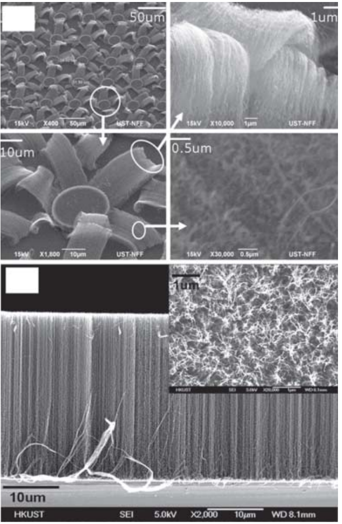
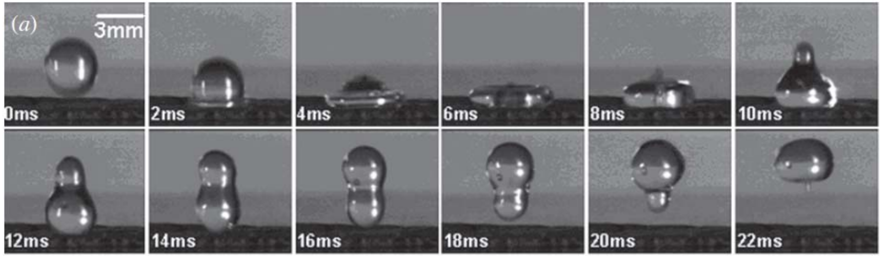
Impact of a compound drop on a solid surface

Marie-Jean THORAVAL – 陶益壮

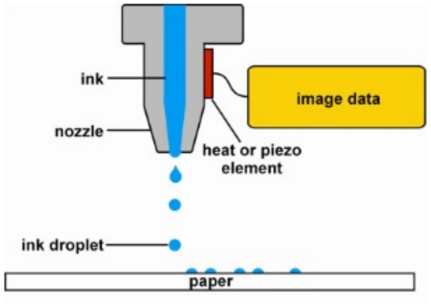
International Center for Applied Mechanics – 国际应用力学中心
School of Aerospace Engineering – 航天航空学院
State Key Laboratory for Strength and Vibration of Mechanical Structures
– 机械结构强度与振 动国家重点实验室
Xi'an Jiaotong University – 西安交通大学

Background





Design of surfaces, Aircraft (damage, icing), windows, clothes, …



Inkjet printing

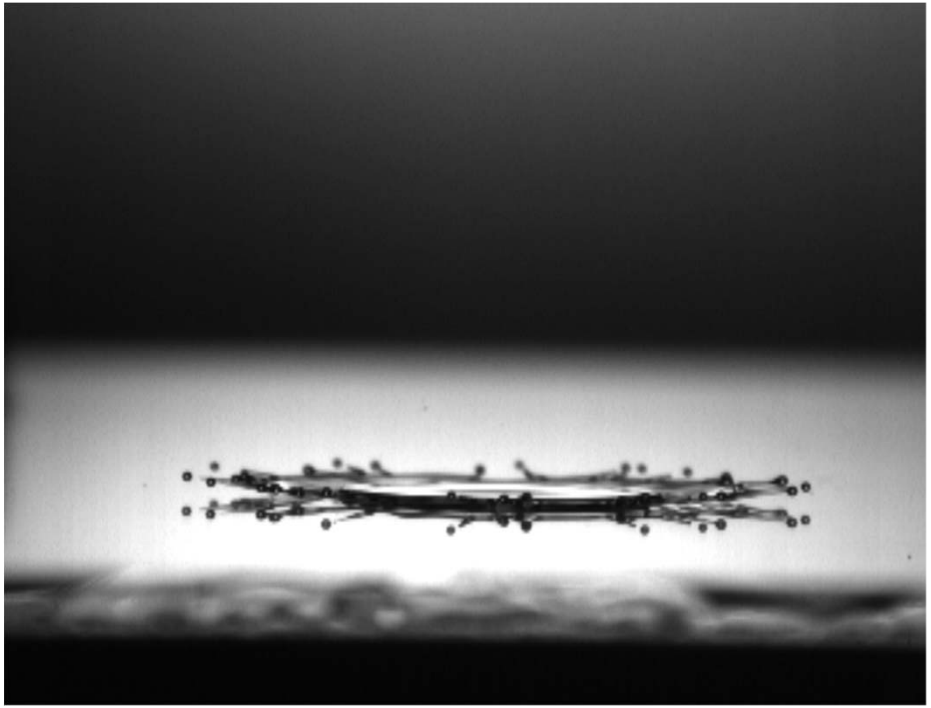
Chen, L., Xiao, Z., Chan, P. C. H., & Lee, Y.-K. (2010). Static and dynamic characterization of robust superhydrophobic surfaces built from nano-flowers on silicon micro-post arrays. *Journal of Micromechanics and Microengineering*, *20*(10), 105001.

Crop Dusting

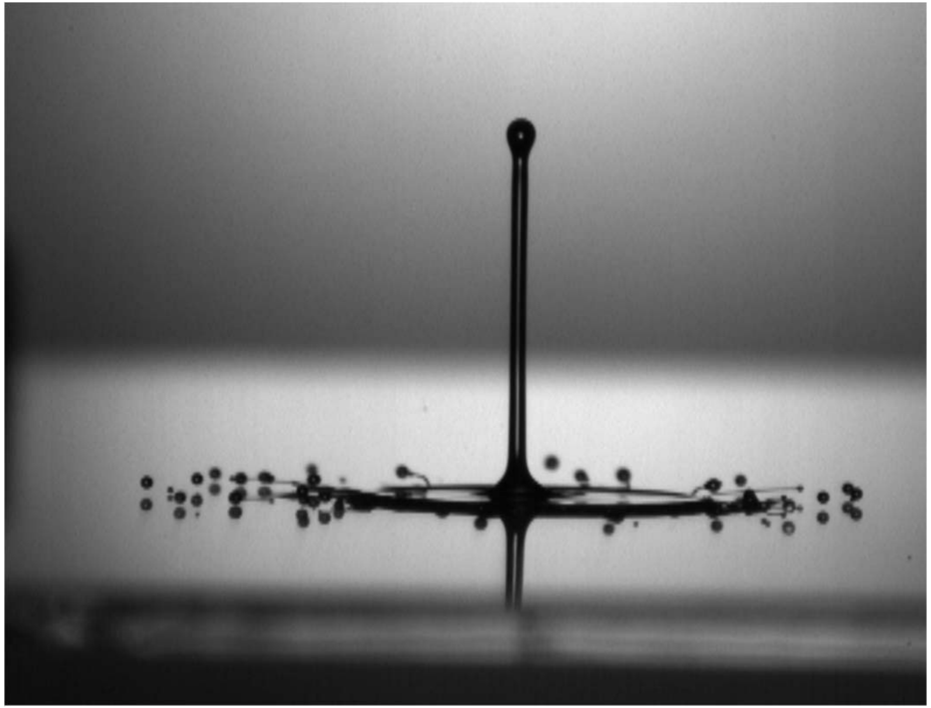
Sprays: Cooling, Coating, Painting, Combustion

3D printing, Printing functional materials
Bio-printing: tissues, organs
New printing technologies (metals, high viscosities, …)

Impact of a drop containing a bubble



Silicone Oil 10 cSt
45 cm



Silicone Oil 10 cSt
150 cm

Applications: Thermal Barrier Coatings

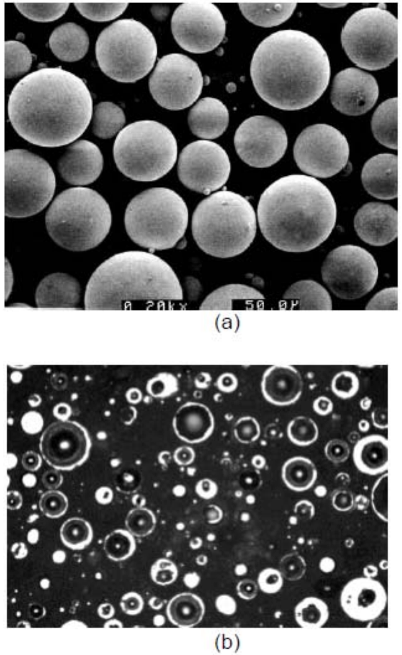


Fig. 3. SEM photos of the hollow spherical particles of a specially prepared YSZ powder. (a) – general view of the particles, (b) – cross-sectional cut of the particles.

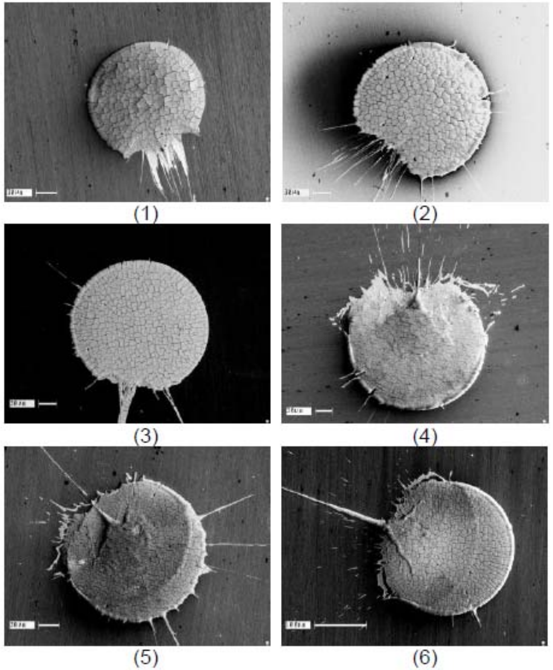
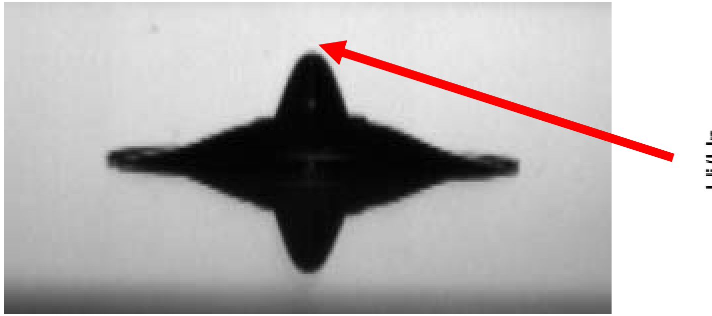
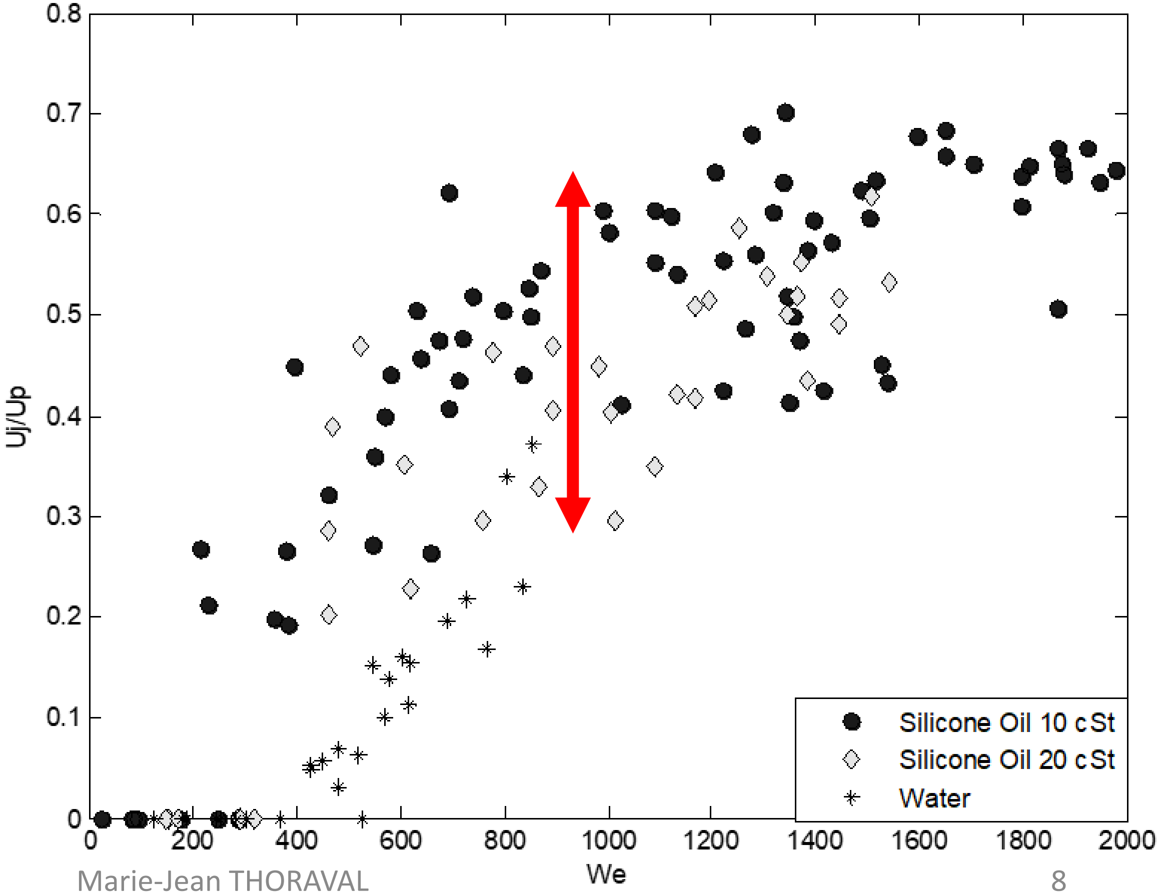


Fig. 4. Irregular YSZ splats formed as a consequence of jet gas emission at the periphery of flattening hollow droplet.

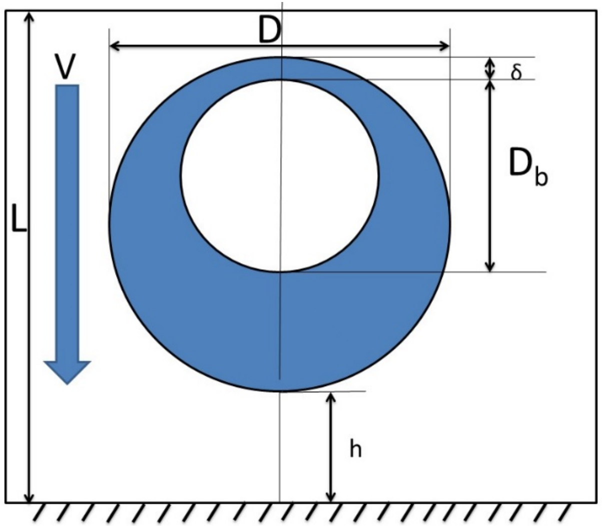
Solonenko, O. P., Mikhalchenko, A. A., & Kartaev, E. V. (2005). Splat formation under YSZ hollow droplet impact onto substrate. In Proceedings of the International Thermal Spray Conference (ITSC-2005) (pp. 1–6). Basel, Switzerland: ASM International.

Vertical splashing

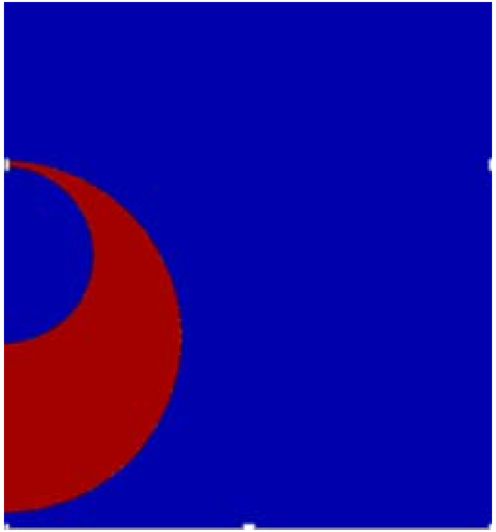


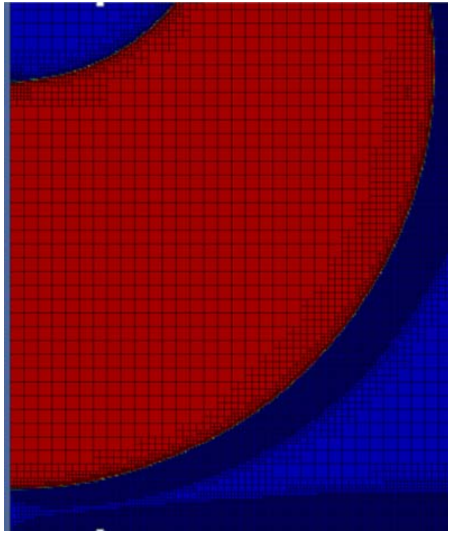


Numerical simulations



D_b^*	D_b/D
δ^*	δ/D
V_j	Maximum Jet velocity
v_j	Jet velocity
V_j^*	V_j/V
v_j^*	v_j/V
P^*	$P/\rho V^2$
∇P^*	$\delta p^*/\delta z$

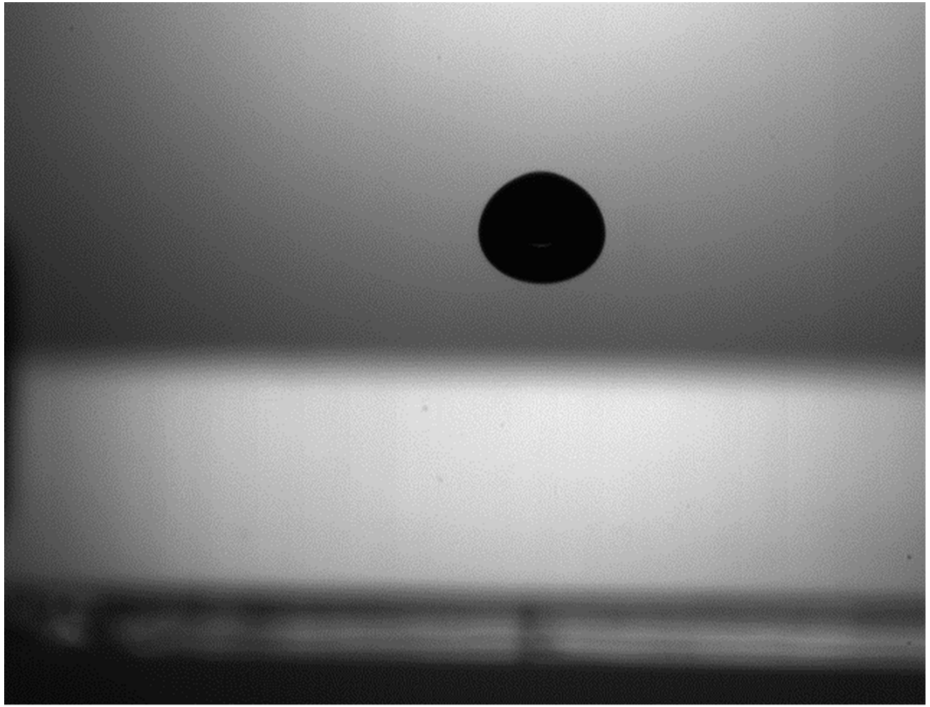




Level of refinement: 10 (2^{10} cells in each direction)
-> $2^{10}*D/L$ = 491 cells per drop diameter
$L/D = 2.08$, $h/D = 0.478$

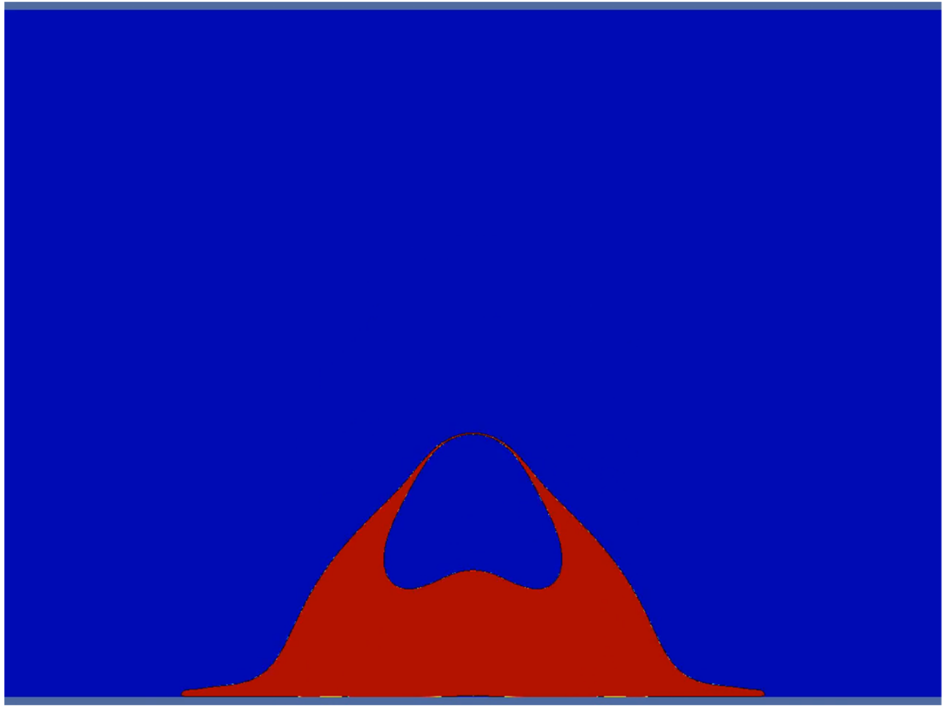
Simulations

Silicon oil 10 cst



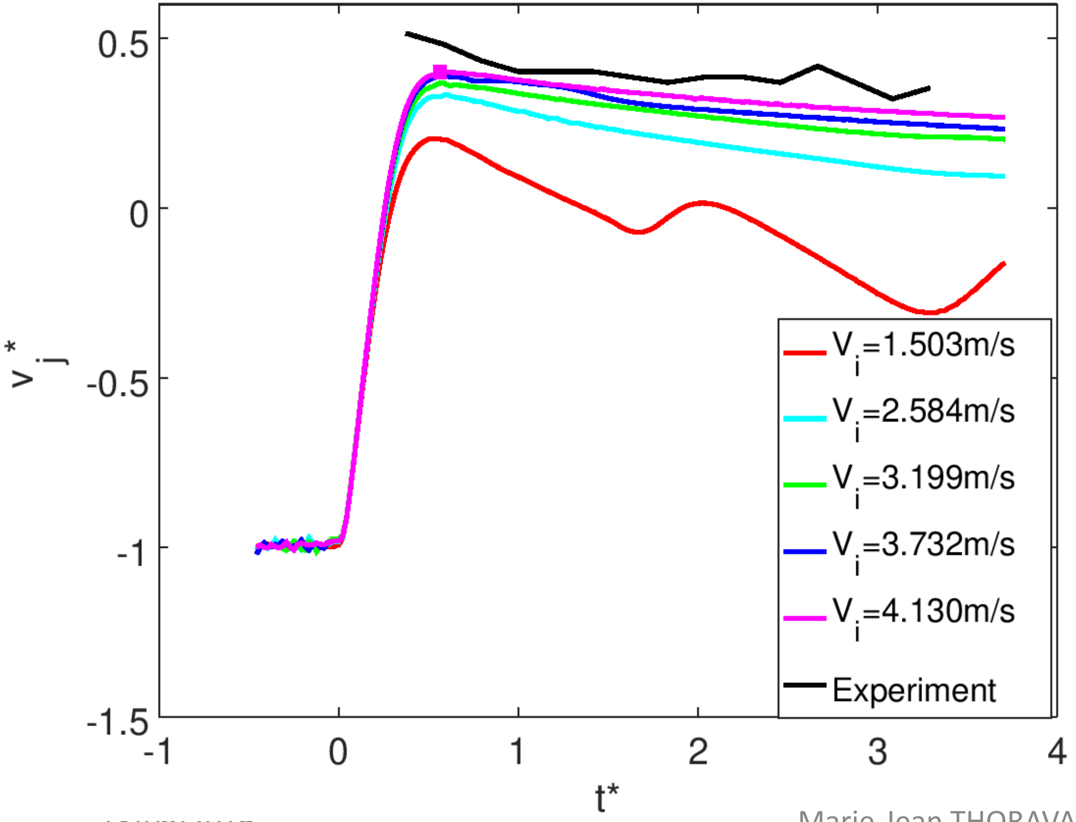
D = 2.75mm, V = 4.59m/s

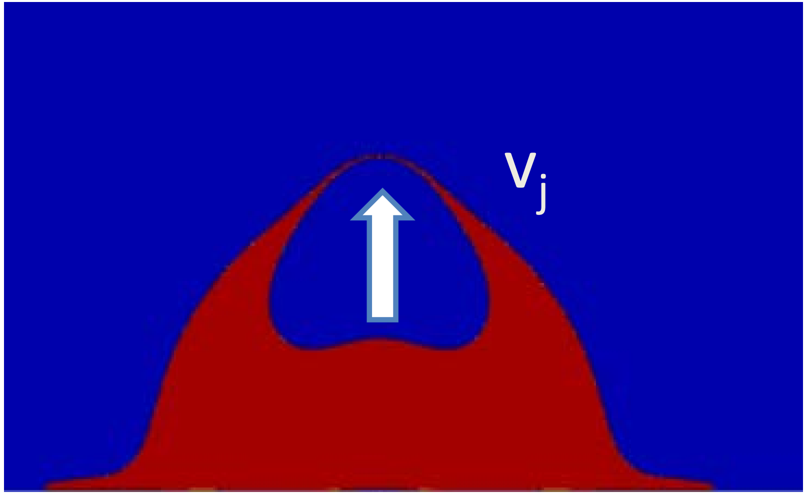
Silicon oil 10 cst



D = 2.75mm, V = 4.59m/s,
δ = 0.0175D, D_b = 0.5D, Re=1010

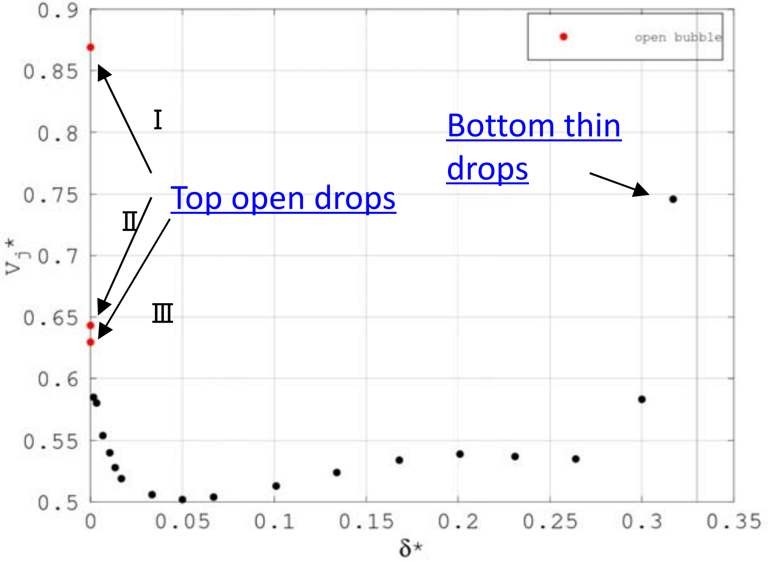
Vertical jetting velocity

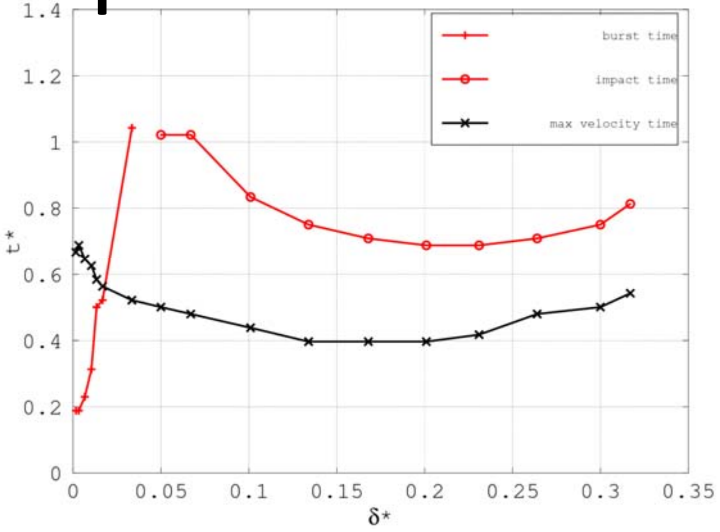




Silicon oil 10 cst

Bubble vertical position

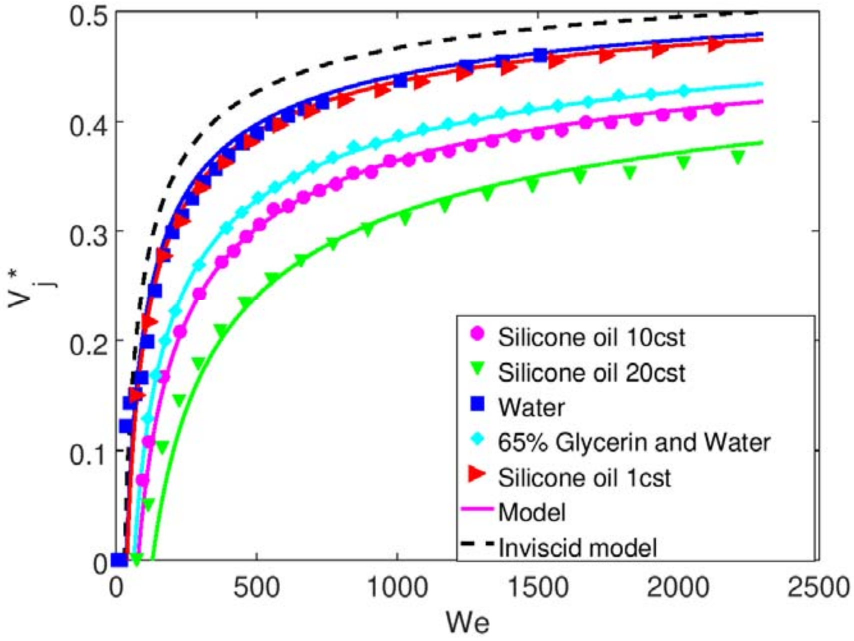


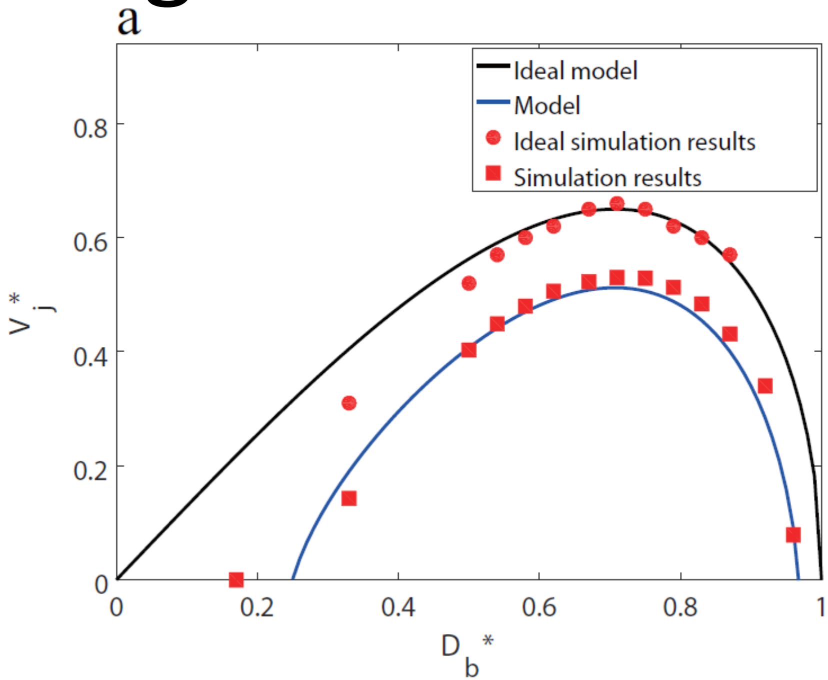


The relation between maximum jet velocity and different film thickness. When δ* < 0.1, the maximum jet velocity decreases at the increasing of film thickness. But after δ* > 0.1, the situation is the opposite.

Burst, impact and maximum jet velocity time of different film thickness

Modelling

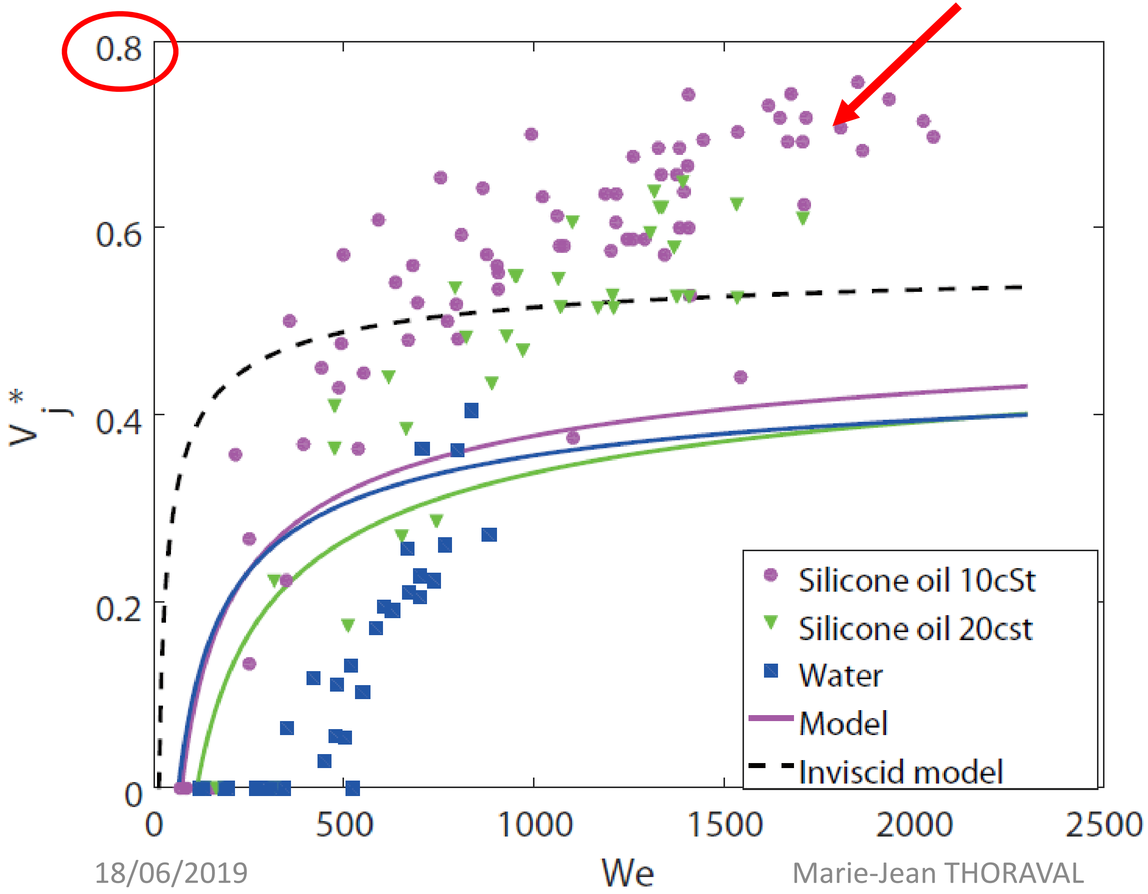




$$V_j^* = \alpha * \sqrt{\kappa^2 - \frac{\beta}{\sqrt{Re}}} - \sqrt{\frac{2}{\gamma * \kappa * We}} \qquad \kappa = D_b^* \sqrt{1 - {D_b^*}^2}$$

α = 1.3, β = 1.7 and γ = 0.5

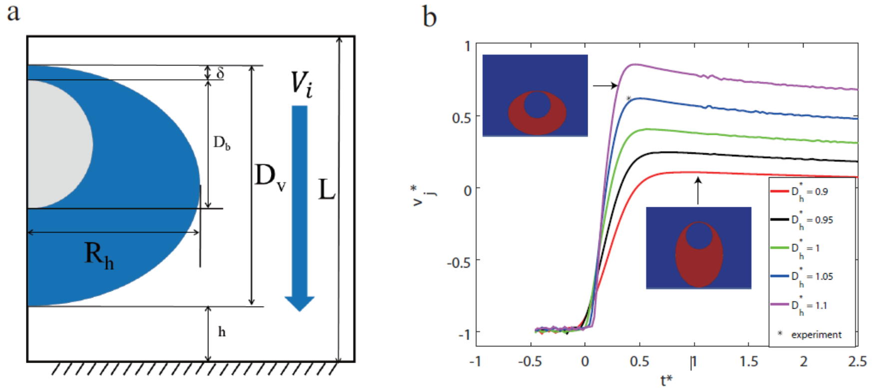
Comparison with experiments

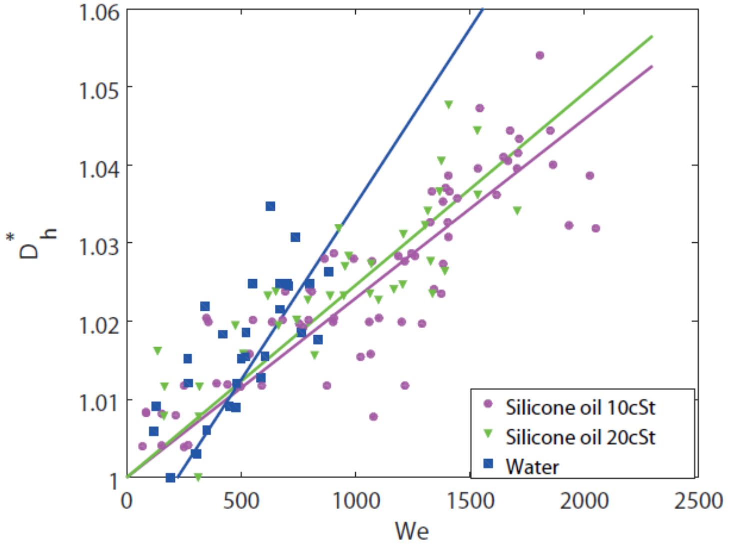


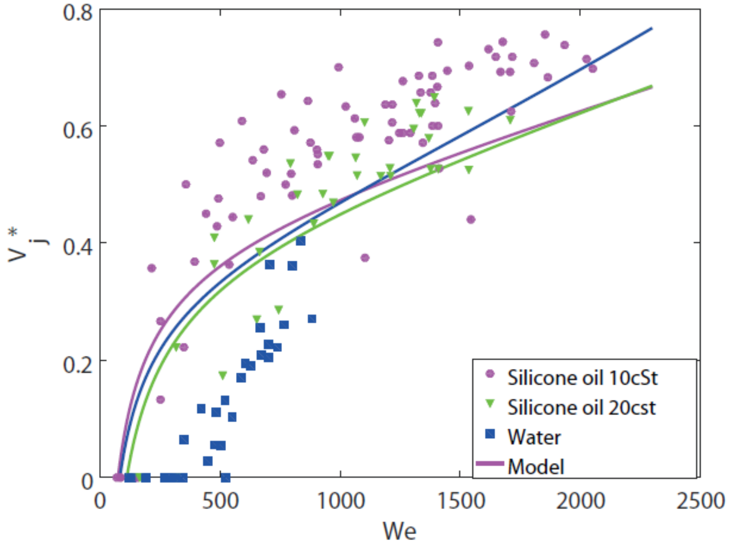
Interpretation:

- Bubble size
- Bubble vertical position
- Compressible effects
- Non-axisymmetry
- Bubble and drop shape
- …?

Effect of drop shape



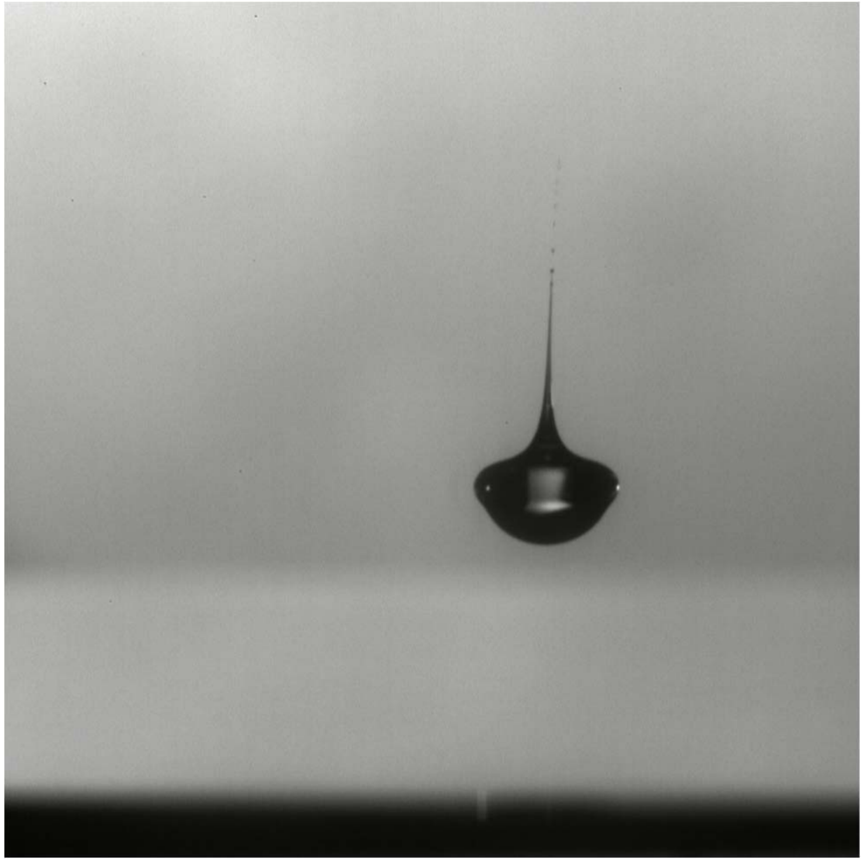




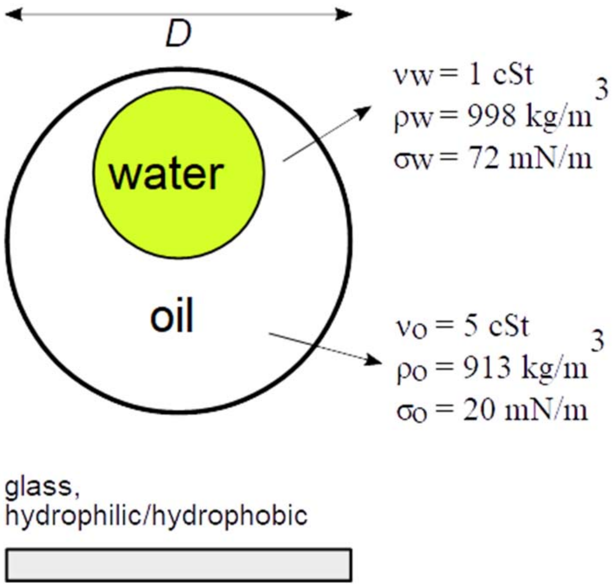
Super-fast jet!

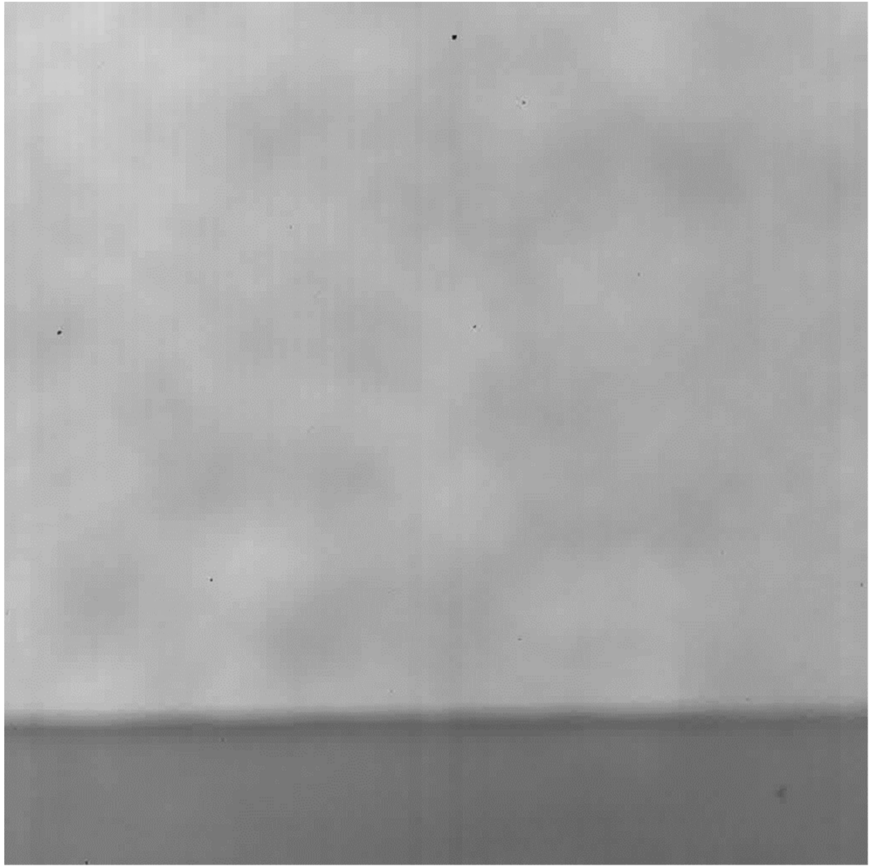
V_j = 4.4!

Bubble bursting in a drop



Impact of a water-in-oil compound drop





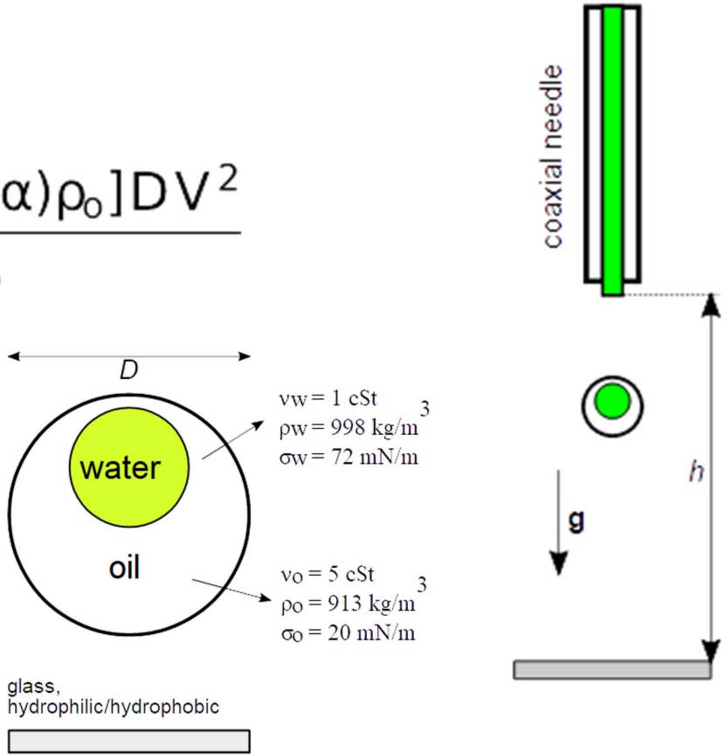
2018 Photron Best Scientific Video Award

Impact of a water in oil compound drop

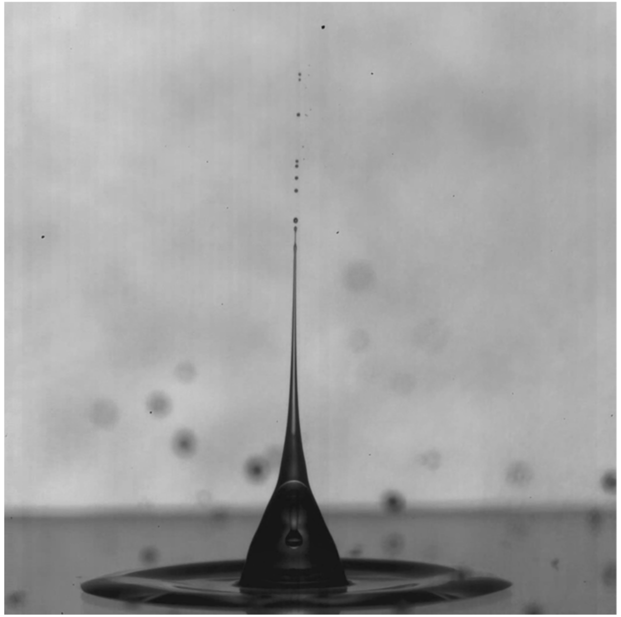
- Volume ratio $$\alpha = \frac{\text{volume water}}{\text{total volume}}$$

- Weber number $$We = \frac{[\alpha\rho_w + (1-\alpha)\rho_o] D V^2}{\sigma_o}$$

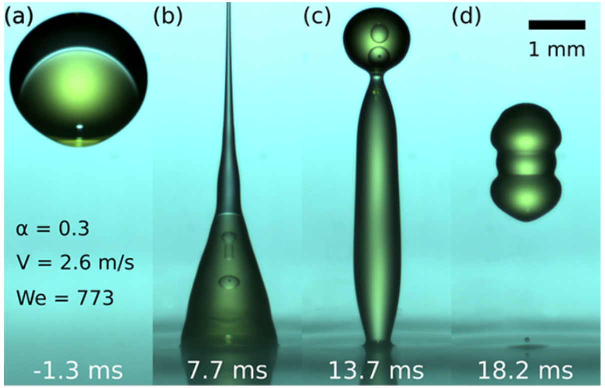
- Variation of impact velocity by varying impact height



Core drop rebound

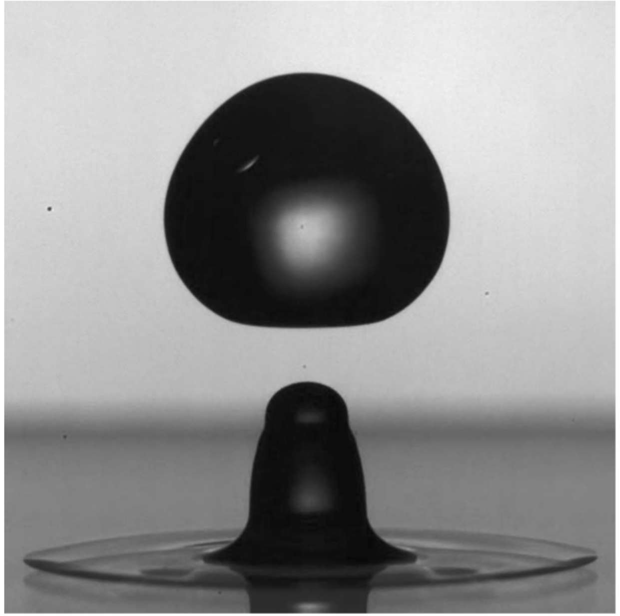


Drop diameter: 2.3 mm
Volume ratio: 0.3
V = 2.4 m/s
We = 631
Capture rate: 20 000 fps
Display rate 30 fps



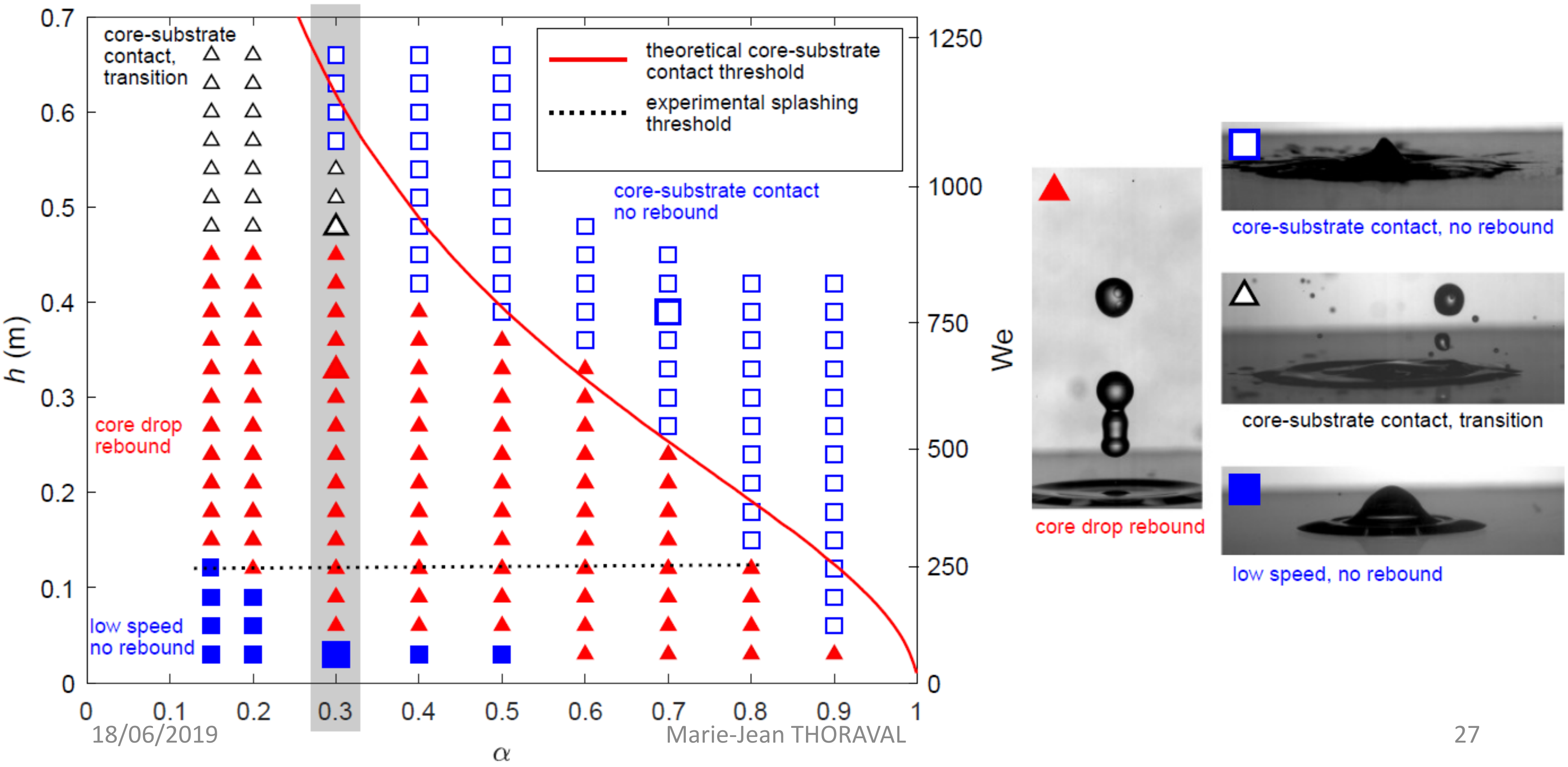
Impact on a hydrophilic surface

Drop diameter: 2.3 mm
Volume ratio: 0.9
V = 0.7 m/s
We = 54
Capture rate: 20 000 fps
Display rate 60 fps

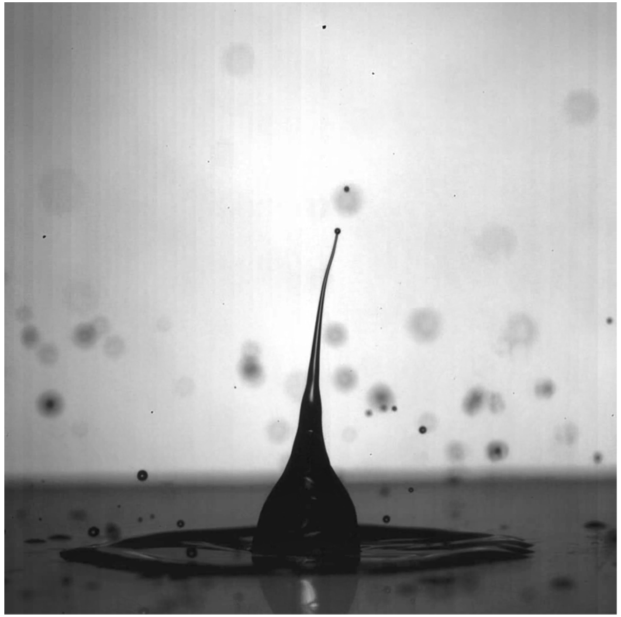


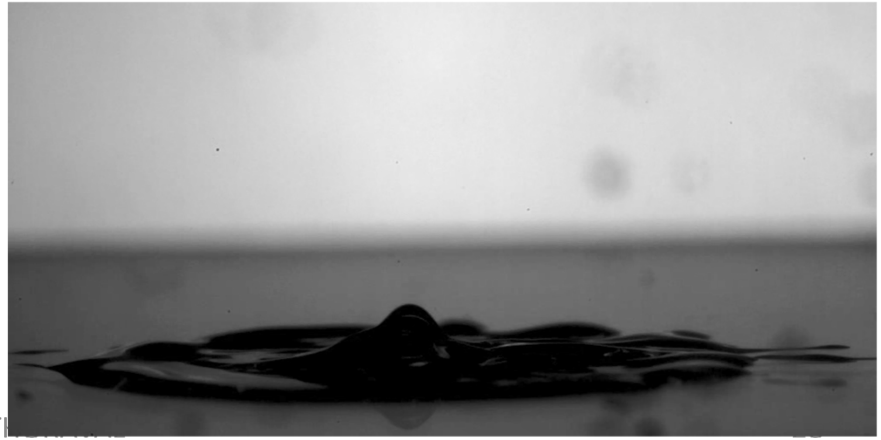
Marie-Jean THORAVAL

Core drop rebound



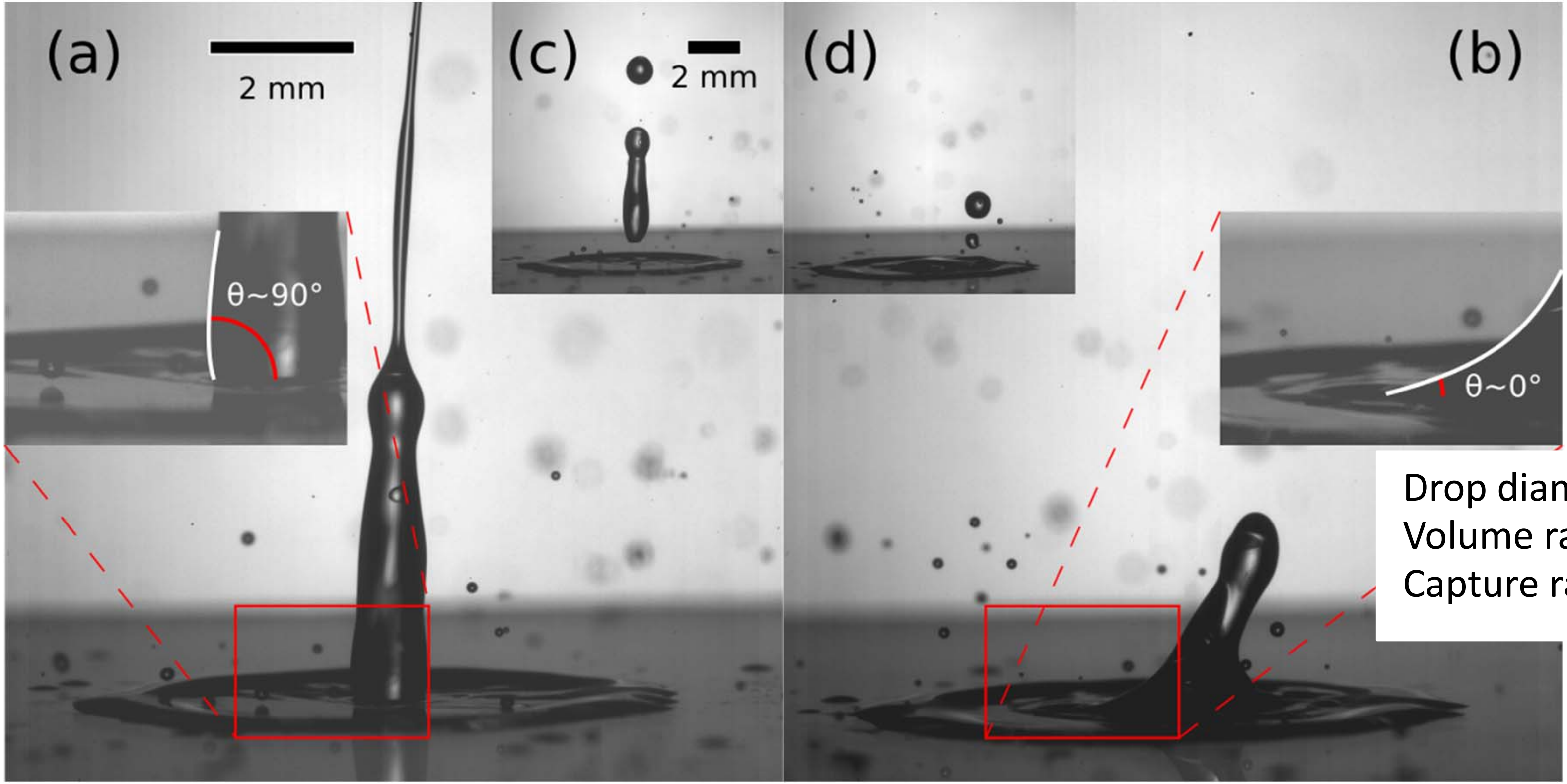
Breakup of the lubricating oil layer?





Drop diameter: 2.3 mm
Volume ratio: 0.3
Capture rate: 20 000 fps
Impact heights (clockwise): 45 cm, 48 cm, 60 cm
Weber number (clockwise): 835, 884, 1080

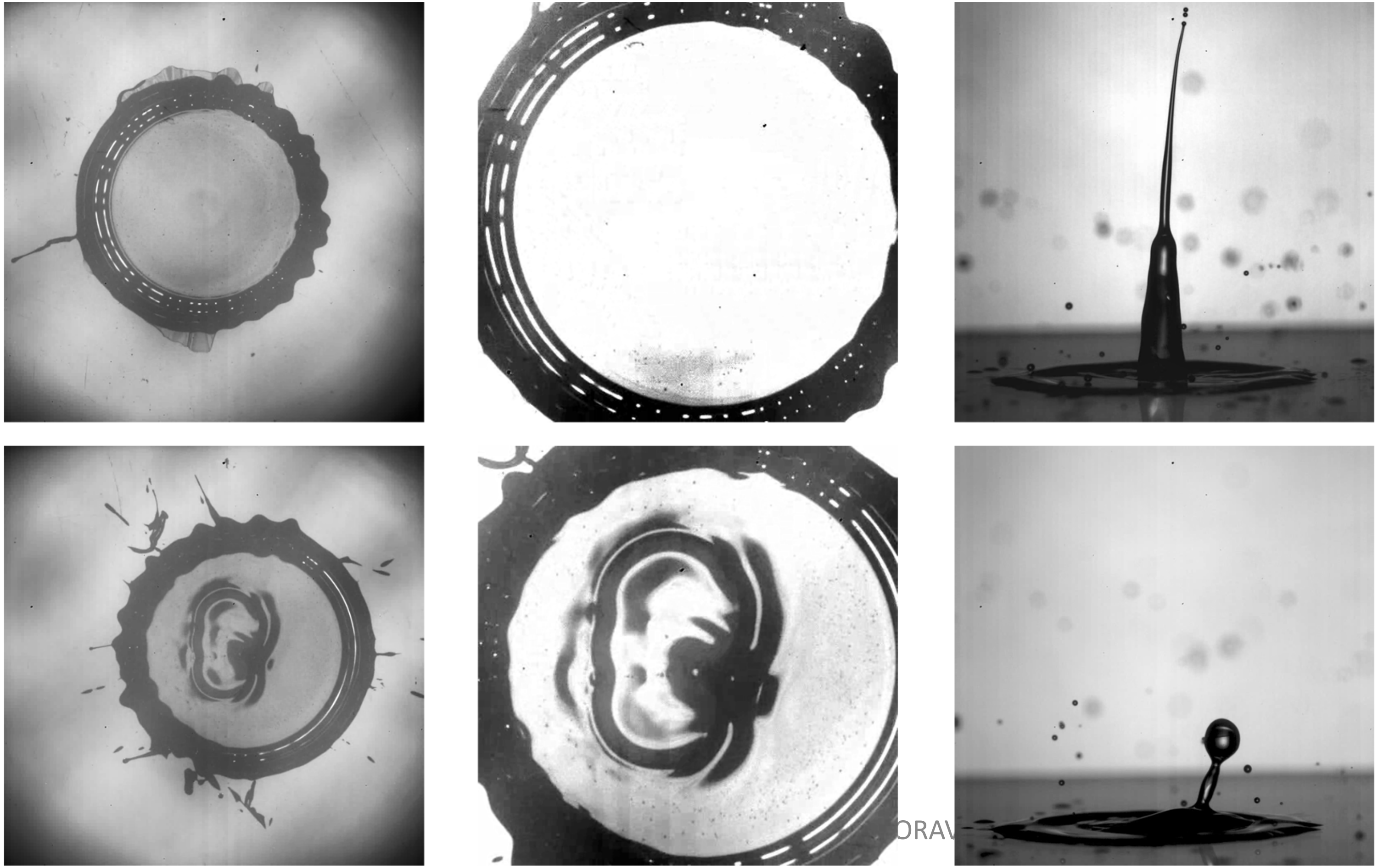
Breakup of the lubricating oil layer?



Drop diameter: 2.3 mm
Volume ratio: 0.3
Capture rate: 20 000 fps

h = 45 cm, We = 835 h = 48 cm, We = 884

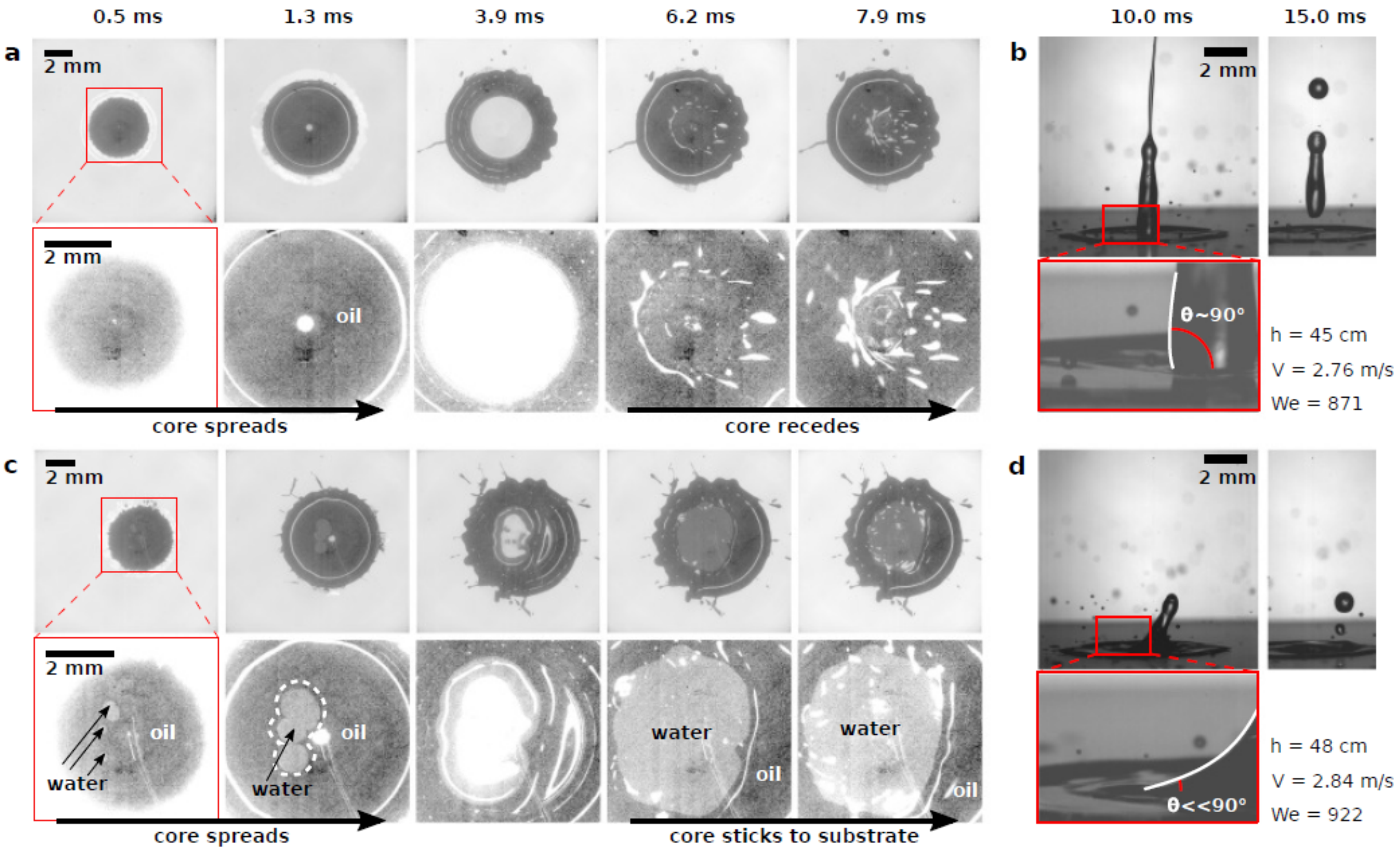
Bottom view



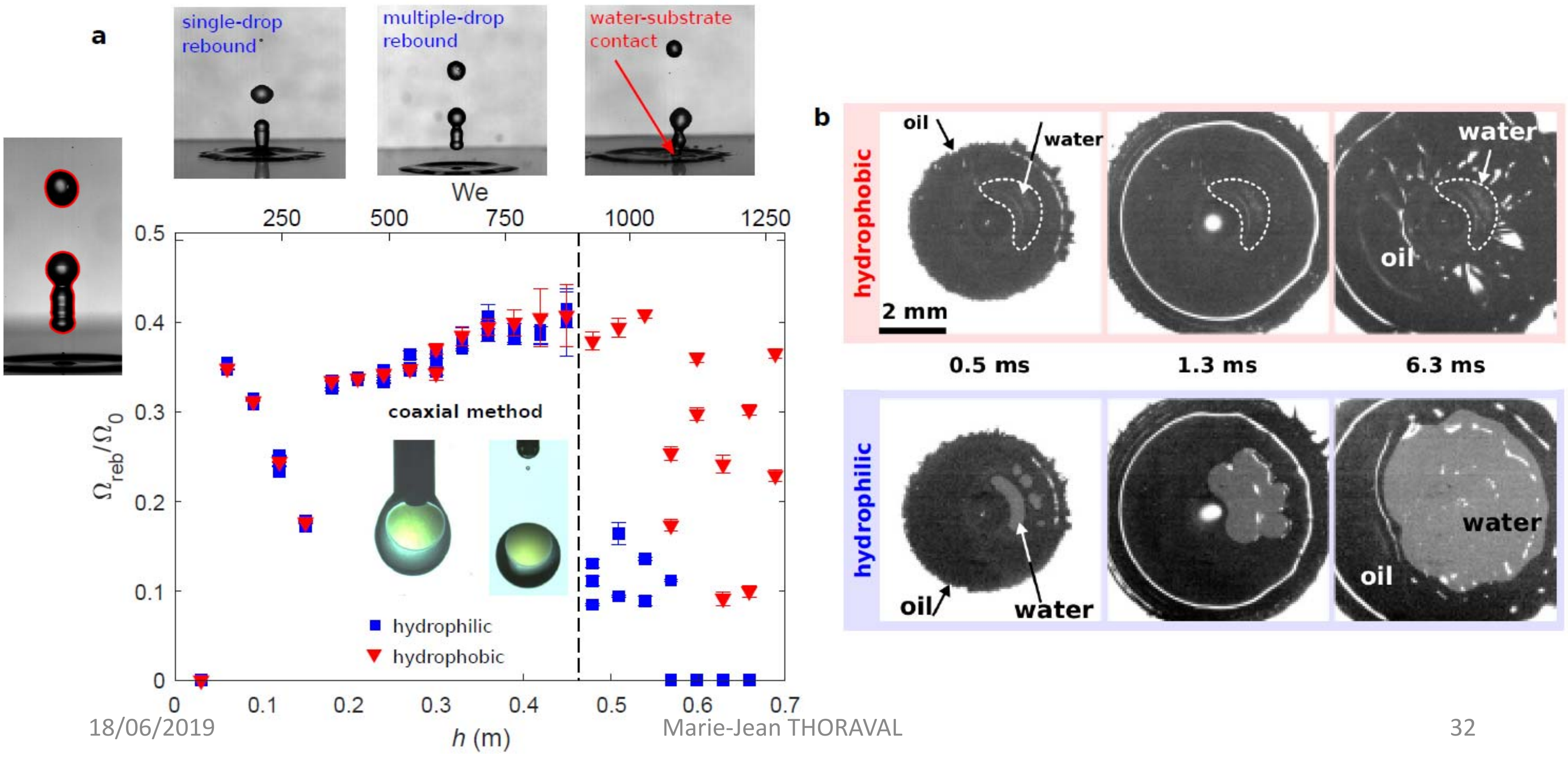
h = 45 cm

h = 48 cm

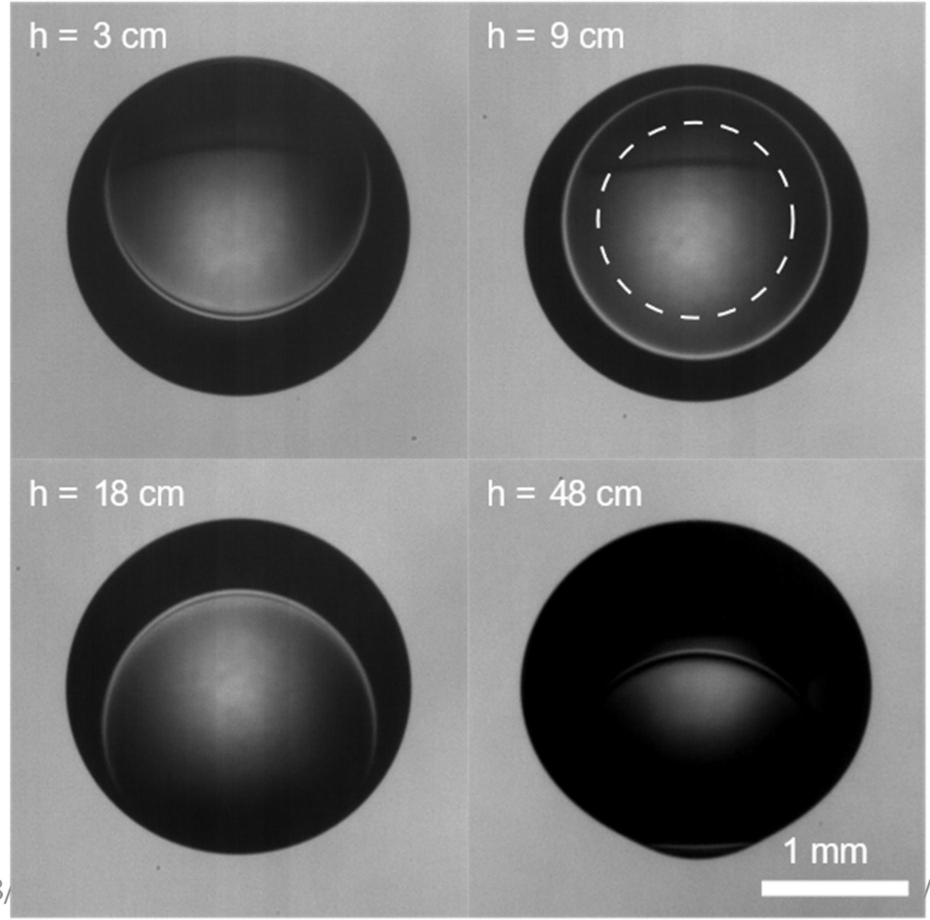
Water core-substrate contact



Effect of wetting properties



Position of the inner drop

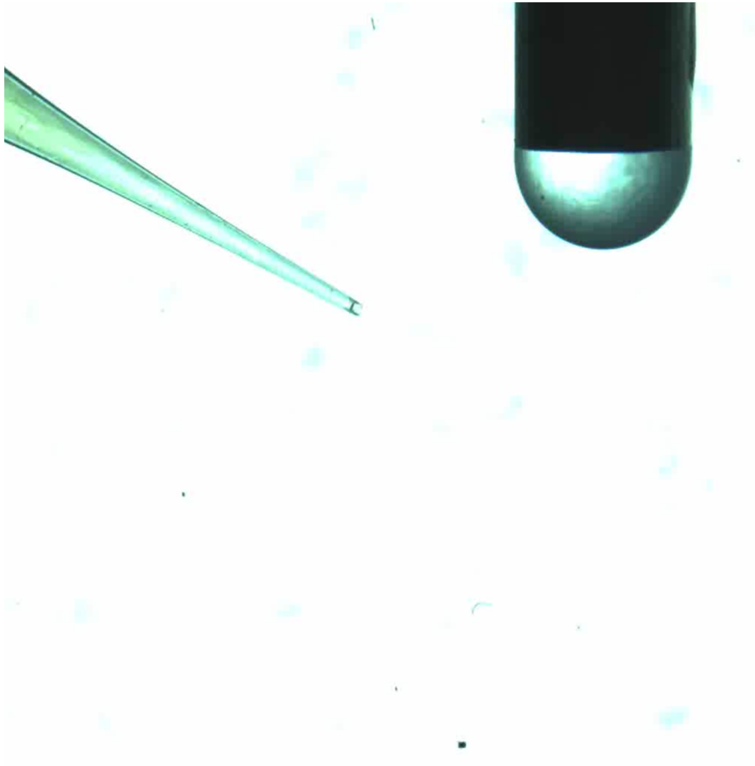


Compound drop falling through air
Drop produced with coaxial needle,
volume ratio = 0.2

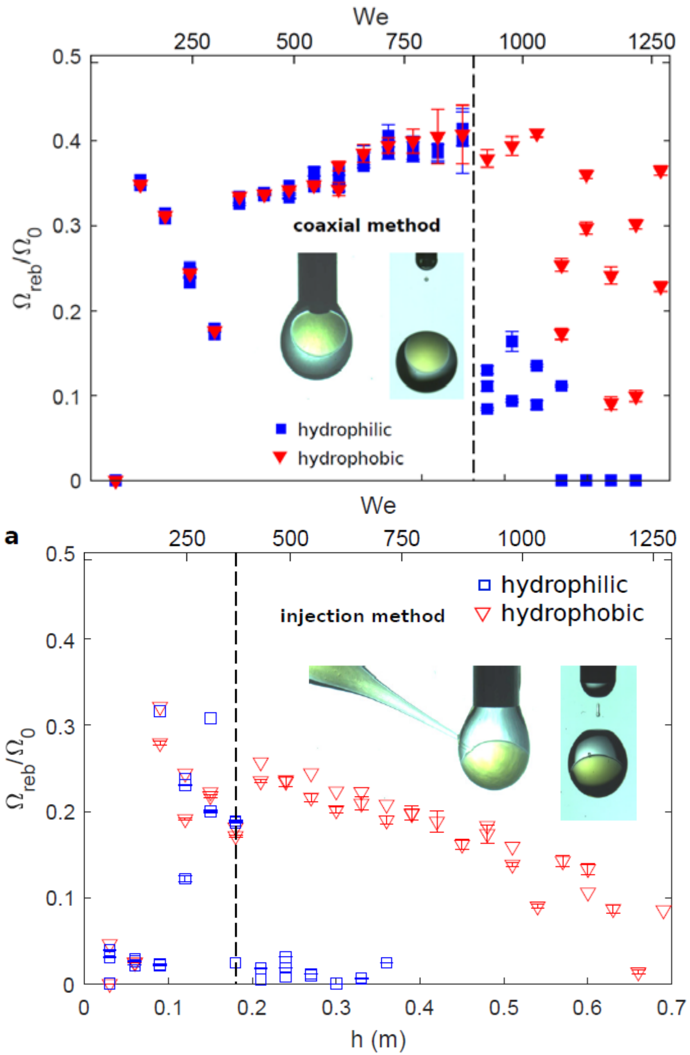
Drop production (position control)

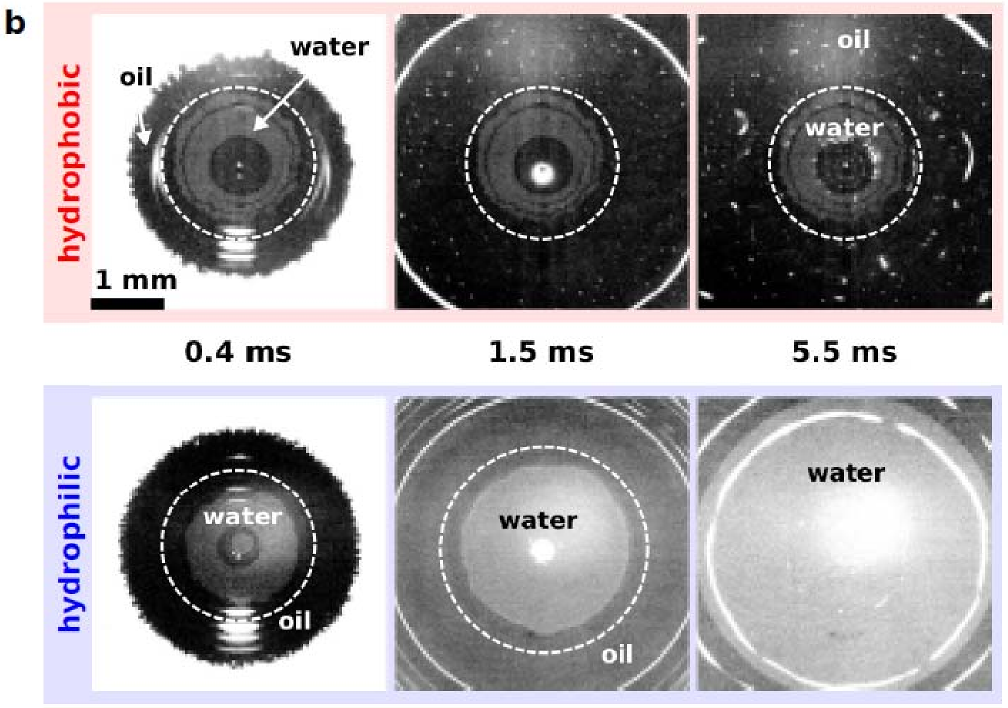
Coaxial needle

Microinjection needle

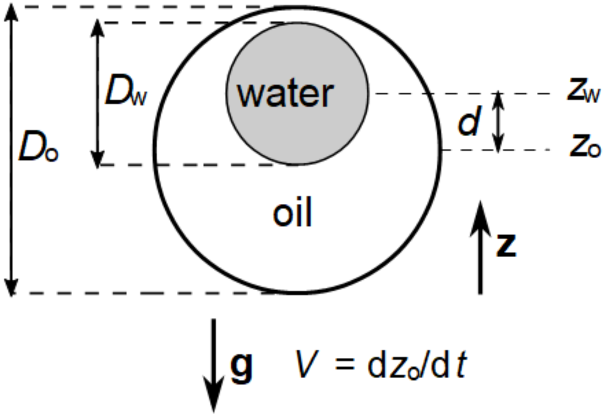


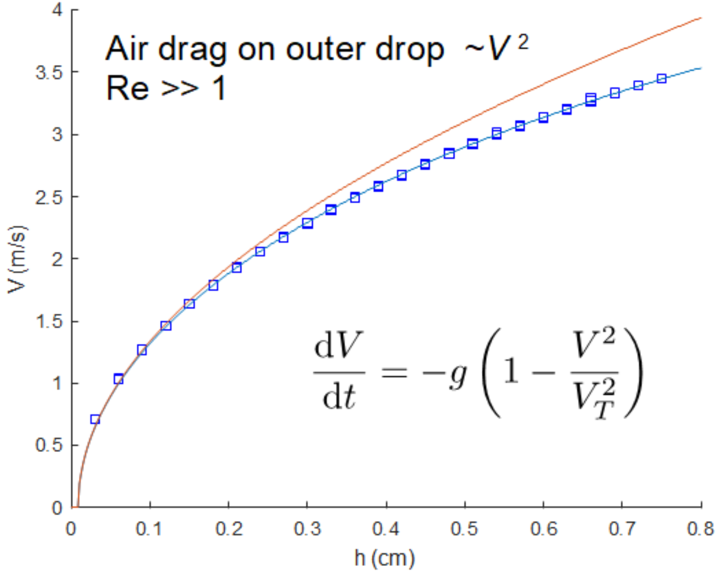
Position of the inner drop





Model for core drop dynamics



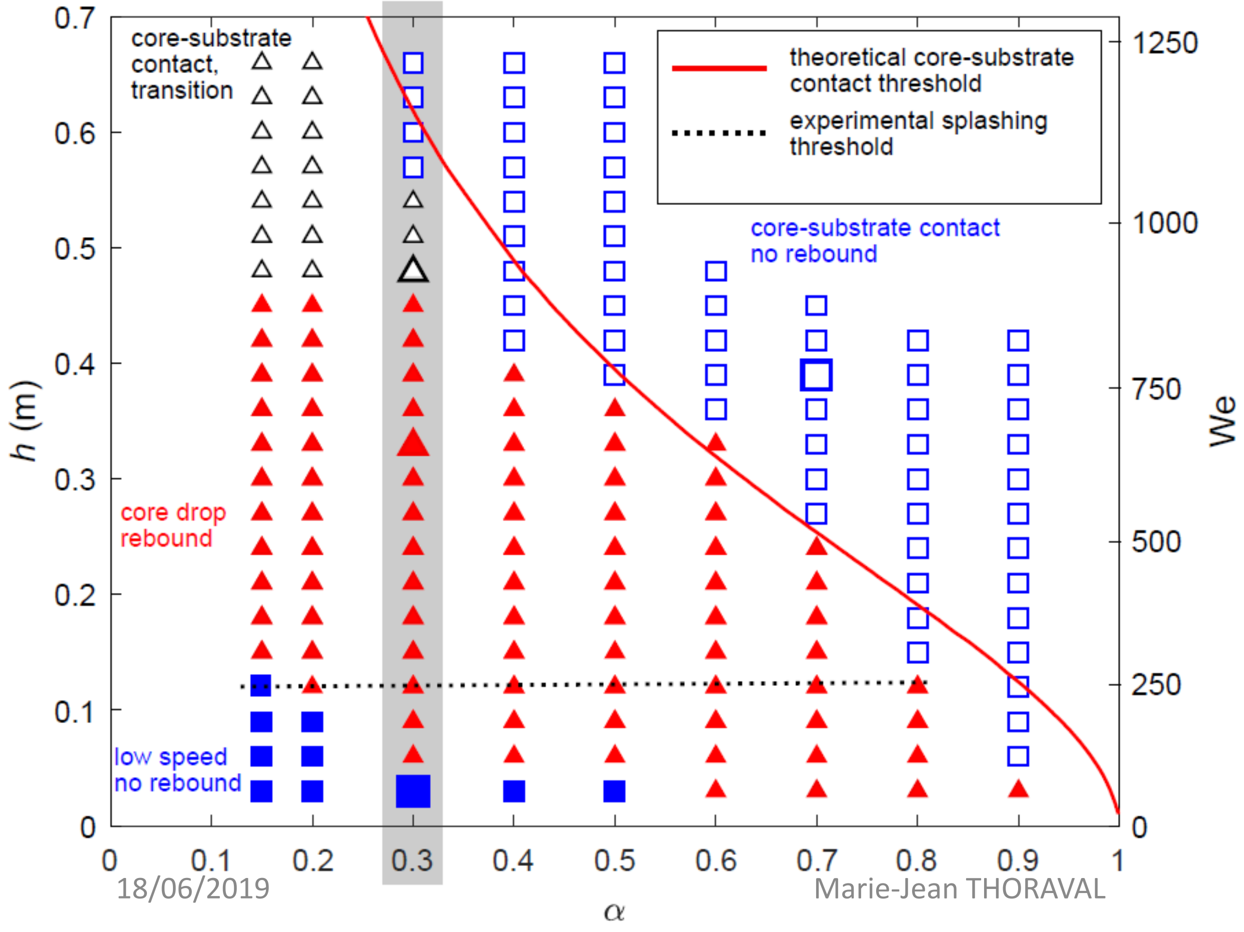


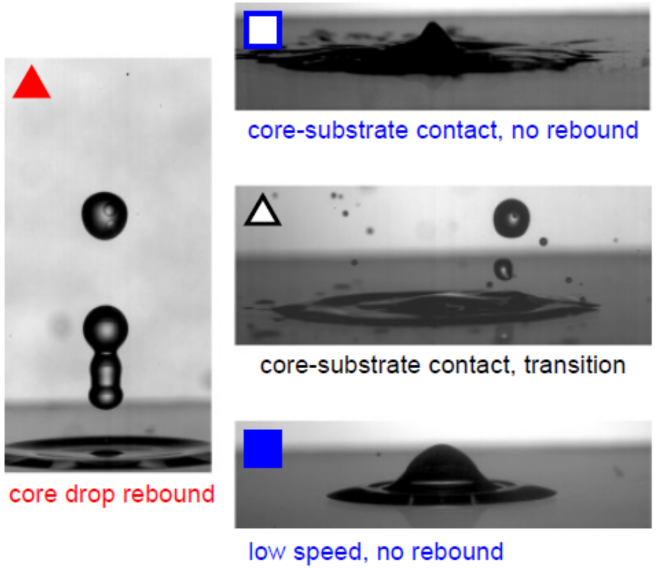
Stokes drag on outer drop $\sim V^2$
Re ~ 1

Compensate for buoyancy

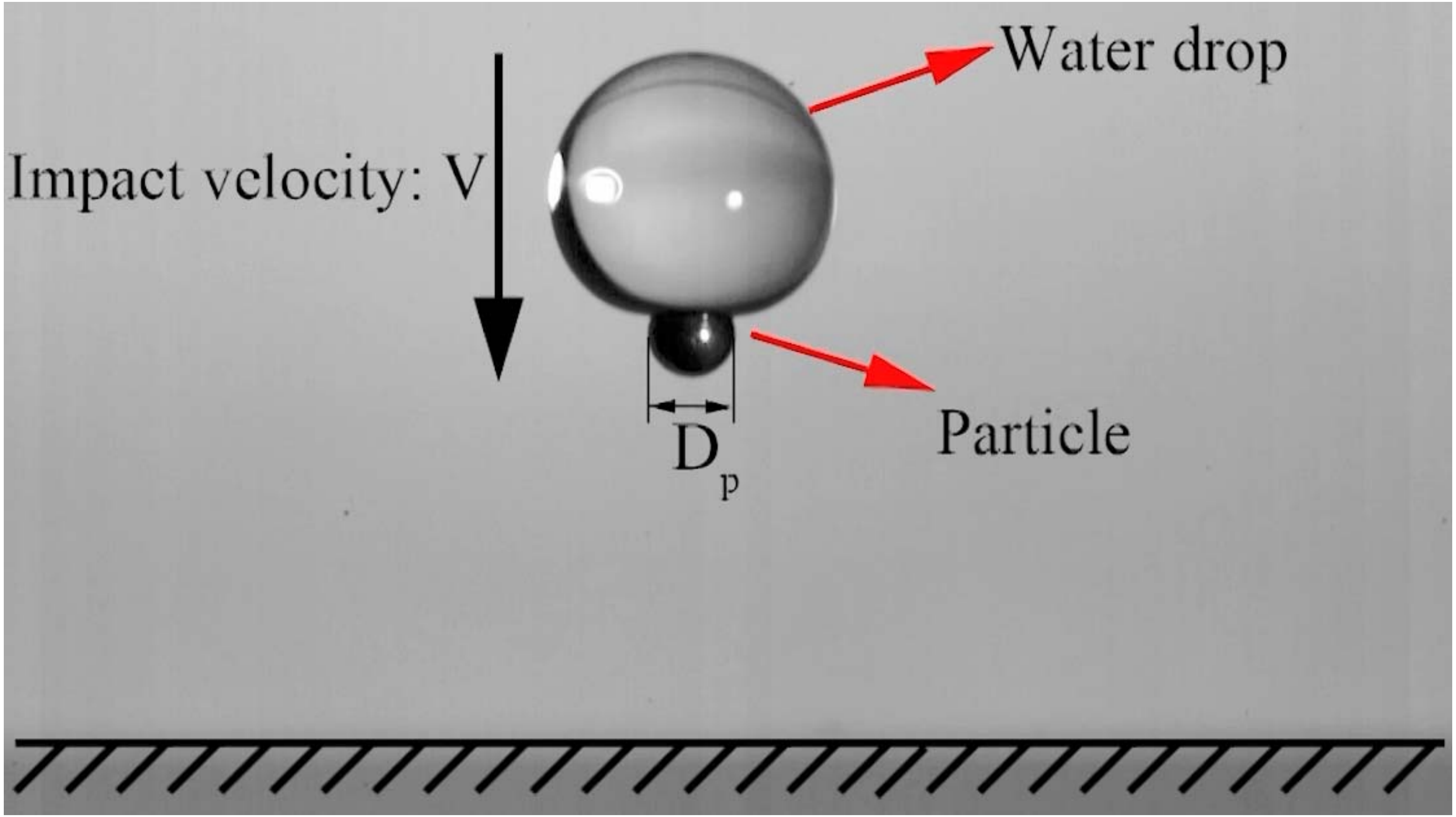
$$\frac{\mathrm{d}^2 d}{\mathrm{d}t^2} = \frac{\mathrm{d}V_{\mathrm{rel}}}{\mathrm{d}t} = -\frac{\rho_w - \rho_o}{\rho_w}\left(g + \frac{\mathrm{d}V}{\mathrm{d}t}\right) - \frac{3\pi D_w \mu_o}{\rho_w \Omega_w} V_{\mathrm{rel}}$$

Core drop rebound



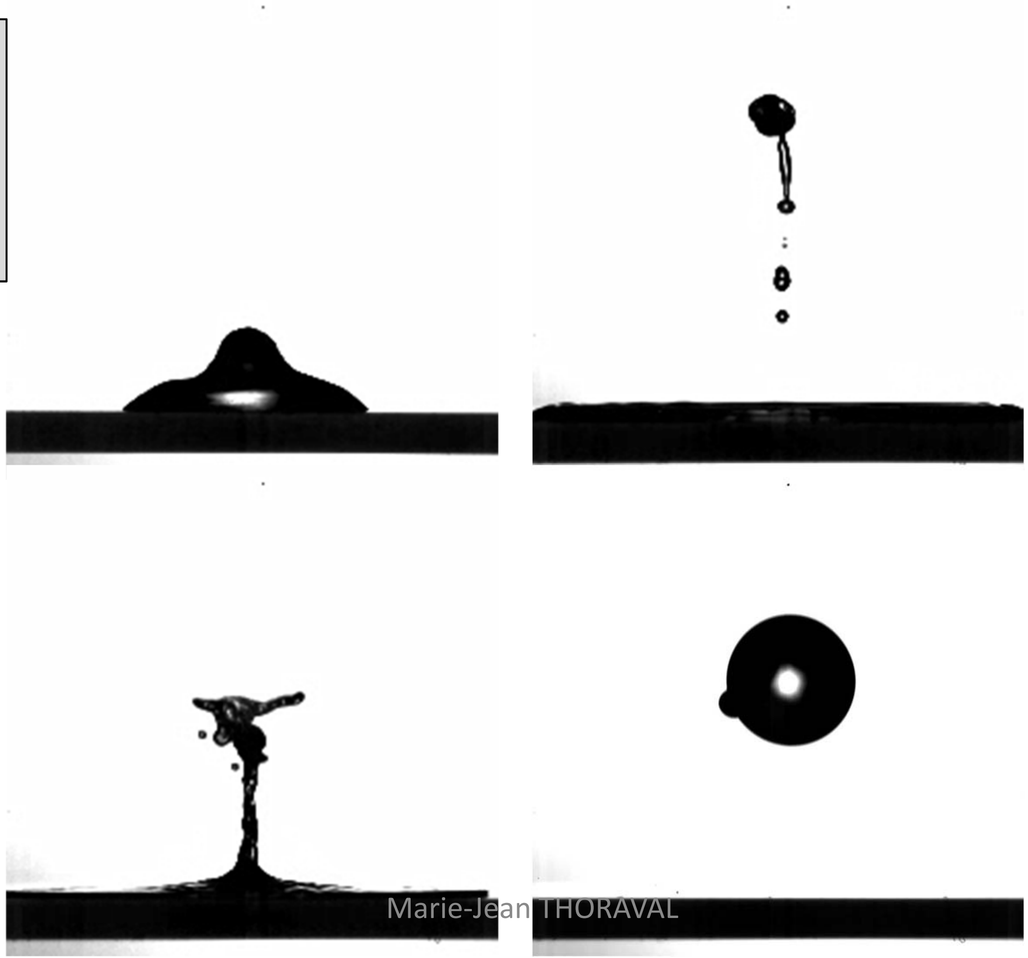


Impact of a drop containing a particle



1 particle in the drop!

Drop: water
D = 3.35 mm
$D_p = 0.8\,mm$
$\rho_p = 7800\,kg/m^3$



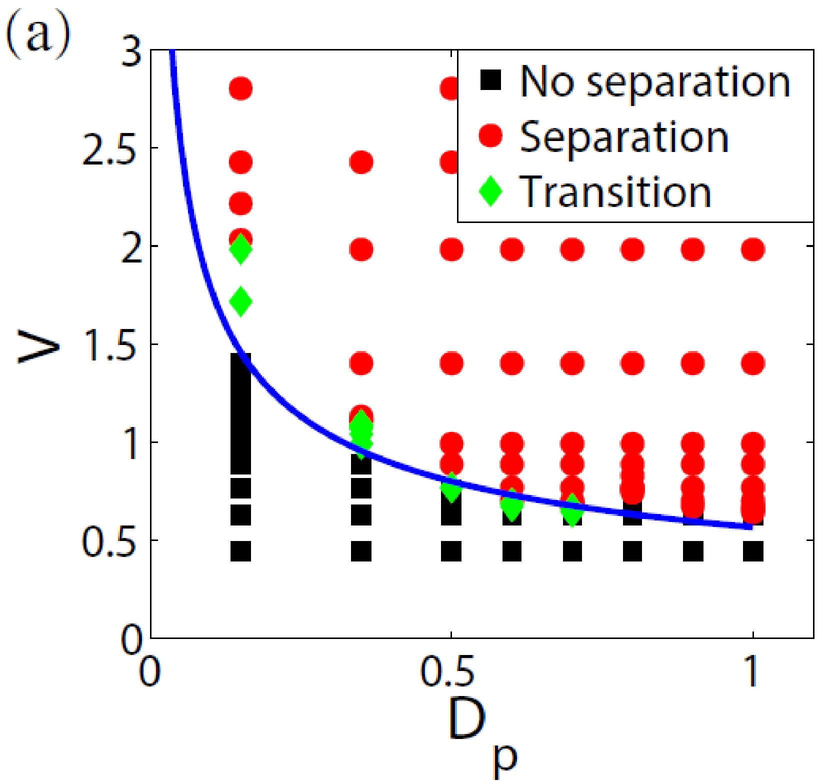
H = 2 cm
No separation

H = 20 cm
Particle splashing

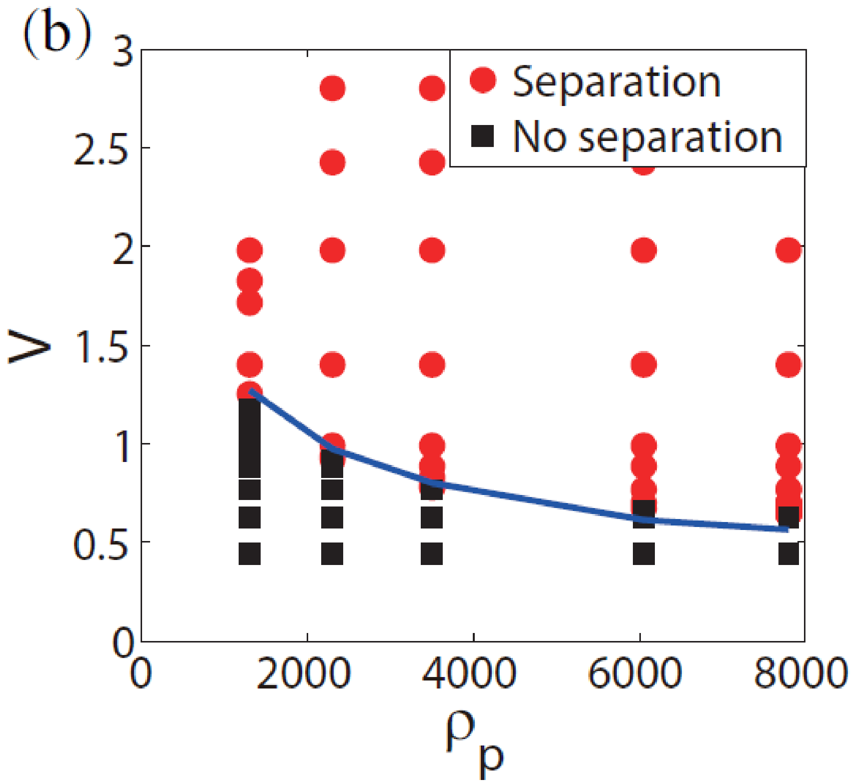
H = 40 cm
Mushroom jet

H = 50 cm
Particle shifting

Critical separation velocity



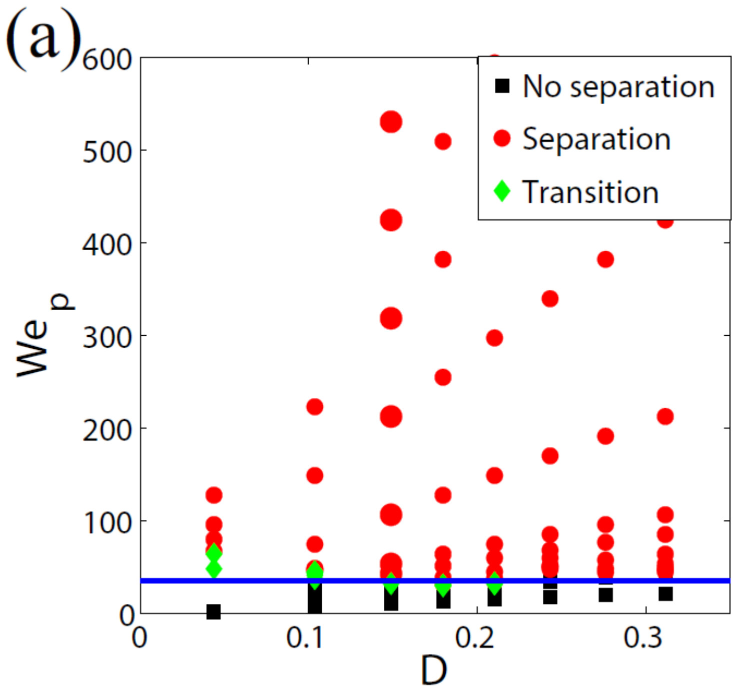
$\rho_p = 7800\ kg/m^3$



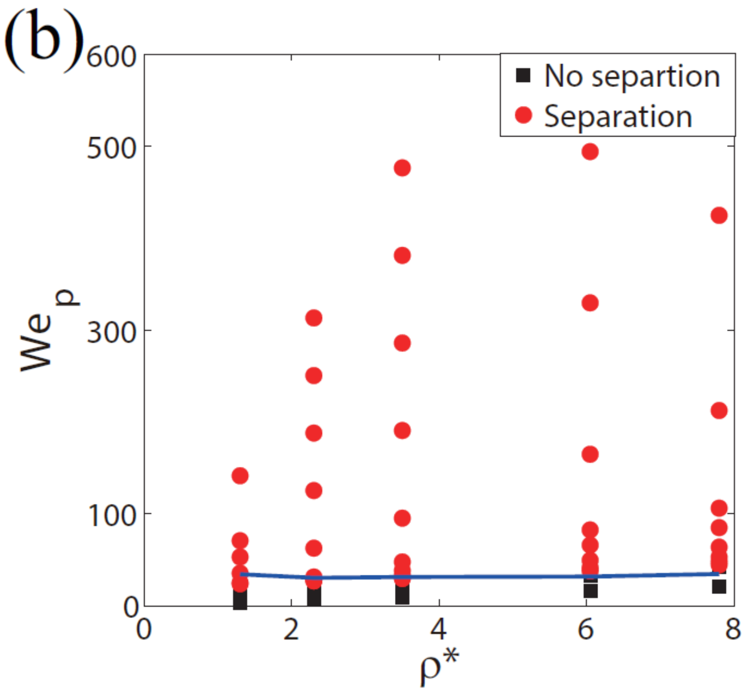
$D_p = 1\ mm$

Critical separation velocity

$$We_c = \frac{\rho_p D_p {V_c}^2}{\sigma} = 34.5$$

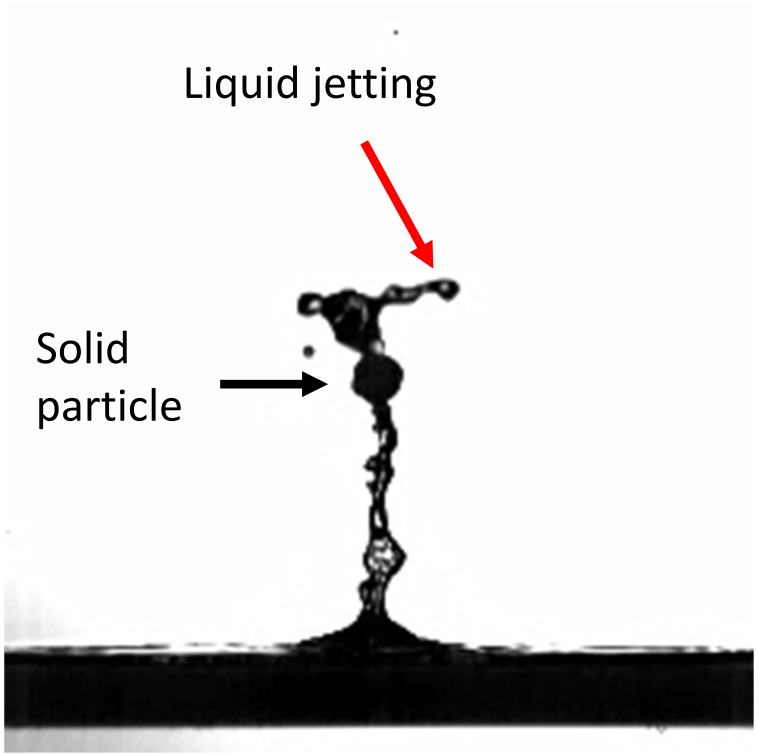


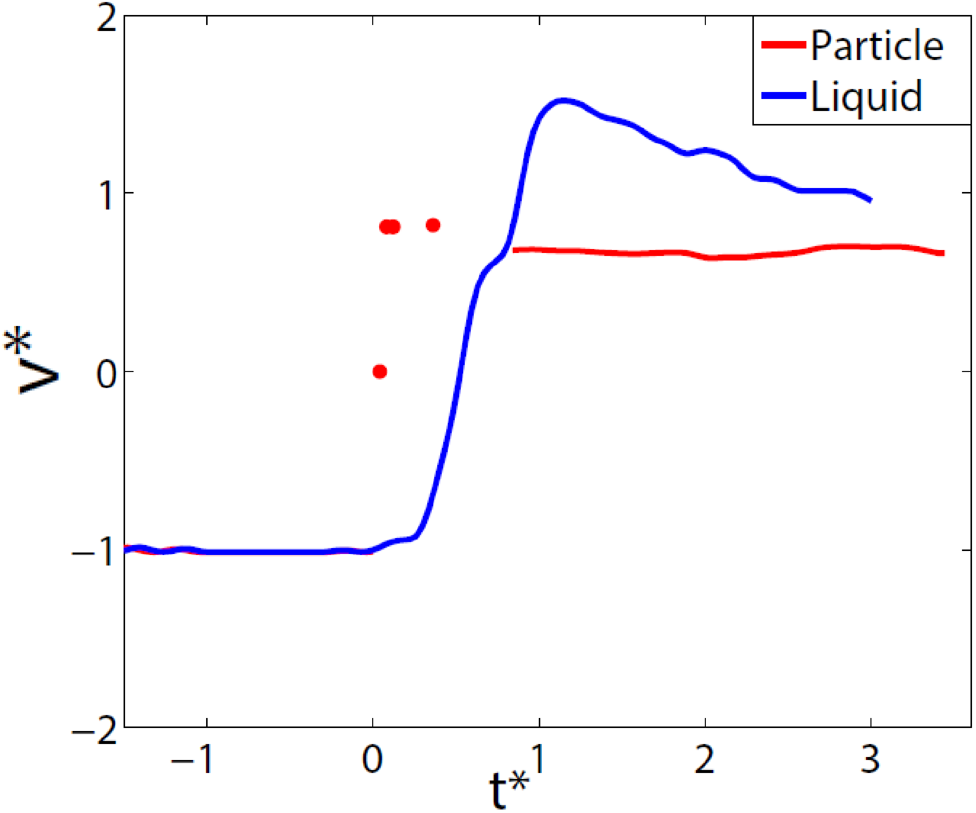
$\rho_p = 7800\ kg/m^3$



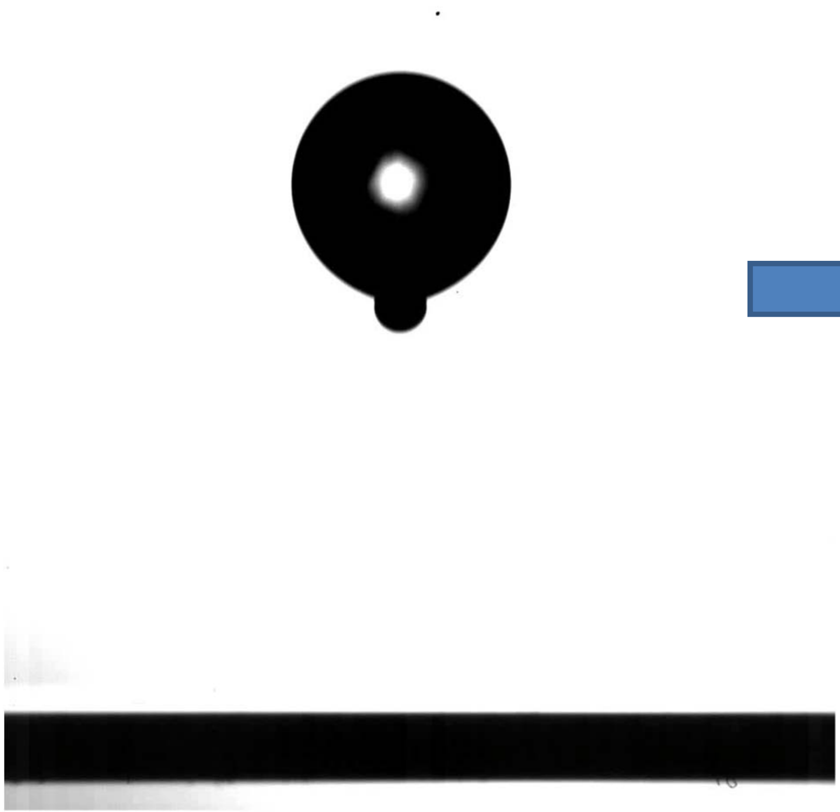
$D_p = 1\ mm$

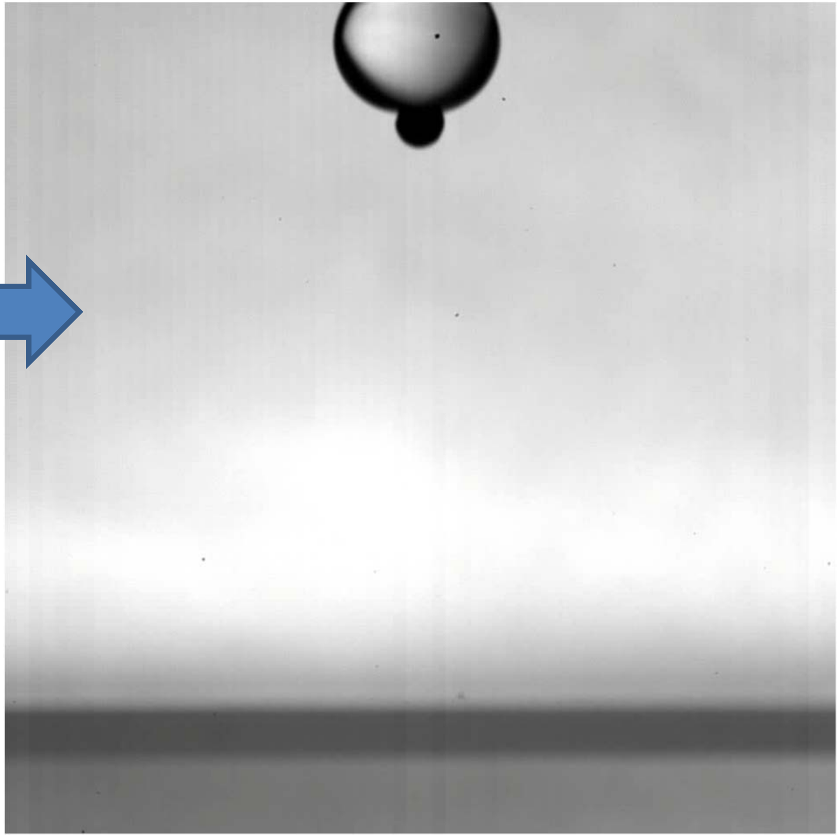
Splashing velocity



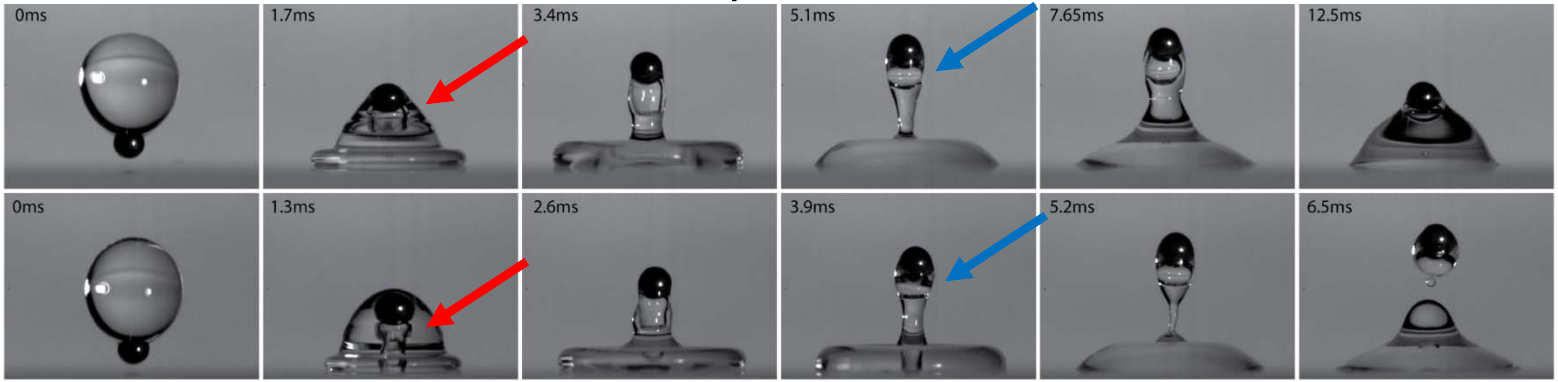


Splashing velocity





Particle separation threshold



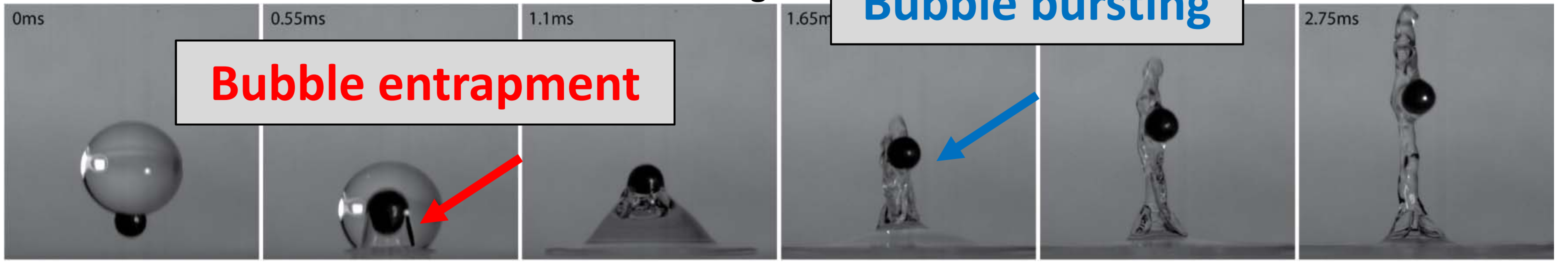
$V_p < 0.77\ m/s$

$V_p \geq 0.79\ m/s$

Jetting afte

Bubble bursting

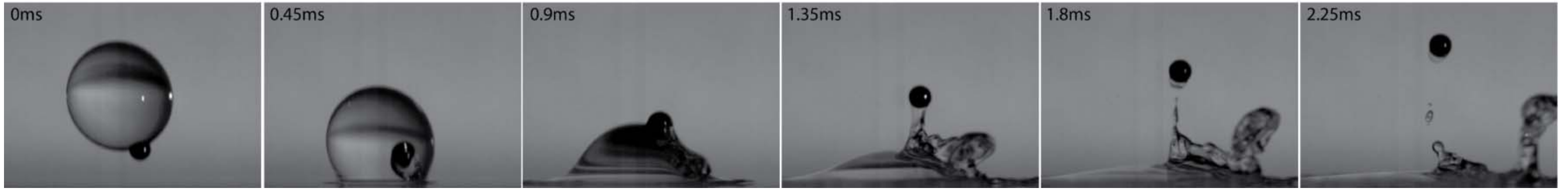
Bubble entrapment



$V_p = 2.43\ m/s$

Drop size: $D_d = 3.20\ mm$ Particle size: $D_p = 1\ mm$
Velocity of particle: V_p Particle density: ρ_p=7.8

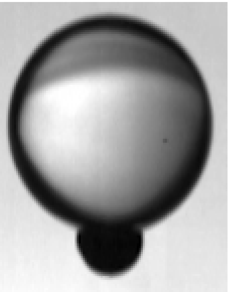
Sideway shifting of the particle due to air drag



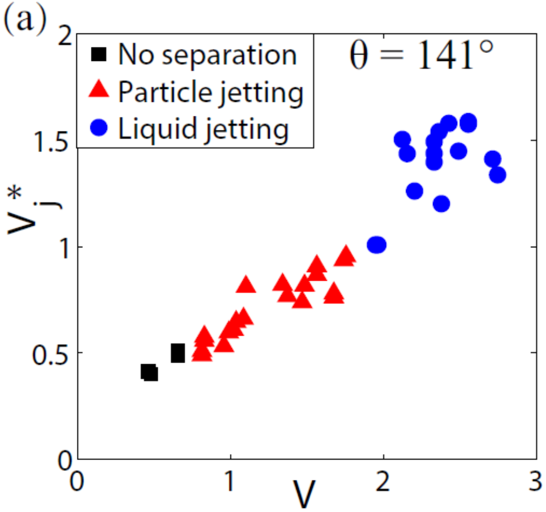
$V_p = 2.50\ m/s$

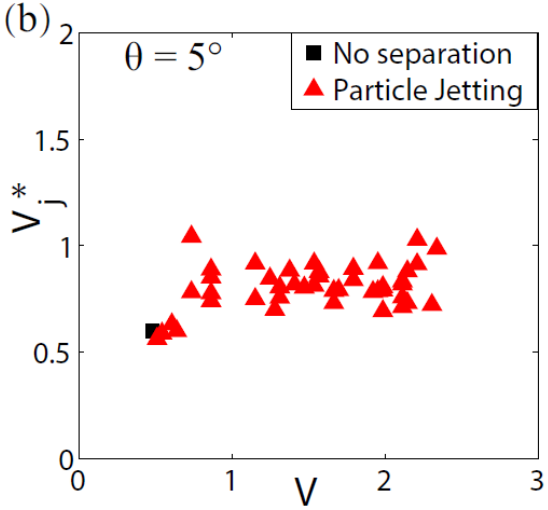
Drop size: $D_d = 3.28\ mm$ Particle size: $D_p = 0.7\ mm$
Velocity of particle: V_p Particle density: ρ_p=7.8

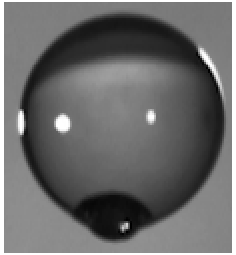
Effect of particle wetting



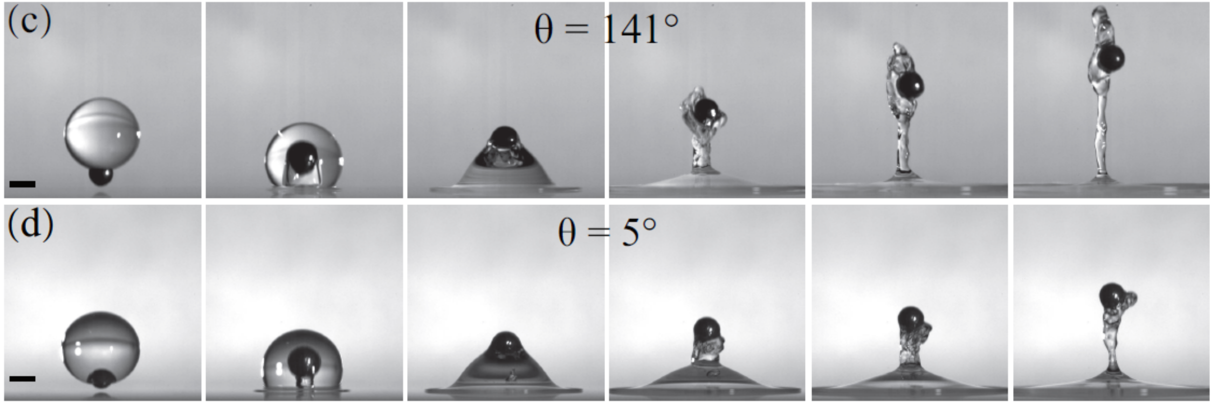
Hydrophobic
θ = 141 °



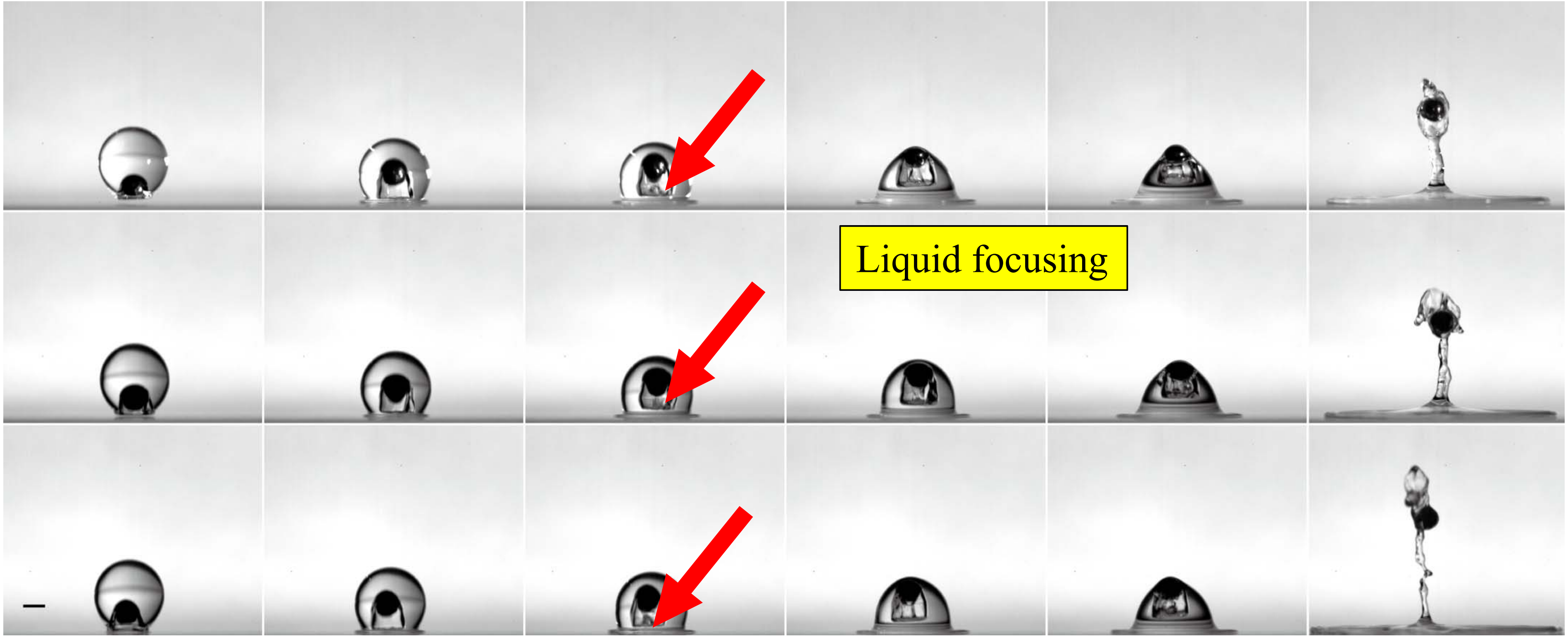




Hydrophilic
θ = 5 °

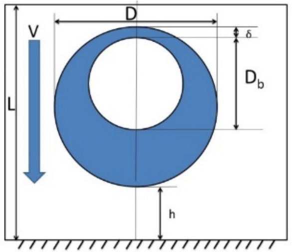


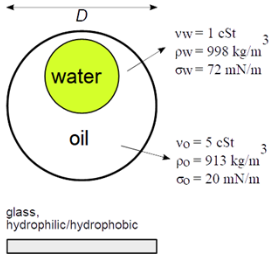
Liquid focusing

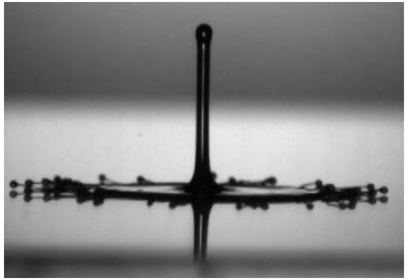


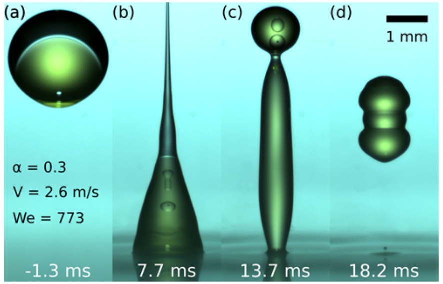
Metal particle $D_P = 1\text{ mm}$ $\rho_p = 7800\text{ kg/m}^3$

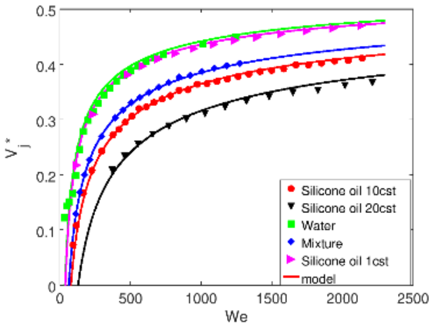
Impact of compound drops

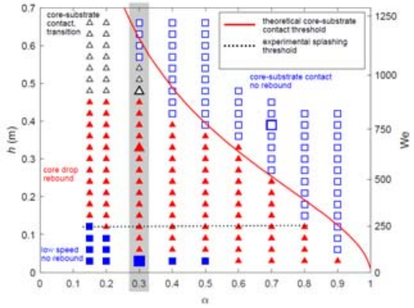


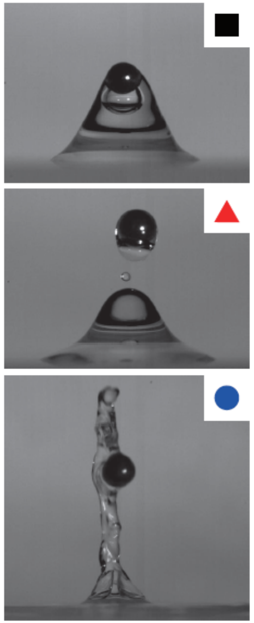


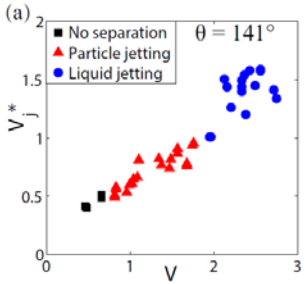


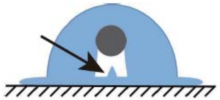


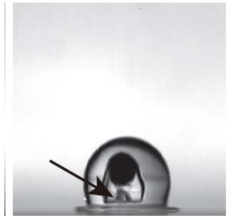












Acknowledgements

- Weiwei ZHAO (赵唯伟), Yu WEI (魏瑀), Nathan Blanken, Muhammad Saeed SALEEM: Xi’an Jiaotong University, **China**
- Carlo Antonini: Empa, Dübendorf, **Switzerland** / University of Milano-Bicocca, Milan, **Italy**
- Shiji LIN (林世玑), Longquan CHEN (陈龙泉): University of Electronic Science and Technology of **China**
- Detlef Lohse, Jacco Snoeijer, Frits Dijksman, Guillaume Lajoinie, Stefan Karpitschka, François Boyer, Enrique Sandoval Nava, …: University of Twente, **The Netherlands**
- Chao SUN (孙超): University of Twente, **The Netherlands** / Tsinghua University, **China**
- Bart Vroling and Stef van der Woerdt: University of Twente, **The Netherlands**
- Munish Chanana, Jonas Schubert : University of Bayreuth, **Germany,**
- Erqiang LI (李二强), Sigurdur T. Thoroddsen: NUS, **Singapore** / KAUST, **Saudi Arabia**
- Stéphane Popinet: http://basilisk.fr

Funding:

- NSFC Grant Nos. 11542016, 11702210 and 11850410439
- 111 project B1804
- State Key Laboratory for Strength and Vibration of Mechanical Structures of XJTU