Impact of a drop containing a bubble

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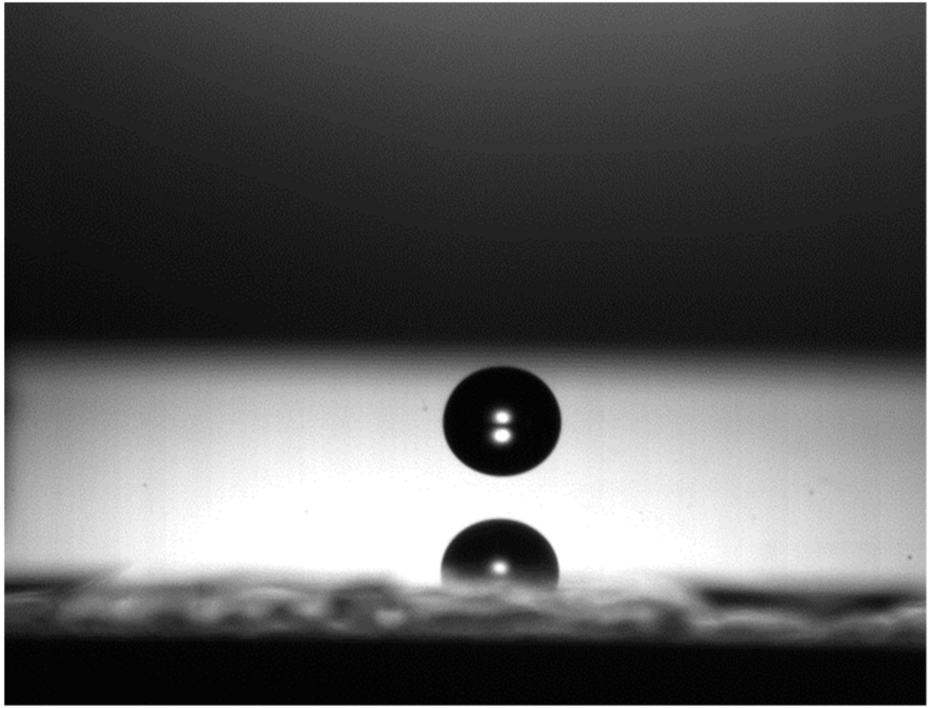
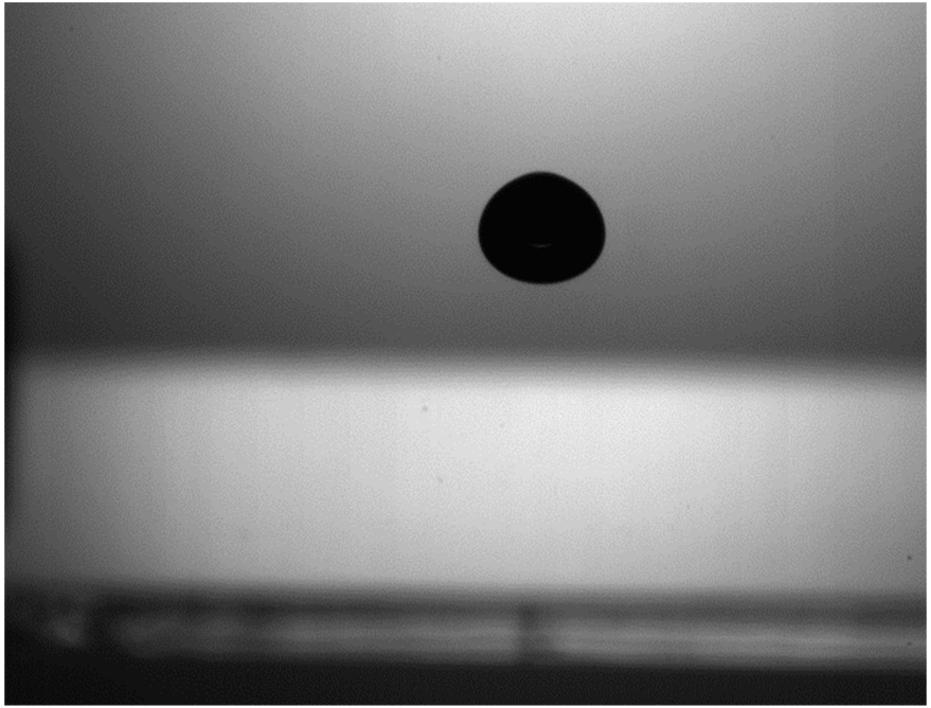
Xi'an Jiaotong University – 西安交通大学

Vertical splashing

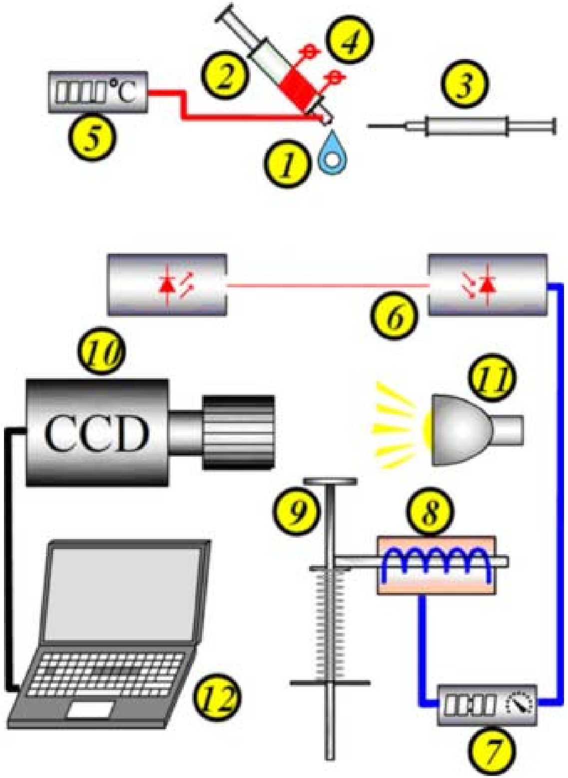


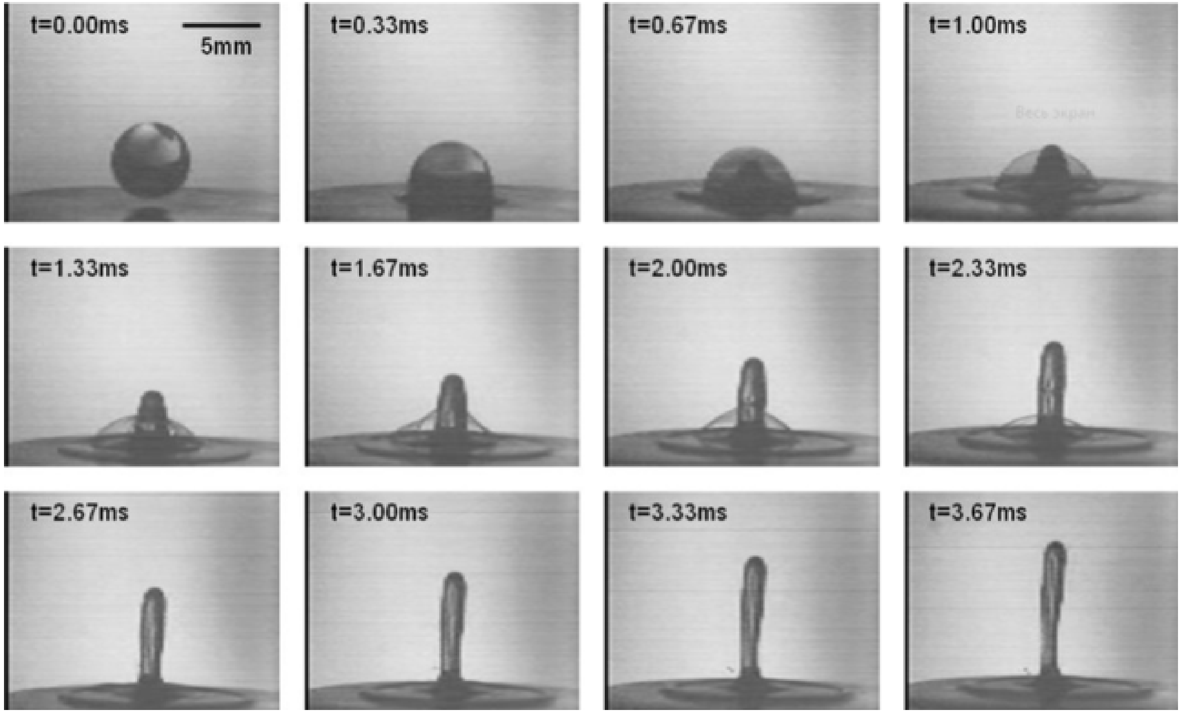
Silicone Oil 10 cSt
45 cm



Silicone Oil 10 cSt
150 cm

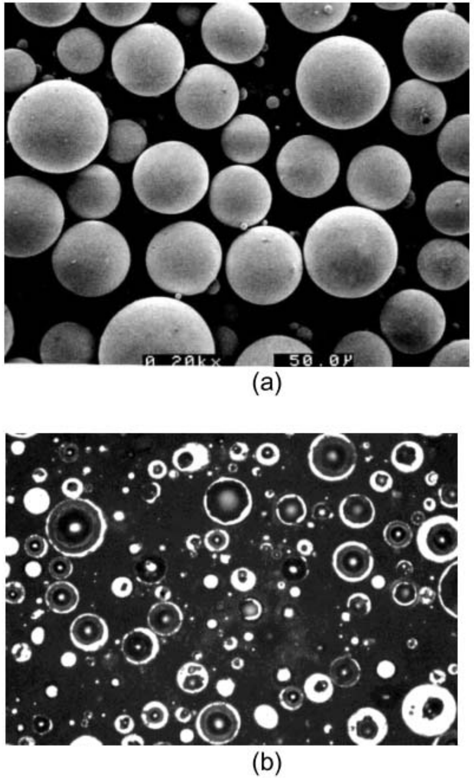
Previous observations





Gulyaev, I. P., & Solonenko, O. P. (2013). Hollow droplets impacting onto a solid surface. *Experiments in Fluids*, *54*, 1432.

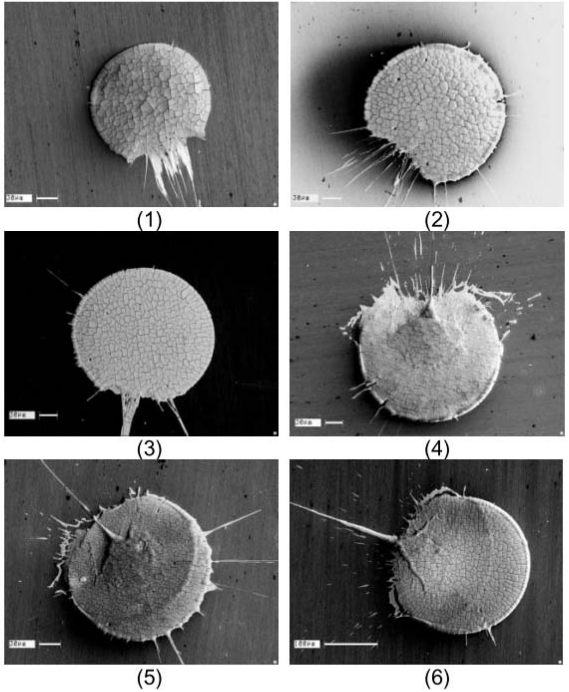
Thermal Barrier Coatings



(a)

(b)

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.



(1) (2) (3) (4) (5) (6)

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.

Previous observations

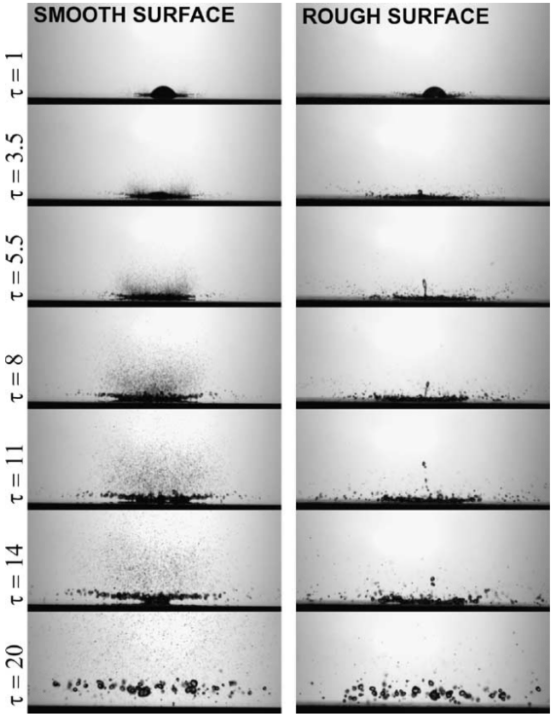


Fig. 6. Time evolution of water drop impact onto smooth (S) and rough (R) surfaces at 260 °C; pure water: $Ca = 0.0431$, $La = 133{,}000$, $We = 247$.

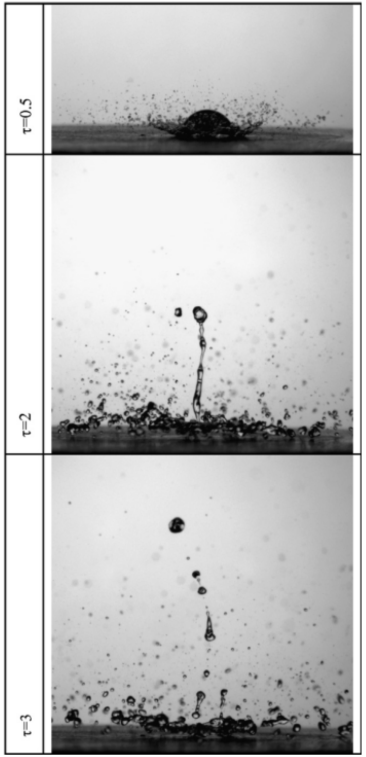


Fig. 4. Impact of a drop under *film boiling* regime ($T_w = 260$ °C, $R_z = 14.5$ μm, $We = 285$, $Ca = 0.046$).

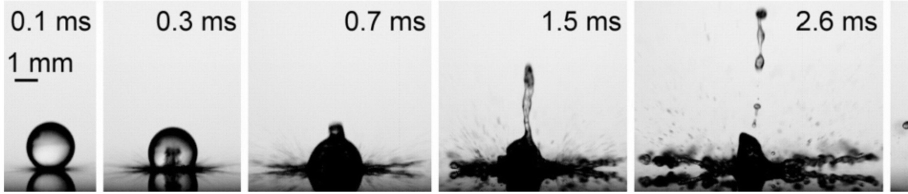
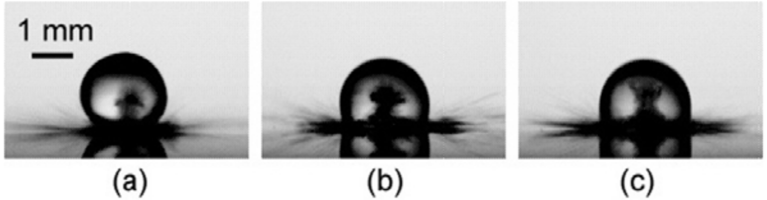


Fig. 7. Central jet of the 5.21% NaCl solution drop with $T_w = 384$ °C and $We = 41$.



(a) (b) (c)

Fig. 8. Initial stage after the 5.21% NaCl solution drop impact with $T_w = 384$ °C, (a) $We = 2$, (b) $We = 22$ and (c) $We = 130$.

Liang, G., Shen, S., Guo, Y., & Zhang, J. (2016). Boiling from liquid drops impact on a heated wall. *International Journal of Heat and Mass Transfer*, *100*, 48–57.

Cossali, G. E., Marengo, M., & Santini, M. (2005). Secondary atomisation produced by single drop vertical impacts onto heated surfaces. *Experimental Thermal and Fluid Science*, *29*(8), 937–946.

Cossali, G. E., Marengo, M., & Santini, M. (2008). Thermally induced secondary drop atomisation by single drop impact onto heated surfaces. *International Journal of Heat and Fluid Flow*, *29*(1), 167–177.

Previous observations

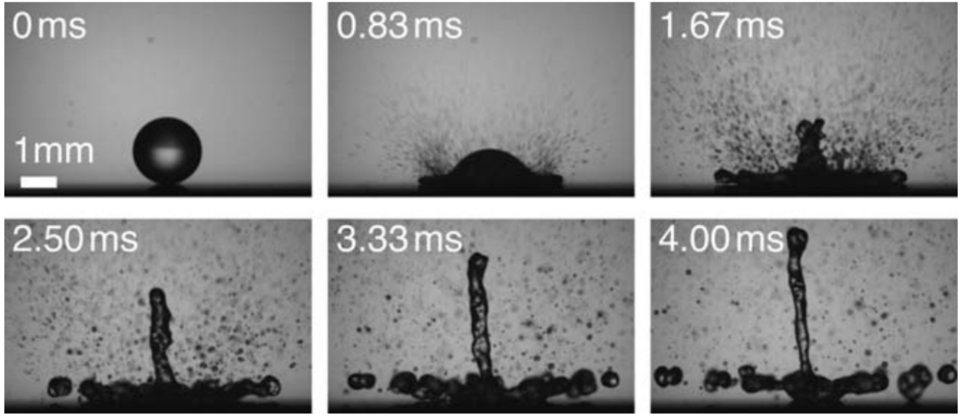
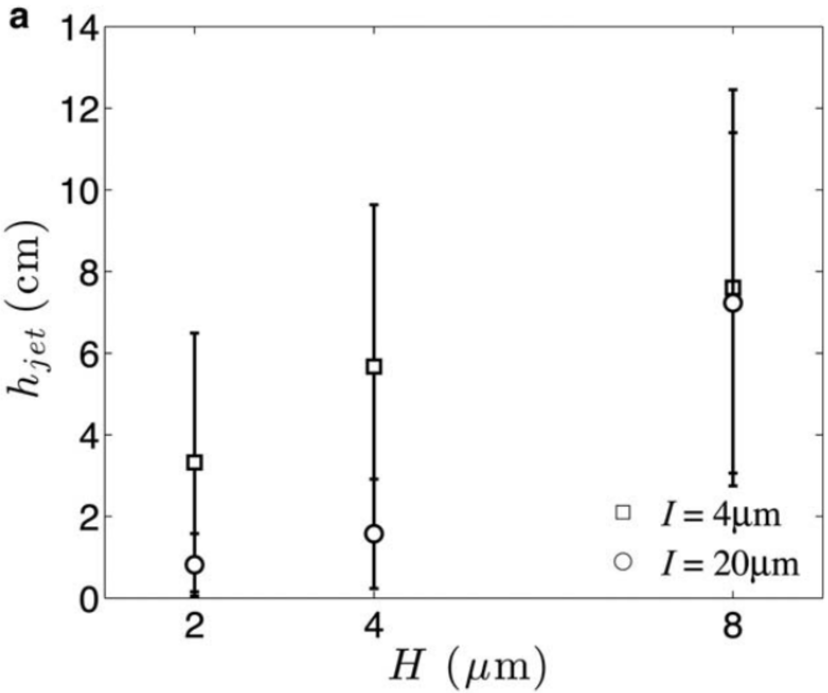


Fig. 11 Jet formation during the impact of a water droplet on a structured surface ($l = 4\ \mu m$, $H = 2\ \mu m$) heated to 300 °C. The diameter of the drop is 2.2 mm, and the impact velocity is 1.3 m s^{-1}.



Tran, T., Staat, H. J. J., Susarrey-Arce, A., Foertsch, T. C., van Houselt, A., Gardeniers, H. J. G. E., Prosperetti, A., Lohse, D., Sun, C. (2013). Droplet impact on superheated micro-structured surfaces. *Soft Matter*, *9*(12), 3272–3282.

Hollow sphere model

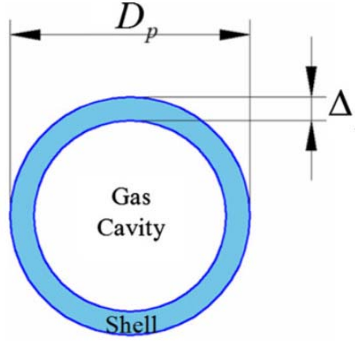
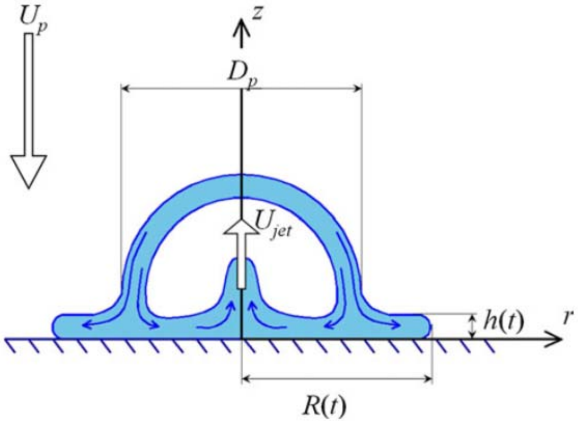


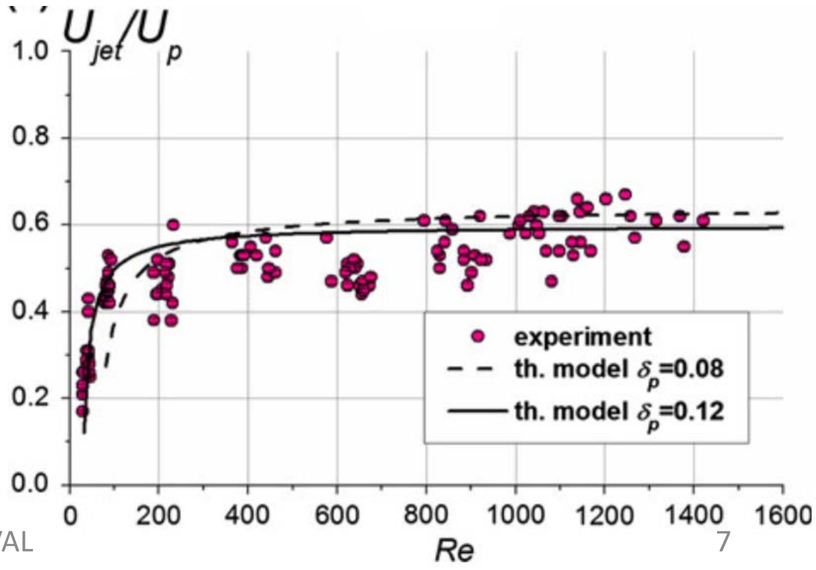
Fig. 1 Hollow sphere



$$Re = \rho D_{\text{p}} U_{\text{p}} / \mu$$
$$We = \rho D_{\text{p}} U_{\text{p}}^2 / \sigma$$
$$\delta_{\text{p}} = \Delta_{\text{p}} / D_{\text{p}}$$

$$\frac{U_{\text{jet}}}{U_{\text{p}}} = \sqrt{A(\delta_{\text{p}})\left(1 - \frac{B(\delta_{\text{p}})}{Re}\right)},$$

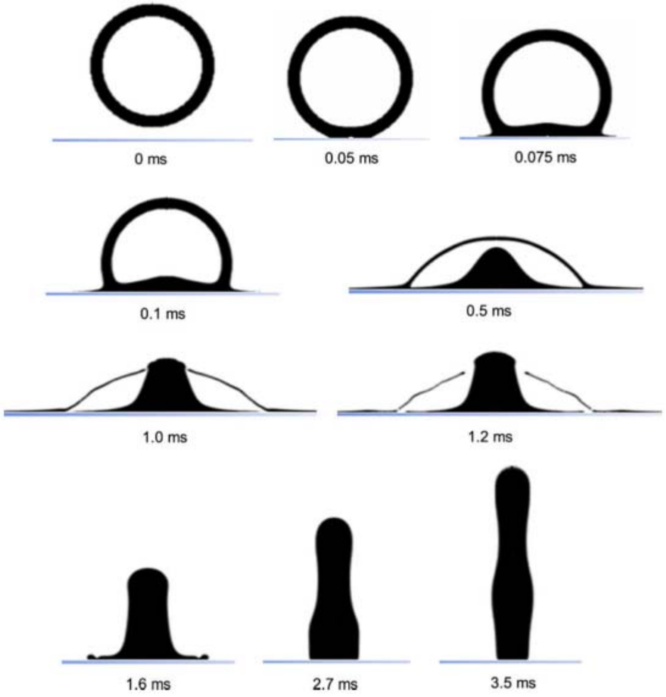
$$\text{where}\, A(\delta_{\text{p}}) = 1 - \frac{3\delta_{\text{p}}}{1-(1-2\delta_{\text{p}})^3},\ B(\delta_p) = \frac{3}{4\delta_p}\cdot\frac{1}{1-(1-2\delta_p)^3-3\delta_p}.$$



Gulyaev, I. P., & Solonenko, O. P. (2013). Hollow droplets impacting onto a solid surface. *Experiments in Fluids*, *54*, 1432.

Previous simulations

“two-dimensional axisymmetric formulation”



Kumar, A., Gu, S., & Kamnis, S. (2012). Simulation of impact of a hollow droplet on a flat surface. *Applied Physics A*, *109*(1), 101–109.

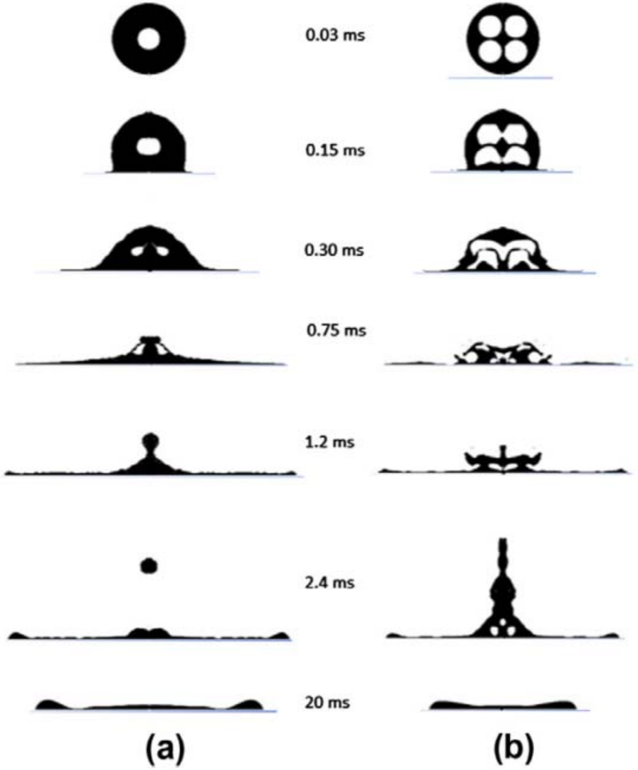


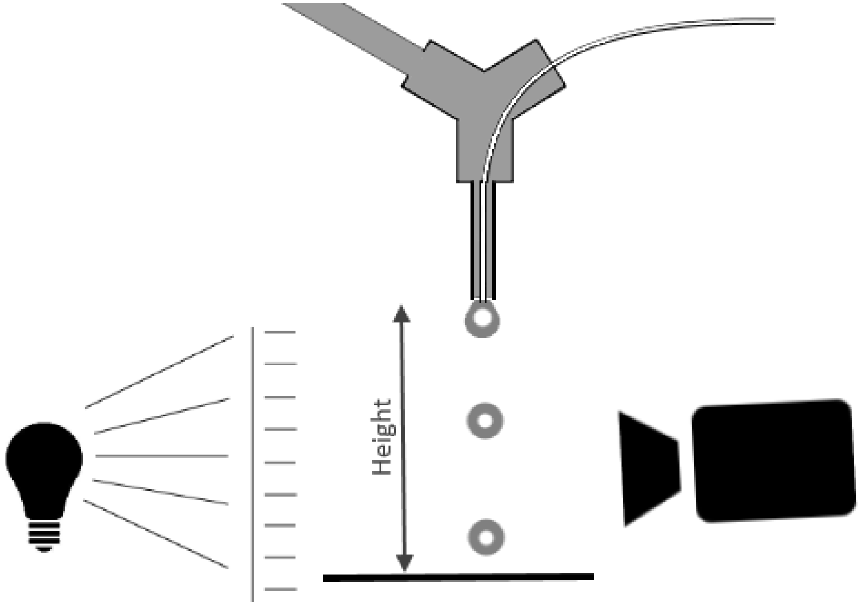
Fig. 6. Snapshots of droplet spreading for different void fraction (a) hollow droplet ($d/D_0 = 0.3$) and (b) hollow droplet with four small distributed voids having the same mass as that of $d/D_0 = 0.5$ hollow droplet.

Kumar, A., & Gu, S. (2012). Modelling impingement of hollow metal droplets onto a flat surface. *International Journal of Heat and Fluid Flow*, *37*, 189–195.

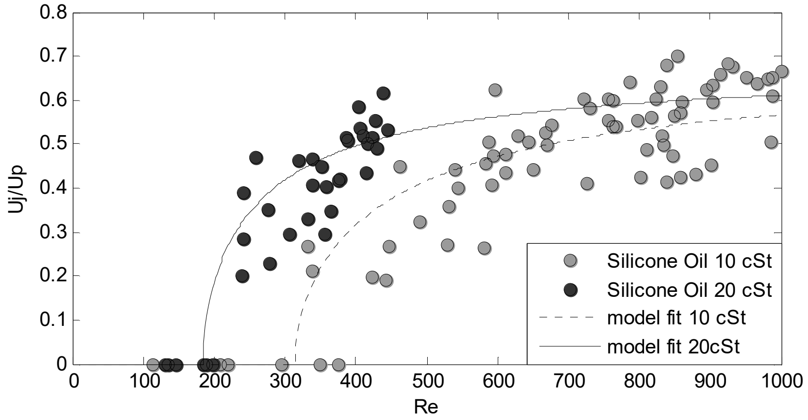
Outline

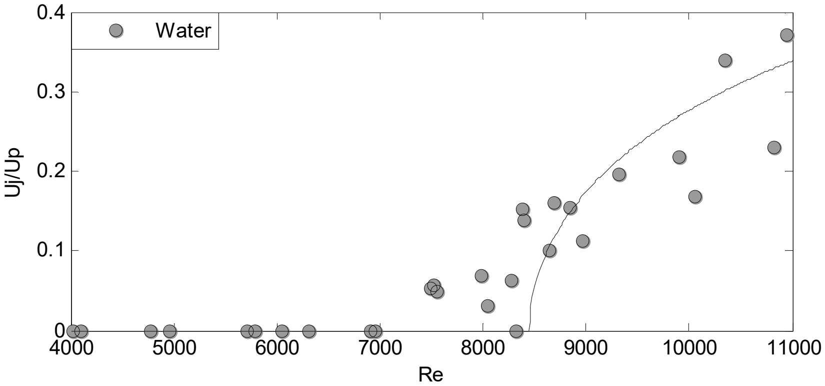
1. Preliminary experiments in Twente
2. Numerical simulations (Gerris):
    a) Impact velocity
    b) Bubble size
    c) Bubble vertical position / Film thickness
    d) Liquid properties

1. Preliminary experiments in Twente



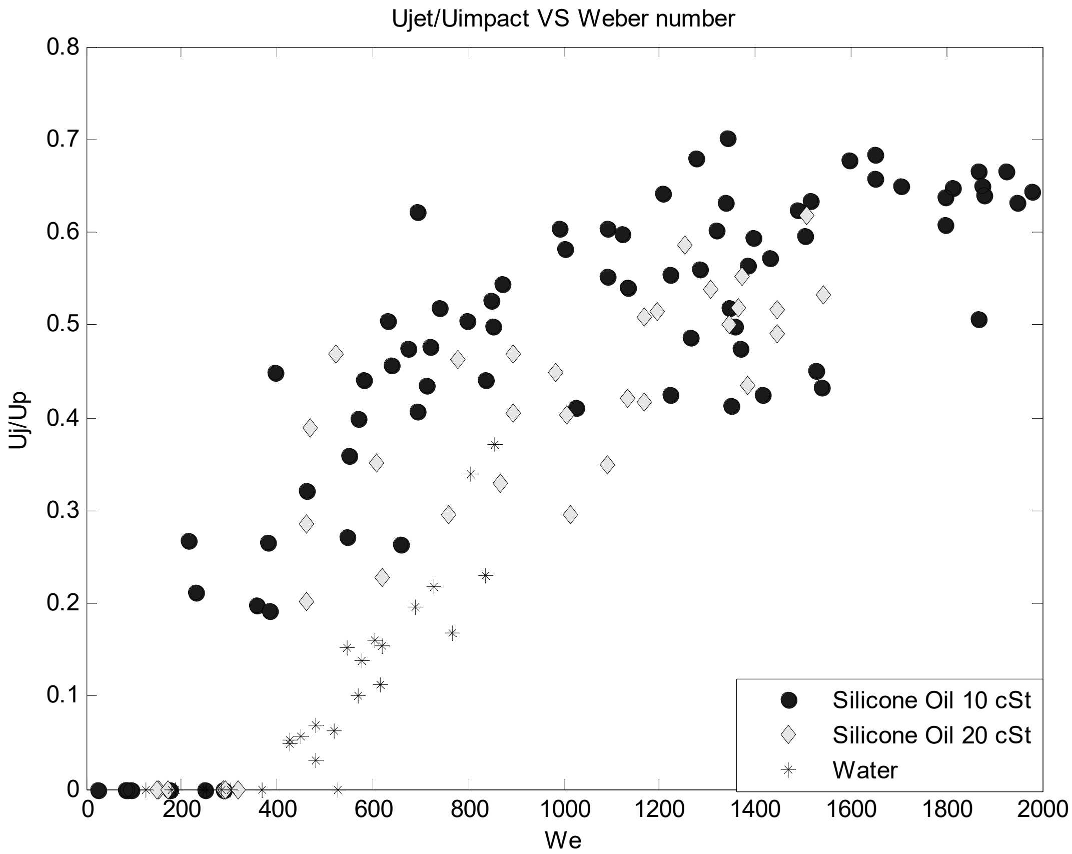
δ_p = 0.03 Silicone oil 10 cSt (estimated δ_p = 0.25)
δ_p = 0.04 Silicone oil 20 cSt (estimated δ_p = 0.31)
δ_p = 0.0055 Water (estimated $\boldsymbol{\delta}$ = 0.25)



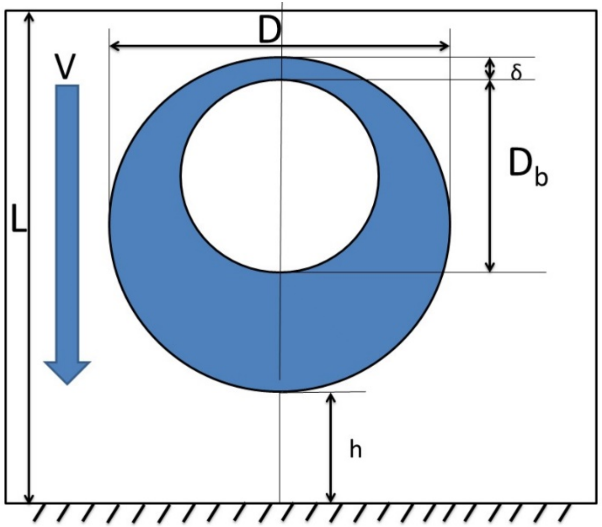


PoF, University of Twente (2014)
Bart Vroling and Stef van der Woerdt

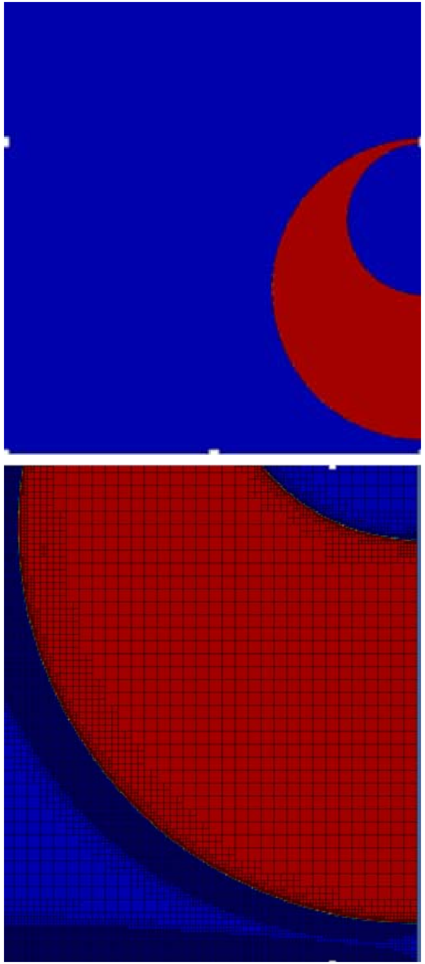
Jet velocity



2. Numerical simulations (Gerris)



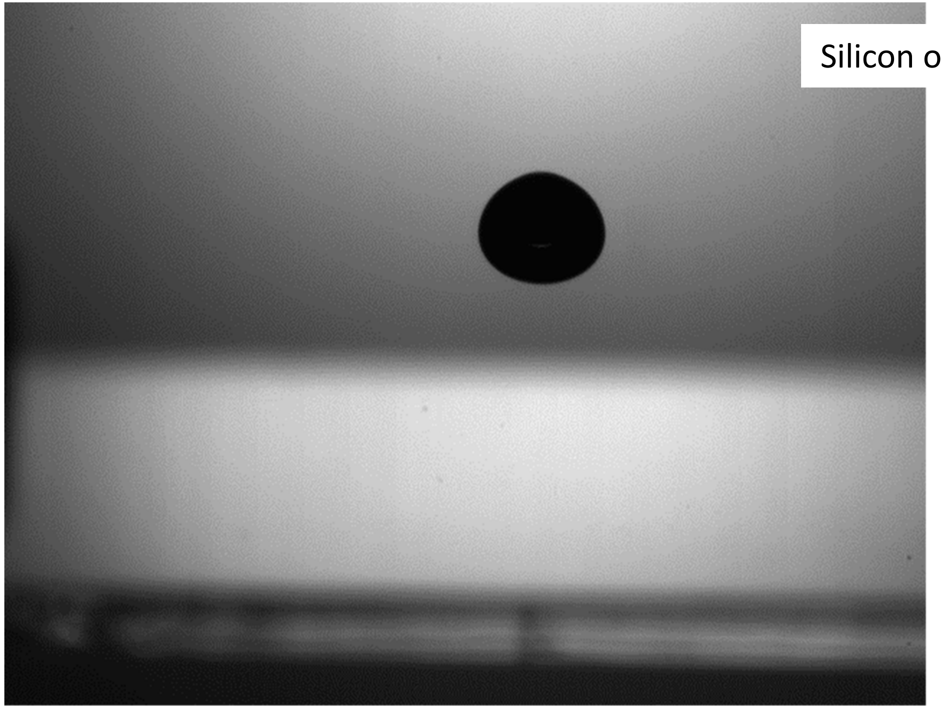
D_b*	D_b/D
δ*	δ/D
V_j	Maximum jet velocity
v_j	Jet velocity
V_j*	V_j/V
v_j*	v_j/V
P*	$P/\rho V^2$
∇P*	$\delta p^*/\delta z$

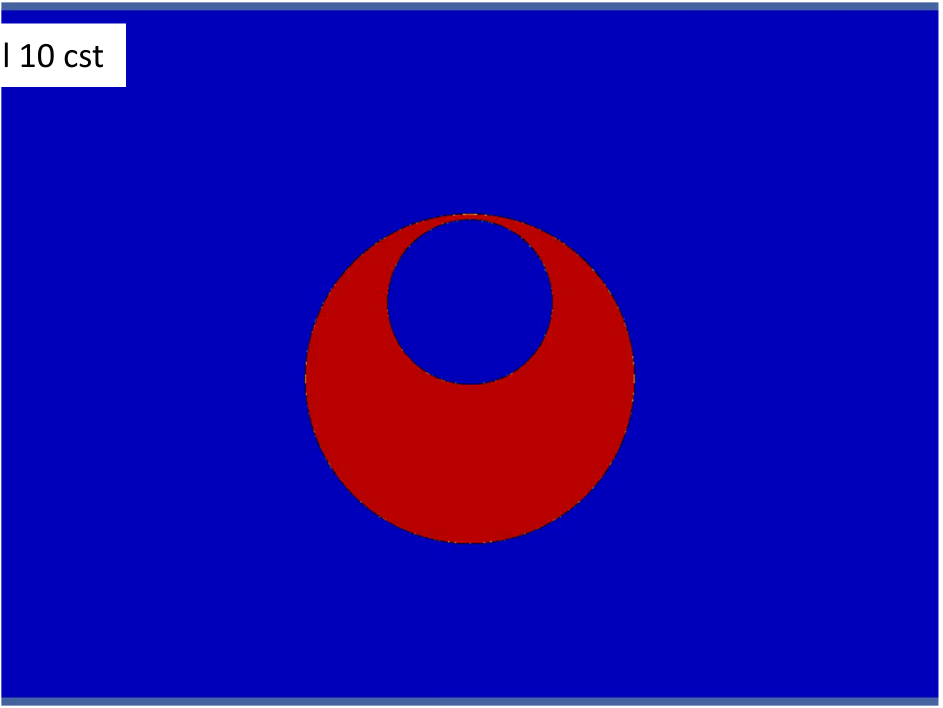


Level of refinement: 10 (2^{10} cells in each direction)
-> 2^{10}*D/L = 491 cells per drop diameter
L/D = 2.08, h/D = 0.478

Validation

D_b^*	D_b/D
δ^*	δ/D





Silicon oil 10 cst

D = 2.75 mm, V = 4.59 m/s

PoF, University of Twente (2014)
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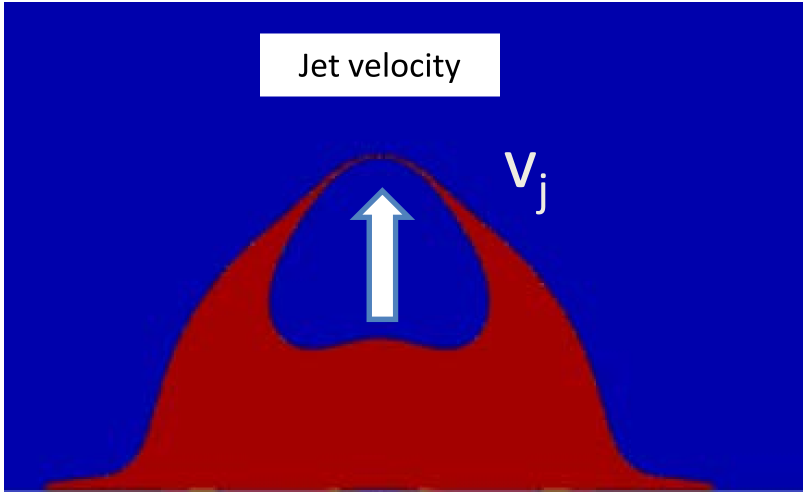
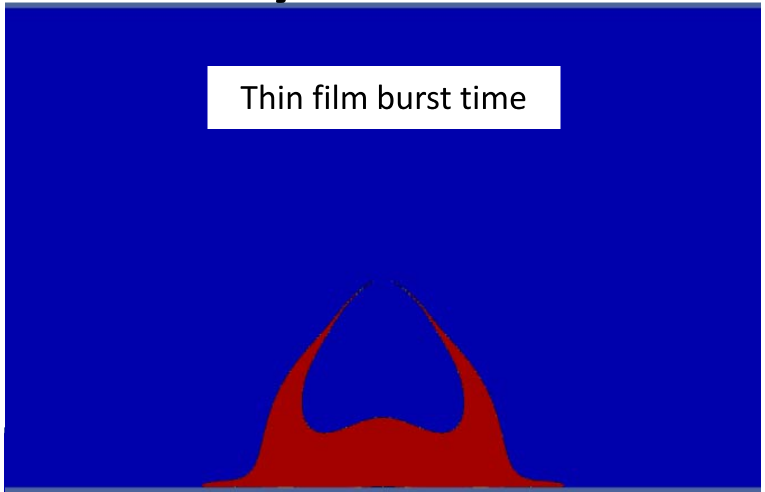
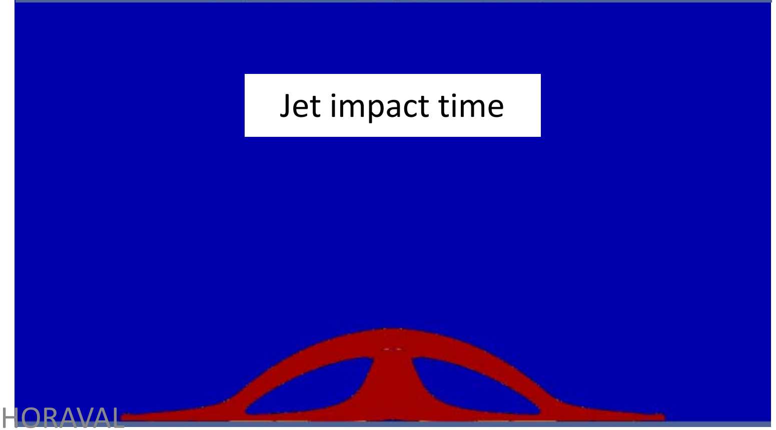
D = 2.75 mm, V = 4.59 m/s,
$\delta^* = 0.0175$, $D_b^* = 0.5$, Re = 1010

Quantitative analysis



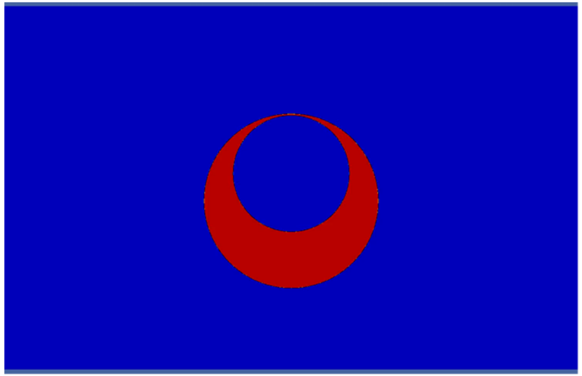




Bursting and impact times

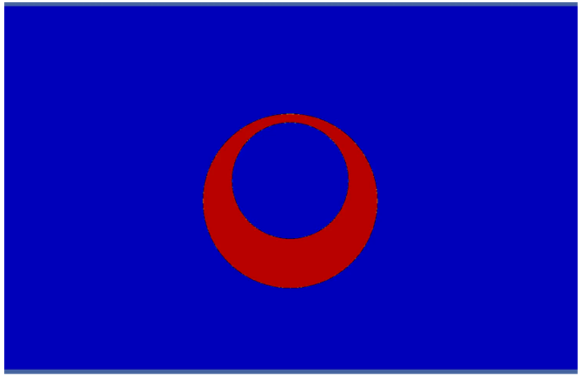
Typical cases of different results on film bursting and impacting of jet and film

Film bursts before maximum jet velocity happens.



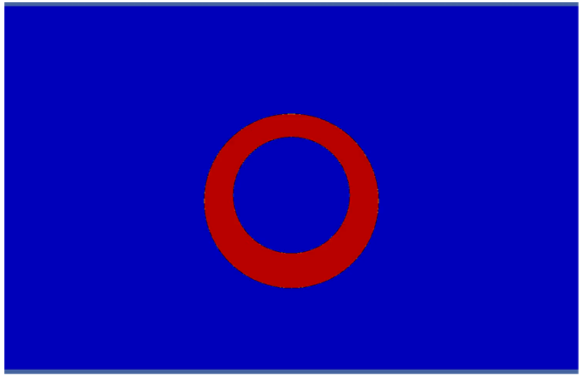
$\delta^* = 0.01$, $V=4.276$ m/s, $D_b^* = 0.67$

Film bursts after maximum jet velocity happens.



$\delta^* = 0.05$, $V=4.276$ m/s, $D_b^* = 0.67$

The jet impacts the film before it breaks.

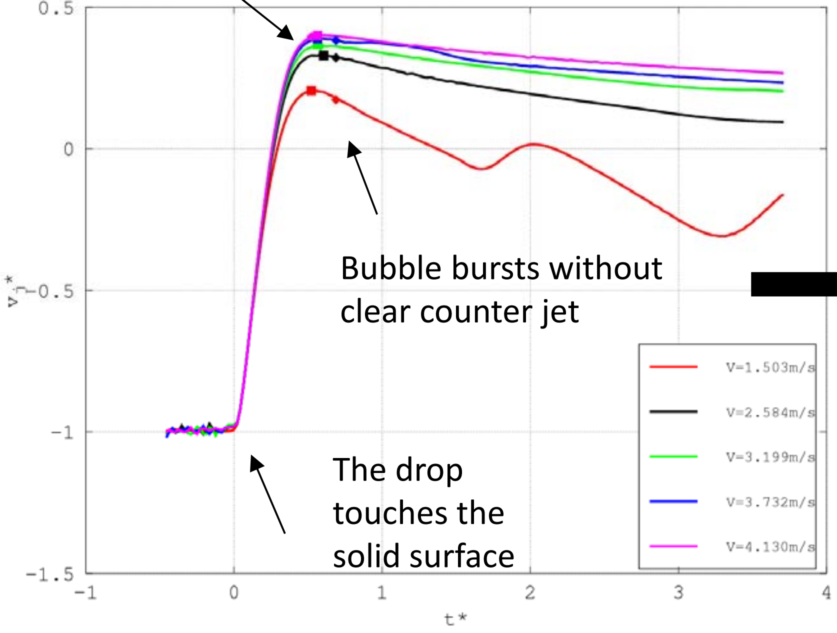


$\delta^* = 0.13$, $V=4.276$ m/s, $D_b^* = 0.67$

2a) Impact velocity

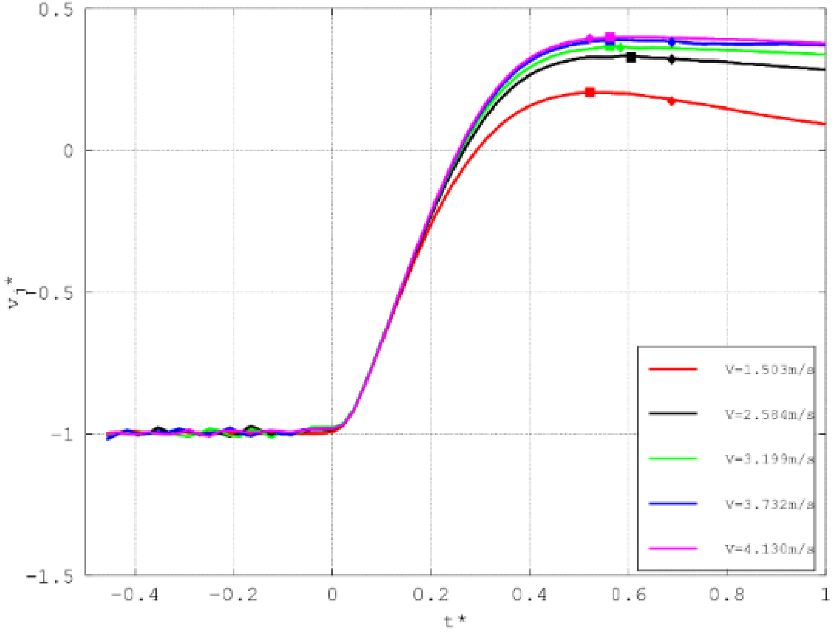
Maximum jet velocity V_j

Silicon oil 10 cst



Bubble bursts without clear counter jet

The drop touches the solid surface

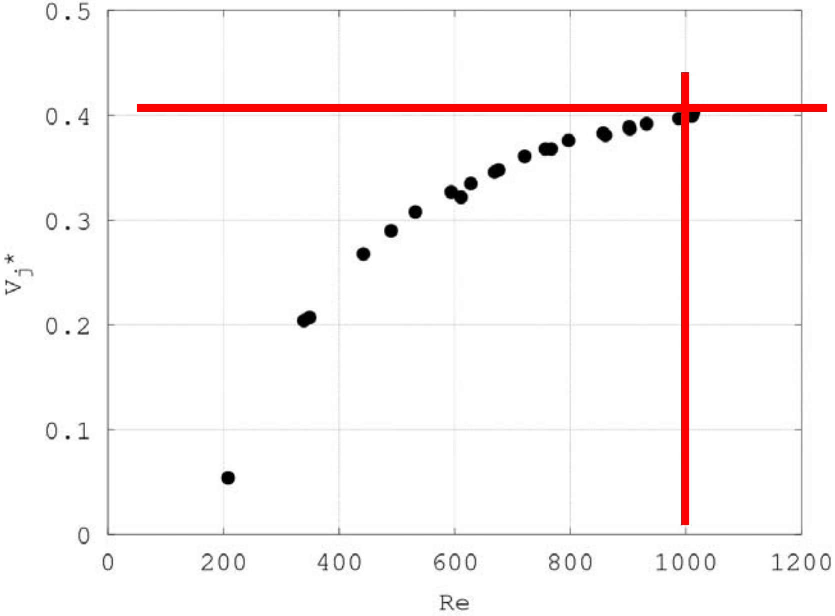


■ Maximum jet velocity time ◆ Burst time

V = 1.50 m/s, 2.58 m/s, 3.19 m/s, 3.73 m/s and 4.13 m/s.
D = 2.75mm, δ^* = 0.0175, D_b^*= 0.5.

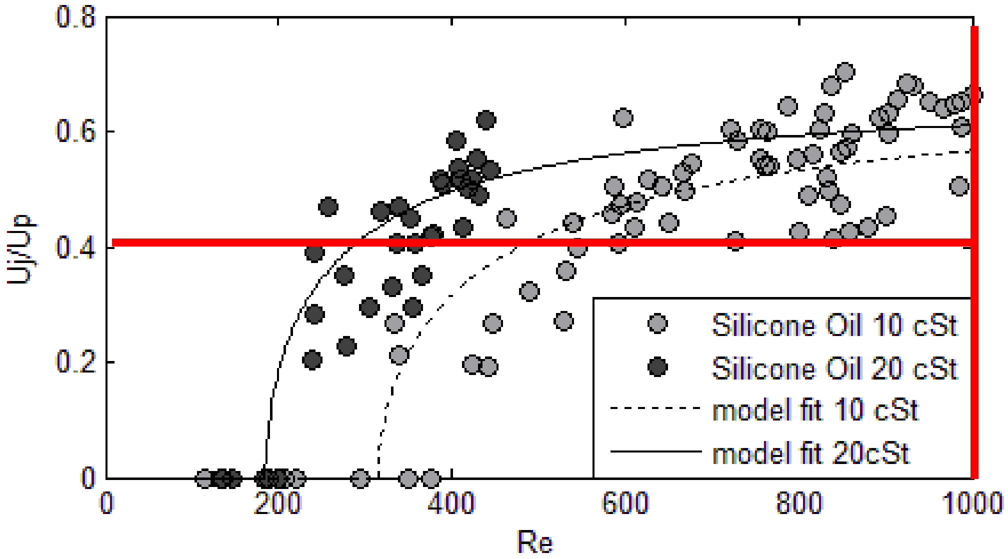
2a) Impact velocity

Max V_j ~ 0.4



Simulations for Silicon oil 10 cst
D = 2.75 mm, δ* = 0.0175, D_b* = 0.5

Max V_j ~ 0.7



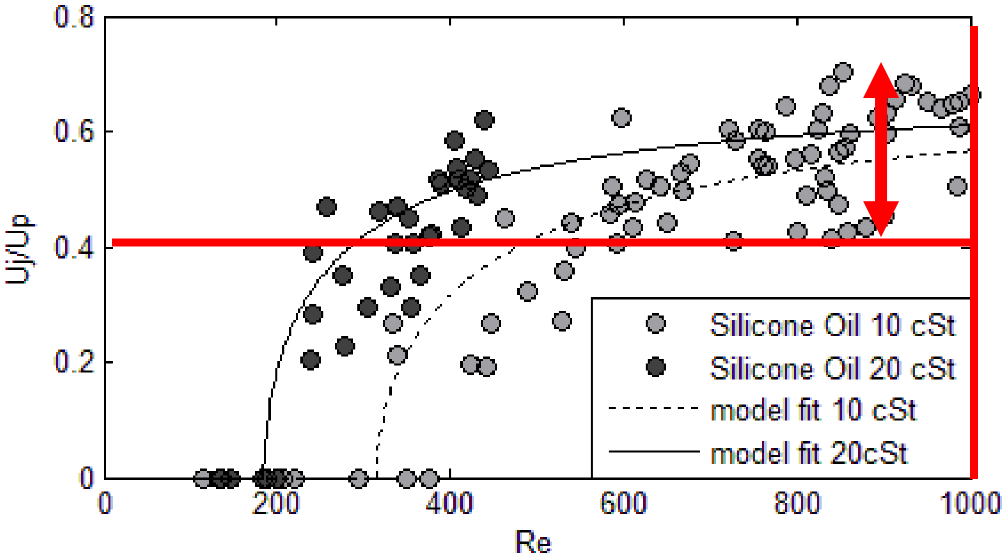
Experiments
PoF, University of Twente (2014)

Origin of the dispersion

Strong dispersion in experiments

Hypothesis:

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



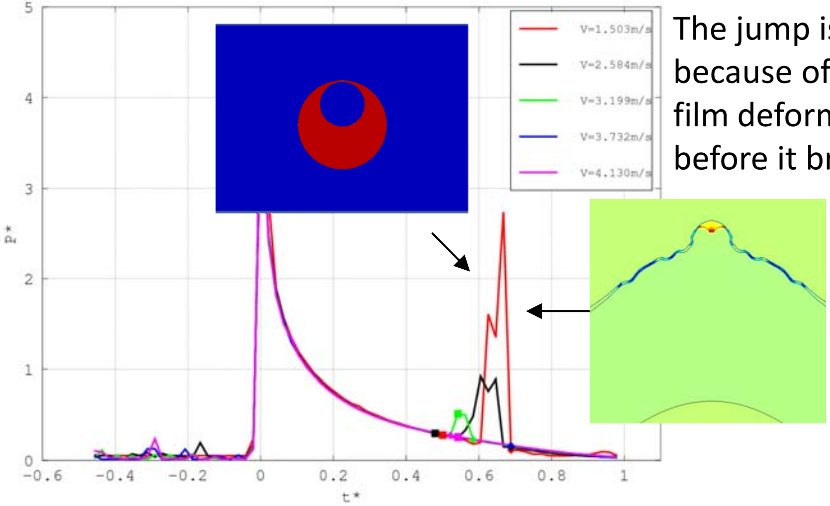
Experiments
PoF, University of Twente (2014)

2a) Impact velocity

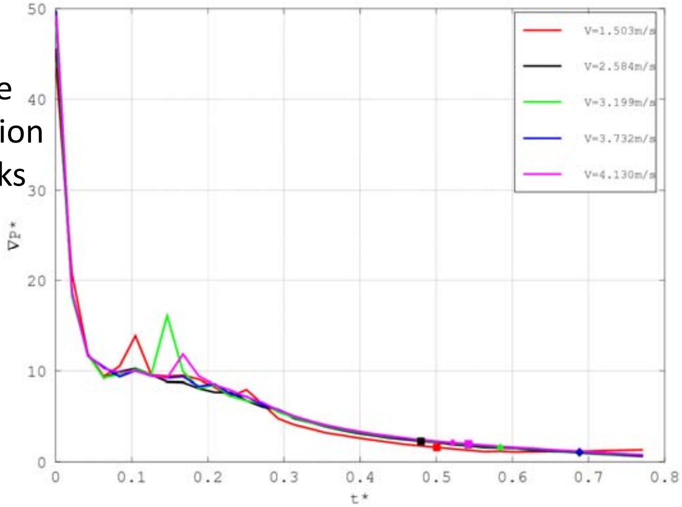
Maximum pressure on axis

Silicon oil 10 cst

Maximum vertical pressure gradient on axis



The jump is because of the film deformation before it breaks



◆ Burst time

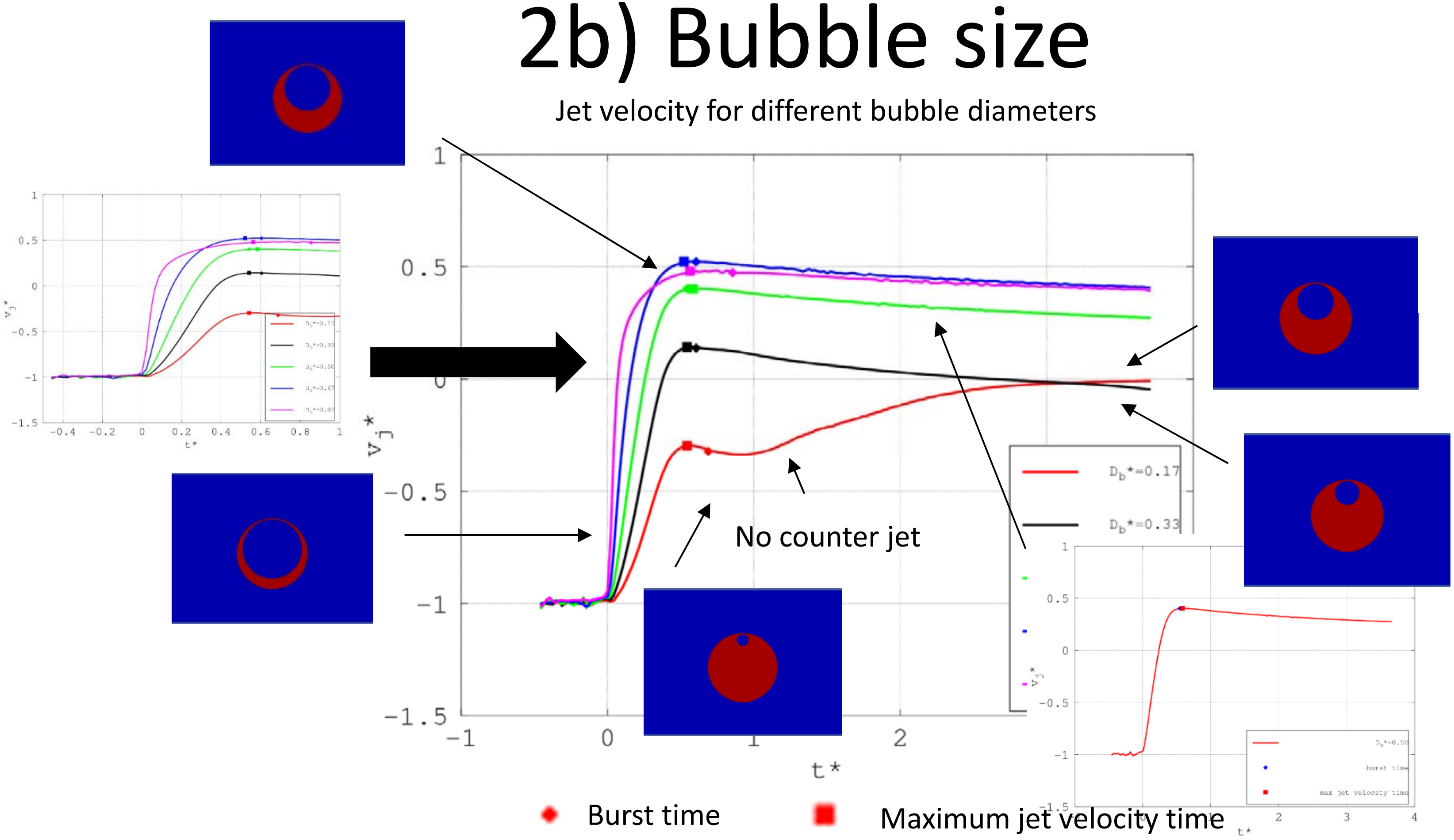
■ Maximum jet velocity time

V = 1.50m/s, 2.58m/s, 3.19m/s, 3.73m/s and 4.13m/s. D = 2.752mm, $\delta^* = 0.0175$ $D_b^* = 0.5$.

Impact velocity has little effect on non-dimensional pressure and non-dimensional pressure gradient.

2b) Bubble size

Jet velocity for different bubble diameters

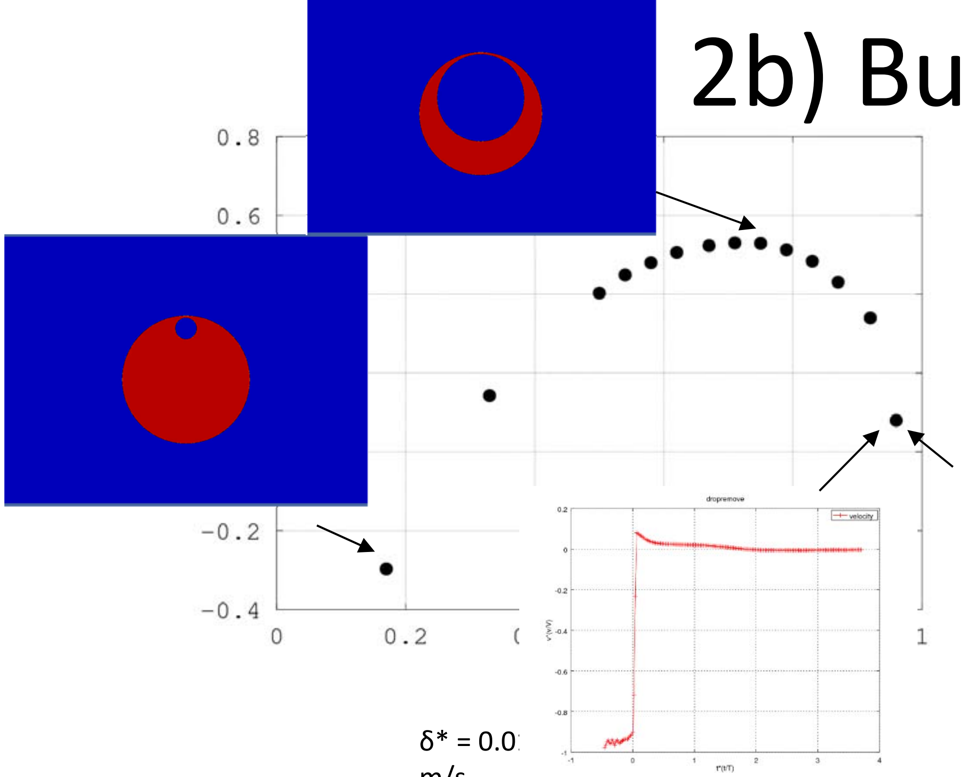


No counter jet

● Burst time ■ Maximum jet velocity time

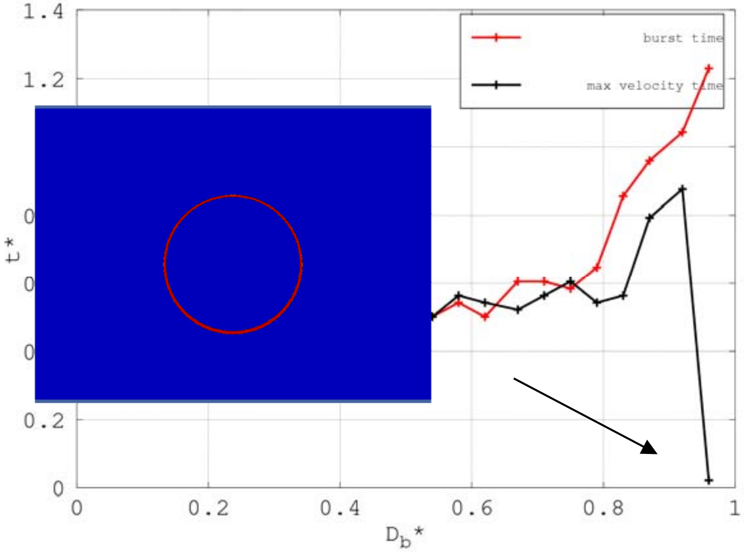
δ^* = 0.017, V=4.276 m/s, D_b^* = 0.17, 0.33, 0.50, 0.67, 0.83.

2b) Bubble size



δ* = 0.0
m/s

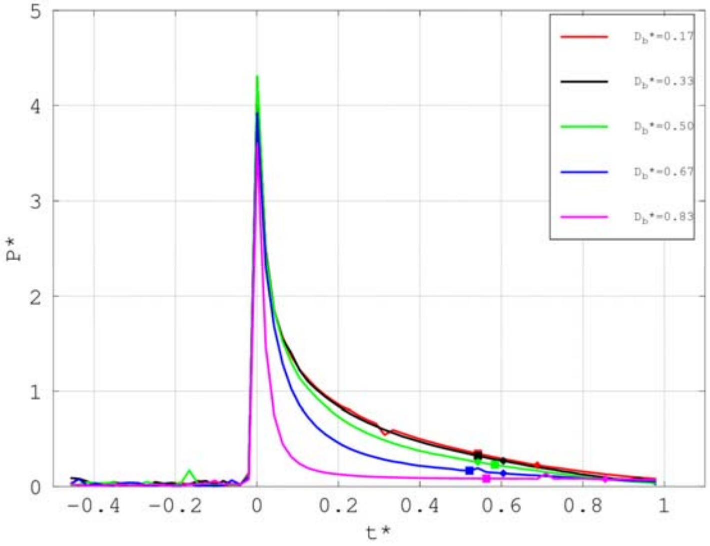
The relation between maximum jet velocity and bubble diameter. The max jet velocity can reach 0.55V at D_b* = 0.63. The max jet velocity is close to the experiment results.



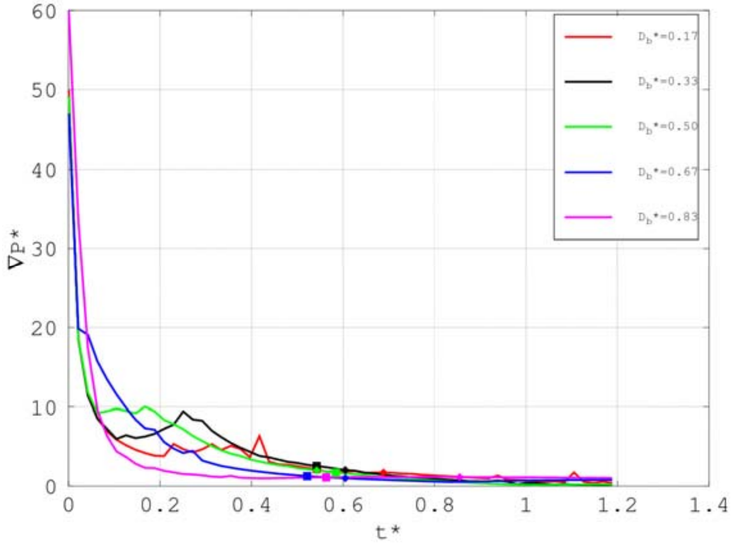
Time scaling of burst of thin film and maximum jet velocity

2b) Bubble size

Maximum pressure on axis



Maximum vertical pressure gradient on axis



♦ Burst time

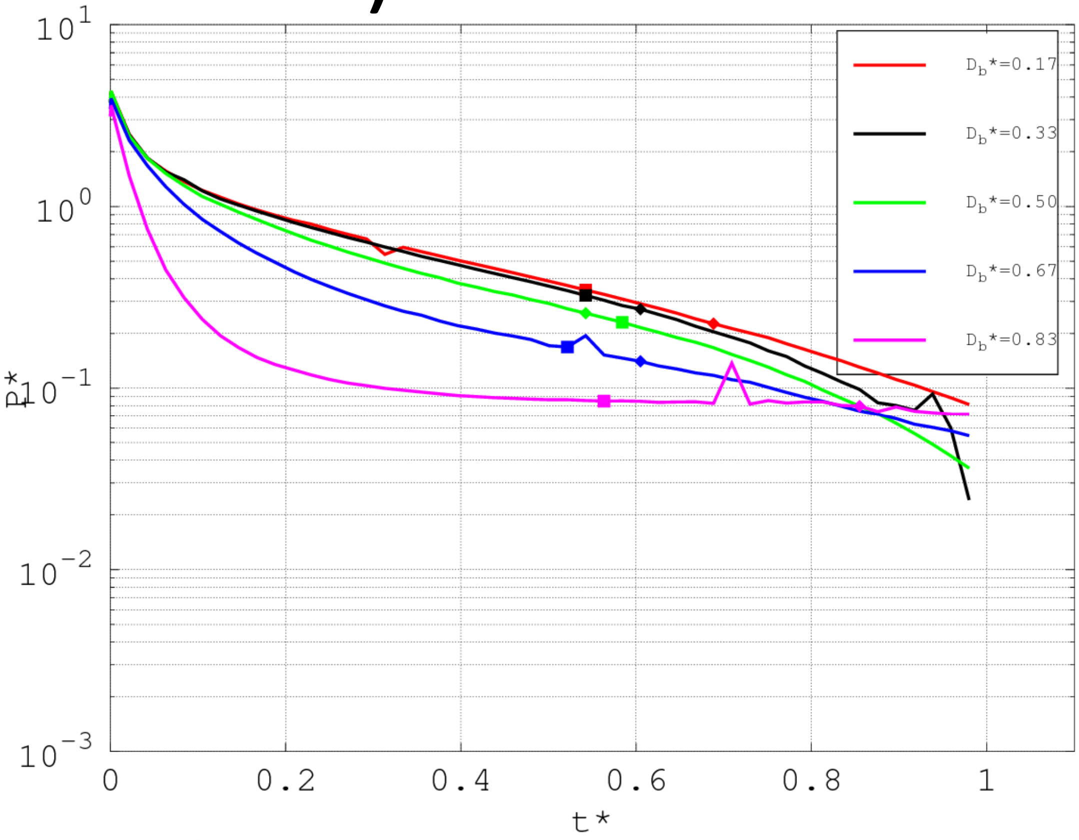
■ Maximum jet velocity time

$\delta^* = 0.017$, V=4.276 m/s, $D_b^* = 0.17, 0.33, 0.50, 0.67, 0.83$.

Bubble size has significant effect on non-dimensional pressure and non-dimensional pressure gradient

2b) Bubble size

Axis pressure of different bubble sizes

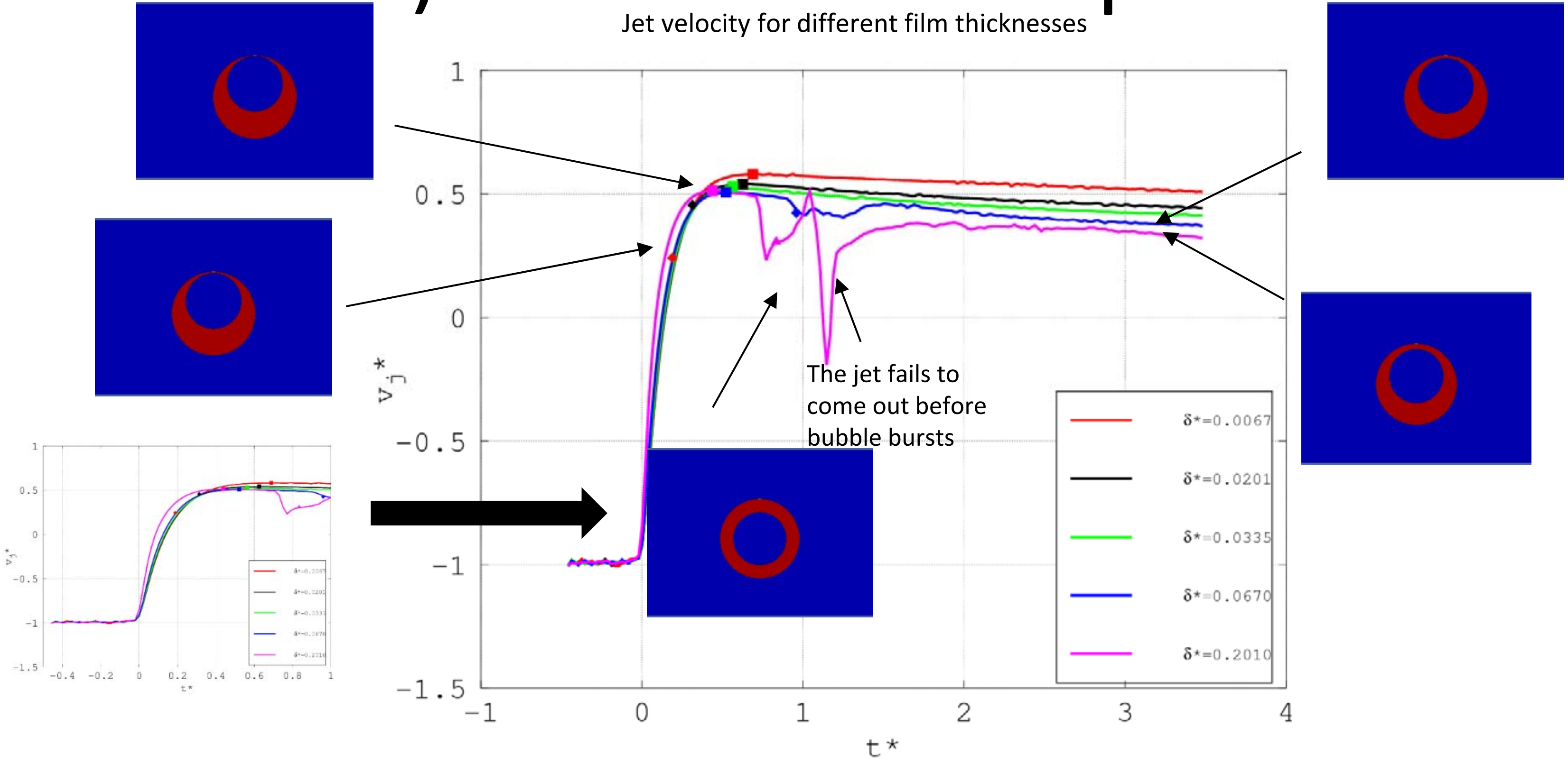


◆ Burst time

■ Maximum jet velocity time

Log plot on pressure coordinate

2c) Bubble vertical position

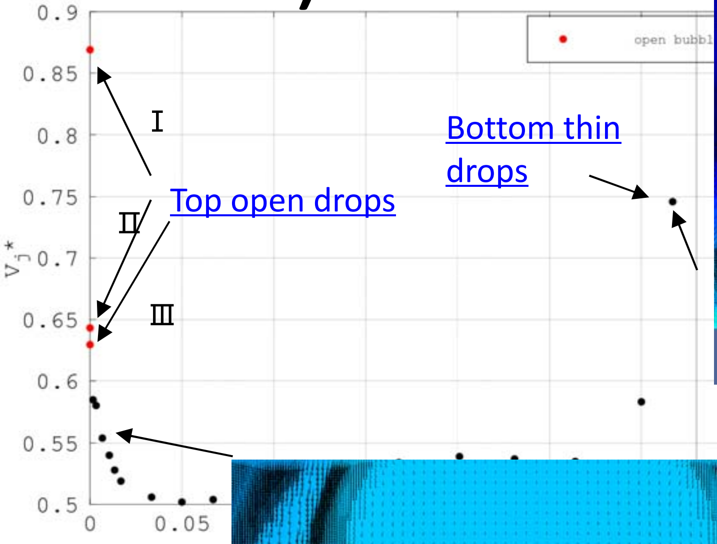


The jet fails to come out before bubble bursts

● Burst time ▲ Jet impact time ■ Maximum jet velocity time

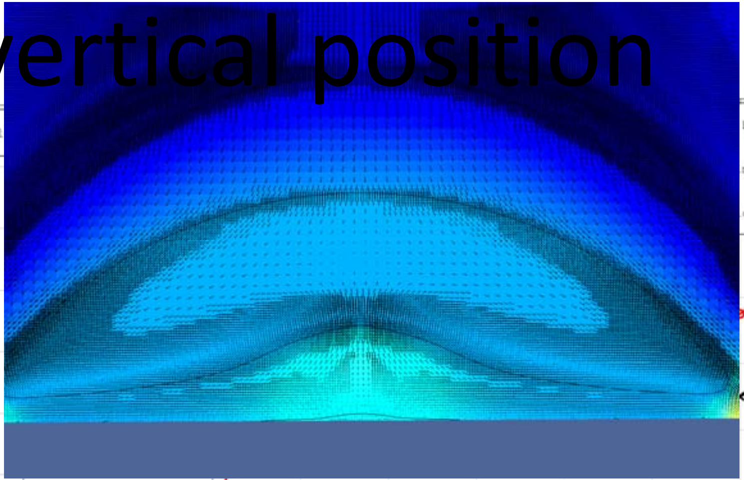
V = 4.276m/s, D_b^*= 0.67D, δ^* = 0.0067, 0.0210, 0.0335, 0.0670, 0.201.

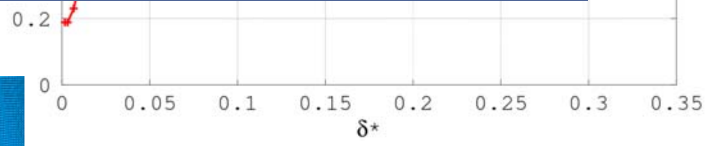
2c) Bubble vertical position

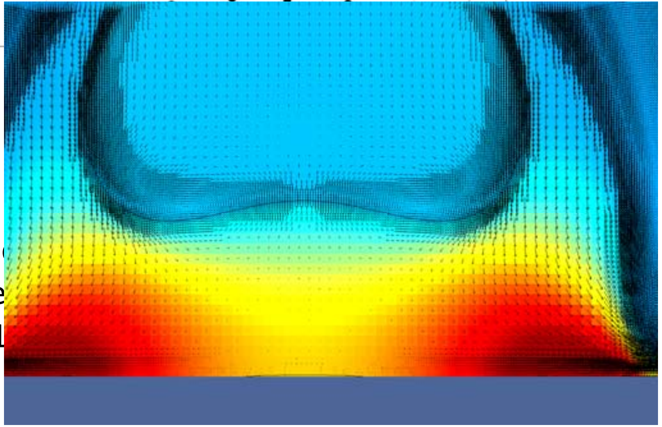


Top open drops

Bottom thin drops





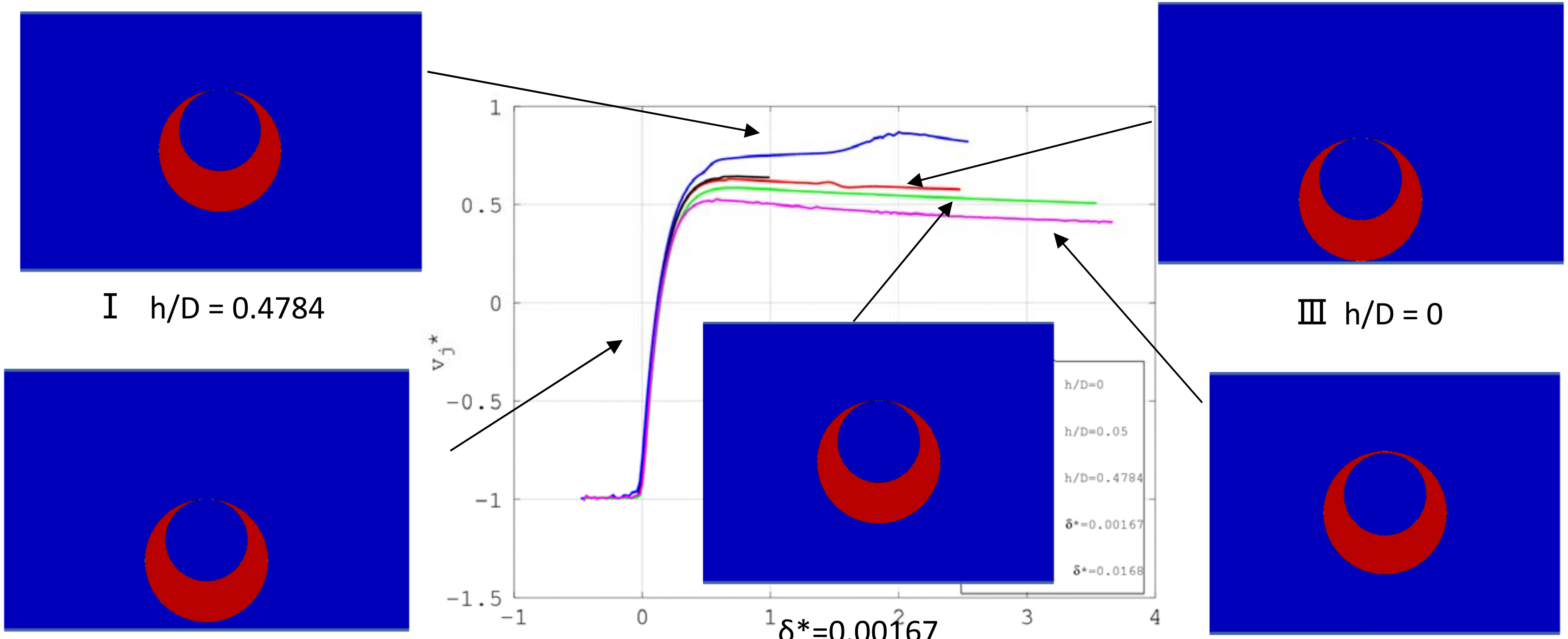


The relation
different film thi
jet velocity decre
But after δ* > 0.1

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

Thin top film

Top open drops with different initial distances to the solid surface



Ⅰ h/D = 0.4784

Ⅱ h/D = 0.05

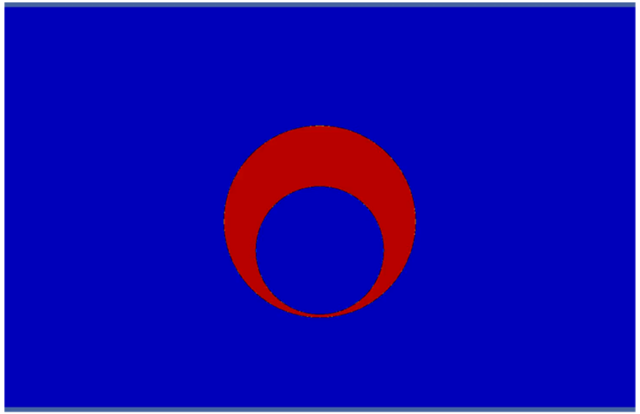
Ⅲ h/D = 0

δ*=0.00167

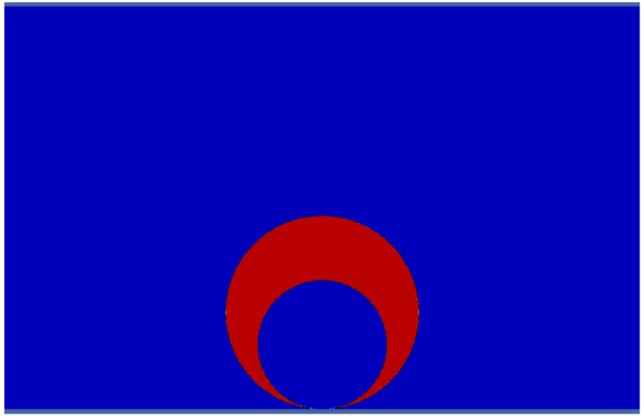
δ*=0.0168

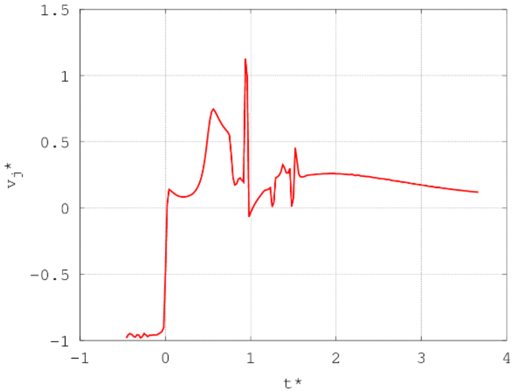
Thin bottom film

Bottom thin drop



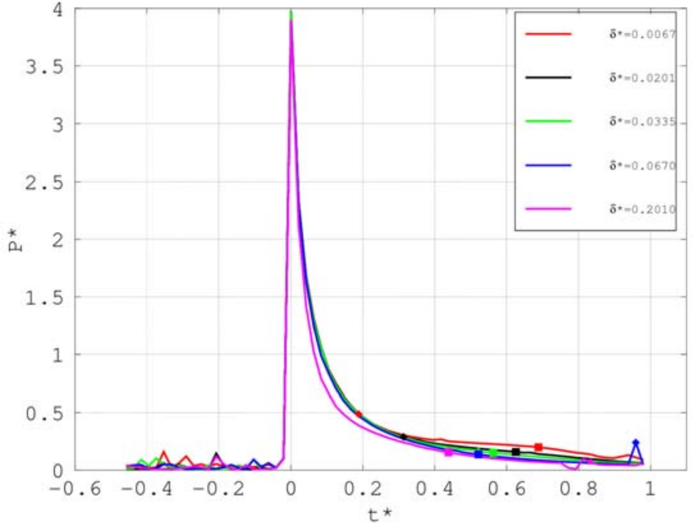
Bottom open drop



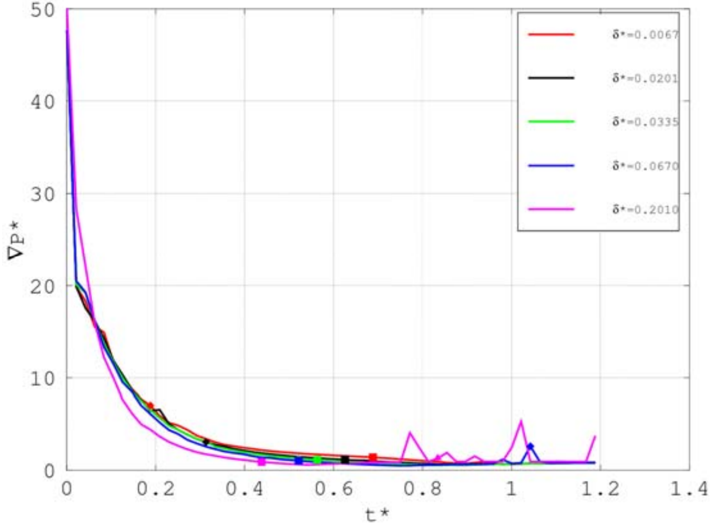


2c) Bubble vertical position

Maximum pressure on axis



Maximum vertical pressure gradient on axis

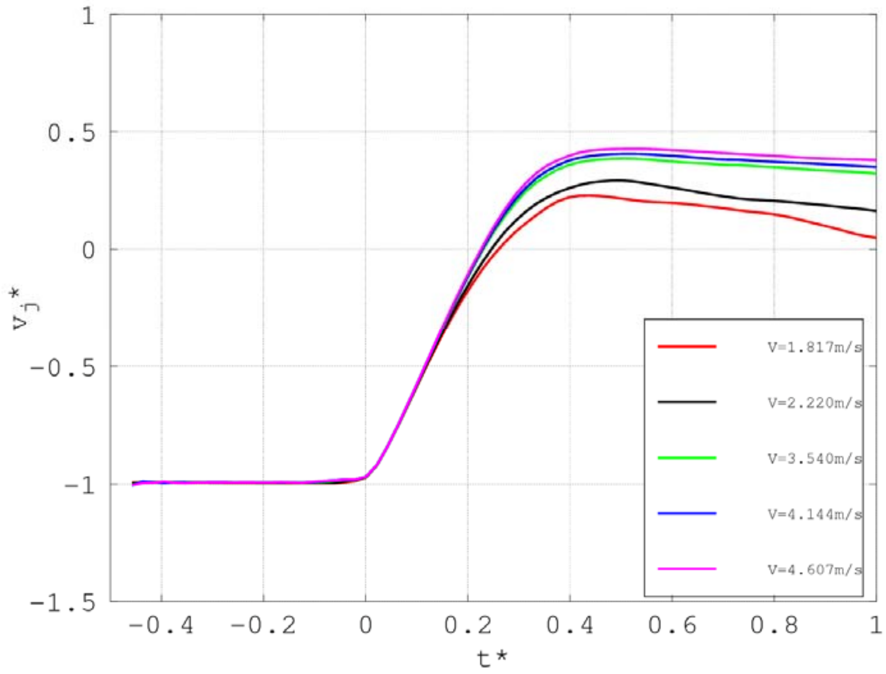


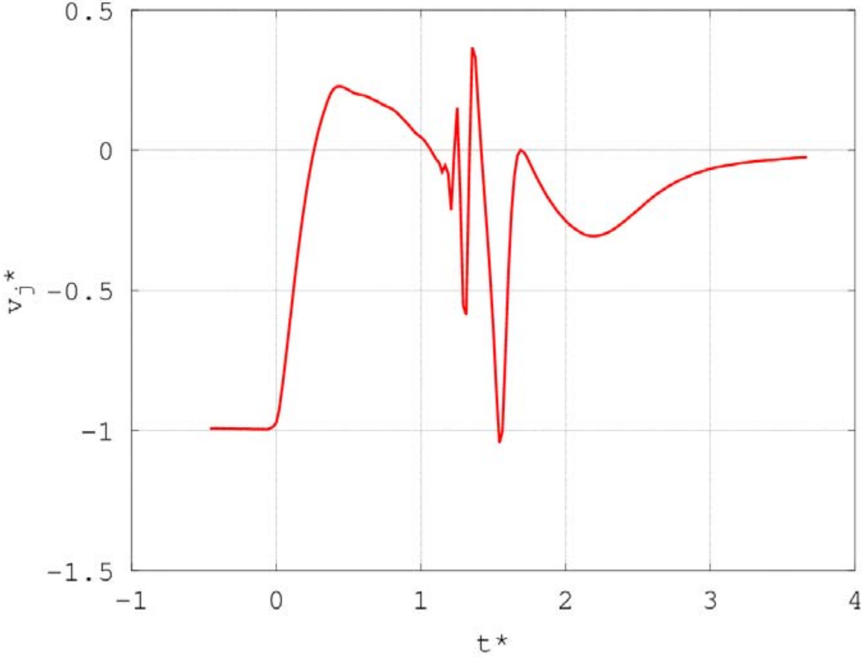
● Burst time ▲ Jet impact time ■ Maximum jet velocity time

V = 4.276m/s, D_b^*= 0.67D, δ = 0.0067, 0.0210, 0.335, 0.0670, 0.201.

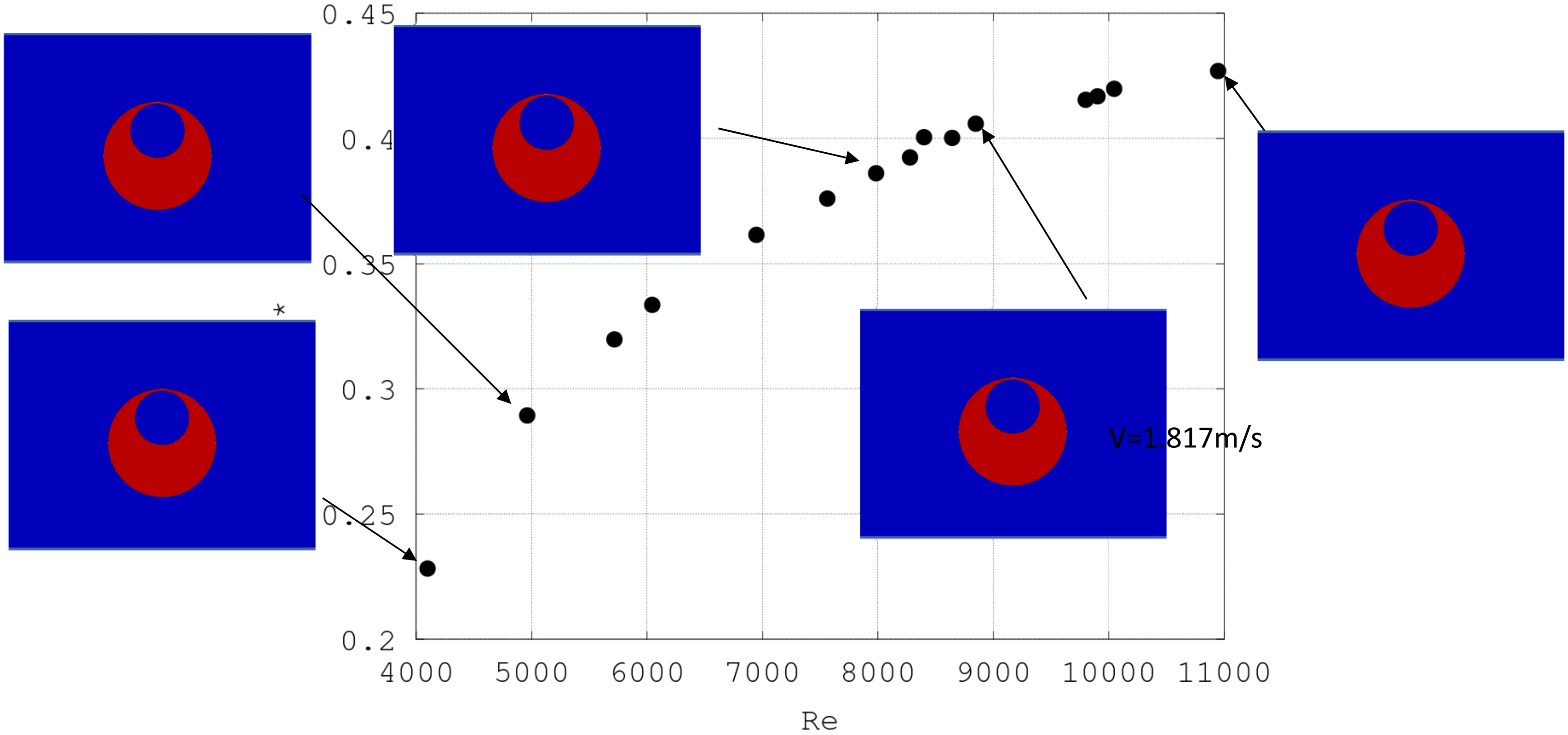
Different film thicknesses can also cause effect on non-dimensional pressure and non-dimensional pressure gradient. But the influence is not as significant as different bubble size.

2d) Liquid properties



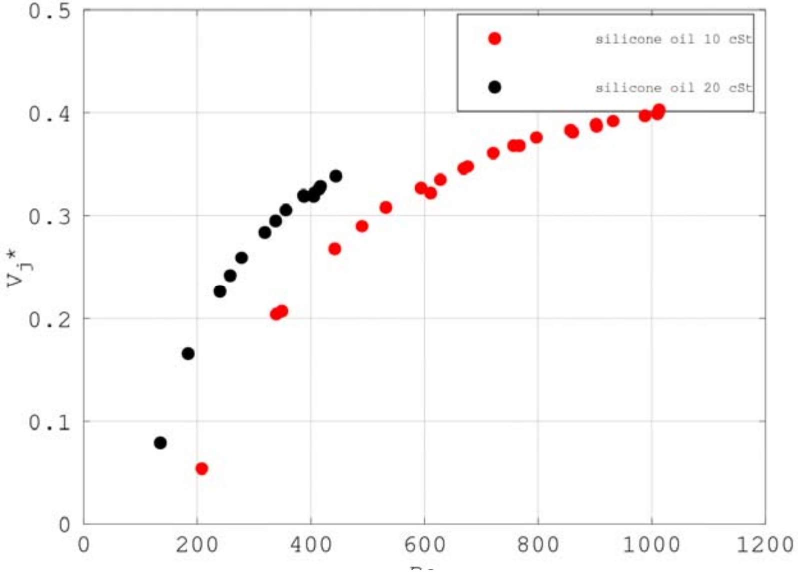


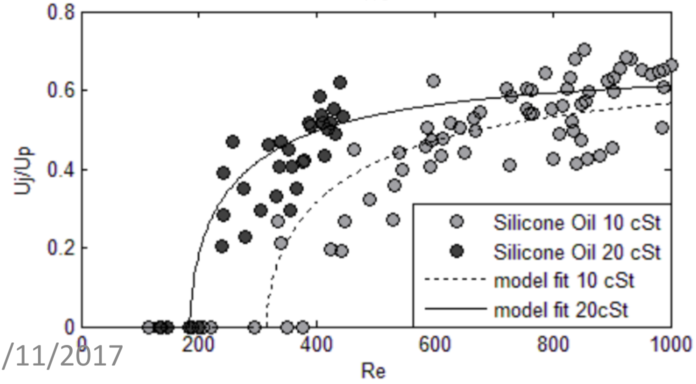
2d) Liquid properties



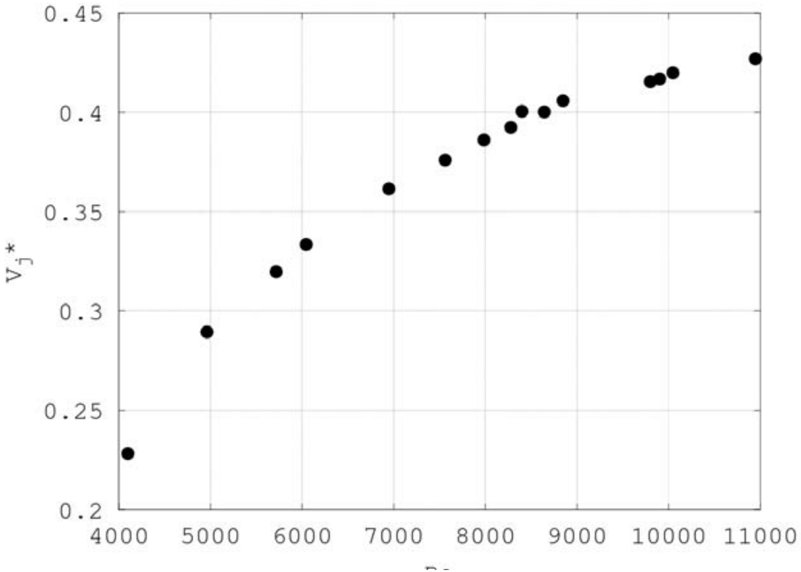
Relation between Re and maximum jet velocity. D_b*=0.5, δ* = 0.0175

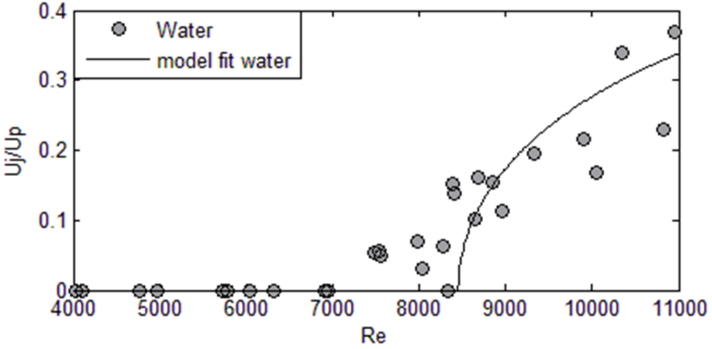
Silicone oil 10 cSt and 20 cSt

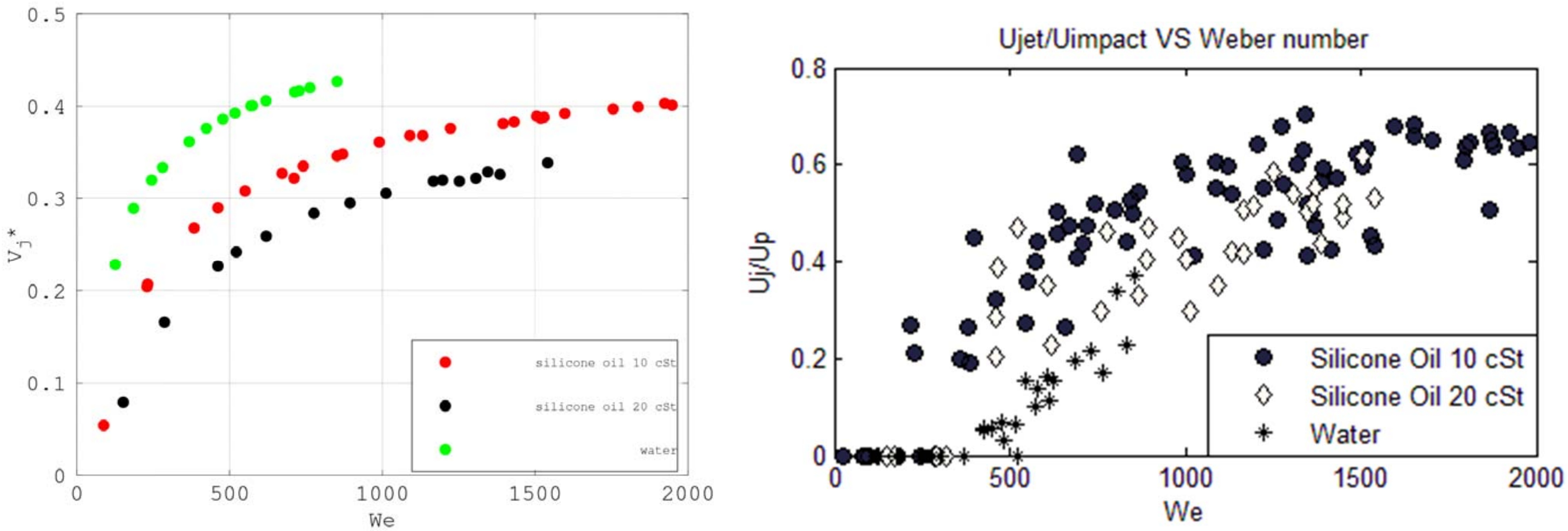




Water

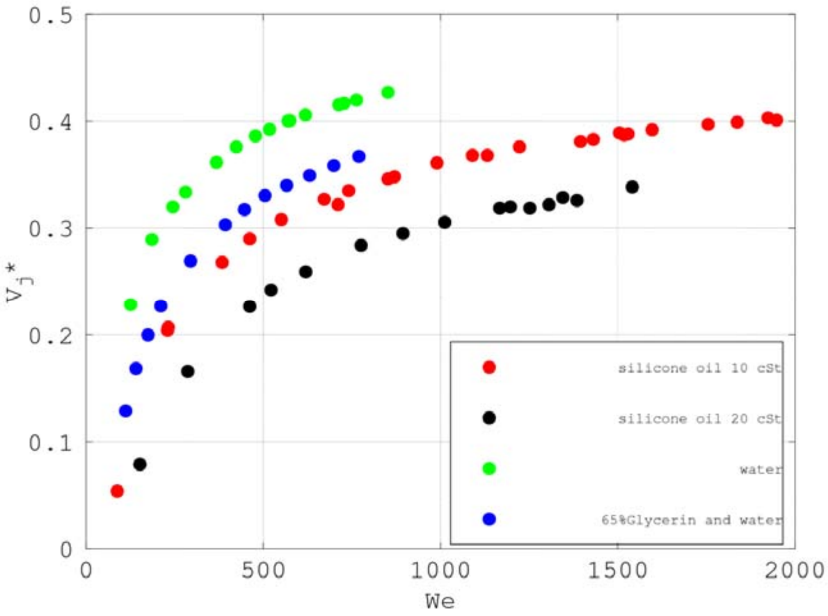






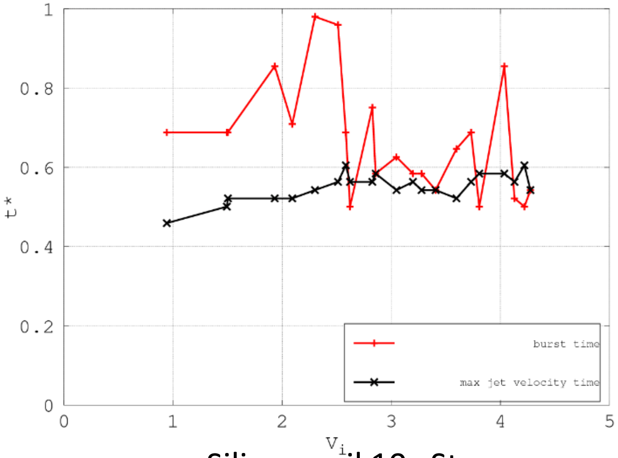
V_j* VS Weber number

Water, silicone 10cSt, 20cSt and 65%glycerin with water

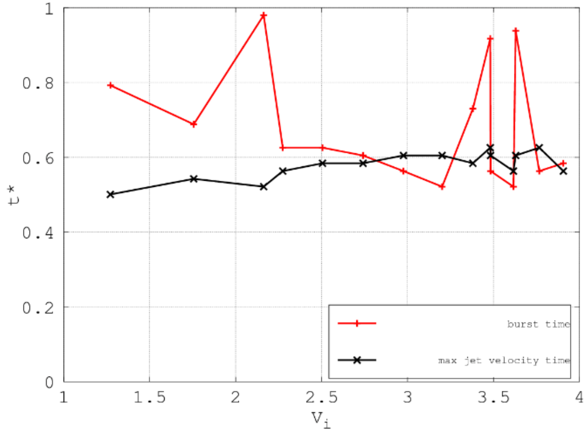


	Density(Kg/m^3)	Surface tension (mn/m)	Viscosity(mPa·s)
Silicone oil 10 cSt	930	20.1	9.49
Silicone oil 20 cSt	950	20.8	18.49
water	997	72	1.216
65% glycerin with water	1165	66.7	12.2

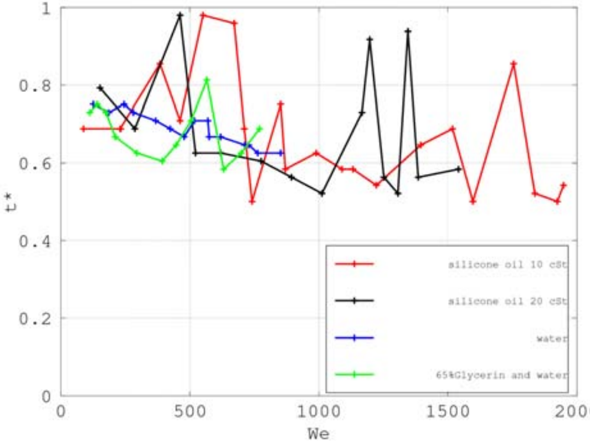
Time analysis



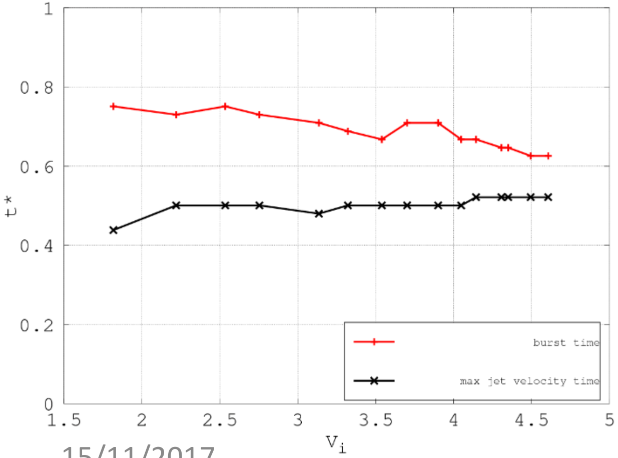
Silicone oil 10 cSt



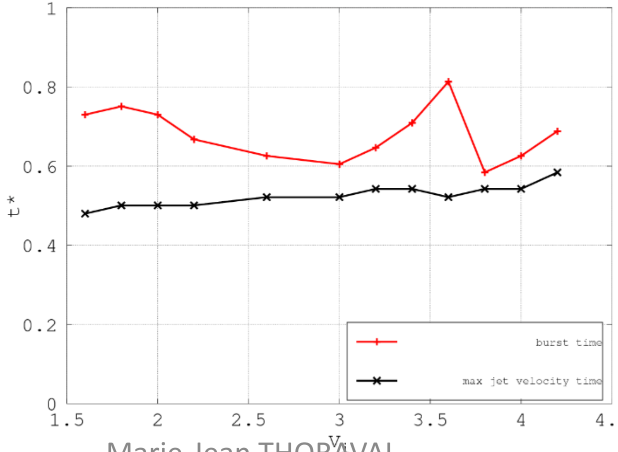
Silicone oil 20 cSt



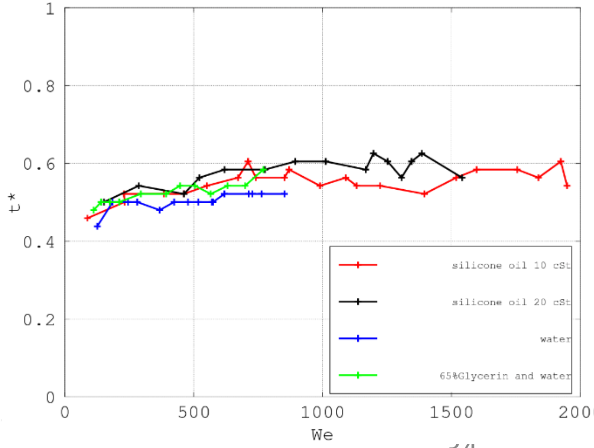
Burst time vs. We number



water



65% glycerin with water



Maximum jet velocity time

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2015-2018

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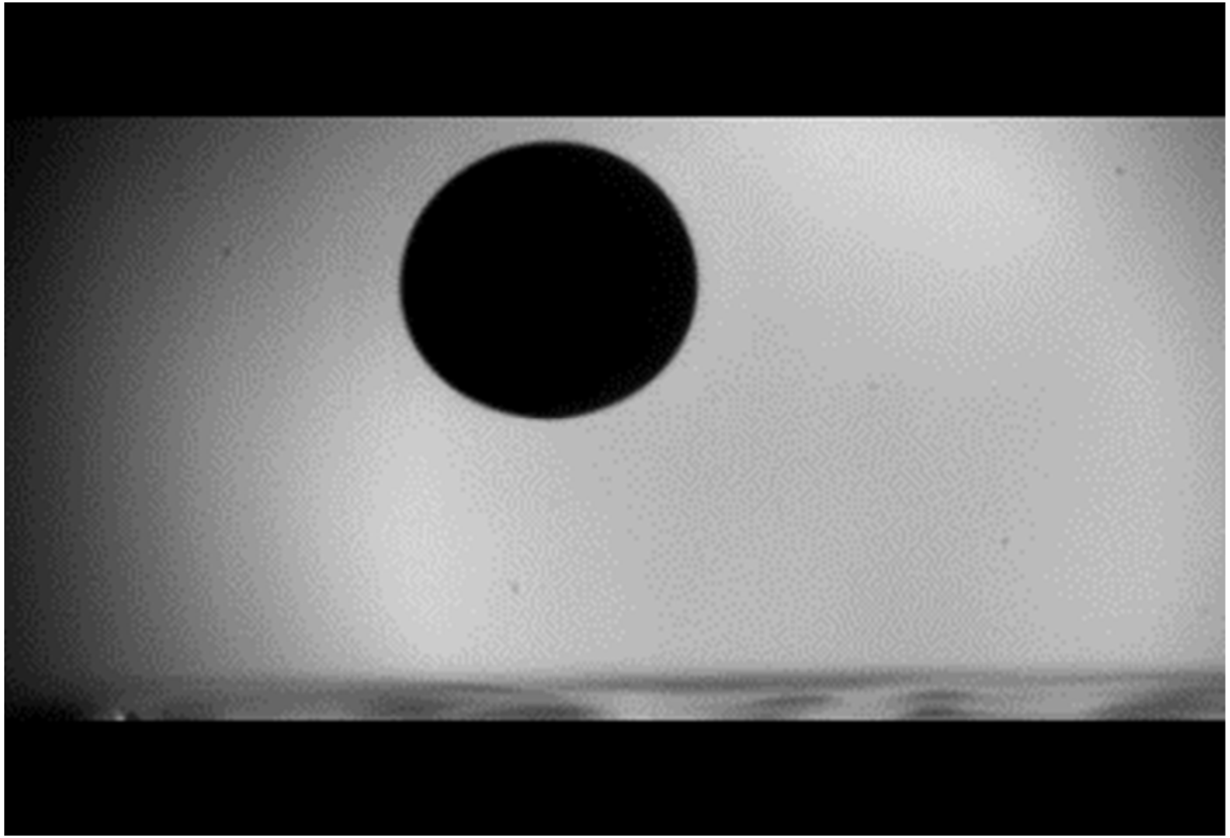
- Profs. Snoeijer & Lohse: University of Twente, **The Netherlands**

Super-fast jet!



V_j = 4.4!