

Atomization through Swirl Nozzle

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ARR-96-03

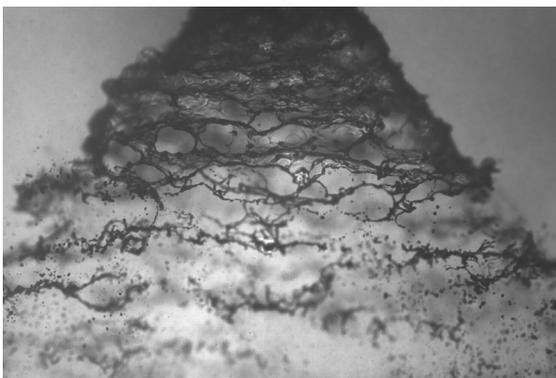
Jerry Chen



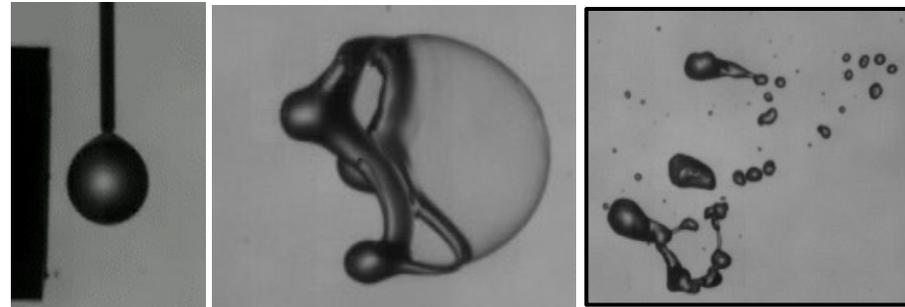
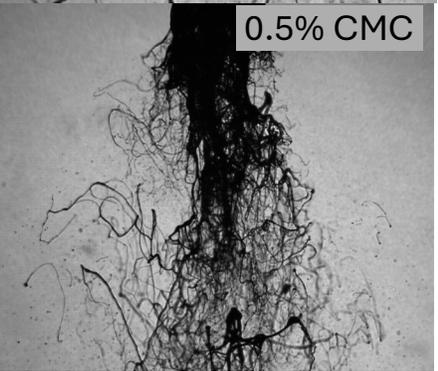
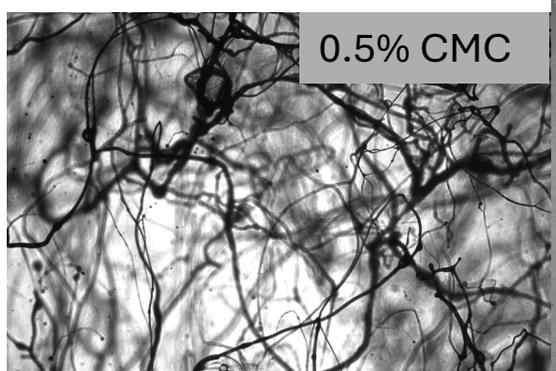
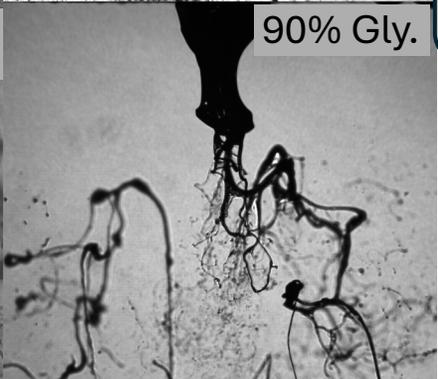
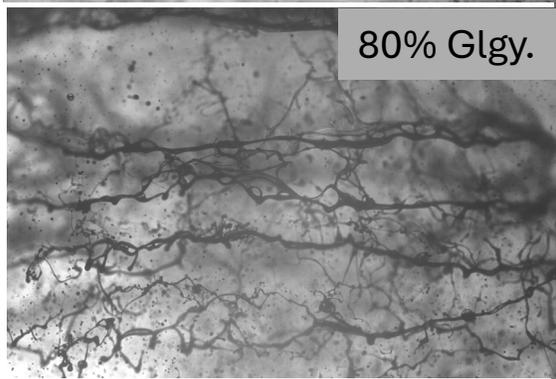
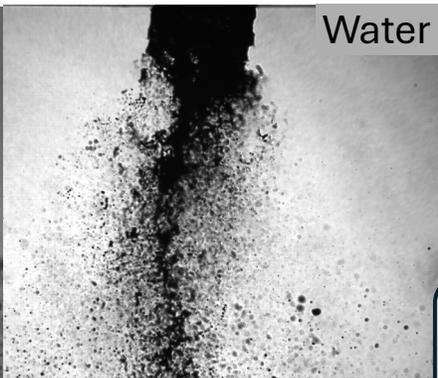
June 2025

Experiments Performed

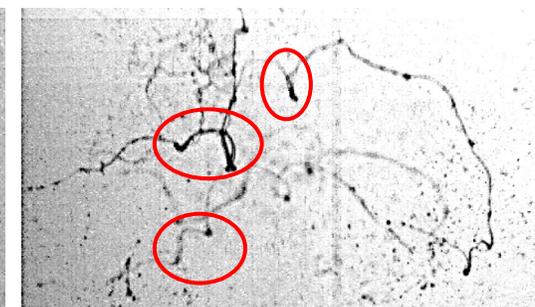
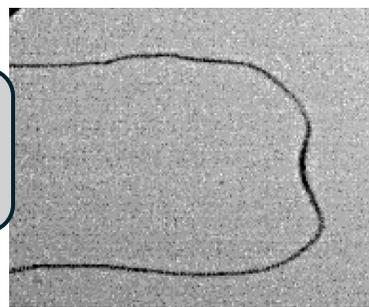
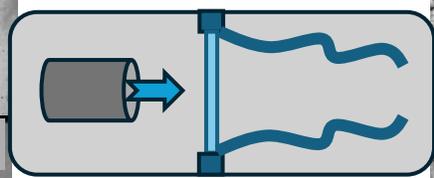
1-Swirl Nozzle



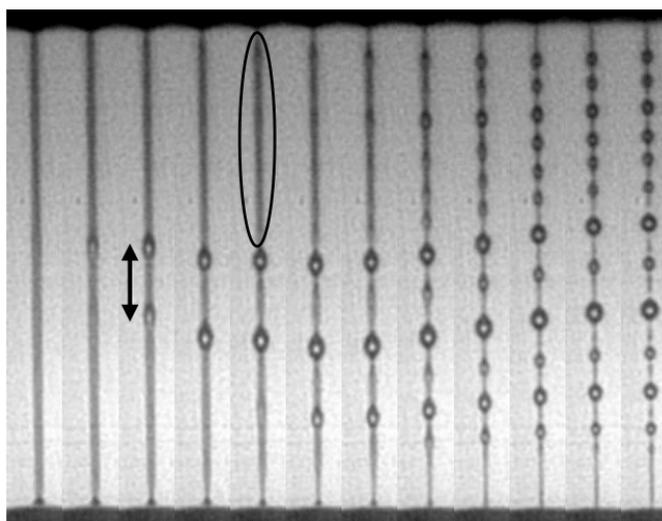
2-Twin Fluid Nozzle



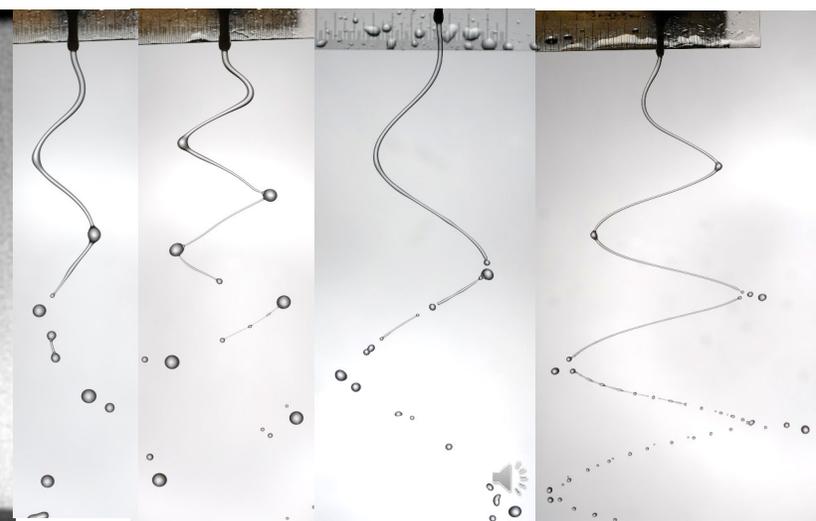
3-Drop Breakup



4-Ligament Breakup in a Crossflow

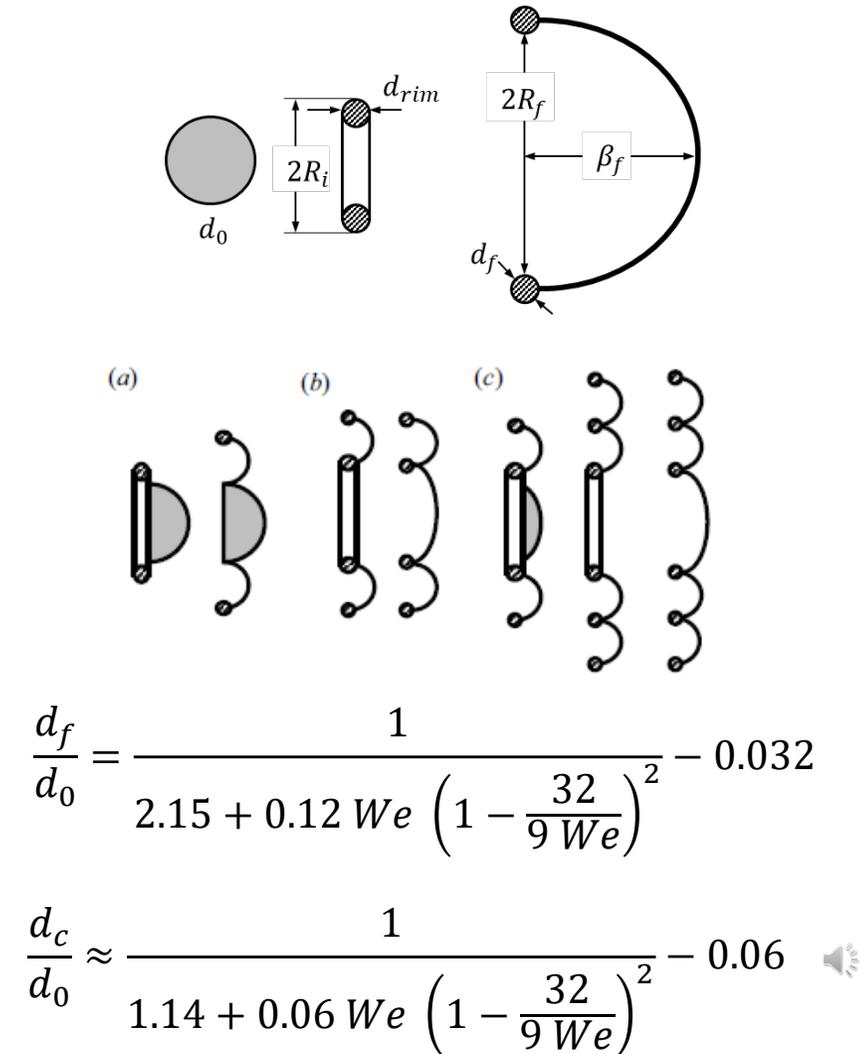
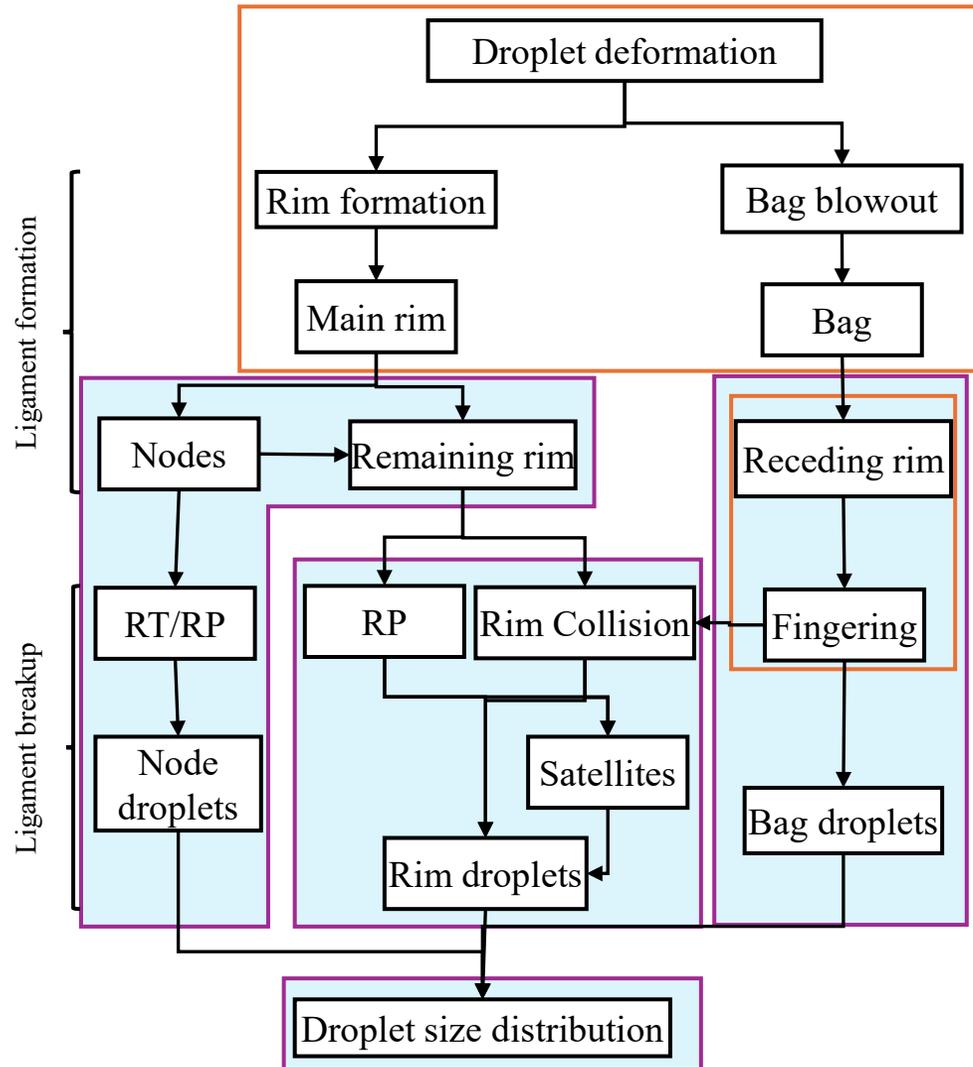


5-Ligament Stretching



6-Flapping Ligaments

Twin Fluids Nozzle Atomization by ADAM (Aerodynamic Droplet Atomization Model)



LISA- Linear Instability Sheet Atomization

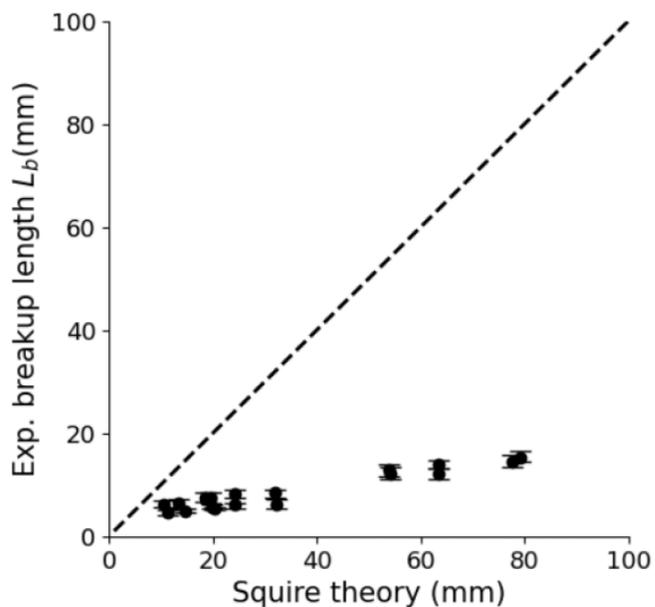
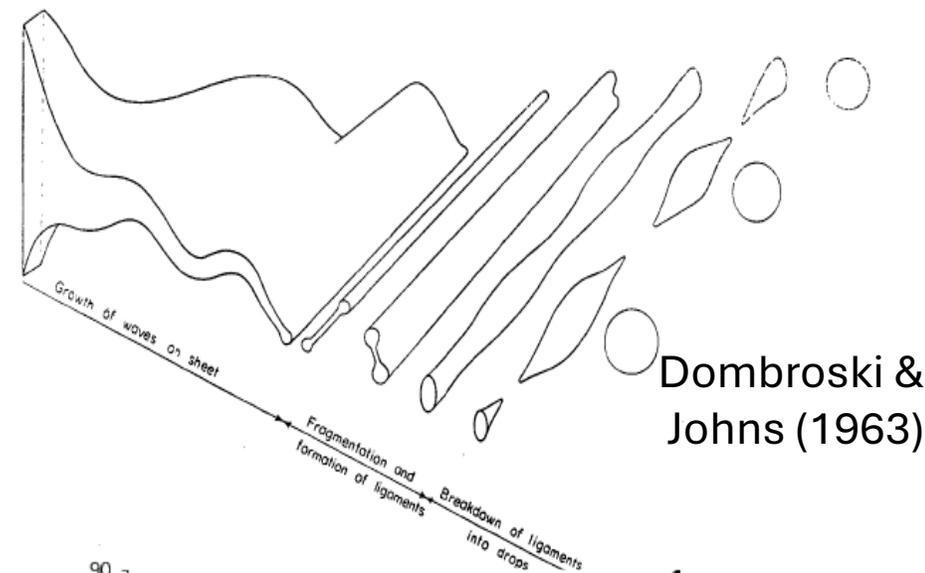
Two-step breakup

- Sheet breaks up into filaments

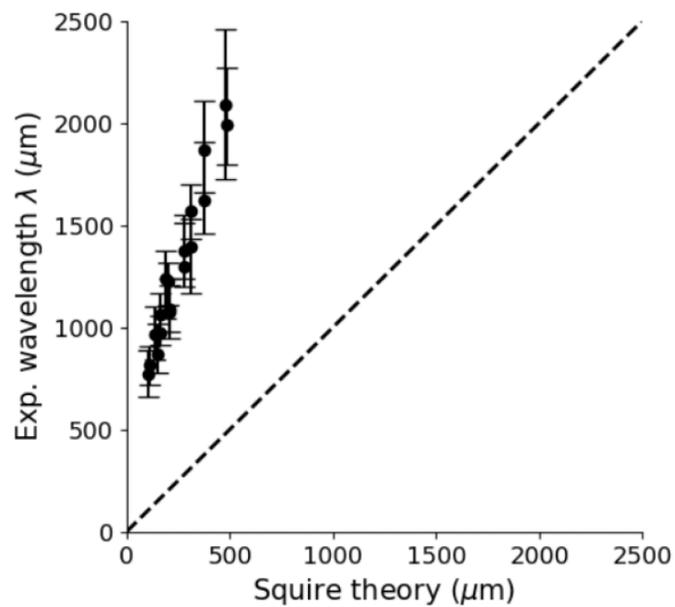
$$\omega = -2\nu k^2 + \sqrt{4\nu^2 k^4 + \alpha U^2 k^2 - \frac{\gamma k^3}{\rho}} \quad \lambda_{max} = 2\pi/k_{max}$$

$$d_{fil} = \sqrt{\frac{2\dot{m}\lambda_{max}}{\pi^2 \rho U L_b \sin\theta}}$$

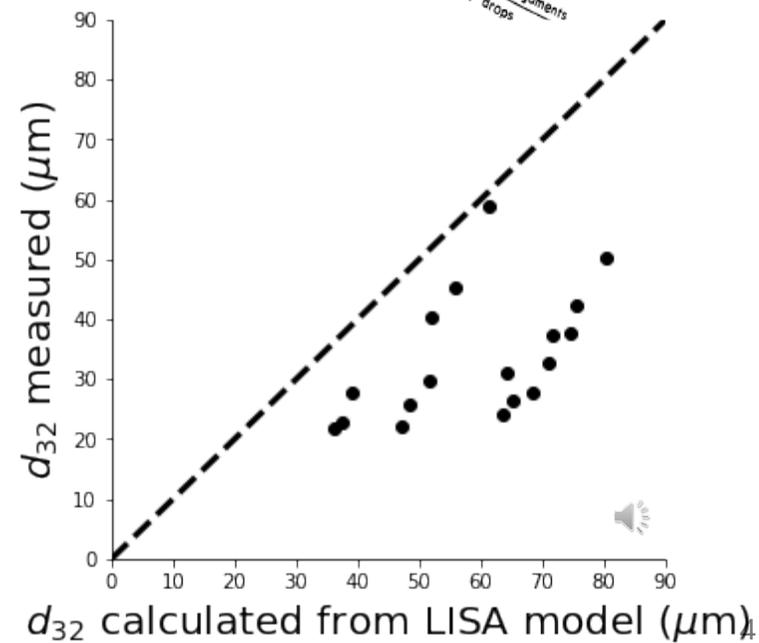
$$d_D = 1.882 d_{fil} (1 + 30h)^{1/6}$$



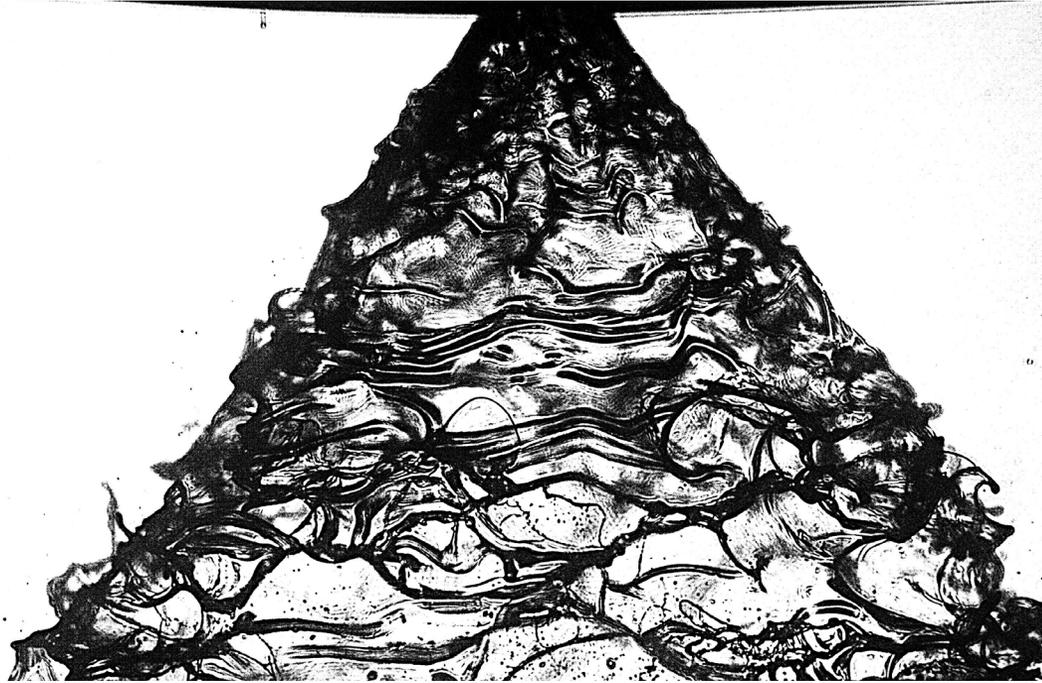
(a)



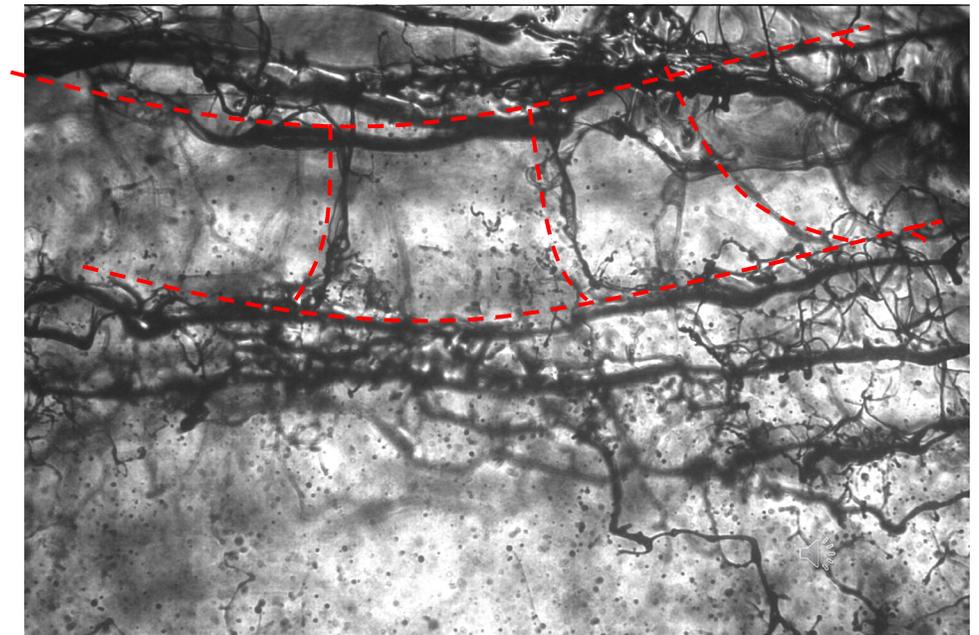
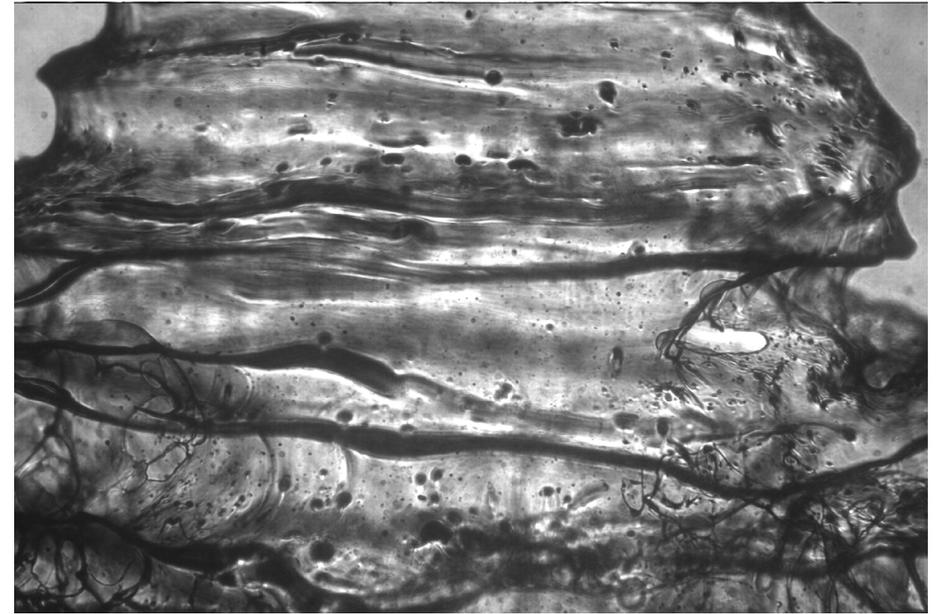
(b)



Near Nozzle Images



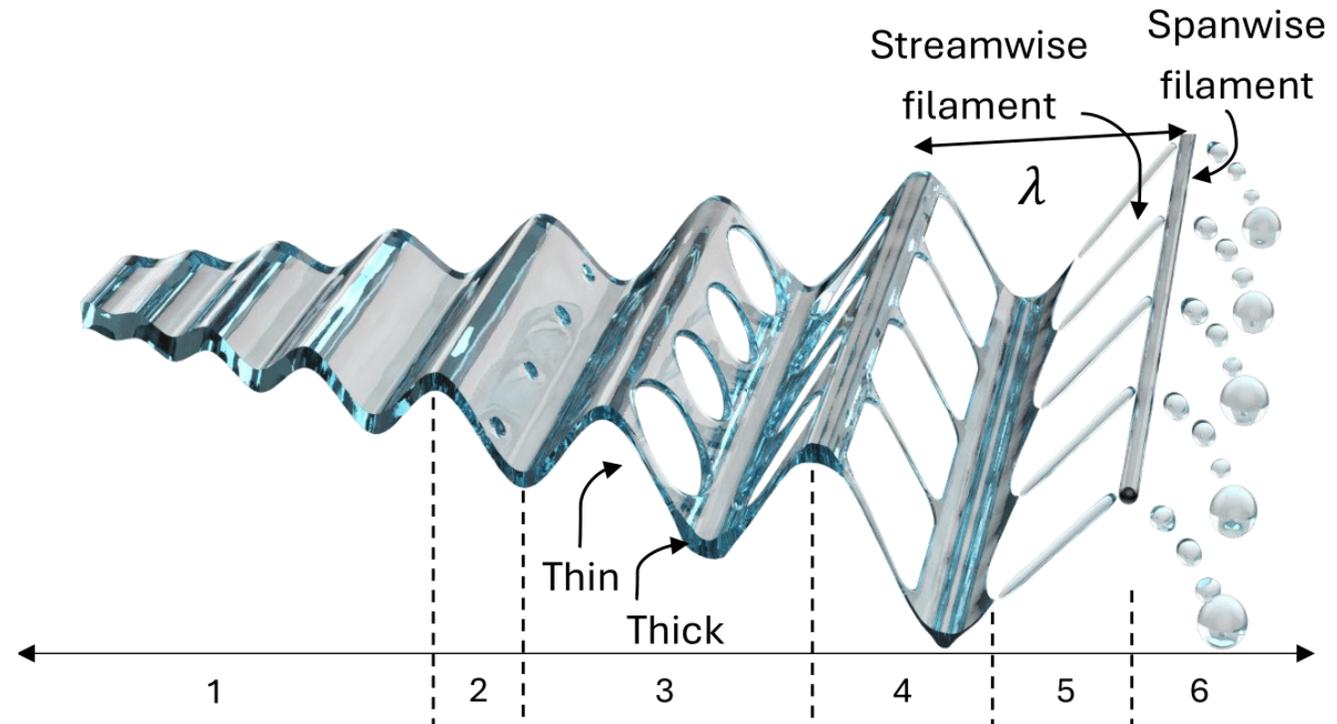
- Wavelength increases along the sheet
- Liquid sheet perforates before it breaks up into ligaments
- Breakup results in thick spanwise ligaments, and thin streamwise ligaments.
- Higher viscosity increase the diameter of spanwise ligament



80% glycerin, 700 psi, $z=5\text{mm}$

Swirl Nozzle Atomization by PSAM - Perforated Sheet Atomization Model

- Wavelength grows as sheet moves downstream
- Non-linearity of surface wave generates alternating thin and thick regions
- Sheet perforates in the thin regions, generating thin streamwise filaments
- Thick regions generate thick spanwise filaments
- Filaments stretch, become thinner and breakup into droplets



Improved Model for the Sheet Instability

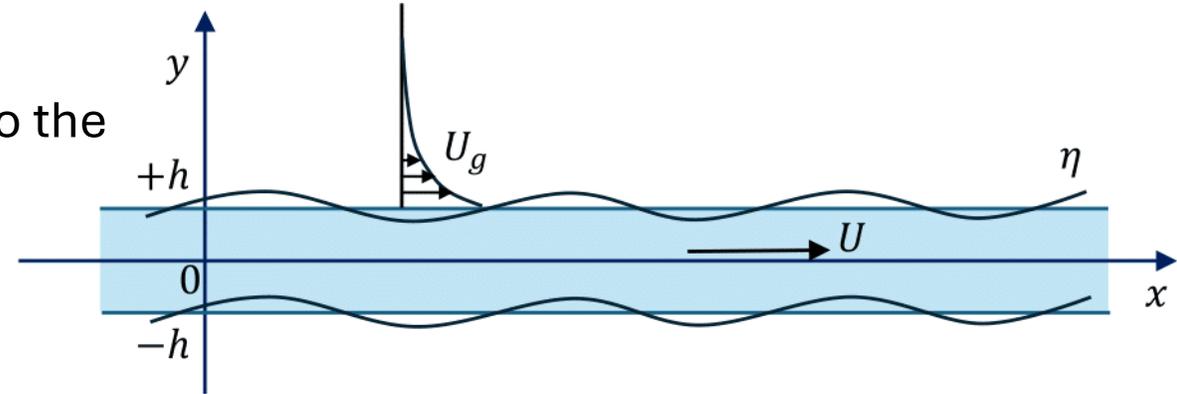
Gas Phase: Consider the induced air flow field due to the high-speed liquid sheet

$$\frac{\partial u_g}{\partial x} + \frac{\partial v_g}{\partial y} = 0$$

$$\rho_g \left(\frac{\partial u_g}{\partial t} + U_g \frac{\partial u_g}{\partial x} + v_g \frac{\partial U_g}{\partial y} \right) = -\frac{\partial p_g}{\partial x} + \mu_g \left(\frac{\partial^2 u_g}{\partial x^2} + \frac{\partial^2 u_g}{\partial y^2} \right)$$

$$\rho_g \left(\frac{\partial v_g}{\partial t} + U_g \frac{\partial v_g}{\partial x} \right) = -\frac{\partial p_g}{\partial y} + \mu_g \left(\frac{\partial^2 v_g}{\partial x^2} + \frac{\partial^2 v_g}{\partial y^2} \right)$$

$$U_g(y) = U \left(1 - \operatorname{erf} \left(\frac{y-h}{2} \sqrt{\frac{Re_g}{x^* h}} \right) \right)$$

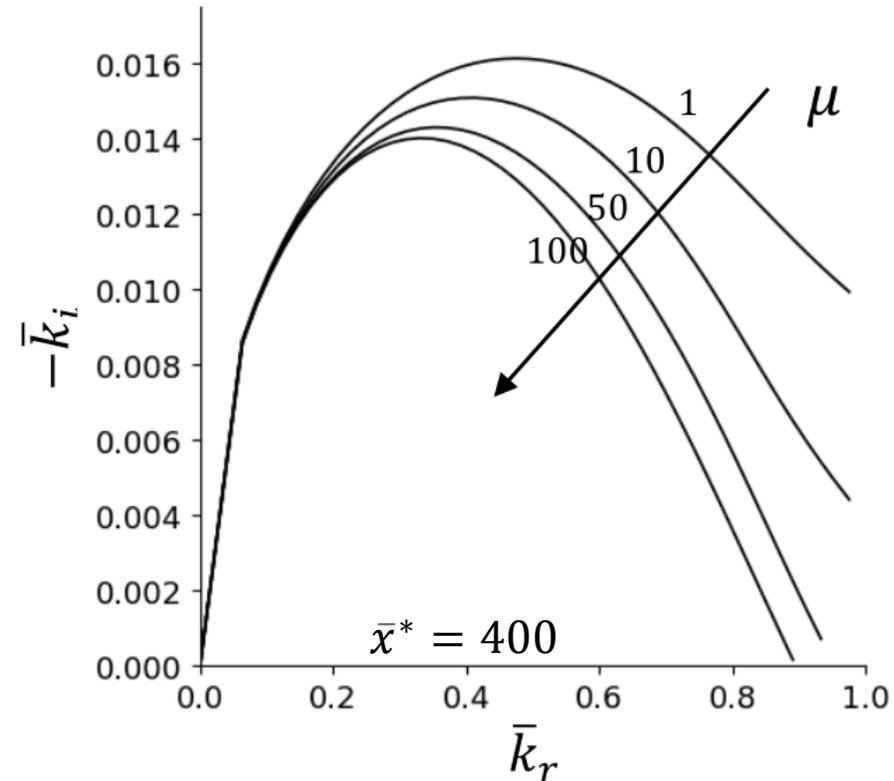
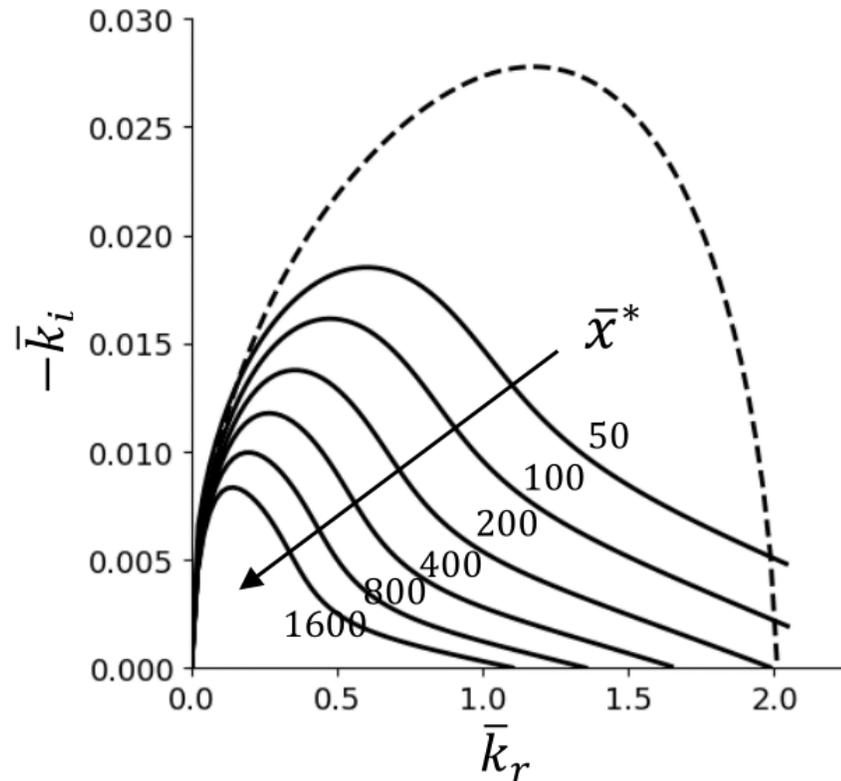


Modified stokes layer model



Sheet Shear Instability

- Spatial shear Instability shows dominant wavelength **increases as sheet moves downstream**, and as viscosity increases.



Increase in liquid viscosity stabilizes the liquid sheet and reduces the cutoff wavenumber, but the effect is not as much as an increase in the boundary layer thickness.

Wavelength at the Breakup

- In order to determine wavelength by integration, we need to determine breakup length L_b
- We have obtained a Semi-empirical correlation based on our experiments:

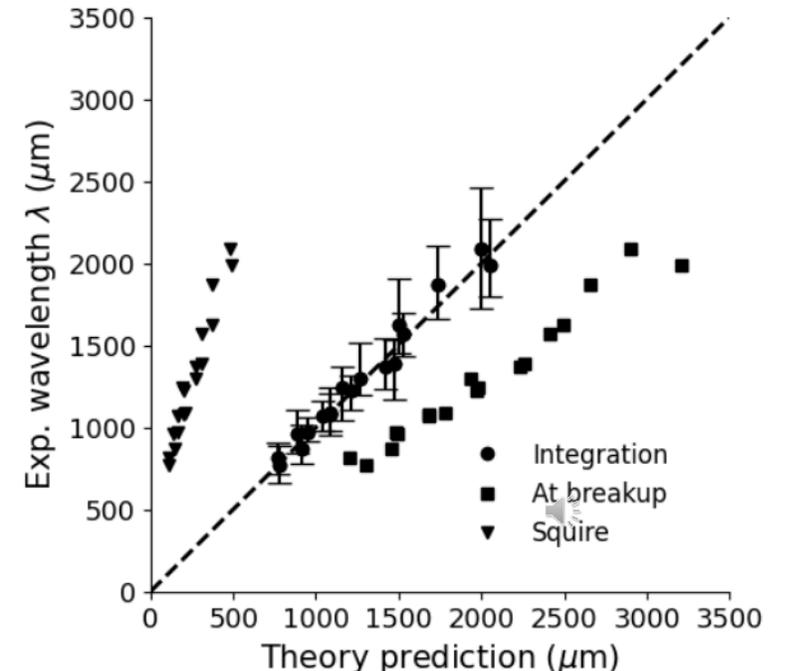
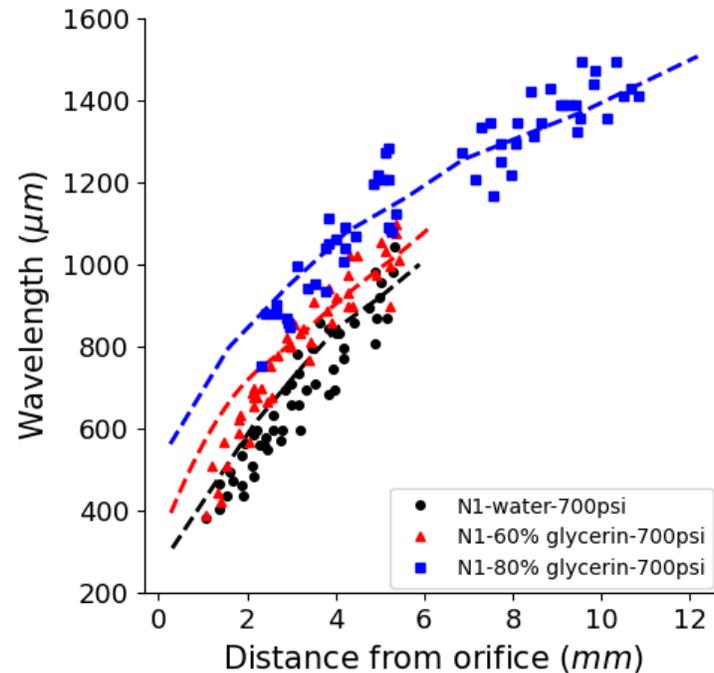
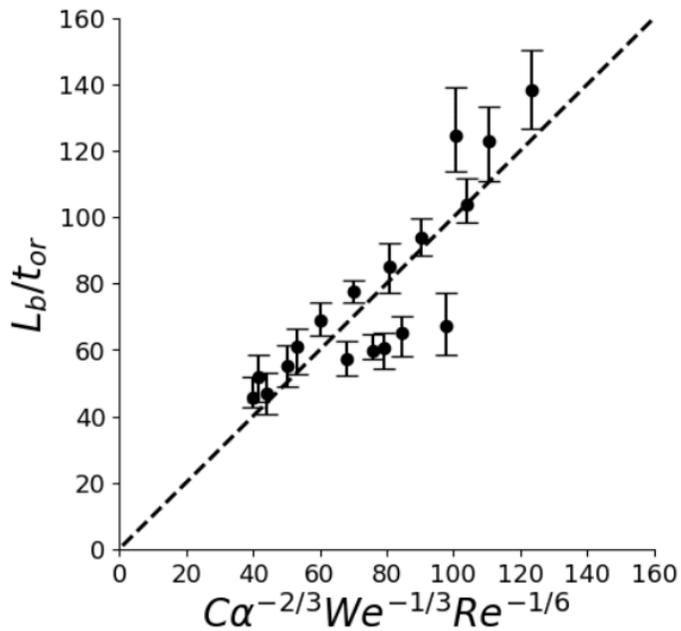
$$\frac{L_b}{t_{or}} = 33.5 \alpha^{-2/3} We^{-1/3} Re^{-1/6}$$

- For ease of use, we developed a correlation based on the integrated result

$$\frac{\lambda}{t_{or}} = 23.4 \alpha^{-2/3} We^{-8/15} Re^{-1/6} = 0.7 We^{-1/5} \left(\frac{L_b}{t_{or}} \right)$$

$$\lambda \propto U^{-16/15} \quad \text{VS}$$

$$\lambda \propto U^{-2} \quad (\text{No BL})$$



Sheet Perforation and Film Thickness

Perforation generates a retracting thick rim, (a)
which expands until it reaches the thick regions,
i.e.

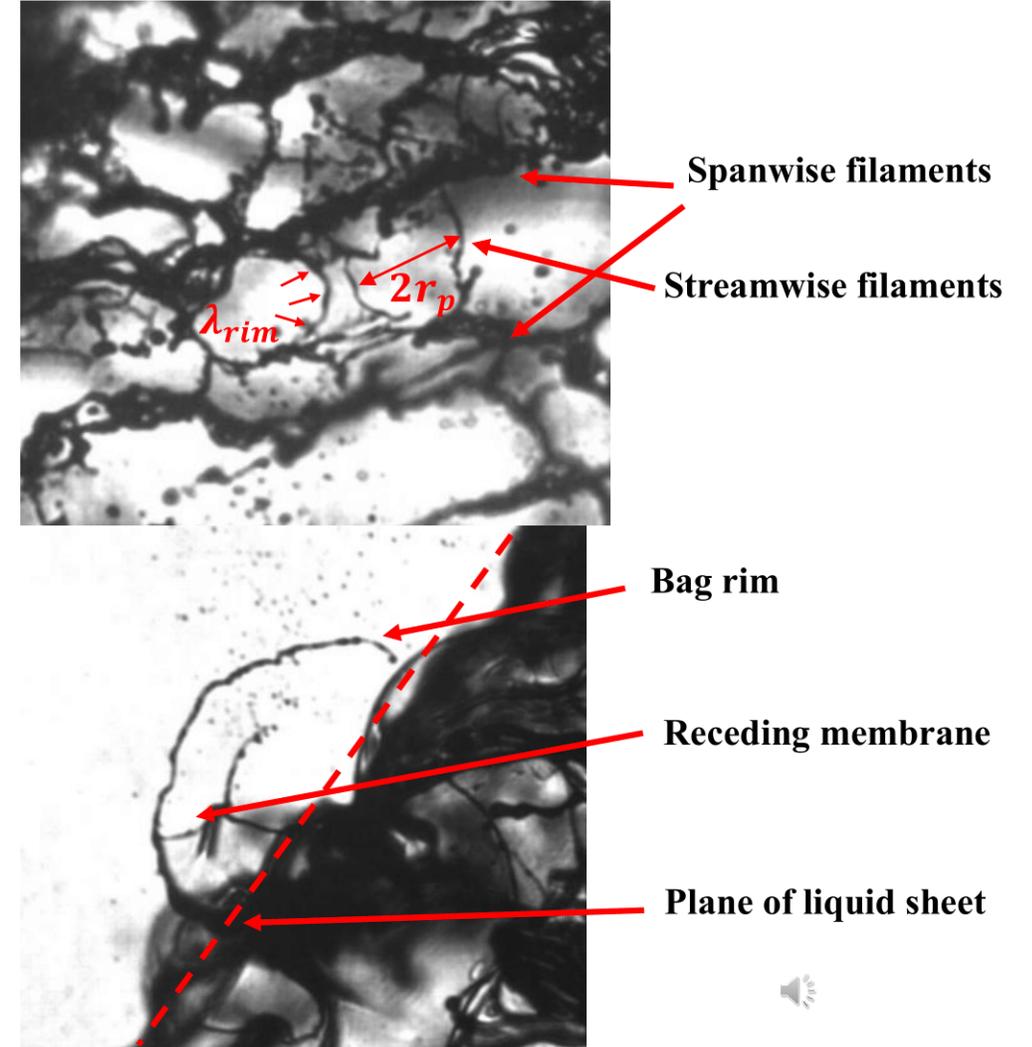
$$2r_p \sim \lambda$$

and forms streamwise filaments.

Rim diameter, $a_{rim}(t)$, is derived by geometric relationships (b)

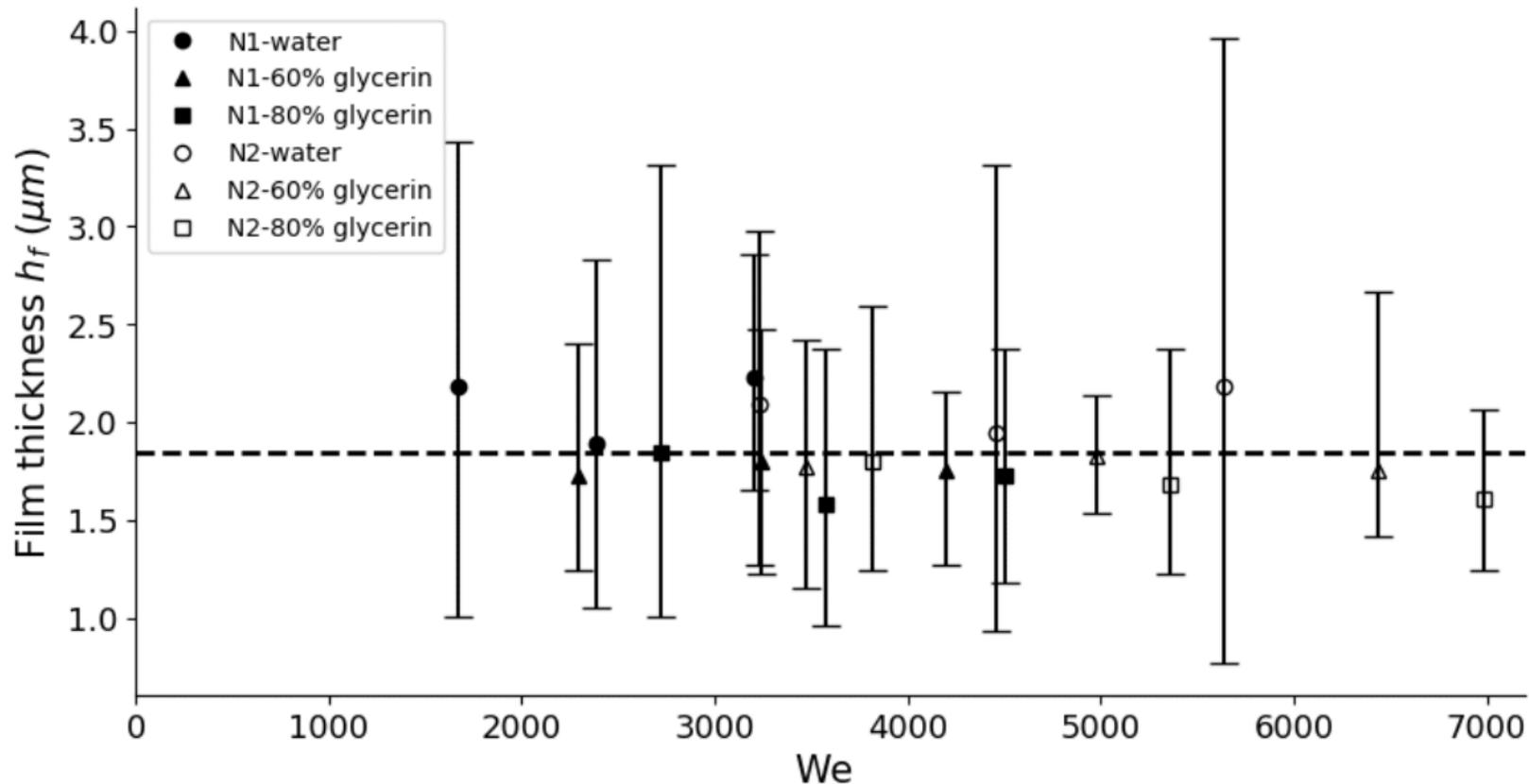
$$\pi r_p^2 h_f = \frac{\pi^2}{2} r_p a_{rim}^2 \Rightarrow a_{rim} = \sqrt{\frac{2h_f r_p}{\pi}}$$

- This relates wavelength on the rim with the film thickness h_f .



Film Thickness

- The rim recedes at the Taylor-Culick velocity: $u_{rim} = u_{TC} = \sqrt{\frac{2\gamma}{\rho h_f}}$
- Film thickness slightly decreases as fluid velocity increases.
- The film thickness is of the order $1\mu m$, with an average of all cases $\bar{h}_f = 1.85\mu m$



Characteristic Filament Thickness

- The streamwise filament thickness is

$$d_S = \sqrt{\lambda h_f}$$

- The spanwise filament thickness is

$$\frac{\pi}{4} d_L^2 = \frac{\dot{m} \lambda}{2\pi \rho U L_b \sin \theta} - \lambda h_f$$

- Spanwise filaments stretched until it breaks. The pinch-off time is estimates as:

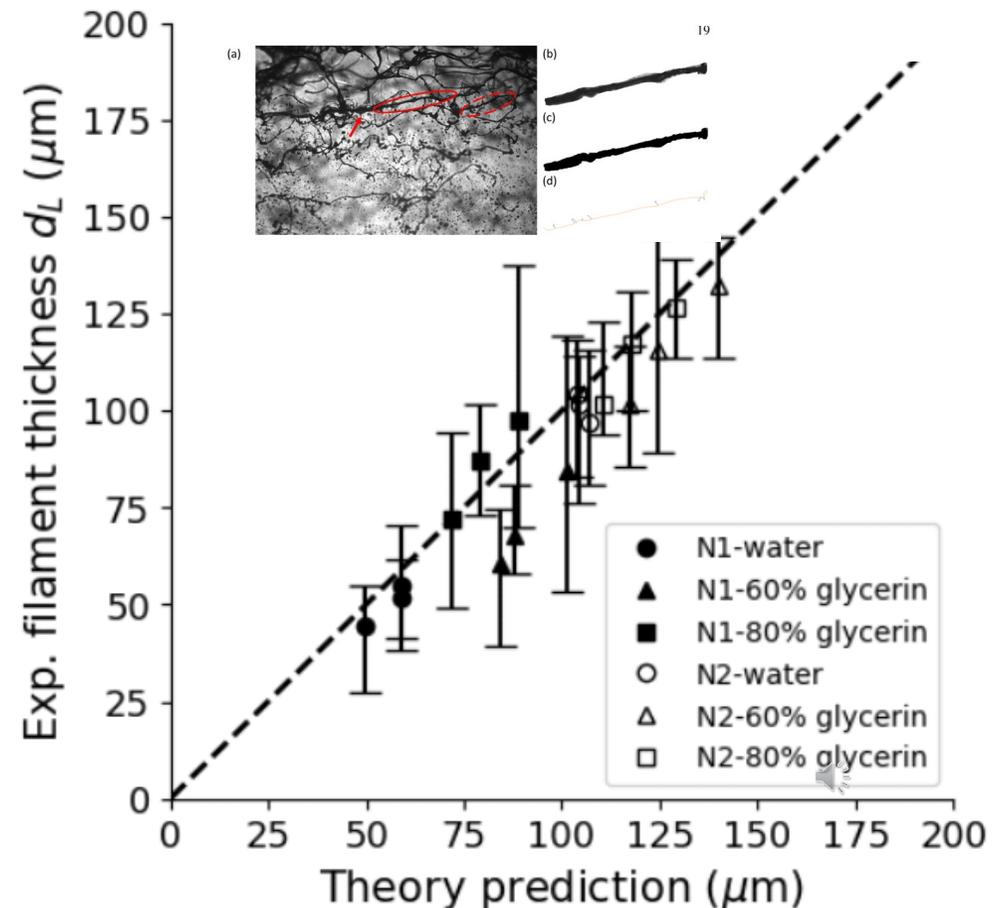
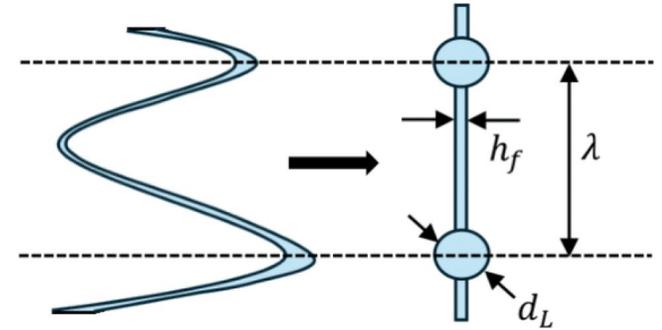
$$\tau_{pinch-off} = \sqrt{\frac{\rho d_L^3}{\sigma}} (1 + 30 h_{d_L})$$

Then the stretched length of the filament is

$$l = U \cos \theta \tau_{pinch-off}$$

And diameter of the filament at breakup is

$$d_{L,b} = d_L \sqrt{1 + \frac{l}{L_b}}$$



PSAM - Sheet Thickness and Breakup Length

1. Calculate sheet velocity, U , knowing injection pressure: $U = 0.7\sqrt{2p/\rho}$
2. Calculate sheet thickness at the orifice t_{or} , knowing mass flow and spray cone angle:

$$t_{or} = \frac{d_{or}}{2} - \sqrt{\frac{d_{or}^2}{4} - \frac{\dot{m}}{\rho\pi U \cos\theta}}$$

3. Calculate the breakup length L_b and λ :

$$\frac{L_b}{t_{or}} = 33.5 \alpha^{-2/3} We^{-1/3} Re^{-1/6}$$

$$\frac{\lambda}{t_{or}} = 0.7 We^{-1/5} \left(\frac{L_b}{t_{or}} \right)$$

4. Calculate streamwise filament thickness $d_s = \sqrt{\lambda h_f}$

5. Calculate the initial spanwise filament thickness d_L :

$$\frac{\pi}{4} d_L^2 = \frac{\dot{m}\lambda}{2\pi\rho U L_b \sin\theta} - \lambda h_f, h_f = 1.85\mu m$$

6. Calculate the spanwise filament thickness $d_{L,b}$ after stretching

$$d_{L,b} = d_L \sqrt{1 + l/L_b}$$

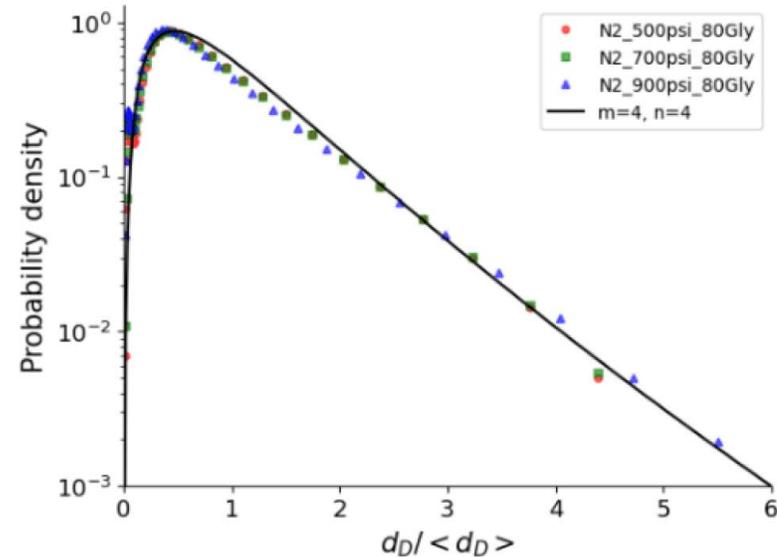
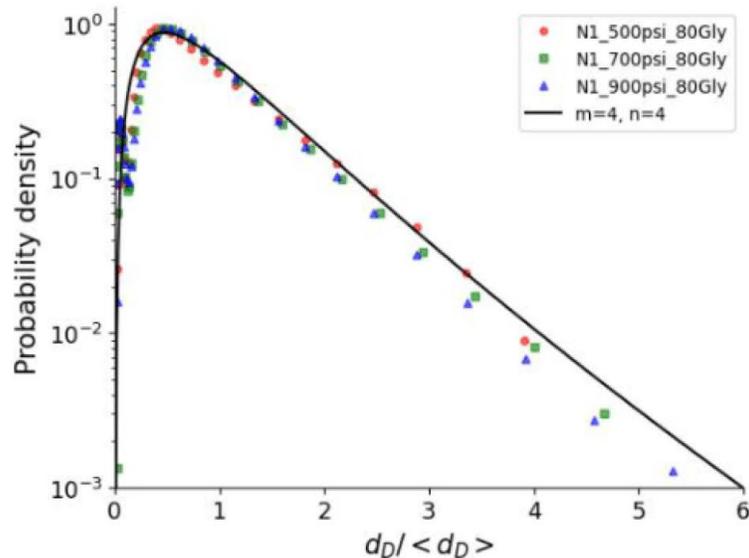
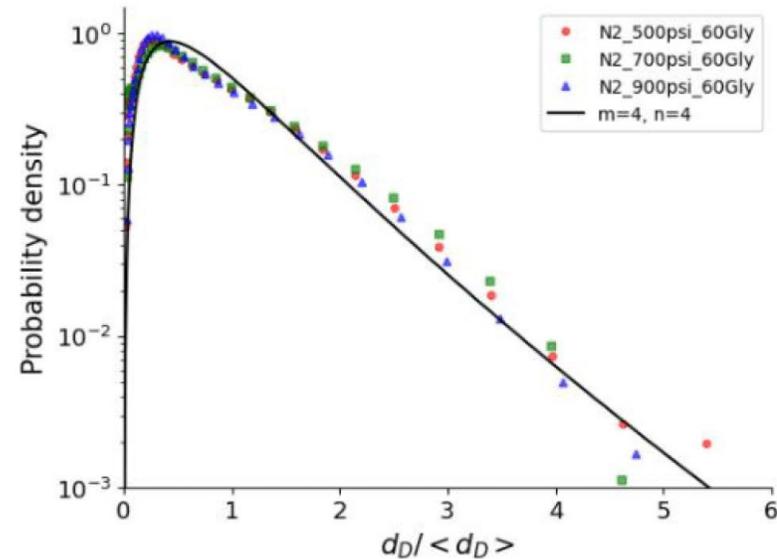
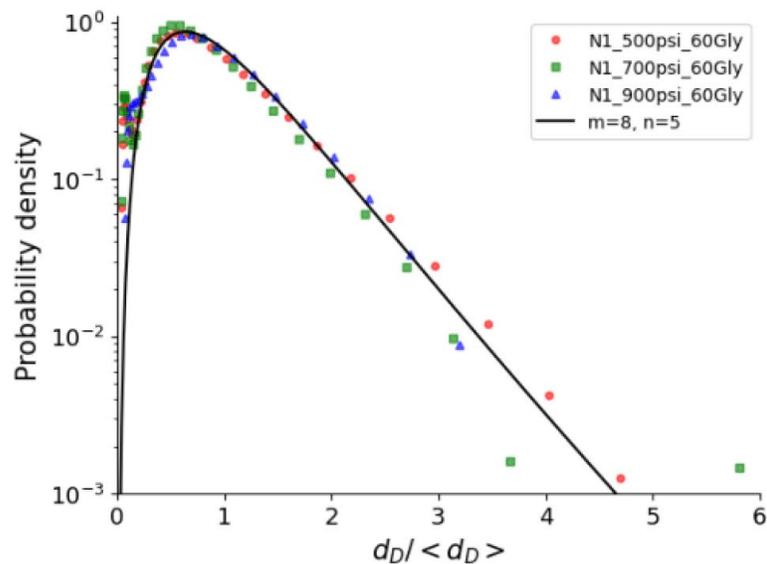
7. Determine the volume ratio between two types of filaments:

$$f = d_L^2 / (d_L^2 + \lambda h_f)$$

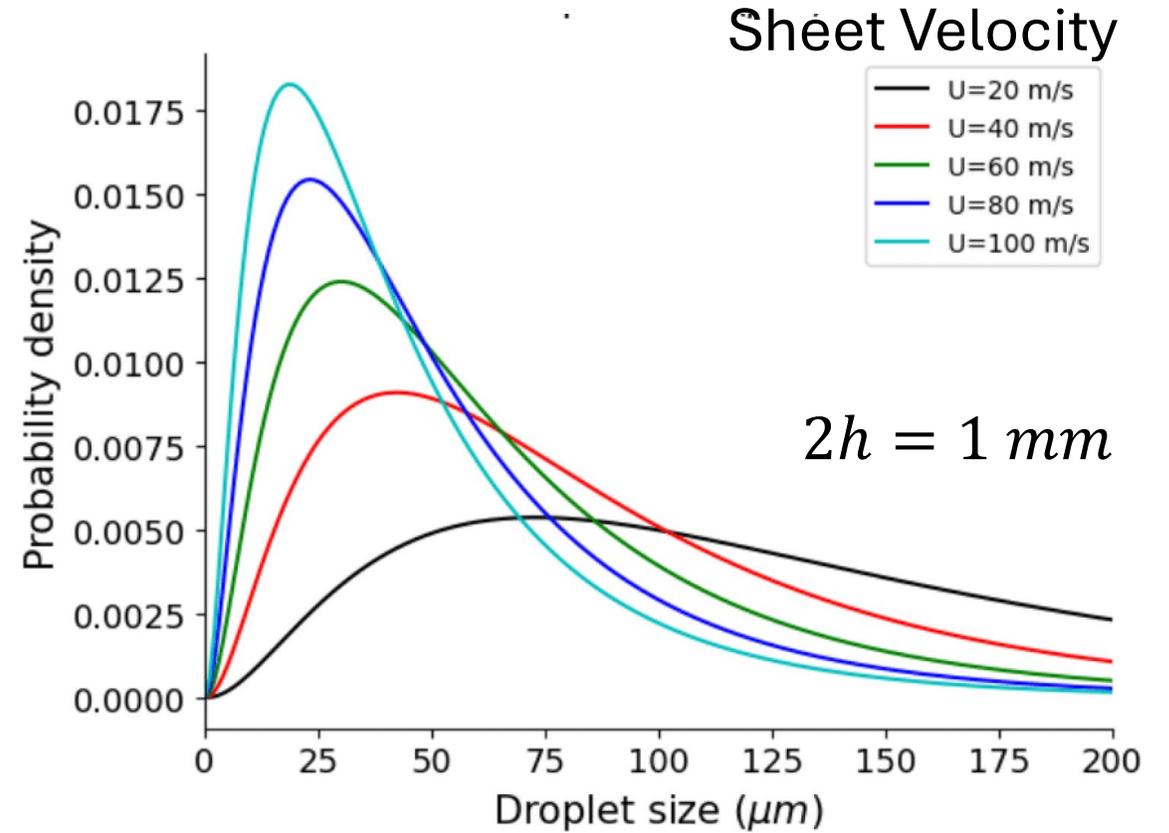
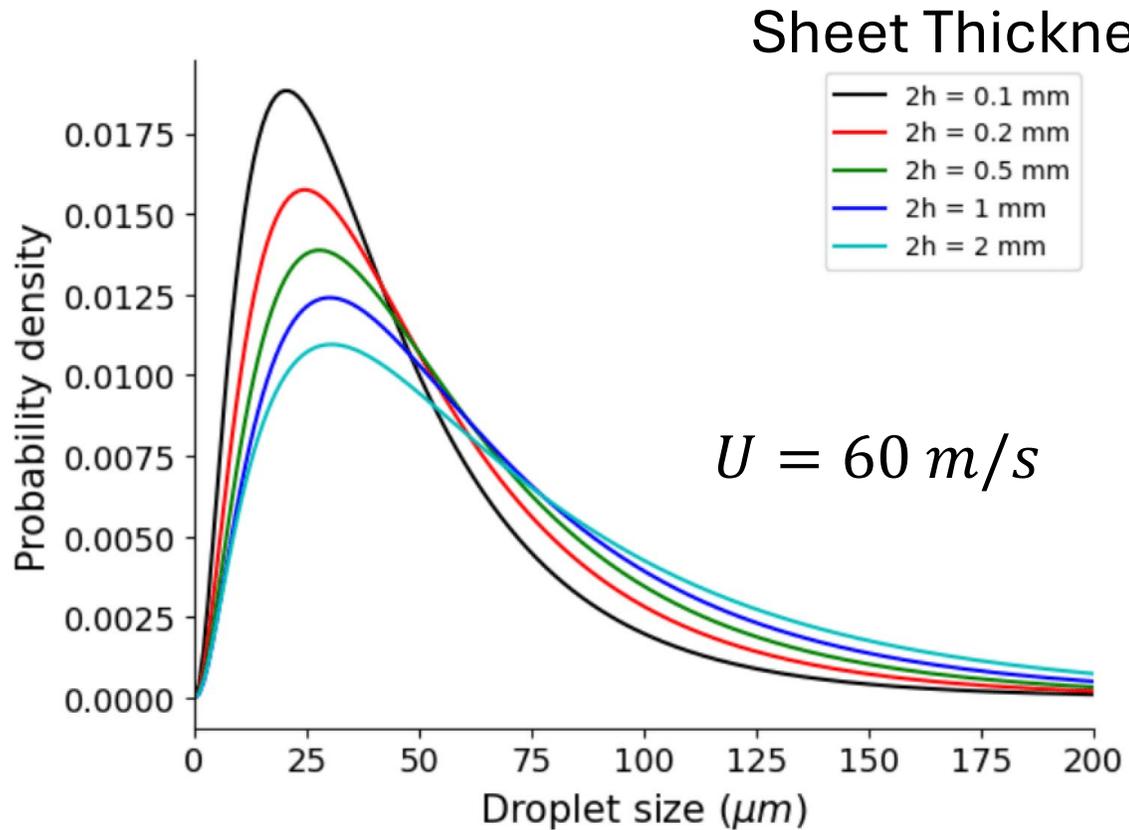
8. The droplet size distribution:

$$p_{m,n} \left(x = \frac{d_D}{\langle d_D \rangle} \right) = \frac{2(mn)^{\frac{m+n}{2}} x^{\frac{m+n}{2}-1}}{\Gamma(m)\Gamma(n)} K_{m-n}(2\sqrt{mnx})$$

Comparison with Experiments - Normalized diameter

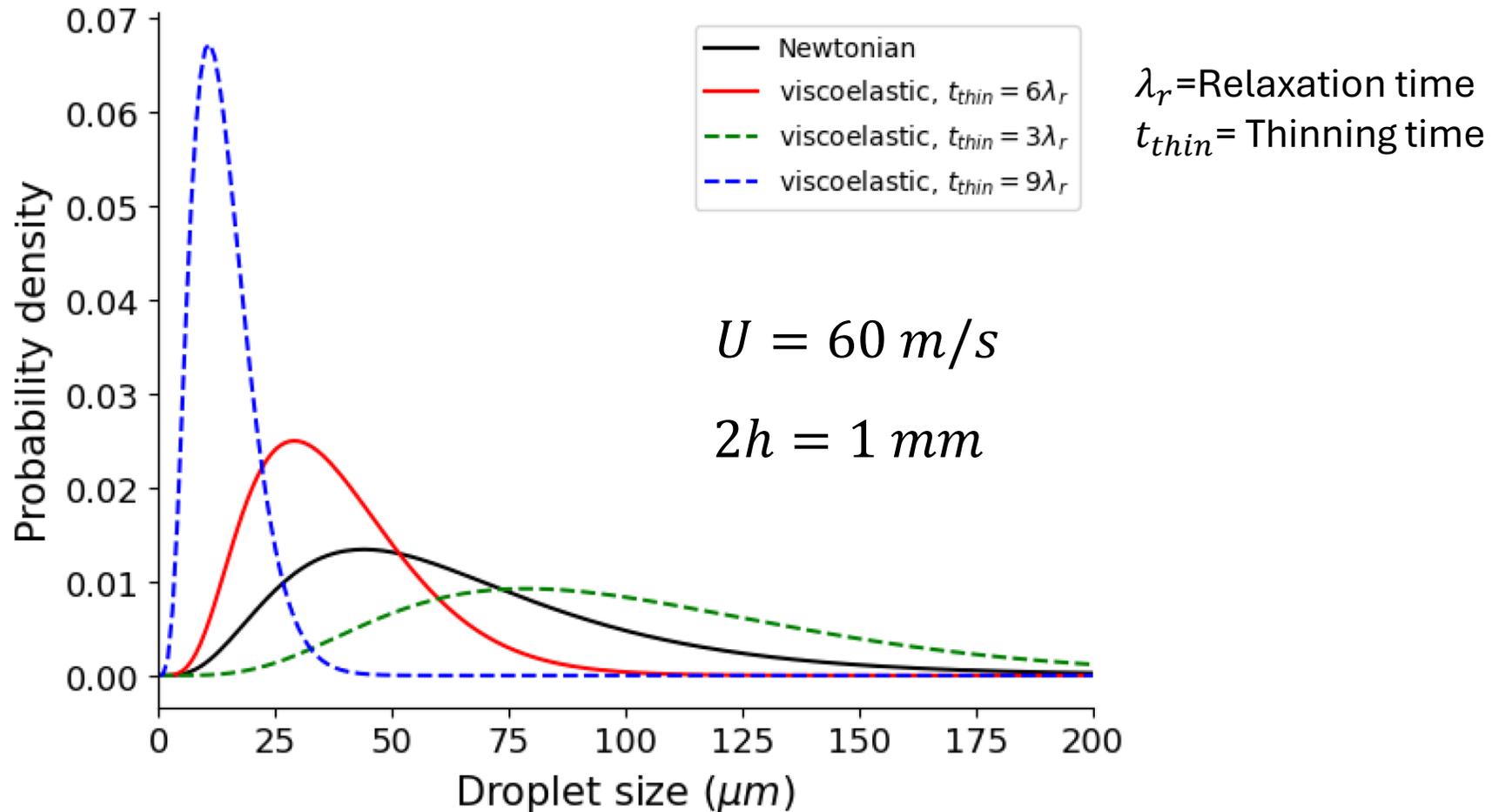


Droplet Size Distribution in Newtonian Fluids



$\rho = 1000 \text{ kg/m}^3$, $\mu = 60 \text{ mPa.s}$, $\gamma = -0.07 \text{ N/m}$, $\dot{m} = 30 \text{ g/s}$, $\theta = 40^\circ$, $m=n=4$

Droplet Size Distribution in Viscoelastic Fluids



$\mu_0 = 1 \text{ mPa}\cdot\text{s}$ at $\rho = 1000 \text{ kg/m}^3$, $\gamma = -0.07 \text{ N/m}$, $\dot{m} = 30 \text{ g/s}$, $\theta = 40^\circ$

Summary

- Atomization of a liquid sheet is studied experimentally with different orifice diameter, injection pressure and fluid viscosities.
- Two characteristic sizes are identified to predict droplet size distribution.
- A perforated sheet atomization model (PSAM) is developed, which well predicts the experimentally measured droplet sizes for a wide the range parameters studied.



References

- 1) Jackiw, I., and Ashgriz, N., “On aerodynamic droplet breakup,” *Journal of Fluids Mechanics*, Volume 913, 25 April 2021, A33.
- 2) Jackiw, I., and Ashgriz, N., “Prediction of the droplet size distribution in aerodynamic droplet breakup,” *Journal of Fluids Mechanics*, Feb 2022, vol. 940, A17.
- 3) Chen, S-Y. and Ashgriz, “Droplet Size Distribution in Swirl Nozzles,” *the International J. of Multiphase flows*, Volume 156, November 2022, 104219.
- 4) Jackiw, I., and Ashgriz, N., “Aerodynamic droplet atomization model (ADAM),” *Journal of Fluids Mechanics*, (2023), vol. 958, A2.
- 5) Chen, S. and Ashgriz, N. “Droplet sizes in the breakup of a viscoelastic filament”, *Physics of Fluids*, 37, 023108 (2025).
- 6) Chen, S-Y. and Ashgriz, “Perforated Sheet Atomization Model (PSAM)”, submitted to *Physics of Fluids*.



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