Abstract: G01.00025

Complex immiscible drop impact morphology

Ziqiang Yang, Yuansi Tian, Siggi Thoroddsen

King Abdullah University of Science and Technology (KAUST)

High-Speed Fluids Imaging Laboratory

Outline

- *1. Introduction: miscible & immiscible drop impact*
- *2. Experiment: Immiscible drop-impact*
- *3. Discovery: Complex impact morphology*
- *4. Conclusion*

Introduction: miscible & immiscible drop impact

1. Introduction

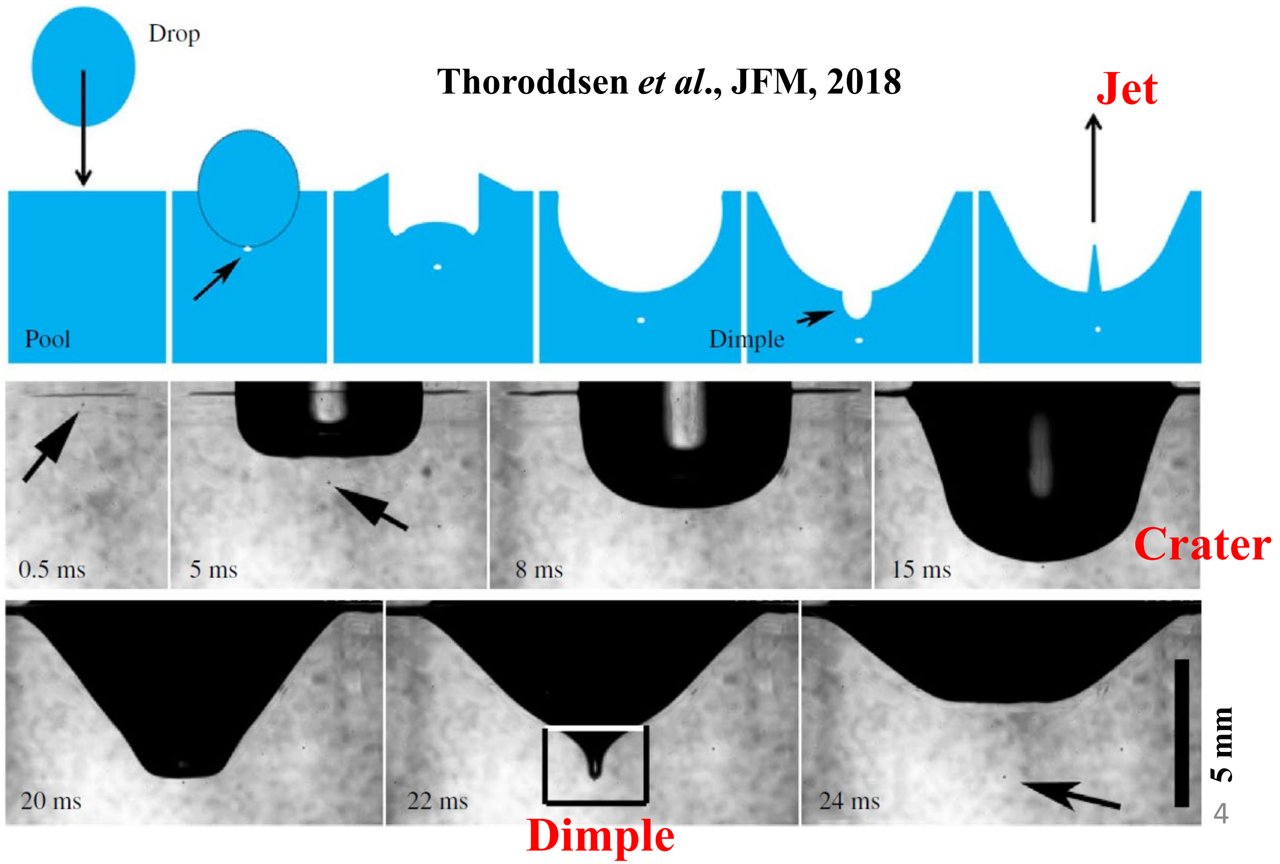
Drop impact into a liquid pool → Bubble entrapment, Worthington jet

Bubble entrapment → Mesler entrainment, Regular bubble entrapment, Irregular entrapment

Same liquid or Miscible liquid

https://www.youtube.com/watch?v=bhWJF9FIBqM

Moderate impact velocity



Thoroddsen *et al.*, JFM, 2018

1. Introduction

Drop impact into a liquid pool

Same liquid or Miscible liquid

Bubble entrapment

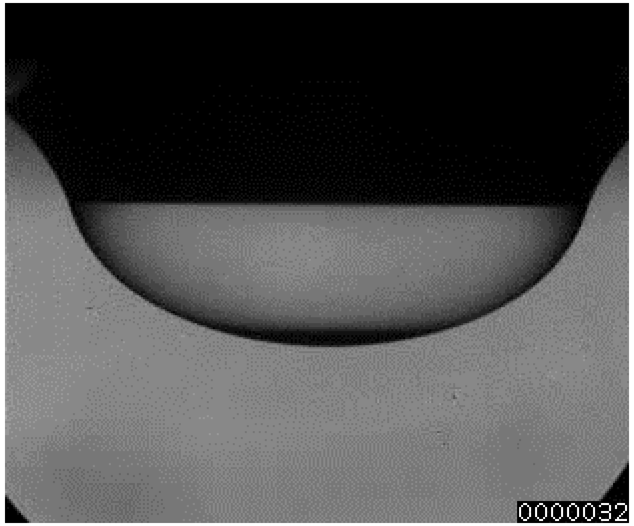
Mesler entrainment

Regular bubble entrapment

Irregular entrapment

Worthington jet

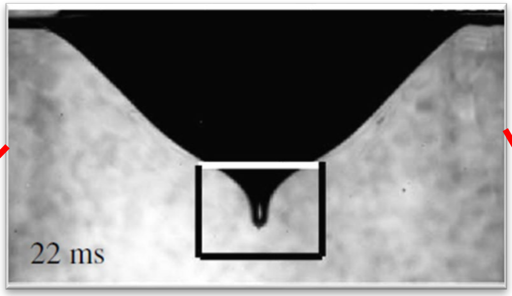
Low impact velocity

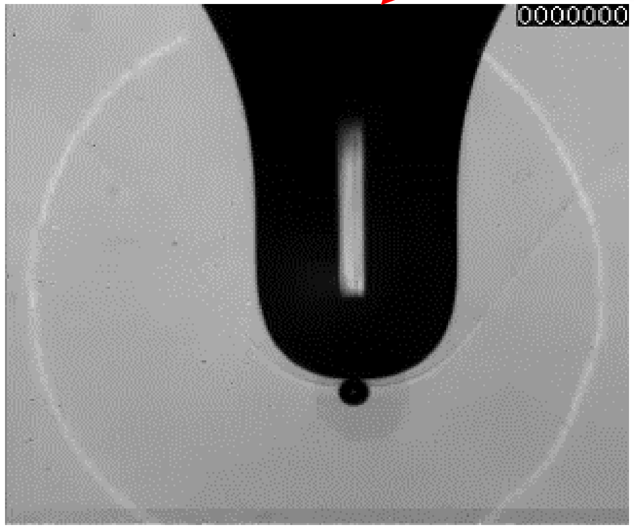


silicone oil, $U = 0.46$ m/s, $D = 2.4$ mm

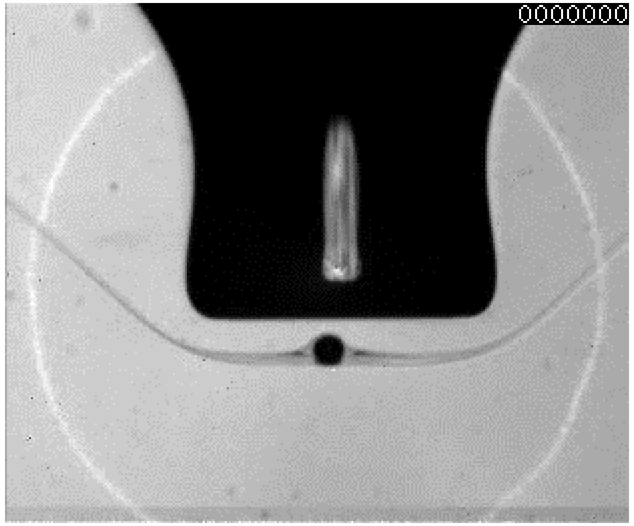
Thoroddsen *et al.*, JFM, 2012

Moderate impact velocity





$U = 1.40$ m/s, $D = 3.3$ mm



$U = 1.27$ m/s, $D = 4.2$ mm

Thoroddsen *et al.*, JFM, 2018 *50 v% water/glycerin*

Bubble entrapment - Regular bubble entrapment

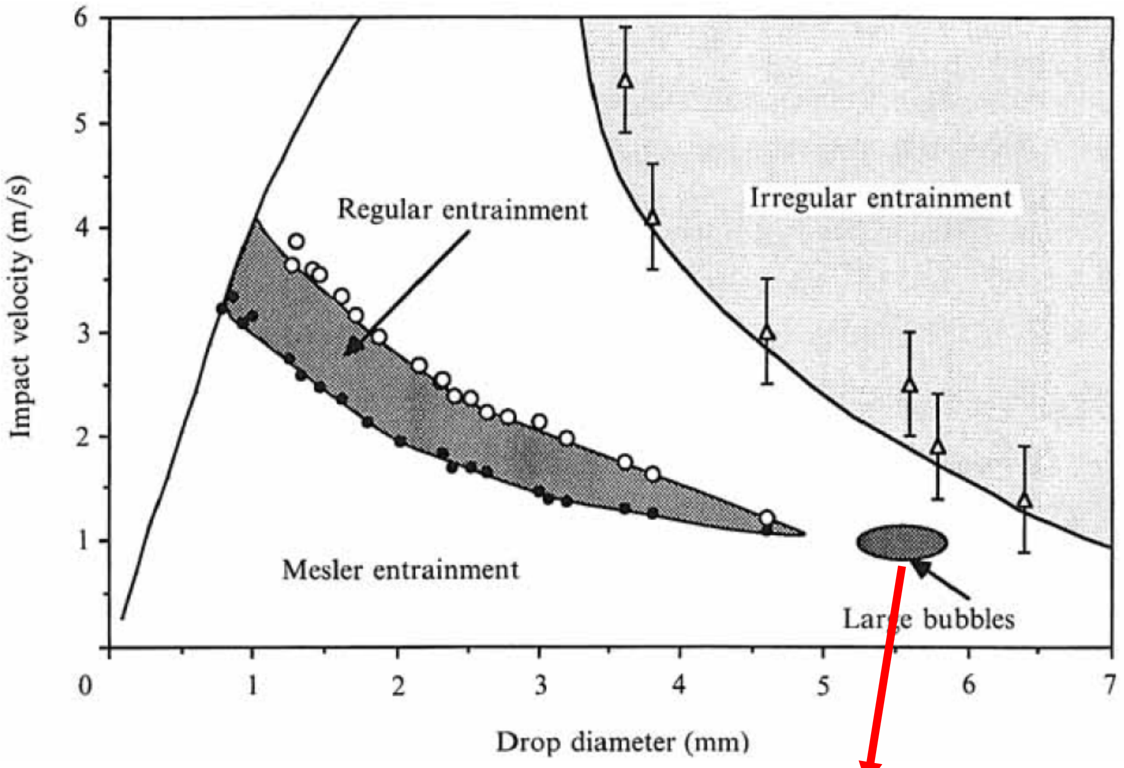
- Pumphrey & Elmore (1990) first observed a single small air bubble can be entrapped at the bottom of the crater.

- Oguz & Prosperetti (1990) simulated this process numerically and derived the bounds of the regular bubble entrapment region

Lower limit $We = 41.3Fr^{0.179}$

Upper limit $We = 48.3Fr^{0.247}$

Water drop falling into a pool of water



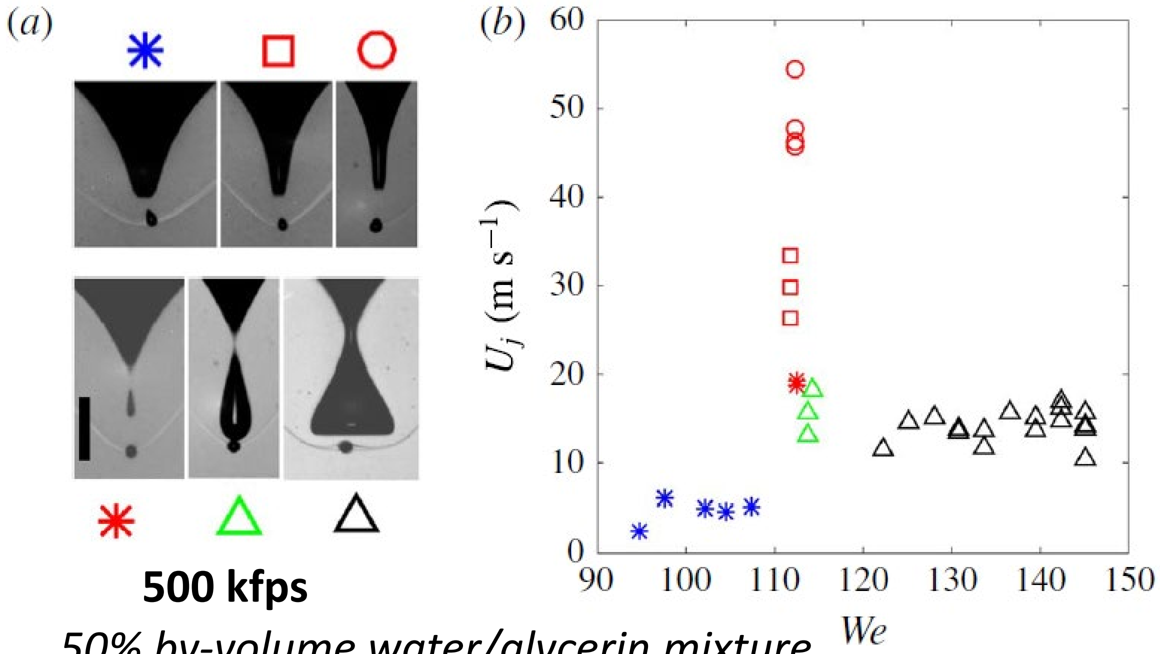
Pumphrey & Elmore, JFM, 1990

1. Introduction

Relationship between singular jets and dimple dynamics?

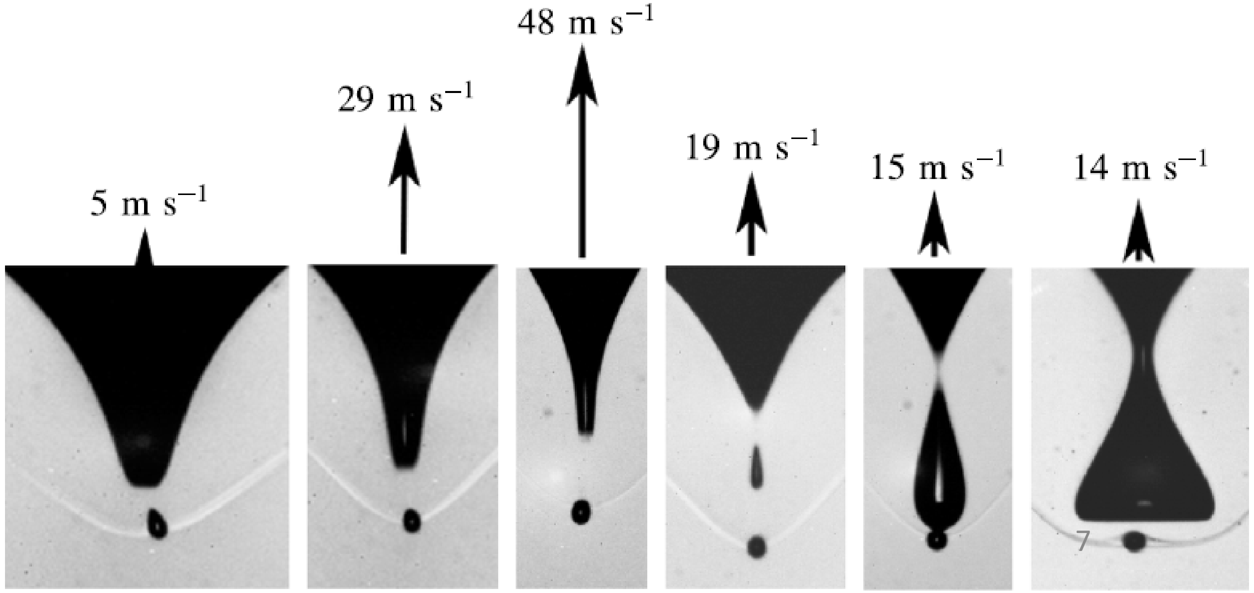
Thoroddsen et al., JFM, 2018

- ***U_j* singular jet ~ 50 m/s**
- ***Inertial dynamics*** without bubble pinched off
- ~ **20** micro-droplets & width of the tip ~ **15 µm**



500 kfps

50% by-volume water/glycerin mixture



1. Introduction

Immiscible liquid *water droplet impact onto a deep silicon oil bath*

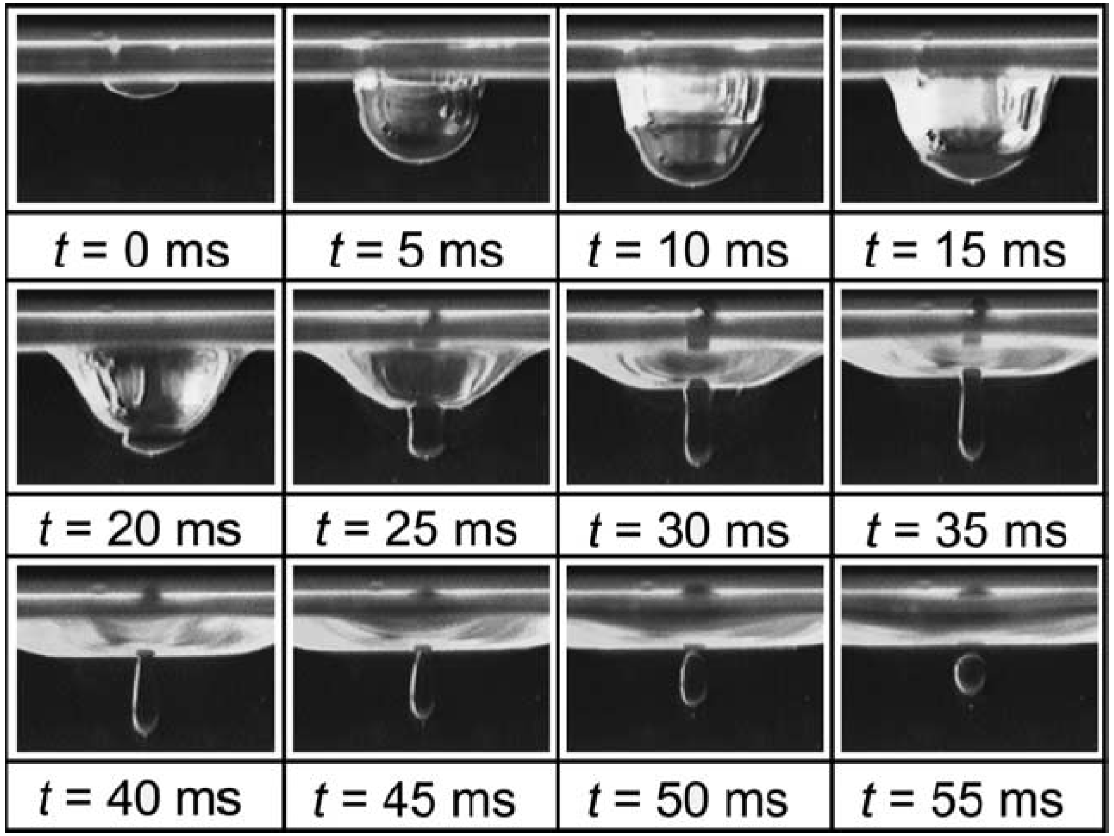


Fig. 2. Impact behavior between a falling water drop and silicone-oil surface ($\nu_T = 5 \times 10^2$ mm^2/s, $K = 59.8$ μJ).

Fujimatsu et al. (2003)

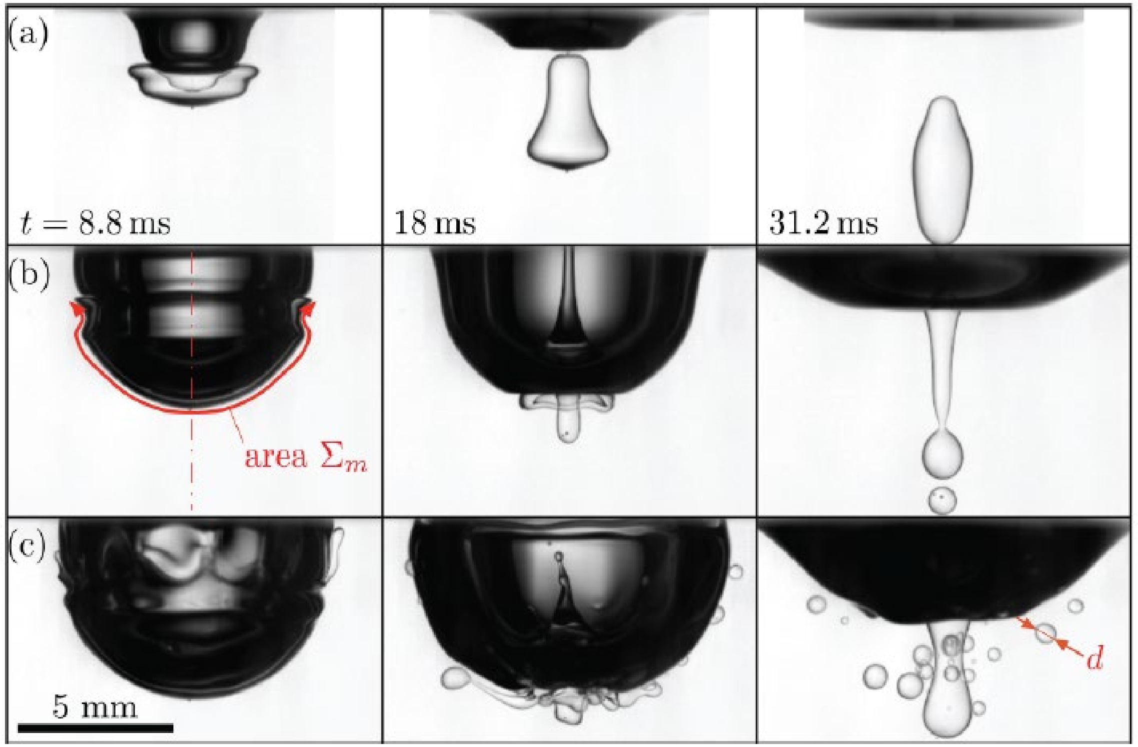
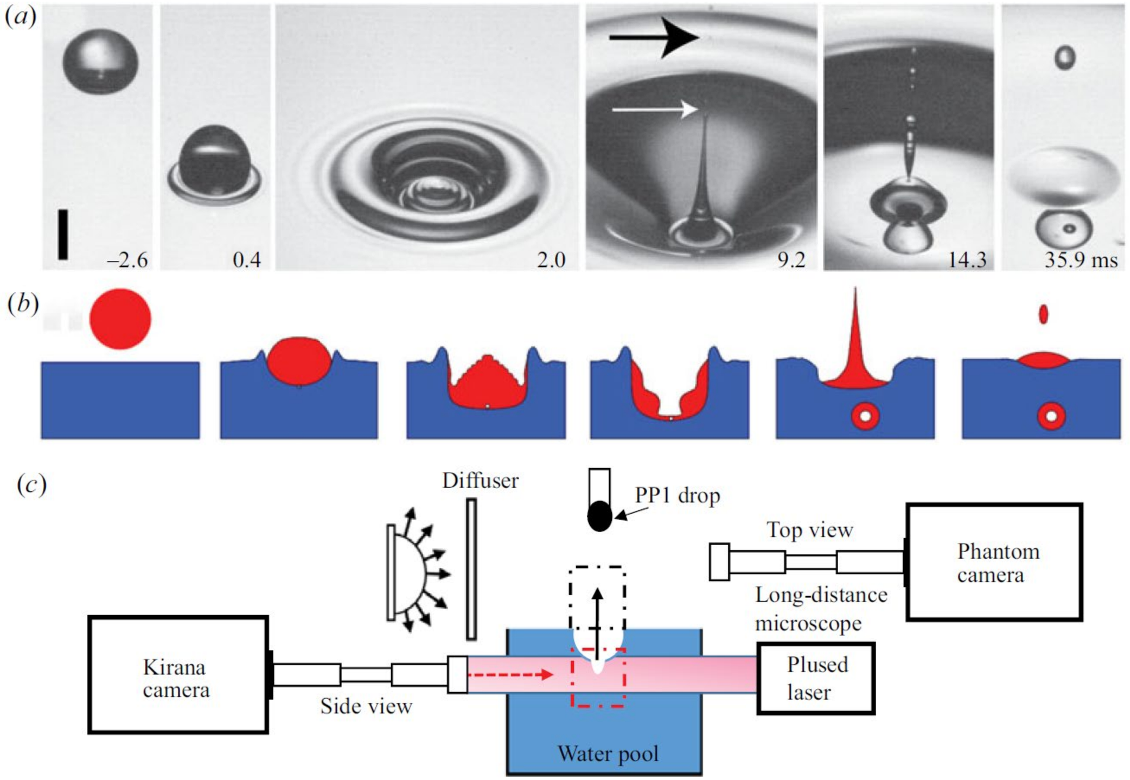


FIG. 1 (color online). Subsurface view of a water drop ($d_0 = 2.92$ mm) impact onto a deep silicone oil bath ($\nu_B = 10$ mm^2 s^{-1}) showing the drop recession after spreading, for increasing impact velocities: (a) $V = 0.73$ m s^{-1}, (b) $V = 2.26$ m s^{-1}, (c) $V = 2.96$ m s^{-1}. For each sequence, the images are taken at the same time t after the first contact.

Lhuissier et al., PRL, 2013

Experiment: immiscible drop-impact

2. Experimental methodology



Sketch of the experimental set-up

- ❖ Dimple dynamics inside the pool 1.02 μm/pixel
- ❖ Jet droplets as they emerge out of the crater 3.5 μm/pixel

- ❑ Drop size: D = 0.6, 0.9, 1.2, 1.5, 2.0 mm
- ❑ Impact velocity: 0.1 - 3.9 m/s

$$Re = \frac{DU}{\nu} = 374 - 13,000;$$

$$Fr = \frac{U^2}{gD} = 10 - 1,800;$$

$$We = \frac{\rho D U^2}{\sigma} = 10 - 2,000;$$

Materials

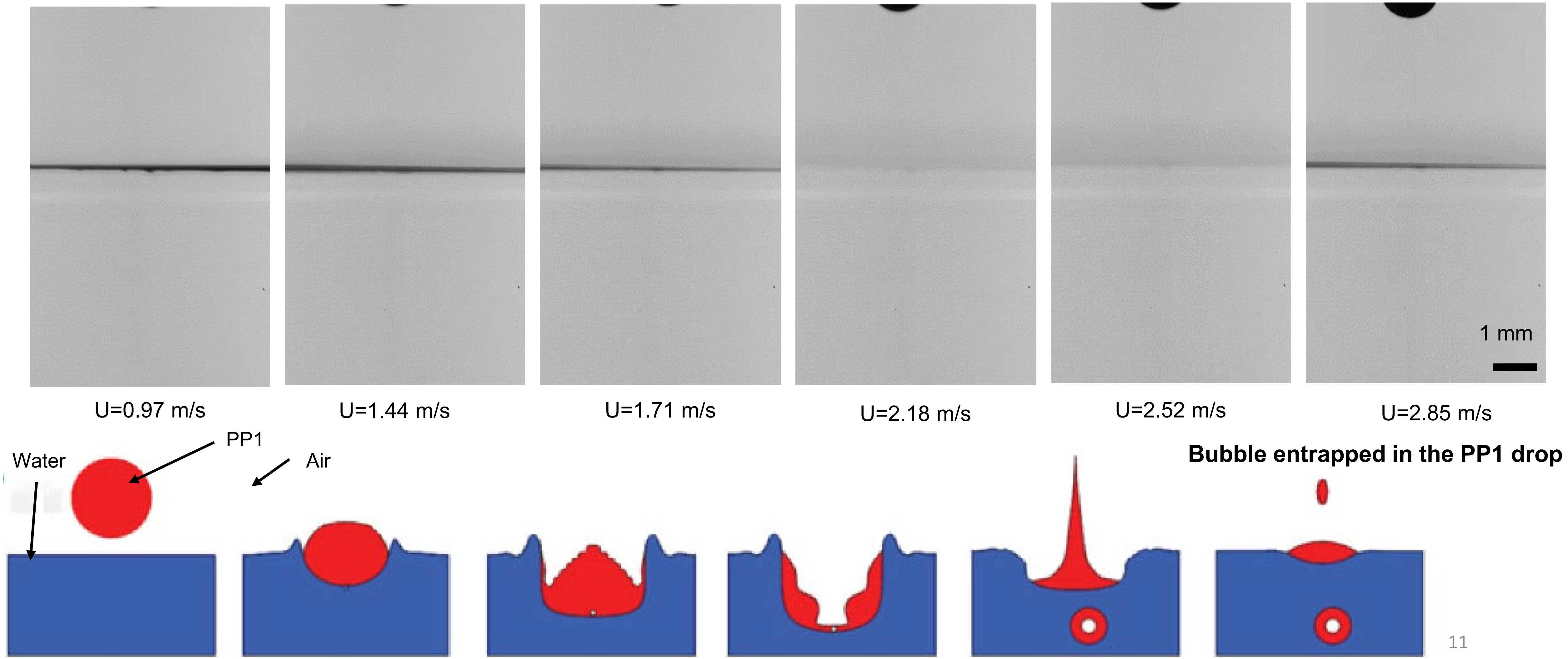
		Chemical formula	Density ρ (g/cm^3)	Dynamics viscosity μ (mPa s)	Kinematic viscosity ν (cSt)	Surface tension σ (mN/m)	Capillary length Lc (mm)	Refractive Index n
Drop	PP1	C_6F_{14}	1.710	0.810	0.47	11.9	0.84	1.252
Liquid pool	Distilled water	H_2O	0.996	1.004	1.01	72.1	2.72	1.333

3. Results

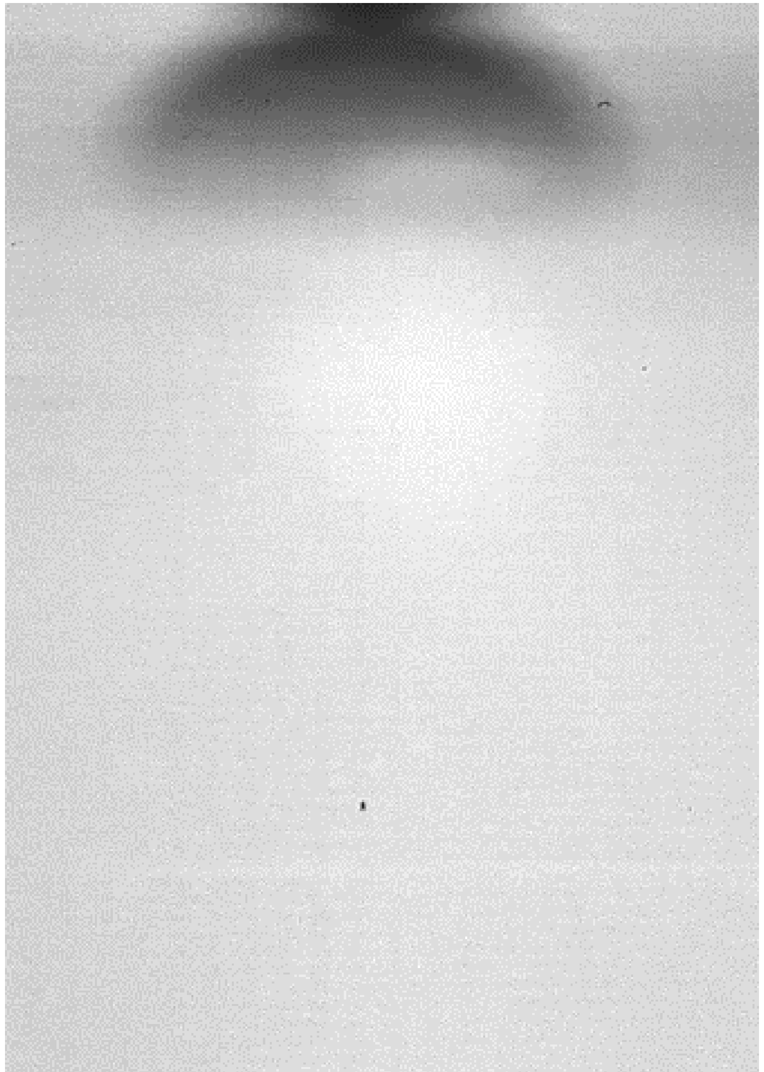
Dimple dynamics & Bubble entrapment

Frame rate: 57,000 FPS

D =1.3mm

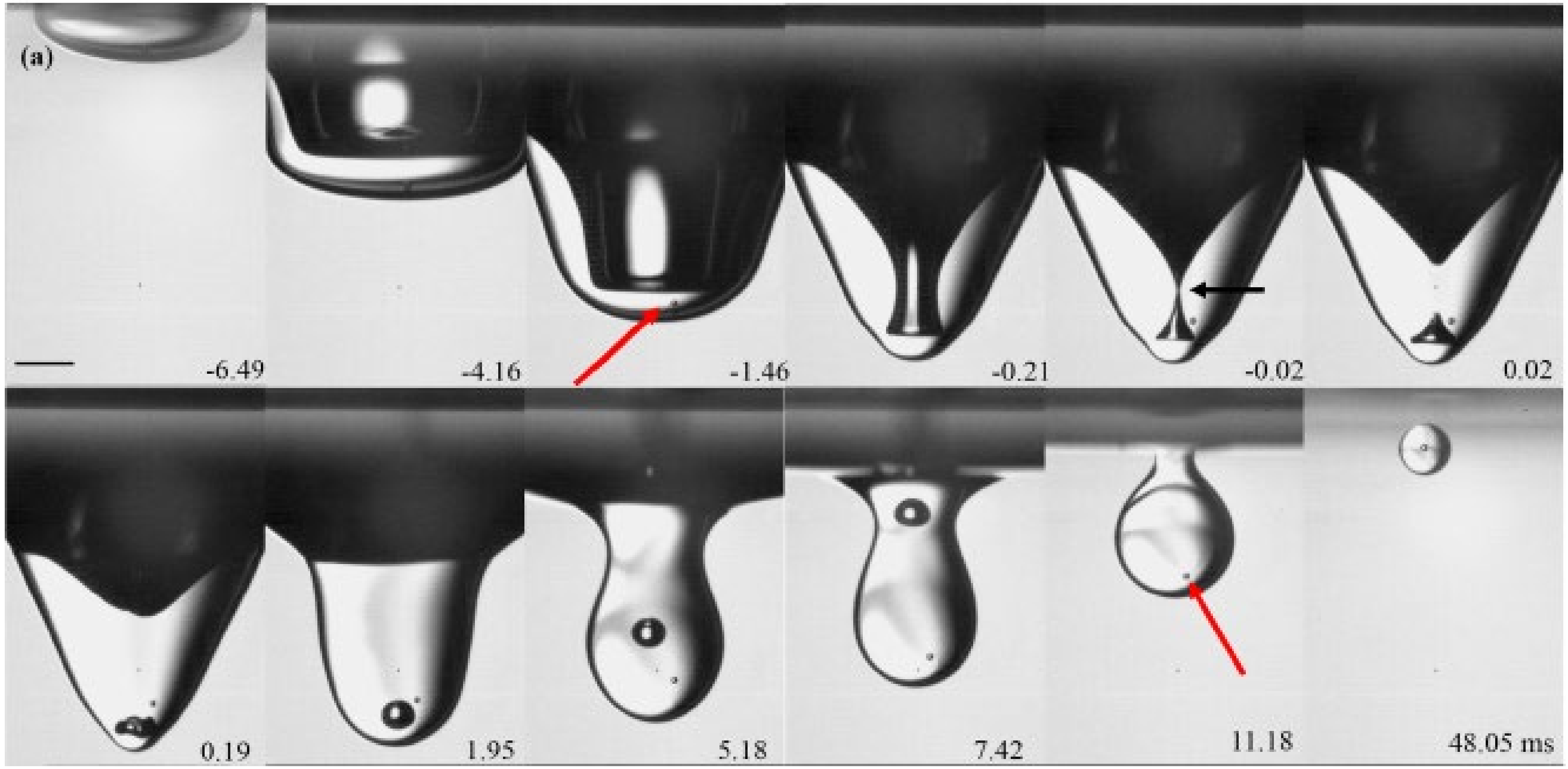


3.1 Dimple dynamics & Bubble entrapment



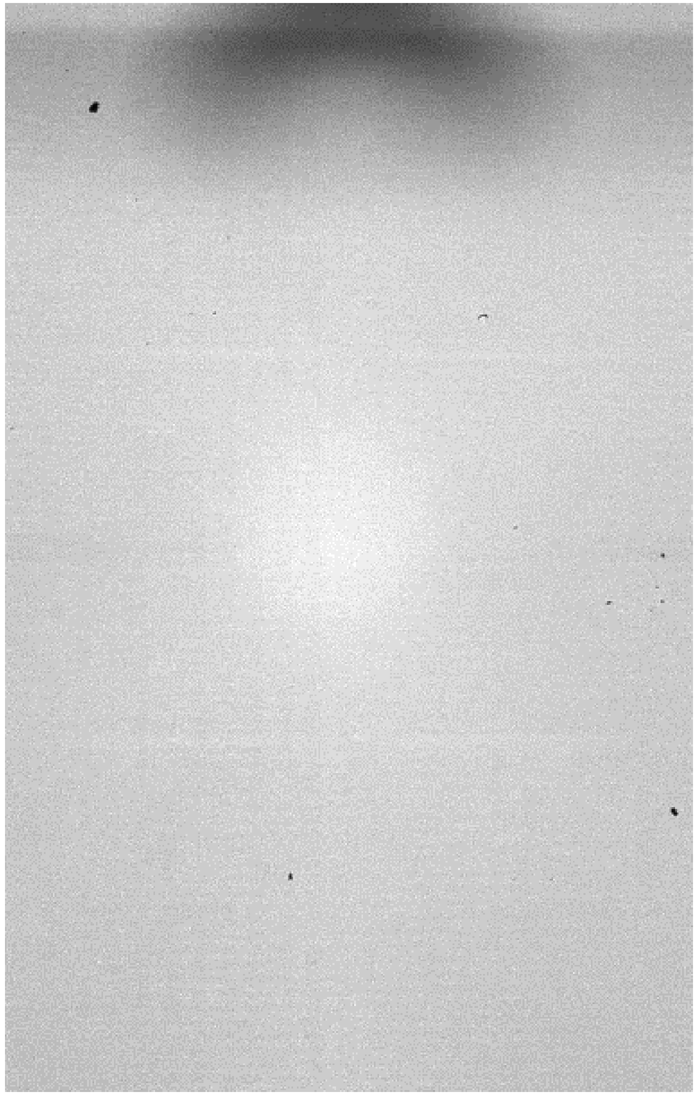
U = 0.97 m/s
D =1.3 mm

Bubble size 294 μm

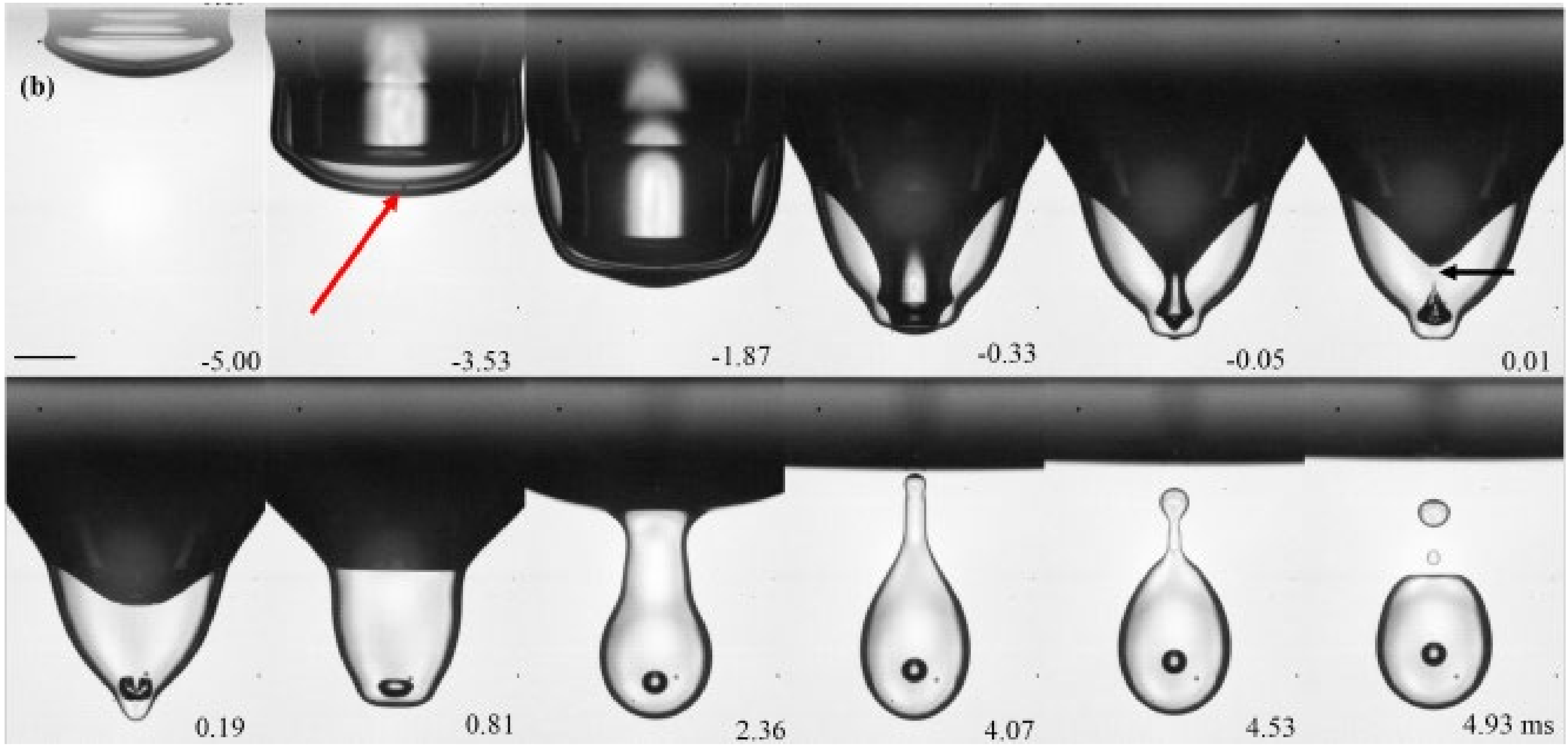


Close-up of typical bubble entrapment process during the crater evolution. (a) at U = 0.97 m/s, D = 1.3mm, Re = 2636, Fr = 74, We = 173. The video is taken at 57 kfps.

3.1 Dimple dynamics & Bubble entrapment



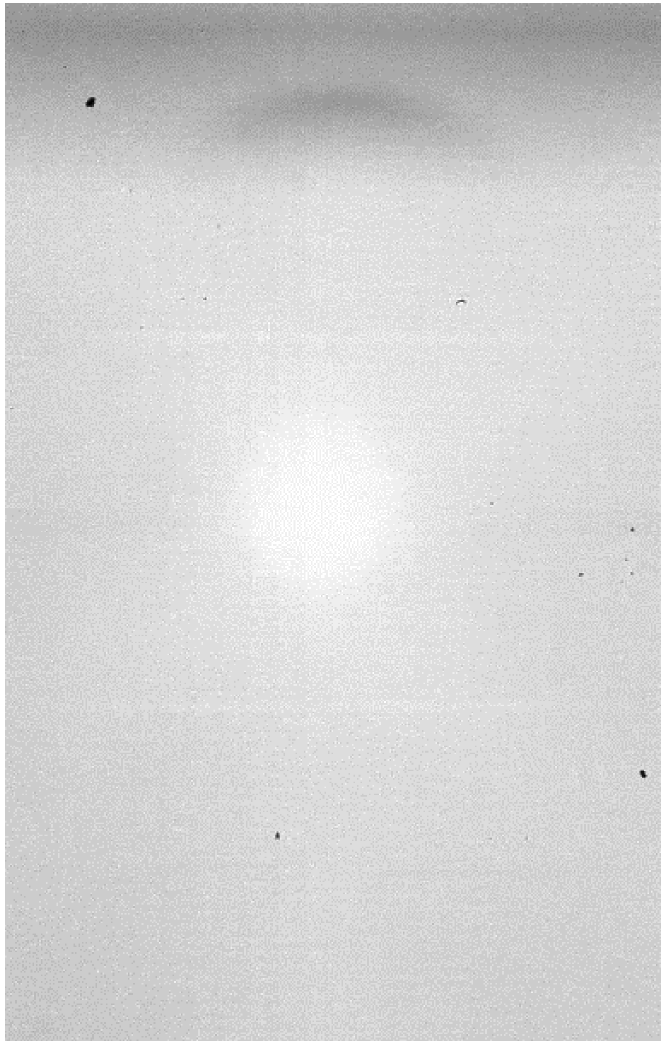
U = 1.40 m/s
D =1.1mm



Close-up of typical bubble entrapment process during the crater evolution. (b) at U =1.40 m/s, D =1.1mm, Re= 3199, Fr = 185, We = 305. The video is taken at 75 kfps.

Bubble size 208 μm 37,500 Hz

3.1 Dimple dynamics & Bubble entrapment



U = 1.72 m/s
D = 1.3 mm

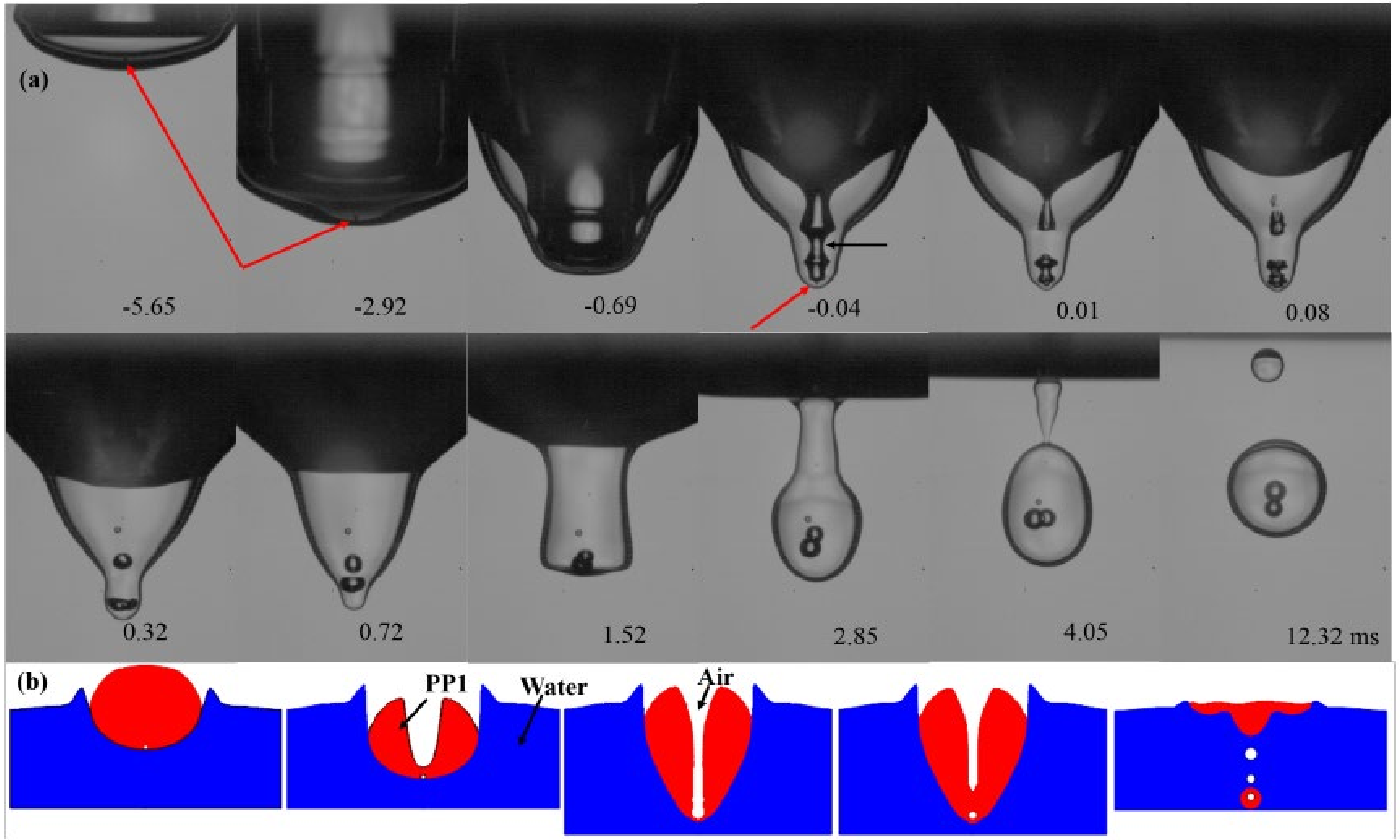
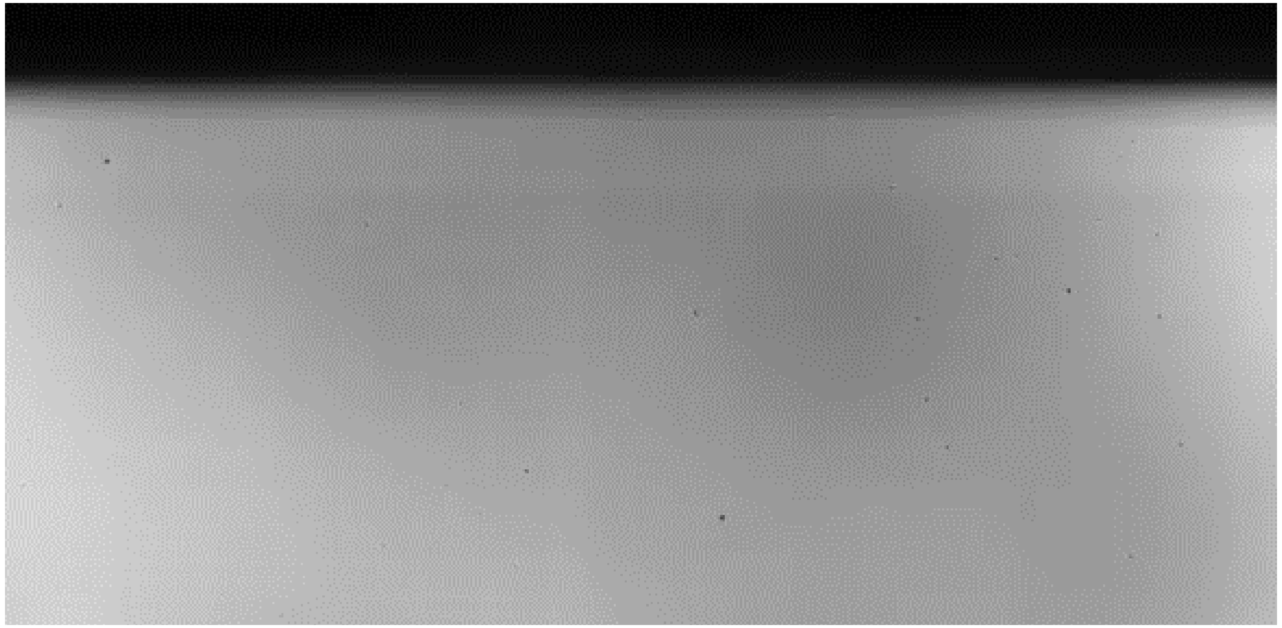


Figure 8: Close-up of typical bubble entrapment process during the crater evolution at U=1.72 m/s, D =1.3mm, Re= 4215, Fr= 259, We= 493. The video is taken at 75 kHz. The small bubble under the drop indicated by the arrow is the central bubble entrapped by the initial drop contacting the liquid pool,studied by Thoroddsen *et al.* (2003) Thoroddsen, Takehara & Etoh (2003). See also supplementary movies.

Bubble size 202 μm & 175 μm 25,000 Hz

3.1 Dimple dynamics & Bubble entrapment

Frame rate: 83,000 FPS



U = 2.29 m/s
D = 1.63 mm

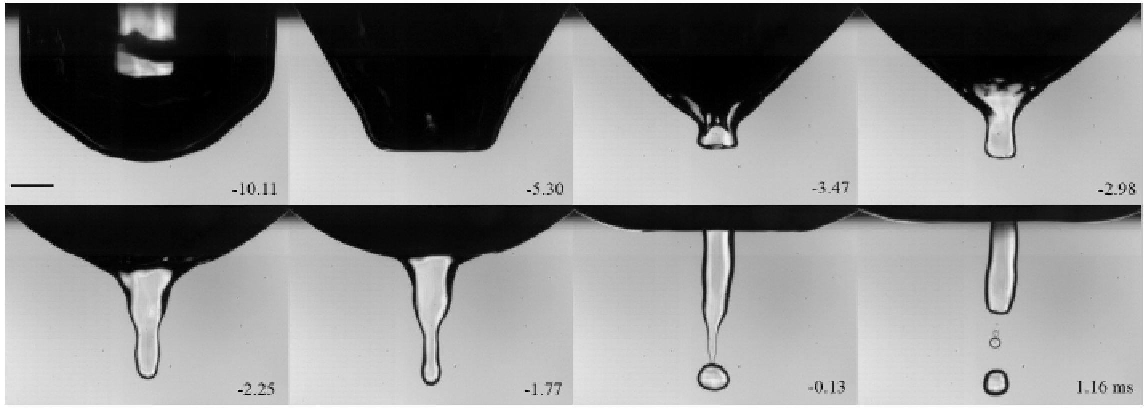


Figure 12: PP1 drop impacting into the distilled water pool at U = 2.29 m/s and D = 1.63 mm, Re= 7862, Fr= 328, We = 1224. No bubble pinch-off from the dimple and the drop liquid PP1 forms a liquid column and pinches off due to Plateau-Rayleigh instability. The video is taken at 83 kfps and the time for pinch-off of the liquid column is chosen as the initial time. The scale bar is 1 mm.

3.1 Dimple dynamics & Bubble entrapment

Frame rate: 83,000 FPS

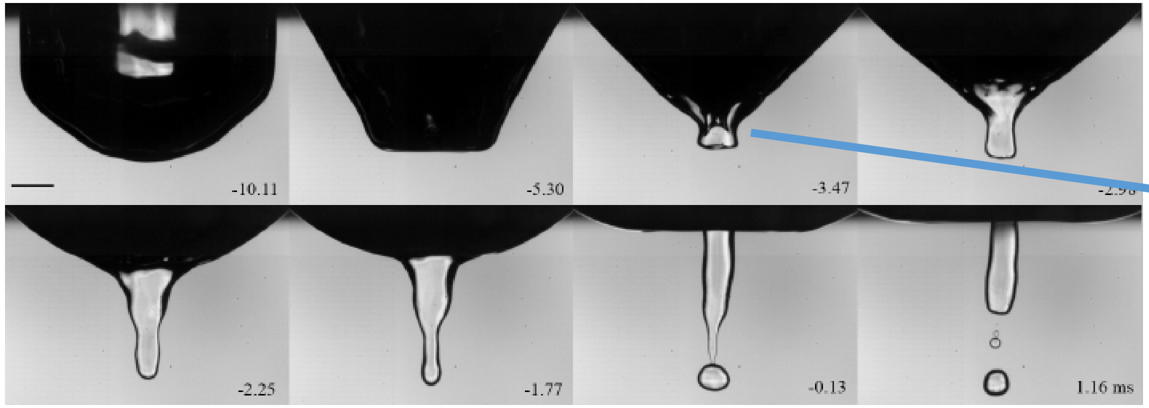


Figure 12: PP1 drop impacting into the distilled water pool at $U = 2.29$ m/s and $D = 1.63$ mm, $Re = 7862$, $Fr = 328$, $We = 1224$. No bubble pinch-off from the dimple and the drop liquid PP1 forms a liquid column and pinches off due to Plateau-Rayleigh instability. The video is taken at 83 kfps and the time for pinch-off of the liquid column is chosen as the initial time. The scale bar is 1 mm.

U = 2.29 m/s
D = 1.63 mm

Secondary entrapment

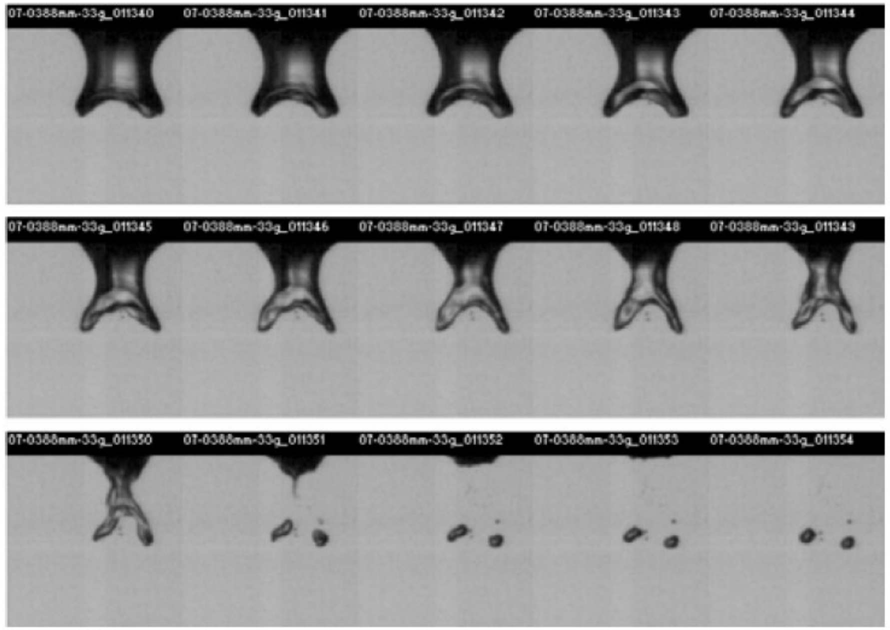
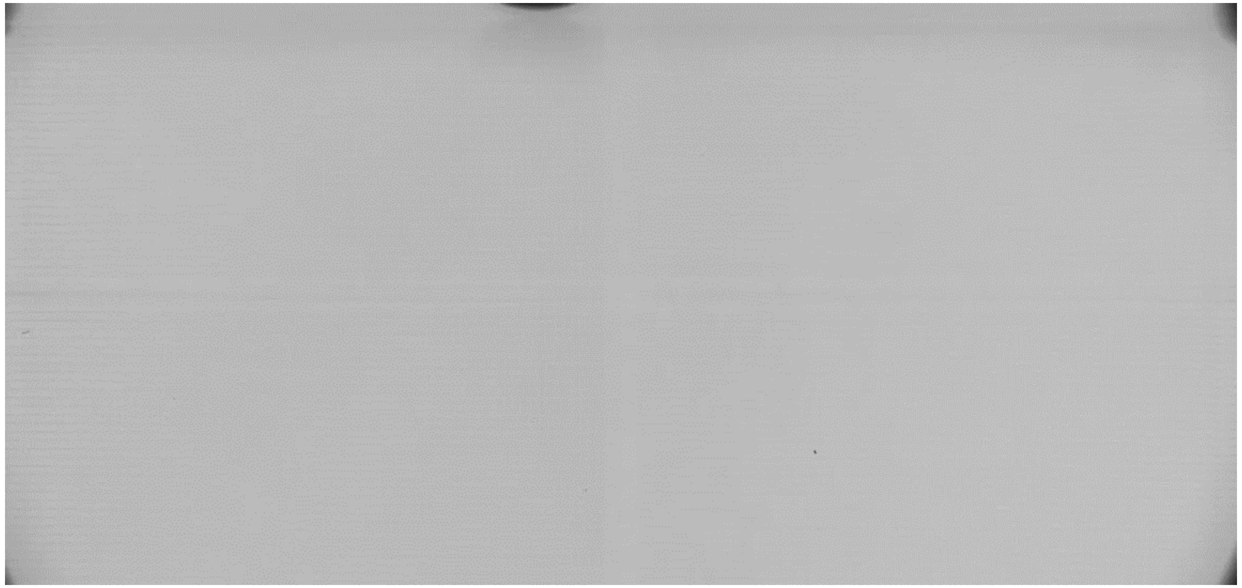


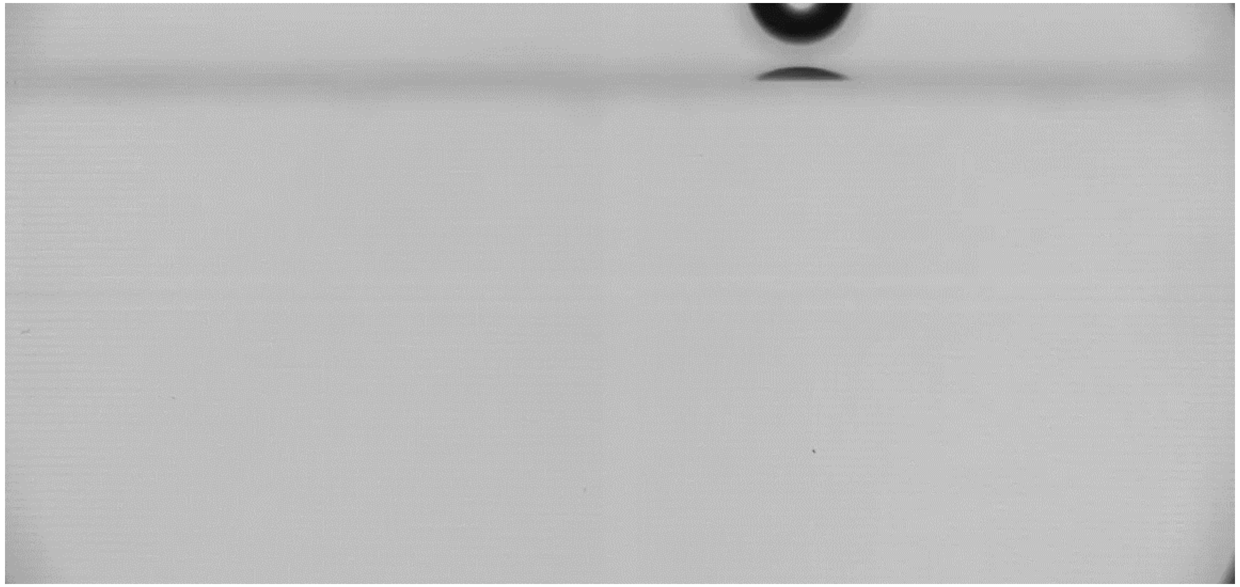
Figure 6. Formation of secondary bubbles. $d = 2.06$ mm, $U = 2.68$ m/s, $Fr = 356$, $We = 202$, $Re = 4904$. At 40000 fps.

Liow and Cole (2007)

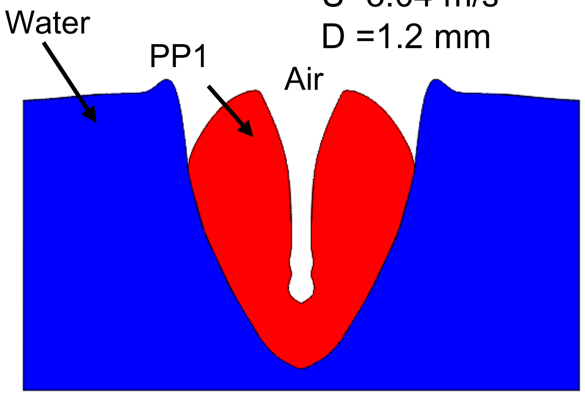
3.1 Dimple dynamics & Bubble entrapment

Frame rate: 40,000 FPS

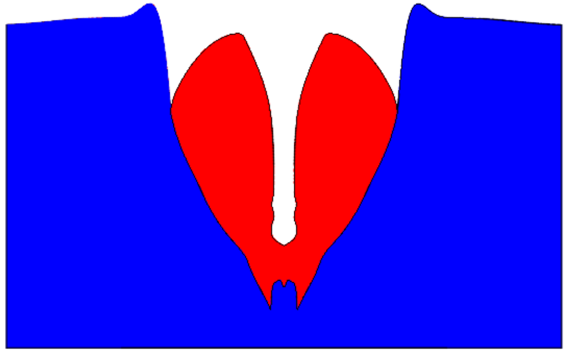


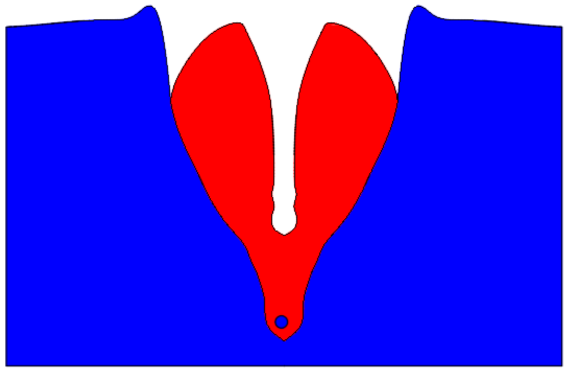


U=3.04 m/s
D =1.2 mm

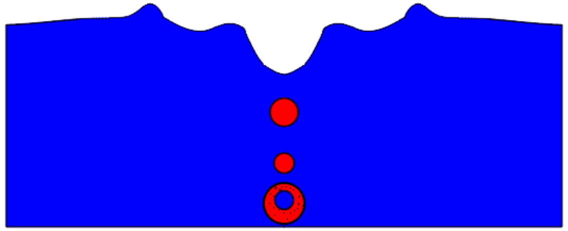


Water drop entrapped in the PP1 drop

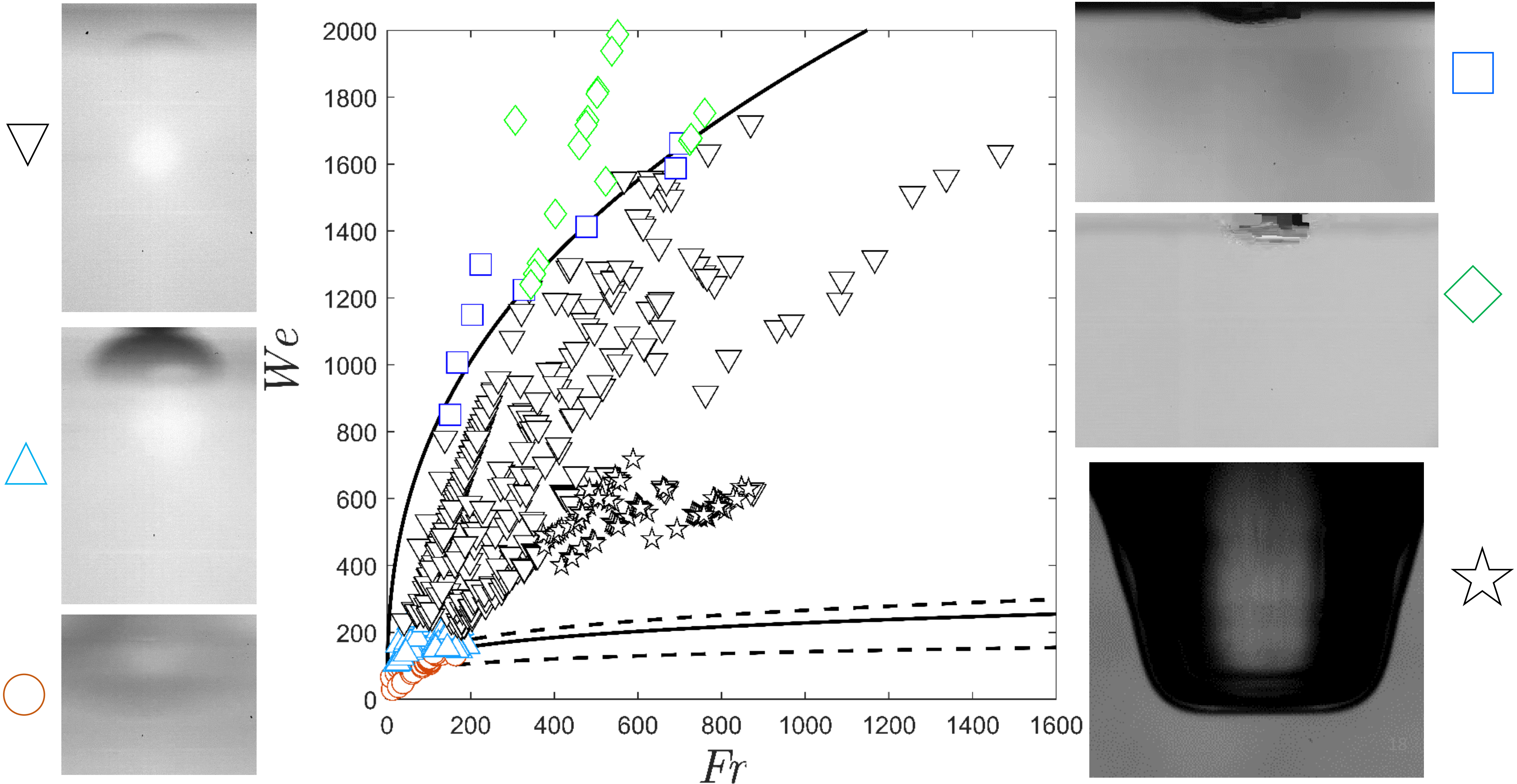




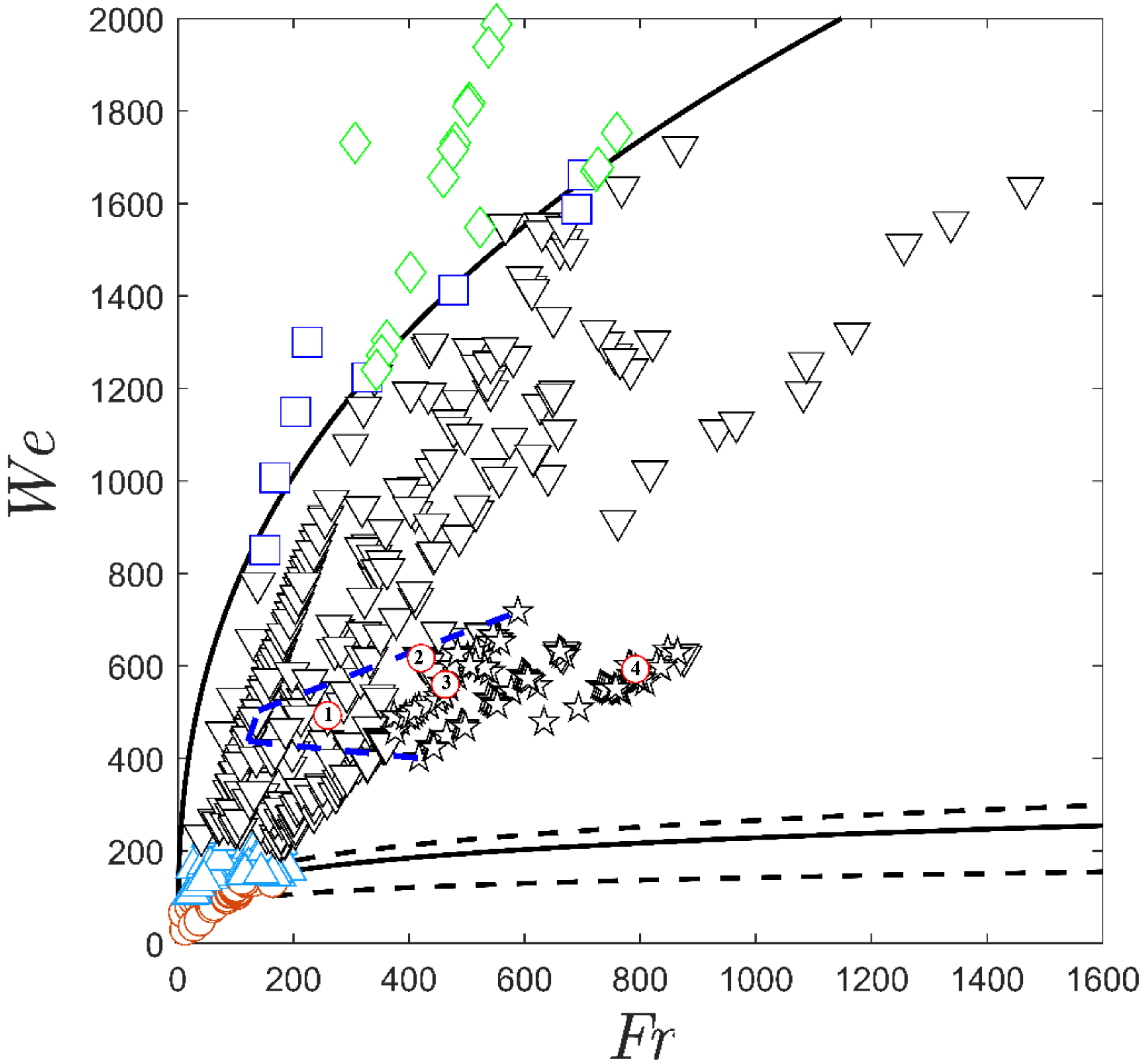
U=3.50 m/s
D =1.2 mm



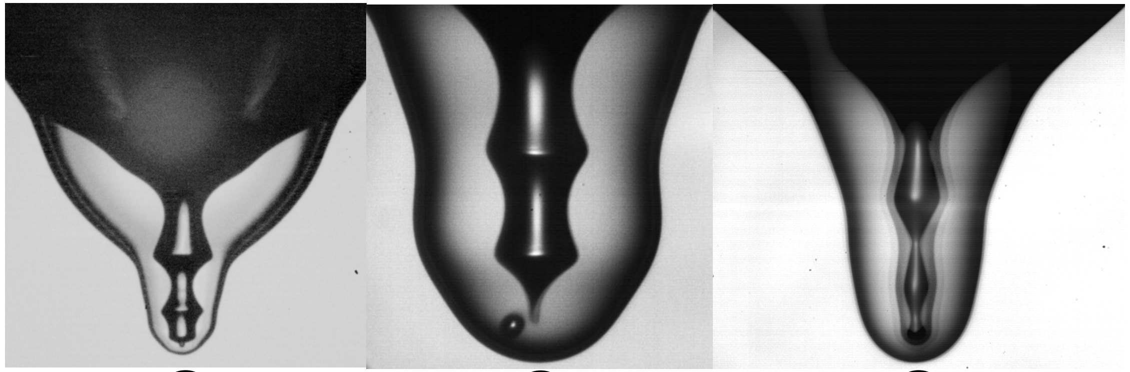
3. Results **Regime diagram**



3. Results Multi Dimple Regime



Multiple dimple pinch-offs



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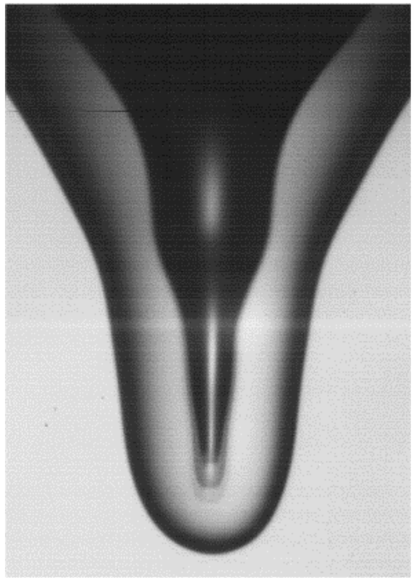
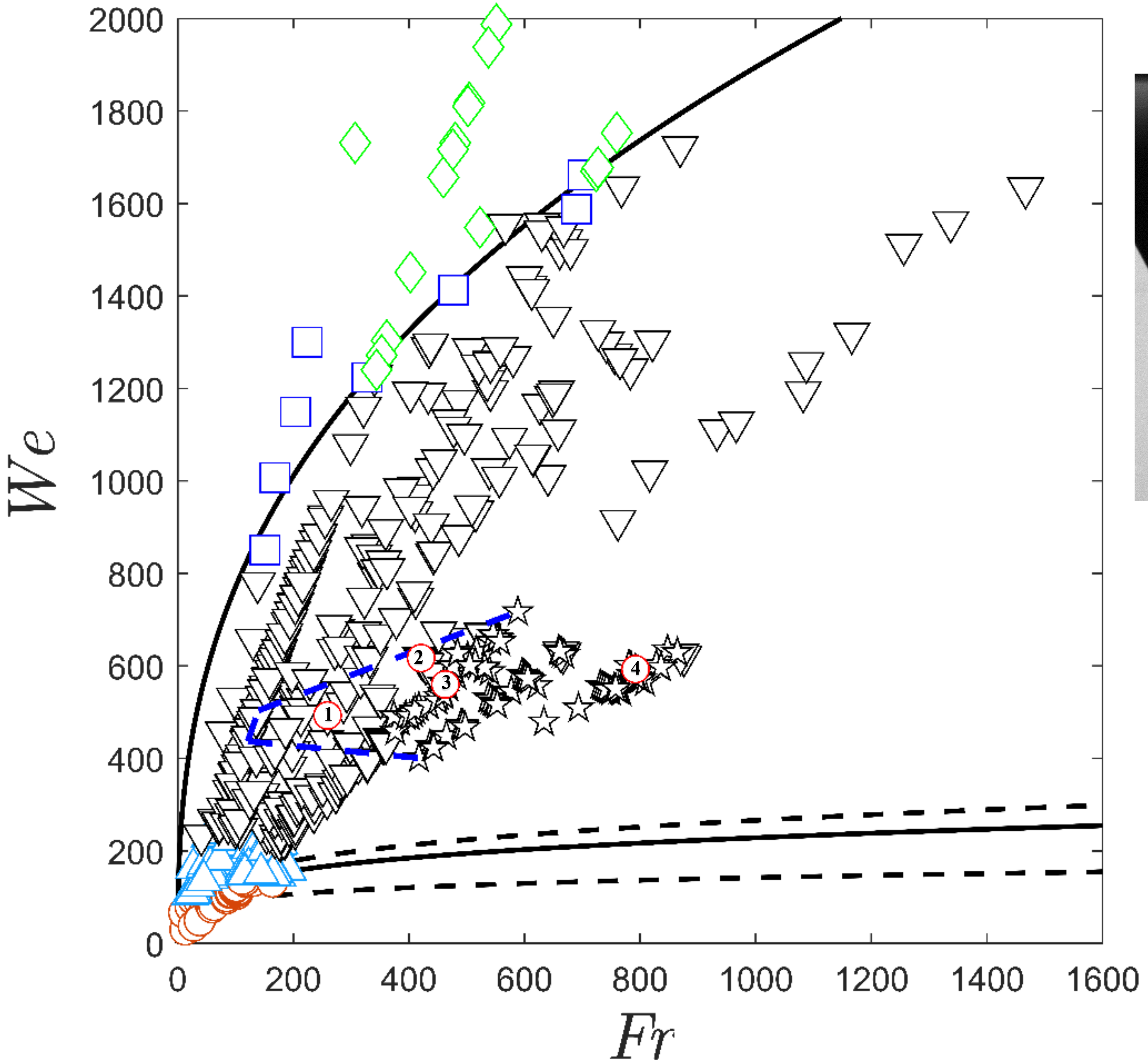
Dimple cascade

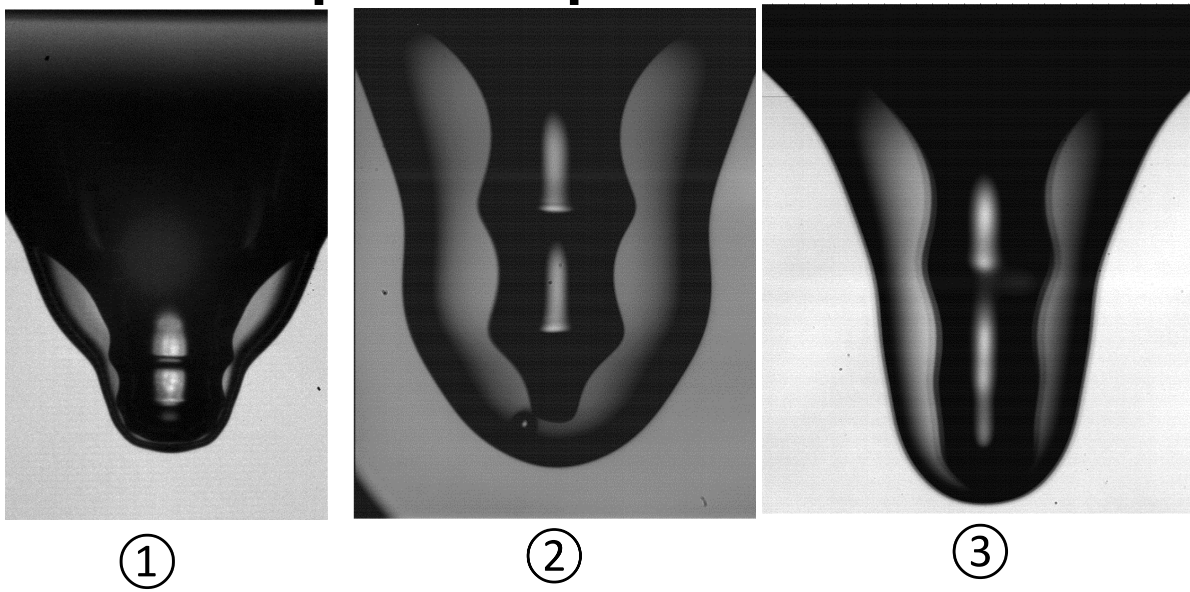


④

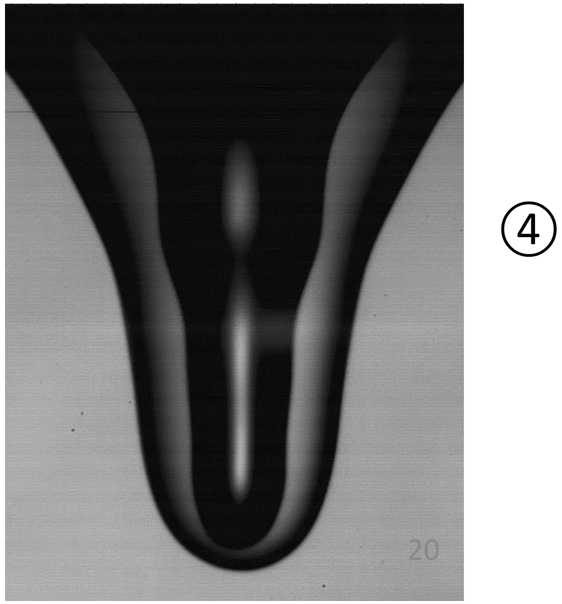
3. Results **Multi Dimple Regime**



Multi dimple with pinch off



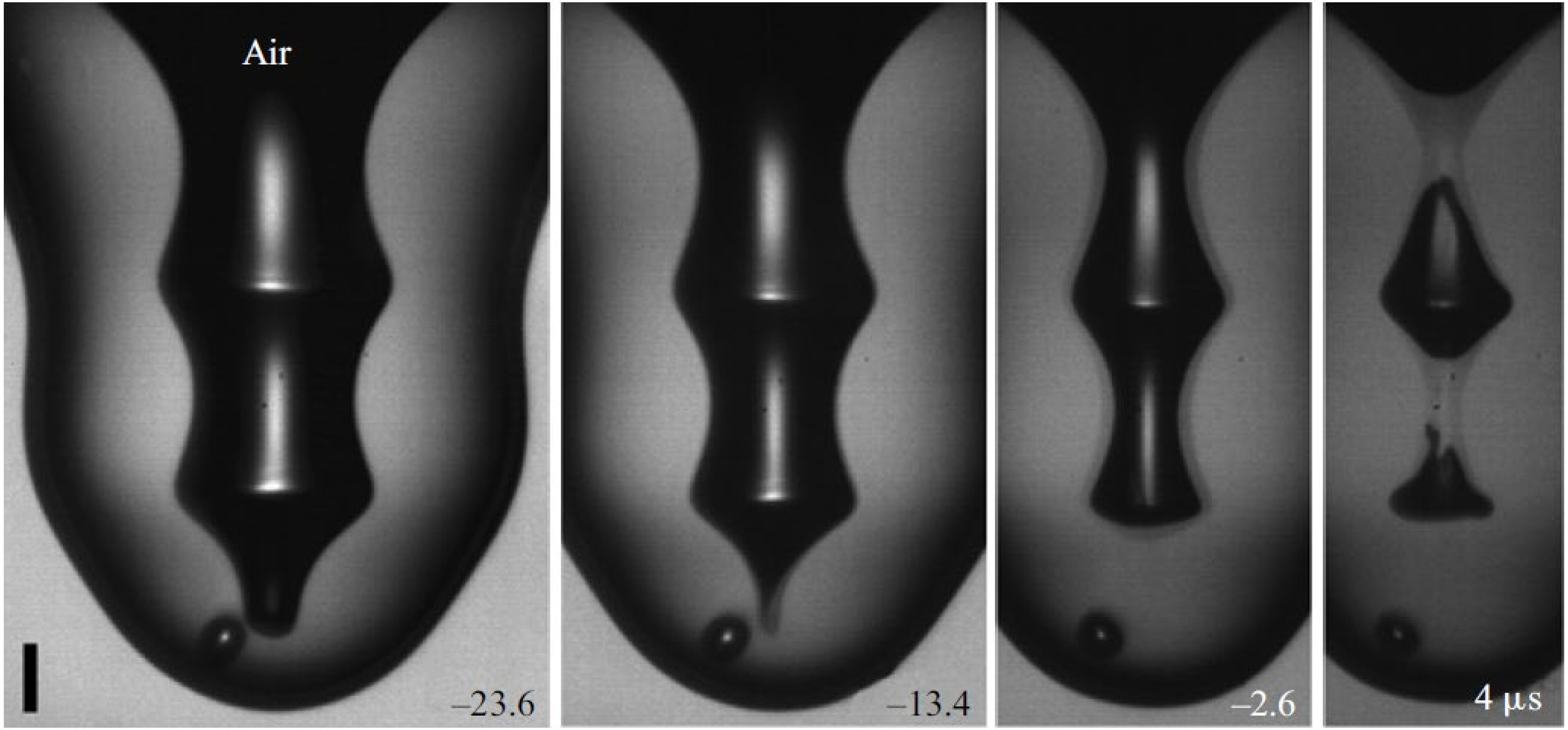
Dimple cascade



Immiscible Impact

$D = 1.0$ mm, $U_i = 2.1$ m/s
$We = 617$, $Fr = 421$

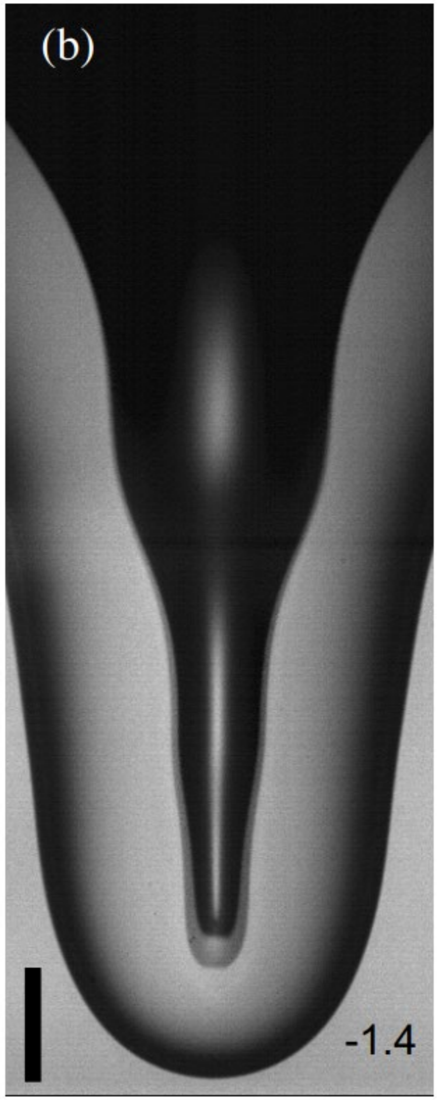
PP1 drop on Water pool



Bamboo-shaped Pinch-off

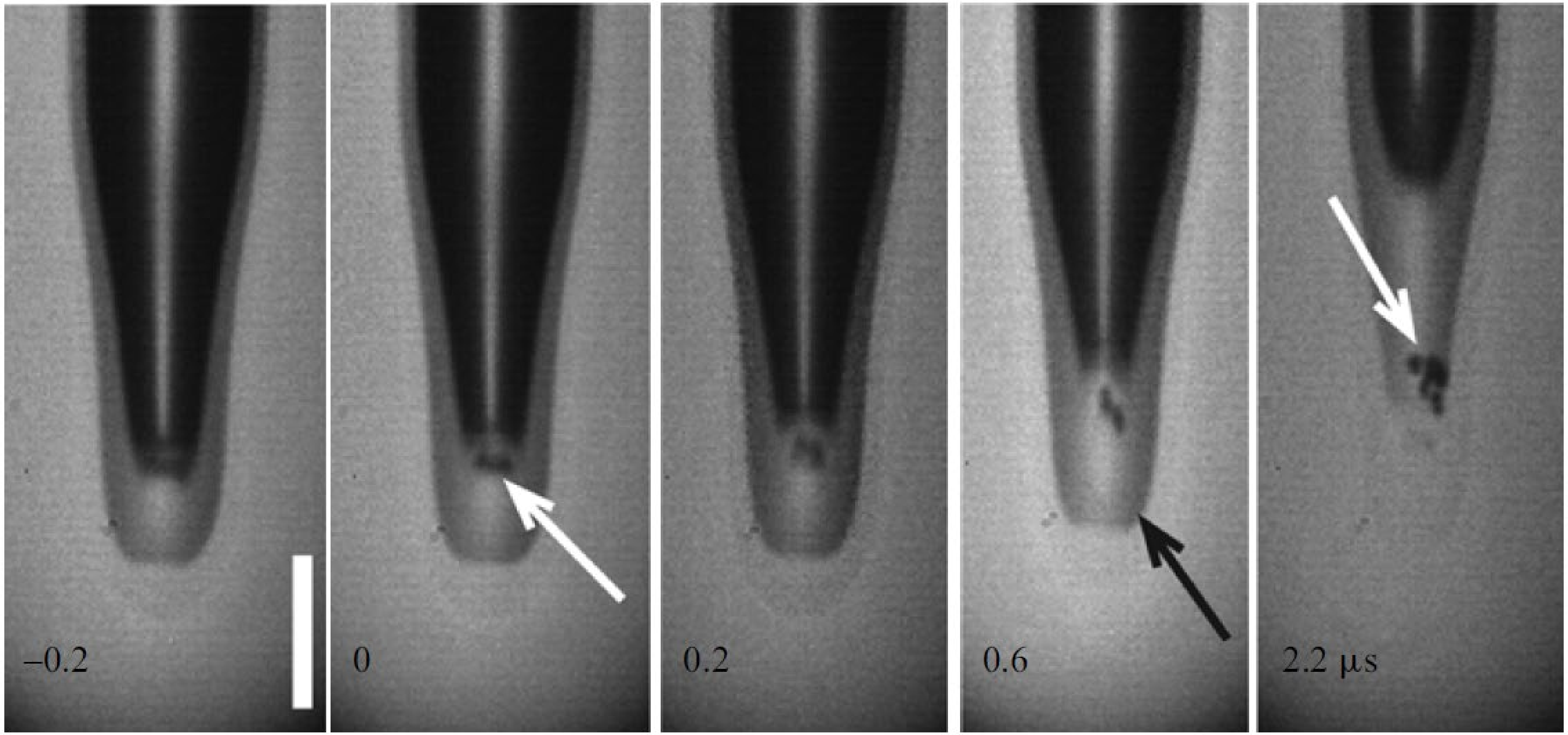
[1] Yang, Tian and Thoroddsen, 2020, JFM

Immiscible Impact



PP1 drop on Water pool

$D = 0.8$ mm, $U_i = 2.2$ m/s
$We = 609$, $Fr = 569$



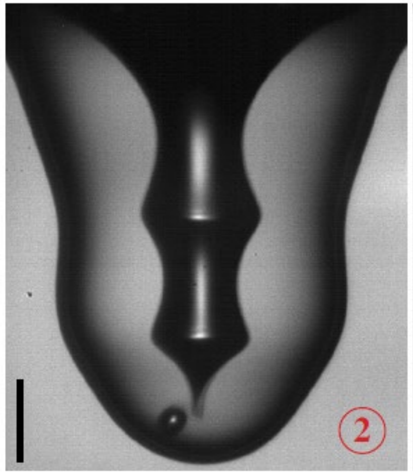
Telescopic-shaped Pinch-off

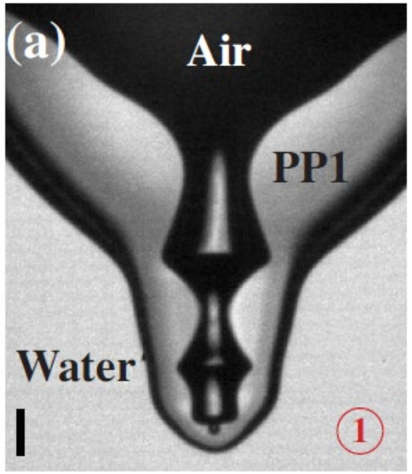
[1] Yang, Tian and Thoroddsen, 2020, JFM

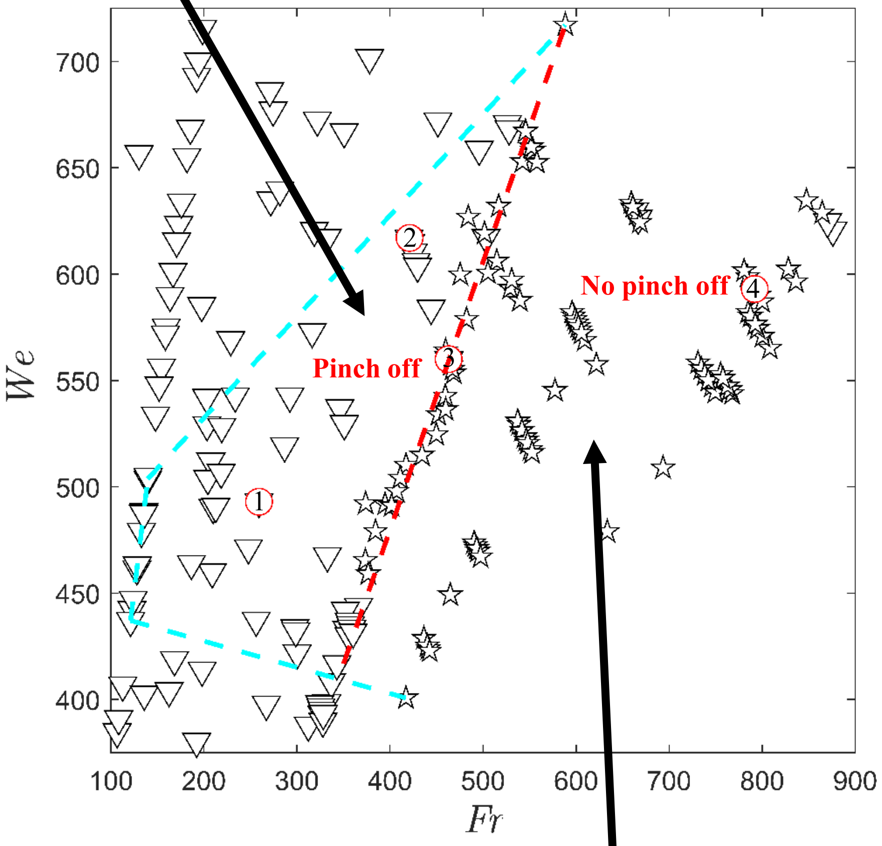
3. Results

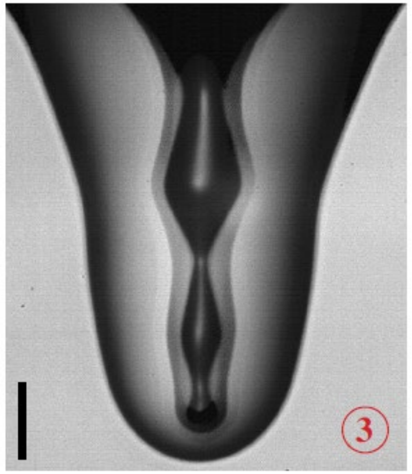
Bamboo multi-dimples

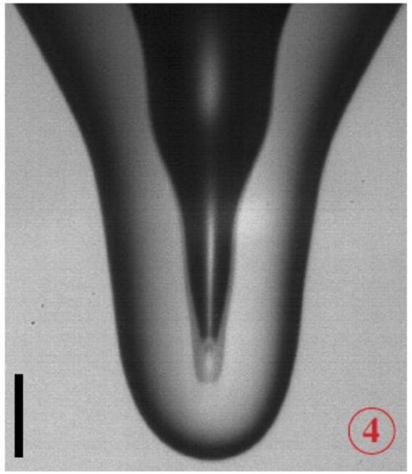
$$We = 1.26Fr - 24.47$$





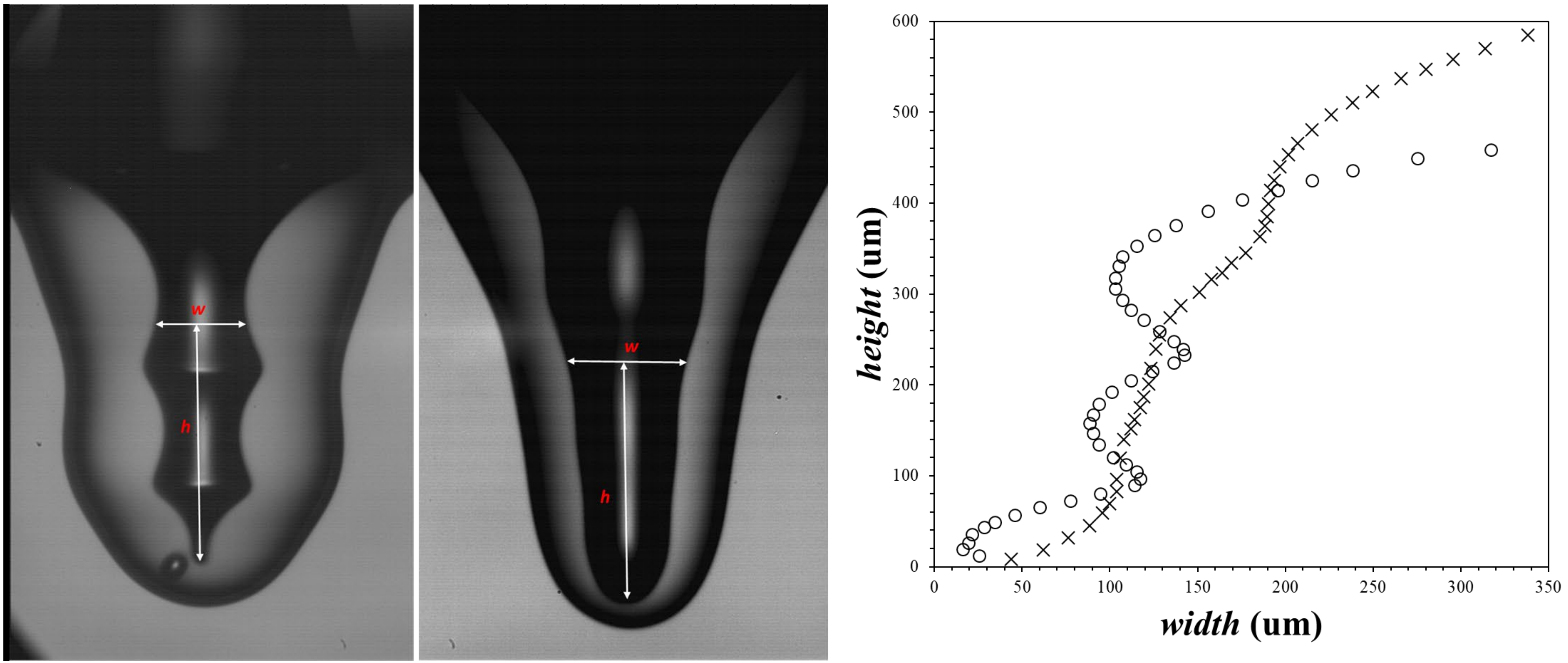






Telescopic multi-dimples

3. Results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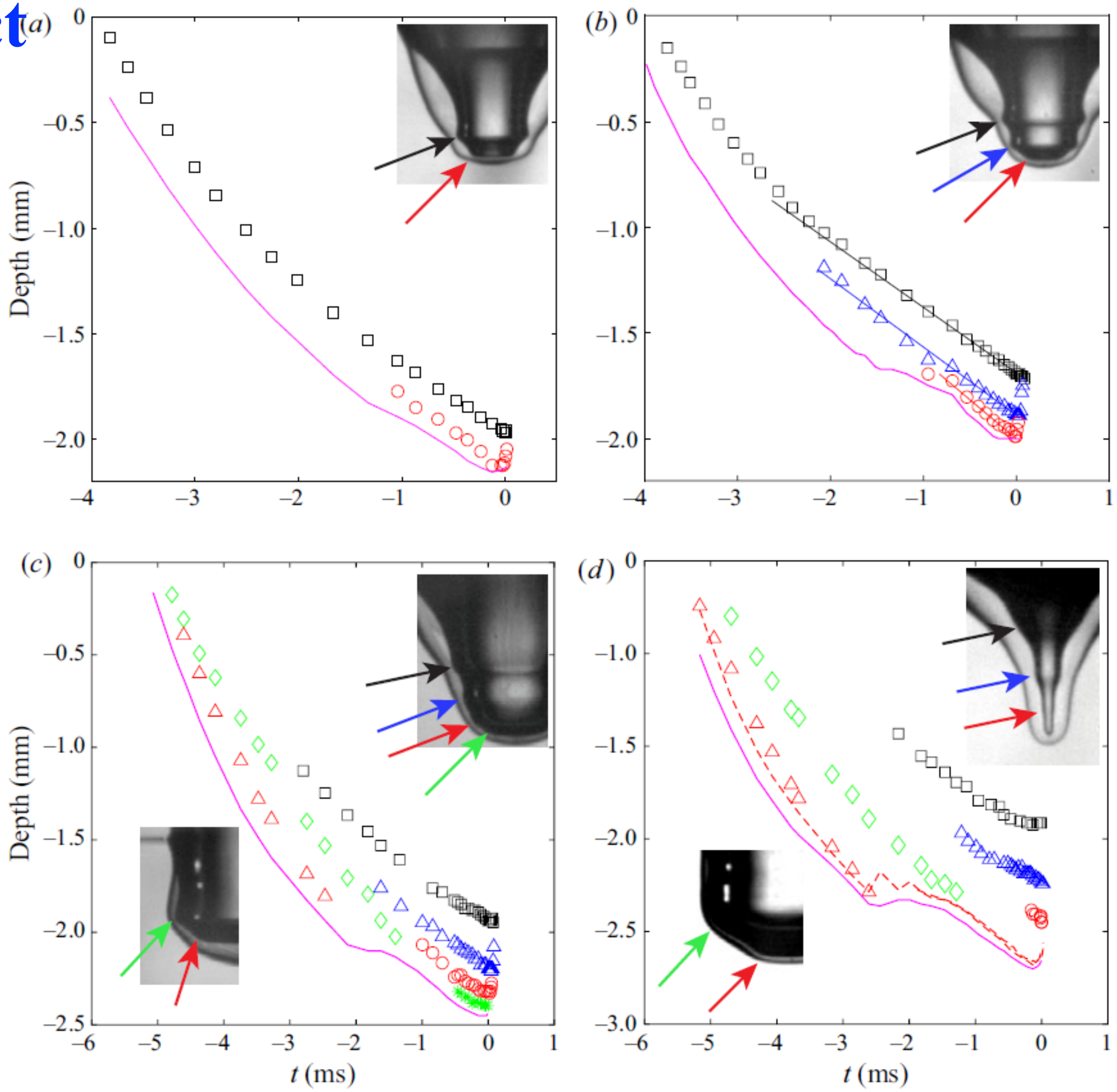
Immiscible Impact



Trajectories of the wave troughs along the crater free surface for four cases

[1] Yang, Tian and Thoroddsen, 2020, JFM

Capillary wave-shapes

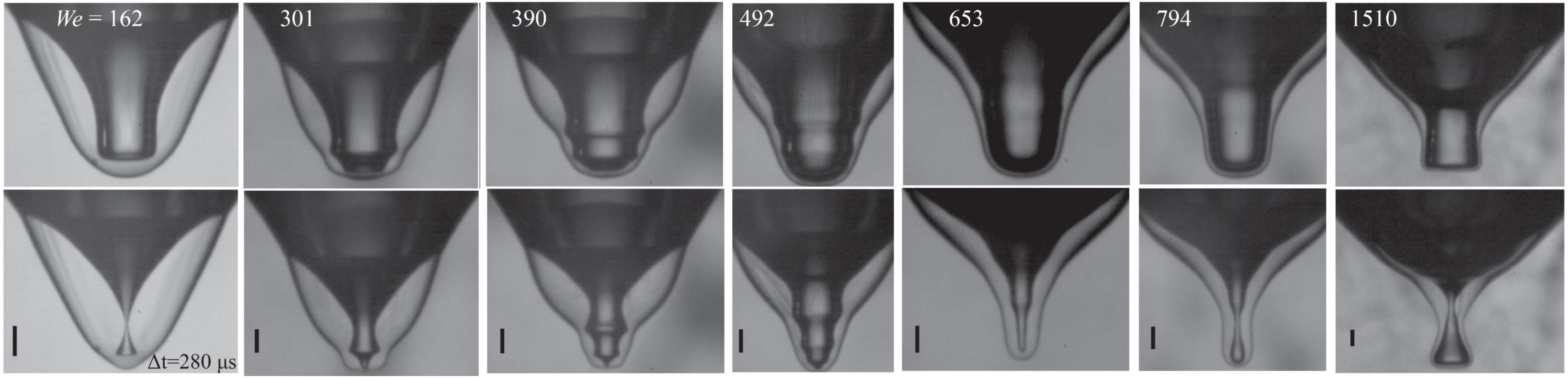


Figure 4. Capillary wave-shapes on the dimple for a range of We, for $D = 0.935 \pm 0.025$ mm and impact velocity increasing from left to right: U = 1.09, 1.48, 1.72, 1.91, 2.23, 2.47 & 3.37 m/s. The bottom row is shown at the most singular point during the collapse, with the top row 280 μs earlier. The scale bars are 200 μm long.

3. Results Dimple shape & Jet velocity

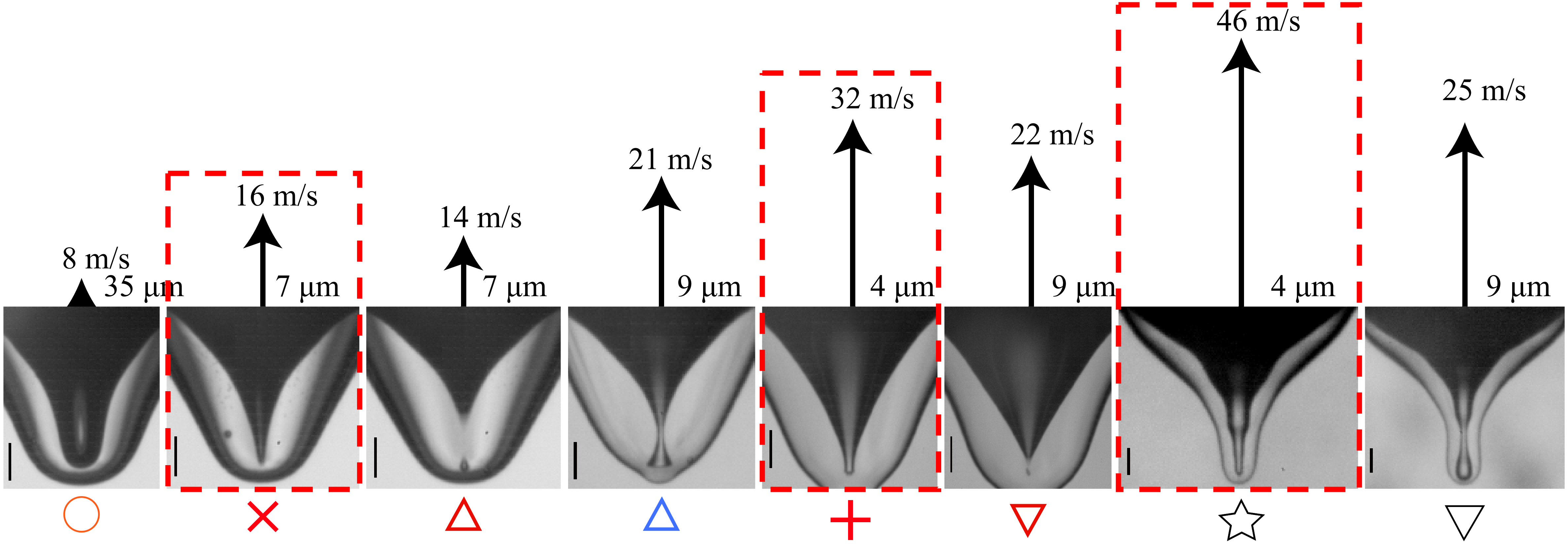
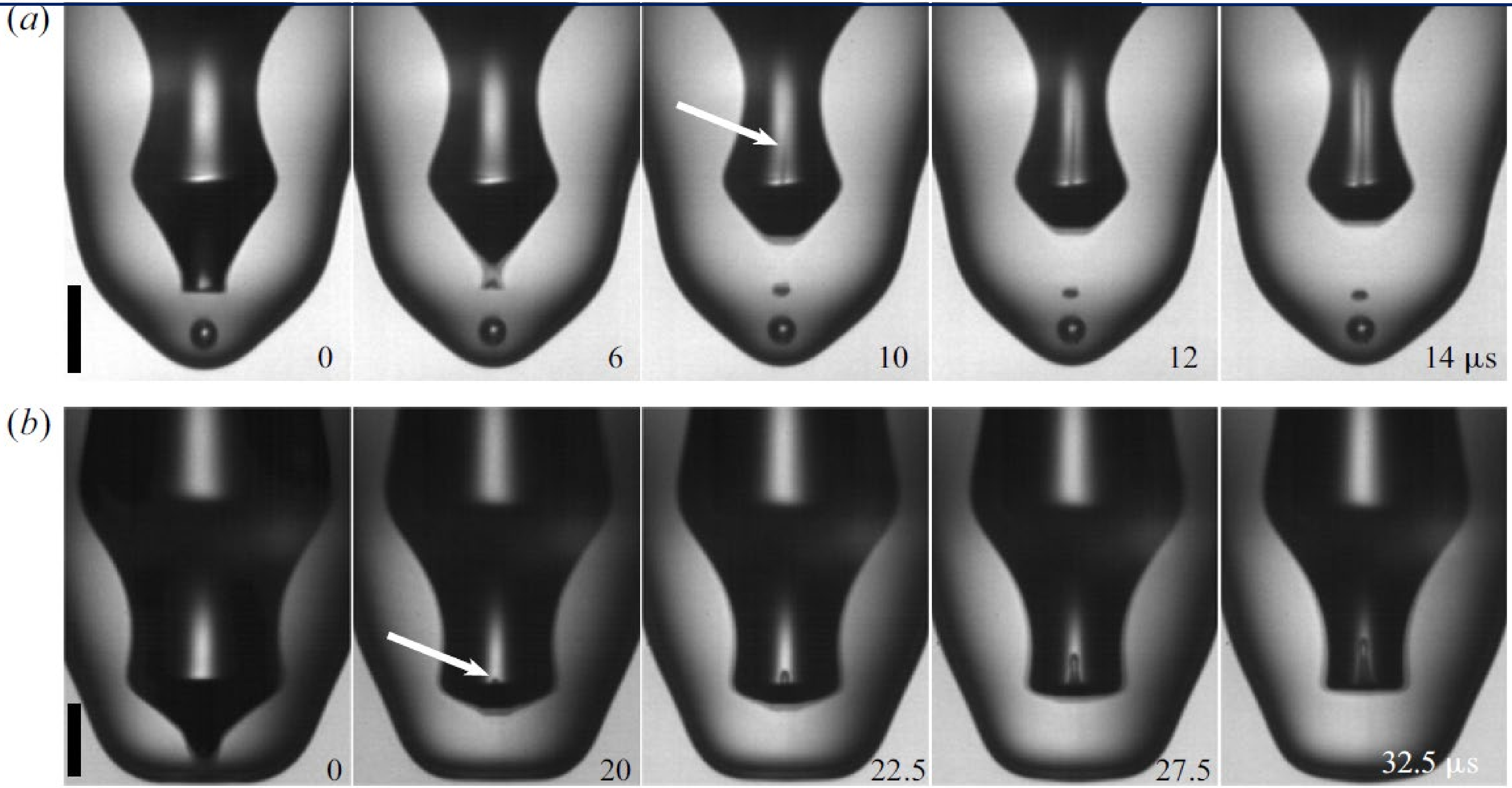


Figure 5. Overview of dimple shape and jet velocity versus We, for drop size 0.92 mm. The arrow lengths indicate the jet velocities. The Weber number grows from left to right (We = 137, 139, 153, 186, 211, 213, 653, 794). The symbols correspond to different dimple shapes: (○) no pinch-off shallow dimple; (×) first critical pinch-off (first singular jet) at the boundary between no and one bubble pinch-off; (△) tiny bubble pinched off near first critical pinch off; (△) dimple pinch-off with bubble going out with jet; (+) secondary critical pinch-off between bubble going out with jet and bubble entrapped in PP1 drop ; (▽) tiny bubble pinched off near Secondary critical pinch-off; (☆) dimple cascade; (▽) pinched-off bubble entrapped in PP1 drop; (□) liquid column break up; (◇) water entrapped in PP1 drop. The scale bars are 200 μm long.

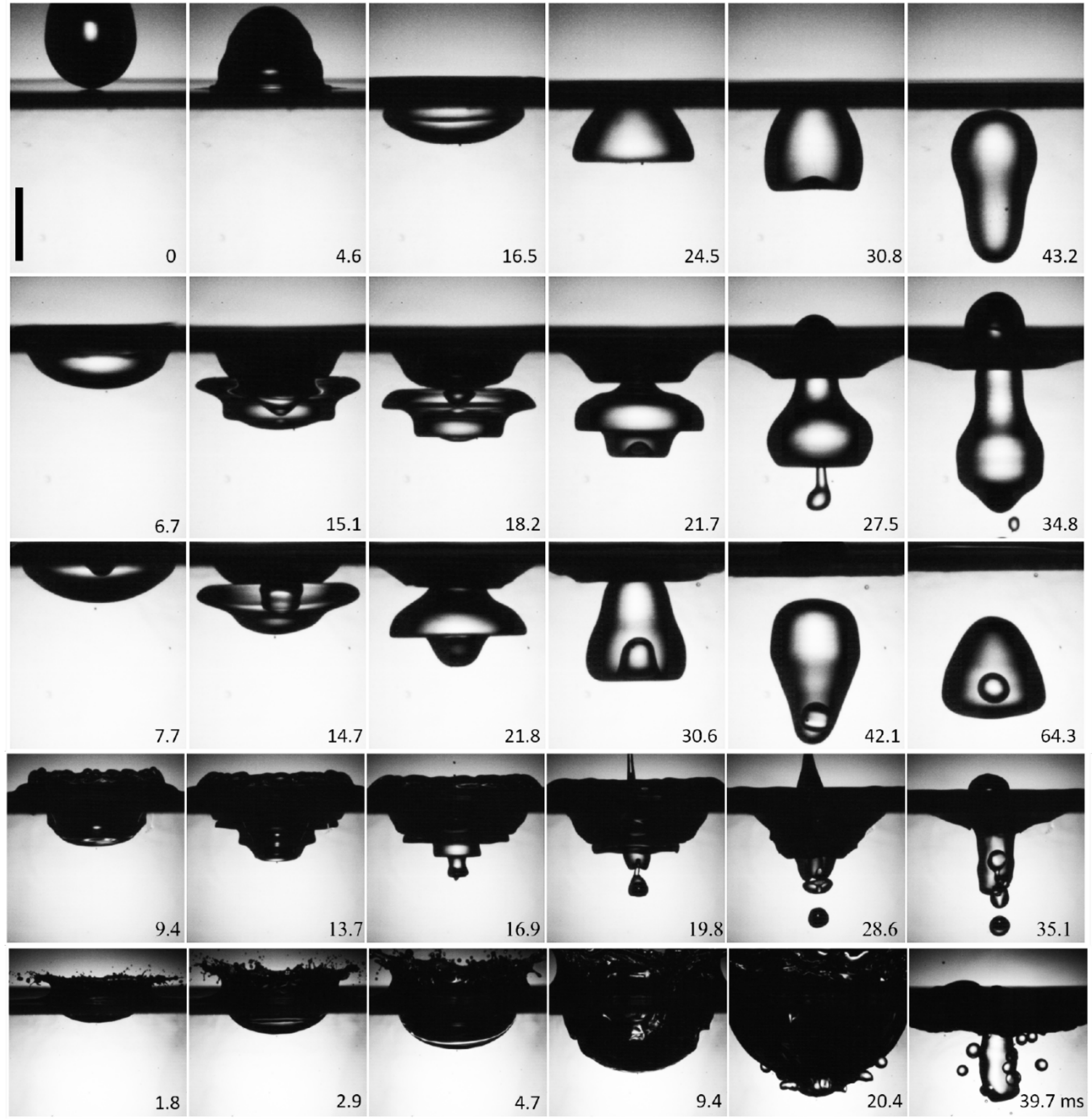
3. Results Dimple shape & Jet velocity



Early-time jet visible inside the air dimple. (a,b) Present the different singular jets in the cavity visualized by our imaging method. The white arrows indicate jettings inside the cavity.

3. Results

Water drop impact into PP1 pool



1. Penetration

2. single ligament and fragments into only a few droplets along the (vertical) axis of symmetry

3. single ligament and pp1-water-pp1 emulsions generated

4. Water cake

5. Drop Fragmentation

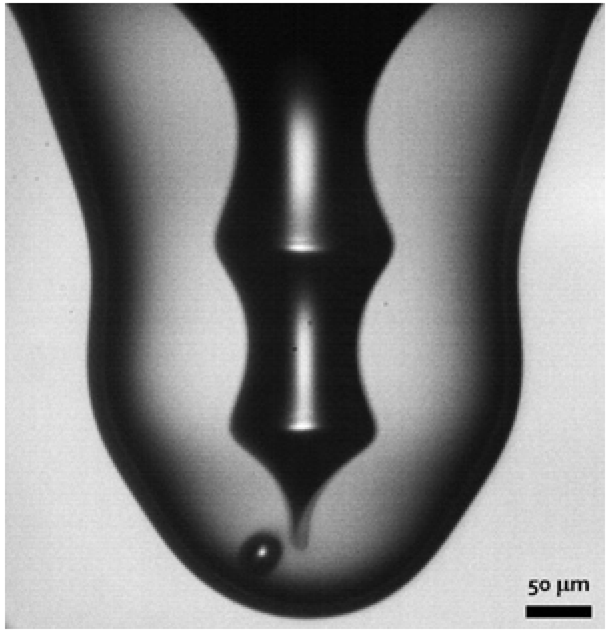
Conclusion

- **New dimple shapes for a drop impact on an immiscible pool**
  - **Bamboo-shaped Pinch-off**
  - **Telescopic-shaped Pinch-off**
- **Singular jets and dimple dynamics for immiscible impact? Three not just one**
- **The finest jets are only 12 μm in diameter and the jetting speeds are up to 46 m/s**

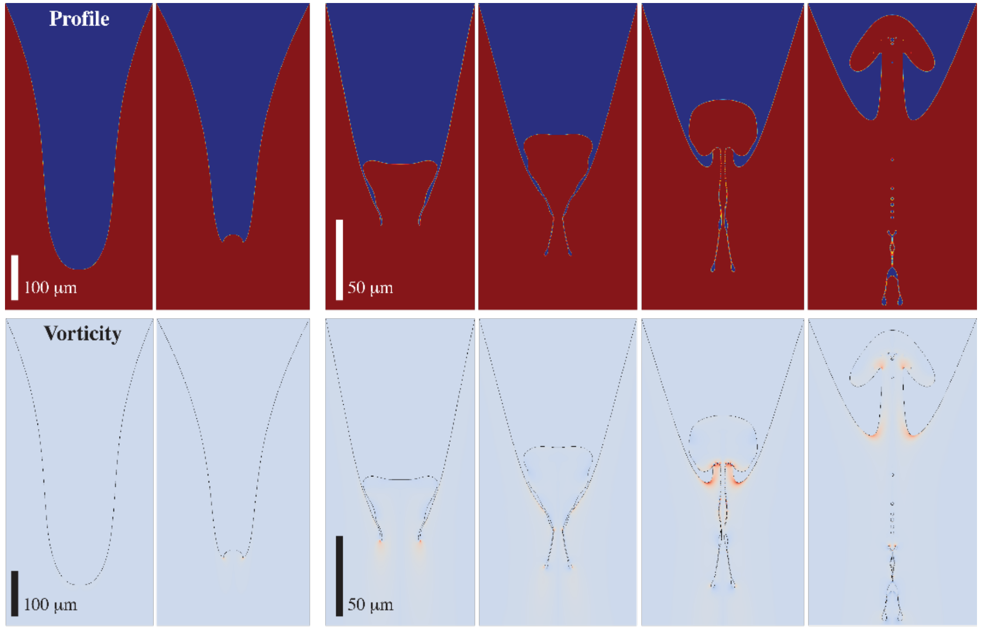
Published Work

Journal Articles

Z. Q. Yang, Y. S. Tian, and S. T. Thoroddsen*, "Multitude of dimple shapes can produce singular jets during the collapse of immiscible drop-impact craters," Journal of Fluid Mechanics, vol. 904, p. A19, 2020.



Y. S. Tian., **Z. Q. Yang**, F. Yang and S. T. Thoroddsen*, "New scaling: cavity collapse from drop impact onto liquid pool under reduced pressures", Planned for Journal of Fluid Mechanics, 2020.



Acknowledgement

Siggi

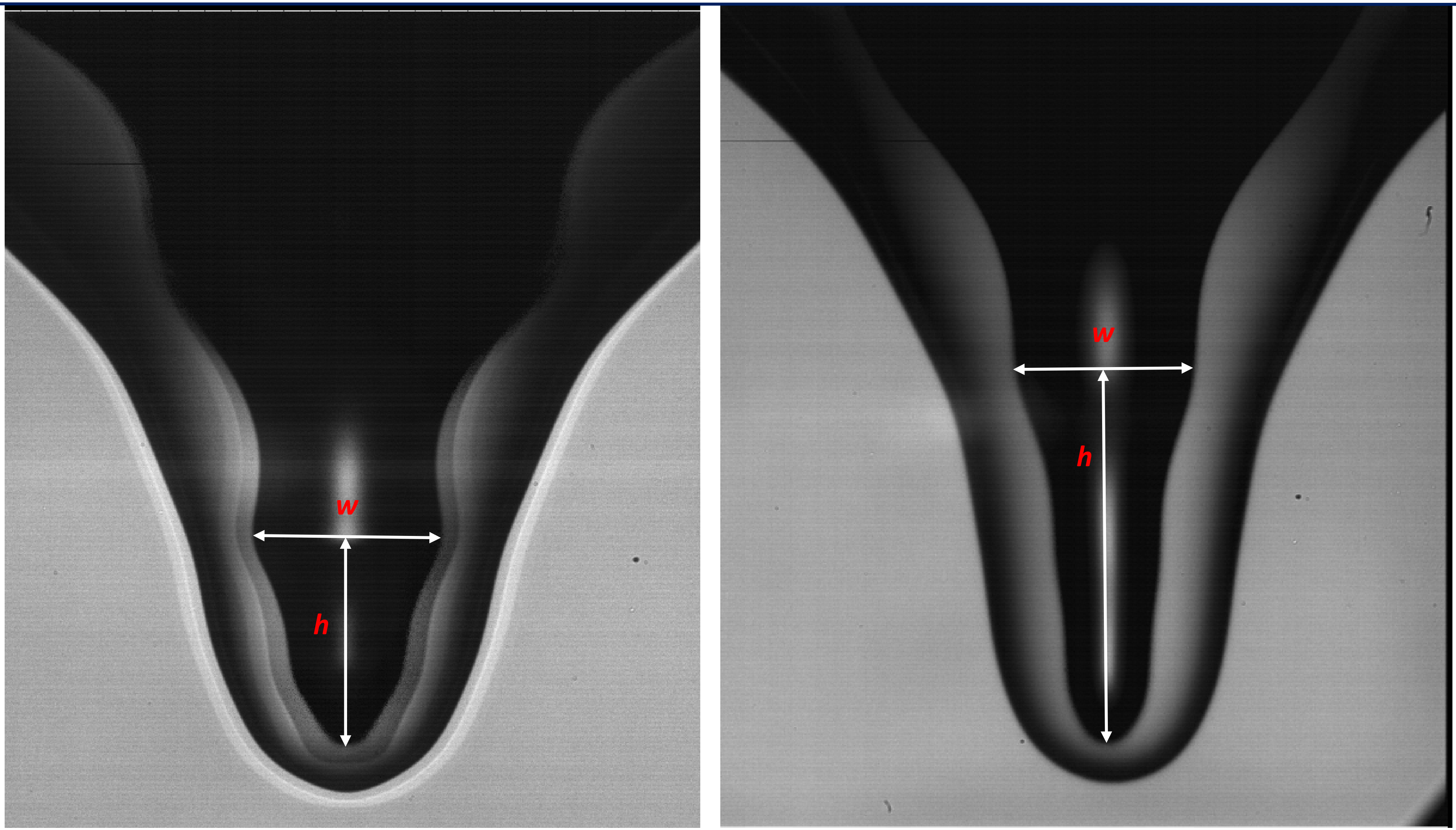
Yuan Si Tian

Zi Qiang Yang

Thank you

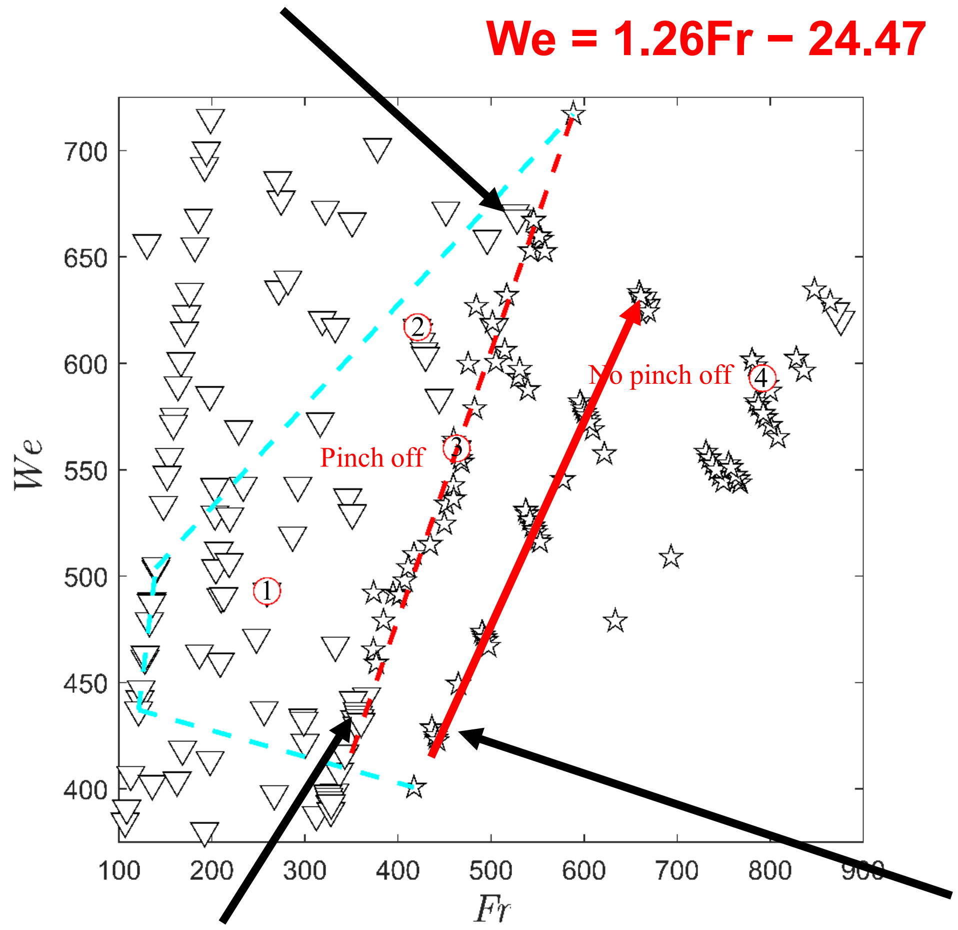
Questions ?

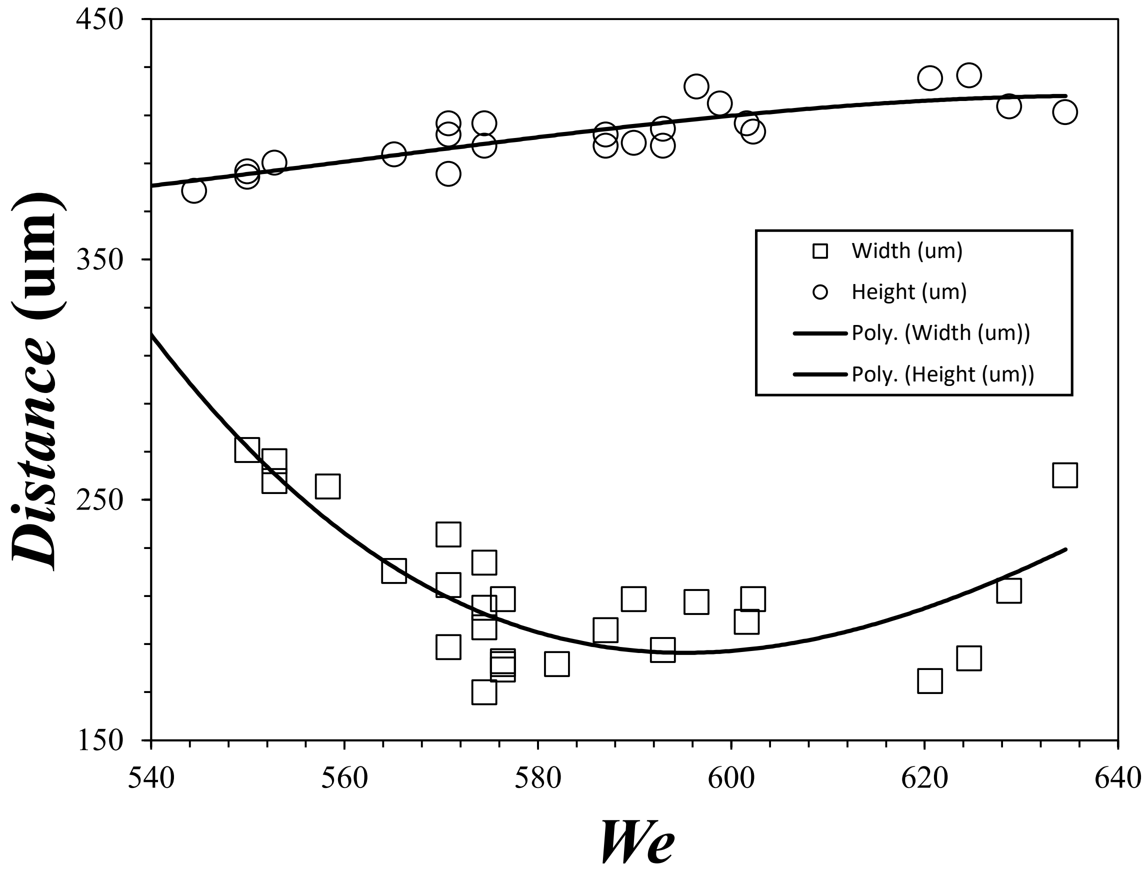
3. Results



3. Results

We = 1.26Fr − 24.47





3. Results

High-Speed Fluids Imaging Laboratory