Spray Characterization at Industrially Relevant Conditions

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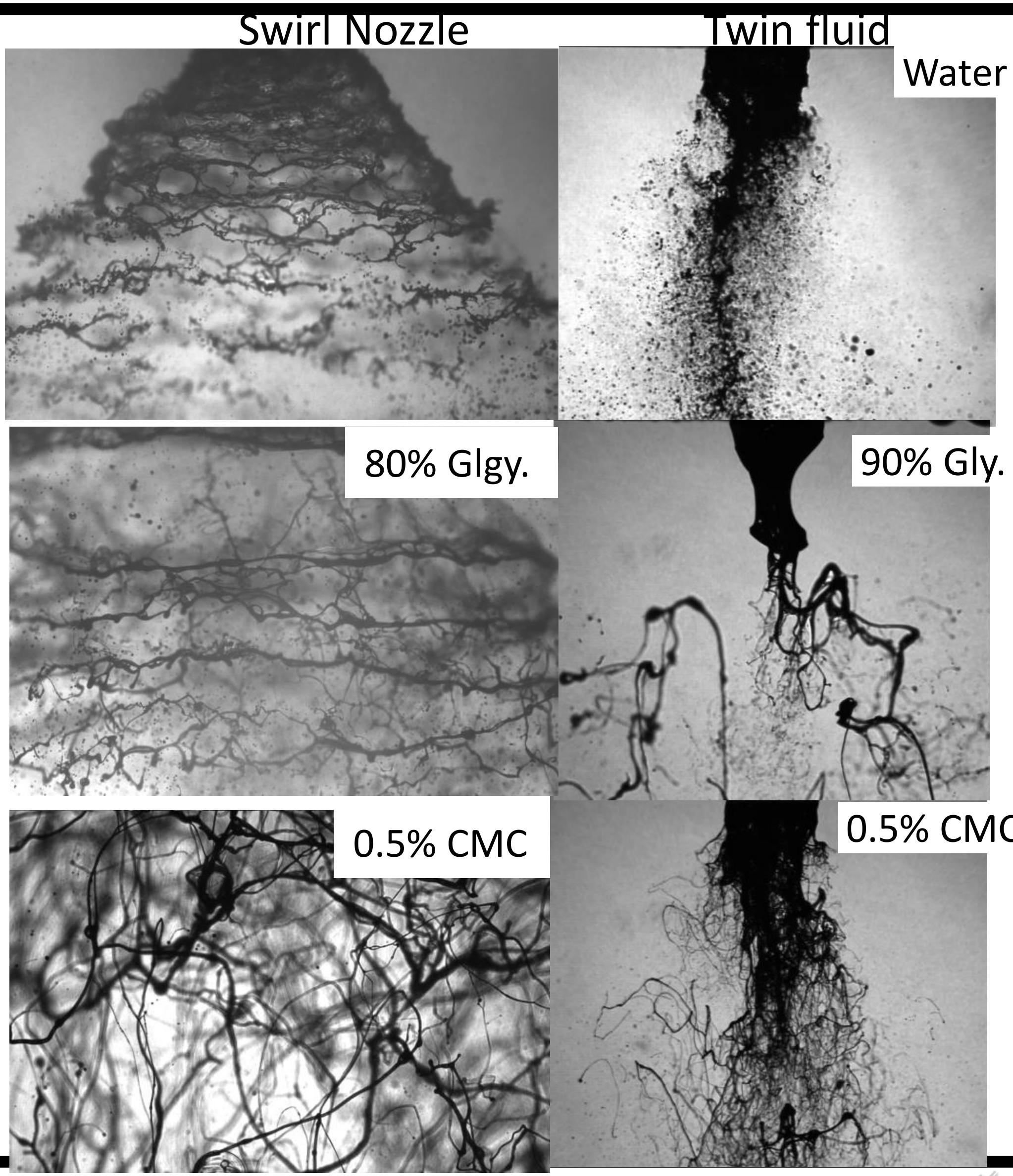
Project goals

1. Develop benchmark database

- Measurements of spray **size distribution & near-nozzle images.**
- Tested commercially available nozzles of varying scales.
- Practical operating conditions.
- **High viscosity & polymeric fluids.**

Completed: working to package and upload data to a shareable location for all to use.



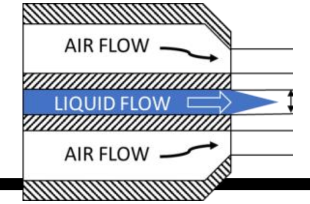
Project goals

2. Physics-based modelling

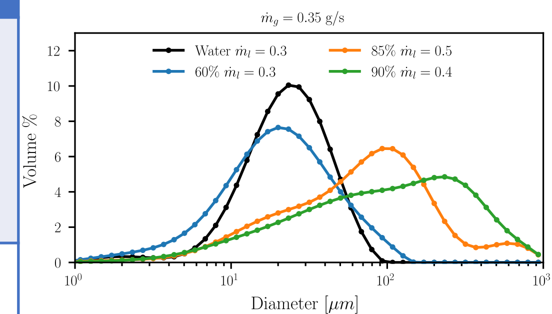
- Identify the mechanism of atomization
- Identify, study and understand the underlying dominant behaviors
- Develop a methodology for applying the mechanistic models to different spray nozzles to predict the spray droplet sizes

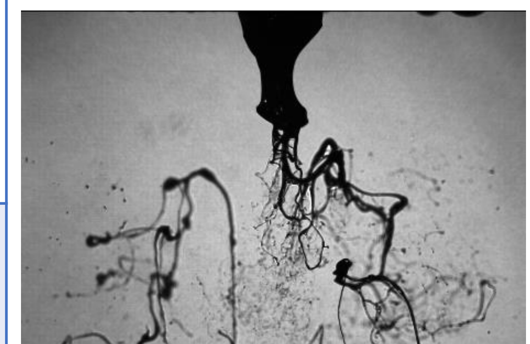
→ **Verify and validate models against the benchmark database**

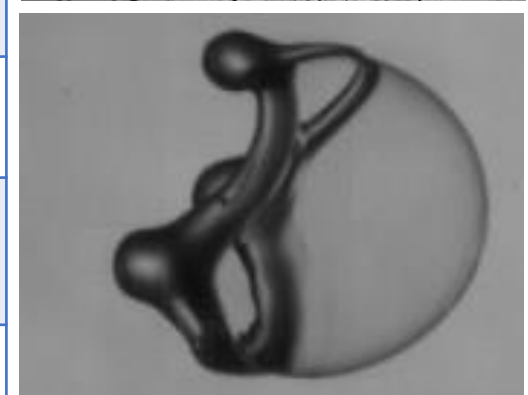
I. Twin-Fluid Nozzles



1	Performed spray sizing on a set of twin fluid nozzles at different operating conditions and fluid properties.
2	Performed close to nozzles imaging. Images showed that the high-speed air flow breaks off liquid masses, which breakup similar to the breakup of a droplet.
3	Performed experiments on droplet breakup.
4	Developed theoretical models for the droplet breakup.
5	Developed a physics-based model for the prediction of the droplet size distribution in twin fluid nozzles.
6	Validated the model with experimental data.

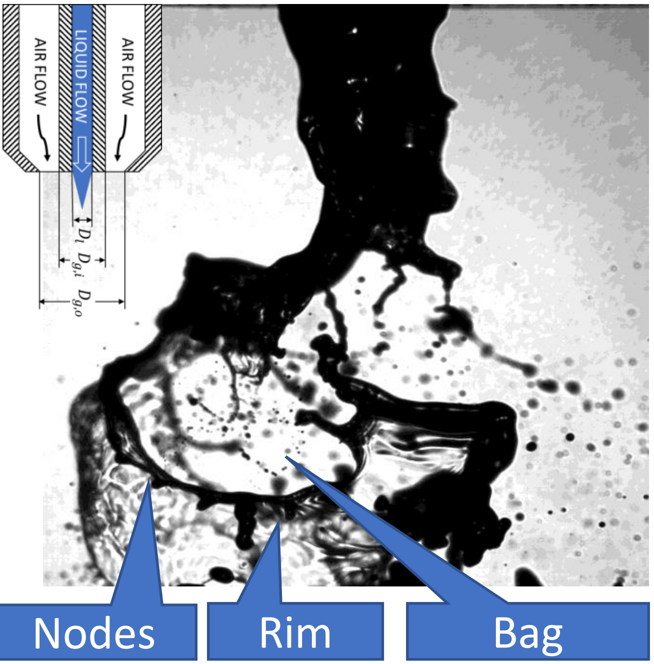


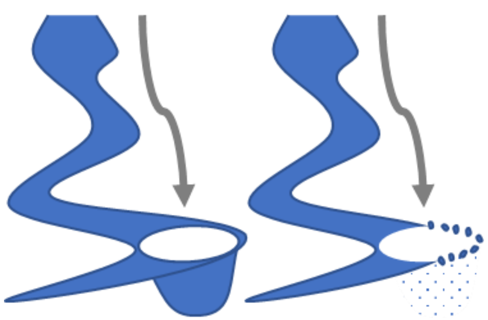




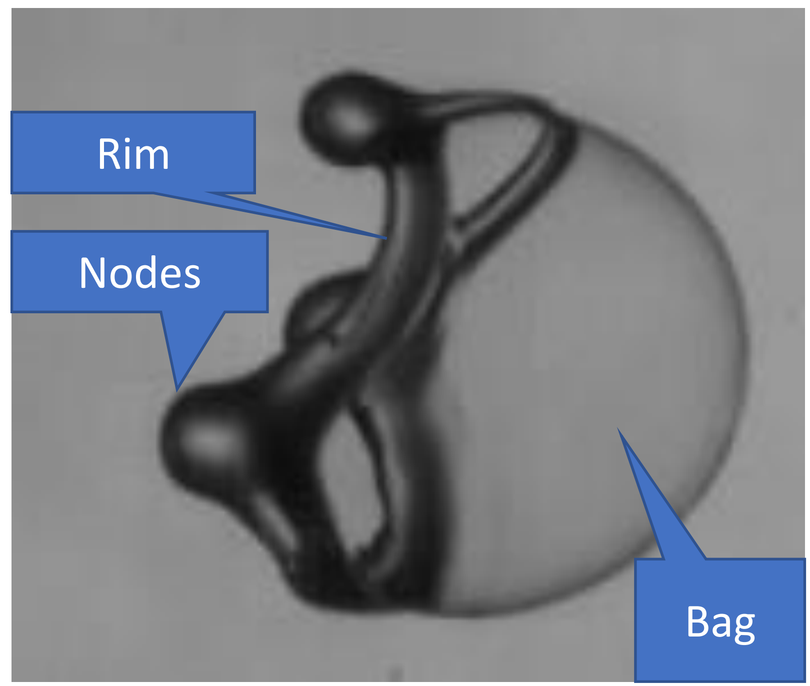
3. Breakup similar to the breakup of a droplet.

Atomization induced by aerodynamic forces

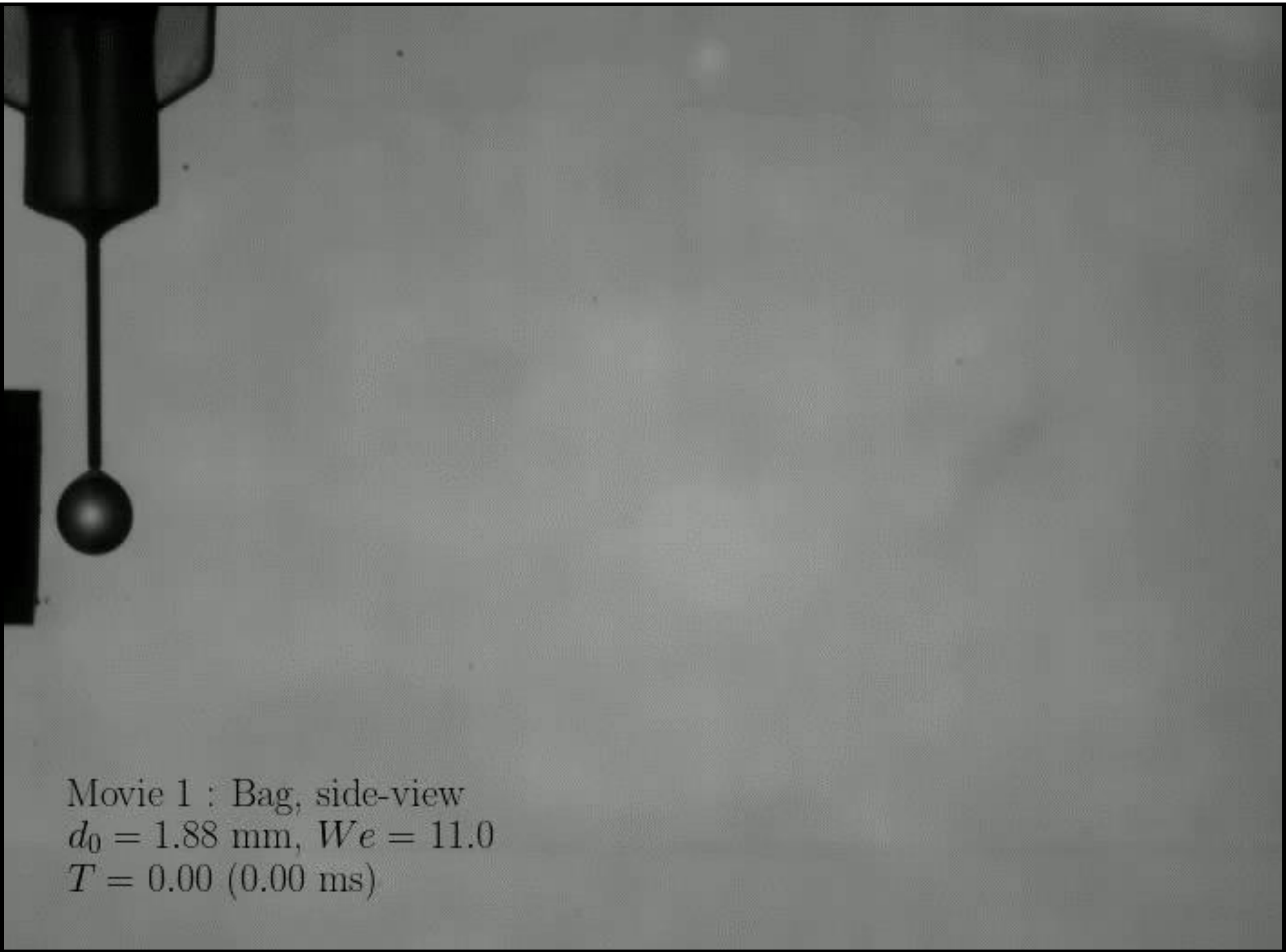




Model: Atomization occurs by a cascades of liquid masses that are atomized by the high velocity air flow. Each atomization step resembles that of a droplet breakup.



4- Droplet Experiments



Underlying phenomenology

1. Deformation

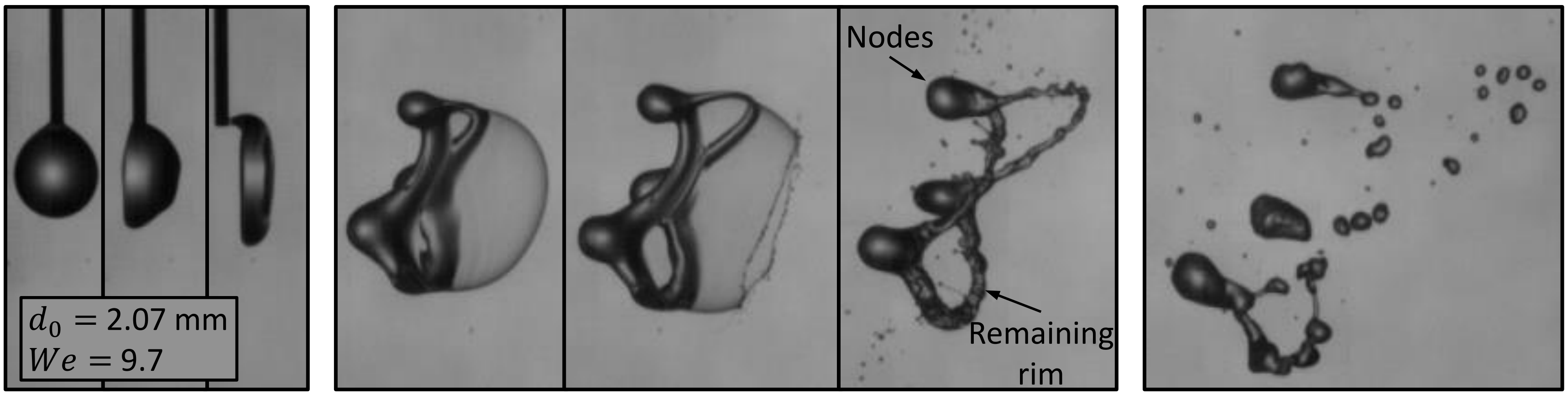
2. Bag expansion & breakup

3. Rim/ligament breakup

$\Delta T = 0.42$ (1.5 ms)

T = 2.12 (7.5 ms), $\Delta T = 0.14$ (0.5 ms)

$T = 2.83$ (10 ms)



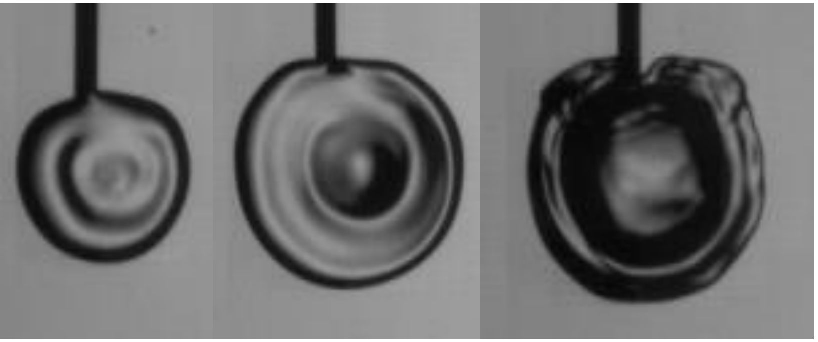
Initiation → Breakup → Breakup of bag — Breakup of rim

1. Ligament formation

2. Ligament breakup

4. Droplet breakup modelling

1. Ligament formation via initial deformation

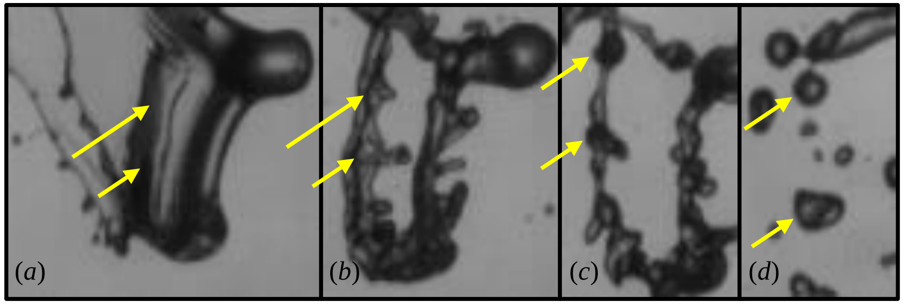


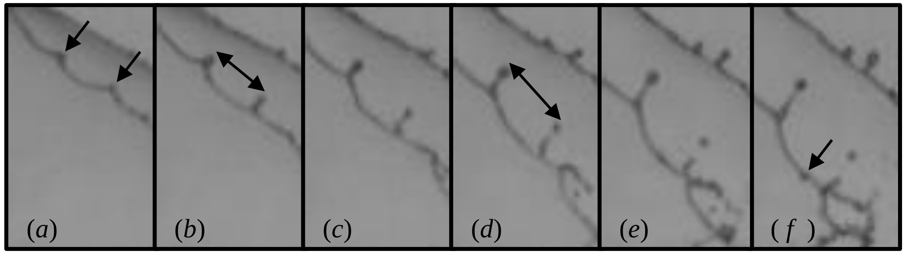
Ligament thickness determined by deformation rate
(higher deformation rate, thinner rim)

$$\frac{d_{rim}}{d_0} = \frac{4}{We_{rim} + 5\left(\frac{2R_i}{d_0}\right) - 4\left(\frac{d_0}{2R_i}\right)} - 0.05$$

$$We_{rim} = \frac{\rho_l \dot{R}^2 d_0}{\sigma}, \qquad \frac{\dot{R}}{d_0/2} = \frac{1.125}{\tau}\left(1 - \frac{32}{9We}\right), \qquad \frac{R_i}{d_0} \approx 1.6$$

2. Breakup via multiple mechanisms



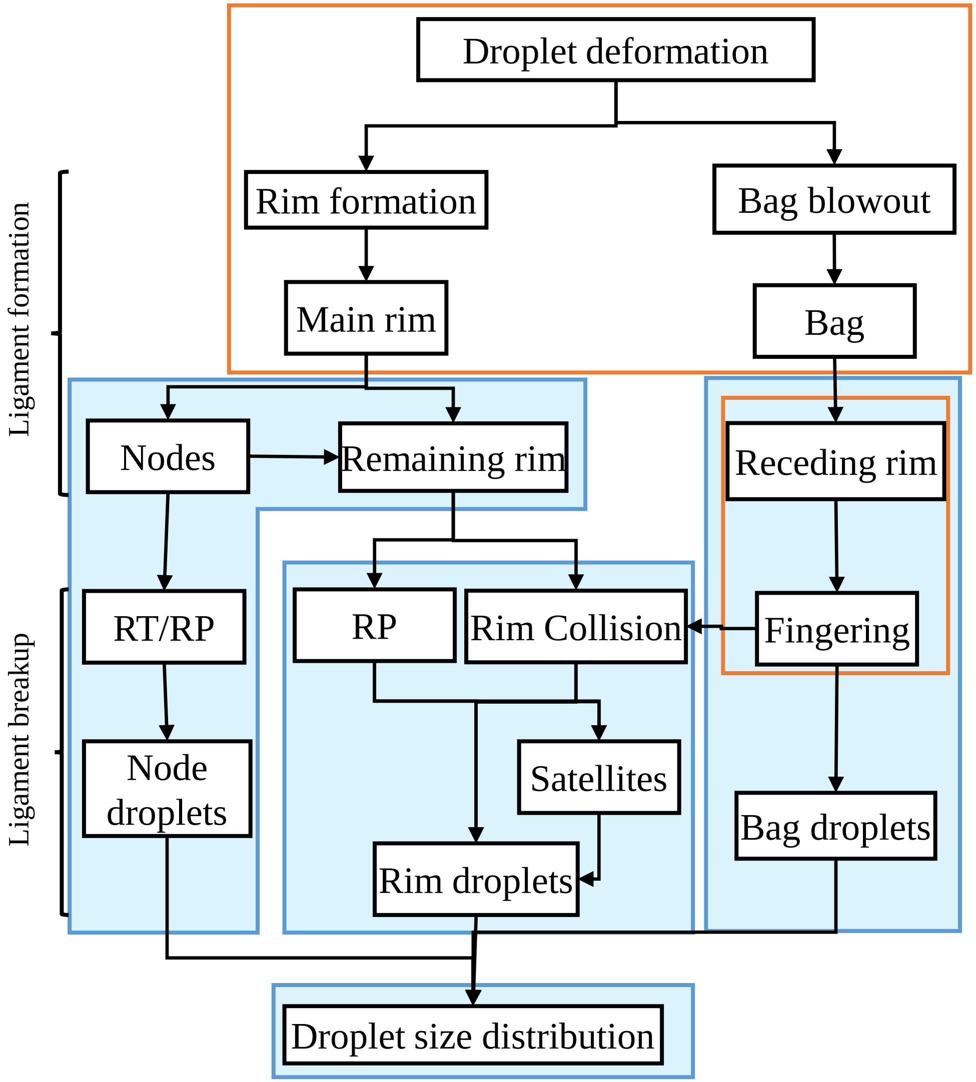


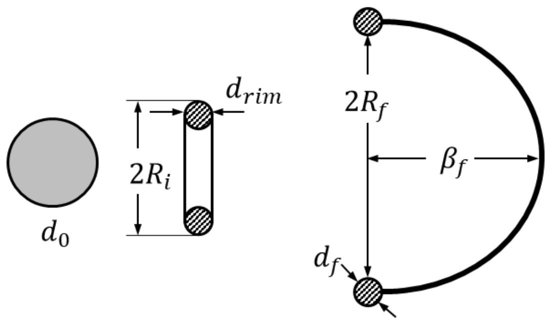
- **Nodes** form on rim due to initial instability
- **Remaining rim** breaks by combination of instability and collision of bag
- **Bag** breaks due to instability
- Undeformed core repeats the breakup

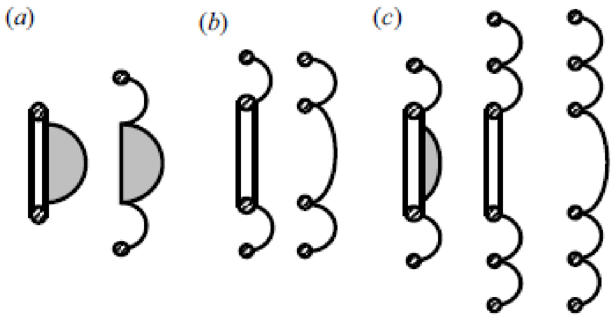
Model gives 11 characteristic sizes for each breakup (e.g., additional core breakups)

- Interpreted as a **distribution**

Droplet Breakup







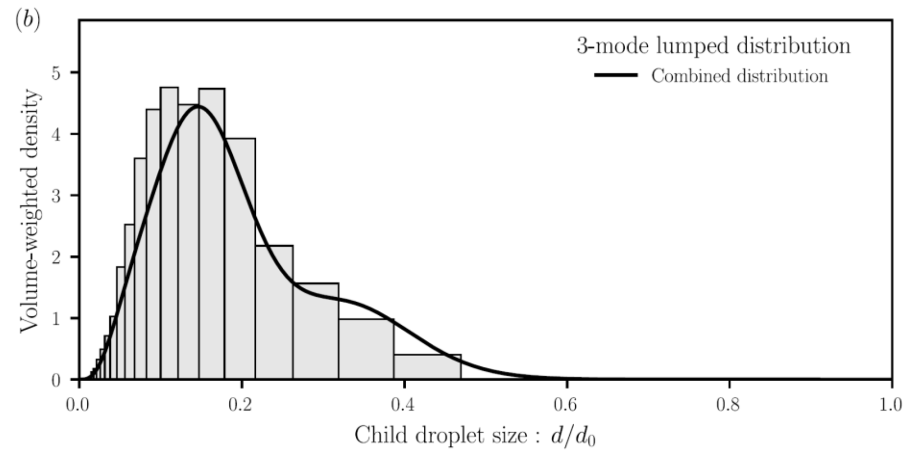
$$\frac{d_f}{d_0} = \frac{1}{2.15 + 0.12\,We\left(1 - \frac{32}{9\,We}\right)^2} - 0.032$$

$$\frac{d_c}{d_0} \approx \frac{1}{1.14 + 0.06\,We\left(1 - \frac{32}{9\,We}\right)^2} - 0.06$$

5. Droplet model to predict spray droplet sizes

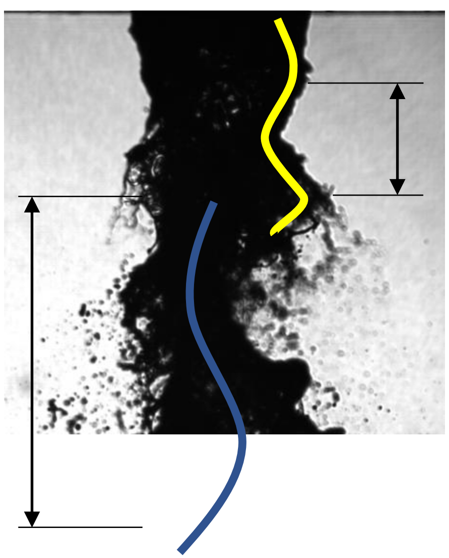
Droplet model inputs
- Liquid and gas properties: ρ, μ, σ
- Initial 'droplet' size: d_0
- Relative gas speed: U_r

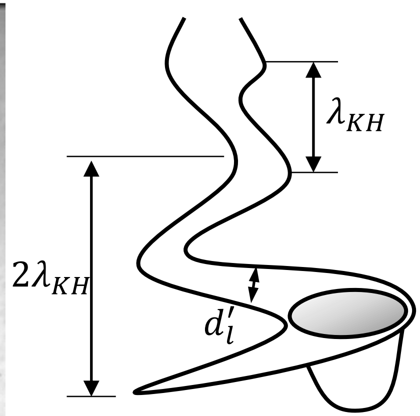
Output



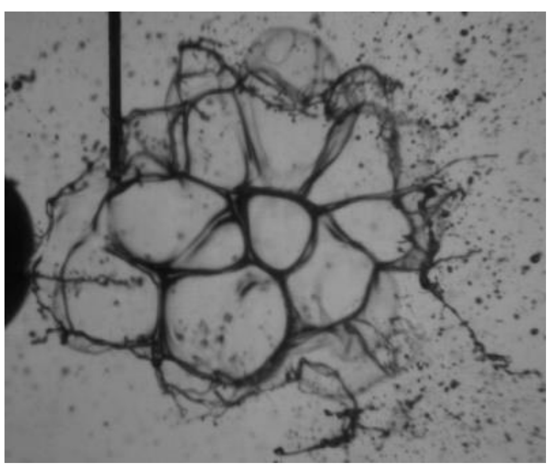
Spray model:

1. Wave formation and segmentation
   - Determine `effective droplet size'





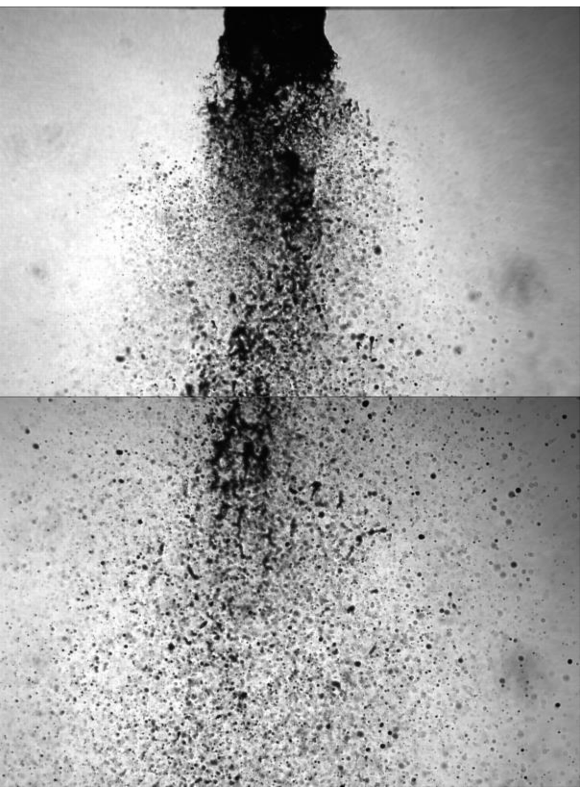
2. Breakup (as droplet)
   - Determine size distribution

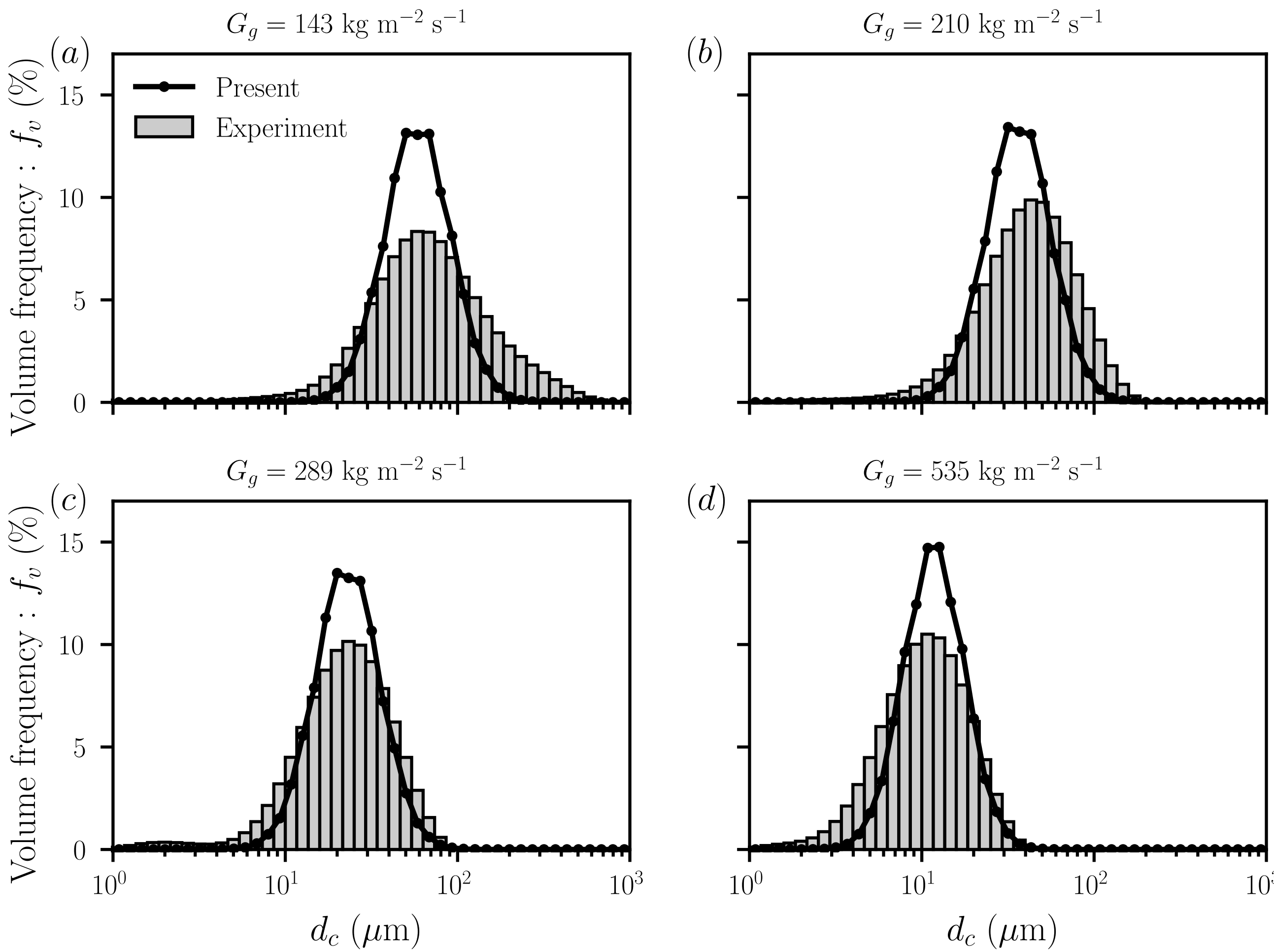


6. Model validation – small nozzle

Small nozzle, varying gas flow rate ($G_g = \rho_g u_g$)

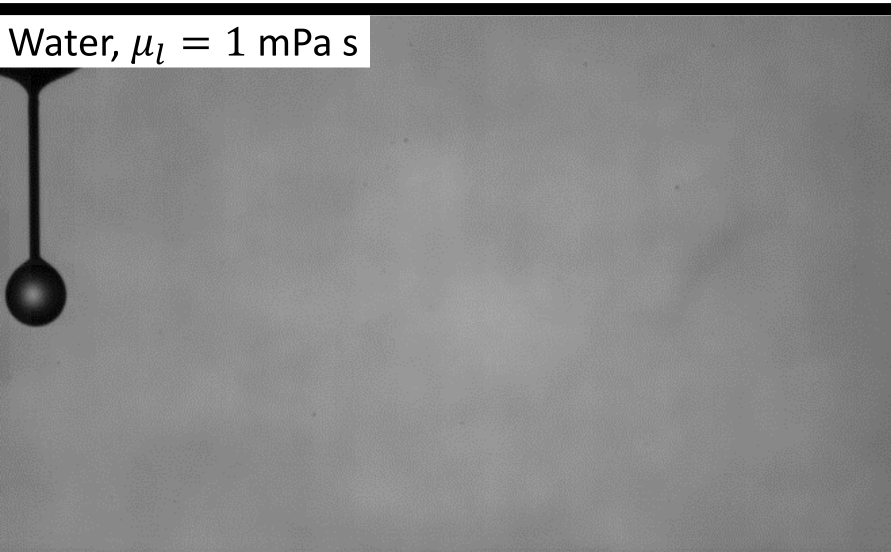
$d_l = 0.71$ mm
$d_{g,i} = 1.27$ mm
$d_{g,o} = 1.78$ mm



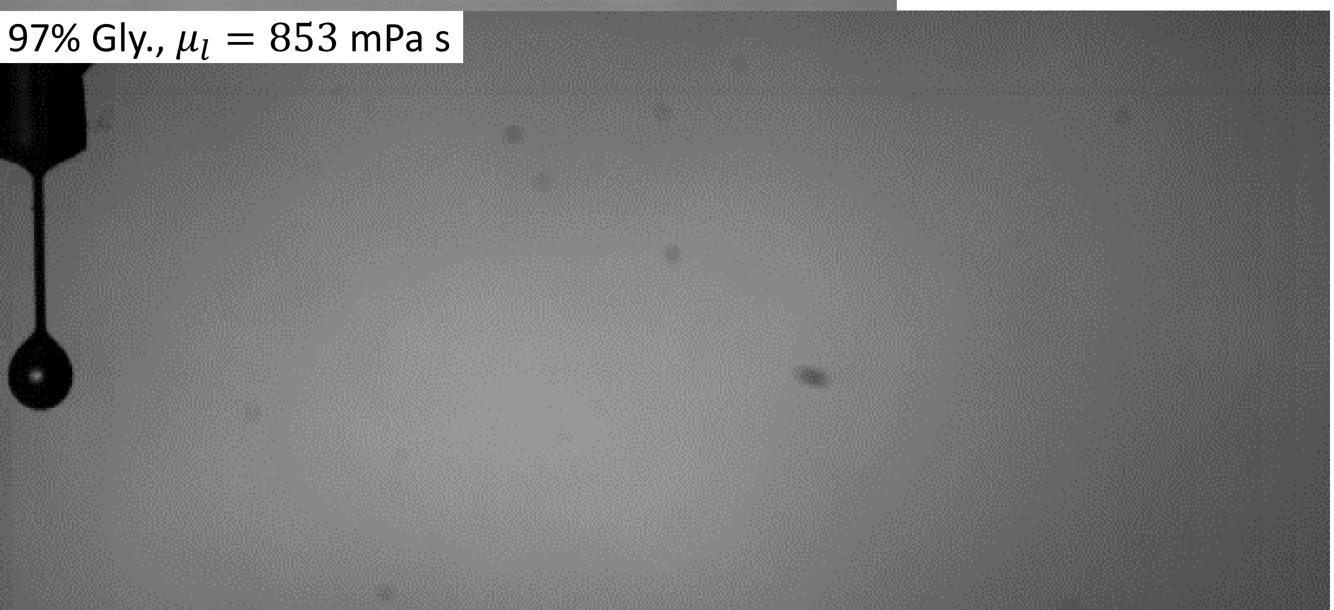


Highly viscous droplets

Water, $\mu_l = 1$ mPa s



97% Gly., $\mu_l = 853$ mPa s



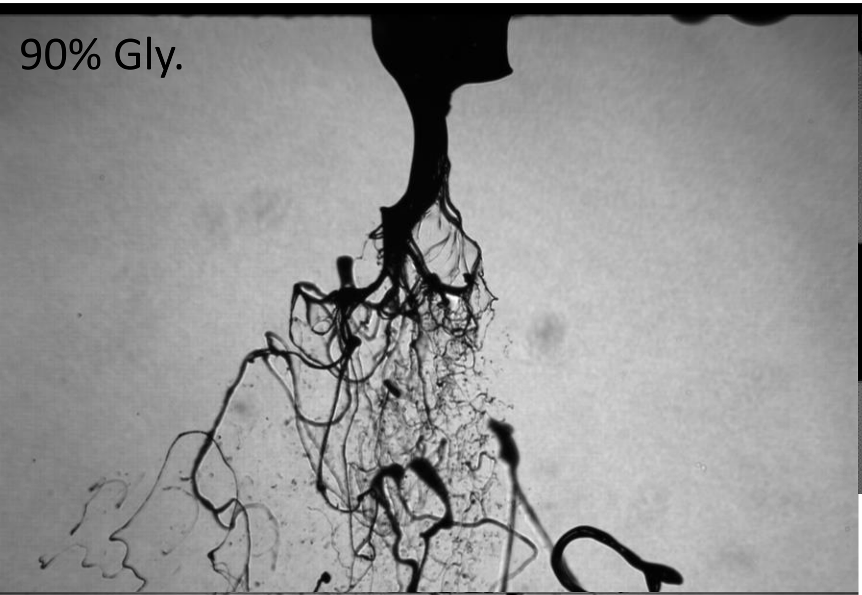
High viscosity leads to:

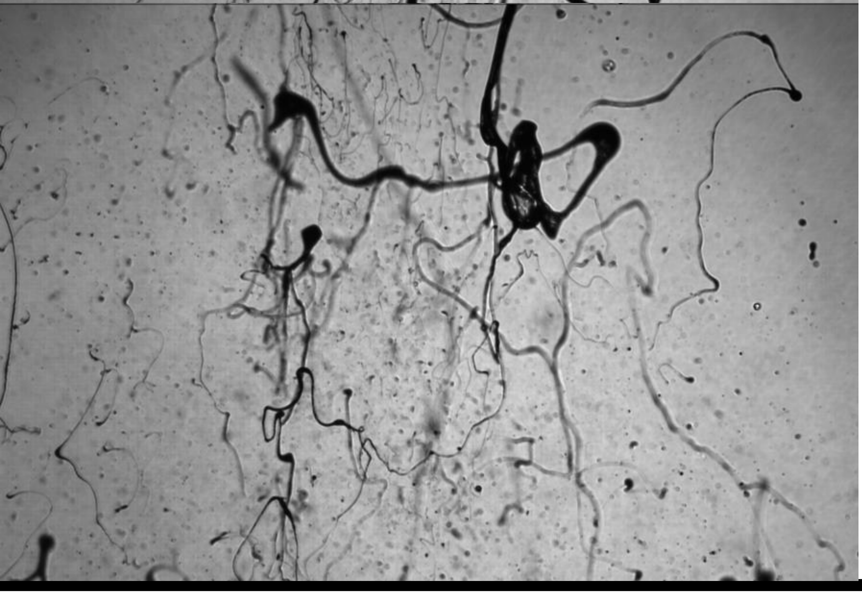
1. **Slow initial deformation and f**ormation of initially thicker ligaments
2. longer-lived ligaments form stringy networks

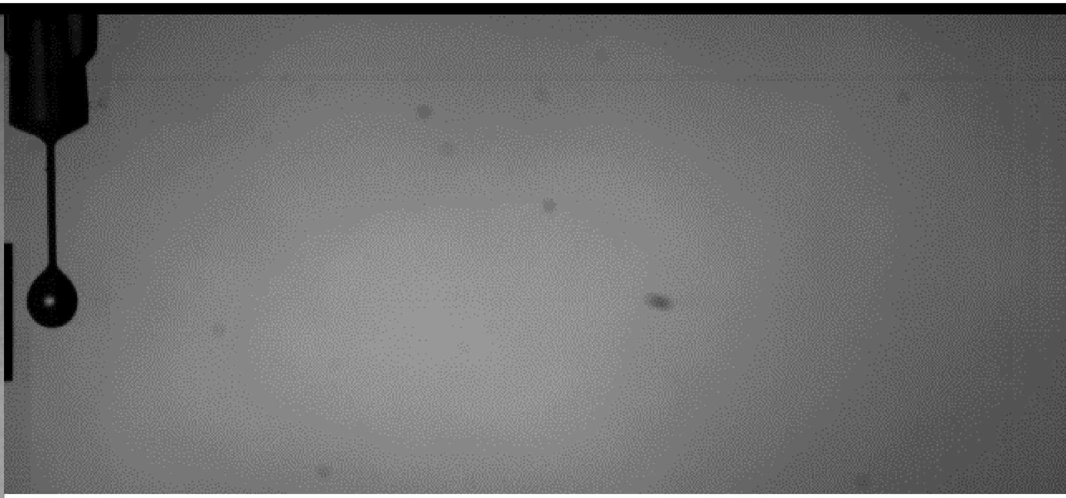
$u_g = 28$ m/s

Highly viscous sprays

90% Gly.







97% Gly., $u_g = 28$ m/s

Same behaviour in sprays

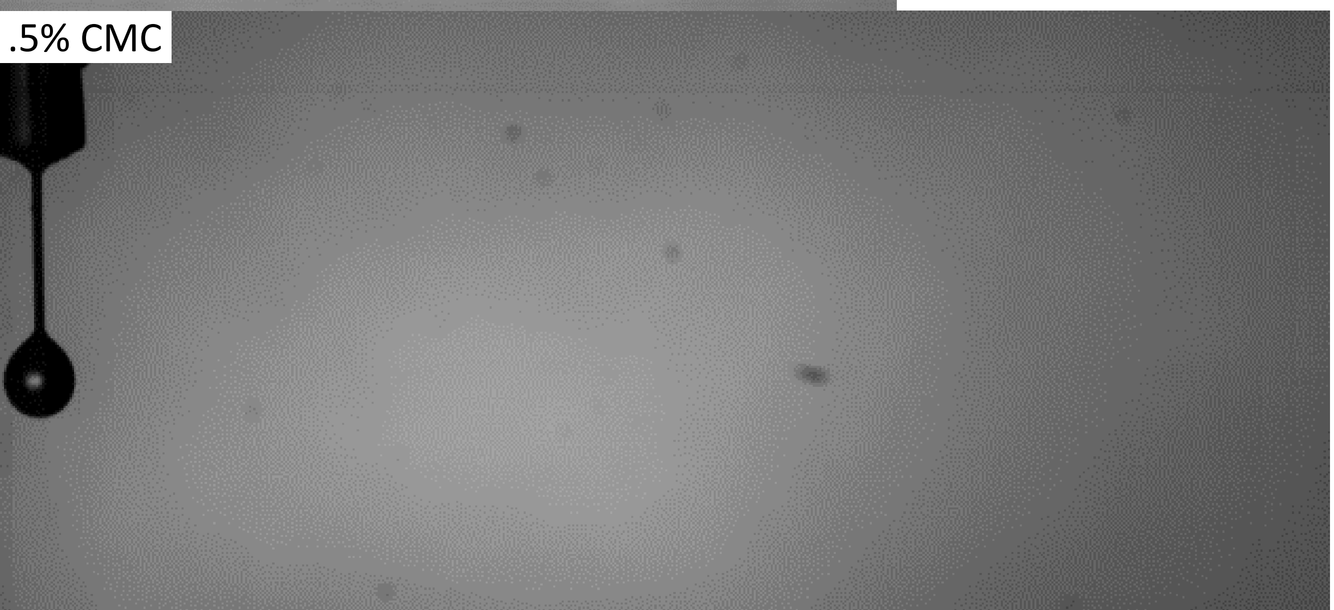
- Thicker ligaments formed
  - mainly from the rims
- Ligaments take a long time to break

Polymeric droplets

Playback 1000x slower, $u_g = 28$ m/s

Viscoelastic properties lead to:

1. **Initial deformation <u>not</u> significantly slowed,** and relatively thin ligaments form
2. **Breakup mechanisms are slowed;** fingering in breakup of bag and the rim breakups lead to stringy loops (ligament networks)

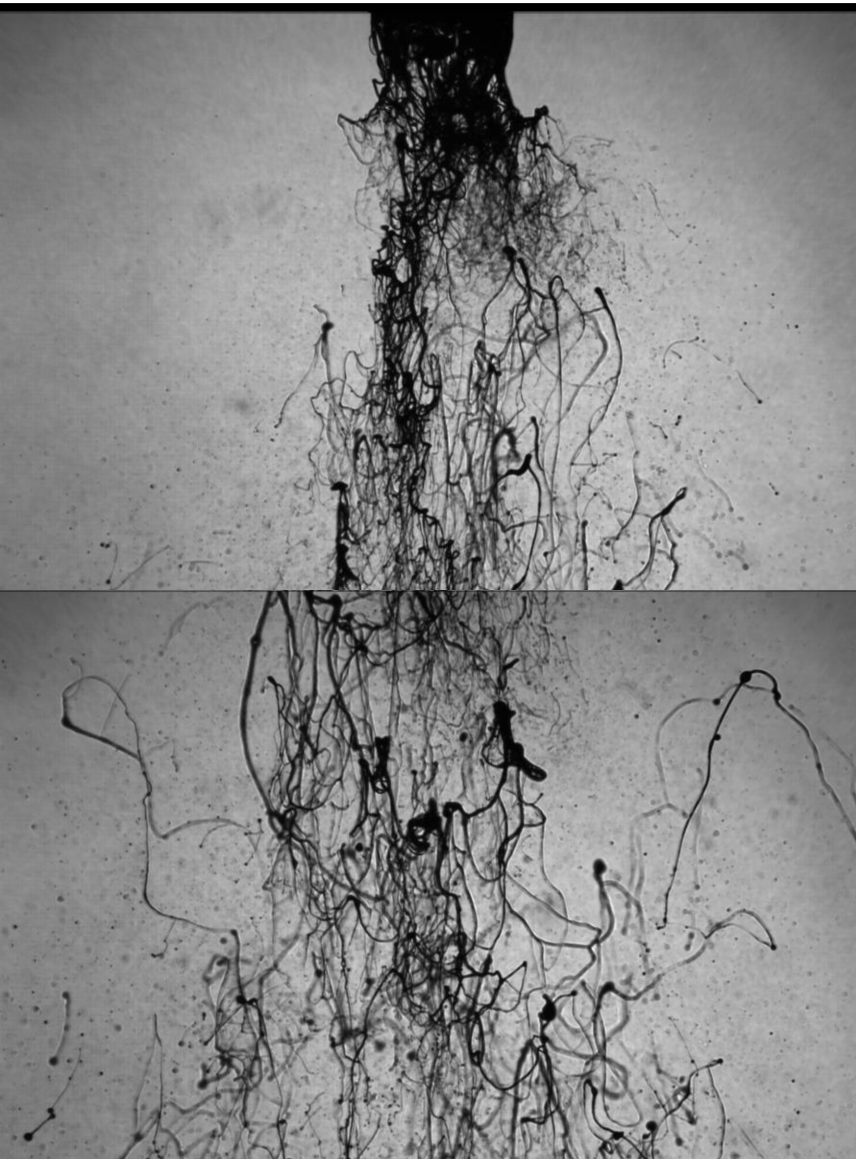


Breakup occurs at two time-scales:

- deformation (slow)
- breakup (fast, stretching)

Each are affected differently by non-Newtonian rheology

Polymeric sprays



0.5% CMC, $u_g = 54$ m/s

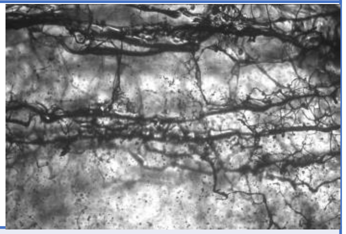
Same behaviour in sprays

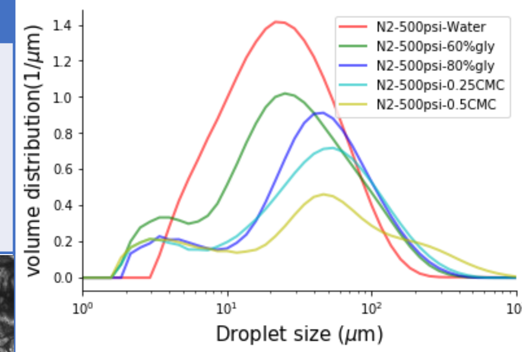
- Thin ligaments formed from rims and stretching of digitations during breakup of bag
- Ligaments take a long time to break
  - Form complex ligament networks

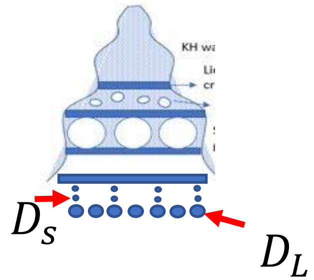
Swirl Spray Nozzles

II. Swirl Spray Nozzles

1	Performed spray sizing on a set of pressure swirl nozzles at different operating conditions and fluid properties.
2	Performed close to nozzles imaging.
3	Proposed an atomization model based on perforation.
4	Developed a semi-empirical correlations based on perforation model.
5	Improved understanding of perforation in atomization using fan spray nozzle.
6	Validated the model with experimental data.



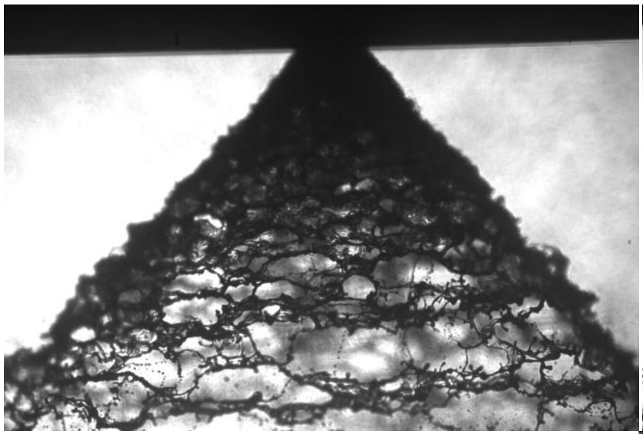




$$f_3(d) = f_{3,1}(d; \hat{\mu}_1, \hat{\sigma}_1)$$

2. Near Nozzle Images

Water, 700psi

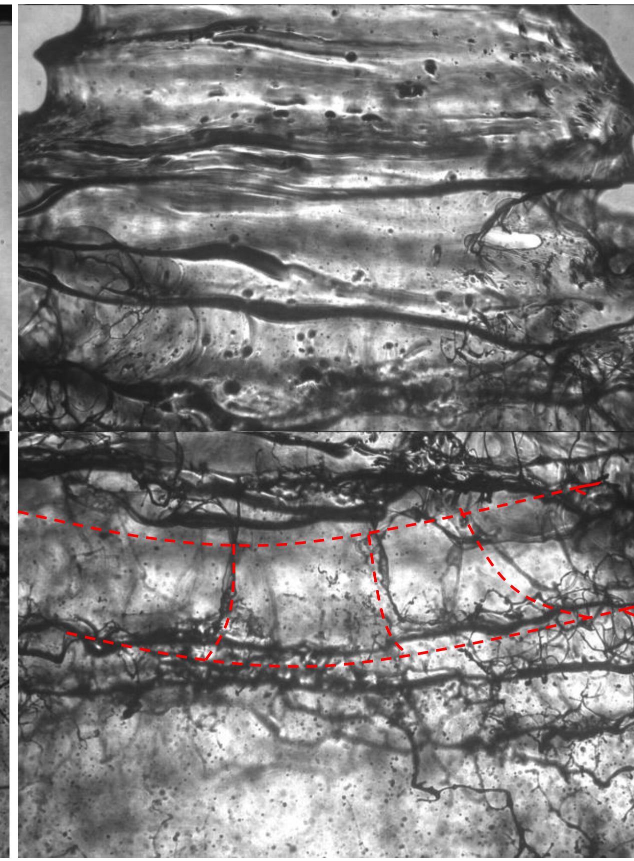


60% glycerin, 700 psi

11 cps

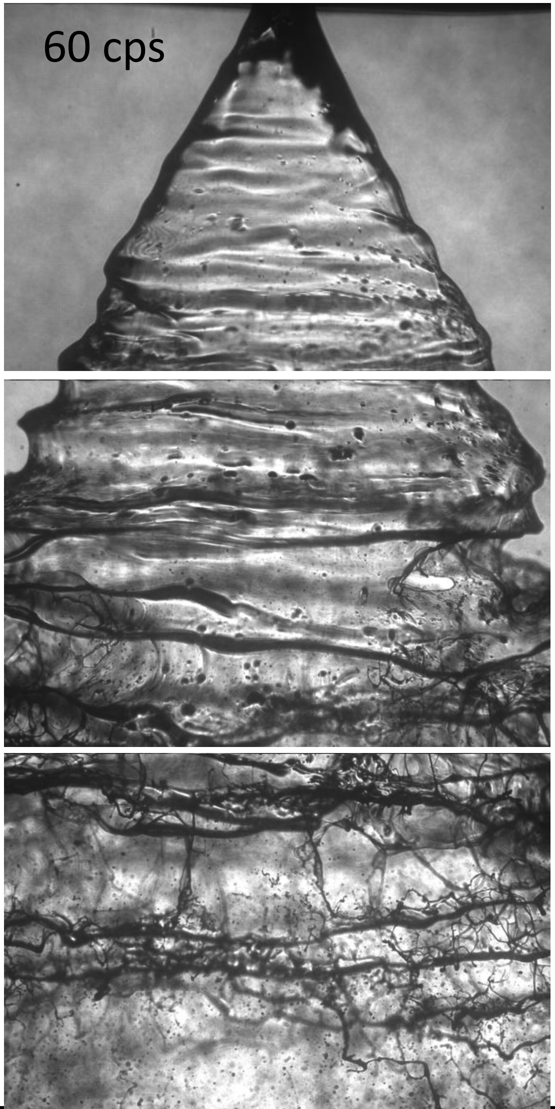
80% glycerin, 700 psi, z=5mm

60 cps

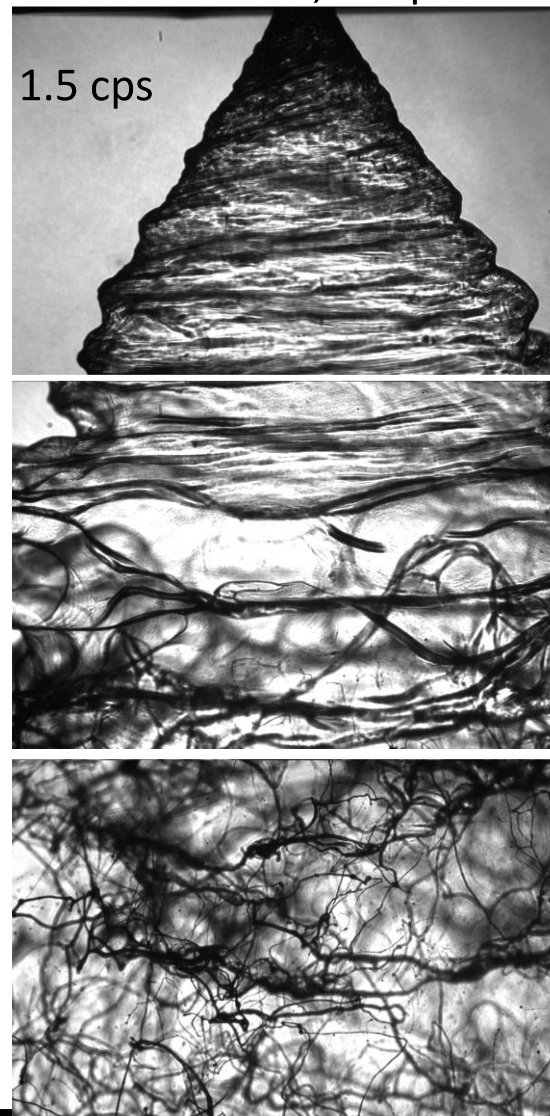


2. Near Nozzle Images

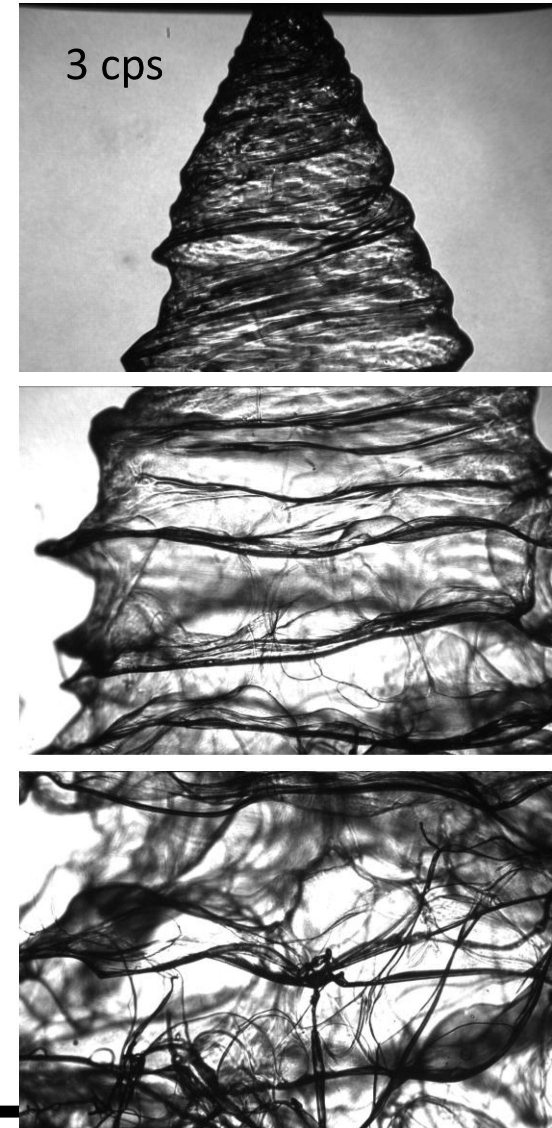
80% glycerin, 700psi



0.25% CMC, 700psi



0.5% CMC, 700 psi



3. Model & 4. Correlation for distribution

$$f_3(d) = k_v f_{3,1}(d) + (1 - k_v) f_{3,2}(d)$$

k_v is the mass ratio between the two types of ligaments, $f_{3,1}(d)$ and $f_{3,2}(d)$ are corresponding drop size distributions from two types of ligaments

The peak for small droplets (minor peak) takes up less than 5% of total volume

Neglecting minor peak will result in +20% of error at most

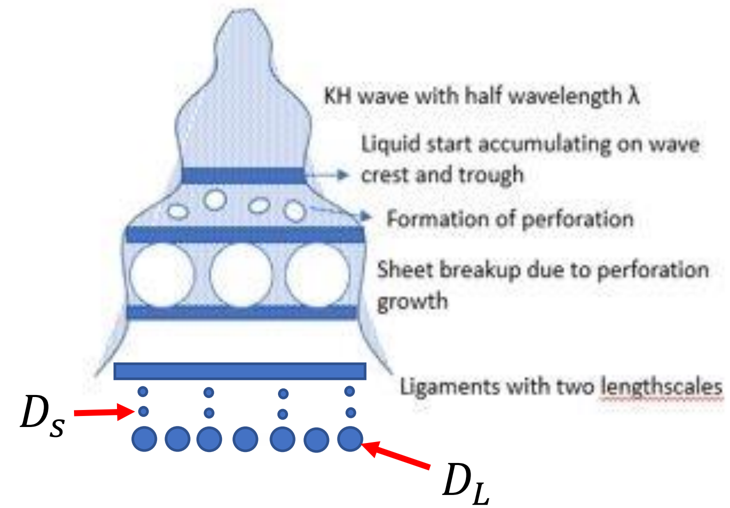
The correlation for distribution is

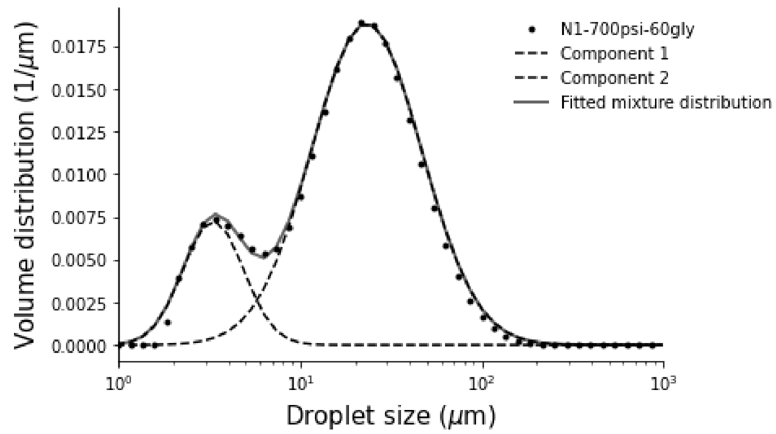
$$f_3(d) = f_{3,1}(d; \hat{\mu}_1, \hat{\sigma}_1)$$

$$f_3(d) = \frac{1}{d\hat{\sigma}_1\sqrt{2\pi}} exp\left(-\frac{1}{2}\left(\frac{ln(d/\hat{\mu}_1)}{\hat{\sigma}_1}\right)^2\right)$$

$$\hat{\mu}_1 = 1.96\lambda_{KH}^{0.589}, R^2 = 0.774$$

$$\hat{\sigma}_1 = 0.065 t_{or}^{0.517}, R^2 = 0.640$$





4. Summary of the model

- Input: Fluid property ρ, μ, σ; Operating condition P, d_{or}.

  Mass flow rate $\dot{m}$ and the spray angle θ.

- Calculate the sheet velocity $u = k_d\sqrt{2P/\rho}$.
- Calculate the sheet thickness t_{or} from $\dot{m} = (\rho u \cos\theta)\,\pi t_{or}(d_o - t_{or})$.
- Solve for the dominant wavenumber k_{max} using the dispersion equation

$$\omega = -2\nu k^2 + \left(4\nu^2 k^4 + \rho_r u^2 k^2 - (\sigma k^3/\rho_l\,)\right)^{0.5}.$$

$$\lambda_{KH} \text{ using } \quad \lambda_{KH} = 2\pi/k_{max}.$$

- Calculate the parameters in the distribution using

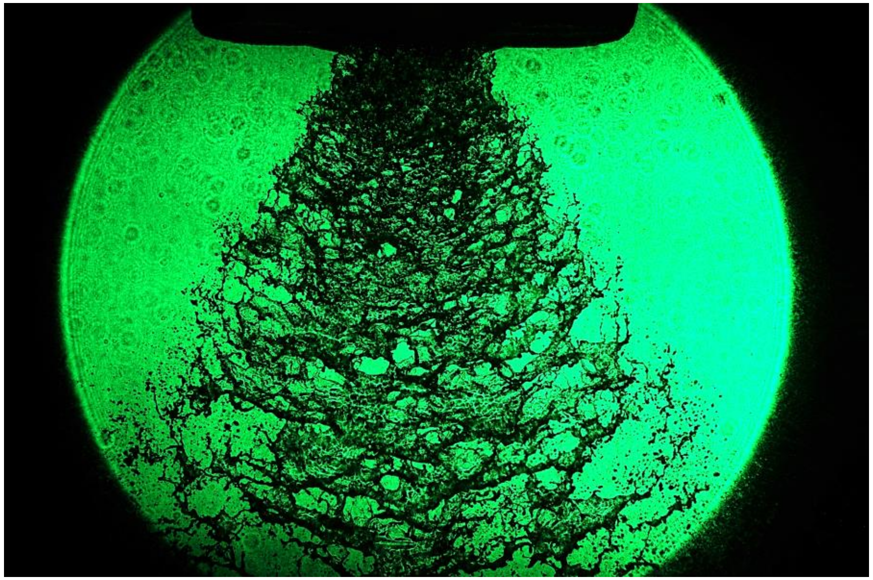
$$\hat{\mu}_1 = 1.96\lambda_{KH}^{0.589} \;\; and \;\; \hat{\sigma}_1 = 0.065 t_{or}^{0.517}.$$

$$f_3(d) = \frac{1}{d\hat{\sigma}_1\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{ln(d/\hat{\mu}_1)}{\hat{\sigma}_1}\right)^2\right).$$

5. Improvement of the model

- Measurement of the spanwise and streamwise ligament sizes.
- Used fan nozzle for this measurement
  - Simpler physics without swirling motion
  - 2D structure is easier for imaging and measurement

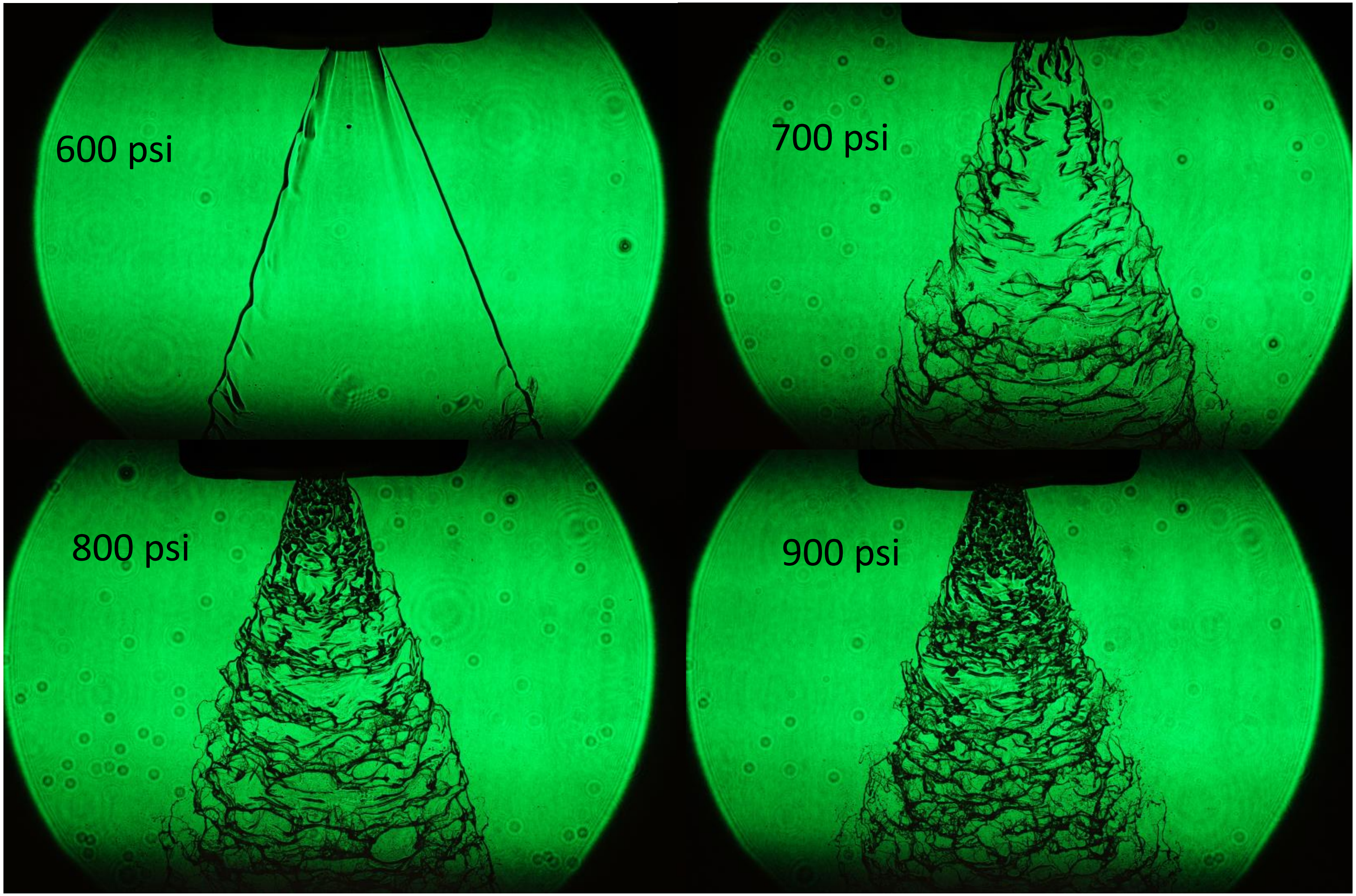
Fan nozzle with similar orifice diameter as swirl nozzle tested



Near nozzle images

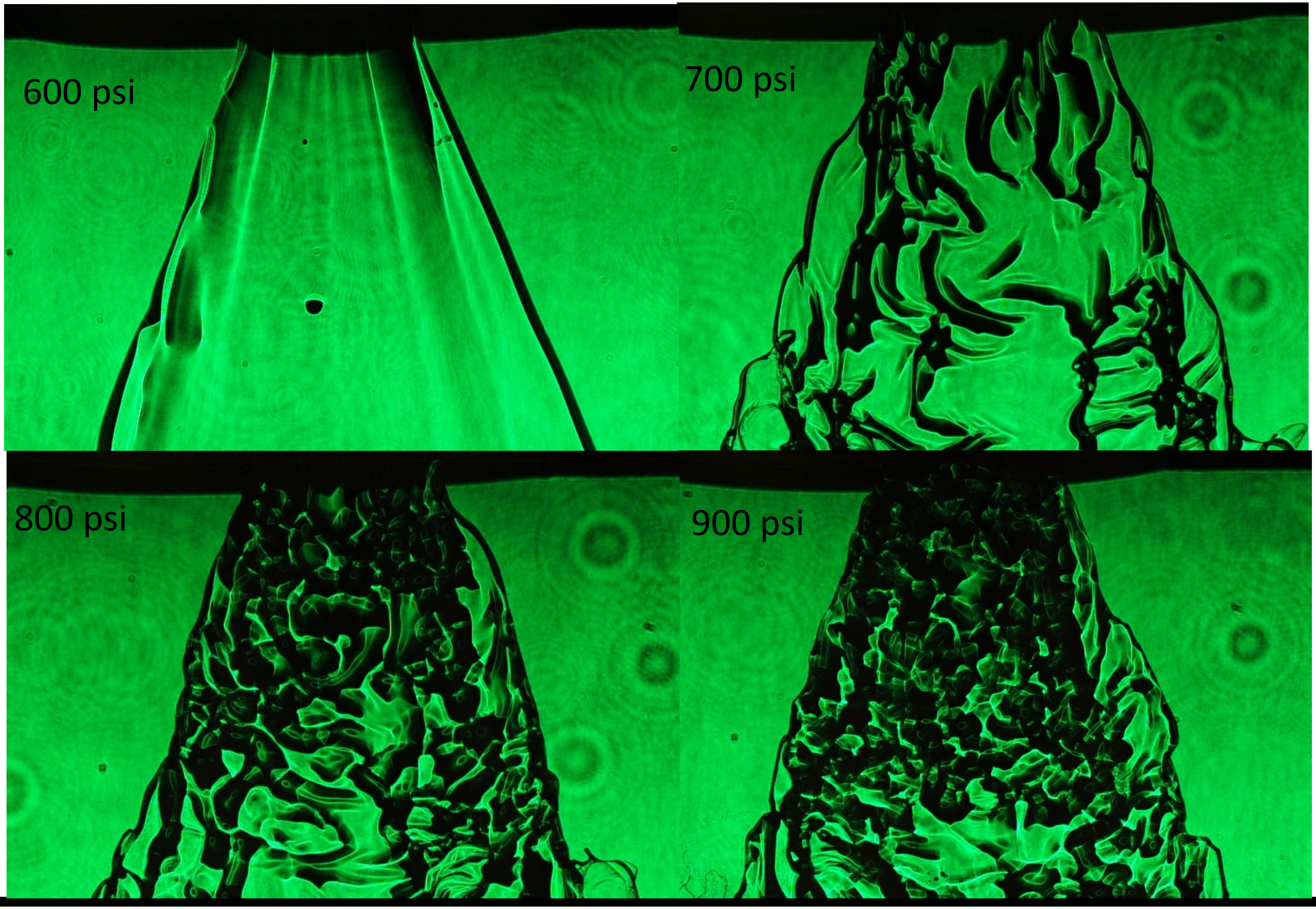
$Re = 1714$

60% Gly

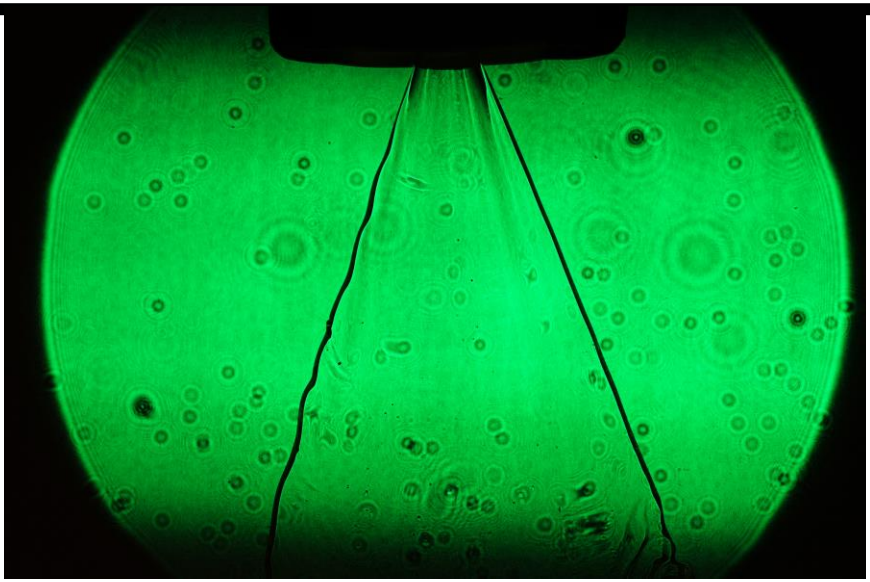


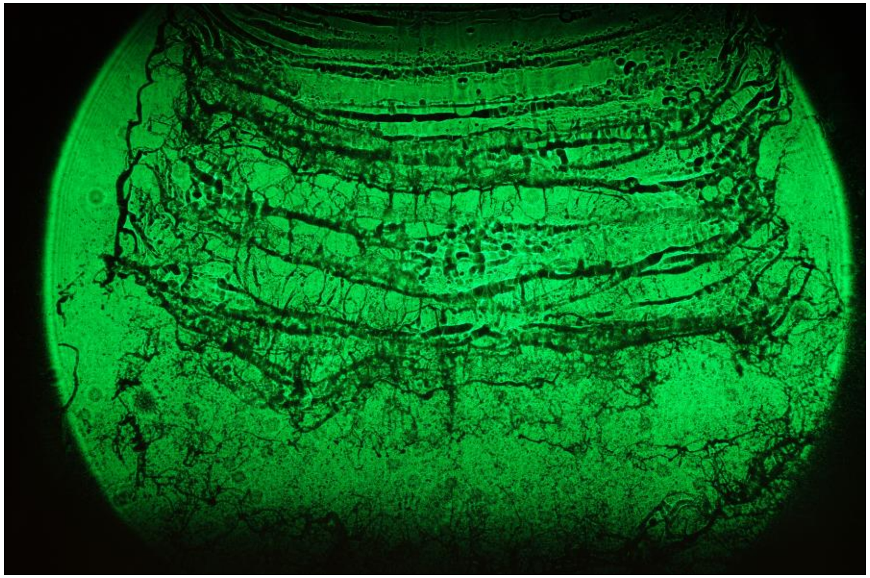
$Re = 2741$

Near nozzle images –cont.



Origin of Perforation



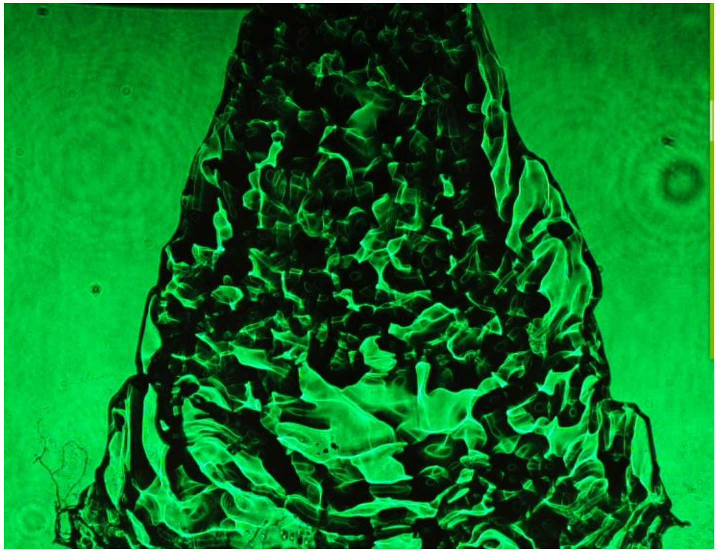


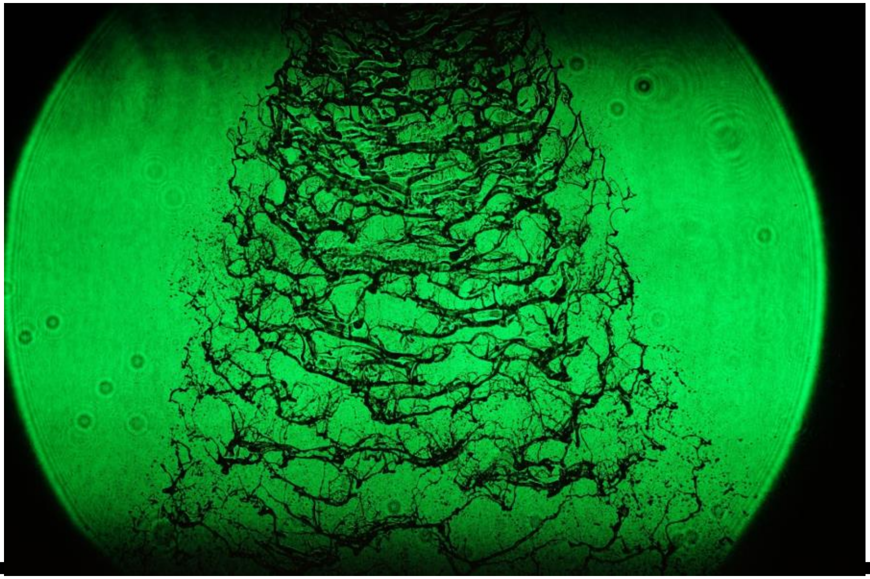
60% glycerin 500 psi

$Re = 1714$ (Laminar)

- Flag instability.
- Kelvin-Helmholtz wave cause acceleration
- The acceleration creates Rayleigh-Taylor instability and generate streamwise ligaments

Origin of Perforation





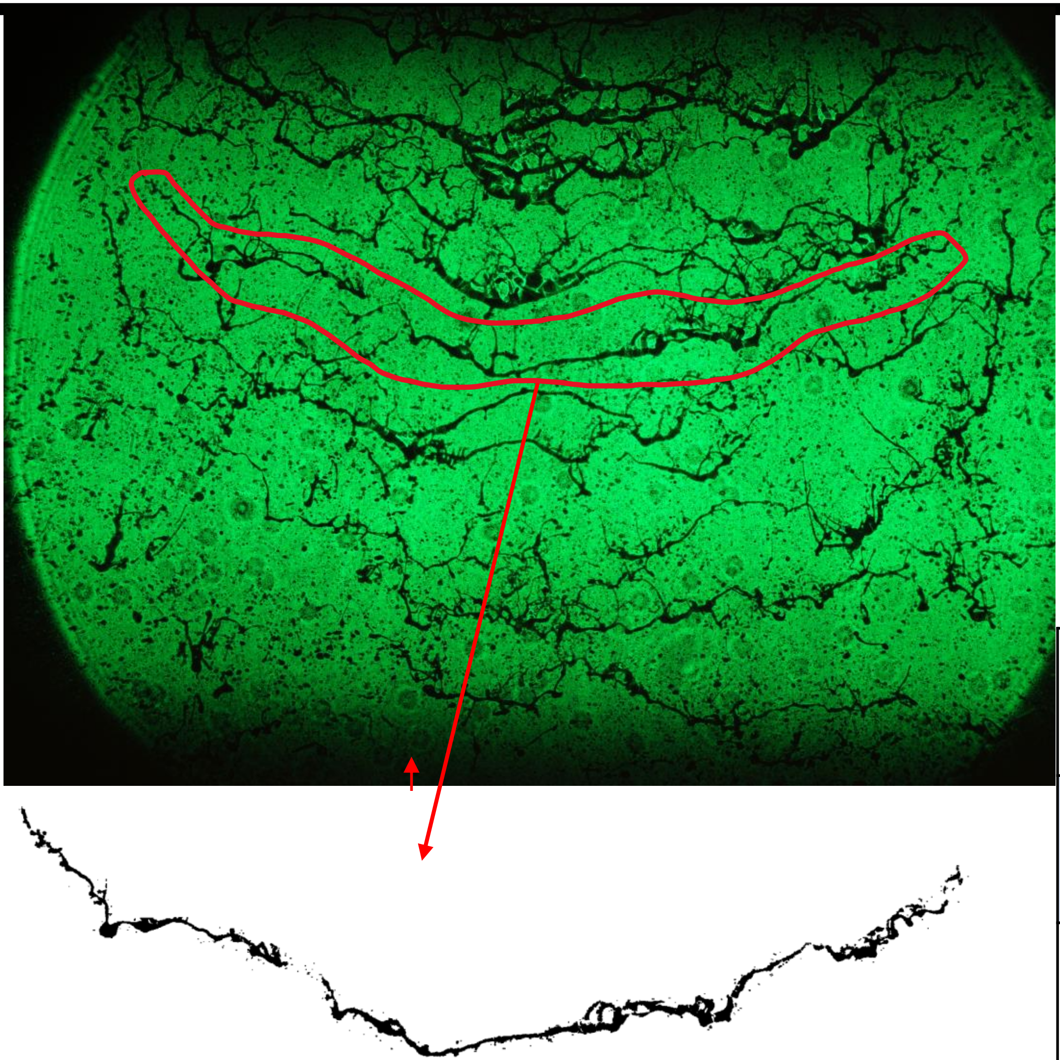
60% glycerin 900 psi

$Re = 2741$ (Turbulence)

- Vortex interact with Kelvin-Helmholtz wave
- Wrinkle on the sheet result uneven distribution of mass

- Turbulence increase the frequency of perforation
- More perforations result in faster breakup

Method of measurement



$$f_3(d) = k_v f_{3,1}(d) + (1 - k_v) f_{3,2}(d)$$

(k_v) relates to mass ratio between two types of ligaments.

$\hat{\mu}$ and $\hat{\sigma}$ relate to diameters of two types of ligaments

Ave. Diam. Spanw. Lig. 170 μm	$\hat{\mu}_1$ = 330 μm
Ave. Diam. Streamw. Lig. 40 μm	$\hat{\mu}_2$ = 80 μm
Vol. Spanwise Lig. in a wavelength = 93%	k_v = 93%

$d_o = 0.59mm, P = 800\ psi$, 60% gly

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Summary

- Generated a library of data,
  - both images and drop size distributions,
  - for different operating conditions & fluid properties, and
  - for twin fluid and swirl nozzles.

- Developed models for the spray size distribution:
  - a droplet-breakup based model for twin-fluid nozzles, and
  - a sheet perforation based model for swirl nozzles.

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Extension proposal

Objective 1. Spray Characterization of Complex Fluids - continuations

- **Fluids with solid suspensions – effect of particle types and sizes** to determine how the atomization is affected;
- **Fluids having significant elongational viscosity**, which influences the breakup of the ligaments during the secondary atomization;
- **Effect of Surface tension**, which was not specifically studied in the previous work; and
- **Molecular weight**, which was also not studied in the previous work. We will use both pressure-swirl and twin-fluid nozzles in this study.

Objective 2. Development of Atomization Models for Fluids with Suspensions

Development of physics-based models with experimentally determined constants to predict the droplet sizes generated by pressure-swirl and twin-fluid nozzles.

I. **Correlations for Droplet Size Distribution**
II. **Secondary Breakup of Ligaments of fluids with suspensions**
III. **Perforation Based Model for Pressure-Swirl Nozzles**

END

IFPRI Burlington, 2019