Impact-Induced Fragmentation of Liquid Rims

Basilisk (Gerris) Users' Meeting 2023

Kaitao Tang[1], Thomas Adcock[1] and Wouter Mostert[1]

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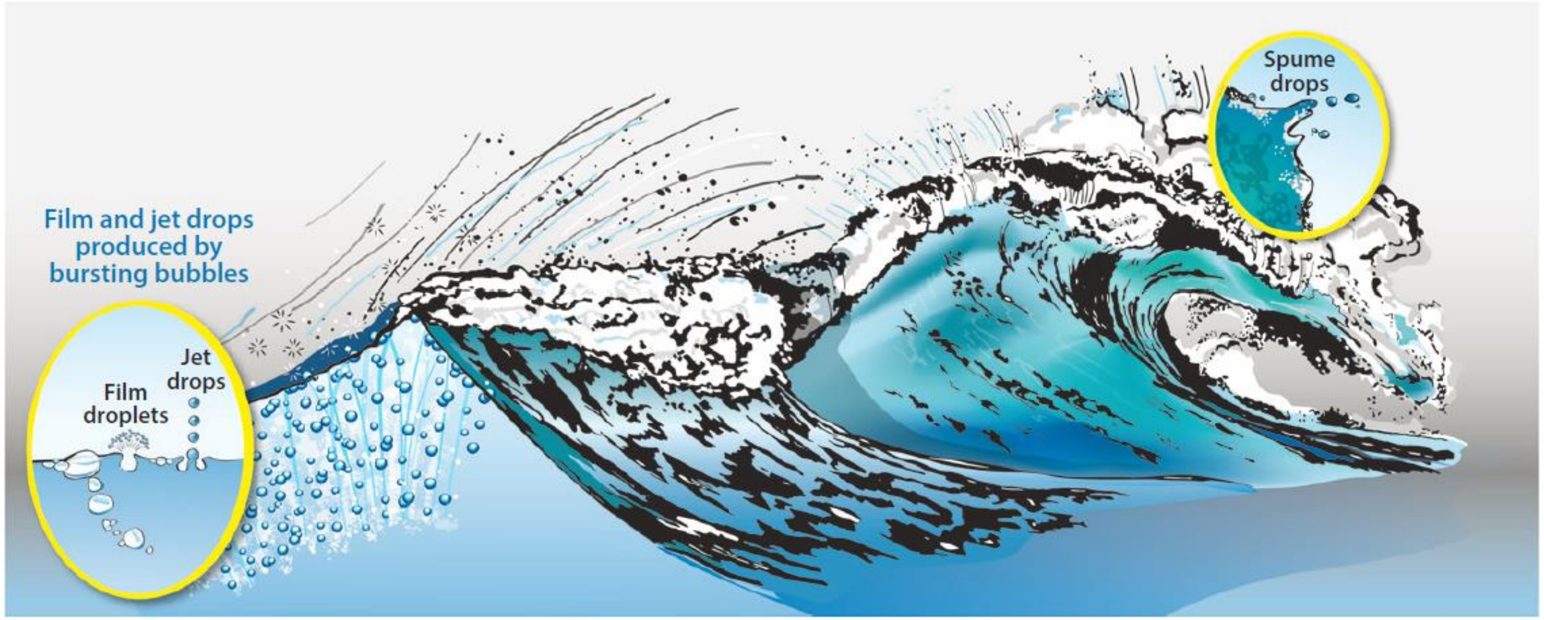
[1] Department of Engineering Science, University of Oxford, Oxford, OX1 3PJ, UK

Introduction: Ocean Sprays



Major pathways of ocean spray generation

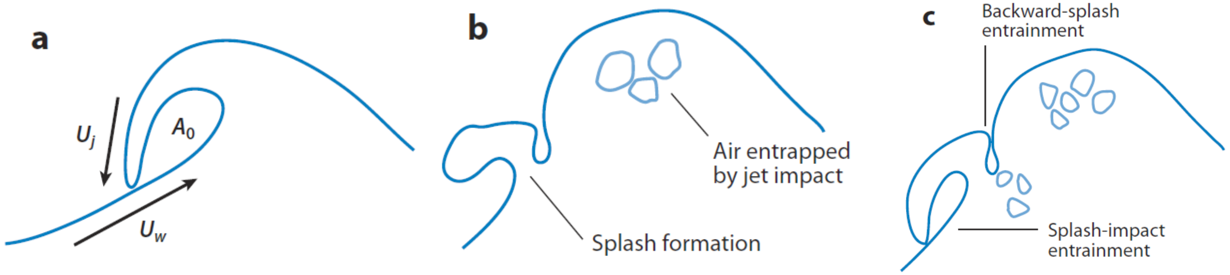
- Significance of Ocean Sprays
  - Enhancing air-sea mass, momentum and energy transfer
  - Regulation by breaking waves
- Pathways of ocean spray generation
  - Bursting of entrained bubbles
  - Spume drop ejection under high winds
  - **Splashing** of plunging waves

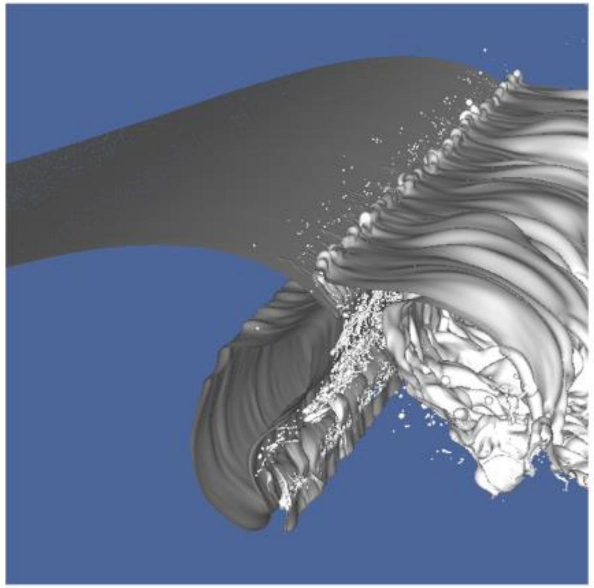
[1] Veron, F. (2015). Ocean spray. *Annual Review of Fluid Mechanics*, *47*, 507-538.
[2] Deike, L. (2022). Mass transfer at the ocean–atmosphere interface: The role of wave breaking, droplets, and bubbles. *Annual Review of Fluid Mechanics*, 54, 191-224.

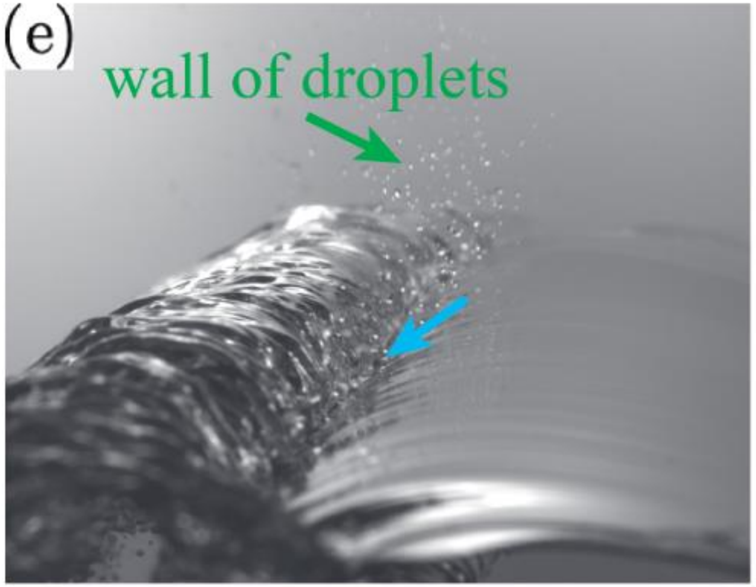
Introduction: Splashing

Multiple splashing events [2]:

- After impact ('forward splashing' [1])
  - Small number of drops
- **Secondary splashing** ('backward splashing' [1])
  - Larger number of drops;
  - Small and vertically-projected drops
  - Curbed at large surface tension
  - **Generation mechanism unclear**
- Small-scale splashing & bubble bursting
  - Last longer and produce larger drops



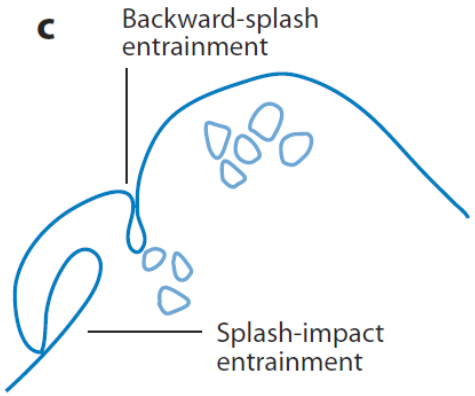


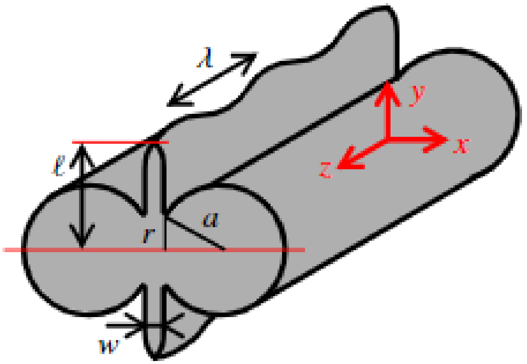


The secondary splashing mechanism

[1] Kiger, K. T., & Duncan, J. H. (2012). Air-entrainment mechanisms in plunging jets and breaking waves. *Annual Review of Fluid Mechanics*, 44, 563-596.
[2] Mostert, W., Popinet, S., & Deike, L. (2022). High-resolution direct simulation of deep water breaking waves: transition to turbulence, bubbles and droplets production. *Journal of Fluid Mechanics*, *942*, A27.
[3] Erinin, M. A., Wang, S. D., Liu, X., Liu, C., & Duncan, J. H. (2022). Spray Generation by Plunging Breakers--Part 2. Droplet Characteristics. arXiv preprint arXiv:2210.01923.

Introduction: Liquid Rim Collision





- Rim collision as a model for secondary splashing
- Experiments of Neel *et al.* (2020) [1]:

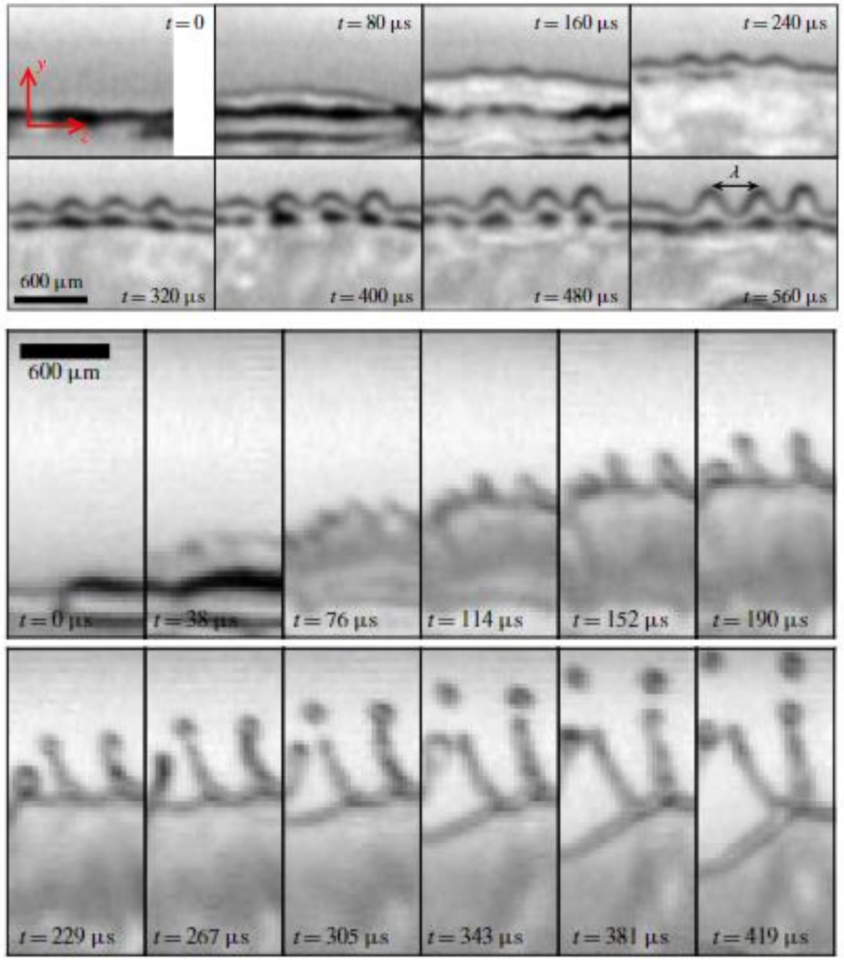
  Collision of rims travelling on liquid films

  $We_c = 66$: RT destabilization of lamellae

  Skewed size distribution functions

    $We < We_c$: Gamma distribution

    $We > We_c$: Bessel-based distribution.



Experimental photographs of Neel *et al.* (2020)

[1] Néel, B., Lhuissier, H., & Villermaux, E. (2020). 'Fines' from the collision of liquid rims. *Journal of Fluid Mechanics*, 893, A16.

Problem Configuration

Controlling Parameters

$$We \equiv \frac{\rho_g (2U_0)^2 d_0}{\sigma}, \qquad Oh \equiv \frac{\mu_l}{\sqrt{\rho_l d_0 \sigma}} = 0.01,$$

$$\rho^* \equiv \frac{\rho_l}{\rho_g} = 833, \qquad \mu^* \equiv \frac{\mu_l}{\mu_g} = 55,$$

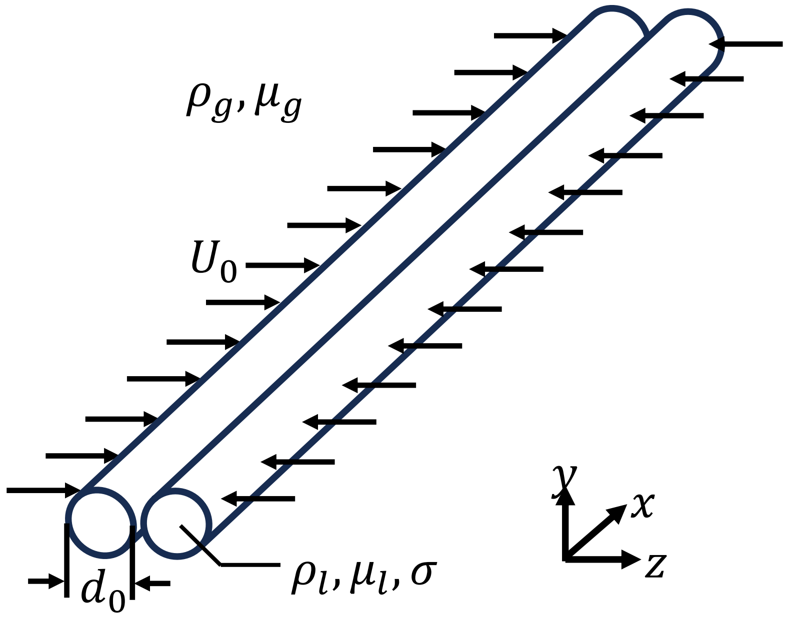
With perturbation:

$$\varepsilon_0 \equiv \frac{2\epsilon_0}{d_0}, \qquad N_{\max}$$

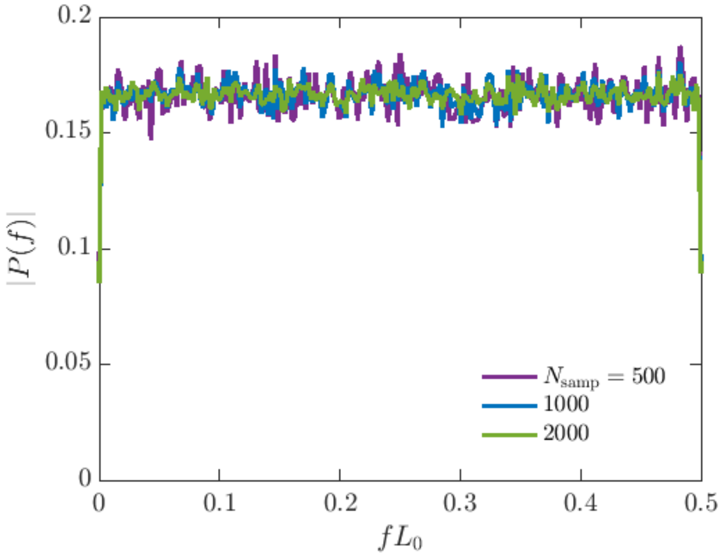
Interfacial Perturbation [1]

1) White noise series
2) Filter and keep only the lowest $N_{\max}$ modes
3) Re-normalize to a variation of ε_0
4) Two cylinders perturbed by different realisations with the same ε_0 and $N_{\max}$.

Basilisk, Two-Phase NS Equation w. AMR



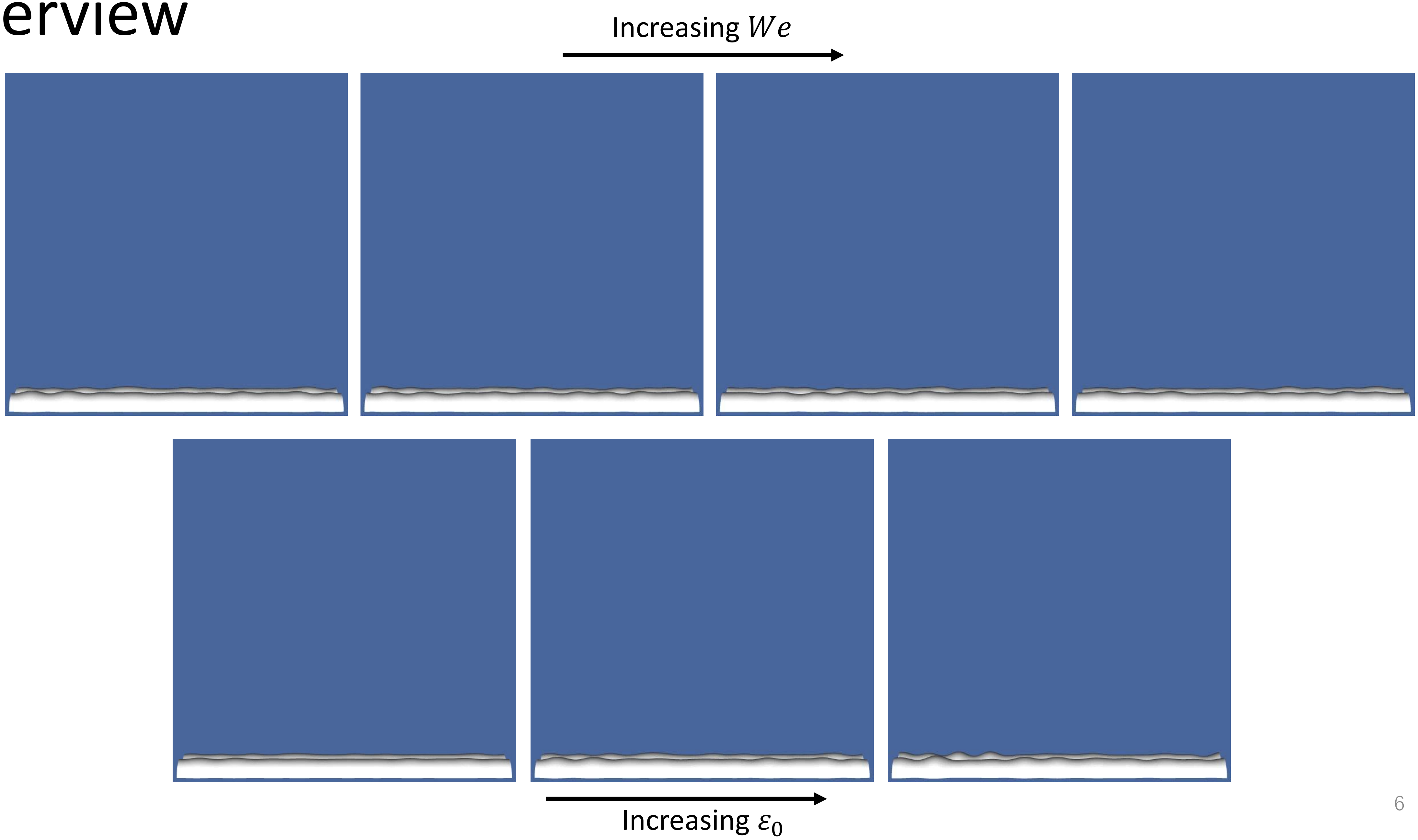
Configuration of the rim collision problem



Power density of the perturbation series

[1] Pal, S., Crialesi-Esposito, M., Fuster, D., & Zaleski, S. (2021). Statistics of drops generated from ensembles of randomly corrugated ligaments. *arXiv preprint arXiv:2106.16192*.

Overview



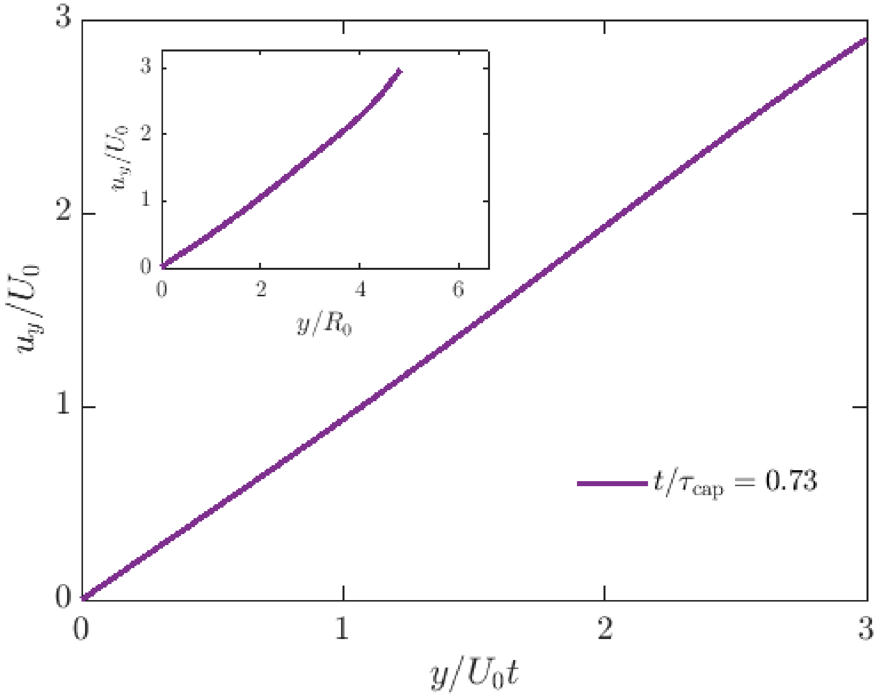
Sheet Kinematics

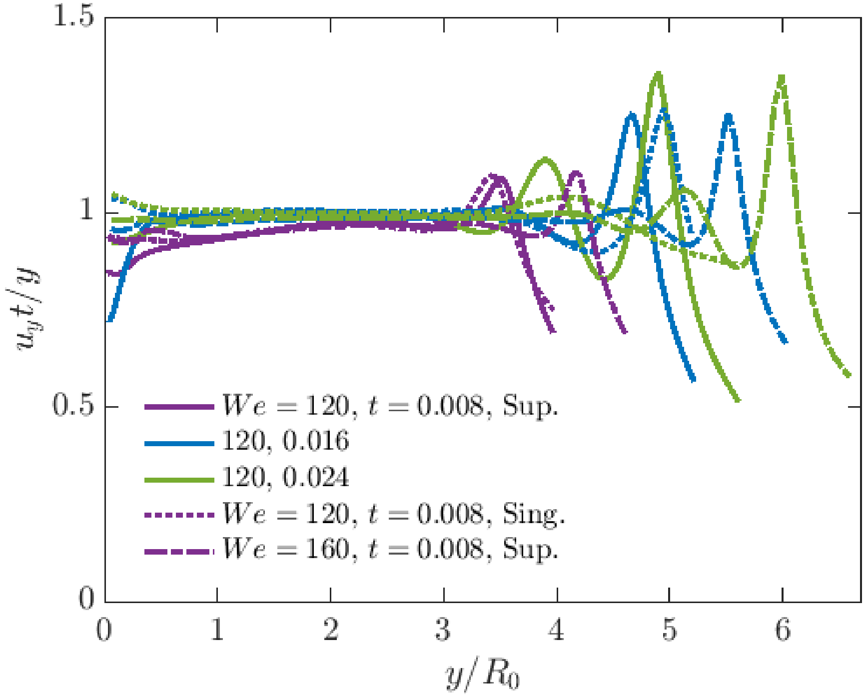
Self-similar evolution of sheet velocity and outer contour :

$$\begin{cases} \boldsymbol{u_y} = \dfrac{\boldsymbol{y}}{\boldsymbol{t}} \\ \dfrac{ht}{R_0\tau} = f\left(\dfrac{y}{U_0 t}\right) \end{cases}$$

Independent of impact We and perturbation waveform

Implication: sheet expansion mostly inviscid, fluid parcel travels at constant velocity [1]





Vertical velocity within liquid sheets

[1] Wang, Y., & Bourouiba, L. (2017). Drop impact on small surfaces: thickness and velocity profiles of the expanding sheet in the air. *Journal of Fluid Mechanics*, *814*, 510-534.

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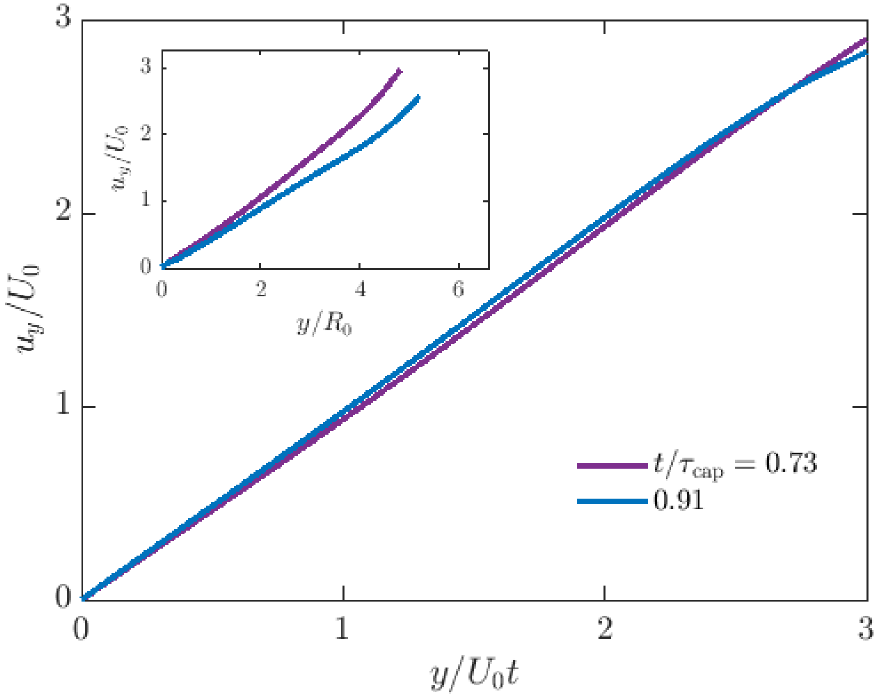

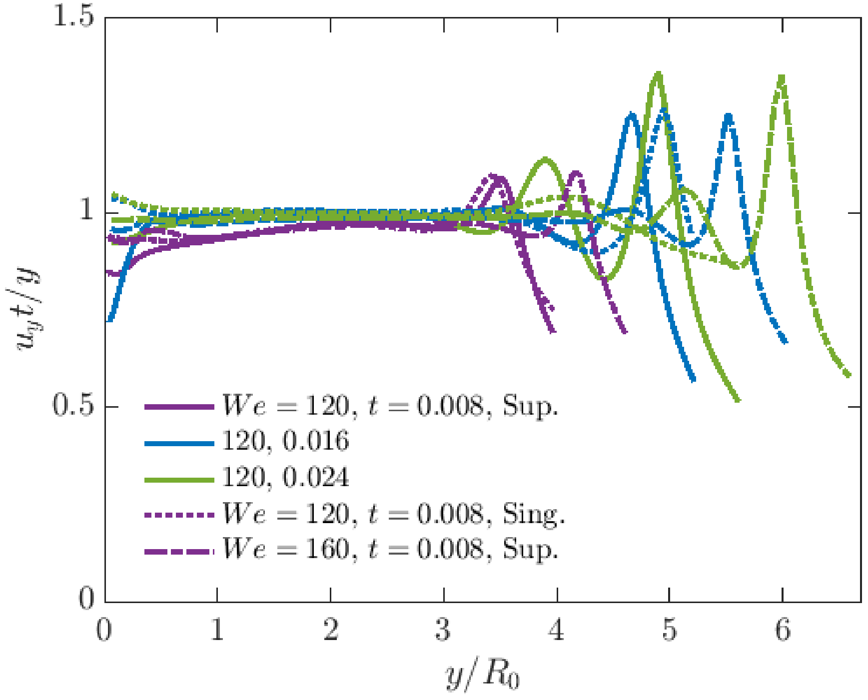

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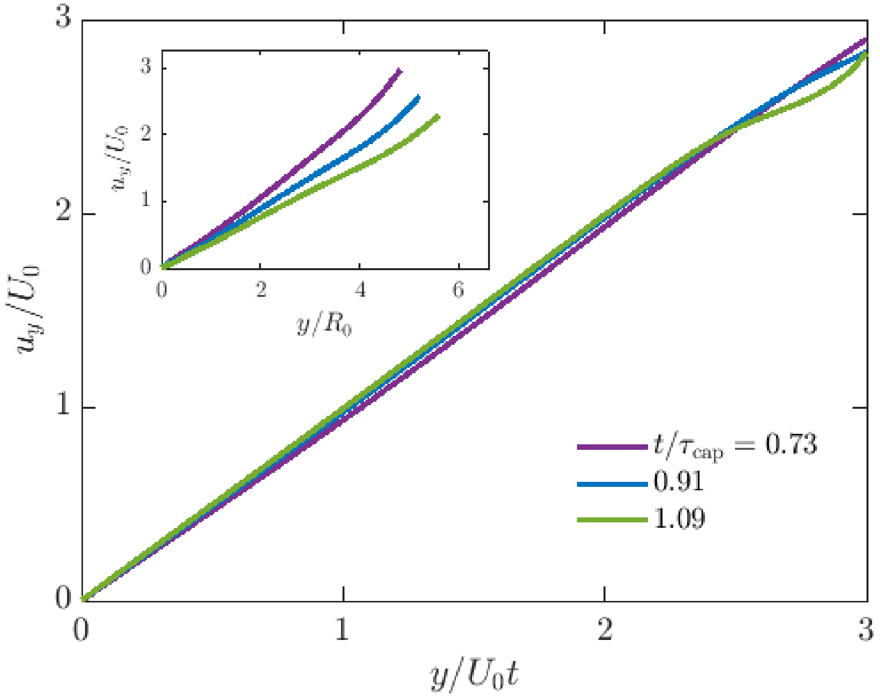

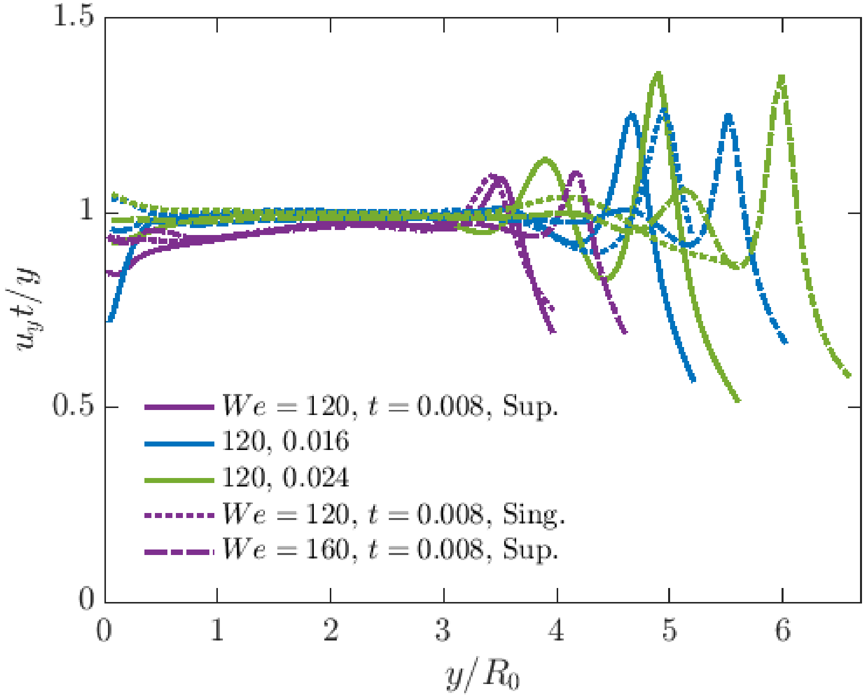

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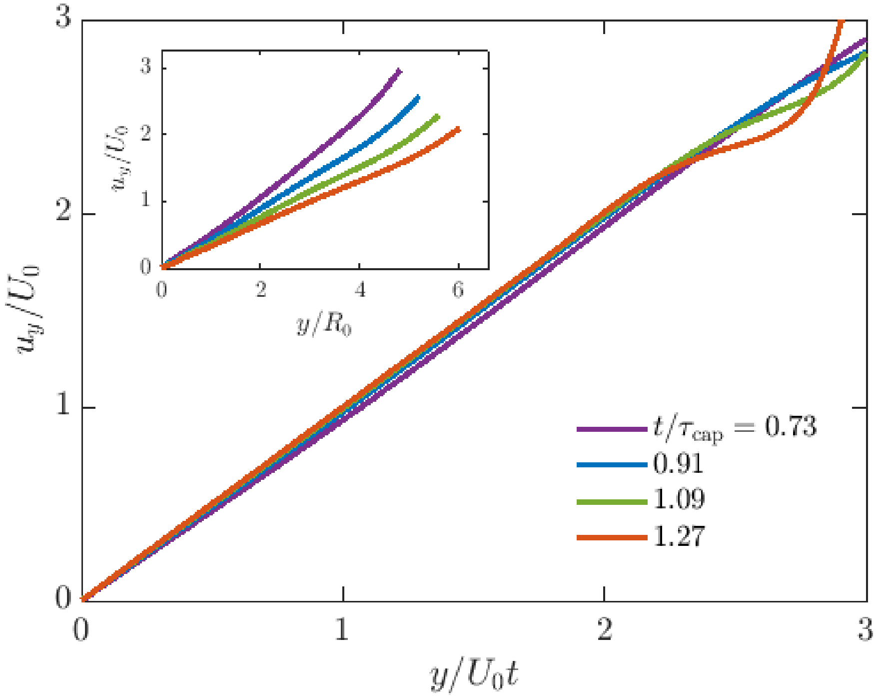

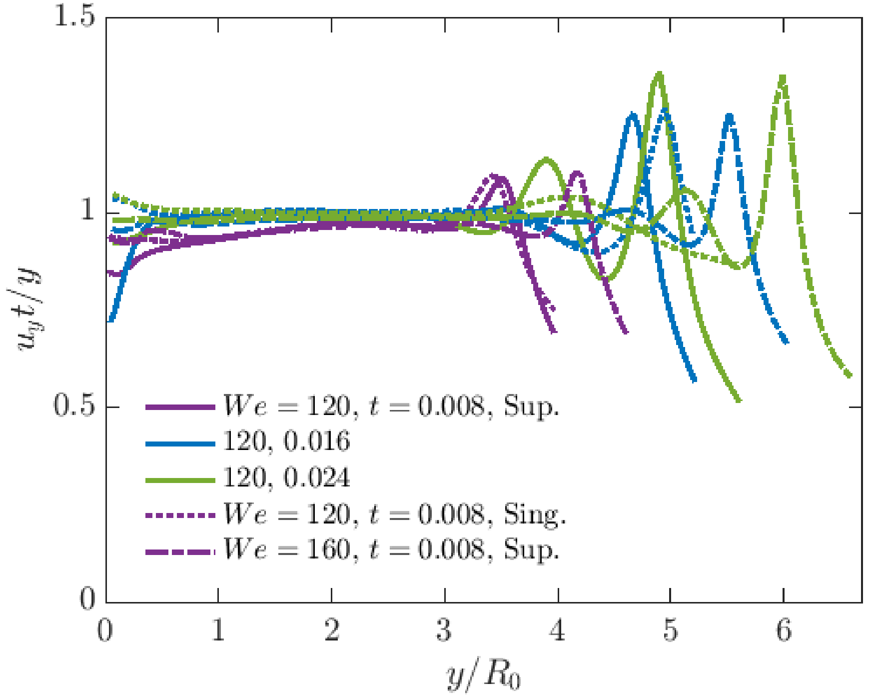

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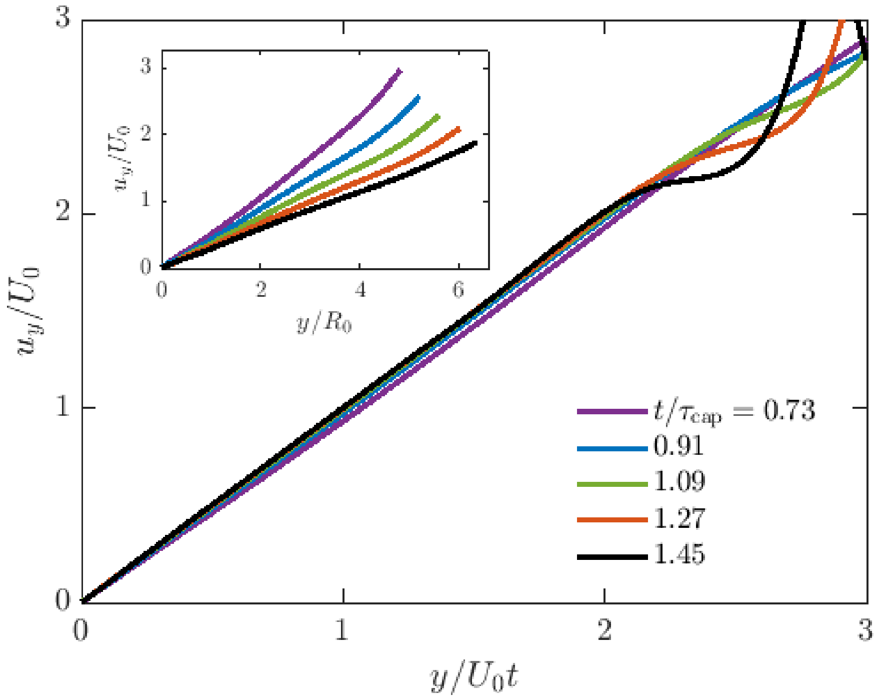

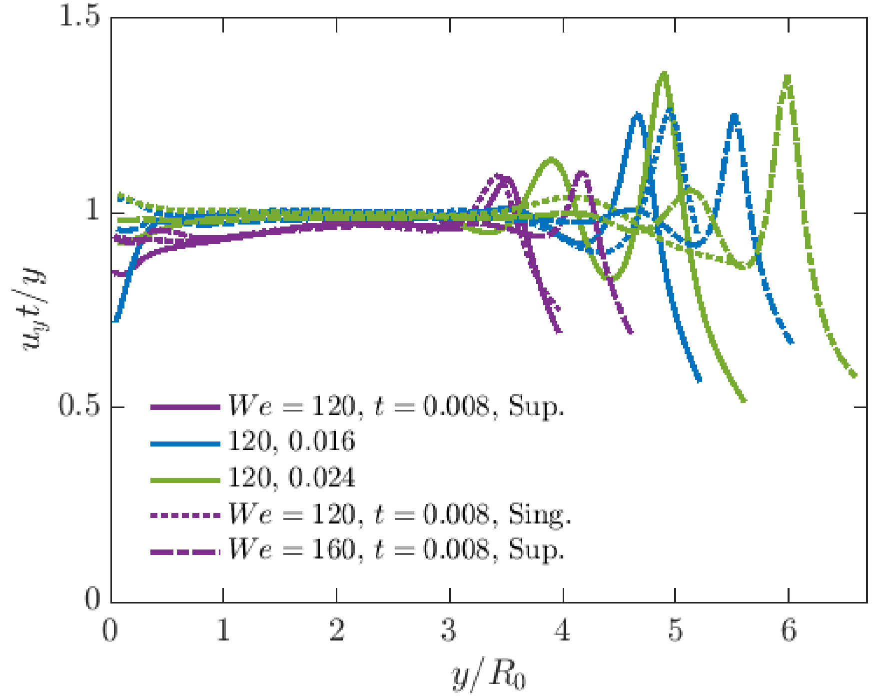

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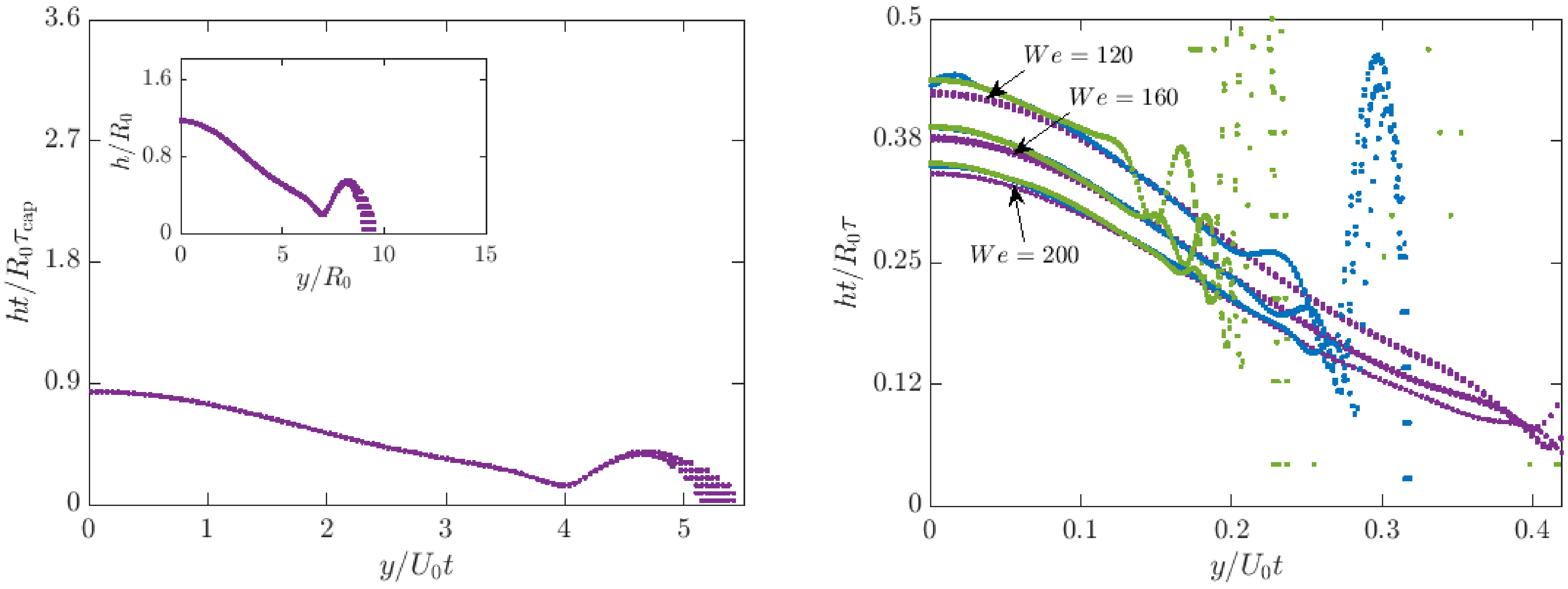
Slight dependence on impact We



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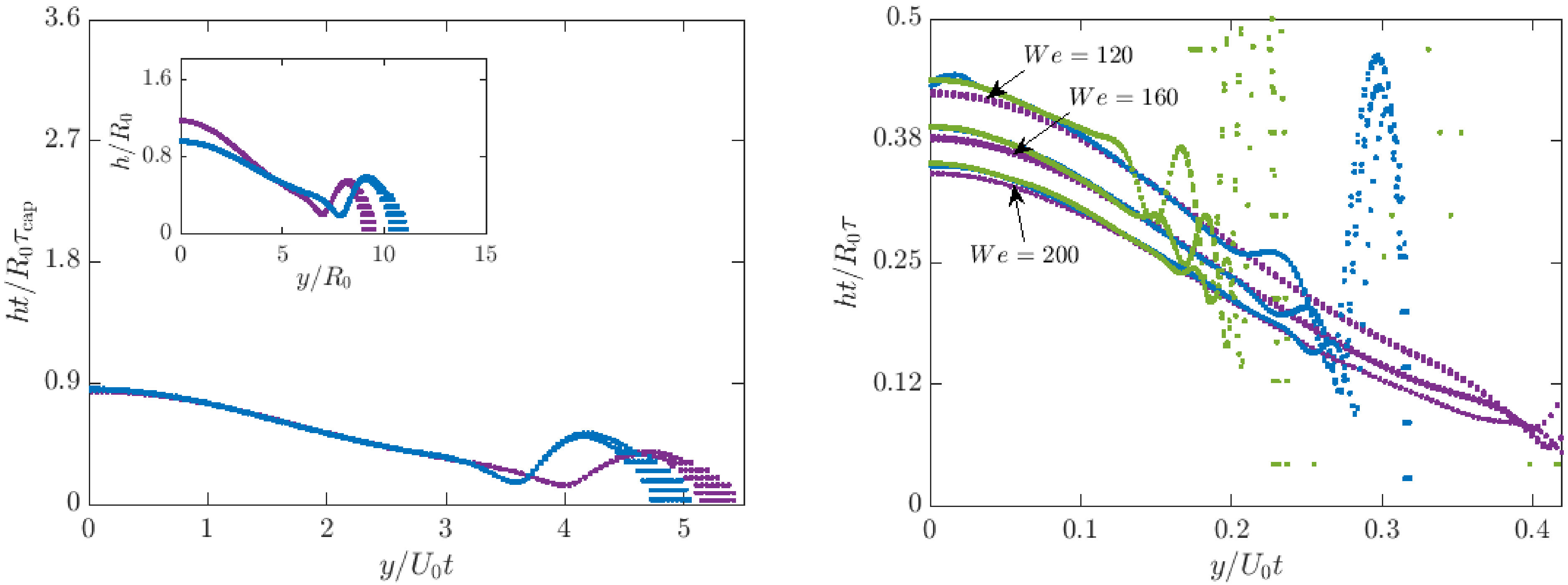

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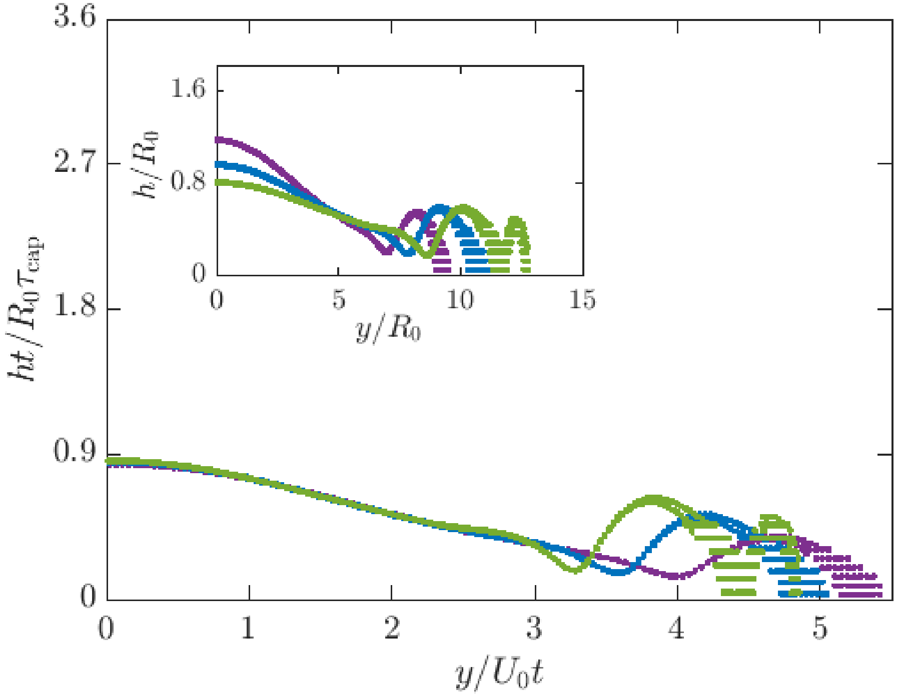

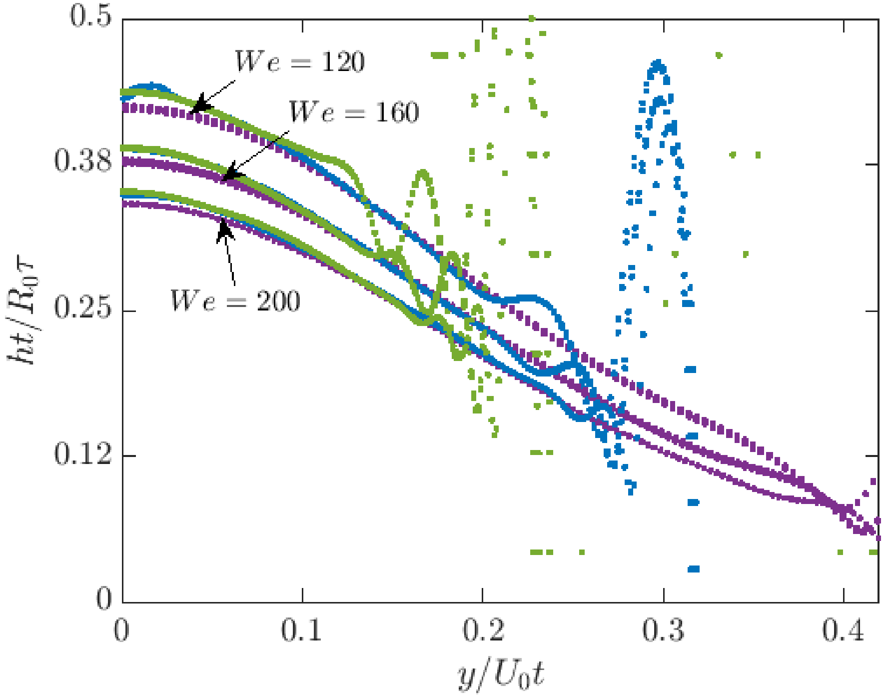

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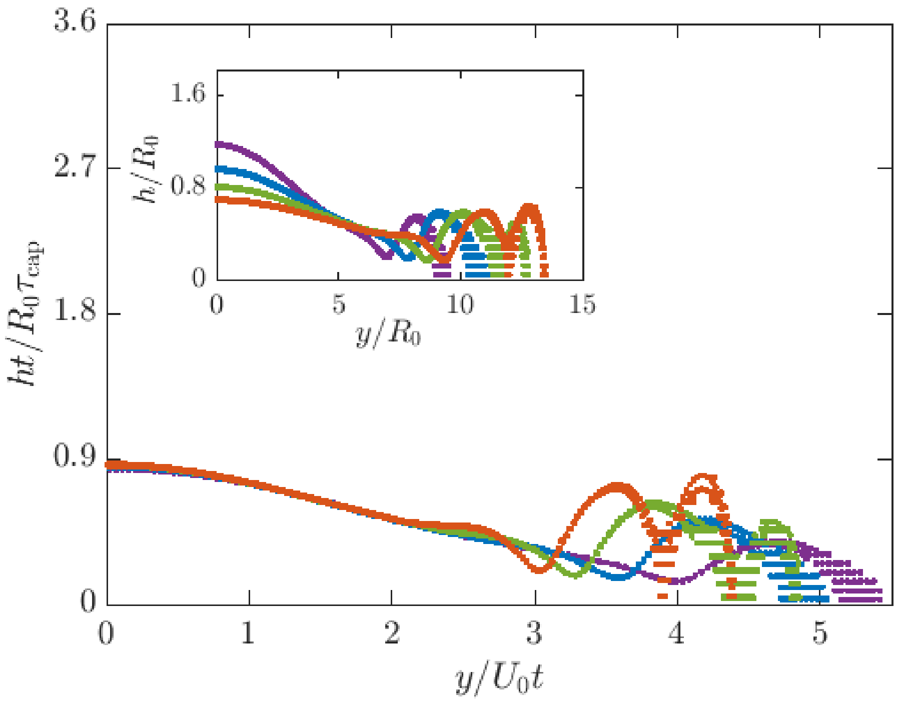

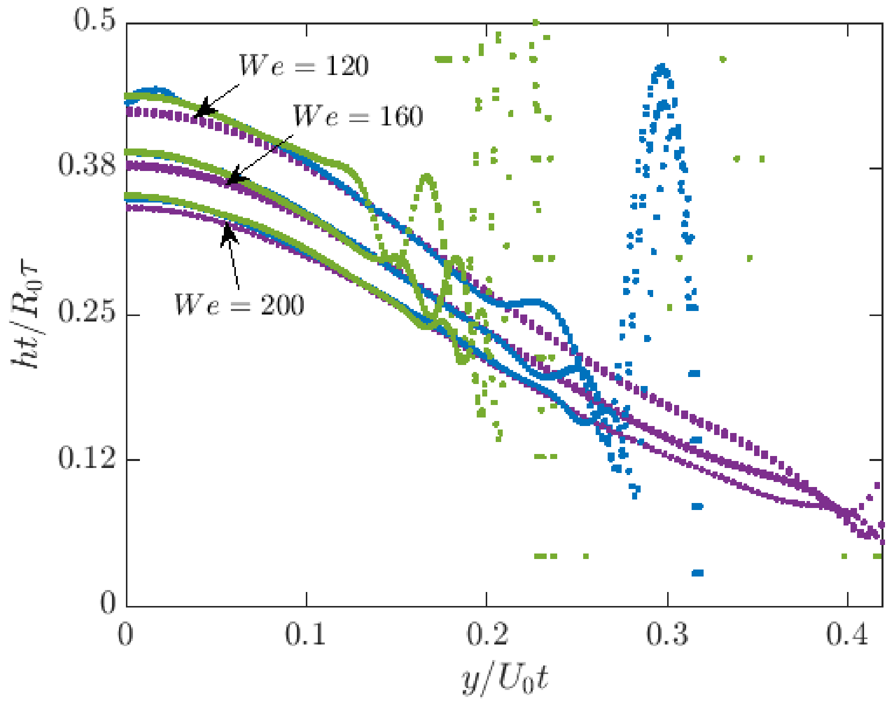

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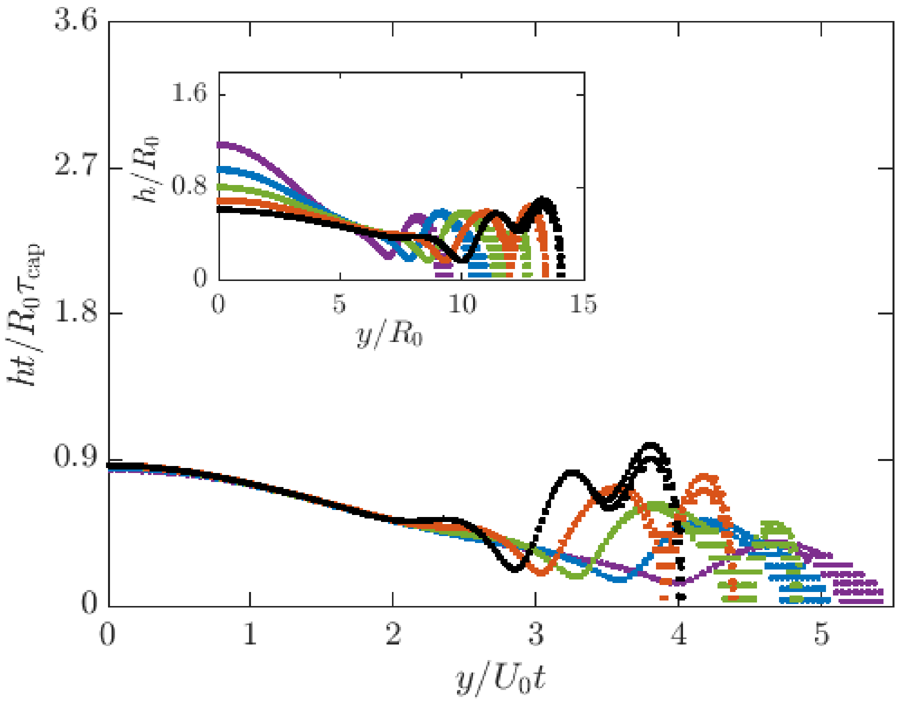

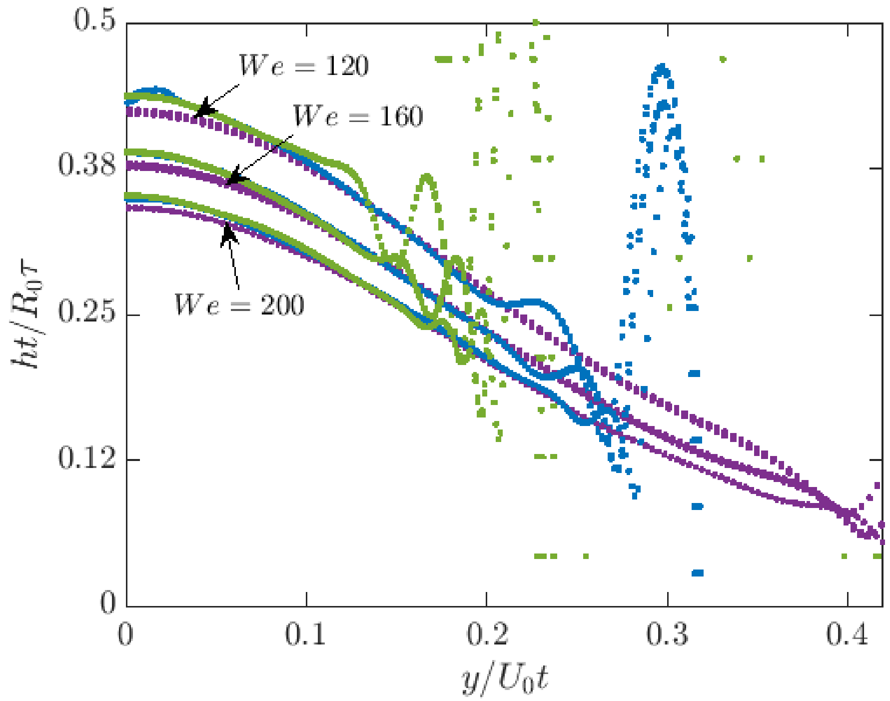

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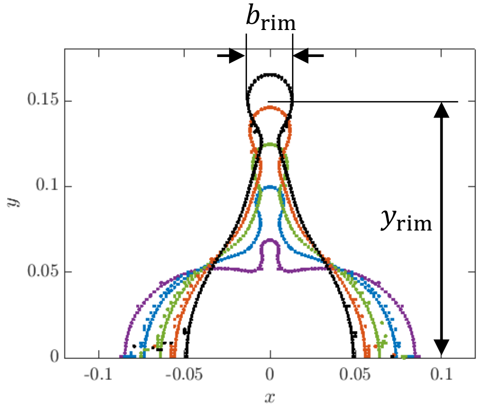
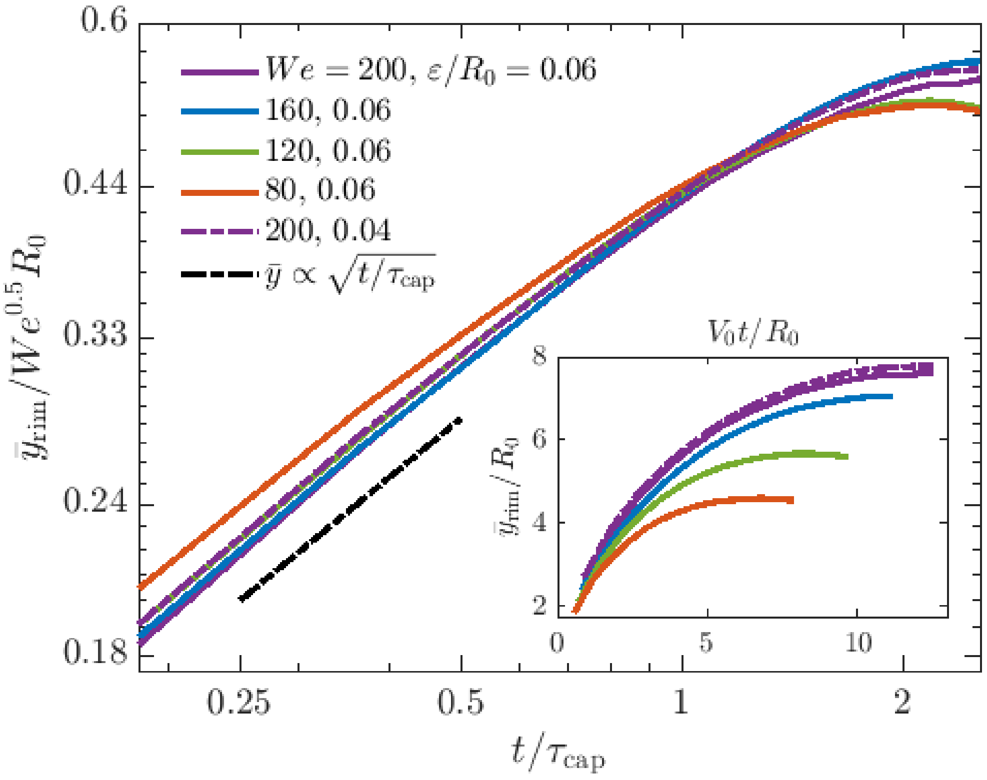
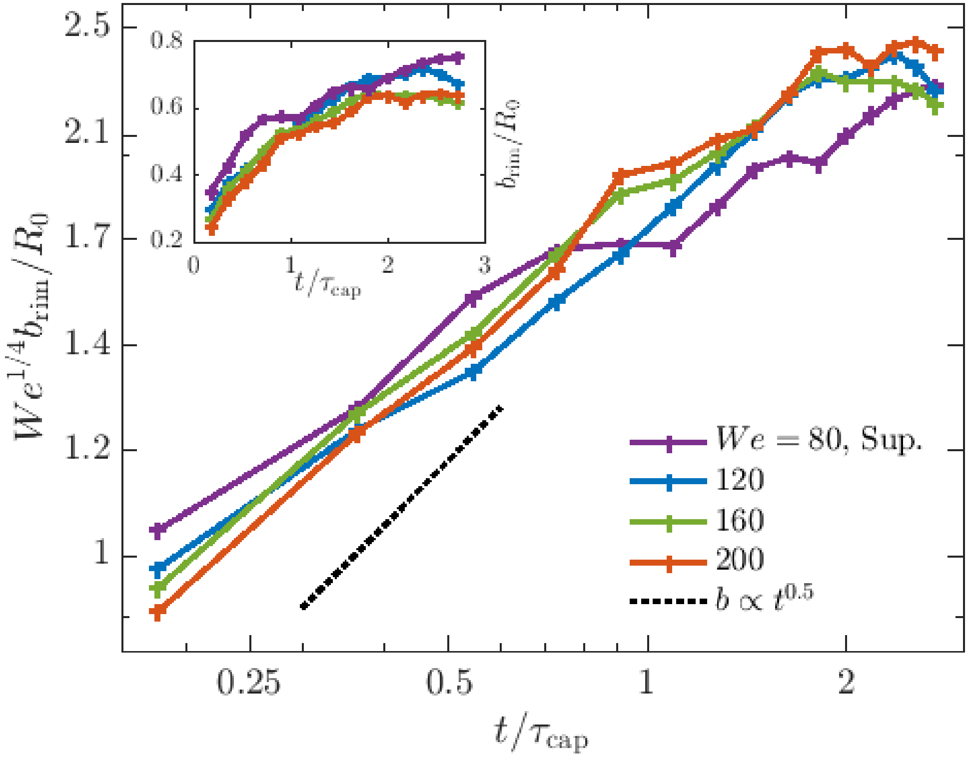
Rim Kinematics



Scaling model for rim position and thickness:

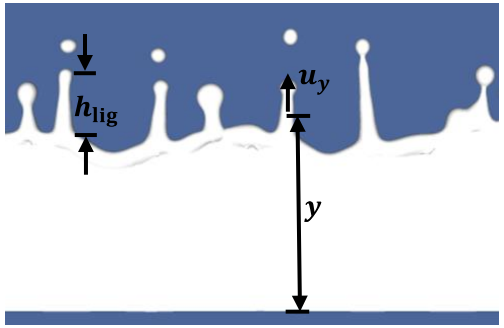
$$\begin{cases} \dfrac{y_{\rm rim}}{R_0} \propto \sqrt{We}\sqrt{\dfrac{t}{\tau_{\rm cap}}} \\ \dfrac{b_{\rm rim}}{R_0} \propto We^{-1/4}\sqrt{\dfrac{t}{\tau_{\rm cap}}} \end{cases}$$

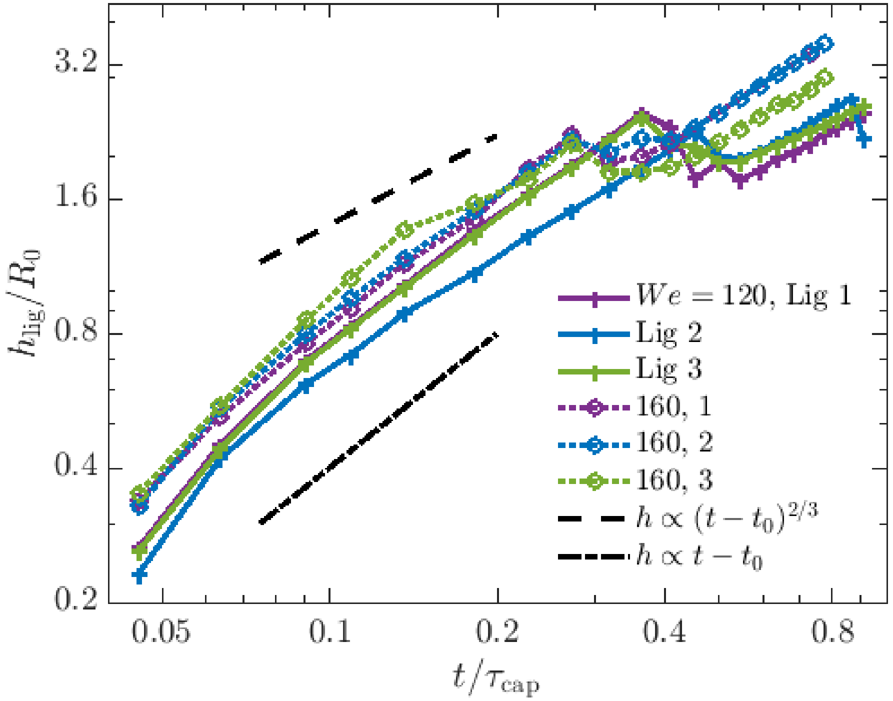




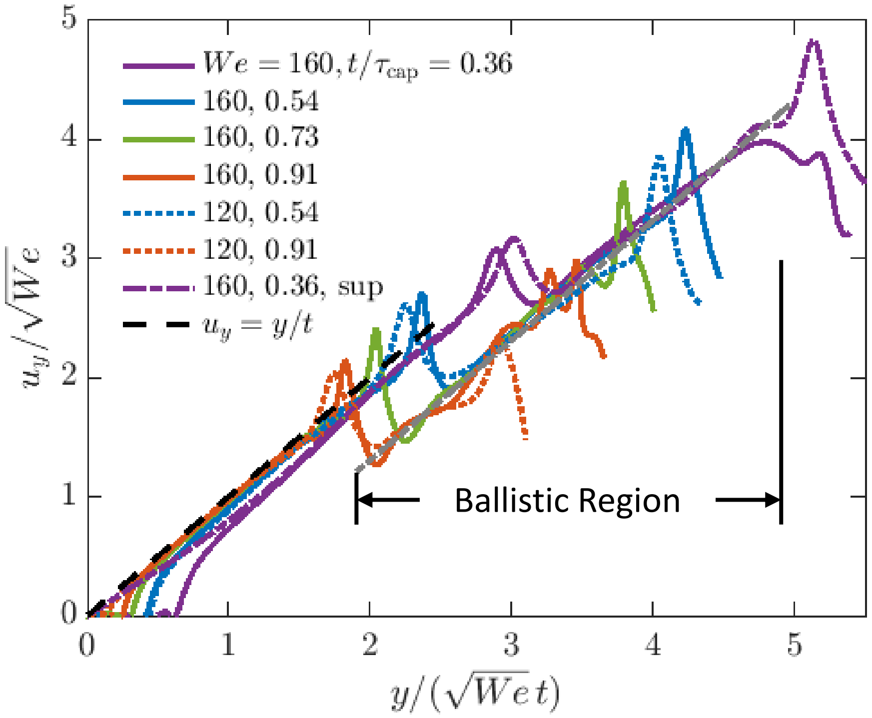
Vertical position (left) and thickness (right) of the rim

Ligament Growth





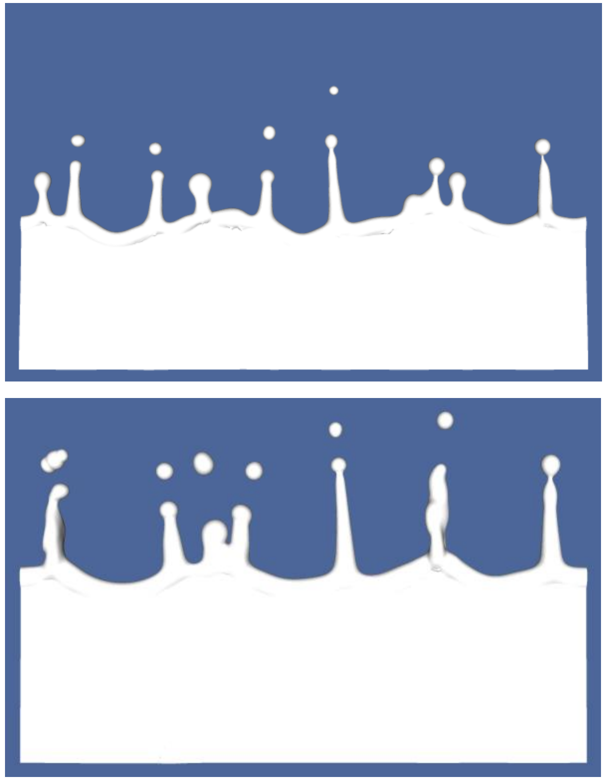
Evolution of ligament length

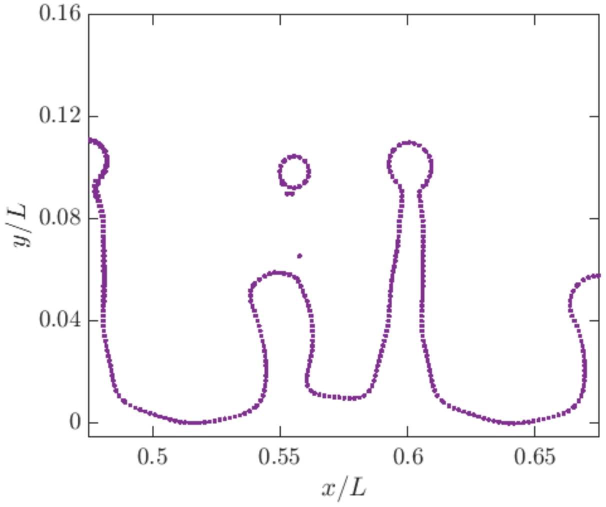


Vertical velocity within sheets and ligaments

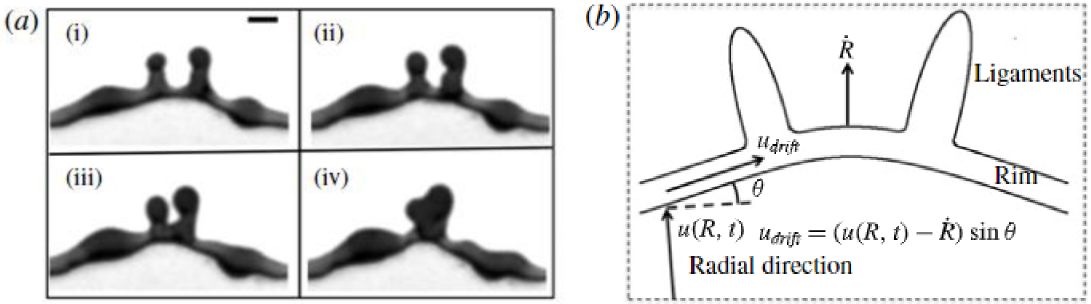
[1] Lai, C. Y., Eggers, J., & Deike, L. (2018). Bubble bursting: Universal cavity and jet profiles. *Physical review letters*, *121*(14), 144501.
[2] Gekle, S., & Gordillo, J. M. (2010). Generation and breakup of Worthington jets after cavity collapse. Part 1. Jet formation. Journal of fluid mechanics, 663, 293-330.

Ligament Merging Phenomena





Ligaments merging on the corrugated rim



- Wang & Bourouiba (2018):

  Ligament merging observed where the inflow is not perpendicular to the rim

  Driven by the tangential component of inflow velocity

  $$u_{\mathrm{drift}} = \left(u(R,t) - \dot{R}\right)\sin\theta$$

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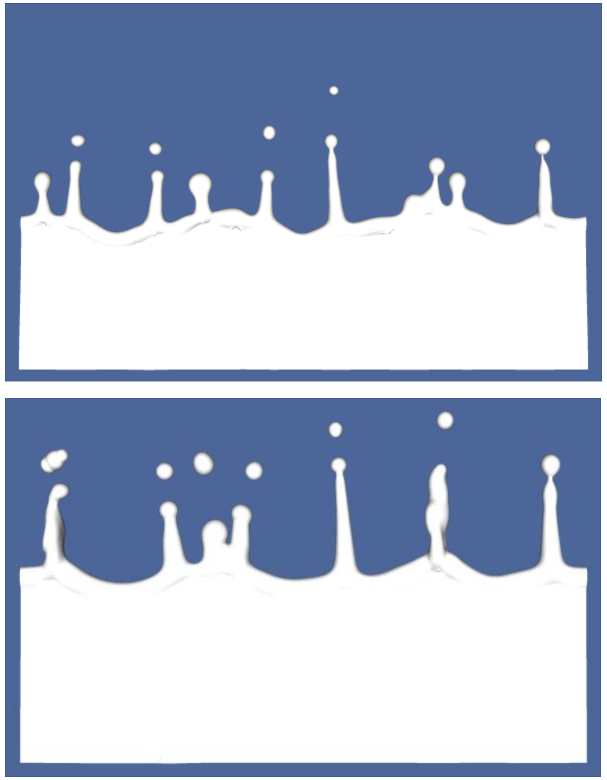

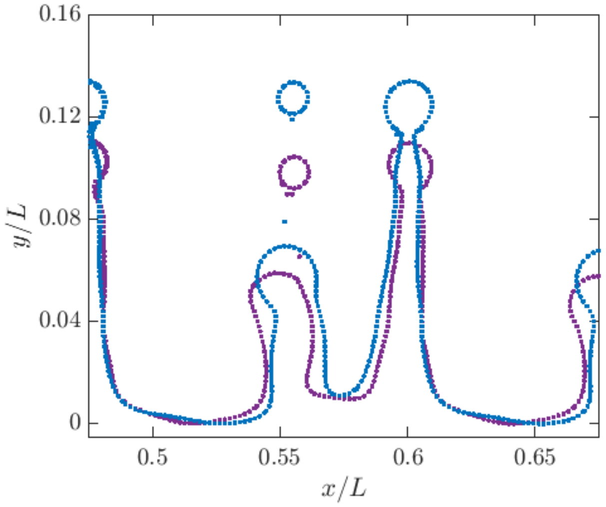

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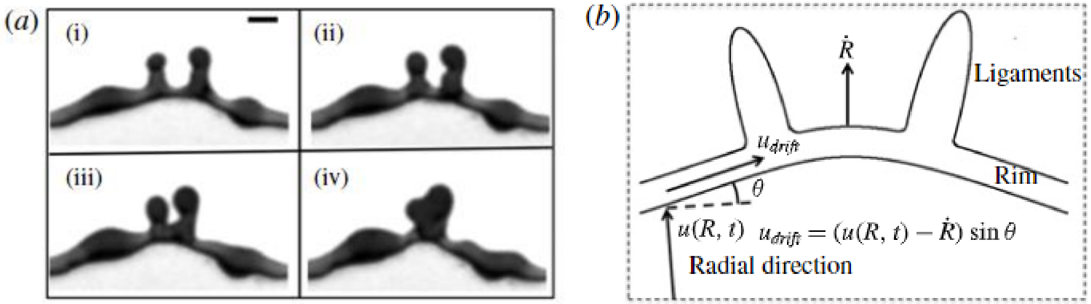

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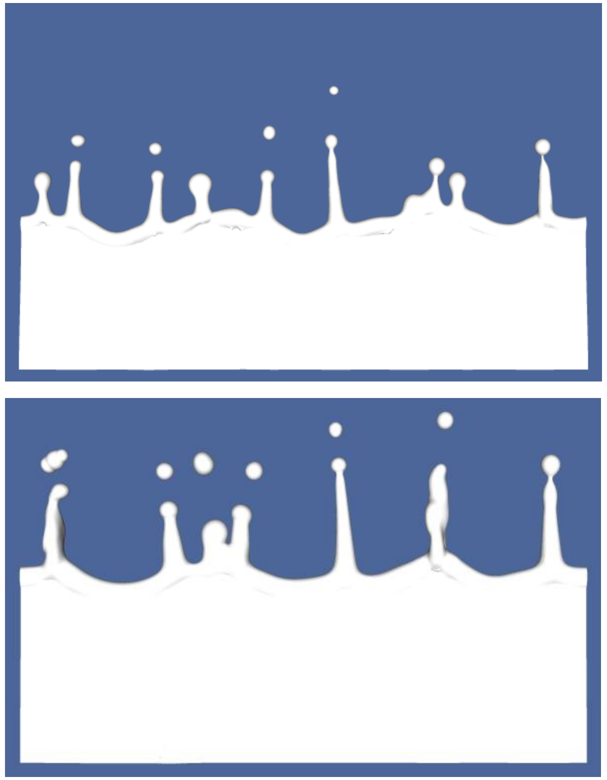

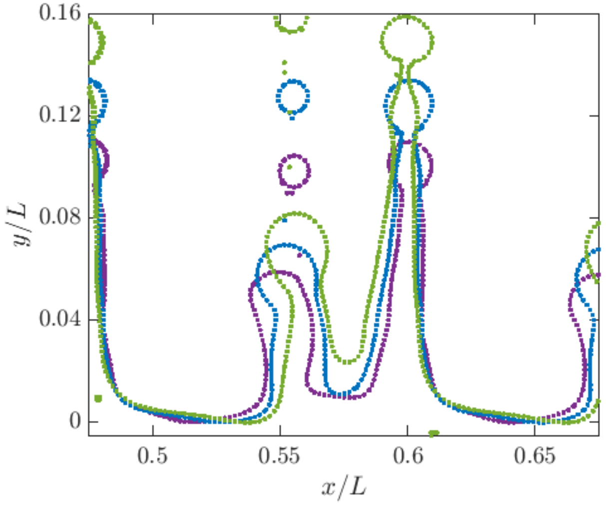

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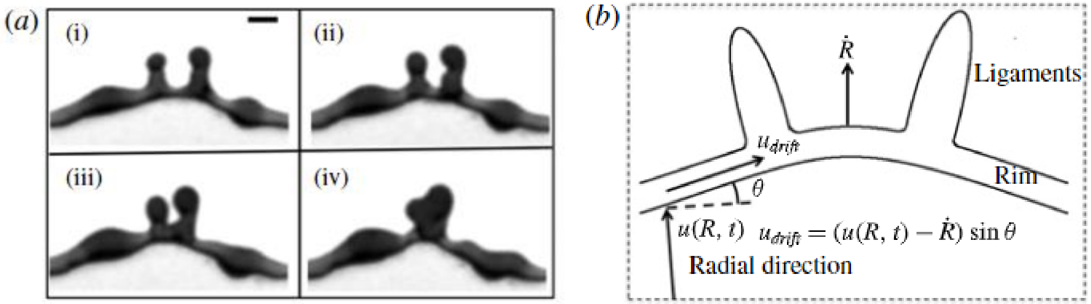

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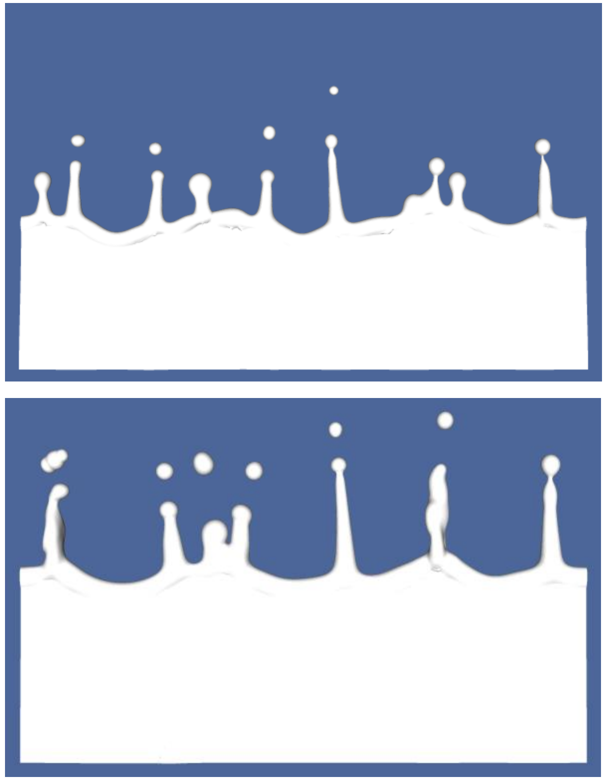

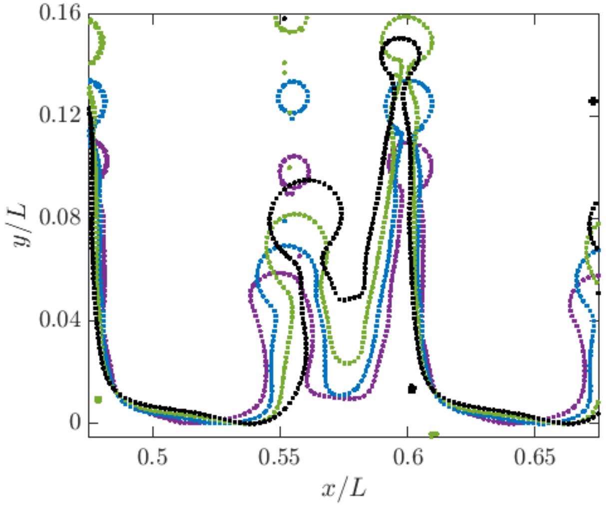

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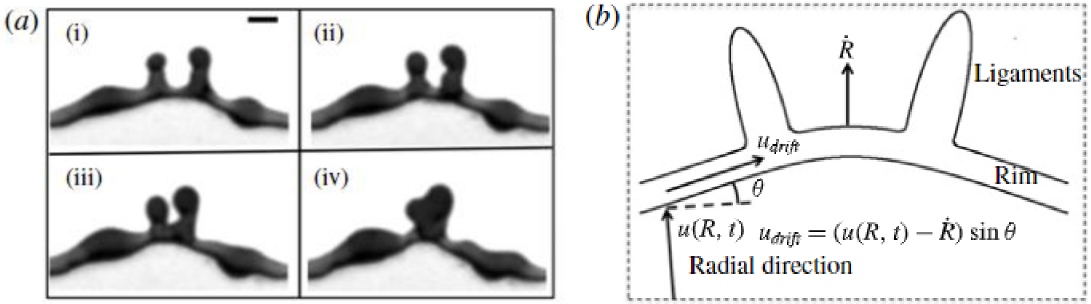

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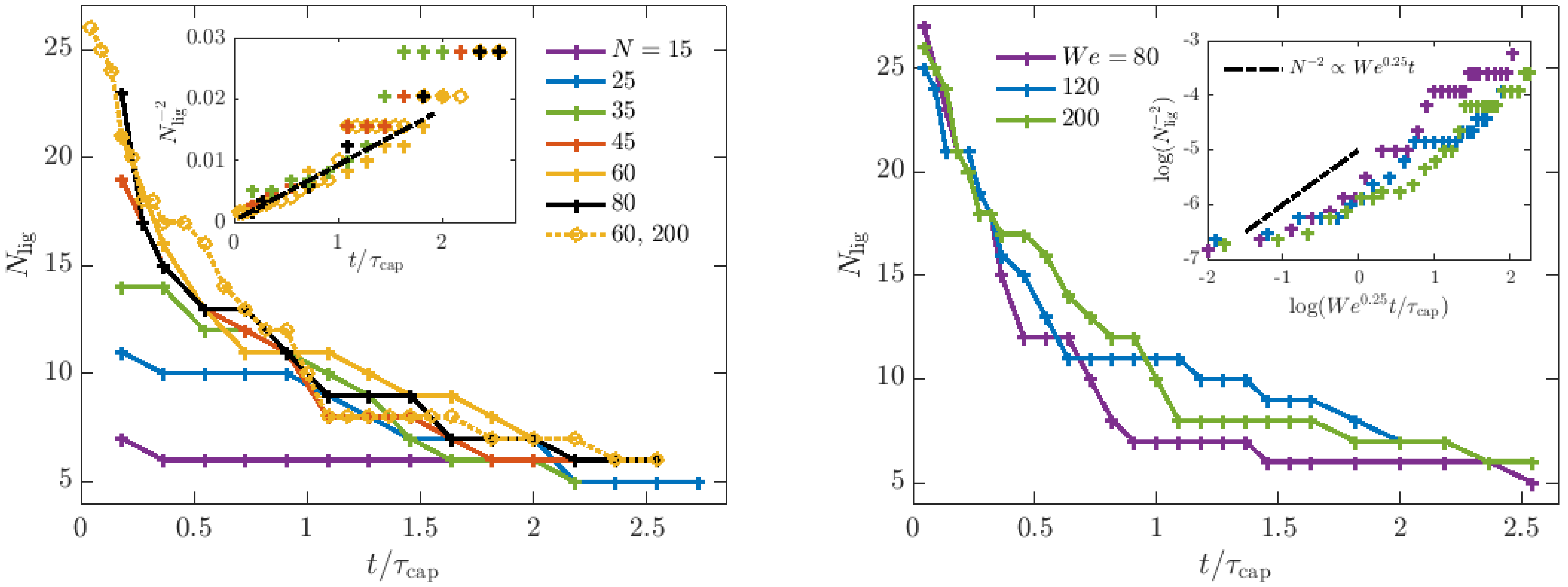
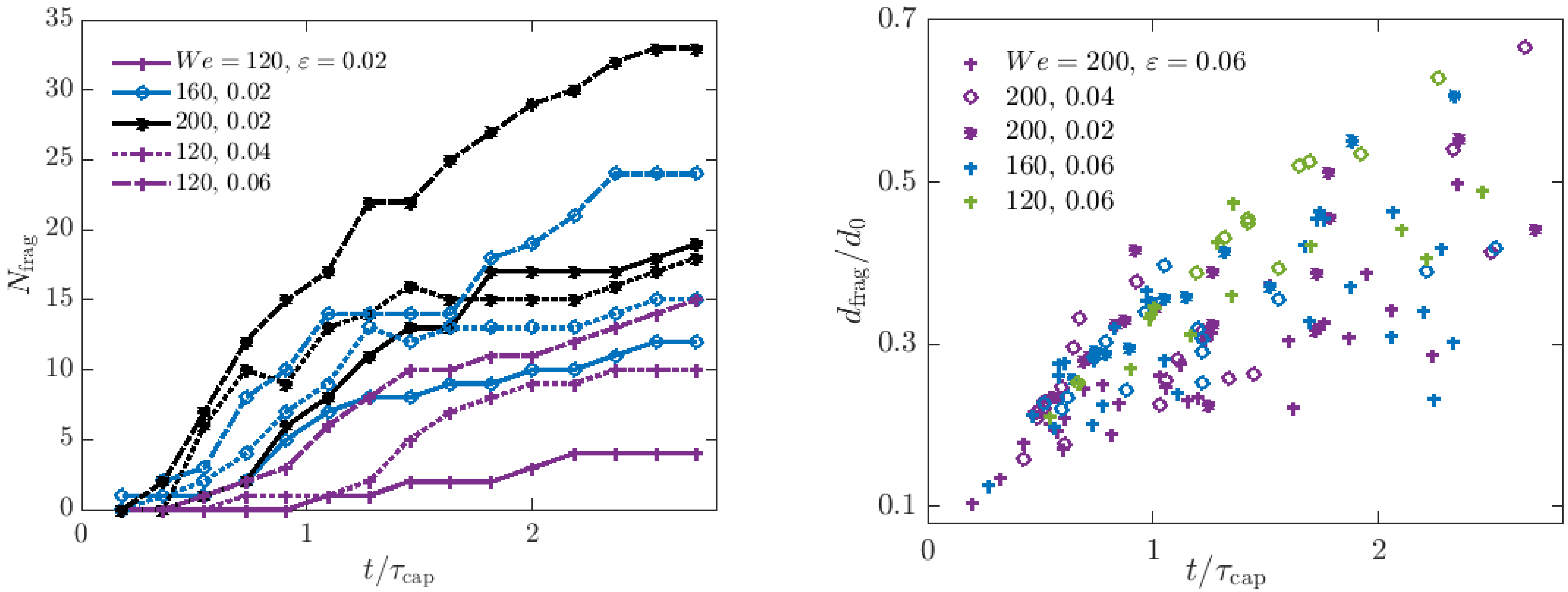
Ligament Merging Phenomena

$$\frac{1}{N_{\text{lig}}^2} = AWe^{0.25}t + B$$



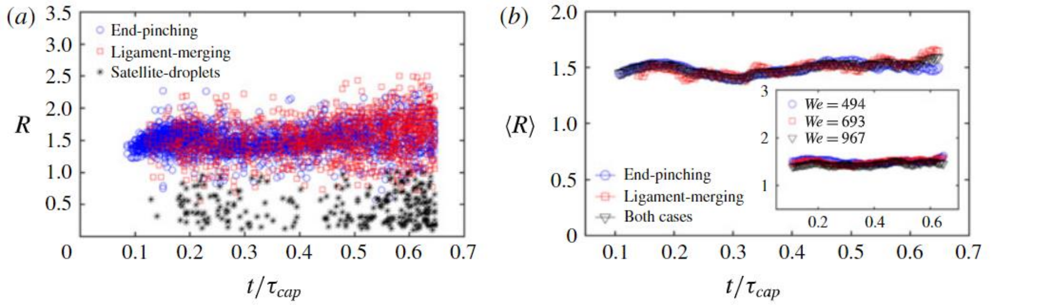
Ligament number N_{lig} at different N_{max} (left) and We (right)

Primary Drop Statistics

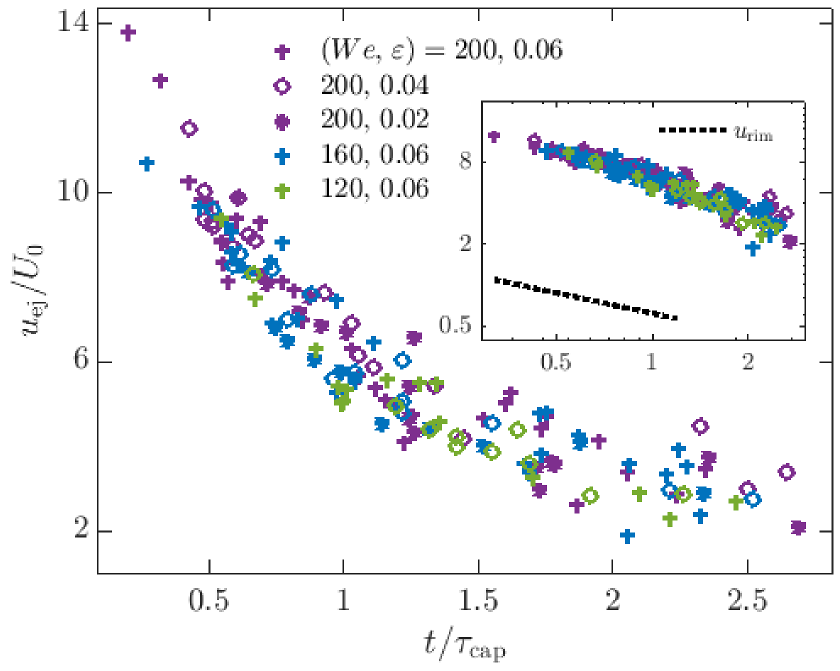


Total number (left) and diameter (right) of primary fragments

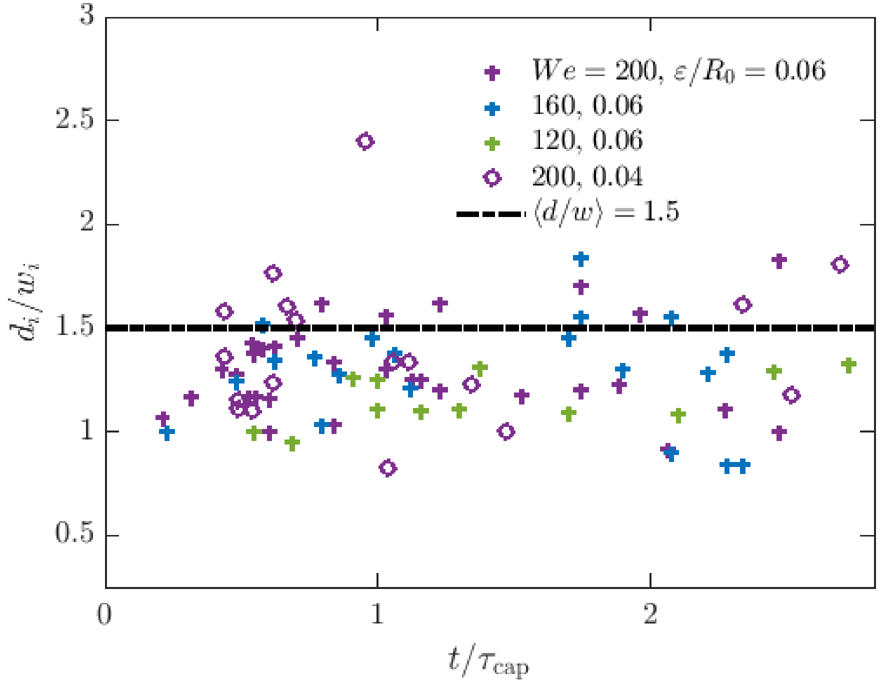
Primary Drop Statistics



End-pinching of Worthington jets: $\langle d/w \rangle \approx 1.5$ [1][2]



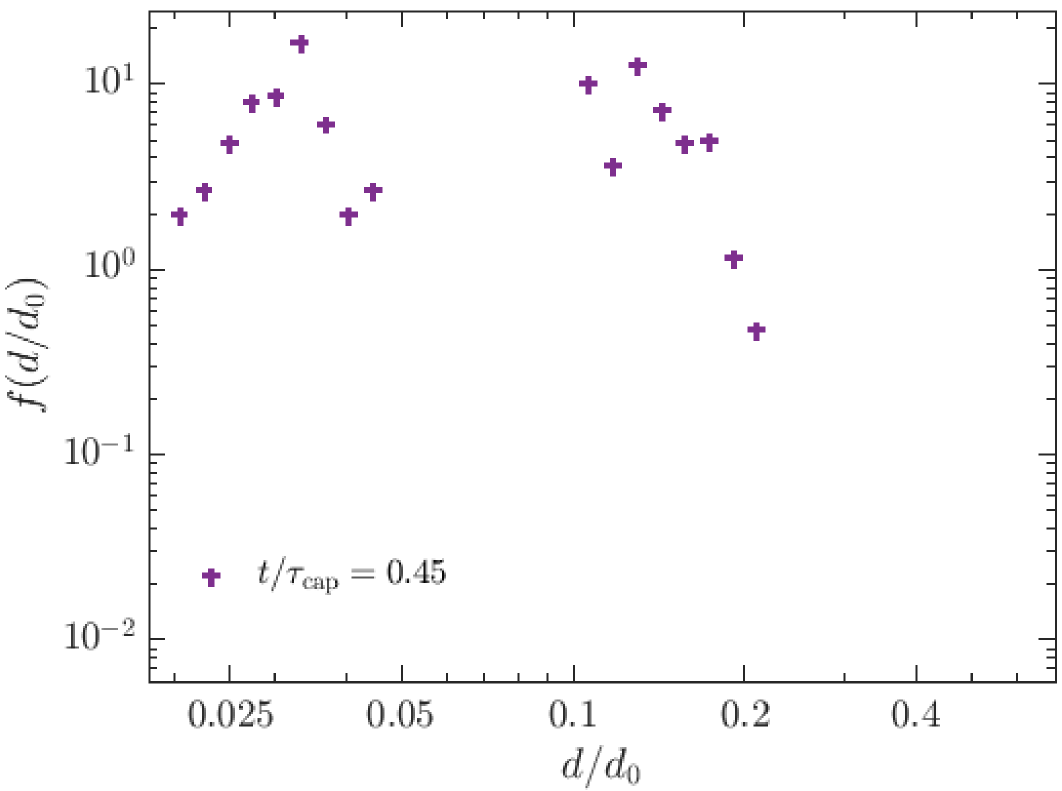
Fragment ejection velocity



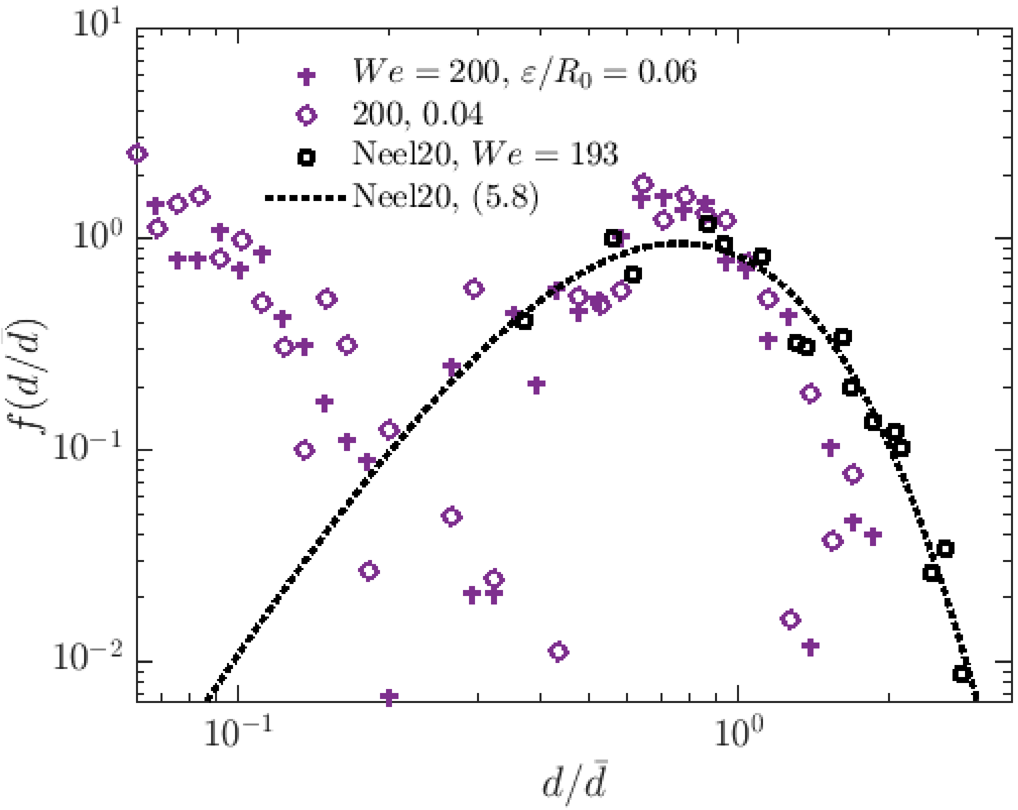
Fragment diameter d_i / parent ligament width w_i

[1] Wang, Y., & Bourouiba, L. (2018). Unsteady sheet fragmentation: droplet sizes and speeds. *Journal of Fluid Mechanics*, 848, 946-967.
[2] Gordillo, J. M., & Gekle, S. (2010). Generation and breakup of Worthington jets after cavity collapse. Part 2. Tip breakup of stretched jets. *Journal of fluid mechanics*, 663, 331-346.

Fragment Size Distributions



Evolution of fragment size distribution



Comparison with Neel *et al.* (2020)

[1] Néel, B., Lhuissier, H., & Villermaux, E. (2020). ‘Fines’ from the collision of liquid rims. *Journal of Fluid Mechanics*, 893, A16.

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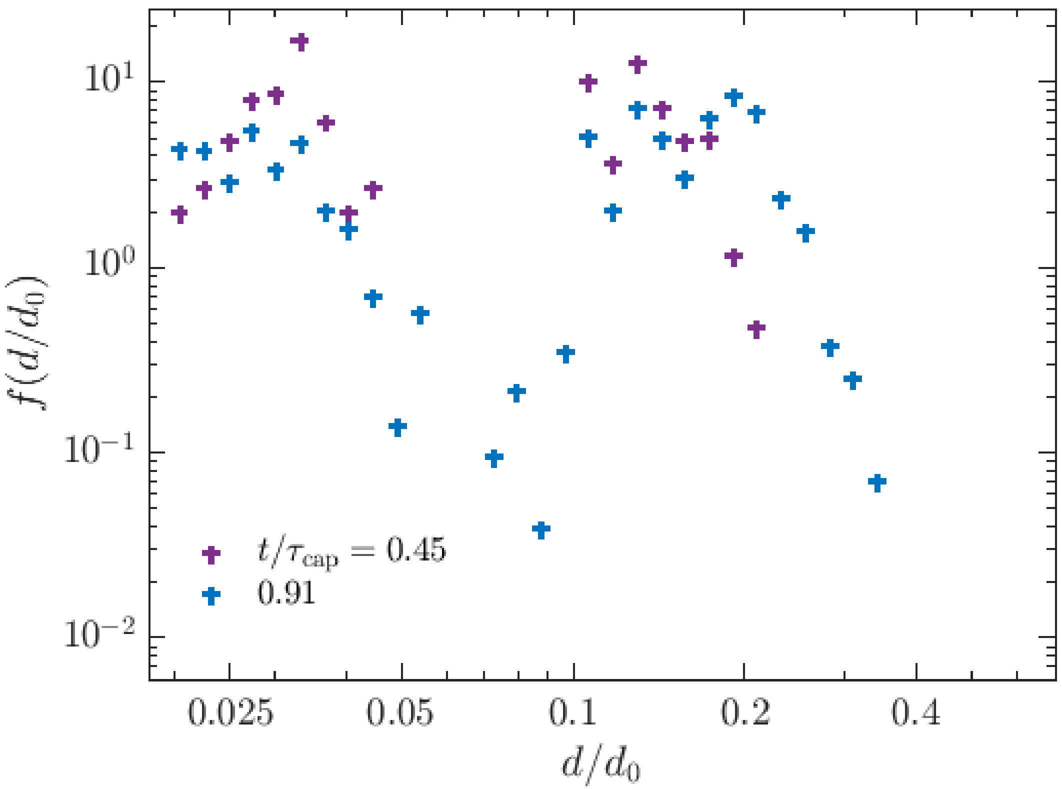

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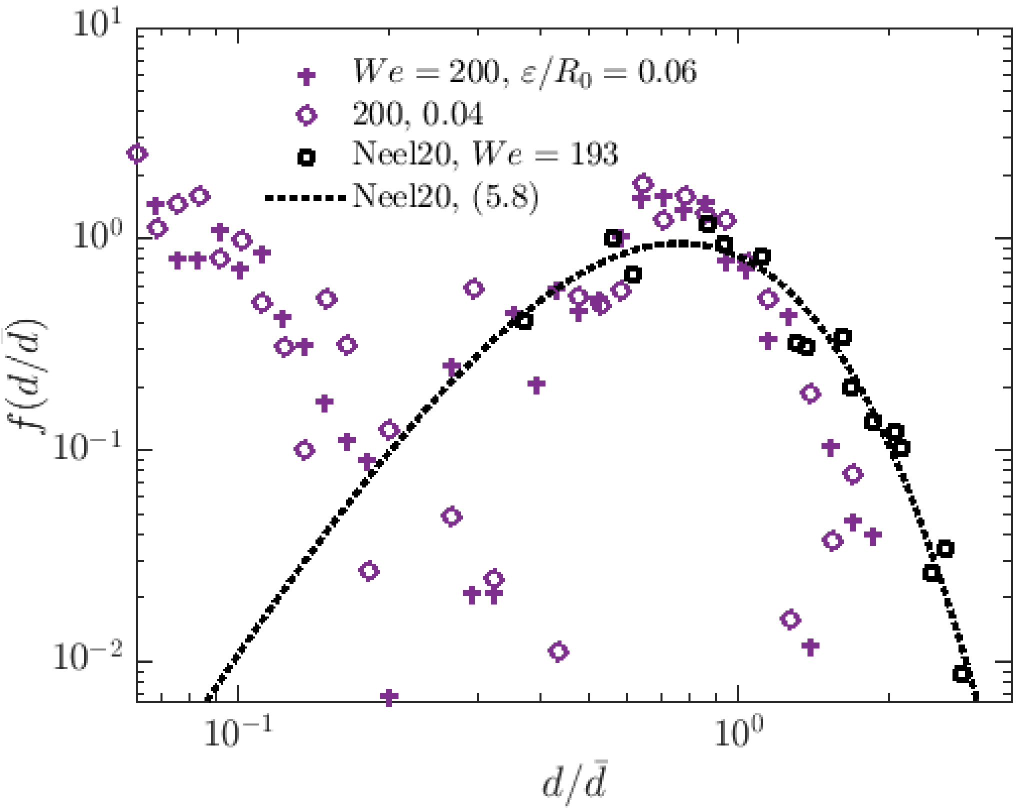

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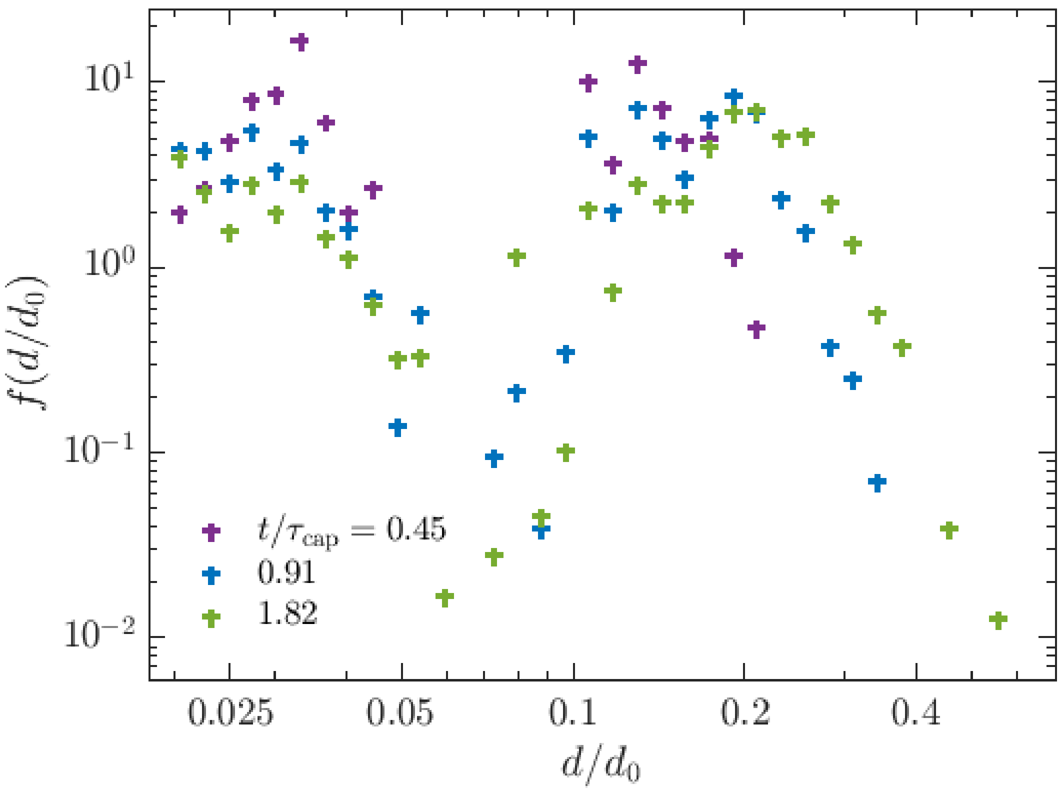

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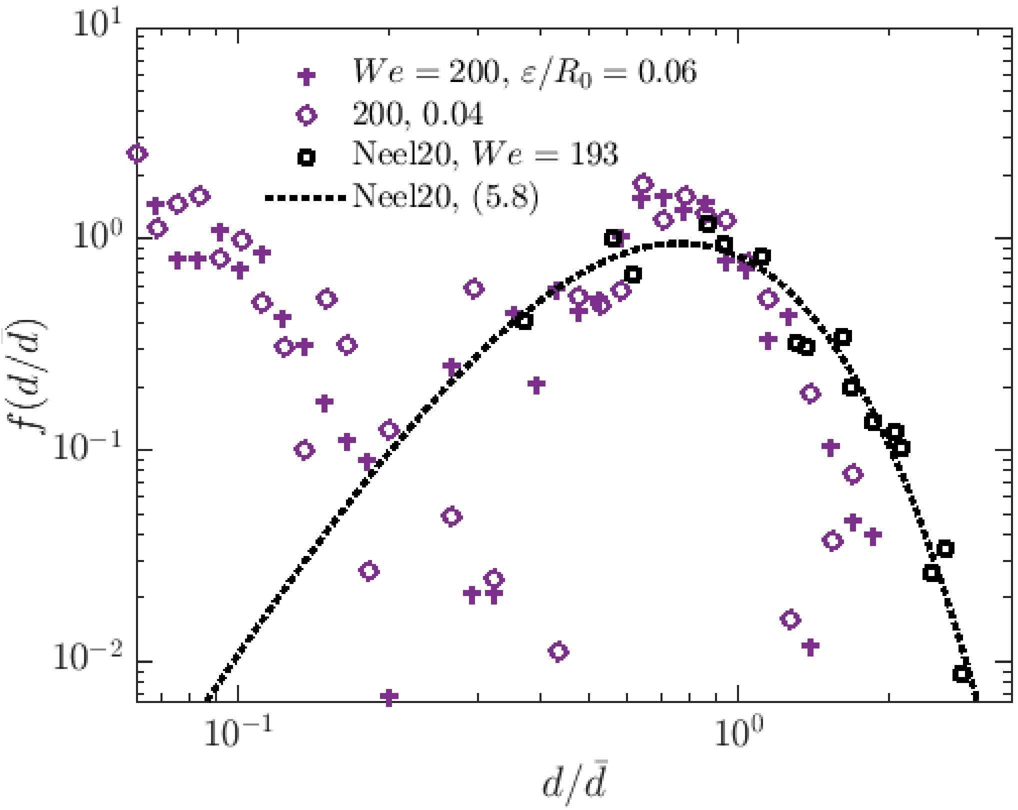

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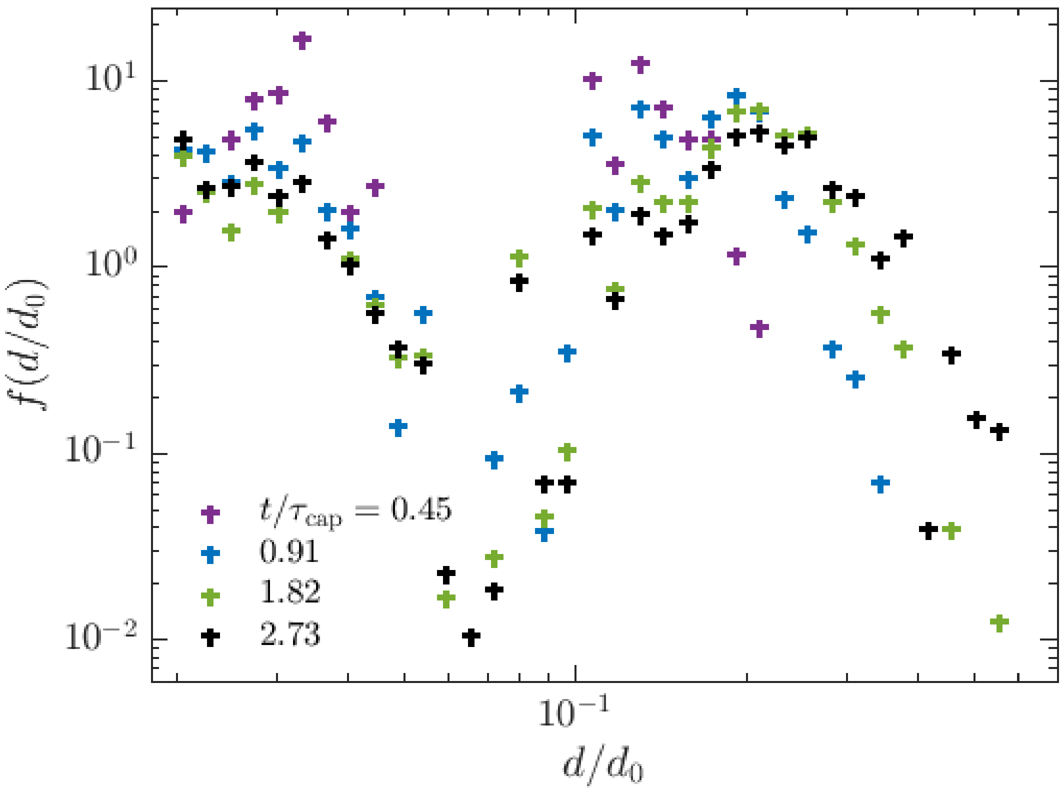

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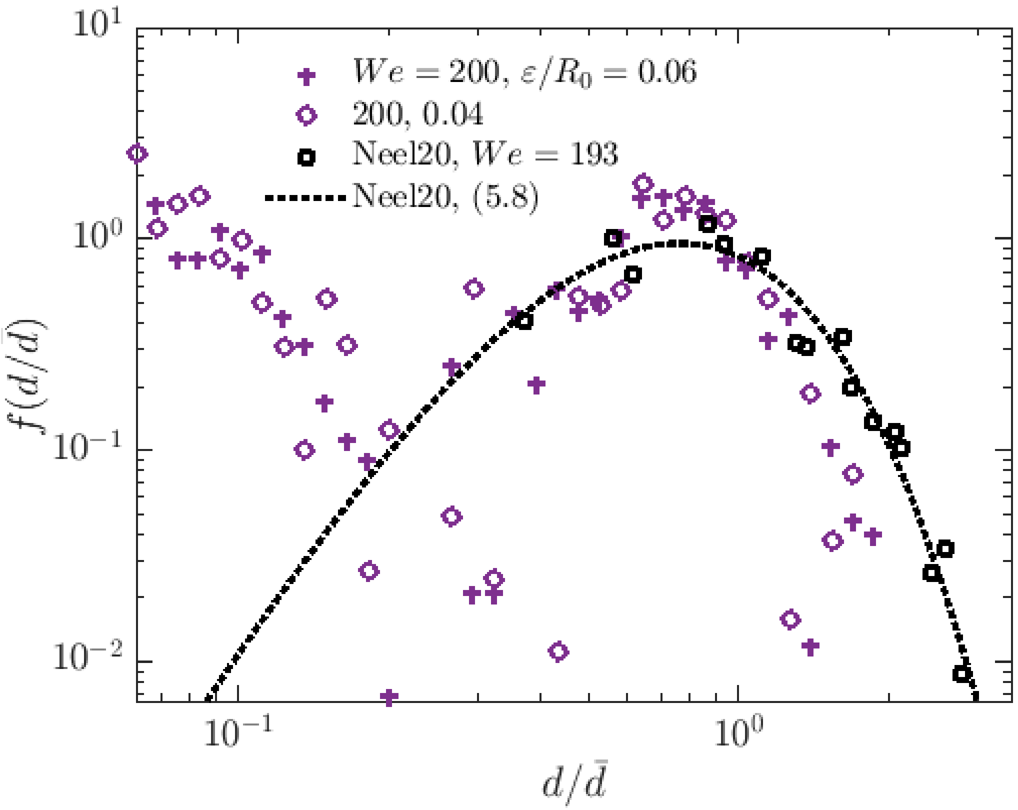

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Conclusions and Future Work

- ✓ 3D simulations of cylinder collision;
- ✓ Liquid sheet expansion:
  - Self-similar models for u_y and h
- ✓ Rim Kinematics:
  - Scaling models for y_{rim} and b_{rim}
- ✓ Ligament Dynamics:
  - Linear growth and ballistic region
  - Theoretical model for ligament merging
- ✓ Fragment statistics: agreement with existing results for large drops

- Refine the ligament merging model;
- Establish grid convergence for fragment statistics;
- Explore connection with the drop size distribution of wave splashing.

Thanks for your attention!