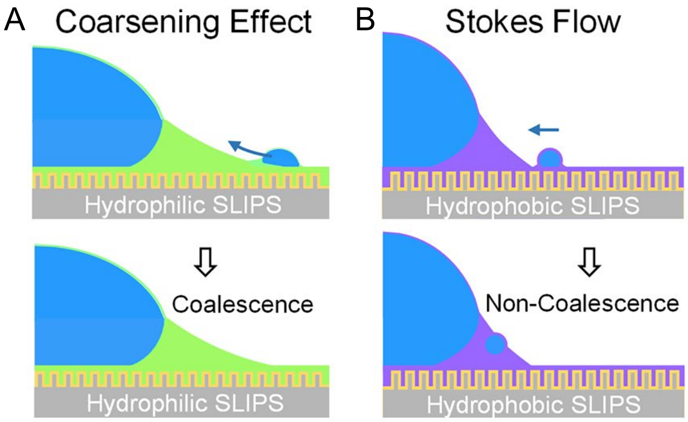

Figure 1. (A). Coarsening effect on hydrophilic SLIPS. A smaller droplet climbing on the meniscus of a larger droplet and coalesce immediately. (B). Non-coalescence droplet on hydrophobic SLIPS. Smaller droplets move to a larger droplet but could not coalesce immediately.

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# Marangoni convection in a slender floating droplet

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The behavior of liquid droplets on a solid substrate was studied extensively in the past few decades. The dynamics of liquid droplets floating on the surface of another liquid ("liquid lenses") is still less explored.

In applications, it can be necessary to change the shape of floating droplets or move them in a controllable way (e.g., in microfluidic devices). The simplest way to influence a liquid droplet is heating which creates Marangoni convection in the droplet and in the liquid substrate.

In the present talk, we consider a droplet of a liquid that floats on the layer of another liquid when being in contact with the gas phase. The substrate bottom and the gas are kept at different values of temperature. Assuming that the liquid droplet is slender because of a small (negative) spreading coefficient or because of the action of gravity, we apply the long-wave approximation that allows to reduce the problem to a closed system of equations that govern the evolution of the shapes of interfaces. In the framework of the precursor model, we describe the droplet on the liquid substrate as a two-layer film. In the region of the droplet, the top layer has a macroscopic thickness, and it is described by standard thin-film equations. Outside the droplet, the equations are amended by corresponding disjoining pressures.

If the temperature of the substrate is constant and the droplet is axisymmetric, a stationary radially symmetric thermocapillary flow, both inside the droplet and in the liquid substrate, is generated. That flow changes the shape of the interfaces, especially that of the interfaces between the droplet and the substrate. With the enhancement of heating, instabilities are developed. By heating from below, the droplets acts as a seed for the development of the monotonic deformational Marangoni instability of the substrate layer leading to its rupture. By spatially homogeneous heating from above, the droplet is unstable with respect to time-periodic in-phase oscillations of both droplet interfaces. The oscillation threshold depends on the initial shape of the contact line. With a further heating's strengthening, a satellite droplet is born; finally, the droplet is broken into fragments that perform asynchronous oscillations.

The spatial inhomogeneity of the substrate temperature leads to a change of the droplet shape and its motion. Typically, it weakens the oscillations.

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# Inkjet Printing on Superheated Surface

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Inkjet printing is a convenient manufacturing technology to direct fabricate electronic devices by depositing functional materials. The quality and accuracy of deposition patterns would be influenced by the resolution of microdroplet dots. Depositing microdroplet onto superheated substrate is a novel method to improve the deposition resolution. Therefore, the silver nanoparticle suspensions were utilized in our experiment to investigate the characteristics of deposition dots, which were printed onto heated ceramic substrates in the temperature range of 80-320 °C. The results revealed that the diameter of deposition dots can be gradually reduced as low as 10 % of the diameter at non-boiling temperature by heating the substrate. Moreover, the deposition patterns are correlated with the traditional droplet boiling morphologies. Thus, four patterns of deposition dots can be recognized, namely evaporative deposition, nucleate deposition, transition deposition, and Leidenfrost deposition (shown in Fig. 1). Among these patterns, the microdroplet dots of nucleate deposition are the most stable with high resolution, which is an ideal pattern for inkjet printing. Consequently, utilizing the superheated substrates could enhance the deposition accuracy with higher dots resolution.

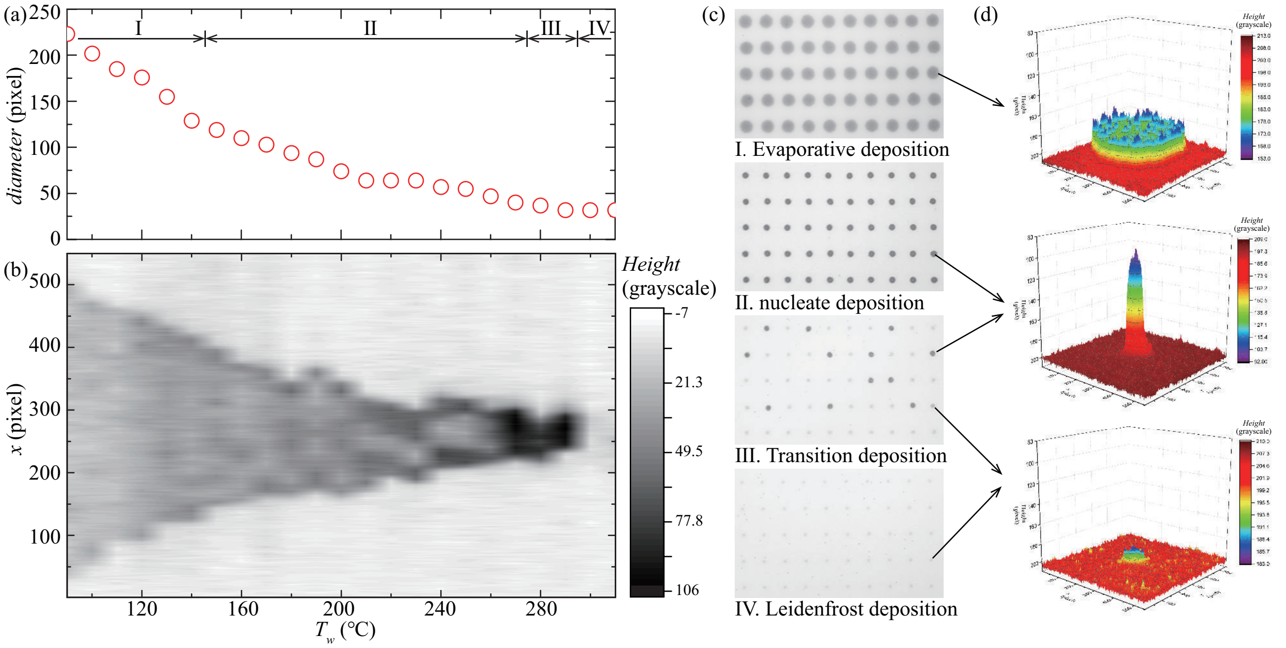

Figure 1: (a) The diameters of deposition dots decreased with higher substrate temperature. (b) The nanoparticle distribution at different substrate temperature. The height were estimated by the grayscale of dots photos. (c) Four deposition patterns were recognized, namely I. evaporative deposition, II. nucleate deposition, III. transition deposition, and IV. Leidenfrost deposition. (d) Three typical nanoparticle distributions were identified.

# Influence of complex fluid properties on highly dynamic interfacial instabilities in gravure printing

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In situ high speed videos of the fluid splitting process in gravure printing at high shear rates and velocities have first been achieved by Schäfer using a Newtonian printing fluid [1]. Schäfer observed highly dynamic interfacial fingering instabilities [2] with a finger frequency proportional to the underlying gravure raster frequency ('lock-in effect') and no printing velocity dependence. We use Schäfer's experimental setup to investigate the influence of complex, shear-thinning fluid properties on the resulting fingering patterns.

We conduct printing experiments at 0.5 to 1.5 m/s with several aqueous polyethylene oxide (PEO) solutions (400,000 to 5,000,000 g/mol @ 2 and 3 wt%) as model fluids for real, water-based printing inks with shear-thinning behavior. Red dye is added to achieve higher optical contrast. For comparison reasons, real printing inks and their diluted versions are also used for the experiments.

Different fluids exhibit diverse pattern formation (Fig. 1). We also observe higher finger frequencies in earlier and lower frequencies in later temporal stages of pattern formation as well as a dependence on printing velocity in later stages. This implies that the lock-in effect might only apply for early temporal stages of fluid splitting. To conclude, complex fluid properties play an important role in pattern formation in gravure printing. In future research, in situ and ex situ approaches [3] shall be combined to take into account levelling and drying dynamics (e.g. droplet coalescence) of the printed patterns and a mathematical model for the influence of complex fluid properties on pattern formation shall be found.

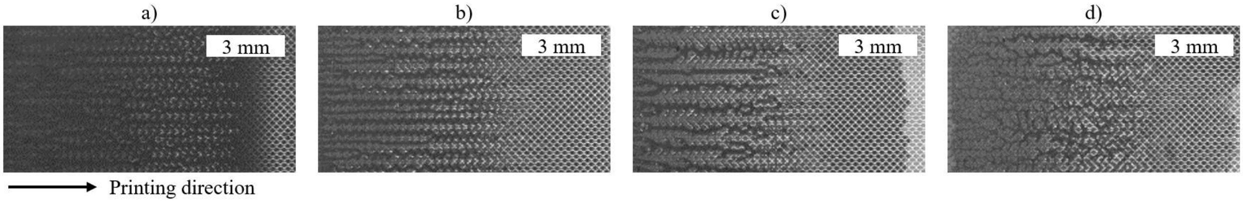

Figure 1. Snapshots of pattern formation for different fluids at same printing parameters. (a) Real printing ink, (b) PEO solution @ 1,000,000 g/mol, 3 wt%, (c) 1,000,000 g/mol, 2 wt%, (d) 5,000,000 g/mol, 2 wt%.

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# Inkjet printing without satellite drops

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We experimentally investigate the formation of drops during inkjet printing. Two different print heads from Microdrop Technologies GmbH and 16 inks covering a wide range of viscosity ($2.9<\mu<41$mPa.s) and surface tension ($28.5<\sigma<72.9$mN/m) are used. Under surface tension effects, the ejected liquid quickly builds up a spherical large bulb. This bulb is connected to a long cylindrical tail originating from the viscous shear at the orifice walls. This typical asymmetric shape influences the dynamics of the liquid ligament that results from the competition between two processes. The first one, named recoil, is responsible for the long tail to be absorbed by the spherical bulb and favours the formation of a single drop without satellites, see Fig. 1a. The second process, called pinch-off, leads to the fragmentation of the ligament between the bulb and the tail. This fragmentation gives rise to unwanted satellite drops, see Fig. 1b. As proposed by Hoath et al. [1], the formation or not of satellite drops can be predicted by comparing the relative kinetics of these two processes.

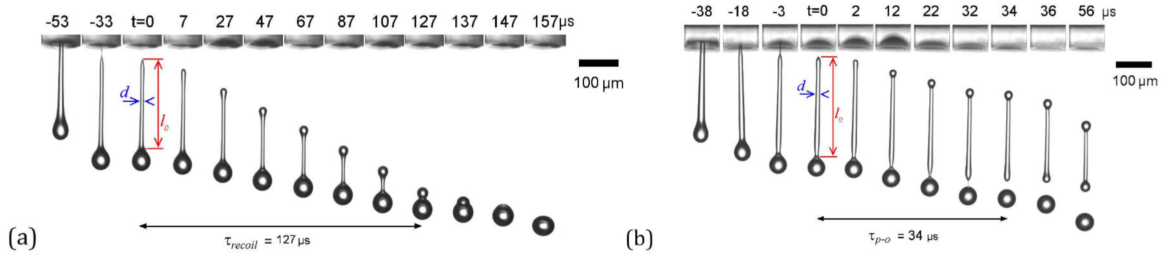

Fig. 1: Inkjet printing (a) without (Oh=0.76) and (b) with (Oh=0.24) satellite drop formation.

In this work, we show that the Taylor-Culick velocity, classically used to estimate the recoil velocity [1], does not correspond to the experimental data. This finding is in agreement with recent numerical simulations made on symmetric but finite ligaments [2]. A model that accounts for the ligament asymmetry and for viscous losses is established and used to predict the recoil time in very good agreement with our measurements [3]. The pinch-off kinetics is then investigated and found to be a function of the initial ligament aspect ratio given by $\lambda=2l_0/d$ (see Fig. 1). Surprisingly, this evolution is not monotonous. For short ligaments, the pinch-off time increases with $\lambda$, while the opposite occurs for long ligaments. The existence of these two regimes can be explained by the influence of the recoil flux. For long ligaments, the inertial pressure of this recoil flux is not strong enough to overcome the local squeezing capillary pressure found just before the bulb. The recoiling liquid accumulates and delays the pinch-off. The pinch-off time is then obtained by introducing an effective ligament diameter [3]. For short ligaments, the viscous timescale is modified to account for the finite size effects [3]. Finally, using the proposed scalings, the ratio T between the recoil and pinch-off timescales is calculated. For $T<1$, no satellite drops are formed, in agreement with a recoil faster than the pinch-off. For $T>1$, satellite drops form, as predicted by the comparison of the modelled timescales. This criterion is of high relevance for any inkjet printing application, as it enables to replace long trial-and-error adjustments by a simple rational approach, which only requires to know the liquid properties and the initial ligament aspect ratio.

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# Magnetic field dependent solidification rate of a colloidal droplet

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The study, presented here, critically investigates the solidification rate of a water-based magnetic fluid, which is responsive to magnetic field. Solidification of droplet via freezing is ubiquitous in nature and affects several aspects of our daily lives and many industrial applications. However, a little is known about a comprehensive model that can predict the freezing or solidification rate of a colloidal droplet while the freezing occurs under the influence of an external body forces other than gravity. In this study, we present a generalized governing equation to describe a magnetic droplet freezing on solid substrate. This model accounts for the strength of the actuating field, physical properties of liquid and ice (solid), in addition to the associated interfacial and surface energies and curvature of the droplet. The mathematical model formulated here is based on the mass, momentum and energy conservation equation, which eventually deduced to an equation similar to the lubrication equation accounting for the phase change and solidification velocity as a function of magnetic field strength. The solution of the governing equation will offer us a mechanism to control the solidification rate of the colloidal droplet, infused with metal nanoparticles, by tuning the magnetic field strength, which we also observed experimentally as shown in Figure 1. Apart from academic interest, this study is essential to freeze casting and additive manufacturing of metallic and organic objects consisting of magnetic nanoparticles. In such processes, solidification rate of a colloidal droplet dictates the pore morphology as well as the strength of the green body.

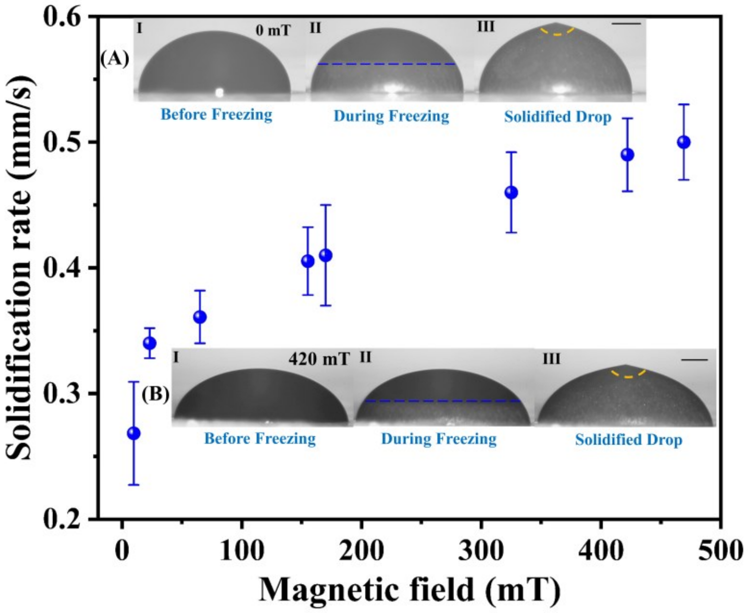

Figure 1. Drop solidification rate as a function of magnetic field: Panel (A) and (B) represent the different stages of the freezing process during the absence and presence of magnetic field, respectively. Blue dotted line indicates solidification front and the yellow curved line indicates tip angle after freezing. Both scale bars in insets (A) and (B) represent 0.5 mm.

# Poster Presentations

# Scaling of novel forces on droplets in non-Newtonian confined flow

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[2] *University of Waterloo, Canada*
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We discover lateral migration dynamics of droplets in non-Newtonian matrix in microflidic confinement is underpinned by several forces. Any deformable object would be acted upon by center directed deformability induced $F_{NIL}$ and matrix viscoelasticity induced force, $F_{VM}$. By comparing cross-stream migration behaviour of Newtonian castor drops and viscoelastic polydimethylsiloxane drops in viscoelastic polyvinypyrrolidone (PVP), we propose the presence of droplet phase viscoelasticity induced force, $F_{vd}$ which switches its direction based on PVP concentration (Fig.1(a)). We empirically develop expression of $F_{vd} = 2.0\,\frac{\alpha}{|\alpha|}(\mu_d/\mu_c)^{-0.33}(Wi_d)^{0.90}(\lambda_d/\lambda_c)^{0.01}\left(\frac{\mu_c D^3\dot{\gamma}}{z}\right)$ [1]. We verify validity of this expression for a few limiting conditions. (i) in case of rigid beads, drop-to-medium viscosity ratio $(\mu_d/\mu_c) \rightarrow \infty$ and hence $F_{vd} \rightarrow 0$ which is the case practically observed. (ii) for a Newtonian discrete phase (such as castor oil drop), drop-to-medim elasticity ratio $\lambda_d \rightarrow 0$ and thus from Eqn.1, $F_{vd} \rightarrow 0$, which is also observed experimentally. (iii) at channel center, since $\dot{\gamma} = 0$, other lift forces vanish and hence, $F_{vd} = 0$ (iv) For air bubbles, $\lambda_d \rightarrow 0$ and $\mu_d \rightarrow 0$, but from Eqn. $F_{vd}$ is a stronger function of $\lambda_d$ thus $F_{vd} \rightarrow 0$ in case of air bubble. Since $F_{vd}$ vanishes in case of air bubbles, $F_{NIL}$ and $F_{VM}$ pushes bubbles towards channel center which is in agreement with the literature. On the other hand, comparing lateral migration behaviour of a castor oil droplet in viscoelastic PVP and shear-thinning polyethylene oxide (PEO) we propose presence of wall directed matrix shear thinning induced force, $F_{SM}$ which scales as $\mathrm{F_{SM}} \sim ((\mu_U - \mu_L)(\dot{\gamma}_L - \dot{\gamma}_U)\,D^{3.7})/h^{1.7}$ [2]. We verify the above expression for $\mathrm{F_{SM}}$ to following boundary conditions: (i) In case of Newtonian and constant viscosity viscoelastic phases (e.g. PVP), $\mathrm{F_{SM}} = 0$ as $(\mu_U - \mu_L) = 0$, (ii) at the channel centre, $\mathrm{F_{SM}} = 0$ as $(\mu_U - \mu_L)$ and $(\dot{\gamma}_L - \dot{\gamma}_U)$ both vanish due to symmetry and objects would not migrate in the lateral direction.

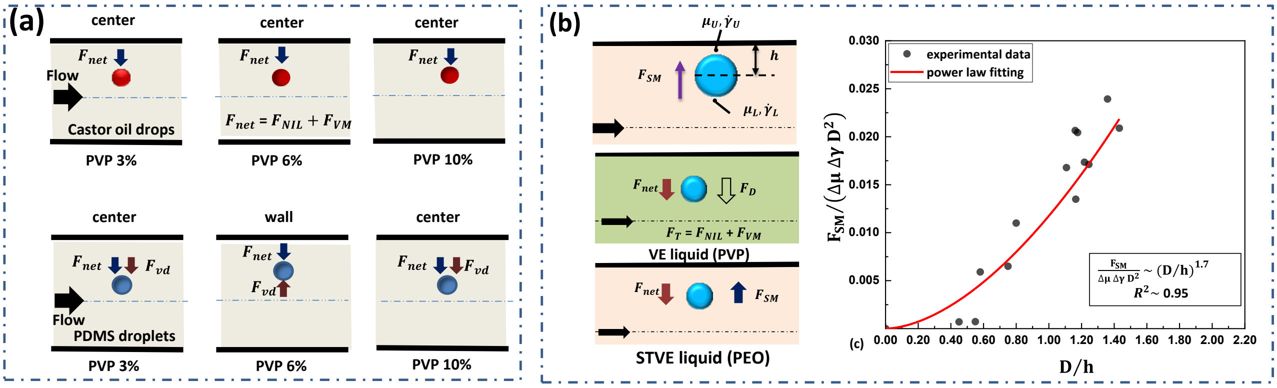

Figure 1: (a) Migration dynamics of droplets in viscoelastic PVP, (b) Migration dynamics of droplets in shear-thinning viscoelastic PEO

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# Ouzo Effect in Droplet Evaporation under Controlled Environmental Condition

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Multi-component droplets are the heart of numerous industries such as biodiagnostics, microfabrication, coating technology, and ink-jet printing. Although evaporation of a single component droplet is well understood, the interconnected mechanisms during evaporation of a multi-component droplet are complex and not yet fully understood. Mechanisms like Marangoni effect, multi-component diffusion, nucleation of microparticles, absorption/adsorption and possible condensation of a second component make the problem highly non-axisymmetric. In the present work, we study the effect of environmental effects on evaporation of a ternary methanol-anise oil-water droplet through infrared thermography and optical microscopy. Various evaporation patterns are observed during droplet evolution based on the humidity level of surrounding. Our results show that the behavior of a multi-component droplet under different humidity of the environment can be tuned by changing the substrate temperature. The current study opens inexpensive and easier approaches to better control and enhance the quality of final products such as light emitting diodes and biosensors.

# Governing equations and solution multiplicities for a static ridge of nematic liquid crystal

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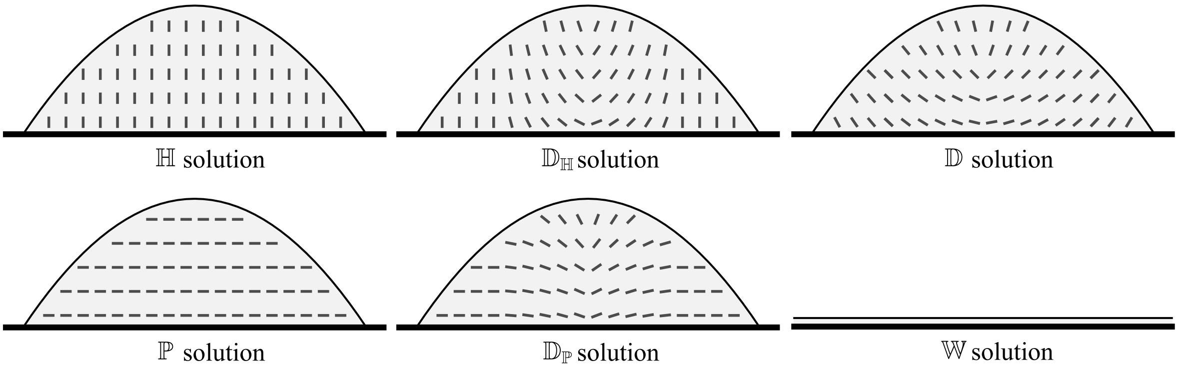
Technological interest in nematic liquid crystal (nematic) droplets and films includes their applications for liquid crystal display manufacturing [1,2] and emerging technologies, such as microfluidics [3], adaptive lenses [4], and microelectronics [5]. Many of these complicated multiphase systems involve interfaces between the nematic, a solid substrate, and a passive gas, and include nematic–solid–gas three-phase contact lines. Theoretical studies of these systems often use well-established theories of Newtonian droplets and films [6], which fail to account for the non-Newtonian nature of nematics.

Motivated by a desire to increase understanding of nematic droplets and films, we use constrained energy minimisation of the nematic Oseen–Frank and Rapini–Papoular energy densities [1] to formulate and analyse the full governing equations for a static sessile two-dimensional ridge of nematic. We then consider the special case of a thin symmetric ridge, for which we obtain insight into the multiplicity of solutions for the free surface height and the nematic molecular orientation. In particular, depending on the values of material parameters, we find solutions for the free surface height and the nematic molecular orientation with uniform molecular orientations, denoted $\mathbb{H}$ and $\mathbb{P}$ solutions, with partially distorted molecular orientations, denoted $\mathbb{D}_{\mathbb{H}}$ and $\mathbb{D}_{\mathbb{P}}$ solutions, with completely distorted molecular orientations, denoted $\mathbb{D}$ solutions, and a wetting $\mathbb{W}$ solution for which the nematic wets the solid substrate completely, as summarised in Fig. 1.



$\mathbb{H}$ solution

$\mathbb{D}_{\mathbb{H}}$ solution

$\mathbb{D}$ solution

$\mathbb{P}$ solution

$\mathbb{D}_{\mathbb{P}}$ solution

$\mathbb{W}$ solution

Figure 1: Schematic diagram summarising all of the possible solutions for the nematic molecular orientation for the case of a thin symmetric ridge.

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# Self-Assembly and Phase Separation in Globular Protein Drying Droplets with and without Thermotropic Liquid Crystals

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Self-assembly and phase separation are ubiquitous phenomena in soft matter-like systems such as colloids, polymers, proteins, etc. These systems can be easily relaxed from one state (initial multi-colloidal fluid) to another (dried organized film) through a non-equilibrium process that exchanges energy and matter with the environment to drive their assemblies. This experimental work involves an in-depth study of the biologically relevant complex systems where the behavior of three different globular proteins, bovine serum albumin (BSA), myoglobin (Myo), and lysozyme (Lys) with and without the thermotropic liquid crystal (5CB) is studied using optical microscopy and quantified using image processing techniques and statistical tools. The textural image analysis reveals three regimes during the drying process in 5CB, whereas no intensity variation is observed in its absence. The surprising outcome is the emergence of the different patterns- the umbilical defect of [+1] strength in each cracked domain of the dried BSA droplet near the periphery, whereas 5CB is randomly distributed the Myo and Lys droplets (Fig. 1). This study motivates researchers to consider such systems in a new light; an initial complex fluid that can consume its internal chemical potential as its solvent evaporates and drives the self-assembly of complex structures.

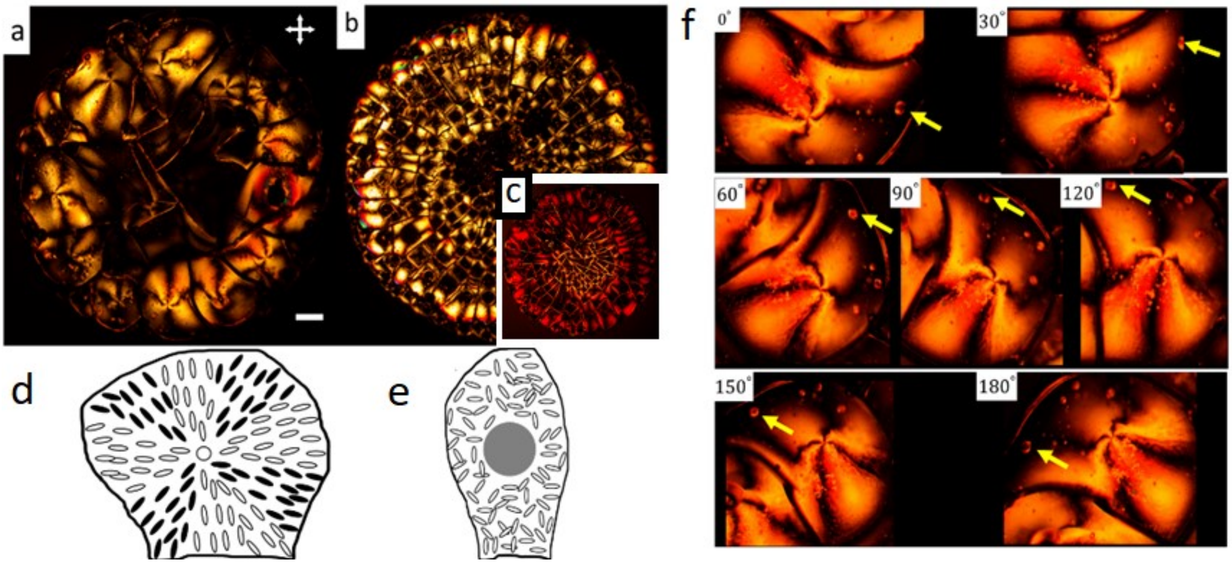

Figure 1. Dried films of the protein droplets under crossed polarizing microscopy (represented with the crossed arrows) in the presence of 5CB: (a) BSA, (b) Lys, and (c) Myo. The scale bar is of length 0.15 mm. The orientation of 5CB is shown in (d) and (e). (f) One domain of the BSA droplet is magnified, confirming the defect structure's strength where the yellow arrows indicate the reference point.

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# Colloidal deposits of an evaporating sessile droplet in confined geometries

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The morphology of deposits obtained from the evaporation of a sessile droplet depends on a variety of factors, including but not limited to wettability, particle size, solvent liquid, relative humidity, and temperature of the surface [1,2,3,4]. The radial capillary flow, induced by evaporation at the three-phase contact line, results in the well-known “Coffee Ring Effect.” While several researchers have experimented with the parameters mentioned above to manipulate the deposits left by a sessile droplet in open conditions, the underlying physics in confined geometries still has many available questions. We have explored the evaporation dynamics of particle-laden water droplets in the parallel plate confined geometry in the current work. Evaporation, in such cases, is limited by the diffusion of vapor to the surrounding environment and hence, results in longer evaporation times. The deposits are analyzed via profilometry and scanning electron microscopy. We observe that the deposits can be substantially manipulated by varying the extent of confinement. The obtained deposits are explained through the capillary flow and pinning at the three-phase contact line observed through optical microscopy. The insights obtained could enhance the understanding of diffusion-limited evaporation in confined geometries and provide an alternative to the traditional methods of coffee ring suppression.

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# Single droplet impingement of urea water solution on porous surfaces

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Selective catalytic reduction (SCR) is an important technique to reduce $NO_x$-emissions in the exhaust gas of diesel-powered vehicles. Ammonia is used as reducing agent, which is carried in the vehicle in form of an urea water solution. The urea water solution is injected into the exhaust pipe in front of the catalyst, where the evaporation of the solution and the decomposition of urea releases the required ammonia. Due to transient operating conditions and the compact design of the exhaust aftertreatment system, incomplete evaporation of the urea water solution may occur. A liquid film can be formed and leads to the formation of solid deposits, which significantly reduce the efficiency of the SCR-system. Due to high dosing rates and short distance between injector and SCR-catalyst droplets impinge not only on the exhaust pipe wall, but also on the porous catalyst surface. For avoidance of deposit formation, detailed understanding of the droplet/wall-interaction is required. Subject of the present work is the investigation of single droplet impingement of urea water solution on porous surfaces under variation of the droplet momentum, target temperature and porosity. Droplet impact is recorded by high-speed shadowgraphy. Image processing is used for determination of droplet properties and identification of characteristic interaction regimes.

The results allow the development of regime maps describing the hydrodynamic and thermal phenomena *deposition, splash, boiling induced breakup, rebound with breakup* and *total rebound* as a function of the kinetic and thermal parameters K and T*. For the first time, regime maps are developed which describe the droplet/wall-interaction of urea water solution on non-smooth surfaces. Based on systematic investigations the influence of the surface properties on the transition boundaries can be shown. The porosity of the surface leads to a significant shift of the wetting boundary to higher temperatures, as the resulting steam can escape through the pores. The regimes *partial rebound with breakup* (Figure *1*) and p*artial rebound* are introduced to describe the single droplet impingement on porous surfaces. The experimental results serve as a database for modelling the droplet/wall-interaction on porous surfaces.

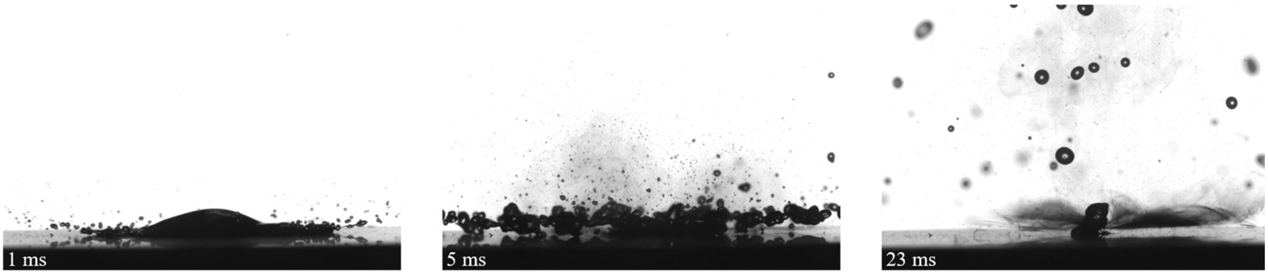

Figure 1: Characteristic behavior of droplet impact on porous heated surfaces in the *partial rebound with breakup* regime.

# Wetting behavior of surfaces with tunable topography

**Gissela Constante**[1], Indra Apsite[1], Dennis Schönfeld[2], Thorsten Pretsch[2], and Leonid Ionov[1,3]

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Various living organisms have structured surfaces with specific wettability that allows their efficient adaptation to the environment and improves their survival rate. For example, the rice leaves have micro- and nanoscale structures on their surface that form a superhydrophobic surface for self-cleaning and water repellence[1]. Bioinspiration of these natural surfaces in science can be beneficial for applications in biotechnology, microfluidics, textiles, fabrication of sensors, etc[2]. Addressing these challenging goals requires the development of both materials with tailored properties and methods for the fabrication of structured surfaces. In comparison to previously reported surface patterning techniques, melt-electrowriting is a novel and solvent-free technique that is based on 3D printing and electrospinning which allows programmed deposition of polymeric microfibers [3]. Shape memory polymers offer a very interesting combination of properties such as switching of mechanical properties and capability of stimuli-induced restoration of shape after deformation [4, 5].

In the present study, we use report fabrication of structured surfaces with shape-memory features (continuous vertical lamellas) with high aspect ratio using melt electrowriting as well as investigation of their wetting behavior. It was observed that wetting behavior depends on the state of features, which could be either soft or hard depending on temperature, height, and distance between them. The lamellas can be deformed by water droplets at elevated temperatures and can be frozen in a deformed state by cooling. The deformed state can be completely recovered at an elevated temperature.

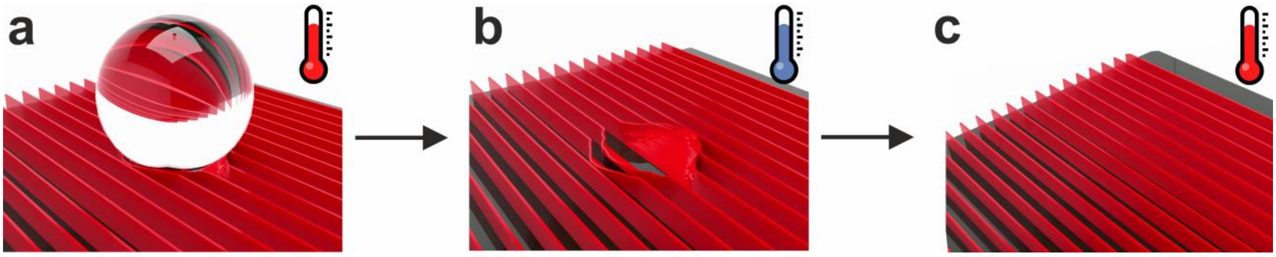

Figure 1. Shape-morphing actuation of the surface of lamellas. a) Deformation of the soft surface by the advancing volume of the drop made at melting temperature, b) Fixation of the deformed surface by lowering the temperature until the crystallization point, and c) recovery of the original topography at melting temperature.

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# Contact Angles and Dewetting Dynamics in Visco-Elastic Substrates

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When a micron sized droplet is sitting on a (visco-) elastic substrate gravitational forces can be neglected, and its shape is determined by an interplay of capillary and elastic forces. If the elasticity of the substrate is reasonably low, the three-phase contact line is pulled upwards and the droplet/substrate interface is deformed like a circular cap. Theory predicts that the exact contact angle (Neumann triangle) depends on an interplay of droplet size and elasticity of the substrate. Consequently, the contact angle is expected to impact also the dewetting velocity. And even that droplets on soft substrates have been widely studied experimentally in the recent years, only few experiments were conducted for very small droplets and very soft polymers ($E < 10$ kPa) enabling sufficient resolution to confirm or falsify the theoretical predictions.

In our study we investigate the dewetting dynamics and rim shapes of circular holes and the shape of sessile droplets in their equilibrium state. The substrates consist of different polydimethylsiloxane (PDMS) rubbers spanning an E-module between 2 MPa and 3 kPa (Sylgard 184 [1:10] – Dowsil Cy52-276 [1:1]). As dewetting liquid we use polystyrene with a molecular weight of 18 kg/mol that is glassy at room temperature with typical film thickness between 80 and 200 nm. The resulting droplets have a typical size between 1 and 6 µm and result from the dewetting of a thin PS layer. At a desired stage of dewetting the polystyrene rims or droplets are quenched to room temperature and imaged in their glassy state by atomic force microscopy (AFM) in tapping mode. The buried interface is obtained by embedding the PS films or droplets in a UV-curable glue (NOA-60) and lifting them off from the PDMS substrate. The deformation of the PS/PDMS interface is frozen into the PS and can be obtained by imaging also the bottom side or rim or droplet by AFM.

# Liquid Droplets over a Liquid-impregnated Surface: Cheerios and Reverse-Cheerios Effects

**Butunath Majhy**[1], and Ashis Kumar Sen[2]

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[2] *Affiliation of the second author (Indian Institute of Technology Madras)*

Droplets and solid particles at a liquid surface and droplets on soft solid substrates exhibit a long-range interaction. Here, we show that adjacent volatile liquid droplets exhibit long-range attraction or repulsion on an immiscible liquid-impregnated surface. We study the interaction between adjacent liquid (water) droplets on an immiscible liquid (oil)-impregnated surface. When the liquid drops are introduced, the native flat interface of the impregnating liquid will deform owing to the gravitational and capillarity forces[1]. The interface height will increase closer to the edges of the droplets, where the contact angles will be governed by Neumann's law[2]. The droplets will experience the capillary force originating due to the interface curvature and buoyancy force. Whereas evaporation of the droplets will create a denser vapour cloud at the adjoining sides leading to asymmetric evaporation, giving rise to a surface tension gradient and resulting in the surface tension force on the droplets. Remarkably, we find that initially, the interaction is attractive, analogous to the "Cheerios effect" but beyond a critical time the interaction becomes repulsive, depicting "Reverse-Cheerios effect". The wettability of the impregnating immiscible liquid to the liquid droplets will decide the contact angles at the edges of the droplets and hence the migration dynamics. Also, we study the interaction between non-volatile liquid (oil) droplets on an immiscible volatile liquid (water)-impregnated substrate and observed similar observations. Thus, our work provides a fundamental understanding of the mechanism of interactions on liquid-impregnated surfaces from our daily life observations to complex phenomena observed in research. Its collective dynamics find application in droplet condensation, self-transport, drug transport.

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# Drop recoil after impact on hydrophobic glass

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[2] *Northwestern Polytechnical University, School of Marine Science and Technology, Xi'an, Shaanxi, China*

There are two regimes of drop recoil [1] after impact on hydrophobic glass. In viscous regime, it seems there are two stages and dynamic contact angle is key point to understand those dynamics. In the first, drop almost recoil at constant speed while its shape likes inverse disk. With the impact velocity rises, the constant speed reaches an upper limit value fast and then keep constant regardless of impact velocity. This upper limit speed shows dewetting characteristics as same as dry hole growing in viscous liquid film [2]. In the second, the recoil slows down until static while the shape turns to spherical cap. In inertial regime, there is two sages too. Drop tend to recoil at constant speed first and then rebound on substrate. With the impact velocity rises, the constant speed rises too but all recoils collapse into one uniform process as predicted by model. The slope also agrees with the prediction and regardless of substrate wettability. In this study, a series of glycerinwater and ethanol-water are mixed, respectively. With glycerol rate and alcohol rate rise, both kind of mixtures show the same drop recoil and turns from inertial to viscous regime. It indicates viscous recoil not depends on liquid viscosity but others.

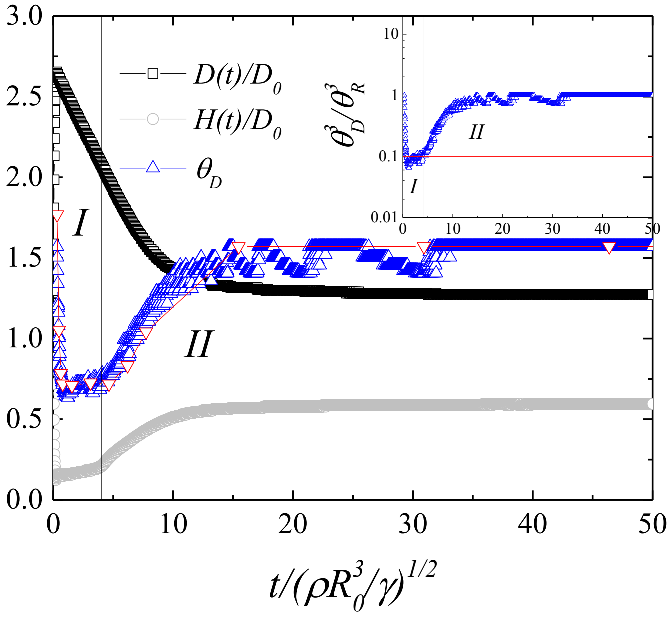

Figure 1: The evolution of spreading diameter ($D(t)$), height ($H(t)$) and dynamic contact angle ($\theta_D$) after glycerin (80wt%) and water mixture drop impact on glass substrate at 4m/s. There are two stages of drop recoil. It's distinguished well by a relationship of dynamic contact angle and receding contact angle ($\theta_R$). The red triangle data are manual measure results.

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# Sessile drops in weightlessness: an ideal playground for challenging Young’s equation

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[1] *1Aix-Marseille University, CNRS, IUSTI UMR 7343, Marseille 13013, France*

Sessile drop creation in weightlessness is critical for designing scientific instruments for space applications and for manipulating organic or biological liquids, such as whole human blood or DNA drops. It requires perfect control of injection, spreading, and wetting; however, the simple act of creating a drop on a substrate is more complex than it appears. A new macroscopic model is derived to better understand this related behaviour. We find that, for a given set of substrate, liquid, and surrounding gas properties, when the ratio of surface free energies to contact line free energy is on the macroscopic scale, the macroscopic contact angle can vary at static equilibrium over a broad volume range. It can increase or decrease against volume depending on the sign of this ratio up to an asymptotic value. Consequently, our model aims to explore configurations that challenge the faithful representativity of the classical Young’s equation and extends the present understanding of wetting.

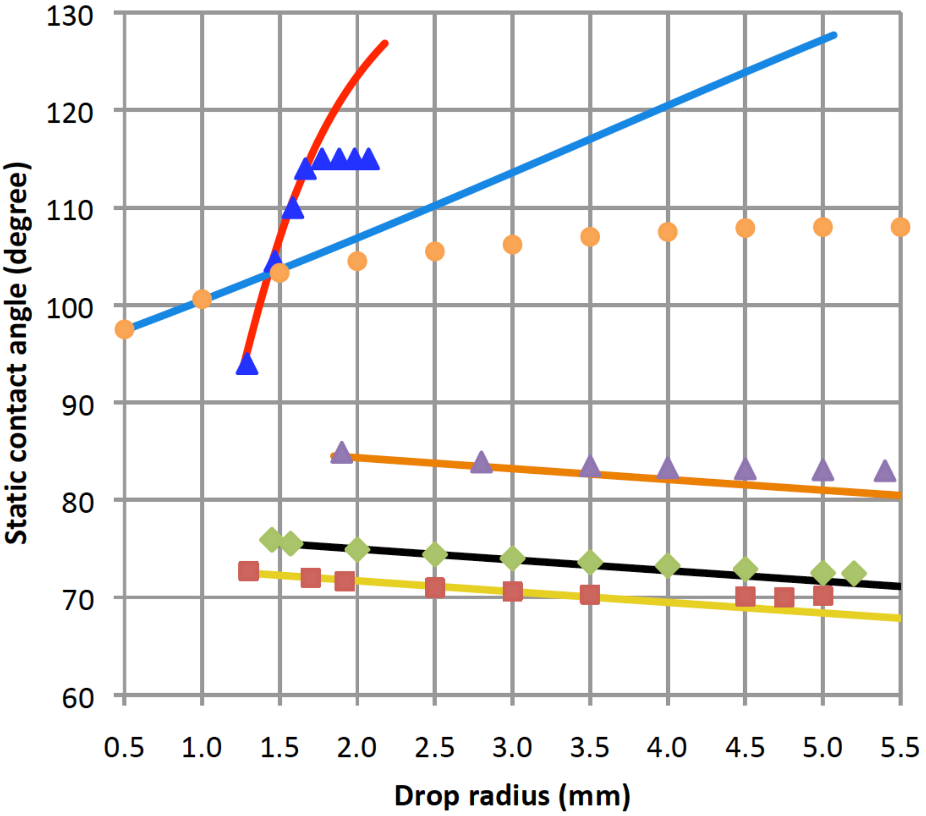

Figure 1. Comparison of proposed model with published experimental data.

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# Floating liquid marbles, their stability and collapse patterns

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## ABSTRACT

Liquid marbles (LMs) are non-wetting particle coated drops of liquids which are isolated systems. Due to their Cassie Baxter state, they are capable of floating on a liquid substrate and collapse after a certain time period. We prepared these liquid marbles by using hydrophobic PTFE by rolling a drop at a particular angle and a fixed distance. These reproducibly coated marbles showed fascinating collapse patterns and collapse times by changing surface tension. Petal shaped patterns were obtained in the case of no surface tension gradient and uniformly spread patterns were obtained by introducing surface tension gradient. Using methylene blue in the core of LM exhibited high stability towards collapse which remained stable upto 6 hours during the course of which they underwent buckling. Inherent charge of the dye allowed tuning of the stability of the liquid marble. Incorporation of surfactants in the coating of liquid marbles also gave us ultimate clues about the nature of coating itself. Effective surface tension was calculated using the puddle height method and it was directly proportional to the stability of floating LM. Calculation of the capillary interaction forces allowed to understand both the nature of forces between particles. Finally, changing the temperature of the underlying liquid substrate led to change in the stability of LM without using any special coating.

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# Influence of surrounding pressure on the dynamics of spreading and wetting

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In this work, the role of elevated surrounding pressures on spontaneous and controlled drop spreading is studied. Spreading of drop with four viscosities (ranging between 12.09 mPa.s - 713.4 mPa.s) on PTFE (Polytetrafluoroethylene) substrates is analysed in four different surrounding pressures. As observed in atmospheric conditions, three distinct spreading regimes: an initial spreading regime, a brief transition regime followed by a late-stage viscous regime are observed. The early time dynamics conform itself to a power law where the empirically obtained exponent, $\alpha$, that defines the rate of spreading, is a function of surrounding pressure. Specifically, an increase in surrounding pressure decreases $\alpha$ in the inertial regime as depicted in Fig. 1(a). Additionally, an increase of surrounding pressure reduces the onset time of transition from one regime to another thus the pressure has a greater influence on the switchover time for this transition. This in turn lowers the transition radius at the terminal end of the inertial regime. Overall Energy Balance (OEB) approach with Lucas empirical model for role of pressure on viscosities is considered for theoretical understanding of surrounding pressure effect on the controlled droplet spreading behaviour. With a needle-in-drop arrangement, droplet spreading was also studied, and dynamic wetting of droplet was measured through the quantification of advancing contact angle ($\theta_a$). A close agreement between the experimental findings and the analytical predictions is observed as shown in the inset plot of Fig 1(b). It was observed that an increase in pressure during the advancing stage lowers the spreading radius and simultaneously increases the contact angle. Therefore, with the increase in surrounding pressure, the increment in the advancing contact angles ($\theta_a$) was observed. Furthermore, the drag force on the droplet becomes more dominant over the cohesive force as pressure is increased. This subsequently increases the relative significance of viscous forces over inertia forces acting on the droplet in the same manner.

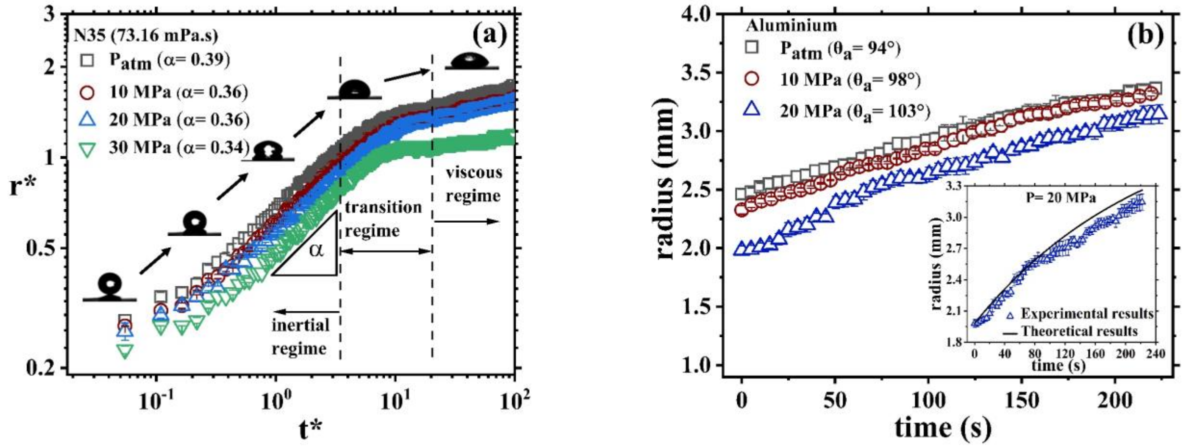

Figure 1 Dynamics of droplet spreading various chamber pressures: (a) Temporal evolution of the dimensionless initial spreading radius for N35 droplets on PTFE substrate, (b) Theoretical and experimental advancing droplet radius of water spreading on Aluminium substrate.

# Anomalous flow behavior of viscous fluid droplets

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Author list: **M. Vuckovac**, M. Backholm, J. V. I. Timonen, and R. H. A. Ras

Viscosity plays a crucial role in limiting fluid flow and mass transfer [1,2] at all length scales and in a wide range of systems from industrial processes to biological circulatory networks [3]. Here we show an unusual viscosity-enhanced phenomenon for droplets moving under liquid-repellent confinement [4]. Specifically, we find that the velocity of a gravity-driven, highly viscous glycerol droplet inside a sealed superhydrophobic capillary exceeds more than ten times the low-viscosity water droplet velocity. Further, we show that the low-viscosity droplets exhibit rapid rotational internal flow with velocities higher than the center-of-mass velocity. As opposed, the faster moving high-viscosity droplets show nearly vanishing internal flows. We find that this anomalous viscosity-enhanced droplet motion is due to viscosity-suppressing deformation of the drop-air interface. Finally, our work demonstrates the unexpected role of the plastron (air trapped within the micro/nanostructure of the superhydrophobic coating) in controlling fluid flow beyond the mere reduction in contact area and friction.

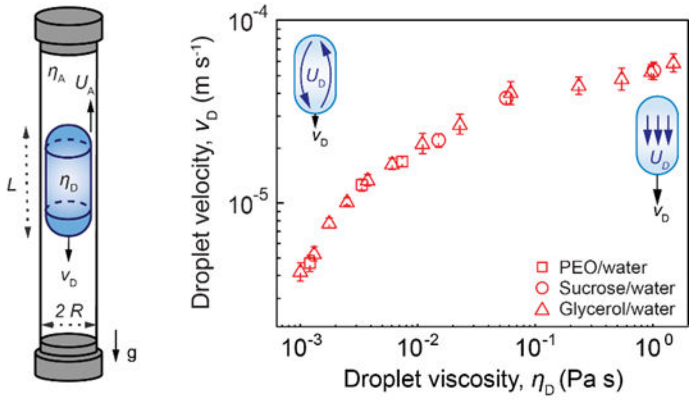

**Figure 1.** Schematic illustration of the gravity-driven droplet motion inside superhydrophobic capillary with observed droplet velocities as a function of fluid viscosity. Insets are illustrations of internal flows for low-viscosity (left) droplets and high-viscosity droplets (right). Here $\eta_D$, $L$, $v_D$, and $U_D$ stand for the droplet viscosity, droplet length, droplet center-of-mass velocity, and droplet average internal flow velocities, respectively, while $R$ is the capillary radius, $\eta_A$ is the air viscosity, and $U_A$ is the average air velocity through the plastron.

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# Experimental study on cold Leidenfrost phenomenon for droplets of low surface energy fluid

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Droplet behavior of working fluid with low surface energy are widely used in a variety of industrial fields and advanced technologies, such as refrigerant spray cooling[1], lab on a chip[2] and so on. Their wetting and kinetic behavior play a very important role in improving the efficiency of industrial processes. In this paper, the superwetting behavior of FC-3283 droplets with low surface energy was overcomed by using the action of micro-airflow on the surface of regular micropores. A suspension oscillation state similar to superhydrophobicity was developed, as shown in figure 1. Droplet behavior in this situation was identified as Cold-Leidenfrost phenomenon. Analogous to Young's equation, the concept of pseudo contact angle for the dynamic process of Cold-Leidenfrost droplet was put forward. The state variation of droplet wetting behavior was discussed. The conversion relationship between kinetic energy and surface energy of droplets during oscillation was found, which make droplets oscillate periodically at a stable frequency. The relationship between the contact angle of droplets and Weber number under the influence of inertia force and surface tension was explored.

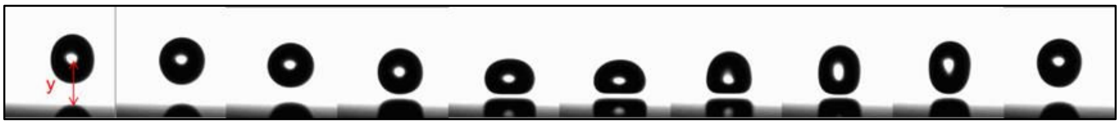

Figure 1. Oscillation behavior of cold Leidenfrost phenomenon of droplets on regular micropore surface.

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# Investigation of Cassie-Wenzel transition on thin porous material

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The ubiquitous nature of wetting and spreading phenomena has sustained interest in the topic since the time of Thomas Young and Pierre-Simon Laplace. The behaviour of liquid droplets on solid surfaces is of importance due to the transferrable applicability to modern lifestyle and industries like medical, biological, environmental, and engineering [1]. Also relevant for aerospace, oil drilling, and micro/nano fluids and nano fabrications [2]. For these practical applications many droplets will encounter rough and porous surfaces, therefore it is important to understand wetting and spreading kinetics on porous substrates for the designing and controlling wetting processes on those substrates. In the case of spreading over porous substrates, an important phenomenon is to be considered. The liquid can either be in the Cassie-Baxter state, where the droplet bridges between surface features with trapped air underneath or the Wenzel state, where the liquid wets entirely the surface and no air is trapped. Transition from the Cassie-Baxter to the Wenzel state occurs when the contact angle reaches the critical value a transition from Cassie-Baxter state to Wenzel state takes place. After that the liquid from the droplet penetrates into the porous substrate (see Figure 1). Cassie–Wenzel wetting transition can be seen in the wetting of hair. When the advancing contact angle reaches a critical value the liquid starts to penetrate inside the hair array [3].

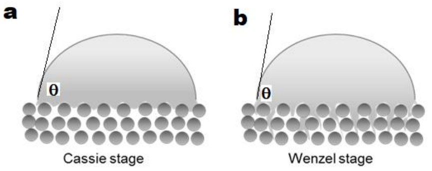

Figure 1. Behaviour of liquid droplet on the porous substrate in the case of partial wetting.

The investigation of simultaneous spreading/evaporation/penetration of liquid droplets deposited on a porous substrate in case of partial wetting is presented. The dependency of the behaviour of spreading/evaporating/penetrating droplet of surfactant solutions on the relation between the critical contact angle, initial contact angle and hysteresis contact angles is investigated as function of surfactant concentration.

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# Negative Dielectrowetting of Thick and Thin Films

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The static wetting behaviour of a solid surface by a droplet of a dielectric liquid in air can be modified using a surface localised non-uniform electric field, created using a voltage $V$ applied to embedded interdigitated electrodes [1]. Liquid dielectrophoresis forces spread the droplet over the surface until the overall energy (interfacial plus dielectric) is minimised. This "dielectrowetting" effect reduces the contact angle, $\theta$, of the droplet [1,2]. Our recent work has shown that low dielectric permittivity air bubbles in high dielectric permittivity liquids can also be fully controlled using negative dielectrowetting [2], where the outer high dielectric liquid displaces the air bubble up to and including bubble detachment [3]. In this work, we replace the air bubble with another immiscible low dielectric liquid that fully wets the surface and creates a liquid film in the absence of the applied voltage. When the voltage is applied, we find that negative dielectrowetting occurs, spanning the full contact angle range of 0° to 180° (see Fig. 1). In the limit that the liquid film is thick (> 100 μm) we have found excellent agreement with the dielectrowetting modified form of Young's law ($cos\theta \propto V^2$) theory across the full contact angle range. However, when the thickness of the low dielectric permittivity film is significantly reduced, the liquid dielectrophoresis forces induce destabilisation of the film producing various interesting rupture patterns. These observations are well described by our recently developed Lattice-Boltzmann simulations that solve the hydrodynamic equations for dielectric liquids in the presence of electrostatic fields.

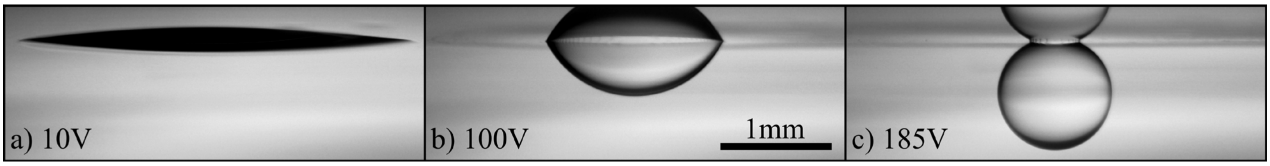

Figure 1. Experimental images of the contact change in response to voltage of a thick low dielectric liquid film.

Acknowledgements: We gratefully acknowledge UK EPSRC funding (grants EP/K015192/1, EP/K014803/1, EP/R042276/1 and EP/R036837/1)

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# Impact behaviour of compound droplets on superamphiphobic surfaces

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Recently, increasing interest has been shown in the impact of compound drops due to its various applications and academic significance[1]. However, the study of compound drops is mostly focused on hydrophilic and weak hydrophobic surfaces. Here, we perform an experimental investigation on the impact of oil-in-water compound droplets on superamphiphobic surfaces. Compound drop with five different oil volume ratios $\alpha$ were produced, aiming to reveal the effect of the presence of the oil core and the oil ratio on the impact dynamics. It is found that the water and the compound drop follow the similar spreading process in terms of the variation of the contact diameter during the spreading process and the maximum spreading factors. However, the oil ratio shows non-monotonic influence on the bubble formation during the retraction process. The velocity range for bubble formation of water drop impact is limited in $\sim 0.47-\sim 0.50\ \mathrm{m/s}$ with water Weber number $We$ in the range of $\sim 4.6-\sim 5.2$ due to the capillary wave propagation and cavity collapse. For $\alpha \lesssim 0.09$, the bubble entrapment is inhibited, while for $\alpha \gtrsim 0.09$, the bubble entrapment is enhanced in oil core. E.g., when $\alpha = 0.32$, the velocity and $We$ range and are enlarged to $\sim 0.36-\sim 1.08\ \mathrm{m/s}$ and $\sim 3.0-\sim 27.05$, respectively. Further, the increase of oil ratio slightly decreases the splash threshold. The promoted splash mechanism is similar to that by imposing a viscous part in the impact of janus compound drop.

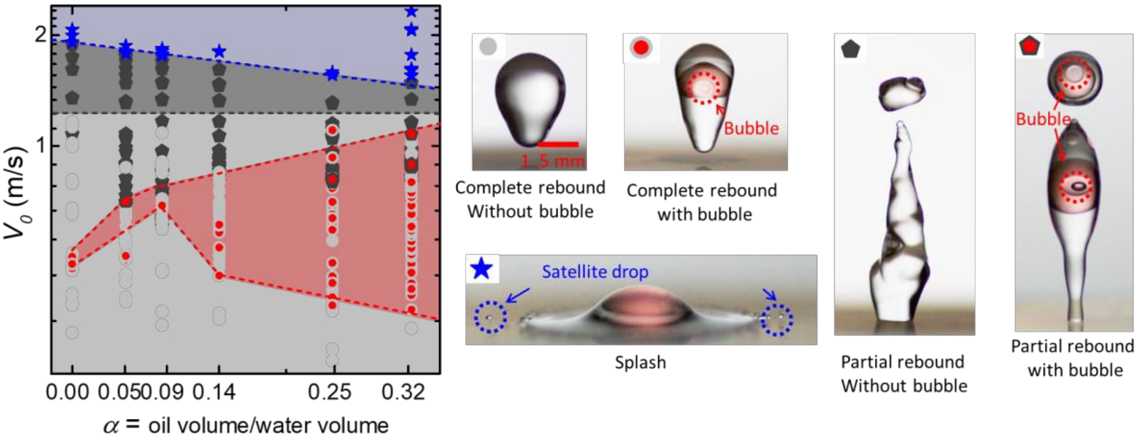

Figure 1. Impact phenomena phase figure as function of oil ratio $\alpha$ and impact velocity $V_0$. The gray/black region indicates the complete/partial rebound without bubble entrapment. Red and blue regions are for the range of bubble entrapment and splash, respectively.

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# Ultrafast Bubble Bursting and Passive Anti-Foaming by Superamphiphobic Surfaces

**Katharina I. Hegner**[1], William S. Y. Wong[1], and Doris Vollmer[1]

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The formation and accumulation of bubbles and foams challenge a wide variety of industrial applications ranging from the food processing and commercial cosmetic sector, to electrocatalysis and flotation processes in mineral mining and waste-water treatment. If uncontrolled, this can result in product losses, equipment downtime or damage and cleanup costs. Passive, surface-induced rapid bubble bursting and anti-foaming without the need for chemical additives are highly desirable. Here, we demonstrate how the speed of bubble bursting can be controlled via the surface morphology.[1] Superamphiphobic coatings are prepared using liquid flame spray which allows simultaneous tuning of nano- and microscale structures. We identify the parameters required to achieve ultrafast bubble bursting: the nanoprotrusions should be as small as possible (diameters below 100 nm) and assembled into rough microscale features. By optimizing the surface morphology, bubble bursting can be induced within 2 ms in water. The released air is absorbed the Cassie-state's plastron layer. The coatings demonstrate long-term ultrafast bubble rupturing and chemical and mechanical stability even in the presence of surface-active species. Furthermore, superamphiphobic surfaces are able to increase defoaming rates and inhibit foam formation.[2] They improved defoaming of highly stable wet foams (50 %) and anti-foaming of growing dry foams (>> 100 %) using beer and aqueous soap solutions as model systems.

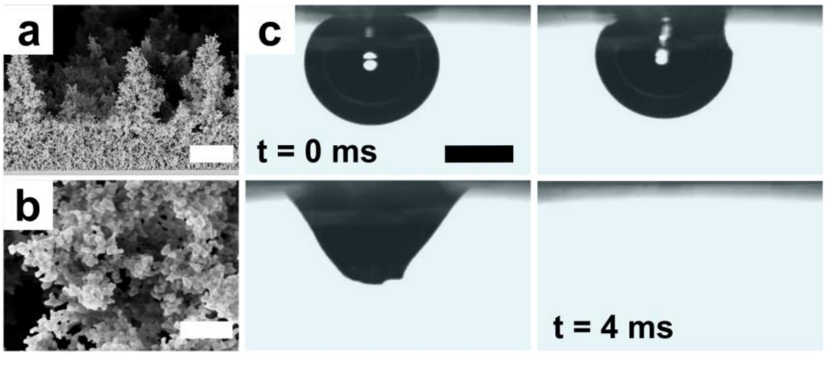

Figure 1. a,b) Side-view scanning electron microscopy images of particulate superamphiphobic structures prepared by liquid flame spray (scale bars are a) 20 µm and b) 1 µm). c) Images acquired by a high-speed camera show a single air bubble rupturing immediately upon contacting the surface in water (scale bar is 1 mm). After 4 ms, the released air is absorbed and fully reorganized into the coating's plastron layer.

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[2] Wong et al., Super Liquid Repellent Surfaces for Anti-Foaming (2021). [under review]

# IMPACT OF A DROPLET ON A CIRCULAR SUPERHYDROPHILIC REGION SURROUNDED BY A SUPERHYDROPHOBIC REGION

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Droplet impact on wettability difference surface received significant attention owing to its varied applications [1]. Herein, we investigate the impact of a droplet on a circular superhydrophilic region (SHL – Diameter $D_S$) surrounded by a superhydrophobic region (SHB). Our work employs the energy conservation approach to develop an analytical model to predict the maximum spreading ratio ($\beta_{max} = (D_{max})/(D_0)$ where, $D_{max}$ is the maximum spreading diameter and $D_0$ is the initial droplet diameter. The schematic has been shown in Fig. 1(a). The droplet spreading time 'τ' has been modeled in two parts ($\tau = \tau_{SHL} + \tau_{SHB}$), scaled with their respective maximum velocities. Our model predictions and comparison with experimental values are plotted in Fig. 1(b). A non-dimensional number ( $Re^{1/2}/We$) is introduced to investigate the effect of non-dimensional diameter ($\beta_S = (D_S/D_0)$ of the superhydrophilic region on $\beta_{max}$ where Reynolds number, $Re = \rho u_0 D_0/\mu$), Weber number, $We = \rho u_0^2 D_0/\sigma$, where $u_0$ is the impact velocity. The interrelation between transient and storing energies in the system is also investigated using the number. It is found that for $Re^{1/2}/We$ > 1.82, the effect of $\beta_S$ is significant. Our study aims to facilitate better understanding of droplet dynamics on hybrid surface having both superhydrophilic and superhydrophobic regions as necessiated in technologies like inkjet printing and droplet condensation studies.

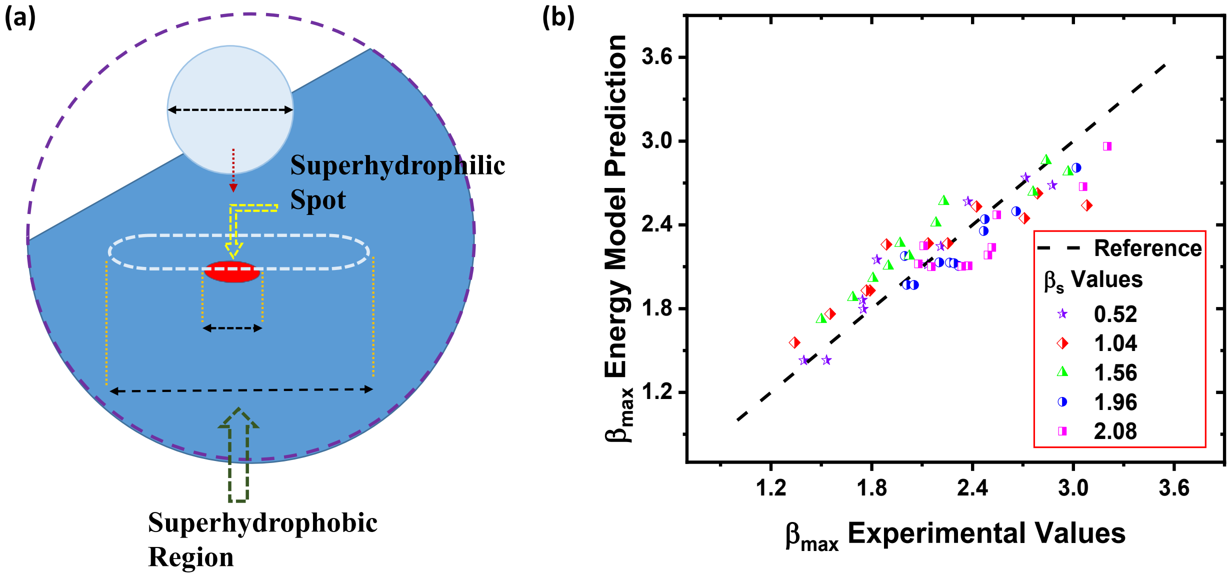

Figure 1. (a) The figure depicts the experimental setup (b) Comparison of experimental and energy conservation model values of $\beta_{max}$ for different $\beta_S$

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# Inertial stretching separation in binary droplet collisions

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[2] *EPSRC Centre for Doctoral Training in Fluid Dynamics, University of Leeds, Leeds, United Kingdom*
[3] *Department of Engineering Science, University of Oxford, Oxford, United Kingdom*
[4] *School of Engineering and Materials Science, Queen Mary, University of London, London, United Kingdom*

Predicting the outcomes of binary droplet collisions is of fundamental physical importance and remains a challenge due to the complex physics involved. In off-centered collisions, there exists a transitional boundary from fast coalescence to stretching separation. It is generally accepted that increasing viscosity shifts this transitional boundary towards higher Weber numbers (We). Phenomenological models have been proposed in the literature, however, they do not have a unique criterion for the transition from fast coalescence to stretching separation. These models treat viscous loss empirically or via free fitting parameters, which undermines these models further. Based on extensive experimental measurements across a wide range of droplet viscosities and sizes, herein, we propose a new model in which the criterion and the viscous loss are explicitly treated. The experiments supported by analytical efforts reveal that the transitional boundary occurs at a fixed We for a wide range of Ohnesorge number, which implies the existence of an inertial behaviour in this range (the viscosity has no role). These findings are of significant interest in many applications ranging from nuclear operations to spray drying and combustion engines to spray systems, such as painting, coating and inhaler design.

# Dependence of Drop-on-drop Impact Dynamics on Droplet Deposition Boundary Condition on a Superhydrophobic Substrate

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Understanding droplet impact dynamics on already deposited droplet is important due to its occurrence in various applications. Investigations have highlighted the dynamics and droplet impact regime outcomes in such scenarios [1, 2]. However, the role of deposition of sessile droplet (droplet #1, as shown in Fig. 1) plays a very crucial role, and the subsequent dynamics is different with gentle ($\mathrm{We}_{\mathrm{droplet}\ \#1} < 1$) and impact deposition ($\mathrm{We}_{\mathrm{droplet}\ \#1} > 1$) of sessile droplet [3]. The pinning of droplet and breaking due to wettability transition from Cassie-Baxter to Wenzel state is observed with impact deposition which is absent in gentle deposition. The numerical prediction (ANSYS Fluent®) and evolution of pressure along with comparison of base diameter with experimental values is also investigated. Important time-scales based on balance of surface tension, inertia, and viscous forces are delineated. Increase in We number of droplet #2 (Fig. 1) results in larger maximum spread factor ($\beta_{max} = D_{max}/D_0$). Furthermore, the experimental values of $\beta_{max}$ are compared with prediction from the existing model, which is based on energy balance before the impact and at the instant of maximum spread. The role of droplet #1 deposition condition on drop-on-drop impact dynamics is presented.

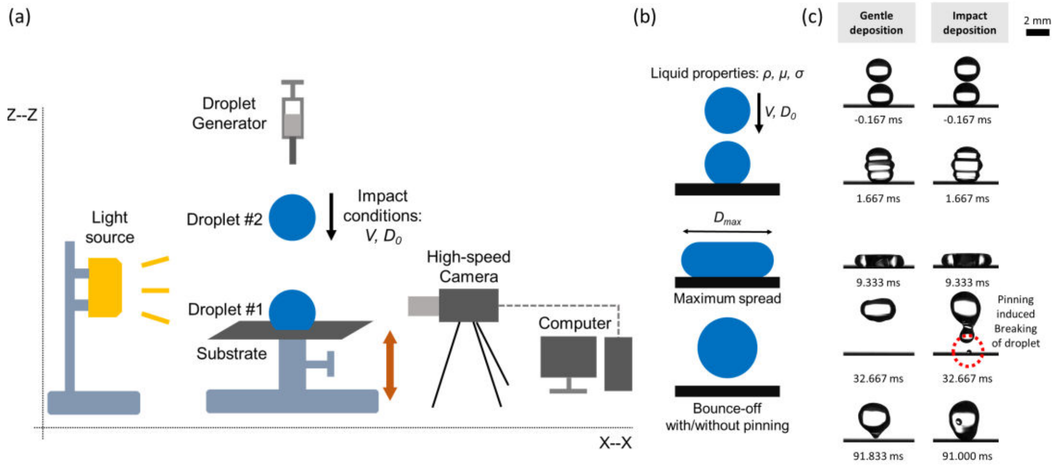

Figure 1. (a) Schematic of the experimental setup (b) representation of the drop-on-drop impact dynamics: droplets coalesce, spread, and bounce-off with/without pinning (c) evolution of interfacial shapes at various time instants for drop-on-drop impact dynamics on a superhydrophobic substrate (~ 155°) with gentle ($\mathrm{We}_{\mathrm{droplet}\ \#1} < 1$) and impact ($\mathrm{We}_{\mathrm{droplet}\ \#1} > 1$) deposition of sessile droplet for $\mathrm{We}_{\mathrm{droplet}\ \#2} \sim 9$.

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# A FRET study of droplet collisions in microemulsions

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Limonene microemulsions are used as a green alternative to traditional microemulsions containing potentially harmful hydrocarbons for enhanced oil recovery. These microemulsions containing micelles of a non-ionic surfactant swollen with limonene. When microemulsion droplets coalesce, they can solubulise more oil due to an increase in the ratio of volume to surface area. At equilibrium, microemulsion droplets continuously fuse and then break up again through the formation of "transient dimers". Studying transient dimer formation is thus a way of understanding the kinetics of solubilisation. Fluorescence Resonance Energy Transfer (FRET) between NBD-PE and 18:1 Liss Rhod has been used to determine the rate of exchange between swollen micelles during a fusion process. FRET involves the interaction between the excited states of two dye molecules, in which excitation is transferred from a donor molecule to an acceptor molecule. If a donor probe is in a certain micelle and acceptor in another, the fusion process will allow an acceptor and a donor probe to be in close enough proximity for FRET to occur, increasing the acceptor emission and reducing the donor emission. By measuring the change in the intensity ratio of donor/acceptor emission following mixing in a stopped flow device, it is possible to quantify the exchange of contents and the kinetics of mixing. The kinetics of exchange measured by FRET in microemulsions is compared with exhange between micelles in a limonene-free formulation.

# Floating and bouncing dynamics of water droplets on immiscible liquid pool

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The phenomenology of drop impact have huge technological implications and has ubiquitous importance in various domains such as such as inkjet printing, spray cooling, surface coating, and forensic sciences. Bouncing on liquid pool and its transition to coalescence is affected by pool depth, Webber number (*We*), physical properties of the liquid and external perturbations such as pool vibrations. Several effects are shown to delay the merging where in most of the studies, the role of entrapped air film which is strong enough to keep the surfaces separated is taken up into consideration. The previous studies utilize the lubrication theory to model the entrapped thin air film draining dynamics. Levitation of heavier droplet as a result of non-isothermal conditions, Leidenfrost effect and due to the vabration liquid bath are well explored. The prolonged leviation and film draining dynamics are explained as function of temperature difference and Marangoni number.

Contrary to the normal intution, we observed that water drops impacting on a pool of immiscible oils at exceptionally low Webber numbers exhibits a finite rescidence time on the oil air interface before sinking to the deep oil pool. Here we explore the situation of a water drop impacting on an immiscible oil pool of relatively lower density in the absence of any external perturbations such as vibrations or addition of surfactants at considerably lower Webber number regimes. The drop residence time is found to be function of *We*, impacting liquid and oil properties especially the volatility governed by the coupled effect of droplet bouncing characteristics, vapor pressure of impact oil pool as well as thin film draining dynamics. Detailed theoretical nanlysis has been carried out to understand the physics behind the finite residence time of the impacting drops on the pool surface. The bouncing-sinking regime map has been developed based on the experimental data. Experimental evidences and scaling analysis indicates that vapor entrapment due to volatility of oil pool has a considerable contribution towards the film draining dynamics.

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# Viscous droplet impact on a cantilever beam

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Droplet impact over flexible substrates has recently gained much attention due to the complex dynamics and its ubiquitous nature. The impact dynamics in such cases is dictated by the interplay of time scales of both the droplet and the substrate. This dependence can further be utilized to manipulate the overall dynamics of the system, mainly maximum deformation of beam and droplet, contact time, and energy transfer. In this work, we have studied the impact of water-glycerine mixture's droplets at different Weber numbers, $We$ over flexible cantilevers. The beams were made of copper for hydrophilic cases and sprayed with a commercial nanoparticle-based coating for superhydrophobic cases. Beam lengths were varied to cover a range of beam stiffnesses and timescales. We have identified the critical parameters dictating the overall dynamics of the system and studied the effect of changing viscosity. Conditions for minimum and maximum contact time, and maximum energy transfer are highlighted [1]. Continuous variation of contact time was observed for the case of superhydrophobic beams with significant variations at larger $We$. The overall dynamics of the systems has been theoretically captured by extending preexisting models and a spring-mass equivalent. The information garnered can aid in designing as per need dynamics of the system for a range of potential applications including pesticide sprays, micro air vehicle design, and rain energy harvesting.

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# Coalescence cascade during merging of unequal droplets: a numerical study

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The mering dynamics of binary droplets are a subject of significant interest owing to their importance in various applications such as emulsion formation, separation processes, and microfluidics. In the current study, the coalescence of two unequal sized droplets that are initially stationary are numerically investigated using the Volume of Fluid approach [1,2]. The results from the simulations are compared against the experimental results of Zhang et al. [3] both spatially and temporally for various drop merging sequences based on the parent droplet size ratios and Ohnesorge number of the mother droplet ($Oh = \mu/\sqrt{\rho\sigma R_m}$) (Fig.1). The simulations predict the first, the second, and the third-stage cascade (Fig.2) and agree well with the previously published experimental data. The formation of liquid bridge, merging responses owing to initial conditions, the novel pinch-off dynamics together with the daughter droplets are further explored through a parametric phase-space to characterize and distinguish the various stages of coalescence cascade during drop-drop interactions.

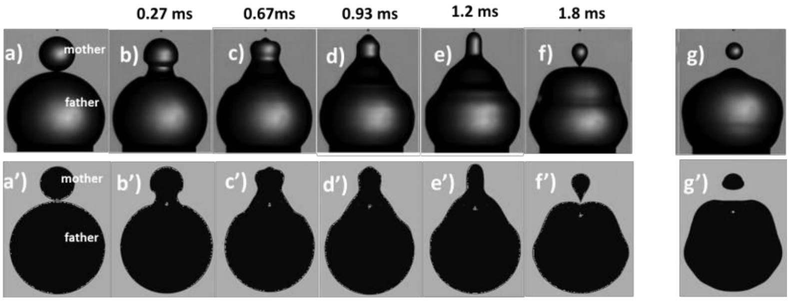

Figure 1. A comparison of numerical results (bottom row: **a'-f'**) against the experimental results from Zhang et al. [3] (top row: **a-f**) for droplet size ratio of 2.72 and *Oh*=0.0058 for the times listed above. The merging response illustrates a partial coalescence and first stage pinch-off. The final panel shows the formation of daughter drop (time-sequences are different).

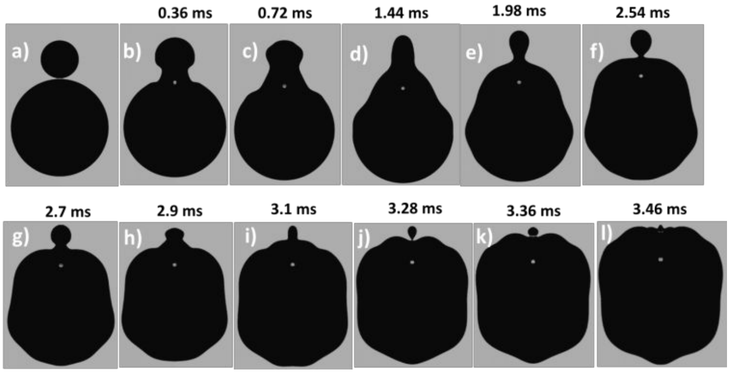

Figure 2. Numerical results that reveal a third-stage coalescence cascade for size ratios of 2.56, *Oh*=0.0116. The panel **f)** shows a local necking behaviour that stops shrinking but grows (shown in panels **g)** and **f)**). A new neck formation is observed in panel **j)** but no pinch-off is predicted (unlike in Fig.1).

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# Coalescence in surfactant-stabilized concentrated emulsions: The hole nucleation theory revisited

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Coalescence is an important problem in emulsions and foams. We quantitatively study the coalescence occurring in the water-in-oil concentrated emulsion - in the regime where it is activated thermally - through a model system using the mixture of surfactants (Span 80/Tween 20). By monitoring the kinetics of separation from bottle test experiments, we can estimate the characteristic coalescence frequency per unit area $\omega$ between the droplets [1]. In addition, we have performed isolated drop-drop experiments having the same experimental conditions with bottle tests in order to measure the coalescence frequency $\omega$ in a different manner. The very good coherence between these two methods for measuring $\omega$ is witnessed. Motivated from the hole nucleation theory introduced by Kabalnov and Wennerstrom [2], we develop a complete theoretical model which allows estimating the coalescence frequency $\omega$ from the physical-chemical parameters at play, and its dependence to the surfactant proportions. A very good agreement between theoretical predictions and experimental measurements is showed.

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# Fragmentation of optically and acoustically levitated droplets by femtosecond laser

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[2] *NASA-Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109, USA*

We aim to investigate the breakup behaviour of acoustically and optically levitated droplets of different properties (such as surface tension, viscosity, and absorption coefficient) by a femtosecond laser pulse. First, the droplets will be optically levitated [1] inside a cell, which will then be fragmentated by a focused femtosecond laser pulse (775 nm wavelength, 150 fs pulse width) [2]. A 532 nm continuous wave linearly polarized laser will be focused to levitate the droplets. The breakup characteristics such as bubble and shock dynamics, sheet expansion and propulsion, and ligament breakup will be visualized using a high-speed camera. Subsequently, the droplet breakup behaviour in an optical trap will be compared with droplet dynamics in an acoustic levitator [3]. The two primary objectives of the work are: 1. to study the effect of a focused femtosecond laser on droplets at different focal lengths in two distinct systems (acoustic and optical levitation) and 2. to understand the influence of acoustic pressure in an acoustic trap and radiation pressure induced by the laser in an optical trap on the breakup dynamics of the droplet. The study will be important for the fundamental understanding of the non-contact manipulation and fragmentation of significantly small droplets (< 50 μm) of viscous liquids i.e., glycerol, silicone oil in an optical trap. The fragmentation of droplets by femtosecond laser in an optical trap can have important applications in medical technology (such as intraocular microsurgery) since significantly small droplets (~ 10 μm) can be levitated and manipulated using completely non-intrusive techniques.

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# Adaptation of PS/PAA copolymer to water

**Xiaomei Li**[1], Mirela Encheva[2], Gunnar Kircher[1], Kaloian Koynov[1], Hans-Jürgen Butt[1], Ellen Backus[1,2] and Rüdiger Berger[1]

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[2] *Department of Physical Chemistry, University of Vienna, Währinger Straße 42, 1090 Vienna, Austria*

When a droplet is sliding on surfaces, adaptation of the surface leads to changes of the dynamic contact angles [1]. Hereby two adaptation processes play a role: (i) the adaptation of the surface upon bringing in contact to the droplet (wetting) and (ii) the adaptation of the surface after the droplet passed (dewetting). In order to study both processes, we investigated samples made from polystyrene (PS) polyacrylic acid (PAA) random copolymers by using a tilted-plate method and by sum-frequency generation spectroscopy (SFG). For the wetting process, the advancing and receding contact angles of water droplets decrease when PS/PAA surface adapts to water. We measured a relaxation time of ~1 ms for 40 - 100 nm thick PS/PAA films adapting to water by a tilted-plate method [2]. Here, both water diffusion and polymer reorientation play a role in the adaptation process. For the dewetting process, the sliding droplet velocity decreased for subsequent droplets with different droplet intervals. From the drop interval and the drop velocity, we calculated the time that is required for the surface to (re-)adapt to air. While for the wetting process water diffusion and copolymer reorientation played a role, it is not clear to which extend both effects are present during dewetting. Therefore, we performed SFG experiments on PS/PAA surfaces to determine the contribution of both effects.

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# Dynamic wetting behavior and hydrophobic loss of tunable PDMS-based elastomers for high-voltage applications

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[3] *TU Dresden, Organic Chemistry of Polymers, Germany*

Silicone elastomers are widely used as housing material for outdoor high voltage applications. A series of material requirements and material-specific tests in accordance with IEC TR 62039 [1] has to be passed until a silicone rubber is meant to be suitable for service. One part of these tests is the so-called dynamic drop test (DTT) for the accelerated simulation of combined electrical and electrolytic stress on polymeric insulating material surfaces [2]. This stress occurs, for example, by dewing or rain on the surfaces of insulators. During the DTT, aqueous electrolyte droplets slide continuously down an inclined plane. Applying high voltage, partial discharges are induced from the sliding water droplets onto the insulating material, making the surface hydrophilic. The test ends as soon as a continuous electrolyte film has formed between the electrodes and a leakage current is detected (see Figure 1). The longer a material withstands stress, the more suitable it is as an insulating material for high voltage applications.

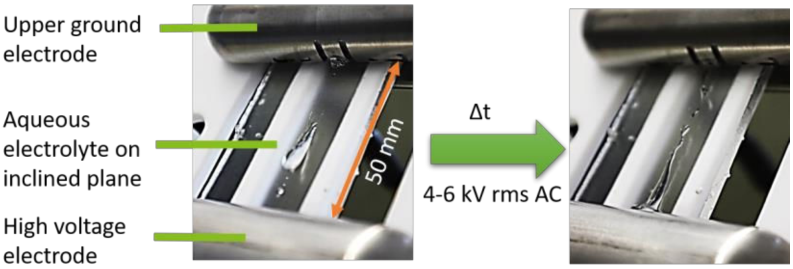

*Figure 1: Loss of hydrophobicity of unfilled silicone rubber during the DTT, due to partial micro discharges.*

Investigating commercial silicones poses the challenge of unknown material compositions. These silicone-based composites contain, beside the polymeric PDMS-scaffold, highly dispersed silica as mechanical reinforcer and aluminium trihydrate as an anti-flame retardant in unknown concentration, particle size and surface functionalization. Hence, we synthesize tunable model-systems. Platinum-catalysed crosslinking of vinyl-terminated PDMS and tetrakis(dimethylsiloxy)silane results in a polymeric scaffold in which freely moving sol is still present. By varying the chain lengths of the vPDMS used or changing the stoichiometry of the components used, it is possible to produce unfilled silicones with defined network properties and sol proportions.

We observed that the roll-off behaviour of water droplets in the test set-up varies considerably even without applying a high voltage. Effects such as pearling (adherence of small droplets along the water path) and longitudinal elongation of the droplets depend on the network properties. These effects also lead to a significant influence on the downtime in the DTT, when high voltage is applied.

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# Nanodroplets Wetting an Elastic Half-Space

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Wetting of deformable surfaces is of a particular interest for the realm of interface science. Two approaches are mainly used to describe the reshapement of a solid surface evoked by a liquid droplet. The first approach employs localized Young traction combined with curvature-induced traction where the latter is often taken as following from a spherical cap assumption. However, despite allowing for the eased usage of the analytical machinery such as Hankel and Fourier transformations, it deprives one of the understanding of the nanophysics behind the soft wetting and of the effect the surface forces have on the wetting ridge geometry. Alternatively, the disjoining pressure can be considered responsible for the substrate deformation.

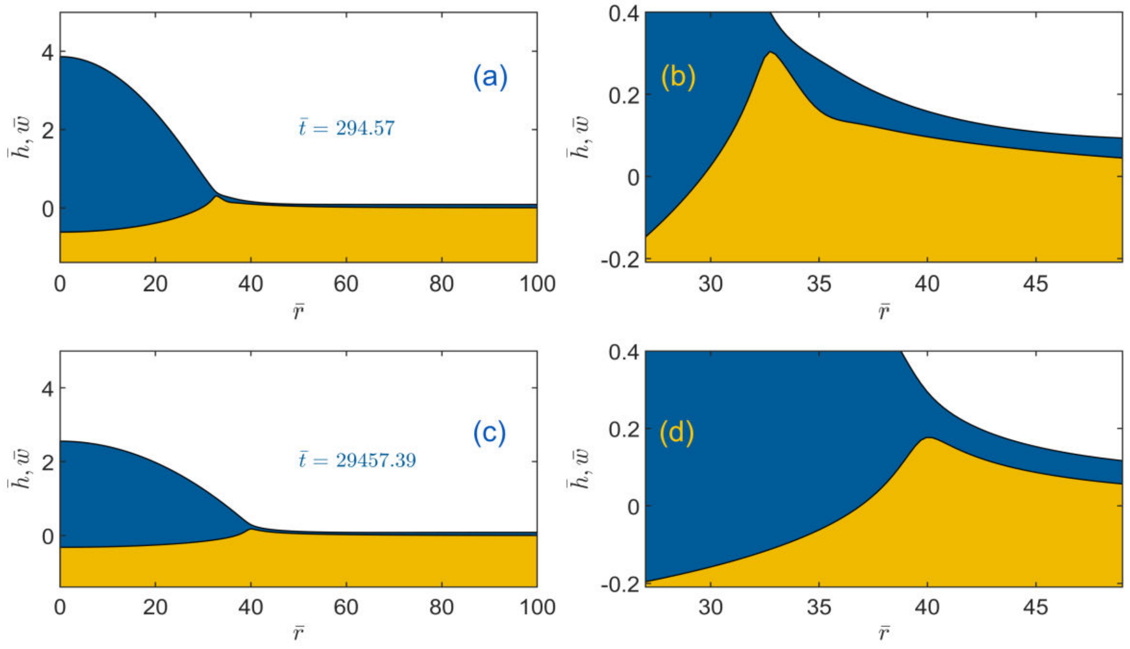

Figure 1. The droplet (blue-filled) spreading over an elastic surface of infinite thickness (yellow-filled) at different moments of time: (a) and (b) correspond to the beginning of the spreading while in (c) and (d) the droplet is close to its steady state.

In the present work, we employ the disjoining pressure concept [1] to model statics and dynamics of wetting of the elastic half-space by the liquid droplets of size comparable with the range of the surface force action. Besides, we compare the profiles obtained within the classical Young approach and the surface-force based approach. We show that the shape of the wetting ridge tip for such droplets is affected by the surface forces. When the droplet spreads, the wetting ridge undergoes a significant reshapement and demonstrates a non-linear dynamics reaching a maximal height and further relaxing to the steady state.

[1] M Gielok, M Lopes, E Bonaccurso, T Gambaryan-Roisman, *Colloids Surf, A Physicochem Eng Asp*, **521** (2017), 13.

# Bioinspired multifunctional glass surfaces: from wettability and antireflectance to antibacterial activity

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Nature-inspired nanopatterning offers exciting multifunctionality spanning antireflectance and the ability to repel water/fog, oils, and bacteria; strongly dependent upon nanofeature size and morphology [1-3]. Broadly, this multifunctionality is inherent to and bridged by the nanocone structure, yet such patterning in glass ($SiO_2$) – a material of great practical importance – remains a bottleneck due to its high chemical stability alongside structuring at the nanoscale itself, which becomes increasingly challenging to manage as the pattern resolution advances (pitch <100 nm). Attaining control over the pitch has, however, transpired to be crucial to advance existing, or unlock additional functionality; with theoretical models and experimental studies in silicon indicating that at these smaller length scales, nanocones are not only capable of resisting droplet impacts of higher velocity, but also of repelling water at the microscale – answering the need for antifogging surfaces [3]. Practically, this enables self-cleaning under various weather conditions permitting raindrops or dew to manage pollutants. Here, we present a facile approach for glass nanostructuring and confirm that engineering superhydrophobic nanocones with enhanced impact-resistance, is achieved through: small pitch, tapered geometry, and uniform structuring. To showcase the potential further, glass features are tailored to achieve: high transparency, broadband, haze-free, omnidirectional anti-reflectivity (>97.5% transmission calibrated to human eye response); impact-resistant super-hydrophobicity (tested up to 4.4 m/s); and lastly, unique antibacterial properties on a glass surface towards *S. aureus* with a competitive >81% killing efficiency. We also replicate our structures into polymers, and apply our method to generate tunable $SiO_2$ hard masks for silicon fine-nanostructuring; overall, enabling us to systematically investigate properties including superhydrophobicity and antifogging. It is envisioned that such structuring in glass will facilitate fundamental studies and be useful for numerous practical applications – from displays to architectural windows.

[1] MJ Kreder *et al*., *Nat. Rev. Mater.* **1** (2016), 15003.
[2] T Mouterde *et al*., *Nat. Mater.* **16** (2017), 658.
[3] DP Linklater *at al*., *Nat. Rev. Microbiol.* **19** (2021), 8.

# Cusps-filaments at receding viscoelastic contact line

**Saksham Sharma** and D. Ian Wilson

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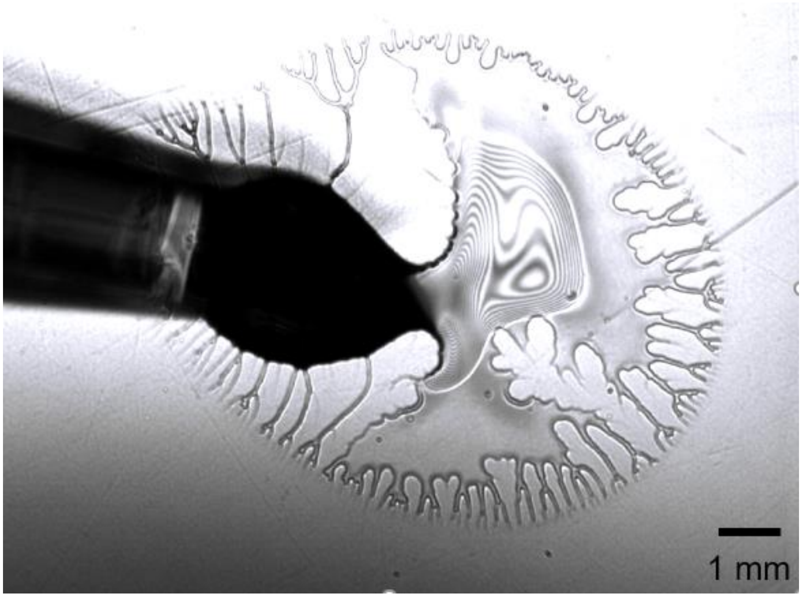
A receding contact line of viscoelastic fluid (PEO solution in water) produces linear patterns of cusps and filaments. While cusp formation signifies the tendency of a receding contact line to form drops, polymeric filaments attached to these cusps prevent such formation. We present experiments showing the dependence of the spacing/wavelength $\lambda$ between filaments on the concentration $c$ of PEO for a fixed contact angle $\theta c$ of substrate. In addition, we find the correlation between minimum Capillary number $Camin$ required to form filaments and $\theta c$ for a given concentration of fluid. A simple analytic model based on Cox-Voinov law and lubrication approximation is presented to qualitatively and quantitatively find out these correlations.



# Nanoparticles modulate contact angle hysteresis in electrowetting

**Sumit Kumar***, Pawan Kumar*, Sunando DasGupta, and Suman Chakraborty
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*Equal Contribution

In electrowetting on dielectric (EWOD), the minimum actuation voltage required to spread the sessile liquid droplet drastically increases due to the presence of significant contact angle hysteresis. Pinning effects further manifest themselves as stick-slip motion at the three-phase contact line (TPCL) and affect the switching speed of the EWOD systems. Various groups have also achieved success in minimizing the contact angle hysteresis by using the energy of mechanical vibration. However, this technique does not suit the purpose from the miniaturization perspective. Unlike mechanical shaking, the control of droplet spreading or transport using electrowetting is much higher, which further helps in minimizing the hysteresis and suits microfluidics applications. Further, it is of significant importance to investigate the effect of the colloidal particles on contact angle hysteresis of sessile droplets under imposed electrical potential. The experimental setup is shown in Figure 1 and is similar to those described elsewhere [1].

The addition of nanoparticles to the sessile droplet was observed to increase the contact angle hysteresis ($\bar{H}$) (Fig. 1). The nanoparticles arrange themselves in a solid-like ordering at the TPCL and cause the pinning of the contact line. During the reduction of voltage after reaching $V_{\max}$ , the capillary forces pull the contact line back to the corresponding value at the new reduced voltage against the push of the electric force component and the pinning force at the TPCL. An increased pinning force upon addition of nanoparticles requires a larger reduction in the local contact angle ($\theta_{local}$) before it becomes equal to the electrowetting receding angle ($\theta_{local,rec}$) and thus a greater contact angle hysteresis (Fig. 1). At higher nanoparticle concentration (0.1 % w/w), a reduction in contact line pinning was observed during the decreasing voltage mode, and consequently, a much lesser contact angle hysteresis was observed for 0.1 % w/w nanoparticle concentration droplet (Fig. 1 ). Another important observation from figure 1 is that that the maximum contact angle hysteresis ($\bar{H}_{\max}$) does not occur at the zero voltage but a finite voltage. The reason for this apparent anomaly is that, due to the pinning of the contact line, the contact angle starts decreasing only when the applied voltage becomes equal to the actuation voltage ($\bar{V}_{act}$) for the system.

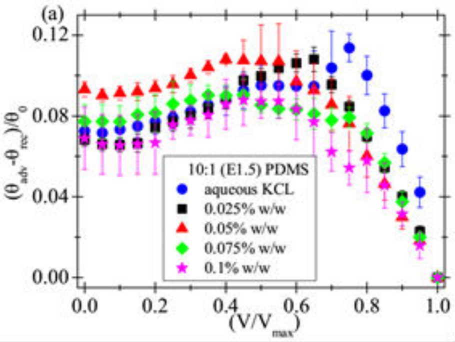

Fig. 1 Variation of non-dimensional contact angle hysteresis ($\bar{H} = (\theta_{adv} - \theta_{rec}) / \theta_0$) with non-dimensional voltage ($\bar{V} = V / V_{\max}$) and sessile droplets containing suspended nanoparticles in 0.025, 0.05, 0.075 and 0.1 % w/w respectively for 10:1 hydrophobic PDMS surface.

Reference

[1] S. Kumar, S. DasGupta and S. Chakraborty, *Physics of Fluids* **32** (2020), 32.

# Adhesion force measurement for liquid-solid interface using force tensiometer

**Palak Jain**[1], Dr. Prashant R. Waghmare[2]

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This work presents a critical analysis of commonly adopted procedures to quantify the magnitude of adhesion force between solid-liquid interface in air as well as liquid medium. Traditionally, the force balance is used to quantify the adhesion force where the measurement is performed in six steps as depicted in Figure 1. The maximum force measured at step (V), i.e., retraction of characterizing substrate away from drop holder, is termed as adhesion or snapping force. In most of the studies, the details of the formation of equilibrated liquid-solid interface, the rate at which interface is being formed and modified and surface energy of the drop holder have been ignored. It was observed that these factors can affect and lead to the erroneous measurement of adhesion force. Additionally, we have scrutinized the role of commonly operating parameters like liquid volume, retracting speed, magnitude of compression (to form the enubilated liquid-solid interface) and surrounding medium. These factors have an explicit and significant influence in quantifying the true magnitude of maximum adhesion force. Hence, we presented a protocol and standard operating procedure to circumvent these erroneous aspects.

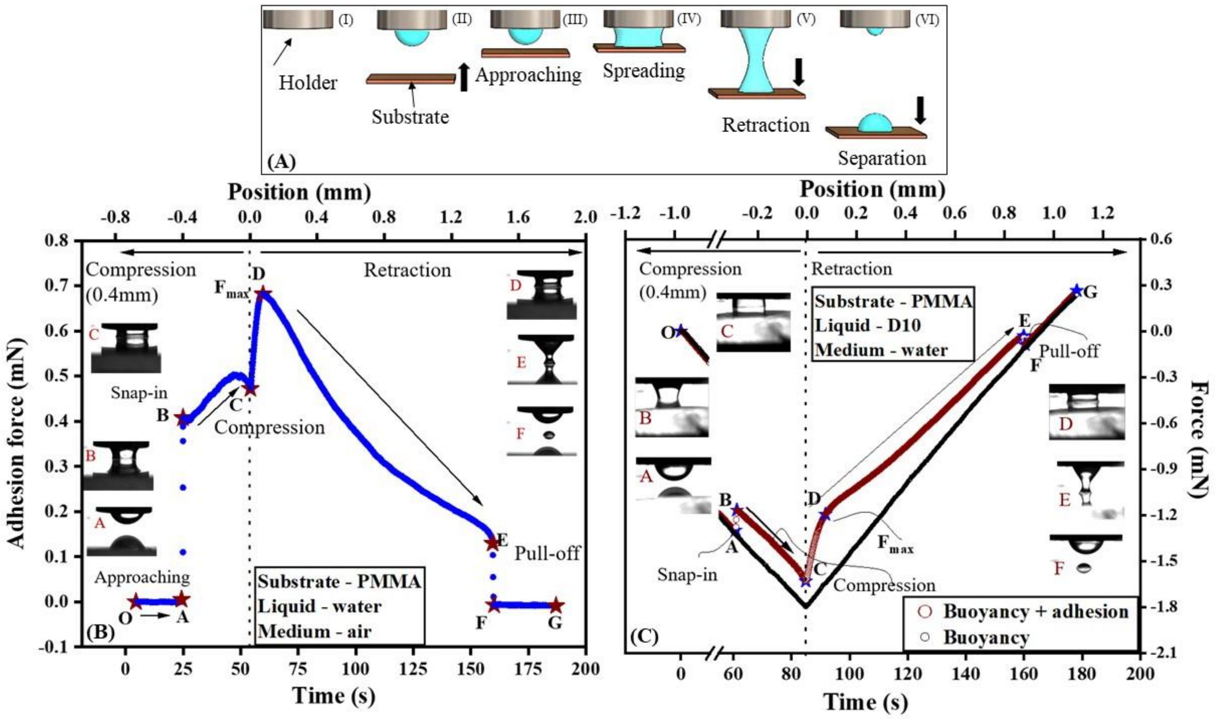

Figure 1. (A): Schematic of different steps involved in adhesion force measurements: I. A standard shape (ring or needle-tip) holder is attached to force balance, II. Drop of a given volume is generated at the tip of the holder, III. Characterizing substrate is brought in the vicinity to the drop, IV. The equilibrated solid-liquid interface is formed through compression, V. Destruction of the equilibrated solid-liquid interface by withdrawing the characterizing substrate away from the holder, VI. Drop detachment, (B): Adhesion force measurement in air medium: between a smooth untreated PMMA surface and water. (C) Adhesion force measurement in liquid medium: between a smooth untreated PMMA surface and oil droplet.

# Electrospreading of Viscous Droplets on a Dielectric Surface

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Electrowetting on dielectric (EWOD) is a technique to alter the spreading characteristics of a droplet placed on a dielectric coated electrode surface using an applied electrical field. Due to fast and reversible change under low voltage in the wettability of a sessile droplet in electrowetting, it is used for several practical applications such as liquid lenses, digital microfluidics, hot-spot cooling, and medical diagnostics. Since the oil medium minimizes the hysteresis and lowers the driving potential, the water-oil-based EWOD systems are very popular in various fields. Also, the presence of a liquid medium around the sessile droplet impedes the dielectric surface contamination caused by biomolecule adsorption. However, at the same time, the viscosity of the oil medium creates resistance against the motion of the droplet contact line (CL). In the past, various works have been reported to understand the influence of viscosity on spreading dynamics and contact line friction during electrowetting. However, most of the works in the existing literature consider only the viscosity of the droplet when it is placed in ambient air. In addition, the combined effect of the viscosity of the surrounding liquid and the droplet on the coefficient of contact line friction and scaling law which can demonstrate governing physics is not thoroughly investigated. Therefore, in this work, we investigate the combined effect of both the viscosities on the contact line friction coefficient and the physics involved with it.

Our experimental setup is shown in Fig. 1 (a). The dielectric surface is prepared by mixing the silicon-based elastomer (PDMS) with a cross-linker by following the standard protocols. By altering the glycerol concentration in DI water, we have obtained solutions of different viscosity ranging from 9 mPas to 260 mPas. We have used silicone oil as a surrounding fluid and its viscosity varies from 1.9 mPas to 970 mPas.

Our studies reveal that the driving force (F) linearly varies with contact line speed (u) during electrospreading. We also observe that the contact line friction coefficient ($\lambda$) increases with increasing viscosity of the surrounding fluid (oil medium) and it scales with viscosity as $\lambda \sim \mu_s^{0.62}$. The $\lambda$ further follows the scaling law as $\lambda \sim (\mu\mu_s)^{0.81}$, where $\mu$ is the droplet viscosity. It shows that the contribution of the surrounding fluid viscosity in the variation of $\lambda$ is higher than that of the droplet viscosity. This understanding of viscosity modulated electrowetting may help to design efficient EWOD devices ranging from biochemical to chip cooling applications.

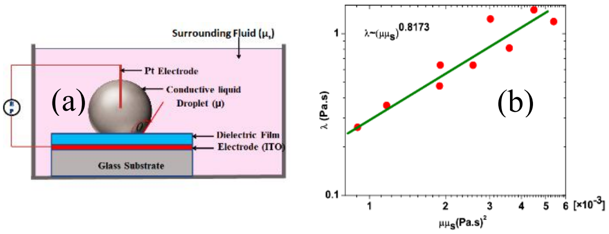

Fig. 1 (a) Electrowetting Setup, (b) Contact line friction coefficient ($\lambda$) versus product of viscosities of fluids

Keywords: Electrowetting, Contact line friction, Viscosity

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# Characterizing the spatio-temporal dynamics of sprays from high speed recordings of gas-assisted atomizers

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[1] *Particle and Process Engineering Department, University Bremen, Bremen, Germany*
[2] *Chemical Engineering Department, University of São Paulo, São Paulo, Brazil*
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Twin-fluid atomizers are characterized by promoting the breakup of the liquid phase by the assistance of a gas stream. They can be found in several industrial applications, such as in the oil industry for cracking the crude oil into lighter products and in the production of metal powder for the additive manufacturing. Both applications are of particular interest in the present work. High-speed recordings of the flow and a consecutive digital image processing are well suited to characterize spray properties, such as flow pulsations, open- and close-wake condition or identify spray shape asymmetries, which are paramount for the nozzle design and atomizer performance.

In this talk we present a methodology to generate spatio-temporal diagrams from high-speed recordings. These spatio-temporal diagrams contain all the information of the raw data images (no image processing was applied a priori) and allow in addition a direct analysis of the temporal dynamics. In our study we extract time series of the spray boundaries, which allow it to determine the mean shape of the spray together with its temporal fluctuations and an identification of the dominating frequencies. We applied this technique to two different air-assisted spray experiments. The first experiment consisted of a close-coupled atomizer used to atomize molten liquid metal. A precession motion was observed with frequencies between 50 and 100 Hz (depending on the process parameters) and an overall asymmetric spray shape was elucidated. The second experiment is an internal-mixing atomizer typically used in the oil industry for the cracking of petroleum. In our laboratory the atomizer was operated with water and air at different gas-to-liquid mass ratios. The frequency analysis revealed the occurrence of a dominating mode directly beneath the atomizer and the onset of its super-harmonic frequencies in the downstream direction. A more detailed analysis will clarify if the dominating mode was excited by external perturbations or by an instability intrinsic to these flows. A change of the process parameters (e.g. water and air mass flow rates) mainly affects the spray width.

We summarize that the method of generating spatio-temporal diagrams from high-speed recording is a powerful tool to characterize sprays. In principle it can be applied to all kind of spray types (and also to numerical data) and has the advantage that spatial as well as temporal dynamics are illustrated in a single diagram.

# Bouncing of liquid drops upon coalescence on a superhydrophobic surface

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Spontaneous bouncing of liquid drops are observed upon coalescence on various biological and synthetic hydrophobic surfaces, with several applications ranging from self-sustained condenser to self-cleaning materials. To scrutinize the mechanism of spontaneous bouncing, numerical simulations of two identical spherical drops coalescing on a flat super-hydrophobic surface are reported. Eulerian approach based volume of fluid (VOF) framework is used to simulate the coalescence cases and to characterise the super-hydrophobic surface ($\theta_E > 150°$) dynamic contact angle model is implemented. The morphology of coalescence and jumping is accurately observed and the deformation of drop interface while coalescence is compared with available experiments [1], shown in Fig. 1. Dynamic behaviour starting from liquid bridge growth to retraction of three-phase contact line and finally jumping of droplet is analysed and detailed flow field is depicted in Fig. 2. The bridge radius is found to grow with square root of time. The retraction dynamics of contact line and jumping of the drop is governed by capillary-inertial effects. The coalesced droplet leave the surface with a constant jumping velocity around 0.2 when scaled by capillary-inertial velocity. Comparison of simulation results between with and without a substrate shows that the coalescence on a contact surface has smaller surface area, which indicates more surface energy is converted into kinetic energy. In the present simulations the effects of droplet size, viscosity and surface tension are also investigated, which will be included in the detailed study.

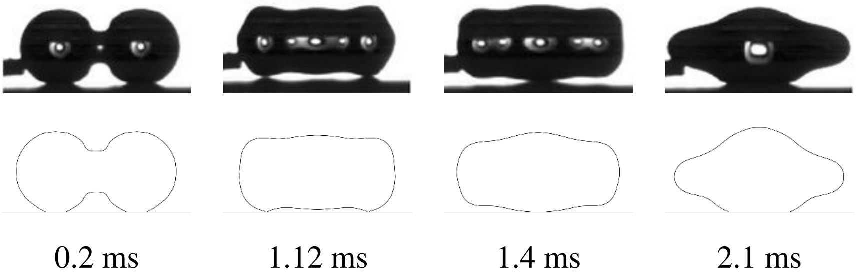

Figure 1: Interface shape evolution at the beginning of the coalescence compared with experimental data (top row) [1].

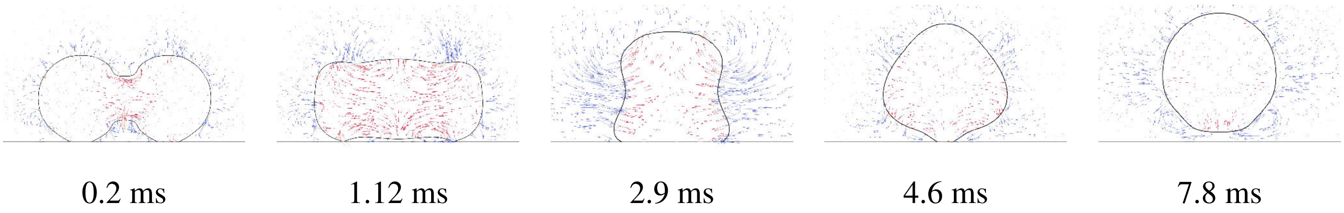

Figure 2: Velocity distribution from coalescence to jump of droplet on a super hydrophobic substrate.

[1] Wang, Kai, Qianqing Liang, Rui Jiang, Yi Zheng, Zhong Lan, and Xuehu Ma. "Morphology evolution and dynamics of droplet coalescence on superhydrophobic surfaces." AIChE Journal 64, no. 7 (2018): 2913-2921.

# Evaporation of Sessile Droplets on Slippery Liquid-Like Surfaces and Slippery Liquid-Infused Porous Surfaces (SLIPS)

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[1] *Wetting, Interfacial Science & Engineering Lab, Institute of Multiscale Thermofluids, University of Edinburgh, UK*

In sessile droplet evaporation, contact line pinning leads to a constant contact area mode and/or a receding contact line displaying stick-slip behaviour. However, this causes undesirable effects such as ring stain formation in applications such as inkjet printing and coating. Recently we have shown a droplet evaporating in a pinning-free mode at a constant hydrophobic contact angle determined by a "liquid Young's law"[2,4]. Here, we report pinning-free evaporation and droplet lifetimes across a far broader range of contact angles from 67°-105° using voltage programmable control of contact angles on two pinning-free surfaces. The first uses a conformal slippery liquid-infused porous surface (SLIPS)[1,2], and the second used a Slippery Omniphobic Covalently Attached Liquid-like (SOCAL) solid coating[3,4]. We find the total time of evaporation over the contact angle range studied is only weakly dependent on the value of the contact angle. On these types of slippery surfaces, droplet lifetimes can be predicted and controlled by the droplet's volume and physical properties (density, diffusion coefficient, and vapour concentration difference to the vapour phase), largely independent of the precise value of contact angle. These results are relevant to applications, such as printing, spraying, coating, and other processes, where controlling droplet evaporation and drying is important.

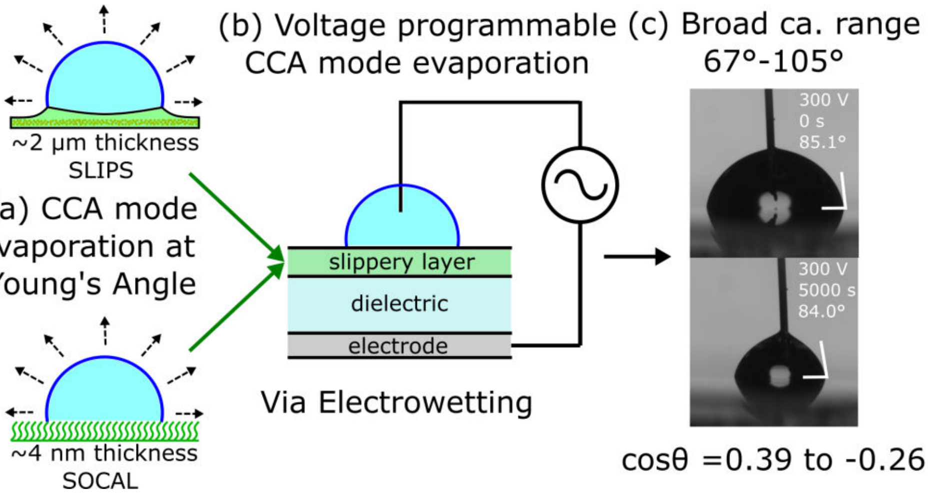

Figure 1. (a) Sketch of a droplet on a conformal liquid SLIPS layer and a smooth-solid SOCAL layer (b) Schematic of droplet in an electrowetting setup with a function generator (c) Constant contact-angle evaporation for a broad range of angles.

[1] T-S Wong *et al.*, Nature **477**, 443 (2011).
[2] G. McHale *et al.*, Langmuir **35**, 4197 (2019).
[3] L. Wang and T.J. McCarthy, Angew. Chemie - Int. Ed. **55**, 244 (2016).
[4] S. Armstrong, G. McHale *et al.*, Langmuir **35**, 2989 (2019).
[5] Z. Brabcova, G. McHale *et al.*, Appl. Phys. Lett. **110**, 121603 (2017).

# Measurement of dynamic wetting of a nanofluids droplet and nanoparticles deposition during evaporation

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[2] *Department of Chemical Engineering, Tohoku University*
[3] *Institute of Multidisciplinary Research for Advanced Materials, Tohoku University*
[4] *Advanced Institute for Materials Research, Tohoku University*

A nanofluid, which is a suspension of nanoparticles, has attracted attention in engineering fields, e.g. nano-ink for printed electronics technique. This paper reports the wetting dynamics of nanofluids during solvent evaporation using a reflection interference microscopy (RIM) and the nanoparticles depositions using a phase-shifting imaging ellipsometry (PSIE)[1].

Alkanes, such as *n*-octane, were used as solvents and decanoic acid-modified $CeO_2$ nanoparticles[2] with the diameter of 5.8 nm were added in the alkanes. A droplet of the alkanes or the nanofluids was deposited on a Si substrate. The 2D thickness profiles of liquid film near the contact line and the nanoparticle depositions were measured by the RIM and the PSIE, respectively.

Figure 1 shows the contact radius $R$ [mm] and the contact angle $\theta$ [deg] of *n*-octane and octane-nanofluids droplets. Here, the concentration of octane-nanofluid was 0.151wt% and the time $t$ when the evaporation was completed was set as $t = 0$ s. The contact radius of *n*-octane decreased gradually, whereas the contact line of octane-nanofluid was pinned for 20 s at the start of the experiment, then the $R$ started to decrease. The $\theta$ of octane-nanofluid decreased during the pinning state and became almost constant after the depinning.

Figure 2 shows a visualization image and the 2D thickness profiles of nanoparticles depositions obtained by the PSIE. The thickness of deposited nanoparticle layer fluctuates from 5 nm to 20 nm. Since the average diameter of the nanoparticles is 5.8 nm, the nanoparticles layer was formed by approximately 1–4 nanoparticles in the film thickness direction.

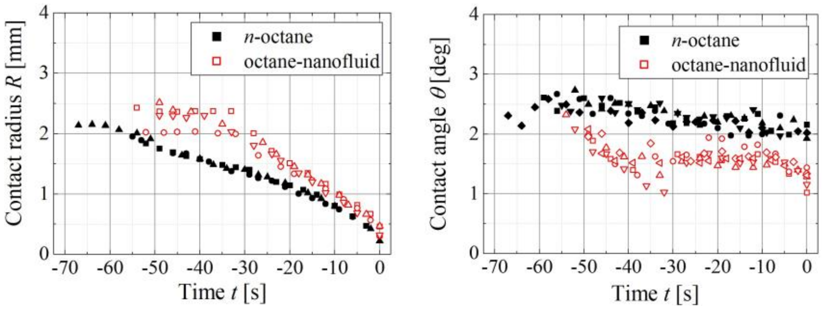

Fig. 1: Time change of the contact radius $R$ and the contact angle $\theta$.

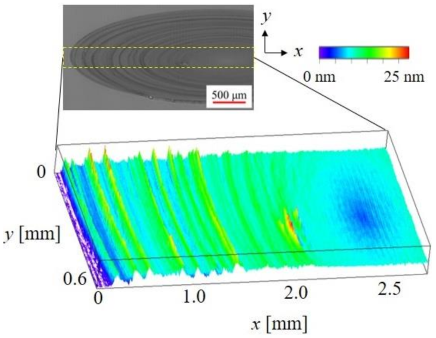

Fig. 2: Thickness profile of the deposited nanoparticle layer.

[1] E. Shoji, A. Komiya, J. Okajima, M. Kubo and T. Tsukada: Opt. Lasers Eng., 2019, vol. 112, pp. 145-150.
[2] T. Tomai, N. Tajima, M. Kimura, A. Yoko, G. Seong and T. Adschiri: J. Colloid Interface Sci., 2021, vol. 587, pp. 574-580.

# Thin liquid film contact boiling and breakup at drop impact

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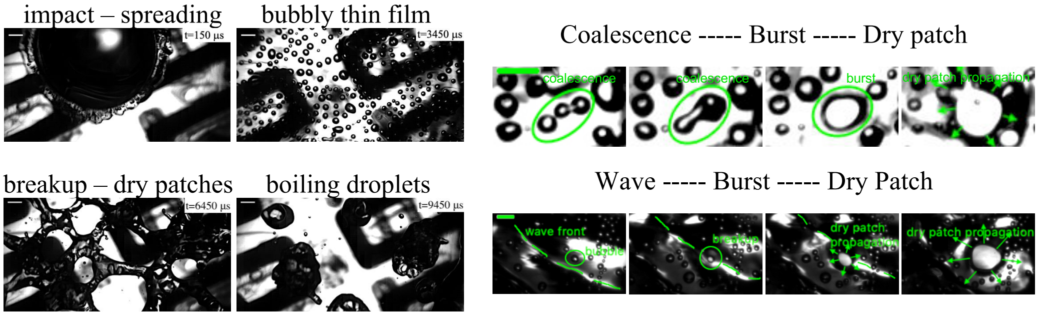
[1] *Kutateladze Institute of Thermophysics SB RAS, Novosibirsk 630090, Russia*
[2] *Novosibirsk State University, Department of Physics, Novosibirsk 630090, Russia*
[3] *Moscow Institute of Physics and Technology, Dolgoprudny 141701, Russia.*

Droplets are the key object in many industrial applications such as engine combustors, inkjet printing and spray cooling. The final outcome of spray impingement process is governed by a multitude of factors including integral and nozzle characteristics, physical properties of liquid, surface and environmental conditions. These complexities from fundamental point of view are often modelled on the results obtained from single drop impact studies.

We investigate bubbles dynamics in thin liquid film occurring at the water drop impact on heated sapphire surface by high-speed visualization with stereomicroscope and IR scanner. The detailed study was done for the surface temperature ranged from 130 to 170 ± 1°C. We present insight into boiling dynamics and the role of bubbles in the rupture of thin liquid films on heated substrates.

We have demonstrated the formation of one layer of bubbles in the thin liquid film of tens microns thick during the drop impact in the hot substrate at normal atmospheric pressure. It was demonstrated that thin liquid film breakup caused by irreversible bubbles burst which is induced by two factors: bubbles coalescence and instability generated by a wave of another bubble reversible bursting, or wave of capillary rim rollback [1].

The time required for the irreversible dry patch occurrence resulting from bubble burst is decreasing with an increase in temperature. We suggest an analytical expression describing drag reduction of liquid film flow over the bubbles situated on the solid surface, which is found to depend on the gas–liquid viscosity ratio, as well as the bubble size and film thickness ratio. Conducted experiments manifest that the bubbles present or originating in the liquid film in the form of small nuclei combined with instability are possible reasons of many situations resulting in a rupture of the thin liquid film.



**Drop impact on the hot surface. Contact boiling.**

**Bubble dynamics leading to irreversible burst.**

Figure 1. The bubbles layer forms in the thin liquid film at drop impact on the hot surface. Bubbles coalescence and instability generated by a wave are the reason for irreversible bubble burst leading to film breakup at contact boiling.

[1] E Ya Gatapova, K B Gatapova, *Soft Matter*. **16** (2020), 10397–10404.

# Dynamic Point Source Modelling of Evaporating Sessile Droplets

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The evaporation of sessile droplets from unheated solid surfaces is a ubiquitous process in many practical applications where simplistic modelling is beneficial. To ameliorate accessibility beyond the current resource-intensive models, a reduced order Point Source Model (PSM) was developed. The PSM is applicable for the axisymmetric, diffusion-dominated evaporation of an isolated sessile droplet surrounded by non-saturated, quiescent air (see Fig. 1). The droplet is modelled as a dynamic point mass source in the limit of an isothermal system with incorporation of the spatial variation in the evaporative flux across the free surface (Fig. 1). The limiting evaporation modes (constant contact radius (CCR) and constant contact angle (CCA)) were considered.

The versatility of the model, with an interchangeable contact angle parameter, allows it to be used for hydrophobic and hydrophilic systems. The PSM was implemented using the Finite Difference Method (FDM) in MATLAB R2020a, which was validated against and found to be in good agreement with literature data. The model predicts evaporation rate in the CCR mode particularly well, which is the prevalent behavioural mode for water droplets in a hydrophilic system.

A Design of Experiments (DoE) approach was taken to quantify the effect on droplet evaporation caused by the droplet radius and surface wettability. In addition, the interaction of these factors was studied. The DoE findings showed accurate control of the water droplet radius and liquid/solid contact angle is constructive in obtaining the required evaporation rate. Manipulating the dominant evaporation mode by pinning the droplet can provide up to 70% greater control over the process. The versatility and accurate predictive power of the PSM allows it to be a robust and computationally inexpensive modelling tool for sessile droplet evaporation in a wide range of technical applications.

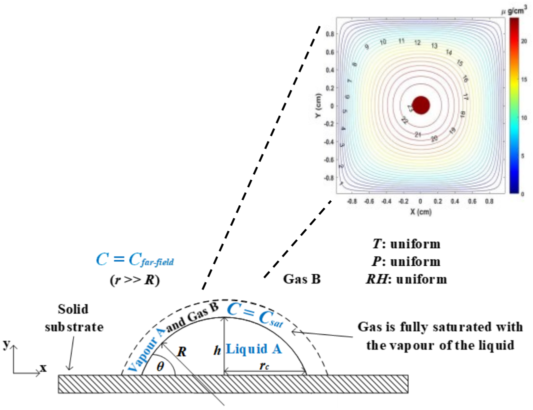

Figure 1. Schematic diagram illustrating the characteristics of the evaporating sessile droplet: contact angle (θ), contact radius ($r_c$), radius of sphere (R) and droplet height (h). The solid line denotes the outline of the droplet. The vapour concentration distribution around a water droplet of $r_c = 0.1$ cm on a glass substrate ($\theta = 41°$) on the substrate plane ($z = 0$) evaporating in CCR mode at ambient temperature and pressure is seen. The droplet surface is filled at the saturated vapour concentration.

# Title: Two-Dimensional evaporation dynamics of a respiratory droplet in context of COVID-19

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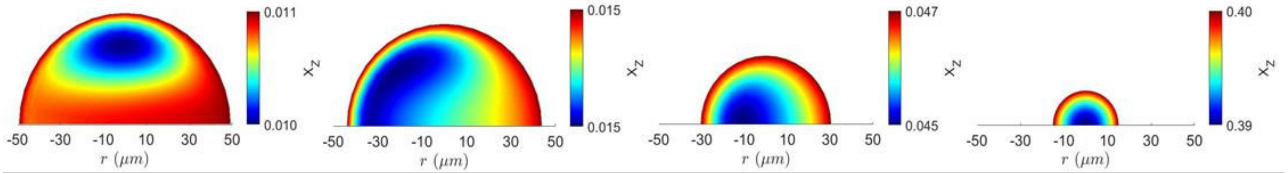
[3] *Institute for Aerospace Studies, University of Toronto, Toronto, Ontario M3H 5T6, Canada*

Respiratory droplets are considered the primary mode of transmission of COVID-19. The droplets ejected through the exhalation process during cough, sneeze, speech consist of a complex mixture of volatile and non-volatile substances. While transmitted and translated in air, these complex liquid droplets undergo a series of coupled thermo-physical processes. Contemplating an individual airborne droplet in a cloud of infectious droplets, boundary layers and wakes develop on account of relative motion between the droplet and the ambient air. The complex phenomenon of the droplet's coupled fluid-dynamics such as shear-driven internal circulation of the liquid phase and Stefan flow due to vaporization or condensation comes into effect. The mathematical description of the coupled subprocesses, including droplet aerodynamics, heat and mass transfer, and precipitation kinetics, which controls the evaporation and precipitation dynamics, were identified and subsequently solved to obtain the solution. The two-dimensional model gives a complete analysis encompassing the gas phase coupled with the liquid phase responsible for the airborne droplet kinetics' complex evaporation phenomenon in the ambient environment.
The model predicts droplet lifetime suspended in the air and provides a good agreement with the experimental data. The 2D model confirms that the droplet's initial thermal gradient diminishes quickly due to strong liquid phase transport. This model is subsequently used to assess the variation in droplet lifetime and distance traveled with the ambient temperature and humidity functions. The results show that, at specific environmental conditions, the distance covered by the most critical droplet before its complete evaporation can be significantly larger than 6feet, a distance generally used as a social-distancing guideline. Moreover, as the droplet moves in the air, salt concentration enhances near the droplet surface due to evaporation, reaching a super saturation point. Salt accumulation slows down the rate of vaporization significantly and crystallization starts from the droplet surface. The temporal salt concentration profiles inside the droplet is shown in fig. 1 and follows similar trends for different ambient conditions.



140ms 2.53s 8.03s 13.53s

Figure 1. Salt mass fraction field inside the droplet at different time steps with $D_0 = 100\ \mu m$ at initial conditions of 30°C droplet surface temperature and 48% relative humidity.

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# Internal flow in evaporating sessile water drops: Dominance of Marangoni flow

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Droplet evaporation has been of great interest to academic and industrial research with applications in ink-jet printing, spray cooling, chemical and biological assays etc [1]. The characteristics of internal flow during evaporation significantly affect overall evaporation kinetics. Recently, presence of a convective cell at the liquid-vapor interface due to the dominance of Marangoni flow is reported [2]. Although the origin and characteristics of this Marangoni flow dominated flow regime are investigated in terms of the evolution of thermal field and the temperature difference within the drop, the internal flow during this regime is not reported [2,3].

Here, the internal flow in evaporating sessile water drops is studied using Particle Image Velocimetry (PIV), with focus on initial stages of evaporation where a convective cell as a cold spot is present at the interface. A continuous wave laser along with a concave cylindrical lens and a plano convex spherical lens are used to create a thin laser sheet. A water drop of 4±0.2 µl volume seeded with 0.002 w/v% of PS-FluoRed-2.5 fluorescent micro particles is gently placed on a hydrophobic substrate (silane coated silicon wafer) maintained at a temperature of 60° C. Using a micro stage, the laser sheet is moved to illuminate the drop in a plane 750±50 µm from the base of the drop which is nearly half the initial height of the drop. Figure 1a shows the schematic of the experimental setup. Fig. 1b shows the streakline image obtained by superimposing 20 consecutive images at a time instant of 25s. Two counter rotating vortices which correspond to the cold regions in the convective cell are visualized. By correlating with the corresponding thermal field captured by an infrared camera (Fig. 1c), the flow is directed from a hotter region to a colder region. A detailed quantitative analysis accounting for 'lens-effect' is to be performed to understand the temporal evolution of the internal flow field. Further, we plan to conduct experiments in an inverted drop configuration where, buoyancy is expected to be non-existent and the internal flow field is dominated by Marangoni flow throughout the evaporation.

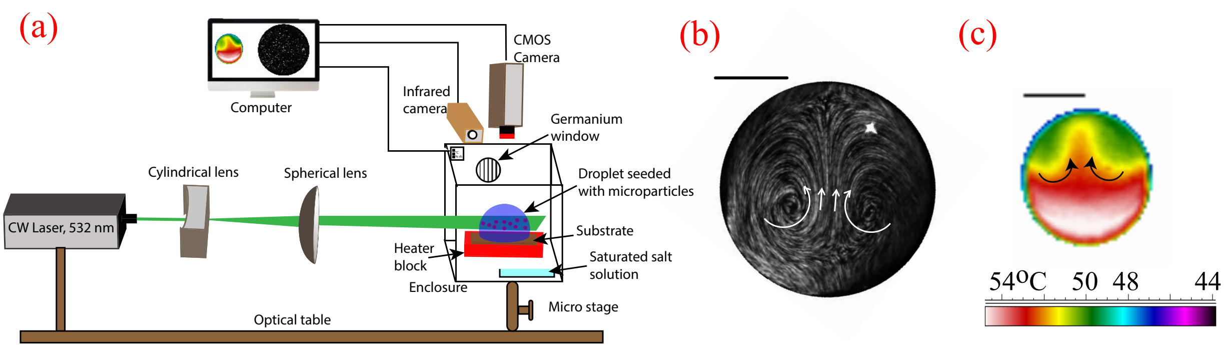

Figure 1: (a) Schematic of the experimental setup. (b) Streak line image showing the presence of two counter rotating vortices inside the drop and (c) shows the corresponding thermal field at the drop surface. Scale bar indicates 1mm.

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# Experimental investigation of the sessile droplet evaporation process based on different surface roughness and wettability

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As one of the most common phenomena in nature, droplet evaporation has been used widely in industries and scientific fields [1]. For the sessile droplet, the wettability of the substrate surface could make significantly affect the evaporation dynamics [2]. Among the many factors influencing surface wettability, surface roughness is one of the common causes [3], but the link between roughness and droplet evaporation processes has not yet been fully revealed. Therefore, the experimental study of sessile pure water droplet located on the copper surfaces with different roughness and wettability has been carried out. In the present study, the effect of roughness as a factor on the evaporation rate is considered. The experimental details could be seen in Fig. 1. The deformation and temperature distribution of the sessile droplet liquid-vapour interface is recorded. Then, an empirical equation relating roughness to the evaporation rate of droplets is proposed. It has been demonstrated that changes in surface roughness not only affect the wetting state of the sessile droplet, but also have an impact on the heat and mass transfer processes at the liquid-vapour interface. The research in this article hopes to provide help to research the relationship between roughness and droplet evaporation dynamics.

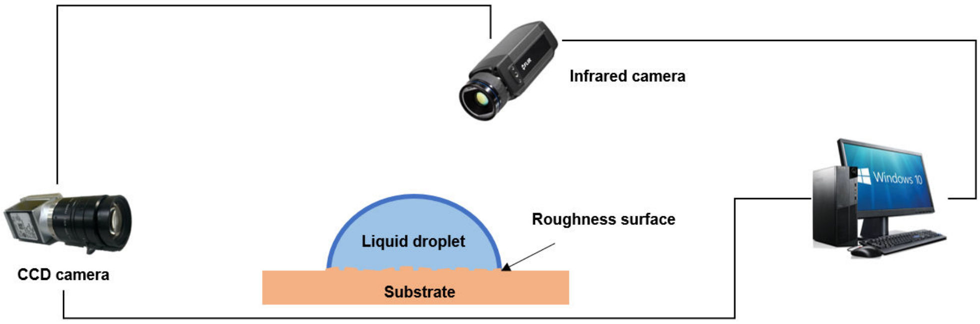

Figure 1. Schematic diagram of experiment layout

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# Flow near the contact line during coalescence of droplets

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This paper describes experimental measurements of fluid flow and interface fluctuations near the contact line of a sessile droplet coalescing with another droplet, to explore the mechanisms influencing the droplet evaporation and coalescence dynamics with different coalescence modes. The results show a clockwise vortex near the contact line formed in the initial stage of pendent-sessile droplet (PSD) coalescence mode, while the opposite direction of the fluid flow in the initial stage of sessile-sessile droplet (SSD) coalescence mode. Compared to the unmixed state, the flow velocity near the contact line increases by two coalescence modes and the droplet coalescence promotes the evaporation process. The interface thickness near the contact line varies in an oscillating mode described by an exponential function superimposed by a local fluctuation function of a waveform. The superimposed function of the interfacial profile agrees with the experimental data of two modes. The results indicate that the oscillation in PSD mode is favourable for adequate mixing and reaction of two coalescing droplets. The evolution of the liquid bridge was deduced from a relationship between the receding and advancing contact lines of the coalescing droplets. These observations help capture insights into the velocity field and the mechanisms of interface evolution near the contact line during droplet coalescence and many issues involving coalescence dynamics and thin-film evaporation.

# Perpetuating drop-wise condensation under cyclic thermal stresses

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Heat transfer rates during surface condensation is limited by thermal conductivities of the intermediate solid as well as condensed liquid. Dropwise condensation has higher heat transfer rates the liquid when compared to filmwise due to reduced surface coverage and higher mobility. The latter is promoted by adding a liquid repellent layer on the condenser. However the ensuing loss in thermal conductivity partially negates the benefits gained from the coating. To this end, several groups have achieved thin and durable coatings with high heat transfer coefficients, mostly at high temperatures and humidity, held constant over long times[1]. This work will present a novel sub-micrometric, conformal and transparent coating based on metal-organic framework[2], which will be subjected to long term thermal stress cycling in order to accelerate coating deterioration. Stability is measured against evolving droplet size distribution while a general notion of heat transfer is gained from droplet growth rates. Robustness of the coating has been tested against mechanical abrasion, chemical corrosion as well liquid impact. This work will discuss the dynamics of droplet formation, growth, coalescence and sliding as well as the rationale of using metal-organic framework.

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# Foam formation using soft porous media

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Foams formation with porous materials is a process of great interest to many industries, including household cleaning and enhanced oil recovery. Interaction of foams with porous media has previously been investigated both theoretically and experimentally by A, Bureiko et al [1] and N, Koursari et al [2]. Foams made by compression of a soft porous media has only been investigated recently. Where the foams were made using a compression device with soft porous media containing surfactant solution. The soft porous media used in these investigations was sponges which matches the application which is of interest. This porous media has many uses including household, car and body cleaning. The amount and quality of foam produced by compression/decompression cycles of different sponges with surfactant solution and surfactant-polymer mixture was investigated experimentally. It was found that the maximum amount of foam is produced when the concentration of the commercial dishwashing solution is in the range of 60-80% m/m. The amount of foam produced was independent of the pore size of the media in the sponges investigated [3]. This process was also explored using pure surfactant sodium dodecyl sulphate (SDS) where it was found that the amount of foam produced increased until ten times the critical micelle concentration (CMC). Any concentrations above 10cmc produced the same mass of foam [4]. For both solutions a theoretical solution was also developed which had perfect agreement with the experimental results obtained.

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# Sol-Gel Derived Tin Oxide Rhombohedra and Fern-Dendrites

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The investigation of pattern formations by drying droplet is the topic of interest not only for academic study but for numerous inventive applications in medical field, surface coating, forensic studies, biosensor, biochemistry analysis, etc. The dynamics of evaporating sessile droplet is determined by the wetting properties and contact angle hysteresis measurements. The growth of tin oxide rhombohedra is reported here using sol-gel technique. A tin salt was allowed to form a gel which was allowed to settle overnight. The supernatant and precipitate were separated and subjected to identical drying environment. Fig. 1(a) and 1(b) show the patterns obtained after drying. While the supernatant yielded fern-like dendritic pattern, the precipitate yielded the faceted rhombohedra indicating a greater extent of crystallization in case of precipitate. The factors such as chemical composition, number of inclusions/salt present in fluid, surface energy of the substrate, interaction between substrate and fluid, rate of drying, and forces acting on/in the droplets also may influence the morphological pattern of the sessile drying droplet. Further convection currents while drying or cavitation effect may also be responsible in influencing such morphologies. Further investigations to study these aspects are underway.

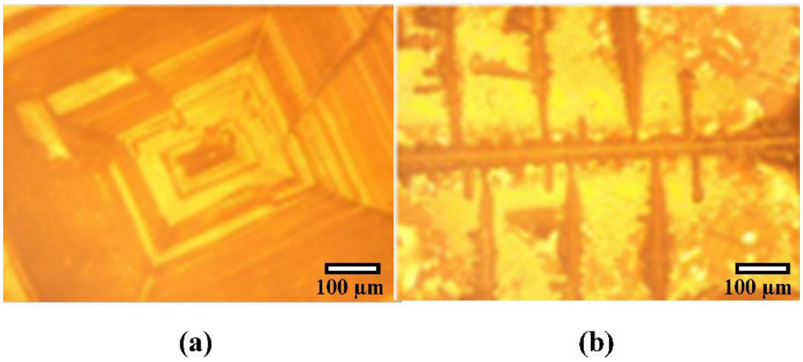

Figure 1. (a) Rhombohedra and (b) fern-like dendritic pattern in dried droplet observed under optical microscope.

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# Optical Fiber: A Potential Method for Critical Micelle Concentration Measurement

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*[2] Key Laboratory of Nondestructive Testing, Ministry of Education, Nanchang Hangkong University, China*
*[3] Department of Mathematics, Physics and Electrical Engineering, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, NE1 8ST, United Kingdom*

Critical Micelle Concentration (CMC) of the surfactants is one of the most significant nominal properties of their solutions. This characteristic affects interfacial phenomena and bulk properties. In this study, two methods are used to measure the CMC of two ionic surfactants, CTAB and SDS. The used techniques are the drop Profile Analysis Tensiometry (PAT) and the optical fiber, respectively[1,2]. The purpose of this research is to find the potential application of optical fiber[3,4] as an alternative way to measure the CMC.

In this work, the surface tension values obtained by PAT for different concentrations of the bare surfactant solutions were compared with the spectrum width center obtained by optical fiber for the mentioned solutions as a function of the surfactant concentration. The preliminary results demonstrated that there is a compliance between optical fiber and PAT techniques, making optical fiber a promising tool in the in-situ CMC measurements of surfactant solutions, opening a wide spectrum of its possible applications[5].

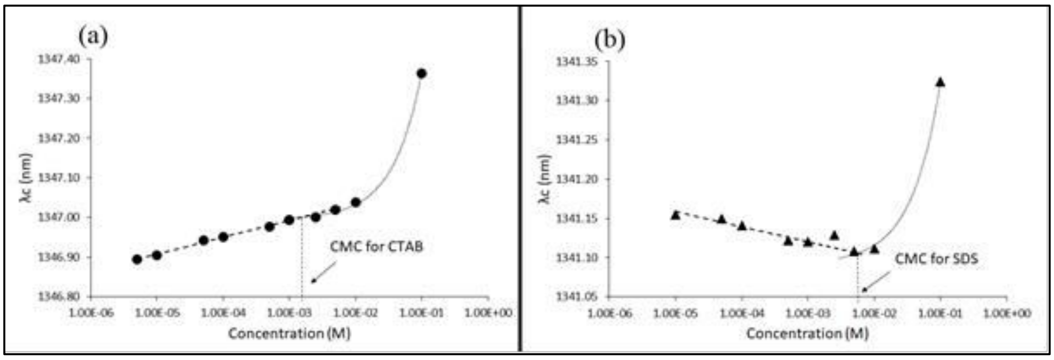

Figure 1. Optical fibre spectrum width center against surfactant concentration for (a) CTAB, and (b) SDS.

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# Harvesting energy from high frequency impinging water droplets by a droplet-based electricity generator

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Harvesting energy from water, in the form of raindrops, river, and ocean waves, is of considerable importance and has potential applications in self-powered electronic devices and large-scale energy needs. Recently, the droplet-based electricity generator has shown an increase by several orders of magnitude in electrical output, overcoming the drawback of traditional droplet-based device limited by interfacial effects [1,2]. Despite this exciting result, the output performance of this novel droplet-based electricity generator is limited by relatively low frequency of impinging droplets owing to the formation of a continuous liquid film at high frequency, which might hinder its practical applications. To overcome this challenge, here we report the design of a superhydrophobic surface based droplet electricity generator, referred to as SHS-DEG, which can timely shed water droplets from the surface without the formation of liquid film at high frequency, and thereby generating enhanced average electrical output. Moreover, our SHS-DEG exhibits many distinctive advantages over conventional design including long-term durability, robustness, and power generation stability under harsh environments. We envision that the ability to harvest electrical energy from water droplets at high frequency has promising applications in various energy-harvesting systems.

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# Raman Spectroscopy of Deposits from Agrochemical Formulations

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Crop protection formulations are complex fluids (often dispersions or emulsions) containing active ingredients (AIs) as well as ‘adjuvants’ that enhance the uptake of the AIs by plants or pests. Once sprayed on a leaf surface, drops dry and the components of the drop are deposited on the surface. The distribution of the various components in the deposit is linked to the effectiveness of the formulation, but there is a lack of good methods for measuring how the components are distributed on a surface, what phase they are in and whether they are co-located or in separate phases. Consequently, it is difficult to relate the morphology of the deposit to the effectiveness of the formulation or to understand how to improve the design of formulations. This work will show how Raman spectroscopy and Raman imaging can be used to quantify the distribution of crop protection formulation components in droplet deposits.

# Numerical Model of Milk Droplet Spray Drying

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Spray drying is a commonly used method to rapidly produce a dry powder from liquids or slurries. This method is preferred for producing milk powder in the dairy industry in order to extend the shelf life, as well as making the product denser for transportation [1]. In this work, we have studied the drying process of skim milk droplets under the conditions of a real-sized spray dryer. The heat and mass conservation equations were solved on a shrinking computational domain as the droplet radius decreases using the finite volume method, developed in MATLAB. The model predicts the non-uniform temperature distribution and solute concentration within the evaporating droplet. Four drying stages including initial heating, isothermal evaporation with shrinking (left droplet in Fig. 1), crust formation (middle), and wet-core evaporation (right) are simulated. We verified our code implementation by comparing results with COMSOL Multiphysics v5.5, and validated our model against numerical and experimental data from the literature [2]. We examined the difference between the effects of applying uniform (lumped mass) versus non-uniform temperature distributions. This model is used to predict the infant formula drying process (100-200 microns droplets) within an industrial spray dryer.

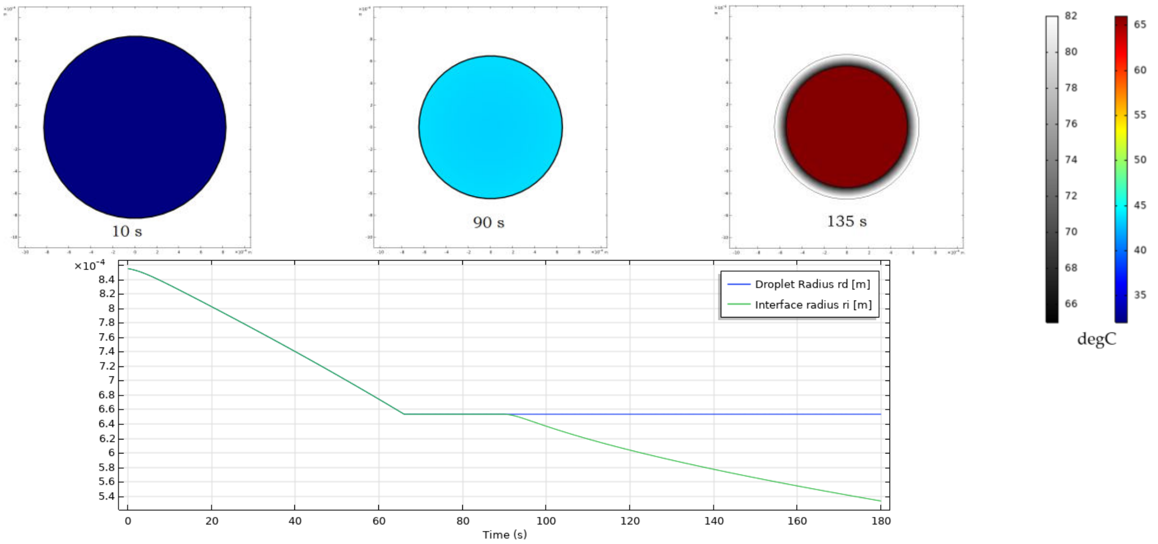

Figure 1. Evolution of droplet radius with a non-uniform temperature field and crust formation, with snapshots of the droplet cross-section over time (top) and droplet radius $r_d$ and interface radius $r_i$ (bottom).

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# Viscosity-induced suppression of coffee-ring effect in pharmaceutical drops

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[3] *School of Pharmacy, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ*

Drop-based technologies such as inkjet printing lie at the forefront of development of disruptive solutions in many areas including pharmaceuticals. However, the evaporation of a solute-laden drop typically yields highly undesirable ring-stain patterns due to the coffee-ring effect (CRE) [1].

Here, we demonstrate how controlling the viscosity of the drop allows the suppression of the fluid flow from the bulk of the drop to its edge, which lies at the heart of CRE[1]. 0.2% w/w of Paracetamol, our model drug, formed a ring-stain pattern in the absence of chitosan-viscosity, as shown in Figure 1 (left column). Increasing the chitosan content and hence viscosity suppressed the outward motion of our drug to the periphery of the drop and produced a thin layer (mid column). Further increase of chitosan resulted in a thicker solute layer due to the additional polymer content (right column). However, in both cases CRE has been suppressed, as evidenced by the complete lack of paracetamol crystals/ring in the polarised light microscopy (PLM) images in bottom row of Figure 1.

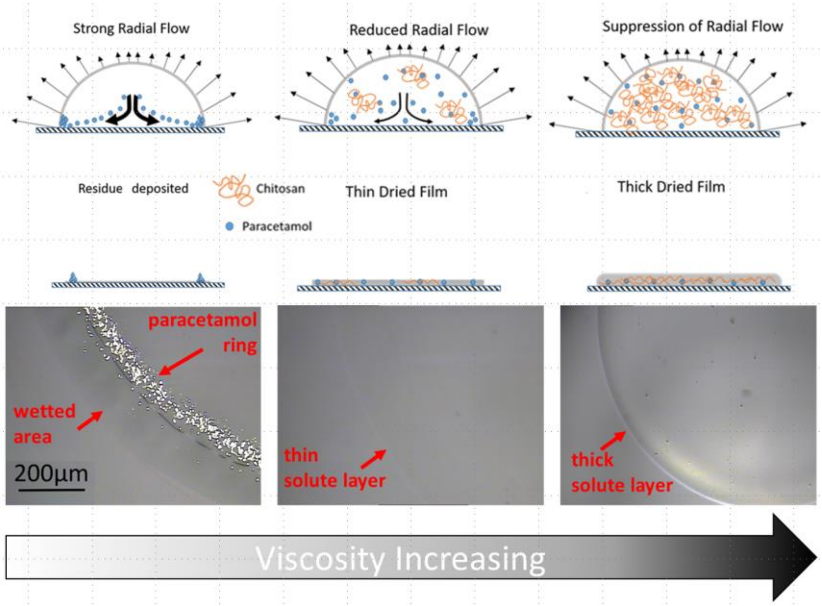

Figure 1. Top row, cartoon of deposition mechanism and the effect of increasing concentration of chitosan (orange chains) on the internal flow and accumulation of solute (paracetamol, blue dots); middle row, cartoon of deposit patterns; bottom row, PLM images of the actual paracetamol accumulation. Viscosity increases to the right and CRE is suppressed. Image adapted from [2].

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[2] Wilkinson et al., *Coll. Surf. A*, **614** (2021), 126144.

# Influence of varying evaporation conditions upon dry drop pattern differentiation of serum and plasma collected from four volunteers

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[3] *Institute of Integrative Medicine, University of Witten/Herdecke, 58313, Herdecke, Germany*
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Pattern formation in drying body fluids constitutes an often-studied topic nowadays, since it may find application in several medical, scientific, and technological areas [1, 2].
In this study, serum and plasma droplets from four apparently healthy volunteers were evaporated in a series of 13 experiments conducted in different temperature and relative humidity conditions. In each experiment, samples were analyzed in three replicates; each replicate consisted out of ca. 10 droplet-patterns. The patterns were photographed in dark and bright field and analyzed with *ImageJ* for grey level distribution, texture parameters, and crack features (Fig. 1). In total 3787 dark field and 3768 bright field photos were analyzed. The experimental design stability was tested by means of systematic control experiments. Additionally, blood count analyses of the samples were performed in the laboratory of the Clinic Arlesheim. All volunteers signed a declaration of consent for use of samples for research purposes; the samples were anonymized.
It was found that in varying evaporation conditions certain pattern features were more pronounced. In all 13 experiments, in both serum and plasma patterns there were statistically significant differences between the four volunteers. However, best differentiation between the volunteers was possible at 15% rH for cracks and 45% rH for crystalline structures present in the droplet center. Strong correlations were found between pattern evaluation parameters and blood count *inter alia* ions, proteins, bilirubin, triglycerides, glucose, cholesterol, sedimentation reaction, and creatinine serum. Our experiments showed that evaporation conditions strongly influenced the pattern formation and so the methods' outcome. Therefore, for diagnostic use, the evaporation conditions must be standardized and controlled. Moreover, it should be investigated at which evaporation conditions the pattern features differentiate most for certain diseases.

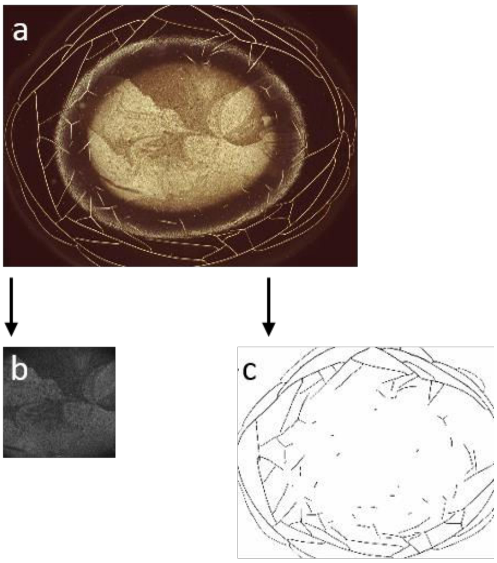

Figure 1. Example of an dark-field original serum pattern (a), region of interest in 8-gray bit image (b), cracks extracted from a bright field image by means of color threshold (c). On (a, b) grey level distribution, inverse difference moment, and contrast were measured, whereas on (c) crack total area was evaluated.

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# Spread and retraction for non-Newtonian drop impacts on micropatterned surfaces

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[2] *The MacDiarmid Institute for Advanced Materials and Nanotechnology, New Zealand*

Drop dynamics studies are essential for controlling and optimizing drop deposition on any surface. Droplet interactions with micropatterned surfaces in particular are important for microfluidic applications such as surgical endoscopes, biological fluids, MEMS, and applications related to cell growth platforms [1-3]. Although such drop impacts have been studied widely for Newtonian fluids, non-Newtonian fluids have not been studied in detail [2,4]. Moreover, impacts of non-Newtonian fluids are of significant interest owing to the common use of such fluids in industrial and biological processes [4]. In this study, the effect of surface patterning on drop spreading and retraction has been studied for both Newtonian (glycerol) and non-Newtonian (Carbopol) aqueous solutions, and preliminary results will be discussed. Control experiments on a flat surface are included for comparison. We aim to investigate the underlying mechanism between surface patterns and drop dynamics for various non-Newtonian solutions.

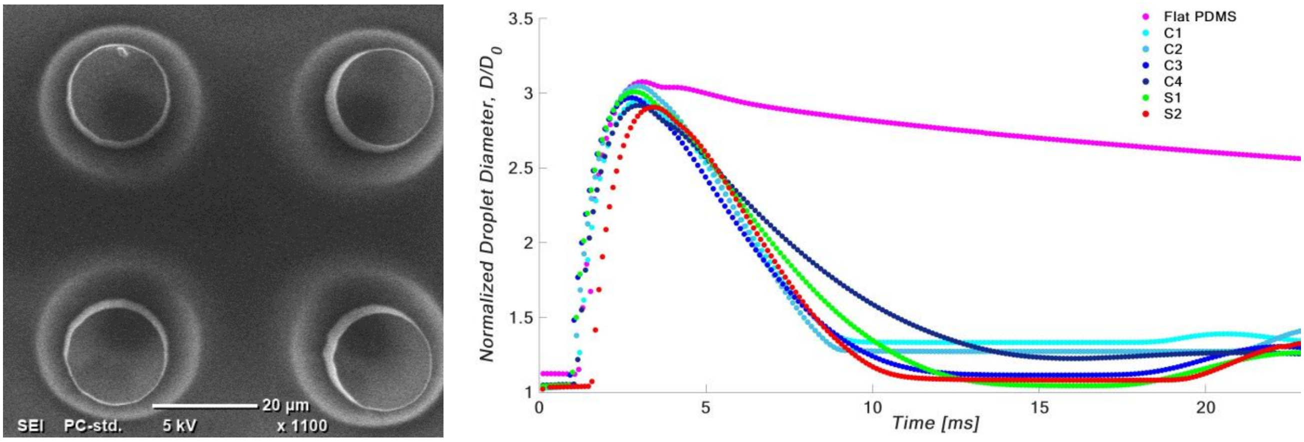

Figure 1: Left, SEM image of patterned circular micropillars used in experiments. Right, spread of 0.1% Carbopol droplets on micropillar arrays as a function of time. Colours indicate different micropillar patterns.

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# A hierarchical porous membrane with super liquid repellency for enhanced desalination

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Author list: **Prexa Shah**, Youmin Hou, Michael Kappl and Hans-Jürgen Butt

As a hybrid thermal/membrane based desalination process, membrane distillation (MD) has received increasing attention for small scale desalination applications as well as for treating high salinity brines. To enhance distillation efficiency, an ideal MD membrane demands large pore size and high porosity. However, the large pore size would inevitably increase the susceptibility to membrane wetting, which reduces the salt rejection rate in MD process. To overcome this challenge for membrane design, we developed a composite membrane with hierarchical porous structures by coating superhydrophobic nanofilaments on a micro-porous polyethersulfone (PES) substrate (Fig. 1). The nanofilaments formed a nano-porous layer on top of PES substrate, which can prevent liquid wetting under an extremely high hydrostatic pressure (>11.5 bar). Meanwhile, the inner micro-porous structures guaranteed a rapid water vapor diffusion to facilitate distillation. Under standard MD conditions, the nanofilament-coated PES membrane increased the distillation flux by up to 60% over the state-of-the-art commercial membranes, while showing an excellent salt rejection (>99.99%) and operating stability. This work shows a great potential for development of high performance composite porous membranes on various substrates.

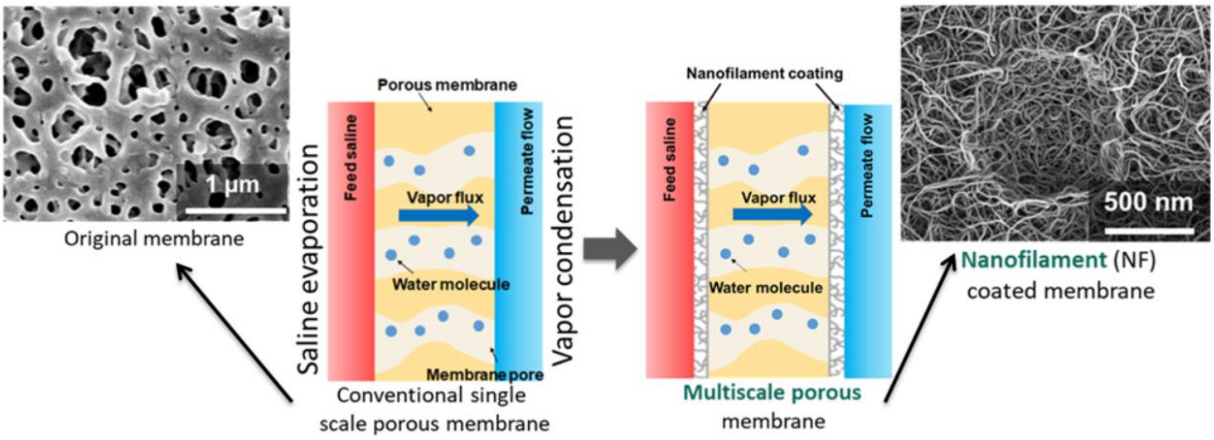

Figure 1. Schematic showing the MD process using single-scale porous membrane and multi-scale porous membrane, respectively. Insets show the scanning electron microscopy images of original micro-porous PES membrane (left) and nanofilament-coated PES membrane (right).

# Ferrofluid drop impacts in a non-uniform field

**Geoff R. Willmott**[1,2,3], Steve Wells[1,2], Amelia Cordwell[2], Alex Chapple[2]

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[3] *School of Chemical Sciences, The University of Auckland, New Zealand*

Ferrofluids are suspensions of magnetic particles in a solvent. When placed in a magnetic field, drops of ferrofluid form spiky Rosensweig instabilities which arise from competition between surface tension and the tendency of the particles to line up along magnetic field lines [1]. This presentation will discuss high-speed photography of vertical ferrofluid drop impacts on to a glass slide. A non-uniform magnetic field is present due to a bar magnet placed under the slide.

The form of the drop is of interest both before and after impact. Prior to reaching the surface, elongation is observed (Figure, left). The drop shape depends on the release height and the positioning of the magnet, and its evolution can be predicted by considering both bulk and surface magnetic forces. In this study, the shape did not reach equilibrium prior to impact, so the tip of the drop was accelerating faster than the centre of mass when impact occurred.

Following impact, instabilities dynamically emerge on the spreading lamella. There appears to be a link between the crown-rim instabilities observed for conventional drop impact and nucleation of Rosensweig instabilities. The position, timing and evolution of instabilities varies according to the impact conditions and magnetic field. At high fields, the ferrofluid can form a rim above the edges of the magnet, an effect which can be quantitatively explained by considering the radial component of the magnetic force.

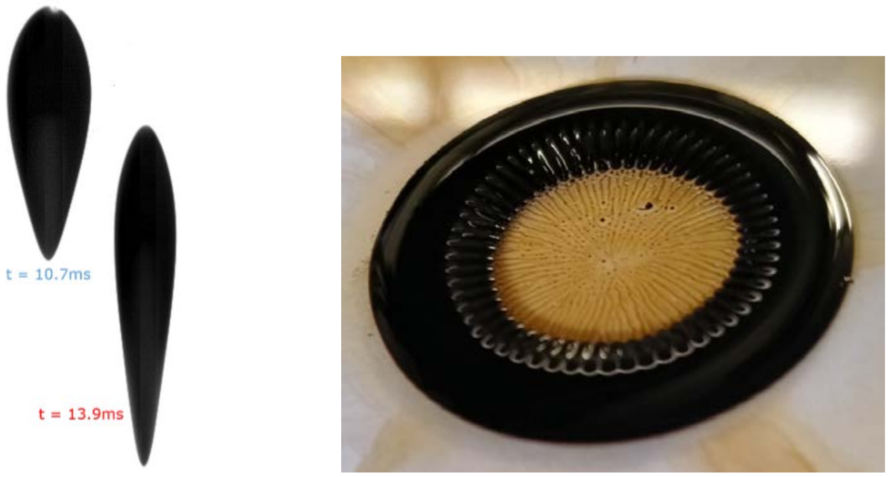

Figure: Left, ferrofluid drop profiles prior to drop impact on a glass slide placed above a bar magnet, labelled with relative time elapsed, and (right) a drop following impact.

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# Outward and inward protections of different mask designs against aerosol transmissions

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We evaluate the outward and inward protections of different mask types (N95, surgical and two different cloth mask designs) taking into account the imperfect fit on the wearer. To this end, we built a manikin to simulate exhaling, coughing and inhaling of aerosol droplets 0.3–5.0 $\mu$m in diameters. The outward and inward protections depend on many factors, including the droplet size, the mask fit and the presence of a filter layer. Here, we show that cloth and surgical masks with a non-woven filter layer can achieve a combined outward and inward protections between 50% and 90% (Fig. 1a, c). Removing the filter layer greatly reduces the protection efficiency (by 40% for the smallest particle size). While a well-fitted N95 masks offer protection efficiencies close to 100%, a poorly fitted N95 mask with gaps offers less protection than a well-fitted surgical/cloth mask. We also found that double masking—the wearing of cloth mask on top of a surgical mask—is only effective at reducing outward particle emission when coughing (by up to 10%), while offering no additional protection when exhaling/inhaling as compared to a single cloth/surgical mask (Fig. 1b, d). The results of our work can inform the implementation of mask mandates to minimize aerosol (airborne) transmissions of COVID-19.

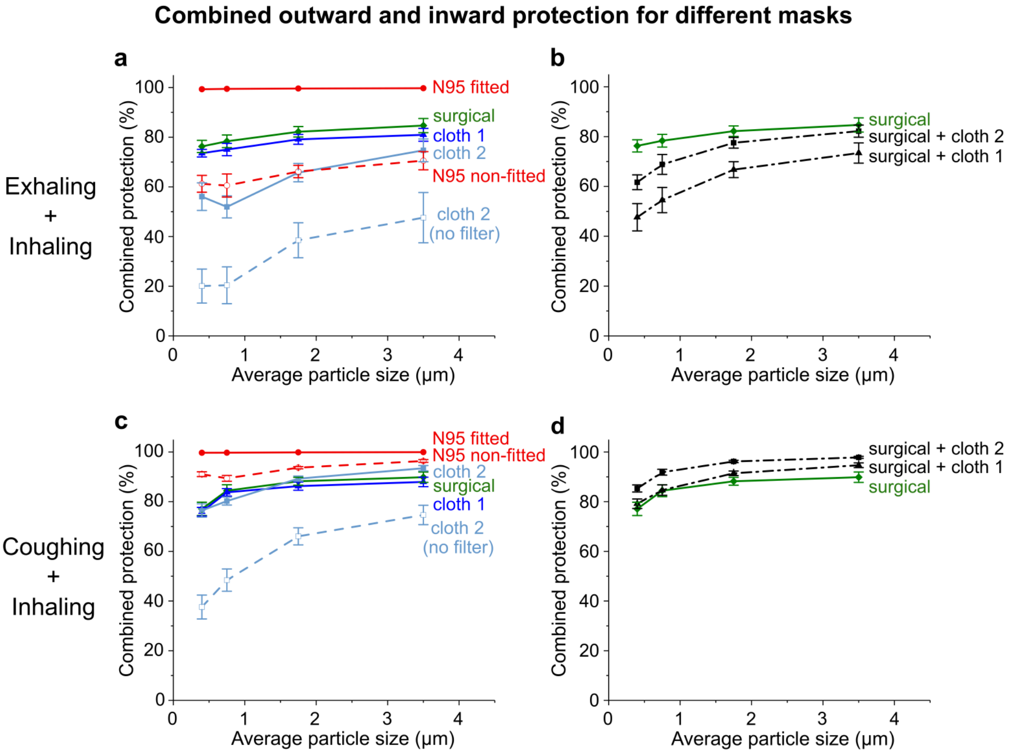

Figure 1: Combined outward protection when exhaling and inward protection when inhaling for (a) single masks and (b) double masks. Combined outward protection when coughing and inward protection when inhaling for (c) single masks and (d) double masks.

# Comparative experiments on the droplet impact of blood onto a glass substrate

**Yuto Yokoyama**[1], Akane Tanaka[2], and Yoshiyuki Tagawa[1]

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[2] *Laboratory of Comparative Animal Medicine, Institute of Agriculture, Tokyo University of Agriculture and Technology, Japan*

Droplet impact of blood is of great importance in forensic science since impacting droplet determines the bloodstain pattern. Previous studies suggest that the behaviour of an impacting blood droplet is similar to that of a Newtonian liquid, which has shear viscosity similar to the viscosity of blood at high shear rate[1]. Here we conduct comparative experiments of droplet impact using four solutions, namely dog's whole blood (deformable red blood cells dispersed in plasma) (WB), plasma with non-deformable resin particles (PwP), inelastic glycerol/water with resin particles (GWwP), and a commercial blood simulant (hard particles dispersed in a water based Newtonian solution) (BS). All these solutions are prepared to have quite similar shear-viscosity at high shear rate. Ranges of Reynolds and Weber numbers in our experiments are $550 < \mathrm{Re} < 1700$ and $120 < \mathrm{We} < 860$, respectively. Two high-speed cameras are used simultaneously for side and bottom views of impacting droplets. As reported in previous studies[2], a spreading radius of impacting droplet of WB agrees well with that of a Newtonian fluid with viscosity similar to viscosity of WB at high shear rate (Fig. 1(a)). In addition, a splashing droplet of WB forms finger structure (*finger-splashing*) (Fig. 1(b)). In contrast, although PwP has viscosity similar to WB at high shear rate, impacting droplet of PwP exhibits the characteristics of impacting suspension droplets[3,4], i.e. a reduced spreading radius (Fig. 1(a)) and the splashing where particles are ejected (particle ejection) (Fig. 1(c)). This result suggests that the high deformability of red blood cells in WB plays a crucial role on the Newtonian-like behaviour of droplet impact of blood. Impacting droplets of PwP and GWwP exhibit no significant difference in the finger-splashing, indicating that the effect of elasticity of plasma is negligible in finger-splashing. Importantly, impacting droplet of BS behaves quite differently from WB in both spreading and splashing. The use of deformable particles rather than hard particles is essential to mimic droplet impact of blood for the development of a blood simulant for bloodstain pattern analysis.

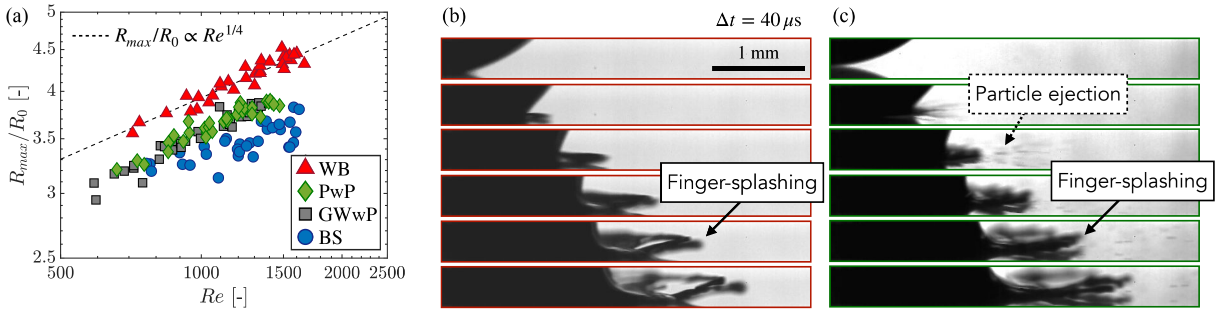

Figure 1. (a) Spreading radius against Reynolds number. Side views of (b) whole blood and (c) plasma with particles.

[1] N. Laan, *et al.*, *Phys. Rev. Appl.* **2** (4) (2014), 044018.
[2] L. Hulse-Smith. *et al.*, *J. Forensic Sci.* **50** (1) (2005) 54–63.
[3] V. Grishaev, *et al.*, *Langmuir* **31** (36) (2015), 9833–9844.
[4] I. R. Peters, *et al.*, *Phys. Rev. Lett.* **111** (2) (2013), 028301.

# Image Feature Extraction for Spreading and Splashing Drops on a Solid Surface using a Feedforward Neural Network (FNN)

**Jingzu Yee**[1], Akinori Yamanaka[1], and Yoshiyuki Tagawa[1]

[1] *Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology, Japan*

This study aims to unveil important image features that classify spreading and splashing drops which are impacting on a solid surface by using a feedforward neural network (FNN)[1]. Ethanol drops of area-equivalent radius $R_0$ = 1.3 mm were allowed to free fall from impact heights $H$ ranging from 4 – 60 cm and impact on the hydrophilic surface of glass substrates (spread-splash transition: $H$ = 20 – 22 cm). High-speed videos were captured and images at characteristic time after impact $\tau = R_0/U_0$ ($U_0$: drop velocity) were selected to train an FNN. After achieving accuracy above 90%, the classification process of the trained FNN was analyzed. Fig.1(a) shows the visualized weight matrix in the hidden layer of the trained FNN, where the negative values (blue) indicate the area which is only covered by splashing drops and becomes zero (green) in the Kronecker product. Remarkably, the areas with large magnitude of negative values are found not only in the area where the ejected droplets of a splashing drop are present but also at the upper part along the contour of the main body of the drop as highlighted by the dashed ovals. For illustration, the typical images of a spreading drop and a splashing drop are shown in Fig.1(b) and (c), respectively. As shown by the dashed ovals, most of the negative values of the weight matrix remained in those areas in the case of a spreading drop, thus not exceeding the threshold for the FNN to identify it as a splashing drop. Previous studies on drop shape evolution during a drop impact in the spreading regime[2,3] can be extended to the splashing regime in order to elucidate the differences between both regimes. Moreover, analysis on the output layer of the trained FNN showed that although without explicit training on $H$, the output value used by the trained FNN to judge an image $q_{out}$ showed an increasing trend with $H$, indicating that the trained FNN can be used to quantify the intensity of a drop impact from the image.

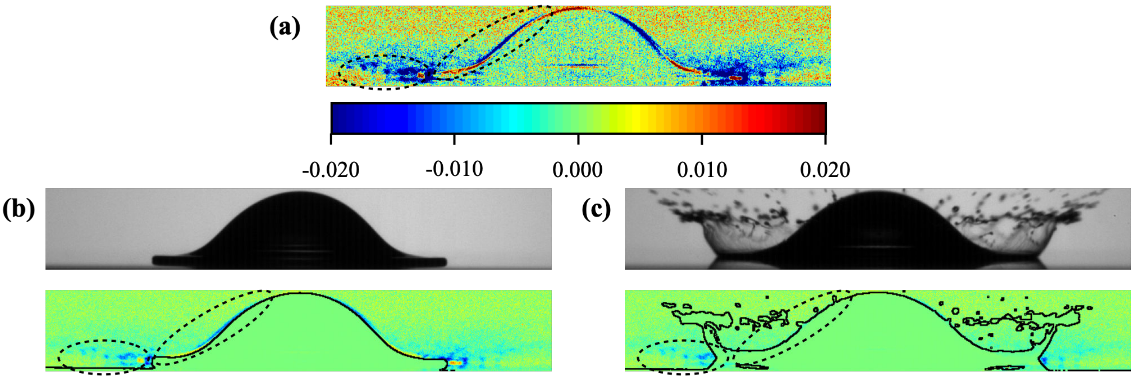

Figure 1. (a) Visualization of the weight matrix of the hidden layer, which its values are multiplied with an image to obtain its $q_{out}$ value for classification. The typical images and their respective Kronecker product with the weight matrix of (b) a spreading drop and (c) a splashing drop.

[1] B Colvert, et. al., *Bioinspiration & Biomimetics* **13** (2018), 025003.
[2] G Lagubeau, et. al., *Journal of Fluid Mechanics* **713** (2012), 50–60.
[3] J Eggers, et. al., *Physics of Fluids* **22** (2010), 062101.

# Phase Field Investigation of Air Bubble Evolvement and the Effect of Dynamic Contact Angle

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Air entrapment is almost inevitable in droplet impact, extensive and constructive research findings have been achieved through theoretical predictions and innovations of experimental observation methods. In 2012, Lee directly captured the profile of the air film and its evolvement into a bubble using ultrafast x-ray phase-contrast imaging technique [1]. But simulation works are relatively scarce.

In this study, numerical investigation of air bubble evolvement is achieved with Phase Field Method by properly setting surface boundary conditions. It turns out dynamic contact angle model extracted from the outer spreading-retraction process could be effectively applied to the inner air bubble retraction simulation. Based on comprehensive and strong validation with Lee's experiment results, we further discussed the influence of advancing contact angle and slip length to the daughter droplet generation and bubble attachment/detachment. Our research tends to predict a new pattern where the seperated air film converges after detaching from the surface due to low advacing contact angle and it is the shedding vortex that pushes the convergence and the subsequent pinching off of the daughter droplet.

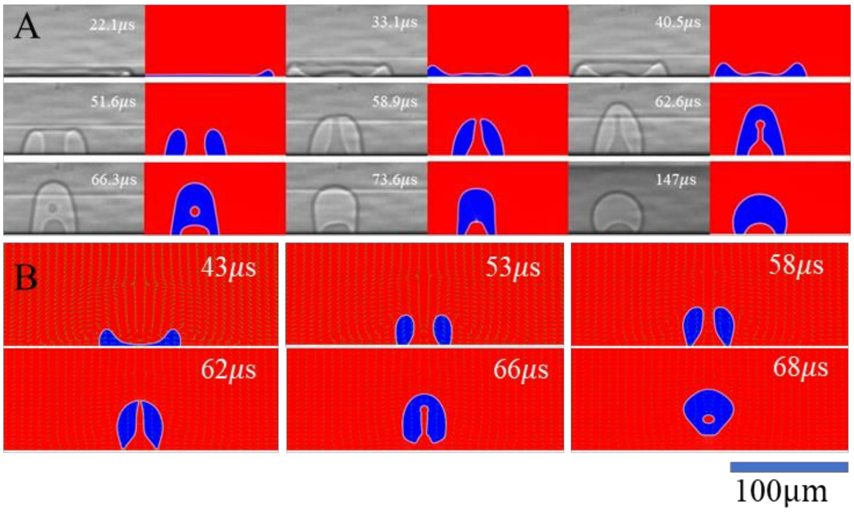

Figure 1. (A) Comparison of air film evolving into a bubble between simulation results and experiment results. Droplet diameter is 2.6mm, impact velocity is 1.25m/s, static contact angle of the surface is 50°. (B) A predicted new pattern where the pinching off of daughter droplet happens after detachment. Advancing contact angle used is 70°.

[1] Ji, S. L. , Weon, B. M. , Je, J. H. , & Fezzaa, K. . (2012). How does an air film evolve into a bubble during drop impact?. Physical Review Letters, 109(20), 204501.

# Numerical study of droplets on fibres - spreading and motion on fibre strands.

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[1] *Department of Mathematics, Computational Multiphase Flow, Technical University of Darmstadt, Germany*

In this work, numerical simulations of the spreading and sliding of a three-dimensional droplet on a single fibre strand are considered. The simulations are performed using our diffuse interface phase-field solver – phaseFieldFoam (FOAM-extend 4.0 and 4.1). The solver has been enhanced to use a moving reference-frame technique, to follow the droplet's centre of mass, effectively reducing domain size, which is used in cases where a sliding droplet is studied.

The diffuse interface solver is validated for several test cases including the equilibrium shape of a droplet on a flat and spherical surface by comparing to analytically derived results. Furthermore, cases of droplets spreading on single fibre strands are simulated, where the equilibrium shape of the droplet is compared to analytical solutions. In all these cases, very good agreement with results from the existing literature is observed.

After this validation work, the study of droplets moving on a fibre is performed, where we investigate the effects that droplet volume, viscosity and fiber inclination angle have on the droplet velocity and the forces acting on it.

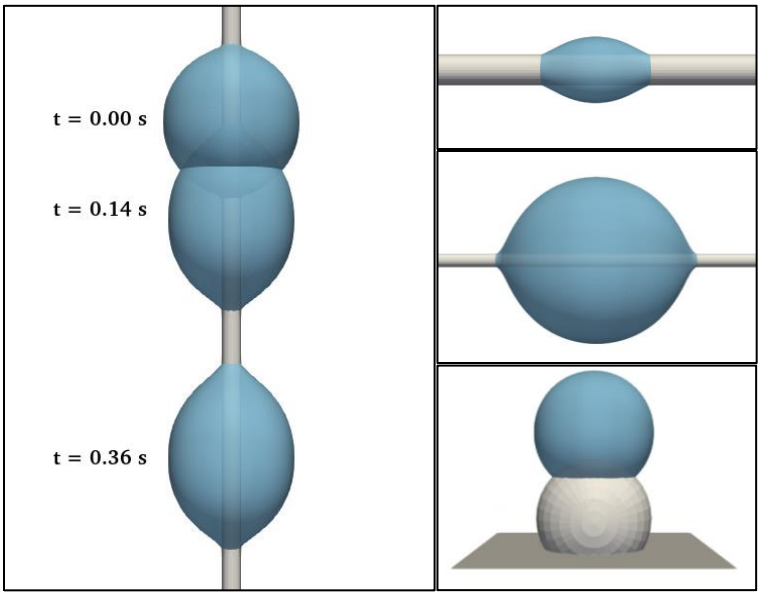

Figure 1. *Clockwise:* Direct Numerical Simulation of a 20 cSt droplet sliding along a vertical fibre of diameter $d_v = 80\ \mu m$, a droplet with radius $r = 0.1$ mm and $r = 0.5$ mm (respectively) spreading on a fibre of diameter $d_v = 80\ \mu m$ and a droplet with radius $r = 1$ mm spreading on a spherical surface of equal radius.

# A numerically consistent, semi-implicit, collocated, unstructured Finite Volume discretization of the two-phase Navier-Stokes equations in a single-field formulation for high density ratios

Tobias Tolle, Jun Liu, Dieter Bothe, and **Tomislav Marić**

*Mathematical modeling and analysis, Mathematics Department, TU Darmstadt, Germany*

Simulating fluid phases that do not mix and have significantly different densities is still challenging for many numerical methods for two-phase flows, evident by the number of recent literature contributions that address this problem, e.g., [1-4]. The vast majority of improvements proposed in the literature rely on structured (staggered) domain discretization. We improve the collocated *unstructured* Finite Volume (FV) discretization of the two-phase Navier-Stokes equations in a single-field formulation to accurately handle two-phase flows with high-density ratios in geometrically complex domains. The proposed method alleviates numerical inconsistencies in the discretization of the momentum conservation equation's mass flux, removing severe numerical instabilities for two-phase flows with very different densities on unstructured meshes. Like [1], the proposed method focuses on a numerically consistent mass flux; however, the discretization of the two-phase momentum equation's convective term is *implicit*. Compared to [2], the proposed method is fully Eulerian, and it does not require geometrical re-mapping of volume fractions. The verification consists of canonical cases involving droplets with strongly different densities than their surrounding fluid $\rho_1/\rho_2 \in [1, 10000]$. Furthermore, the proposed method is independent of the interface tracking / capturing method, and we demonstrate significant improvements for three different methods: the unstructured LENT Level Set / Front Tracking [5,6], the algebraic VOF [7], and the isoAdvector-plicRDF method [8]. Results demonstrate the recovery of an exact solution for the passive advection of the two-phase momentum. Significant improvements are also achieved for challenging cases introduced in [1], involving a significant momentum exchange between the two phases. Numerically stable solutions are obtained in terms of the $L_\infty$ velocity error norm for the translating droplet case used for testing parasitic velocities, with realistic viscosities and strong surface tension forces.

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[2] Le Chenadec, V., & Pitsch, H. (2013). A monotonicity preserving conservative sharp interface flow solver for high density ratio two-phase flows. Journal of Computational Physics, 249, 185-203.

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# Rebound Suppression of a Droplet on a Solvophobic Surface by a Small Amount of Polymer

**Eunsang Lee**[1], Hari Krishna Chilukoti[2], and Florian Müller-Plathe[1]

1. *Eduard-Zintl Institut für Anorganische und Physikalische Chemie, Technische Universität Darmstadt, Alarich-Weiss-Straße 8, 64287 Darmstadt, Germany*
2. *Department of Mechanical Engineering, National Institute of Technology Warangal, Warangal, Telangana 506004, India*

A small amount of polymer in a droplet reduces the tendency to rebound on a solvophobic solid surface. Using multi-body dissipative particle dynamics simulations of an impacting droplet, we showed a molecular picture of two anti-rebound mechanisms, the slow hopping and the slow retraction mechanisms, acting simultaneously. An increase in the polymer concentration and the molecular weight encourages both mechanisms to occur. The origin of the slow hopping mechanism is the elastic elongation force of polymer whose one end is pinned on the surface. The slow retraction mechanism is attributed to the additional friction by adsorbed polymer on the moving contact line, which is manifest for the strong polymer adsorbability to the surface. We developed the molecular kinetic theory of dilute polymer solution to explain the contact angle-velocity relation of the receding contact line. The theory is also confirmed by simulations of a capillary bridge under steady shear with better statistics, which has the similar physics of a contact line with droplets' spreading and retraction.

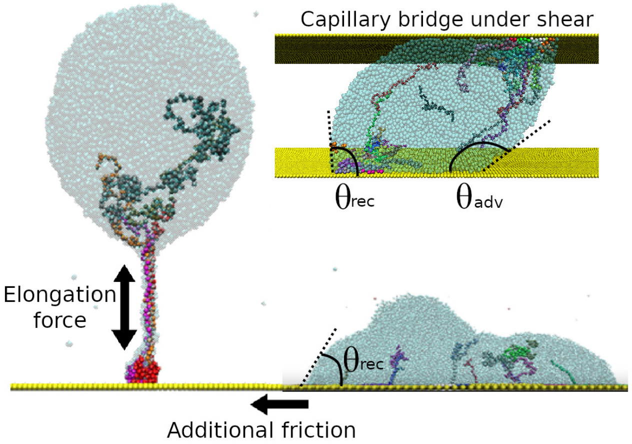

Figure 1: Simulation snapshots for (left) the slow hopping and (right bottom) the slow retraction mechanisms. A snapshot of a capillary shear under steady shear is also shown on top right. The contact angle-velocity dependence of the receding contact line is understood by that of a capillary bridge under shear.

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[2] E. Lee, H. K. Chilukoti and F. Müller-Plathe, preprint, arXiv:2103.15401

# On a toroidal method to solve the sessile drop oscillation problem

**Saksham Sharma** and D. Ian Wilson

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*Philippa Fawcett Drive, Cambridge CB3 0AS, UK*

We present a fully analytical solution for the natural oscillation of an inviscid sessile drop with small Bond number (surface tension dominates gravity) and a fixed contact line on a flat horizontal plate. The governing equations are expressed in terms of the toroidal coordinate system which yields solutions involving *hypergeometric functions*. Resonant frequencies are identified for zonal, sectoral and tesseral vibration modes. The predictions show excellent agreement with experimental data reported in the literature, particularly for flatter drops (lower $\theta_c$, but not so low as to incur significant viscous dissipation) and higher modes of vibration.

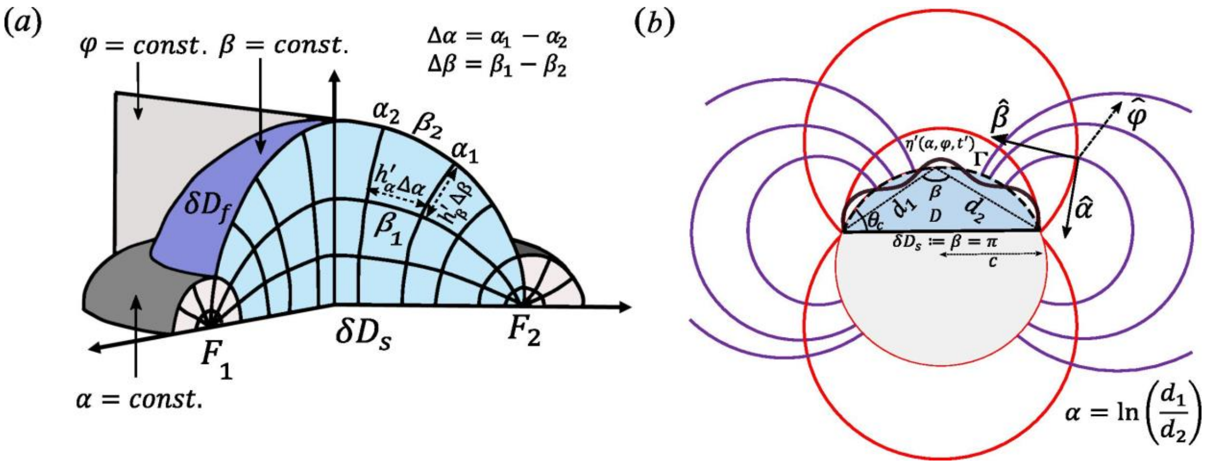

Figure 1. (a) 3D schematic of toroidal coordinate system $\boldsymbol{r}' = \boldsymbol{r}'(\alpha, \beta, \varphi)$ overlaid on a sessile drop. (b) Diametral section of the drop (blue shaded region) with toroidal gridlines embedded into it. On a red circle, $\beta$ is constant, and on a purple circle, $\alpha$ is constant. Defining expressions for $\alpha$ and $\beta$ are also displayed.

Under revisions in JFM: **Sharma, S.**, & Wilson, D. I. (2020). Natural oscillations of a sessile drop: Inviscid theory. *arXiv preprint arXiv:2010.14797*.

# Non-Newtonian Slippery Liquid Infused Porous Surfaces using the lattice-Boltzmann algorithm

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Slippery Liquid-Infused Porous Surfaces (SLIPS) coating consist of a nano/micro-structured porous material infused with a lubricant fluid. When a droplet is deposited on a SLIPS, the lubricant prevents most of the contact of liquids with the underlying solid, thus virtually suppressing the friction forces arising from contact line pinning [1]. Consequently, by hindering the material defects and imperfections, SLIPS provide a unique approach to coating surfaces for more precise tuning of the fluid properties, with the advantage of reducing the solid contamination by repelling almost any fouling challenge a surface may face, for example from bacteria.

We investigate the interplay of the non-Newtonian lubricant on the droplet behaviour. We use a lattice Boltzmann algorithm based on a ternary model on SLIPS for the lubricant and the droplet recently developed within our group [3], implementing a strain-rate dependent viscosity and investigating the motion of non-Newtonian liquids on both simple and complex lubricants. Our goal is to gain insight into this system at a fundamental level, to inform the design of experiments. To do so, we validate the numerical method for a variety of non-Newtonian fluid models in the shear-thinning or shear-thickening regimes, such as the power-law, Casson, Carreau-Yasuda and Wyart-Cates [3,4]. We study the SLIP behaviour under actuation by external forces by quantifying the dissipative forces and by measuring the response of the apparent contact angle of a droplet when actuated by a body force.

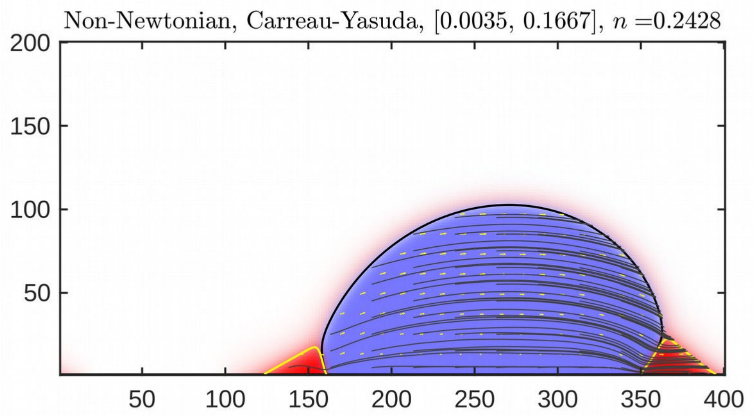

Figure 1. Droplet sliding on a non-Newtonian lubricant modelled using the Carreau-Yasuda fluid model [3] with n = 0.2428, a = 2.0.

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[2] M S Sadullah et al., *Langmuir 2018, 34, 8112-8119*.
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# Theory and Simulations of Dielectrowetting

**Élfego Ruiz-Gutiérrez**[1], Andrew M. J. Edwards[2], Glen McHale[1], Michael I. Newton[2], Gary G. Wells[1], Carl V. Brown[2] and Rodrigo Ledesma-Aguilar[1]

1. *Institute for Multiscale Thermofluids, School of Engineering, University of Edinburgh, The King's Buildings, Mayfield Road, Edinburgh EH9 3FB, UK.*
2. *SOFT Group, School of Science and Technology, Nottingham Trent University, Clifton Lane, Nottingham NG11 8NS, UK.*

When a dielectric fluid interacts with an electric field, its molecules will respond to the field by polarising the medium. As a consequence, this produces forces that act on the fluid, a phenomenon called liquid dielectrophoresis (L-DEP) [1]. The ability to accurately control this forces has realised and revolutionised technologies such as inkjet printing, optical devices, micro-assembly and electrospinning. One important application of L-DEP is dielectrowetting [2], similar to electrowetting, it is a novel technique used to control the spreading of a droplet on solid surfaces. However, dielectrowetting differs from electrowetting in that dielectrowetting occurs due to the electromechanical force that arises from the polarisation the molecules of the droplet due to a non-homogeneous electric field, as opposed to the free charges of a conducting liquid in electrowetting setups (see Fig. 1). Also, dielectrowetting does not suffer from the contact angle saturation observed in electrowetting. This last feature allows the creation of thin films of dielectric liquids which can be controlled due to the anisotropic spreading of a droplet. In this contribution, we carry out a theoretical analysis of dielectrowetting. We deduce from first principles the forces produced by the electric field and support our findings by recently developed lattice-Boltzmann simulations [3] capable of solving the hydrodynamic equations for dielectric fluids in the presence of electrostatic fields. We examine the anisotropic spreading of a droplet in the two principal directions, namely, in the parallel and perpendicular directions of the subjacent array of electrodes. We analyse the morphology of the droplet in response to an applied voltage, for example, how the contact angle decreases, thus leading to the dielectrowetting equation, but we also examine the behaviour of the droplet beyond the voltage for complete spreading.

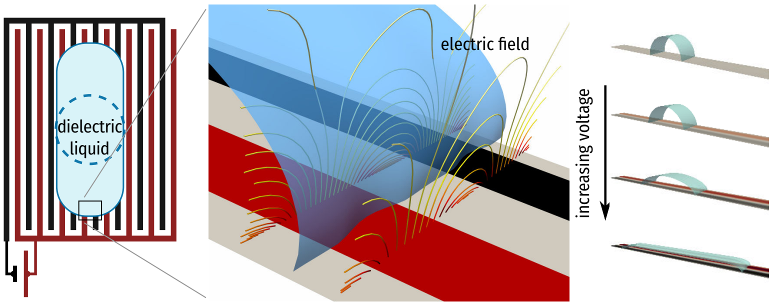

Figure 1: The spreading of a droplet in a dielectrowetting setup.

**Acknowledgements:** EPSRC Grants EP/R042276/1, EP/R036837/1 and EP/R035837/2.

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# Numerical analysis of water hammer pressure during high speed droplet impact

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[3] *Wellcome/EPSRC Centre for Interventional and Surgical Sciences (WEISS), UCL, London, W1W 7TS, UK*

During the early phases of high speed [O(100 m/s)] droplet impact on a solid surface, liquid near the contact zone gets highly compressed. However, the rest of the liquid remains unaware of contact (Fig.1). This is attributed to the propagation of a compressive wave (*shock wave*) often referred to as '*water hammer pressure*'[1-3]. The erosion induced by this water hammer pressure is quite significant in various industrial applications such as rain erosion on aircraft, rotor blade erosion in large steam turbines, water jet cutting etc. [4] and hence, gained attention regarding prediction of its features. It is evident from literature [5-6] that numerical prediction of the water hammer pressure transients is quite complex, as several factors like liquid compressibility, substrate acoustic impedance as well surface texturing ultimately determine the intensity of the pressure peak and subsequent damage.

The present work aims on analysing the hydrodynamics associated with such high speed (100-500 m/s) water droplet (100-1000 μm) impact on solid surfaces, using computational simulation, and more specifically the Volume of Fluid method. Compressibility of both air and water phases will be taken into account. Importantly, this study will focus on the effect the impact dynamics have on the solid substrate: we will couple the fluids modelling with a Finite Element method allowing us to investigate the distribution of loads on and inside the solid; a topic that has not been visited properly in the open literature, to the best of our knowledge. We will consider air as an ideal gas, whereas, for incorporating water compressibility, Tait's Equation of State will be adopted. Accounting for the fast pressure peak due to water hammer effect will be the overarching objective for this task. A detailed systematic investigation will be carried out for different droplet speeds and diameters.

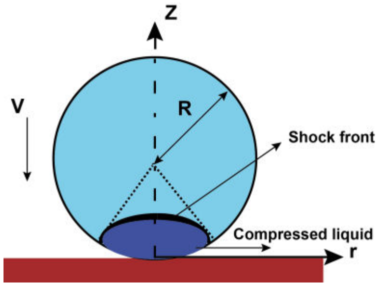

**Figure 1.** Schematic diagram during impact of a spherical liquid droplet on a rigid surface

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# Numerical Investigation of Hydrodynamics and Heat Transport during the Coalescence of Multiple Drops Impacting a Hot Wall

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This work describes the numerical investigation of the hydrodynamics and heat transport during the vertical and horizontal coalescence of multiple drops impacting a smooth, heated wall. Refrigerant perfluorohexane (FC-72) in a pure, saturated vapor atmosphere at ambient pressure is used as working fluid. Simulations are carried out using an incompressible solver within the OpenFOAM library based on the volume-of-fluid method. The solver includes evaporation at the liquid-vapor interface. A subgrid model is implemented to account for the significant heat transfer close to the moving three-phase contact line [1].

The single drop impacting a hot, solid wall at moderate Reynolds and Weber numbers undergoes three phases: spreading, receding and sessile drop phase. For the case of the consequent drop impact onto a previous drop in a sessile phase, the numerical prediction is compared to experiments. High-speed infrared as well as black and white cameras capture the temperature profile at the drop footprint from the bottom and the drop shape from the side [2, 3]. The comparison of temperature and heat flux fields as well as the contact line radius and heat flow from the wall to the drop shows a good agreement between the simulations and experiments. However, the predicted peak heat flow reached during the spreading phase flow overestimates the experimental data.

A numerical study reveals a significant influence of the drop frequency on the hydrodynamics and heat transport. The impact of the second drop during the spreading phase of the initial drop is found to be the best setup in regards to both spreading and heat transfer. The overall heat transfer of this setup is even better than in the case of an impact of a single drop with twice the volume of each drop during the vertical coalescence. This behaviour is also observed during the impact of a drop chain consisting of five drops impacting successively during the spreading phase when compared to the impact of single drop with five times the volume.

In the case of the horizontal coalescence, the outcome of two simultaneously impacting drops strongly depends on the spacing between the two drops. After the impact, the drops coalesce and either form one or two individual drops at the end of the impingement process. These cases are studied numerically and compared to experiments.

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# Local acceleration of liquid film spreading on smooth substrate induced by interaction with a single short pillar

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Georg F. DIETZE[4], Farzam ZOUESHTIAGH[5], Lizhong MU[6], and Ichiro UENO[2]

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[4] *Univ. Paris-Saclay, CNRS, FAST*
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Control of the dynamic wetting and delivery of the liquid are indispensable technology under not only terrestrial but also microgravity environments for a range of industrial applications and for environmental control of on-orbit facilities. The phenomenon that liquid erodes in the gap of innumerable tiny structures (hemiwicking) has attracted researchers for such applications[1-3]. Experimental[4] and numerical[5] investigations have indicated that the interaction between a liquid film spreading on a horizontal substrate and multiple structures accelerates the fluid near the contact interface (contact line: CL) of the liquid film. In this study we focus on the effect of the height of the tiny structure on the acceleration phenomenon.

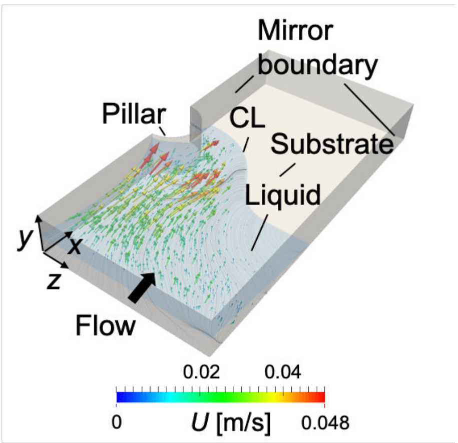

Figure 1. Target geometry; liquid film spreading on smooth substrate with a pillar.

Target system is a liquid film spreading on a horizontal substrate on which a single short pillar (outer diameter $D = 50$ μm) is installed (Fig. 1). The analysis is conducted by varying the height of the pillar to 70, 40, 30, 20, and 10 μm. The temporal variations of the position and the velocity of the CL on the substrate are compared in systems with different pillar heights. It is indicated, in the case of short pillars, that the liquid near the CL is hardly driven, and that the damping of the velocity becomes more significant. We will discuss the correlation between the flow field inside the film and the CL mobility.

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# A Multiscale Simulation Method for Droplet Dynamic Wetting

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The volume of fluid (VOF) has been proved to be a powerful tool for the simulation of dynamic wetting at the macroscale, while the sensitivity and uncertainty of boundary conditions in VOF limit its applications at the nano and sub-micron scales. Here we introduce a multiscale simulation method that enhances VOF simulations using self-consistent boundary conditions derived from molecular dynamics (MD), based on the recent work of Zhang et. al. (2017) [1] and Boelens et. al. (2019) [2]. Specifically, the boundary conditions include the particular slip model based on the molecular kinetic theory for the three-phase contact line and the classical Navier slip model for the remaining part of the liquid-solid interface, as well as a new source term supplemented to the momentum equation in VOF to replace the convectional dynamic contact angle model. We find that with these new boundary conditions, the VOF simulations can provide consistent predictions with full MD simulations for the dynamic wetting of nanodroplets on both smooth and pillared surfaces, and its performance is better than those with other previous models, especially for the pinning-depinning phenomenon. Such a multiscale method provides an access to the simulations of dynamic wetting at the sub-micron scale, where the pure MD simulations are inaccessible due to the computational cost.

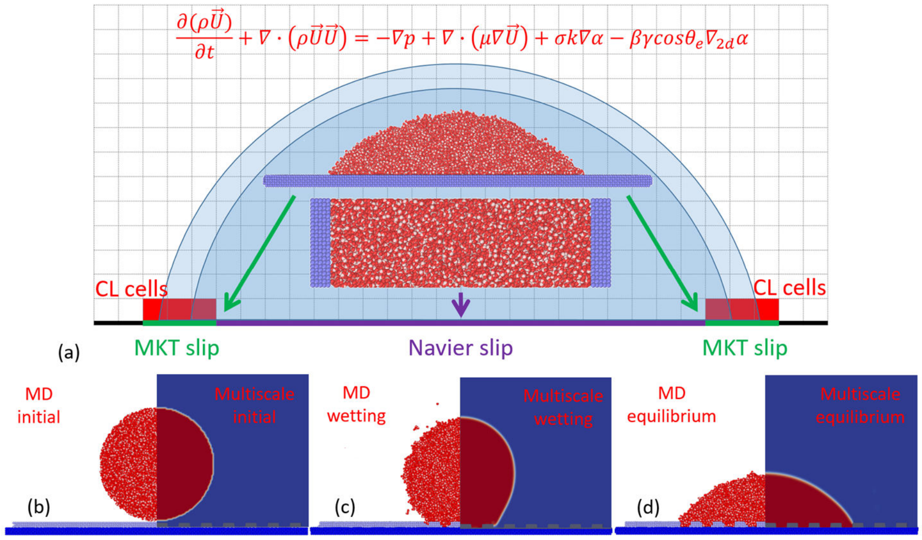

Fig 1. (a) Schematic of the multiscale simulation method. (b) ~ (d) Comparisons of the snapshots obtained by MD and by the enhanced VOF at the same instant of time during the nanodroplet wetting on the pillared surface.

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# Numerical Simulation of Evaporation of Pinned Urea-Water Droplets in Restricted Domain

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*Institute for Technical Thermodynamics, Technical University of Darmstadt*

Modeling the evaporation of urea-water solution droplets is important for prediction of deposit formation in Selective Catalytic Reduction systems, which can lead to a significant loss in efficiency. In this work, the Finite Element Method has been used to simulate the transport of heat and vapor concentration in the gas phase during evaporation of a single pinned urea-water solution droplet. The simulations are performed for the Bond number of unity order and for Rayleigh number around 15. The effect of gravity on both the droplet shape and the heat and mass transport in the gas phase is investigated. In addition, the influence of the domain size on the evaporation rate is studied.

To study the influence of the droplet shape on the evaporation process, two modeling approaches have been used. In the first one, it was assumed that the droplet has a shape of a spherical cap. In the second one, the droplet shape was obtained by solving the Laplace-Young equation in cylindrical coordinates[1]. It has been found that, in the range of conditions studied in the present work, the influence of the droplet shape on the evaporation rate is negligible. On the contrary, the influence of natural convection in the gas phase on the evaporation rate has been found to be significant.

In the literature, correlations are available for droplets evaporating on infinitely extended plates and in an infinitely extended gas domain. In many applications, the droplets evaporate in cells with sizes comparable with the drop size. In this work, the simulations have been performed for a walled cell with an inner radius of around six time the radius of the droplet, and the resulting evaporation kinetics has been compared with experimental results (Fig. 2) showing a good agreement. The simulations show a strong influence of the domain size on the evaporation rate. Based on the results, conditions are derived, at which the surrounding geometry must be taken into account.

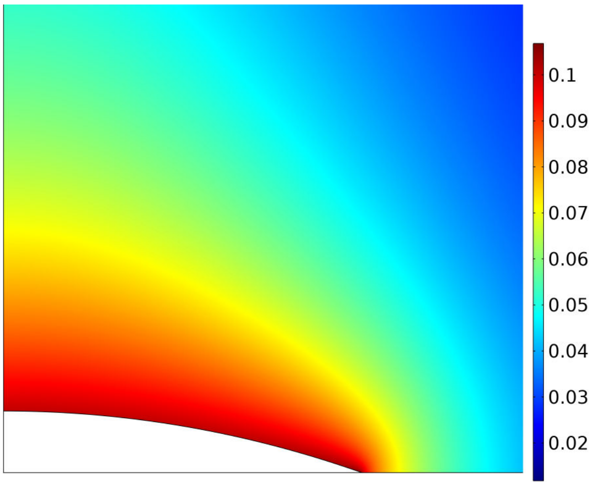

Figure 1: Mass fraction of water in the gas phase around an evaporating urea water solution droplet

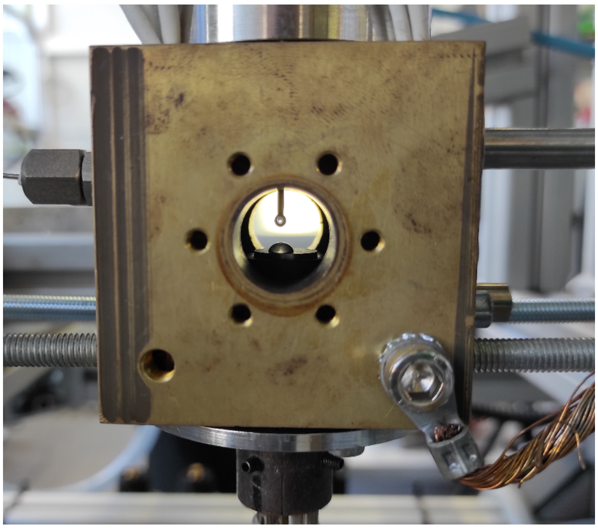

Figure 2: Test cell in which the experiments were conducted

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# Open surface droplet transport and controlled splitting using wettability patterning

**I. U. Chowdhury**[1], P. S. Mahapatra[1], and A. K. Sen[1]

[1] *Indian Institute of Technology Madras, Chennai, India*

Passive droplet transport on an open surface platform has applications starting from vapor condensation to Lab-on-a-Chip (LOC) systems. Although the mixing of two droplets on an open surface can be carried out easily by using wettability patterning, but it is quite challenging to split a droplet in the absence of external stimuli because of the interfacial energy of the droplet. Here, we demonstrate a standalone power-free technique for transport and controlled splitting of a droplet on an open surface using continuous wettability-gradients. Droplet moves continuously from a low to a high wettability region on the wettability-gradient surface [1]. A Y shaped wettability-gradient track laid on a superhydrophobic background is used to investigate the dynamics of the splitting process. A 3D phase-field Cahn-Hilliard model for interfaces and Navier-Stokes equations for transport are employed and solved numerically using finite element method (FEM). Numerical results are used to decipher the motion and splitting of droplet at the Y-junction using the principle of energy conservation. It is observed that droplet splitting depends on the configuration of the Y-junction, droplet splits faster for the superhydrophobic wedge angle of $90^0$ and the splitting ratio (ratio of the sizes of daughter droplets) depends on the widths of the Y-branches. Thus the droplet can be splits into any two desired volumes by manipulating the width of the branches as shown in Figure 1. A critical branch width ratio ( $w_1/w_2 = 0.79$ ) below which the droplet doesn't split and moves towards the branch of higher width and settled there. These findings gives an essential insights of efficient droplet manipulation on microfluidic devices.

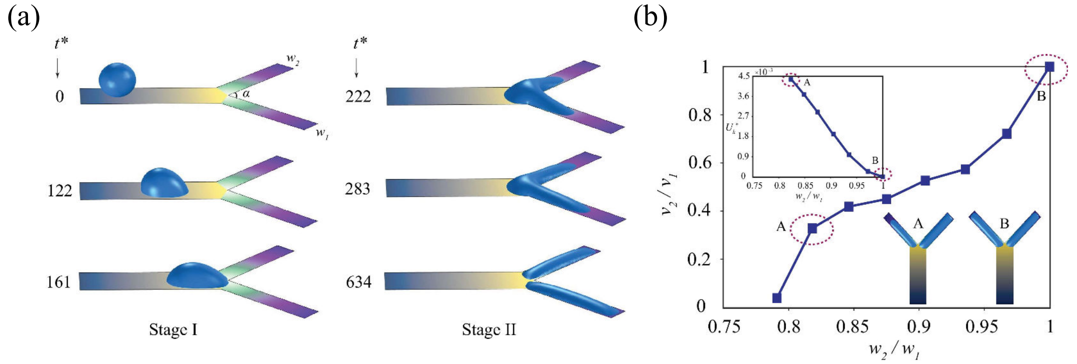

Figure 1. a) Droplet splitting on a Y shaped bifurcated wettability-gradient track with the branch width ratio $w_2/w_1 = 1$ and the superhydrophobic wedge angle $\alpha = 90^0$. A linear gradient of contact angle from $165^0$ to $25^0$ at the base track, whereas $25^0$ to $5^0$ at the branches. b) The splitting volume ratios of the droplet $v_2/v_1$ is plotted with $w_2/w_1$ for $\alpha = 90^0$. t* is the non-dimensional time.

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# Interaction of Droplets with a fluid-fluid interface: instability and migration

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Passive manipulation of droplets across a laminar fluid-fluid interface is often achieved either by hydrodynamic lift[1] or interfacial energy gradient[2]. Herein, we investigate the interaction of oil droplets in the microfluidic co-flow of aqueous polyethylene glycol and immiscible oil phases. In the absence of hydrodynamic lift or favorable spreading parameter, the interaction of droplets with the fluid-fluid interface reveals two key aspects: (1) droplets would perturb the interface, and perturbation would grow downstream (Fig. 1(a)), and (2) droplets would tend to migrate across or collapse at the interface at higher confinement (Fig. 1(b)), which is decided by the ratio of droplet diameter to interface width ($w_1$). Perturbation is characterized by amplitude ($A$) and wavelength ($\lambda$). Droplet size and ratio of co-flow rate decides the confinement, which in turn influences the amplitude of interfacial perturbation. Co-flow viscosity ratio has non-monotonic effect on amplitude while decrement of co-flow interfacial tension increased perturbation. Drop-to-medium viscosity ratio does not have significant effect on perturbation. Interestingly, drops tend to migrate across the interface at higher confinement and migration rate is the maximum for an optimum flow rate ratio which corresponds to minimum interfacial perturbation. Droplets migrate or coalesce depending on their internal property and continuous phases. Our investigation elucidates the unexplored regimes of microfluidic droplet transport across the laminar interface at a low Reynolds number and aims to facilitate a better understanding of droplet migration in a microfluidic co-flowing system.

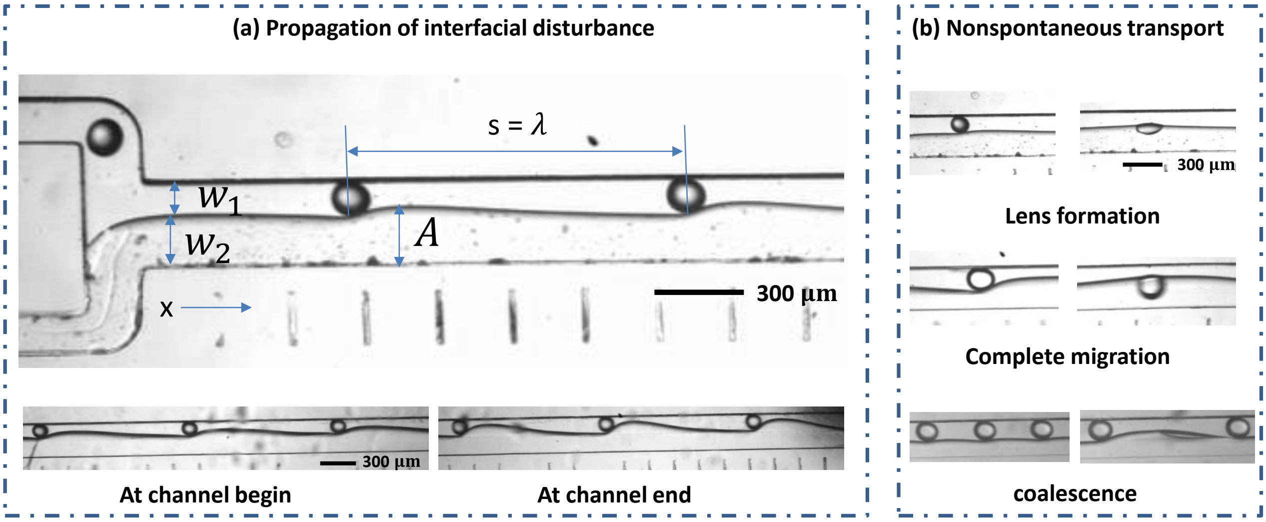

Figure 1: (a) Propagation of interfacial perturbation; waviness amplitude grows from beginning to end of the channel, (b) Nonspontaneous transport of droplets.

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# Self-similar behaviour in a stretching liquid tin sheet after laser impact on a tin microdroplet

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[4] *Fluids and Flows group, Department of Applied Physics,Eindhoven University of Technology, Eindhoven, the Netherlands.*

We will present our experimental studies on the self-similar behaviour manifested by a stretching liquid tin sheet formed by laser-pulse impact on a tin microdroplet. Such liquid sheets serve as mass-limited targets in the industrial extreme ultraviolet (EUV) light sources that are used for state-of-the-art nanolithography. First, we measure the sheet thickness profile and its time evolution over a wide range of Weber numbers ($\mathrm{We}=\rho U^2 R_0/\sigma$, with $U$ the sheet *center-of-mass* speed imparted by the plasma pressure from laser-induced irradiation of tin) by using three independent experimental methods [1-2]. All the thickness profiles obtained can be collapsed into a single curve via a self-similar solution. This behaviour allows us to benchmark a model to predict the sheet thickness and from that, the mass content on the sheet [Fig. 1 (a)]. Second, we study the fragments shed from the bounding rim in terms of their speed and shedding rate. A scaling law for the instantaneous shedding rate will be presented and compared to a previous work on droplet-pillar impact [3]. We subsequently demonstrate that the fragments' speed again follows a self-similar behaviour [Fig. 1 (b)]. We further show our research on ligament growth. Our findings enable a prediction of mass distribution and allow for assessing "debris" issues of liquid tin targets as used in EUV sources for nanolithography.

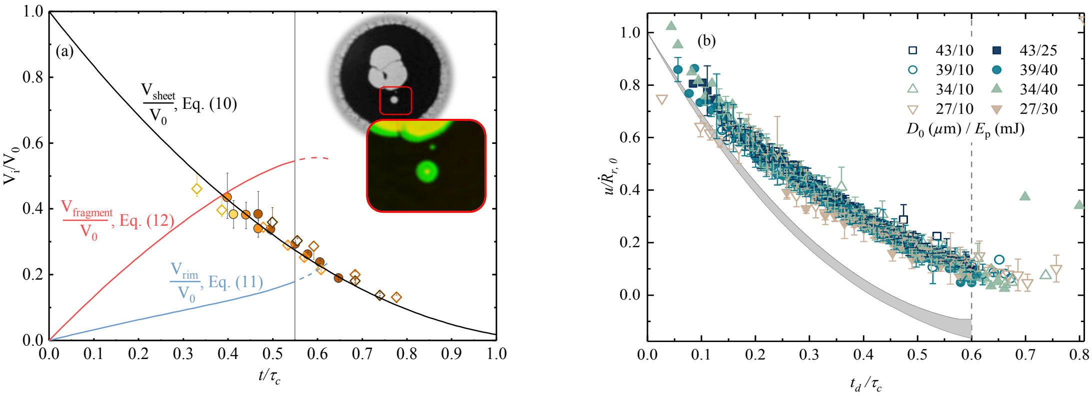

Figure 1. (a): Volume fractions of various channels: sheet, fragment, and bounding rim as a function of $t/\tau_c$, where $\tau_c$ presents the global capillary time of the droplet [1]. The inset shows a shadowgraph image demonstrating the opening of a hole at Taylor-Culick speed, which is employed by us to determine the local thickness of the sheet. (b): Fragment speed scaled by the initial expansion rate of the sheet as a function of $t_d/\tau_c$ for various droplet sizes $D_0$ and laser-pulse energies $E_p$ (see the legend); $t_d$ presents the detachment moment of the fragments. The gray area presents the instantaneous expansion speed of the sheet rim.

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# Design of Stretchable Superamphiphobic Surfaces for Programmable Liquid Manipulation

**Xiaoteng Zhou**, Jie Liu, and Hans-Jürgen Butt

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The simple manufacturing process of elastic, mechanically robust, and superamphiphobic coatings has always been challenging. Here, we propose a simple methodology to prepare nanofilament-structured stretchable superamphiphobic surfaces by spray-coating. As a model substrate, we used a cis-1,4-polyisoprene film. A submicron-thick polydimethylsiloxane (PDMS) layer is used to bind spray-coated silicone nanofilaments onto the stretched polyisoprene substrate. This surface in a highly stretched state (100 %) can repel even low-surface-tension liquids and resists drop impact of both water and n-hexadecane. Both the superamphiphobicity and morphology of the surface are maintained even after a series of 1000 stretch-release cycles. We are able to use the stretchable surfaces to initiate programmable drop coalescences and reactions of multi-component liquid drops by remotely controlling the strain. Based on this, we further find benefits of this surface for synthesizing asymmetric hydrogels with different shapes.

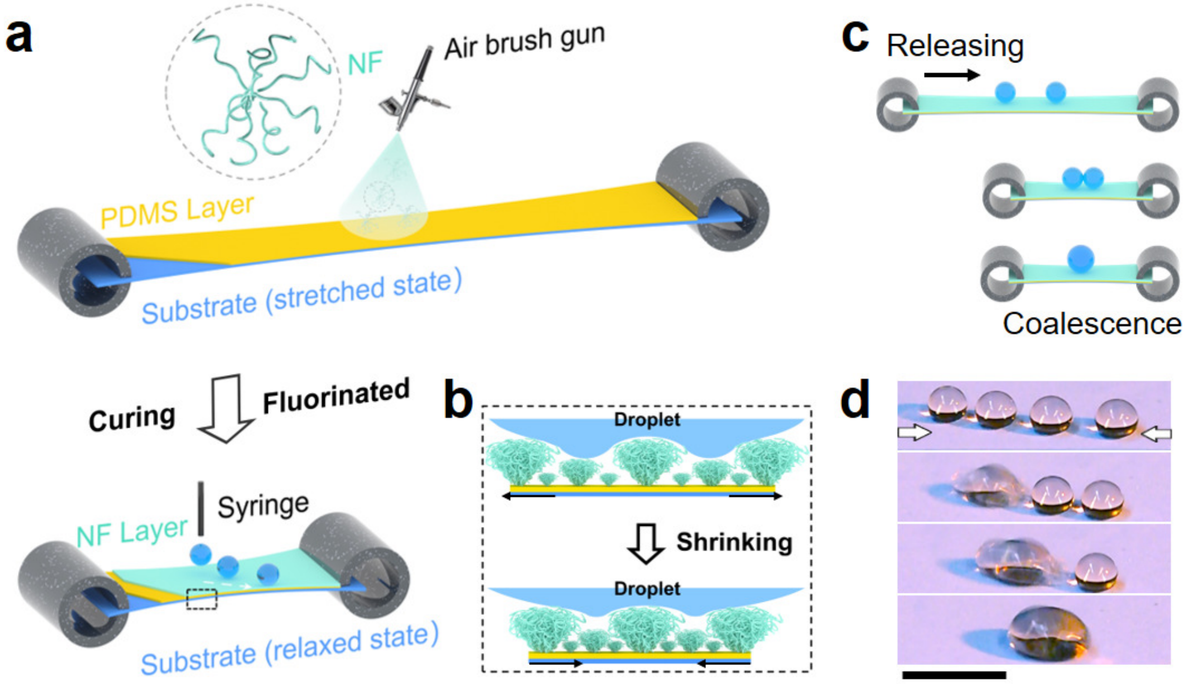

Figure 1. a) Schematic of the fabrication process of the stretchable superamphiphobic surface. b) Schematic to illustrate more compact microstructures of the relaxed superamphiphobic surface after preparation. c) Schematic to show the merging process of drops via controlling release of the stretched superamphiphobic surface. d) Programmable coalescence of four n-hexadecane drops (10 µL) with a linear arrangement. Scale bar: 5 mm.

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# On-demand Droplet Generation Using Bulk Acoustic Waves

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On demand droplet generation from continuously flowing fluid has profound applications in rare event encapsulation studies. The active droplet generation is very much essential when the job is to produce droplets at a specific time. For droplet generation, surface acoustic wave (SAW) devices have been explored for both on-demand generation[1], and size control[2], but bulk acoustic wave (BAW) devices have not been explored yet. Here, we demonstrate on-demand droplet generation from co-flowing fluids based on acoustic relocation[3,4] using BAW.

On-demand droplet generation experiments in two different channels such as bifurcation inlet and trifurcation inlet configurations, are outlined in Figure 1. When aqueous and oil phases are co-flowing in a bifurcation inlet channel onset of instability by interfacial tension seeks to minimize the interfacial area due to which droplets are formed in the process of relocating high impedance fluid to the centre, as shown in Figure 1(a). In the trifurcation microchannel, we performed experiments for two different fluid configurations, one with low acoustic impedance fluid at the central inlet surrounded by high acoustic impedance fluids at the two side inlets as shown in Figure 1(b) and other with high acoustic impedance at the center inlet surrounded by low acoustic impedance fluid from the two side inlets, as shown in Figure 1(c). We observe that upon onset of the bulk acoustic waves, the configuration with high acoustic impedance fluid at the central inlet of the microchannel remains the same, regardless of the acoustic force density and interfacial tension between the fluids as shown in Figure 1(b). when high acoustic impedance fluids are at sides of the microchannel, aqueous droplets were produced from the sides, as shown in Figure 1(c).

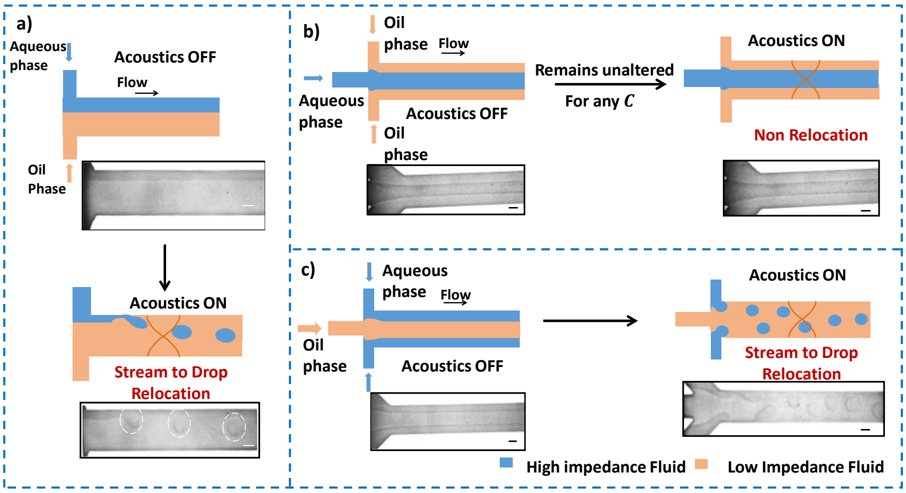

Figure 1. Effect of BAW on different channel configurations. a) Bifurcation inlet configuration. b) Trifurcation inlet with high impedance liquid at the centre. c) Trifuracton inlet with low acoustic impedance at the center .

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# On-demand droplet trap, coalescence and release using standing bulk acoustic waves

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In the present study, we demonstrate a simplistic yet robust inline multinodal acoustic trapping [1] unit designed to trap water-in-oil droplets [2]. Three-dimensional multiphase simulations are performed to (i) reveal the trapping and non-trapping regimes, (ii) understand the effect of coalescence on trapping, and (iii) exemplify the much desired on-demand trap-release operation. We discover that whether a drop gets trapped or not depends only on the dimensionless energy ratio defined as the ratio of acoustic to viscous energy, $\alpha = (E_{ac}D)/(U\eta_c)$, and is independent of the dimensionless size ratio D/W, where $E_{ac}$, D, U, $\eta_c$, and W are the acoustic energy density, drop diameter, average inlet flow velocity of the continuous phase, dynamic viscosity of the continuous phase, and inlet width, respectively. For $\alpha \geq 15$ (Fig. 1(f)), the drop always gets trapped in either the upper or lower part of the chamber depending on its initial streamline before entry to the trapping chamber. In case of multiple drops generated, depending on the drop generation frequency, continuous coalescence before or close to the entry of the chamber tends to greatly enhance the trapping tendency especially for the cases with $\alpha < 15$, or otherwise stabilizes the already trapped drops for $\alpha \geq 15$ owing to the higher acoustophoretic force experienced by the coalesced drops. The on-demand droplet trapping, coalescence, and release are together put into function by controlling the relevant flow and field parameters, and appropriately timing the on/off control for the acoustic field.

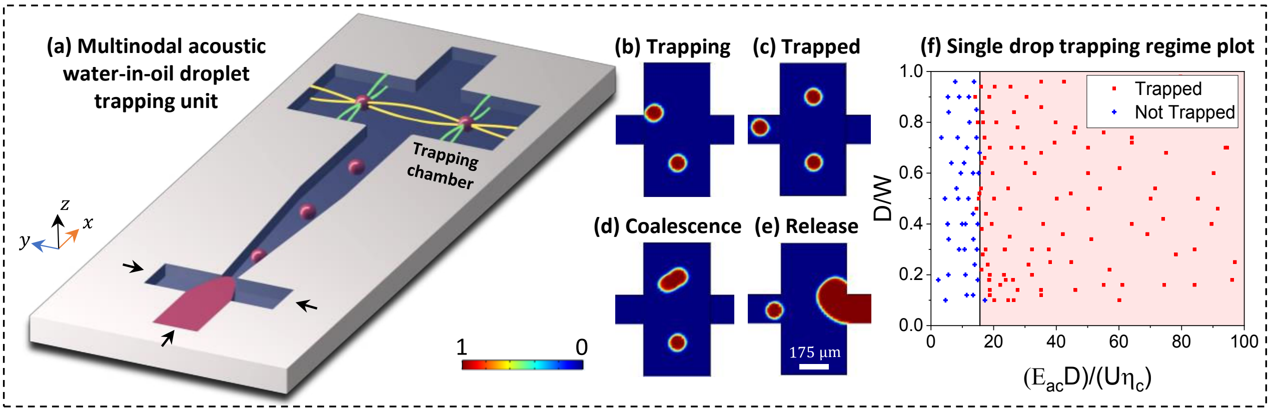

Figure 1: (a) Schematic for multinodal acoustic drop trapping setup with a rectangular trapping chamber with $\lambda/2$ and $\lambda$ modes actuating in the $x$ and $y$ directions, respectively, (b-e) Simulation snapshots delineating the trapping-coalescence-release dynamics. The colour legend corresponds to the volume fraction of water, (c) Regime plot detailing the trapping and the non-trapping regimes for the case of a single drop entering the trapping chamber.

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# Investigation of drop motion in three-dimensional microchannels using a moving-frame boundary-integral method

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The study of drop motion in microchannels has a wide range of applications, such as drug targeting, micro-chemical reactors, and generation of emulsions with low polydispersity. Fundamental understanding of the physics of drop motion in bounded domains is important for designing such systems. Among the main methods to analyze drop motion and fluid flow at low Reynolds numbers, one of the most traditional ones is the boundary-integral method, which consists of converting the governing differential equations into integral equations that can be solved numerically without requiring a full-domain mesh, but only a boundary one. The present work investigates drop motion in three-dimensional microchannels. To this end, we use a three-dimensional boundary-integral scheme coupled with a moving frame that follows the droplet throughout its motion. The use of the moving-frame approach results in a lower computational time if compared to simulations where the full channel is considered. We proceed using this moving frame approach to simulate different problems involving the motion of a single droplet in 3D microchannels, such as drop motion in straight microchannels, where we analyze the effect of the physical parameters (e.g., capillary number and viscosity ratio) and the channel finite depth on the steady-state velocity of the droplet. An increase in capillary number allows the droplet to attain higher velocities, whereas higher drop-to-medium viscosity ratios slow down the droplet. The presence of the front and back panels, in contrast to previous results concerning infinite-depth channels, also decrease the drop velocity as well as produce tail-like instabilities for more deformable drops. In addition, we investigate drop motion in bifurcating channels such as Y-shaped channels, T-shaped channels, and more general geometries, where we determine drop sorting and break-up conditions.

# Negative Magnetophoresis Based Aqueous Droplet Trapping and Coalescence

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Droplet, particularly aqueous droplet manipulation has significant importance in the field of microfluidics, e.g., as micro-vessel to transport biological samples, micro–reactors for chemical reagent transport and reactions, etc. Droplet manipulation includes splitting, sorting, trapping, relocation, merging of droplets inside microchannels using either hydrodynamic forces (passive control) or externally applied fields (active control). Among the active methods (e.g., electrical, acoustic, optical, etc.), magnetic manipulation [1] has certain advantages over others as it is simple, cheap and non-invasive. We observed that the magnetic repulsion (negative magnetophoretic) force on diamagnetic aqueous droplets surrounded by magnetic fluid can be utilized to trap them against the drag and coalesce with follower droplets inside a microchannel (see Fig. 1(a)).

The droplets get trapped where the component of the magnetic force [2], $F_m = \mu_0 \frac{\pi}{6} D^3 (\mathbf{M} \cdot \nabla)\mathbf{H}$ in the flow direction becomes equal to or more than the viscous drag $F_d$. Due to difficulty in accurately determining the magnetic and drag forces, we used the magnetic energy, $E_m = \frac{\pi}{6} D^3 MB$ and viscous energy, $E_f = 3\pi\eta_{cp} D^2 U_{cp}$ as their ratio in magnetophoretic stability number[3], $S_m = E_m/E_f$ and non-dimensionalized drop size, $D^* = D/w$ ; $w$ = channel width, to characterize the phenomenon. In our study we used cubic permanent magnets ($4.76\ mm$ and $12.7\ mm$) to produce the magnetic field and the gradient. We prepared 5%, 1.97%, and 0.48% v/v concentration of oil-based ferrofluid from EMG 901 (Ferrotec, USA) ferrofluid diluting with kerosene and performed several experiments varying flowrates and magnet position. We identified operating regimes (see Fig. 1(b)) of trapping and non-trapping. Also, we found that the trapped droplets gets coalesced with the follower droplets and gets self-released depending upon the $S_{mp}$ $-D^*$ criterion; subscript $p$ denotes peak value. The coalescence time in the form of film drainage Reynolds number, $Re_{fd} = t_{fd}/t_a$; $t_{fd}$ and $t_a$ refer to film drainage and advection time-scale respectively, was found to be dependent on the magnetic Bond number, $Bo_m = \mu_0 H^2 R/\sigma$ as $Re_{fd}^{-1} = 1.48 \times 10^{-7}\ Bo_m^{-1.5}$ with $R^2 \approx 0.95$ (see Fig. 1(c)).

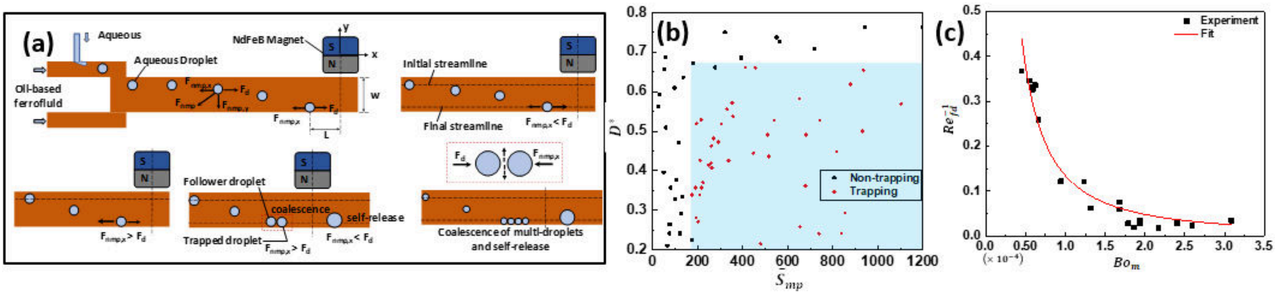

Figure 1: (a) Schematic of the experiment and different scenarios. (b) Regime plot of trapping and non-trapping cases depending on $D^*$ and $S_{mp}$. (c) Dependence of film drainage Reynolds number $Re_{fd}$ on magnetic Bond number $Bo_m$.

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# Formation history of dissipative droplets exploited for micro-structuring

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There is an unresolved, mostly overlooked, discrepancy between the findings of theorists and experimenters on the nature of metal droplets which is particularly noticeable in case of low-melting metals, e.g. indium and gallium, on surfaces of group 6 metals such as molybdenum and tungsten. Thermodynamic calculations indicate that droplet formation is not to be expected here. Instead, wetting layers are predicted. Nonetheless, droplets are found in our experiments [1]. However, these metal droplets seem to behave differently from classical droplets (Fig. 1a). We present the evolution of intermediate states as an energetic explanation for this discrepancy.

Here, we investigated explicitly the unexpected behaviour of molten indium on molybdenum. Indium micro-droplets on group 6 metal substrates form only in a very narrow temperature range, while the wetting angle and nearest neighbour distance depend strongly on external conditions such as temperature and atmospheric pressure, leading to a nonlinear behaviour of the droplets. Evidence suggests that indium on molybdenum forms dissipative structures resembling droplets through a self-organisation process. A closer theoretical and experimental look at thermodynamics in non-equilibrium systems is presented to support the hypothesis.

Ilya Prigogine, Nobel laureate for his work on dissipative structures, repeatedly emphasised the influence of the history of formation or "historicity" in his words on self-organisation [2]. Historicity he defined as the dependence of the properties, morphology and behaviour of a final state on the circumstances of its initial state and all intermediate states. He advocated a rethinking of the concept "from being to becoming" [3]. Our work applies his philosophical thoughts and thermodynamic calculation on the reality of our growth experiment. A molybdenum substrate is structured by a pattern of dots with lower roughness. Indium deposited by electron-beam evaporation selectively forms droplets at the smooth spots and withdraws from the rough areas of the sample, thus dewetting from the molybdenum takes place. However, this behaviour contradicts the classical theory of dewetting and nucleation, but it can be explained by the formation of locally arranged dissipative droplets. We demonstrate how the nonlinear properties of the droplets manifest and how one may utilise this for technical application.

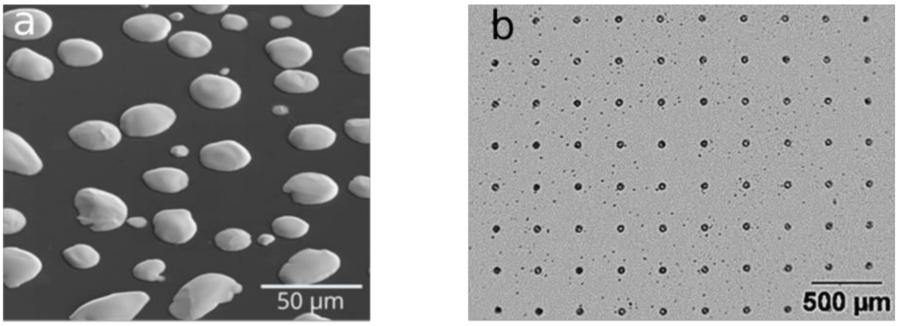

Figure 1. (a) Indium droplets on molybdenum reveal non-linear behaviour which cannot be attributed to classical dewetting or nucleation. (b) By exploiting the historicity of the dissipative droplets, homogeneous arrangement can be achieved.

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# Title: In-field Droplet based Diagnostics using Surface Acoustic Waves Controlled with Opensource Electronics

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Surface acoustic wave (SAW) devices are increasingly applied in life sciences, biology, and point-of-care applications due to their multiple sensing and acoustofluidic actuation functions. Despite the advancements in this field, there is a need to provide the SAW platform with wireless and remote manipulation of liquids that are biocompatible, safe to operate and free of user-induced contamination. To implement remote operation capabilities, there are significant gaps in interfacing hardware and control strategies to enhance the performance of acoustofluidic and sensing procedures. In this work, we present an integral, versatile and digitally controlled acoustofluidic platform, with key functions for biological assays such as droplet movement, mixing and heating, based on integrated close-loop feedback control, image recognition and fluorescence sensing using digital camera and image processing. The setup implements a proportional integral derivative (PID) controller as feedback loop control and is achieved using low cost opensource Raspberry Pi electronics hardware and 3D printed housing. We simulate some of the process steps of microfluidic and sensing functions that are needed to perform DNA amplification with established techniques such as polymerase chain reaction (PCR) and loop-mediated isothermal amplification (LAMP). The platform enables the control of droplet position for sample mixing and dilution, as well as acousto-heating to a chosen target temperature. Finally, we demonstrate in-situ fluorescence sensing capabilities using an off-the-shelve Raspberry Pi camera and digital filters, bypassing the need for expensive and complex optical setups. The platform could be potentially operated remotely, with integration of cloud databases, both of them ideal for disease outbreaks and mass healthcare.

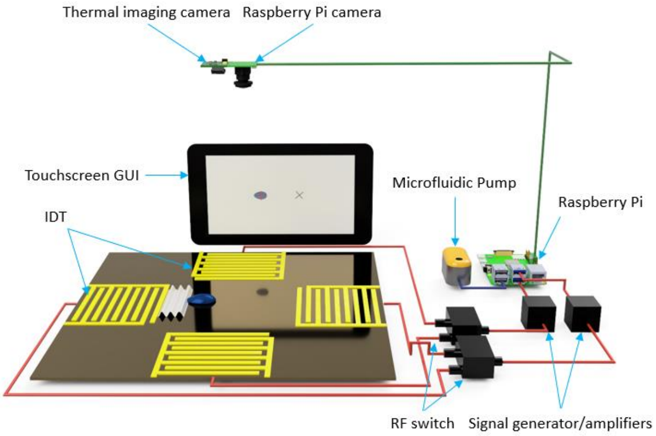

Figure 1. An illustration of SAW platform integrated with Raspberry Pi controlling signal generators, amplifiers, RF switches, visible and thermal cameras interfaced through a touchscreen.

# Investigation of single optically trapped aerosol droplets: Mass transport of water

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Droplet growth rates are of great importance in a variety of disciplines and are inherently connected to interfacial mass transport. A better understanding of the underlying kinetics is important for industrial technologies such as inkjet printing or spray drying, but also in medical engineering where controlled condensational growth influences the efficiency of drug delivery in the lungs. Interfacial transport is influenced by the mass accommodation coefficient, which is defined as the fraction of gas-phase molecules that stick to a surface upon collision. The literature data concerning the mass accommodation of gas-phase water on liquid water is still being debated, and data for water accommodation on organic substances is generally sparse. The reason for the large uncertainties in the value of the mass accommodation coefficient and the lack of data arise from experimental challenges in measuring this quantity.

To address these issues, we utilize a novel measurement technique, which we refer to as Photothermal Single-Particle Spectroscopy (PSPS). In PSPS, a single aerosol droplet is optically-trapped at ambient conditions, and mass transfer processes are probed with photoacoustic spectroscopy (PAS) and modulated Mie scattering (MMS) [1] [2]. Aqueous tetraethylene glycol serves as a well-suited proxy to investigate the water uptake by water-miscible organics. We have previously shown that single droplet PAS has a very high detection sensitivity in the attoliter range (on the order of $10^{-17}$ moles). [3] During PAS measurements, the droplet experiences periodic fluctuations of the heat flux and mass flux of the evaporating species (here water), which give rise to an acoustic signal. Amplitude and phase of the PAS signal serve as individual probes of the heat and mass transfer. The PAS measurement is accompanied by small oscillations in droplet size, water concentration, temperature and refractive index. The miniscule changes of the droplet size and refractive index can also be observed by highly sensitive MMS. The comparison of the experimental data with modelled data allows us to decouple the effects of heat and mass flux and retrieve the values of the mass accommodation coefficient at different particle temperatures and relative humidities. [1] [4] This unique combination of PAS and MMS provides a sensitive, robust assessment of the interfacial mass transport. [1]

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# The influence of contact lines on heat transfer during droplet impact on heated surfaces

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Droplets impacting heated surfaces is important for various applications such as spray cooling and horizontal-tube falling film evaporation in desalination and refrigeration. During this process, the overall heat transfer performance is a combination of convective heat transfer of the spreading and receding droplet and partial evaporation of the liquid. If the wall temperature is lower than the Leidenfrost temperature, a large amount of the evaporation heat flux occurs near the contact line region. As evaporation becomes more significant during receding, altering the contact line length can strongly influence the overall heat transfer performance. By controlling the hydrodynamics of the droplet through surface wettability modifications and the impact Weber number, secondary contact lines can be created during the receding stage. Satellite droplets form additional external contact lines during droplet impact on bi-phobic surfaces (superhydrophobic matrix with hydrophobic patterns), as shown in Fig.1(a). Moreover, entrapped bubbles can also generate an internal secondary contact line during the droplet impact on hydrophobic surfaces, as shown in Fig.1(b). It is expected, though, that this internal contact line behaves differently from the external contact lines. The present research investigates droplet wetting and heat transfer behavior on heated surfaces (superhydrophobic, hydrophobic, bi-phobic), placing special emphasis on the local heat transfer near the external and internal contact lines. Using synchronized high-speed optical and infrared (IR) imaging, we are able to correlate droplet dynamics to the spatial distribution of the solid-liquid interfacial temperature, heat flux, and the total heat transfer to the droplet. The experiments use water droplets ($D$ = 1.6-2.2mm) impacting on heated surfaces with temperatures ranging from 25°C to 75°C. We found that the local evaporative cooling at the external contact line gained importance as the contact line velocities decreased over time. Due to the presence of the additional external contact lines on bi-phobic surface, the single-droplet heat transfer was enhanced by 33% to 46% with respect to the plain superhydrophobic surface, depending on the location of impact relative to the hydrophobic pattern. For the secondary contact line of the entrapped bubble, we observed a very stable contact line position and local heat flux after the bubble is formed. Meanwhile, as the external contact line continues retracting, the local heat flux there decreases and becomes smaller than that at the internal contact line at the later stages of receding. Due to the loss of solid-liquid interface area, the total heat transfer $Q$ is reduced by 5.6% to 7.4% with the existence of the bubble. This study can provide new insights into the fundamentals of the transient phase-change heat transfer process and its applications, such as improving the efficiency of spray cooling applications.

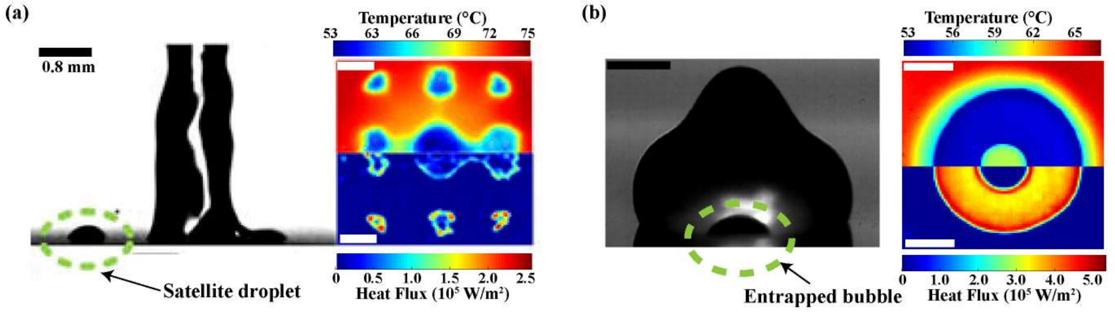

Figure 1. Snapshots of droplet hydrodynamics (left) and corresponding temperature (top right) and heat flux (bottom right) profiles for broplet impact on (a) a bi-phobic surface and (b) a smooth hydrophobic surface.

# Nonuniform heating of the solid base in evaporative lithography

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[3] *Tyumen State University, Photonics and Microfluidics Laboratory, Tyumen, Russia*

Evaporative lithography allows controlling of a colloidal particle deposition shape via nonuniform drying conditions, e.g. using masks, infrared radiation, composite substrates, local air blowing, etc. [1, 2]. Here we are studying the effect of a local substrate heating on a sediment structure. An acrylic glass ring was glued to the welding glass substrate (Fig.1a). In the center of the cell bottom, a copper rod was inserted in the drilled hole and connected with a heater. Heating mainly takes place in the area of the rod, because thermal conductivity of copper is much higher than glass one. Thermocapillary flow occurs because of a temperature gradient on the free surface of the colloidal liquid. The circulating flow transfers particles (Fig. 1b). We have studied the influence of initial film thickness, particle concentration, and heat flux density on the geometry of deposition.

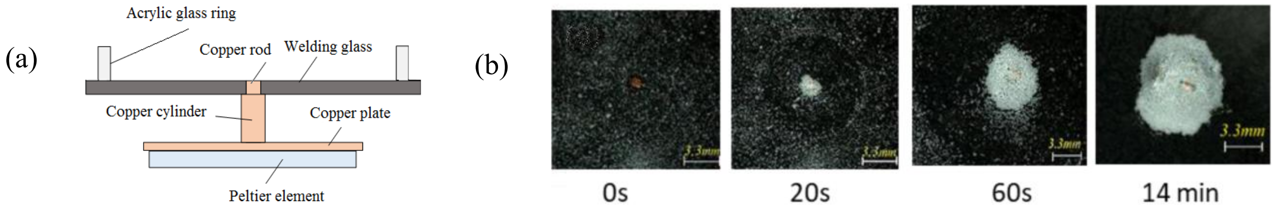

Figure 1. The sketch of an experimental setup (a) and series of top view images of particle assembling (b).

We used heat transfer and heat conduction equations for the simulation of temperature distribution in fluid and cell. Fluid flow was described by lubrication approximation. Particle transport was modelled via the transfer equation. The evaporation flux density is calculated with the Hertz-Knudsen equation. The dependence of the liquid viscosity on the particle concentration is described by the Mooney formula. Numerical results are shown in the Fig. 2. The liquid film gradually becomes thinner in the central area, as the surface tension decreases with increasing temperature. The liquid flow is directed to the heater near the substrate. It transfers the particles to the cell center.

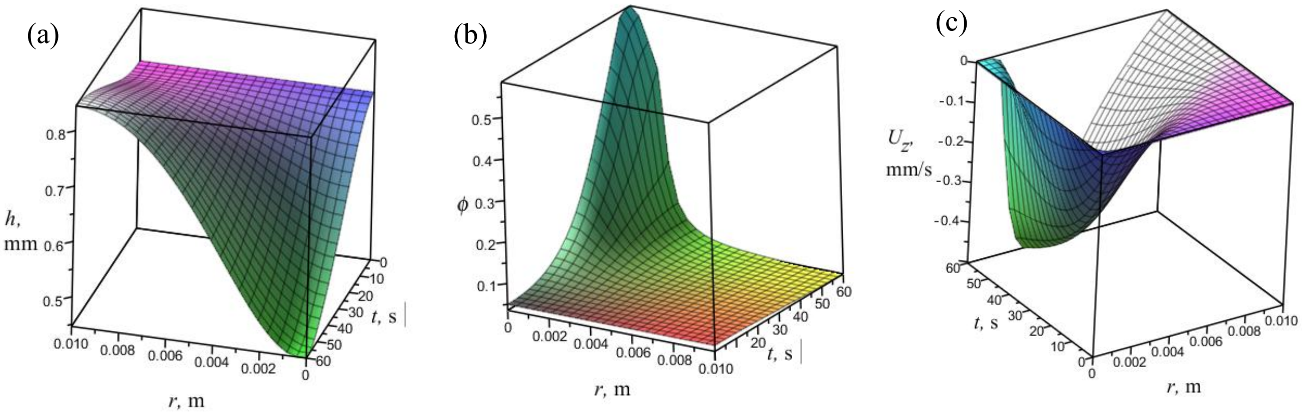

Figure 2. Evolution of the free liquid surface (a), the particle mass fraction (b), and the flow velocity (c).

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[2] D Zang et al. *Phys. Rep.* **804** (2019) . 1–56. DOI 10.1016/j.physrep.2019.01.008

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# The inversion of the fluid flow in a water droplet on a sodium chloride substrate

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Evaporation of droplets on reactive substrates is a new research topic for various applications: nanotechnology, food industry, pharmaceuticals. The complex and variable structures may be obtained from the evaporation of a pure water drop, provided that the drop is resting on a very soluble substrate, namely salt [1]. Particle Image Velocimetry (PIV) experiments showed the inversion of the liquid flow in the water sessile droplet on the sodium chloride crystal. Initially, the flow near the substrate had a direction towards the center of the droplet, then it changed its direction to the drop edge.

This change of flux is more likely the outcome of the homogenization of the concentration inside the drop during the beginning of the experiments. Indeed, due to the rapid dissolution of the salt, a concentration gradient first builds up, giving rise to Marangoni convection exhibiting an inward flow at the bottom of the drop, similarly to the experiments. The progressive vanishing of this initial concentration gradient induces the end of the Marangoni flow and the establishment of a capillary outward flow. Finite element simulations using the lubrication approximation have confirmed this assumption.

[1] A Mailleur, C Pirat, O Pierre-Louis, and J Colombani, Phys. Rev. Lett. **121** (2018), 214501.

# Sessile liquid drop evaporation: analytical solution in bipolar coordinates

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Novel analytical expressions are proposed to calculate the evaporation rate of sessile drop [1]: mass loss per unit surface area per unit time given by

$$J(\omega)=\frac{D(n_S-n_\infty)}{(\pi-\theta)R}(\cosh\omega-\cos(\pi-\theta))^{3/2}\int_{\varsigma=\omega}^{\infty}\frac{d\,\mathrm{sech}\left[\dfrac{\pi\varsigma}{2(\pi-\theta)}\right]}{\sqrt{\cosh\varsigma-\cosh\omega}}, \qquad (1)$$

total evaporation rate (mass loss per unit time), and vapor concentration in the air in bipolar coordinates (ξ, ω) [Fig.1 (a)]. In polar coordinates with angle $\varphi$, Eq.(1) takes the form [Fig.1(a,b)]:

$$J(\varphi)=D(n_S-n_\infty)R^{-1}f(\varphi). \qquad (2)$$

To obtain these results, the H.M. Macdonald's solution for a flat wedge was transformed by J.C. Maxwell’s method of inversion in a sphere with further derivation the solution for a lens based on consideration given by G.A. Grinberg. The new solutions are mathematically equivalent to expressions proposed earlier by Yu.O. Popov [2], but, probably, our solutions given by Eqs. (1) and (2) have more simple form and can be more useful from a computational point of view.

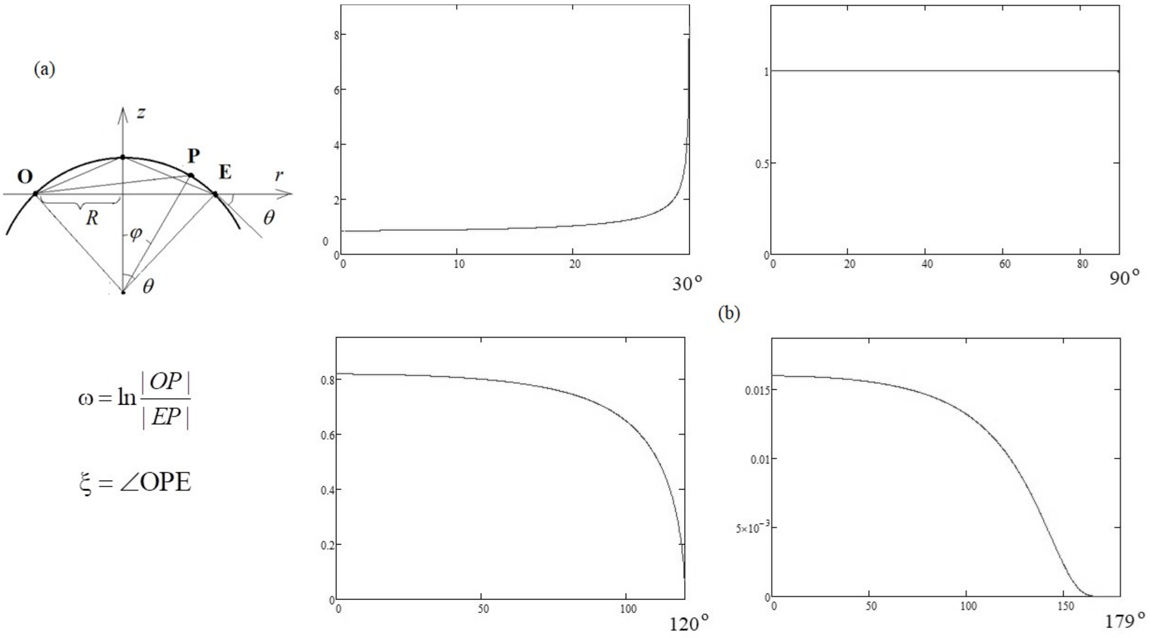

Figure 1. (a) Bipolar coordinates (ξ, ω) centred at points O and E and polar coordinates with angle $\varphi$ on the drop surface with contact angle $\theta$. (b) The graphs of the function $f(\varphi)$ given by Eq.(2) for the different values of contact angles of the drop ($\theta$ = 30°, 90°, 120°, 179°).

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[2] Yu.O. Popov, *Phys. Rev. E.* **71** (2005), 036313.

# Single Droplet Dynamics in Stagnation Flow Conditions

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Condensation is a very complicated subject to fully unveil as it constitutes a complex interplay of momentum, heat and species transport and interfacial physics. Drop-wise condensation (DWC) adds more layers of complexity by introducing droplet dynamics and the two-way interaction with droplets' surrounding. In our other talk in this conference[1], we showed that jet impingement is an excellent means of improving drop-wise condensation. We also illustrated how complicated the droplet dynamics during the condensation process is. Here, we isolate the droplet dynamic problem from the condensation process to study the underlying physics. Microscopical view of droplet shedding shows that the droplet goes through three motion periods; Period I - a waiting period before onset of motion; Period II - a period of droplet acceleration; and Period III - a period of droplet deceleration until the droplet comes to rest. We investigate the retention and aerodynamic drag forces to understand the equation of a single droplet motion.

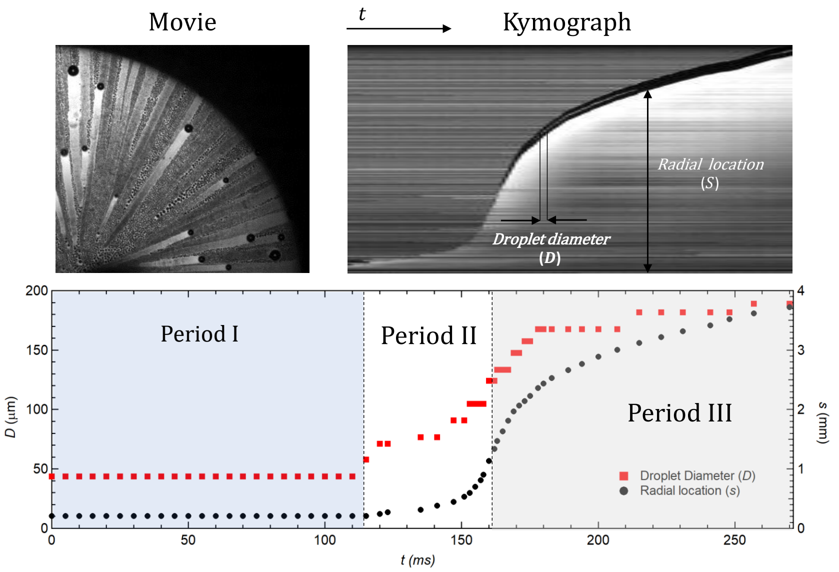

Figure 1: A typical transience of droplet motion and growth under jet impingement action. **A.** A video showing one-quarter of the condensation process. The video traces a single droplet from the onset of departure to leaving the microscopic view. **B.** A Kymograph plotting the location and diameter of a single droplet during its motion. **C.** The diameter of the droplet ($D$) and its center of mass radial location ($s$) as functions of elapsed time ($t$). This plot is generated for a selected case of jet Reynolds number $Re_j = 3600$ and hydrophobic surface ($\theta_A = 107^o$ and $\theta_R = 103^o$).

[1] Talk titled "Continuous Dropwise Condensation in Stagnation Flow Conditions", Droplets 2021.

# Investigation of Droplet Evaporation on Copper Substrate with Different Roughness

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In the present study, we investigated the evaporation process and deposition pattern of saline droplet on a copper substrate with different roughness under 40 ˚C ambient temperature. These four substrates are classified as smooth surface and rough surface based on their droplet contact angles. It has been found in this study that the evaporation pattern of droplets has a strong relationship to substrate roughness. The thickness boundary of the evaporation pattern on a smooth surface is larger than that on a rough surface and the particles are closer to boundary and the tendency is more obvious on a smooth surface. The below factors contribute to the result. On the smooth surface, the contact angle of droplet increases as the roughness decreases. On the rough surface, the contact angle increases as the roughness increases. With contact angle decreasing, the evaporation rate at the boundary increases leading to the particles at the boundary more easily sedimentate. Moreover, the capillary flow is hindered by increasing the substrate roughness, while the Marangoni flow remains constant, resulting in more particles remain in the center of the droplet on the rough surface. To sum up, the deposition pattern of droplet has a strong relationship to substrate roughness. The coffee-ring formation is suppressed by increasing the substrate roughness on a copper substrate under 40 ˚C temperature.

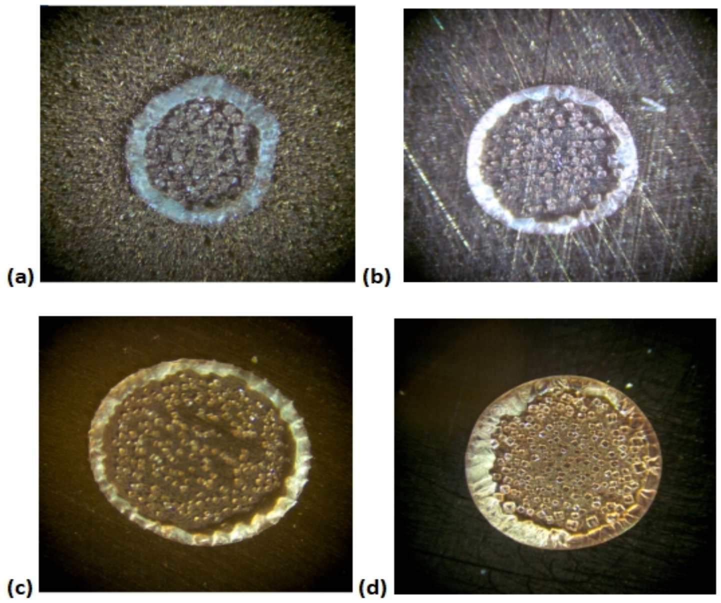

Figure 1. Evaporation patterns of saline droplet on copper substrates with different roughness. (a) Substrate without polishing; (b) 400 pp; (c) 1200 pp; (d) high polishing (0.2 μm).

# Manipulation of Marangoni Convection Inside the Sessile Evaporating Droplet

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[2]*Department of Chemical Engineering, Indian Institute of Technology Guwahati, India*

Particles dispersed in liquid droplet placed on the substrate display rich varieties of patterns left by the particles upon complete evaporation. The dynamics of the deposition as well as pattern formation strongly depends on the fluid flow profile inside the evaporating micro droplets placed on the substrate. It received wide attention to understand the internal fluid motion that can be controlled by changing the conditions of evaporation which in turn affects the deposition patterns. In this study, we have investigated the fluid flow pattern and particle transport inside the evaporating droplet dispersed with 10 μm polystyrene particles (*PS*). To avoid the problems encountered in 3D PIV measurement, a 2D PIV model was used to measure the fluid flow and particle distribution inside the evaporating droplet. [1,2] First, the velocity profile inside the droplet of the localised heating (represented as red bar) at the bottom center as shown in the Fig 1a. In this case, the measured temperature at the apex was higher than the temperature at the edges of the droplet. These surface temperatures was created a surface tension gradient along the interface of the droplet and drive the fluid flow from the lower surface region to higher surface tension region. Thus, two symmetric counter rotating Marangoni convection cells (*MCC*) inside the droplet was observed. While, the differnt velocity profile inside the droplet placed on the heatd substrate near the two edges was observed. The heated area in the left edge is greater than the heated area at the right edge. Therefore, an asymmetric teperature profile was created along the interface of the droplet. As expected the resulting *MCC* at the left region is bigger as compared to the *MCC* at the right region was observed (see Fig. 1b). This clearly indicated that the Marangoni flow can be controlled by the external heating of the droplet. And the resulting particle distribution and final deposition patterns were strongly dependent on the pattern of *MCC* inside the evaporating droplet was observed.

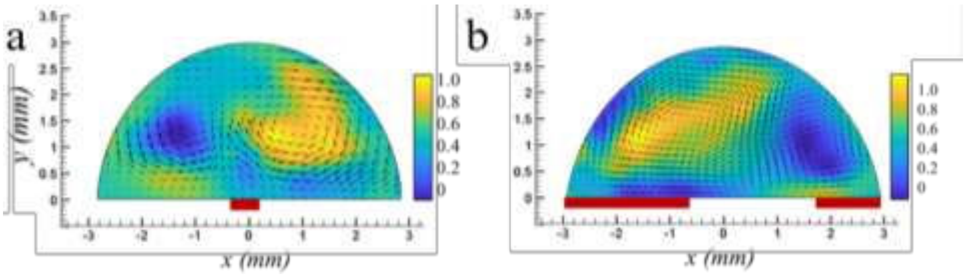

Figure 1. a. Velocity field inside the evaporating droplet placed on localized heated substrate at the bottom center obtained from the experiment. b. Velocity field inside the evaporating droplet placed on heated substrate near the edges.

[1] AK Thokchom, SK Majumder, A Singh. *Internal fluid motion and particle transport in externally heated sessile droplets. AICHE J.* 62 (2015), 1308-1321.

[2] AK Thokchom, A Gupta, PJ Jaijus, A Singh. *Analysis of fluid flow and particle transport in evaporating droplets exposed to infrared heating. Int. J. Heat Mass transfer*. 68 (2014), 67-77.

# Spontaneous dynamics of Leidenfrost drops

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A liquid deposited above a sufficiently hot substrate can generate a thin layer of insulating vapor — a phenomenon known as the Leidenfrost effect. This vapor layer prevents direct contact between the liquid and the substrate, thus considerably slowing down the evaporation process.

Particular attention has been devoted to Leidenfrost drops, namely slowly-evaporating drops in the Leidenfrost state. These drops levitate above their own vapor and experience very low friction, attributes that hold promise in various microfluidic applications. Leidenfrost drops exhibit very rich dynamics, including oscillations, bouncing and directed propulsion using textured surfaces [1].

Recent experiments have revealed that Leidenfrost drops may also undergo "symmetry breaking" leading to a spontaneous "rolling" motion in the absence of any external gradients or asymmetries [2].In detail, a rotational flow can be spontaneously established within an immobilized drop; the rotation induces an asymmetry at the drop base and, when the drop is released, it begins to move at a constant acceleration approximately equal to the "characteristic slope" of the asymmetry times the gravitational acceleration. These discoveries received significant attention, as they may help to explain the exceptional mobility of Leidenfrost drops and open new avenues of practical exploitation.

Motivated by these observations, we theoretically investigate the translational and rotational dynamics of Leidenfrost drops on the basis of a simplified two-dimensional model [3], focusing on near-circular drops small relative to the capillary length. The model couples the equations of motion of the drop, which flows as a rigid wheel, and instantaneous thin-film equations governing the vapor flow, the profile of the deformable vapor-liquid interface, and thus the hydrodynamic forces and torques on the drop.

Our model predicts an instability of the symmetric Leidenfrost drop, which leads to spontaneous motion, and is in compelling qualitative agreement with the experiments. It is shown that the key instability mechanism is the nonlinear coupling between the internal flow within the droplet and the external lubrication flow in the vapor film. Our model serves to illuminate several aspects of the experiments, including the origins of the experimentally measured propulsion force and the role of the experimental "initial conditions" in relation to the observed constant-acceleration motion. Regarding the latter, the model also predicts that other, yet unobserved, spontaneous-dynamics regimes are possible for different initial conditions.

[1] D. Quéré, *Annu. Rev. Fluid Mech.* **45**,197 (2013)

[2] A. Bouillant et al., *Nat. Phys.* **14**, 1188 (2018).

[3] R. Brandão and O. Schnitzer, *Phys. Rev. Fluids* **5**, 091601 (2020).

# The Evaporation of a Tiny Droplet in a Well: Experiment and Theory

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Inkjet printing technology has the potential to greatly advance the efficiency of a number of different industrial processes, not least the production of OLED displays. In this case, droplets are printed into pixels and the solvent is evaporated in order to deposit active material in the pixel. The uniformity of the deposited film is critical for performance.

Our work combines experiment and simulation to attempt to understand the shape evolution of such evaporating droplets in cylindrical wells with radii between 30 and 75 $\mu$m and depths on the order of 2 $\mu$m. Zhida uses light interferometry to measure the height profile of the droplet over time and Seth derives and solves a lubrication equation to simulate the evaporation process. In this joint presentation we will outline the experimental and theoretical approaches and show that we can obtain quantitative agreement in the shape of the profile for a variety of solvents and pixel aspect ratios $\varepsilon$, though there remain unexplained discrepancies in the value of the dimensionless number required to match experiment with theory.

We will also discuss our more recent attempts to add complexity to the system in the form of droplets containing two volatile solvents with different evaporation rates, leading to the possibility of Marangoni flows.

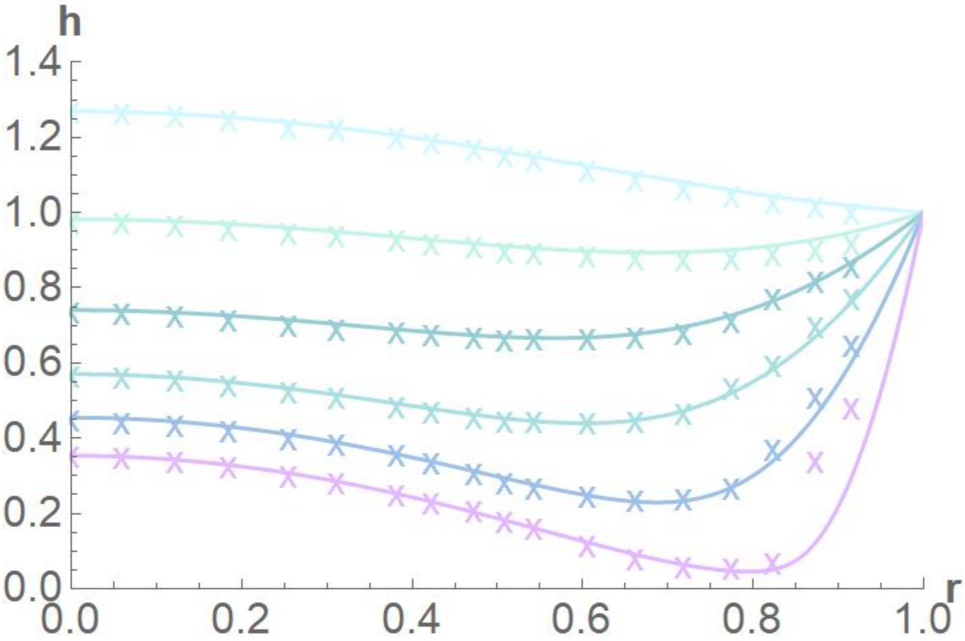

Figure 1: The height evolution of anisole in a cylindrical well at room temperature. Non-dimensionalised experimental data (crosses) and simulations (lines) are superimposed.

Zhida and Seth would like to acknowledge and thank the Chinese Scholarship Council (CSC) and SOFI CDT respectively.

# Enhancing durability of fluorine-free transparent superhydrophobic coatings with metal oxide hybridisation of PDMS

**Norbert J. Janowicz**[1], Hangtong Li[2], Frances L. Heale[2], Ivan P. Parkin[2], Ioannis Papakonstantinou[3], Claire J. Carmalt[2], and Manish K. Tiwari[1,4]

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Superhydrophobic coatings were fabricated utilizing two different methods (aerosol assisted chemical vapour deposition and spin coating) based on one type of nanocomposite formulated with APTES functionalised mesoporous silica particles (120 nm, pore 3 nm) and titanium hybridised PDMS.[1] The resulting coatings were thoroughly characterized using microscopy and their wetting behaviour was evaluated to reach 168° and hysteresis of 3° at particle loading concentrations as low as 9 wt % which facilitated transparency of up to 90 % at 550 nm.[1] The hybridisation of the polymer network with the titania species enhanced durability of the coatings, remaining superhydrophobic after 15 and 25 tape and sandpaper abrasion test cycles. Due to the low hysteresis of the coatings, all samples showed good self-cleaning properties. The figure below depicts the comparison of the morphology and coating methods utilised for fabrication of the discussed coatings.[1]

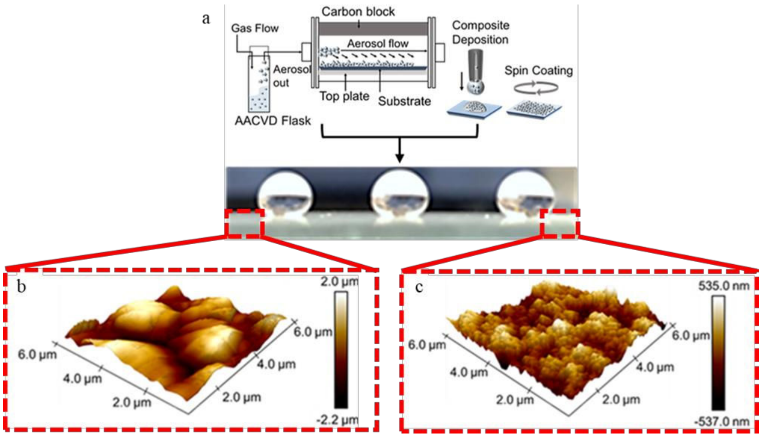

**Figure 1.** Coating fabrication methods and resulting structures. (a) The two methods used for fabrication of coatings being Aerosol Assisted Chemical Vapour Deposition (AACVD) and Spin coatings (b) AFM study of AACVD sample (c) AFM study of spin coated sample.

[1] N Janowicz, H Li, F Heale, I Parkin, I Papakonstantinou, M Tiwari, C Carmalt, Langmuir **36** (2020), 13426−13438

# Separation of Droplet Aerosols in Coalescence Separators

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In the context of environmental protection and the energy transition in Germany and worldwide, gas-fired power plants are increasingly coming into focus to cover the residual load. The reason for this is their fast controllability and comparatively low nitrogen oxide emissions. Before the fuel gas is fed into the turbine, it is compressed, whereby higher hydrocarbons form condensation aerosols. These are separated by coalescence filters immediately before the combustion chamber. This prevents inhomogeneous combustion within the combustion chamber, fouling and damage to the turbine. Such coalescence filters are designed industrially based on empirical values. Therefore, the aim of this project in cooperation with Seebach GmbH is to develop a holistic and industrially applicable modelling to predict the separation efficiency and the pressure drop of these filters. In this context, a better understanding of the functioning of these coalescence filters is crucial to increase the efficiency and effectiveness of the entire power plant.

For this reason, various nonwovens used industrially for this purpose were examined for their saturation behaviour under different operating conditions. In addition, the change in filtration efficiency in the unsaturated and saturated state was considered. For this experiment, a test rig was developed that allows a comprehensive characterisation of the filter media. In addition, the influence of the microscopic inhomogeneity of the porosity and the influence of the macroscopically inhomogeneous surface topology of the filter media and the media thickness derived from this on the liquid transport through the filter media were investigated. It is shown that the varying thickness and the resulting different flow conditions in the filter medium have a significant influence on the local channel formation and thus the liquid transport in the fleece. Optical profilometry, transmitted light photography and computer tomography were used for the investigations.

# Title: Particle deposition study from an evaporating sessile droplet under unfavourable particle-substrate interaction

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Understanding the formation of particle deposition during evaporation of sessile droplets of colloidal suspensions is very important since many technical applications are growing in the past decades [1]. Several parameters effects the final deposit shape: suspension proprieties, thermo-physical proprieties of the substrate, heating temperature of the substrate [2] and surrounding air moistening [3]. In the present work, the coupled phenomena of flow and heat and mass transfer with phase change are modelled by taking into account for the evaporative cooling effect, surface tension gradient effect at the liquid air interface, thermal buoyancy effect inside the droplet, thermosolutal buoyancy effect in the surrounding air and the DLVO interactions between substrate and colloidal particles. Results of figure 1 shows particles concentration distributions in a water sessile drop. Two models are used: (a) model with thermo-capillary effect and (b) model without thermo-capillary effect. Internal flow of the evaporating droplet plays a decisive role to the final morphology of deposit when the DLVO interactions are strongly repulsive and the relative humidity and/or particles diffusivity are small. Thus, the competition among the outgoing radial flow derived by the peak of the evaporation near the pinned contact line, Marangoni cellular flow induced by thermo-capillarity and the transport of particles in the adjacent region of the substrate lead to three deposit shapes : a uniform pattern, a ring like pattern and a shoulder like pattern.

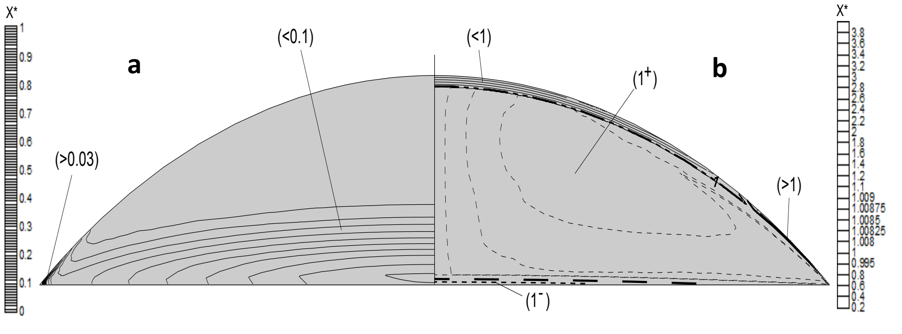

Figure 1. Isoconcentrations in a water sessile droplet containing polystyrene particles. (a) Model without thermo-capillary effect, (b) Model with thermo-capillary effect.

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[2]. *from coffee rings to coffee eyes*. Yanshen Li, Cunjing Lv, Zhaohan Li, David Quere and Quanshui Zheng. 2015, The Royal Society of Chemistry.

[3]. *Effect of relative humidity on contact angle and particle deposition morphology of an evaporating colloidal drop*. V.H. Chhasatia, A.S. Joshi, Y. Sun. 2010, Applied physics letters

# Banded μ-Marangoni Vortex inside the Sessile Evaporating Droplet

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Though a fair amount of investigation has been done, many aspects of the self-assembly of nanoparticles have not yet been well understood. Recently, the formation of multiple bands of particles inside the evaporating microdroplet on the glass substrate was observed [1]. This was strongly influenced by the Marangoni vortex (*MV*) induced by the distribution of polyethylene glycol (*PEG*) along with the air-water interface of the droplet which is dependent on the effective inter-particle distance ($L_c$) as demonstrated in Figure a and b [1,2]. Interestingly, similar particle dynamics can be seen in a partially filled rotating cylinder with the liquid suspension of particles. A similar factor in both cases is that the setting up of an air-liquid interface results in a band of particles by lateral capillary meniscus forces (*CMFs*) acting on neighbouring particles. The dynamics of particle clustering was delineated with the lateral translational motion of the particles due to the *CMFs* of attraction. This may also be affected by particle aggregation, it is necessary to explore more on the effect of the shape of microparticles dispersed in the solution which are not well understood. Hence, in the present study we aim at understanding the impact of particle shape on the band formation using different particle shapes. Water droplet of 2 μL containing sodium dodecyl sulfate (SDS) with dispersed 1 μm polystyrene (PS) particles was placed on the glass substrate. The particles inside the droplet were monitored at various times under an optical microscope at room temperature. At the early stage of the evaporation process, transportation of the particles to the edge of the droplet by radial outward flow was observed. As time progressed, another secondary flow so called *MV* was generated near the contact line with radial fluid flow from the center of the evaporating droplet. The particles inside the *MV* tended to self-aggregate resulting bands of particles during the evaporation process as shown in Figure c and d. However, faster formation of particle bands in the case droplet dispersed with the ellipsoidal particles was observed. This clearly indicated that the phenomenon was strongly strongly influenced by the shape of the particles. The results of the current study would be significantly useful for critical understanding of particle self assemble and pattern formation.

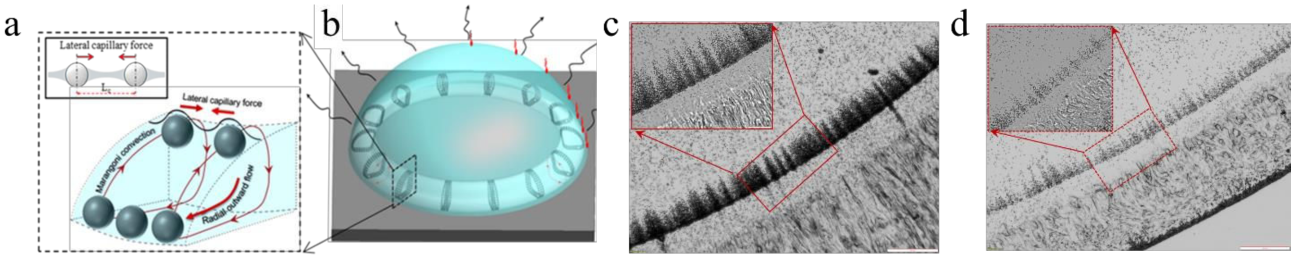

**Figure. a**. Schematic illustration of particles interaction due to *CMFs* along the interface of the droplet. **b**. Representation of banded *MV* inside the microdroplet placed on the glass substrate. **c-d.** Snapshot of particle band in evaporating droplet c. Spherical particles d. Ellipsoidal particles.

[1] Thokchom, Ashish Kumar, and Sehyun Shin. "*Dynamical Clustering and Band Formation of Particles in a Marangoni Vortexing Droplet.*" Langmuir 35.27 (2019): 8977-8983.
[2] Seo, Changdeok, et al. "*Altering the coffee-ring effect by adding a surfactant-like viscous polymer solution.*" Scientific Reports 7.1 (2017): 1-9.

# Interfacial particle transport and aggregation in evaporating water-glycerol droplets: Iridescent Marangoni Ring Formation

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3. *Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands*
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5. *Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Alberta, Canada*
6. *Max Planck Institute for Dynamics and Self-Organisation, Göttingen, Germany*

The dynamics of an evaporating droplets and the fate of the dispersed particles are both extremely sensitive to many parameters. For example, stick-slip motion of the contact line in a particle-laden evaporating droplet can yield multi-ring patterns [1] instead of the well-known coffee-stain pattern [2]. Besides, thermal Marangoni flow can lead to the formation of an additional ring near the droplet apex [2–4]. In this work, we study a particle-laden evaporating water-glycerol droplet experiencing interfacial solutal Marangoni flow, in which the initial glycerol concentration influences the contact line motion (stick-slip, stick-jump and final spreading) and most remarkably the particle deposition (Fig. 1a,b). During evaporation, the particles accumulate at the interface near the droplet apex due to the solutal Marangoni flow, forming "Marangoni ring" (Fig. 1c). Interestingly, by a combined effect of interfacial flow and contact line motion, the particles at the ring are pressed together and a strong iridescent effect is observed [5]. Using fluorescence confocal microscopy, we study the spatio-temporal evolution of this Marangoni ring (Fig. 1d) and show the conditions in which such evanescent colloidal crystals might appear in other systems.

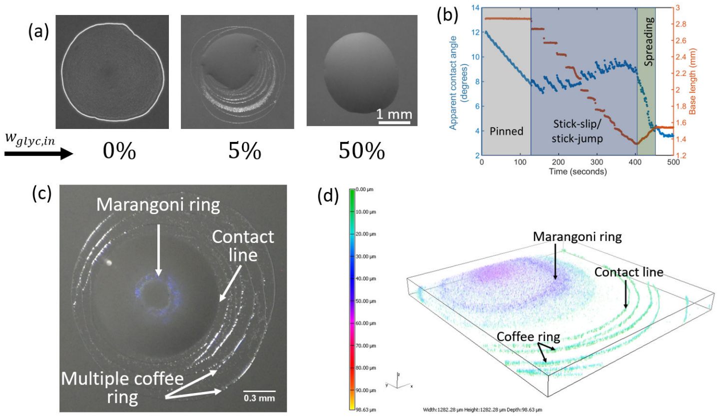

Figure 1: (a) Final deposits obtained from droplets with varying initial glycerol weight fraction ($w_{glyc,in}$). (b) Temporal geometrical measurement for an evaporating water-glycerol droplet ($w_{glyc,in} = 0.05$). (c) Direct observation of Iridescent Marangoni ring during evaporation of the droplet, using top view imaging. (d) Spatial distribution of particles observed using confocal microscopy; color code indicates the height above the substrate.

[1] Wu, M. *et al.*, Langmuir **34** (2018), 9572–9578.

[2] Deegan *et al.*, Physical Review E **62** (2000), 756–765.

[3] Parsa *et al.*, Advances in Colloid and Interface Science **254** (2018), 22-47.

[4] Ren *et al.*, Langmuir **36** (2020), 15064-15074.

[5] Darragh *et al.*, Scientific American **234** (1976), 84–95.

# Understanding flow features in drying droplets via Euler Characteristic Surfaces – A topological tool

**Tapati Dutta**[1], A. Roy[2], and R. A. I. Haque [3]

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Author list: A. Roy, R. A. I. Haque, A. J. Mitra, M. Dutta Choudhury, S. Tarafdar and **T.Dutta**

In this paper we propose a mathematical picture of flow in a drying multiphase droplet. The system studied consists of a suspension of microscopic polystyrene beads in water. The time development of the drying process is described by defining the `Euler Characteristic Surface' which provides a multi-scale topological map of this dynamical system. A novel method is adopted to analyse the images extracted from experimental video sequences. Experimental image data is converted to binary data through appropriate Gaussian filters and optimal thresholding, and analyzed using the Euler Characteristic determined on a hexagonal lattice. In order to do a multi-scale analysis of the extracted image, we introduce the concept of Euler Characteristic at a specific scale $r > 0$. This multi-scale time evolution of the connectivity information of aggregates of polystyrene beads in water is summarized in a Euler Characteristic Surface, and subsequently in a Euler Characteristic Level Curve plot. We introduce a metric between Euler Characteristic Surfaces as a possible similarity measure between two flow situations. The constructions proposed by us are used to interpret flow patterns (and their stability) generated on the upper surface of the drying droplet interface. The philosophy behind the topological tools developed in this work is to produce low dimensional signatures of dynamical systems, that may be used to efficiently summarize and distinguish topological information in various types of flow situations.

[1]F. Giorgiutti-Dauphine and L. Pauchard, The European Physical Journal E **41**, (2018),1-15
[2]S. Tarafdar, Y. Y. Tarasevich, M. Dutta Choudhury, T. Dutta, and D. Zang, Advances in Condensed Matter Physics (2018).
[3]D. Brutin in "*Droplet wetting and evaporation: from pure to complex fluids* "(Academic Press, 2015).
[4]A. Hatcher, *"Algebraic Topology"* (Cambridge University Press, 2002).
[5]L. Snidaro and G. L. Foresti, Pattern Recognition Letters **24,** (2003), 1533-1544

# Changing the flow profile and resulting drying pattern of dispersion droplets via contact angle modification

**Carmen Morcillo Perez**[1], Marcel Rey[1], Benjamin D. Goddard[2], and Job H. J. Thijssen[1]

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Prediction and control over particle deposit patterns obtained from sessile droplet evaporation are essential for many industrial processes, such as inkjet printing and crop protection. Numerous formulations have been studied in order to understand how the different components affect the final dried deposit. Yet, the testing substrates used are generally far from similar to those in the real application. Thus, a key challenge resides in understanding how the substrate properties can affect the drying process. We present a systematic investigation on the effect of surface wettability on the evaporation dynamics of a particle-laden droplet and the final distribution of the particles after evaporation. We tuned the wettability of glass slides using silanisation reactions; and measured the flow inside the drying droplets using fluorescent tracer particles and particle tracking algorithms. We found that the internal flows shift from predominantly outwards flow for low contact angles to predominantly inward flow for large contact angles. Upon increasing the substrates hydrophobicity, the dried deposit gradually changes from the typical coffee-ring to a central stain, as the evaporation is no longer fastest at the contact line. On the basis of the results obtained, we conclude that the substrate plays an essential role on the drying process and supports the need for improved procedures during formulation design.

# Deposition Patterns of Oppositely Charged Polyelectrolyte/Surfactant Droplets

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Oppositely charged polyelectrolyte/surfactant (P/S) mixtures are essential components of countless products such as detergents, paints, and shampoos. Also, the strong attractive interactions of surfactants with charged biological macromolecules such as proteins or DNA play an important role in biological processes as well as in medical applications [1]. The bulk and surface properties of mixed polyelectrolyte/surfactant solutions have been extensively studied, but little has been explored for systems of evaporating P/S droplets in which both the bulk and surface properties experience fast dynamic change with evaporation. The understanding of drying dynamics of P/S droplets on a solid surface is of great importance due to the broad applications of inkjet printing from traditional graphics to functional devices.

In this study, we studied the deposition patterns of picolitre sessile droplets of polystyrene sulfonate (PSS)/ dodecyltrimethylammonium bromide (DTAB) solutions in comparison with the pure PSS or DTAB solutions as well as the weakly interactive polyethylene oxide (PEO)/DTAB solutions. The "coffee-ring" effect (CRE) is found to be effectively suppressed (Fig. 1 for an example of depositions) for a solution of low DTAB and relatively high PSS concentration. The internal flows during drying were observed by addition of tracer particles. Marangoni flows were observed both in droplets of pure DTAB solutions and the PSS/DTAB solutions. Different to pure DTAB droplets which saw dominant capillary flows from around ~ 0.7 $t_f$ (where $t_f$ is the drying time of the droplet) following inward surface flows and outward capillary flows earlier, the inward surface flows in the PSS/DTAB droplets ceased earlier with the tracer particles close to the surface becoming stationary in the radial direction from ~ 0.6 $t_f$. Origins for the suppressed CRE for the PSS/DTAB system were discussed.

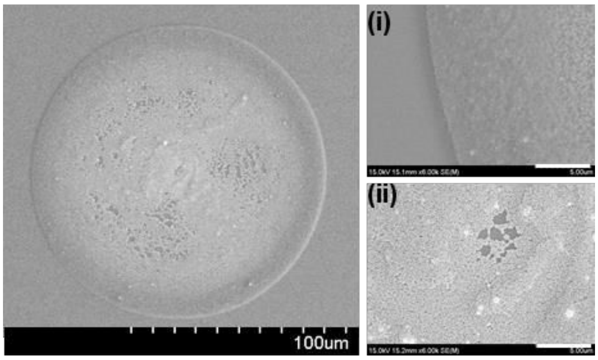

Figure 1. SEM images of deposition upon drying of a 1 mM DTAB/ 2000 ppm PSS droplet with 1 wt.% PS particles (200 nm). (i) shows the part of the deposit edge, and (ii) the deposit center. Scale bars for 5 µm in (i) and (ii).

[1] Campbell, R. A.; Yanez Arteta, M.; Angus-Smyth, A.; Nylander, T.; Varga, I., Effects of bulk colloidal stability on adsorption layers of poly (diallyldimethylammonium chloride)/sodium dodecyl sulfate at the air–water interface studied by neutron reflectometry. *The Journal of Physical Chemistry* B 2011, 115 (51), 15202-15213.

# Absorption of surfactant-laden droplets into porous media

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3. *Canon Production Printing Netherlands B.V., P.O. Box 101, 5900 MA Venlo, The Netherlands*

Droplets can absorb into permeable substrates due to capillarity. Several factors influence this process, including the contact line dynamics and the composition of the droplet. In this research project, it is numerically investigated how these aspects affect the imbibition.

Lubrication theory is employed to model the droplet and Darcy's law is combined with the conservation law of mass to describe the absorption dynamics. For the surfactant transport, several convection-diffusion-adsorption equations are solved (e.g. see [1]).

It is found that moving contact lines result in a parabola-shaped wetted area in the porous medium and a slower absorption and a deeper penetration depth than pinned contact lines. The evolution of the penetration depth was quantitatively validated by comparison with two experimental studies from literature. Surfactants were shown to accelerate the absorption process, but only if their adsorption kinetics are slow compared to the absorption. Otherwise, all surfactant adsorbs onto the pore walls before reaching the wetting front, resulting in the same absorption rate as without surfactants. This behavior agrees with both experimental and analytical literature [2].

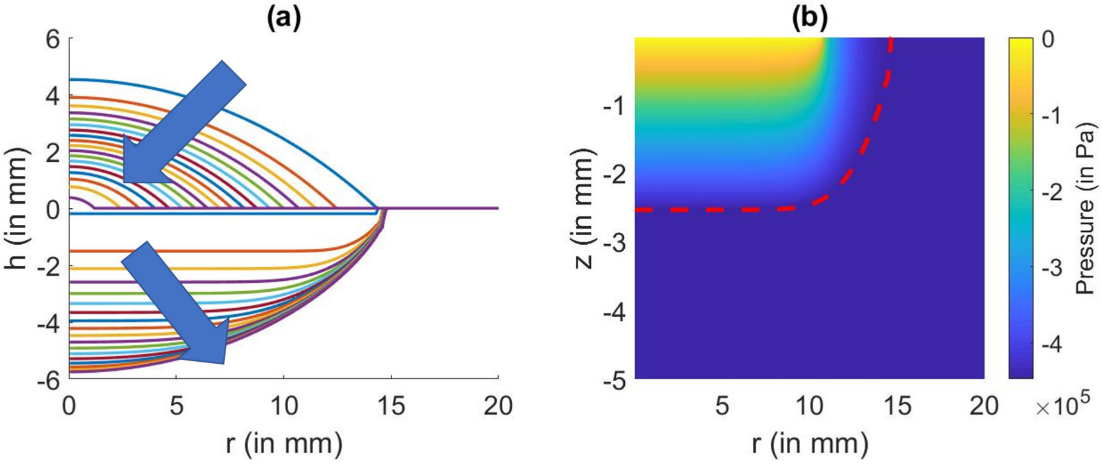

Figure 1: Typical droplet absorption, with (a) the height evolution of both the droplet and the wetted region and (b) a pressure distribution plot in the porous medium. The blue arrows point toward the direction in which the evolution progresses over time and the red dashed line indicates the position of the wetting front.

[1] R.T. van Gaalen, C. Diddens, H.M.A. Wijshoff, J.G.M. Kuerten, Marangoni circulation in evaporating droplets in the presence of soluble surfactants, J. Colloid Interface Sci. 584 (2021) 622-633, https://doi.org/10.1016/j.jcis.2020.10.057.

[2] V.M. Starov, S.A. Zhdanov, M.G. Velarde, Capillary imbibition of surfactant solutions in porous media and thin capillaries: partial wetting case, J. Colloid Interface Sci. 273 (2004) 589-595, https://doi.org/10.1016/j.jcis.2004.02.033.

# Title: Morphologies and dynamics of printing onto a rectangular groove

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As inkjet technology develops to produce smaller droplets, small-scale substrate features such as accidental scratches or manufacturing defects can potentially have a significant effect on the outcome of printing, particularly for printed electronics where continuous tracks are required. Here, the deposition of micro-droplets onto an idealised scratch of similar or smaller size is studied using a 3D multiphase lattice Boltzmann model validated against relevant published experiments and theoretical models. The scratch is considered as a groove of rectangular cross-section, with rectangular side ridges representing material displaced from the groove.

For deposition of a single droplet centred on the scratch, seven different equilibrium morphologies are identified, as a consequence of the contact line becoming pinned on various features of the topography. A regime map is constructed in terms of the scratch depth and width, and the effects of Reynolds number, Weber number, and advancing and receding contact angles on this are discussed. The dynamics of the spreading in each case are described and quantified in terms of spreading lengths along and perpendicular to the scratch, and the implications for printing continuous tracks are discussed. We also study the printing a sequence of droplets across and along the groove.

# Spray impact on a wettability patterned surface

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1. *Department of Mechanical Engineering, Indian Institute of Technology Madras, India*
2. *Nanoengineered Systems Laboratory, UCL, London, WC1E 7JE, UK*
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The drop impact phenomena is widely observed in many natural and industrial process. The dynamics of the drop impact phenomena is very complex due to the interplay of several parameters such as drop velocity, diameter, viscosity, surface tension, surface wettability.[1] Out of these several parameters which influence the drop impact dynamics, the surface wettability has paramount importance in the impact dynamics. Spray cooling of high heat-flux electronic components is a prominent practical application of drop impact on a surface.[2] The heat transfer efficiency of the spray cooling system depend on continuous drainage of the impacted drops and interaction time between the impacted drop and surface.

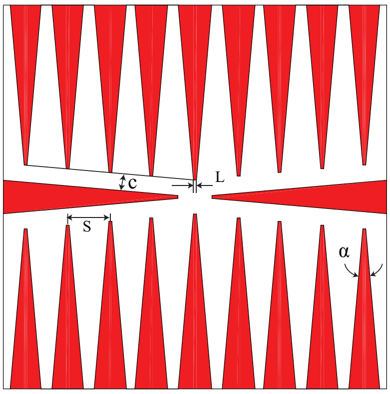

Figure 1: The proposed patterns on superhydrophobic substrate, $L$=0.35 $mm$, $c$=2 $mm$, $s$=5 $mm$, $\alpha$= 10°. Substrate size is 40 $mm \times$ 40 $mm$. Red shaded region represents the superhydrophilic area.

In spray cooling, the superhydrophobic surfaces show poor cooling efficiency due to droplet rebound and on the other hand, hydrophilic surface floods after continuous spray impact, which again bring down the cooling efficiency. So, a hybrid, wettability patterned surface may have better cooling performance compared to the surfaces having homogenous wettability. In the present work, we proposed a design with wettability pattern and investigated the droplet dynamics during spray impact. The wettability patterns comprising of superhydrophilic wedges laid on a superhydrophobic background as shown in Figure 1. During the spray impact, the droplets falling on the superhydrophilic wedge became a film. The droplets falling on the superhydrophobic region transports to the wedge by rolling and finally merging with the wedge's liquid pool. The droplet coalesced with the wedge spreads and continuously drained out from the surface due to the laplace pressure gradient between the wider and narrower part of the wedge. The droplet dynamics were analysed in detail and the different transport modes of the impacted droplet from superhydrophobic to superhydrophilic region were detailed in this work. The droplet dynamics of the wettability patterned surface observed in this study will be useful for the spray cooling and passive liquid-drainage applications.

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[1] Yarin A.L, *Annu. Rev. Fluid Mech* **159-192**, 38 (2006)

[2] Kim J, *Int. J. Heat and Fluid Flow* **753-767**, 28 (2007)