Breakup of Liquid Ligaments in a Cross Flow

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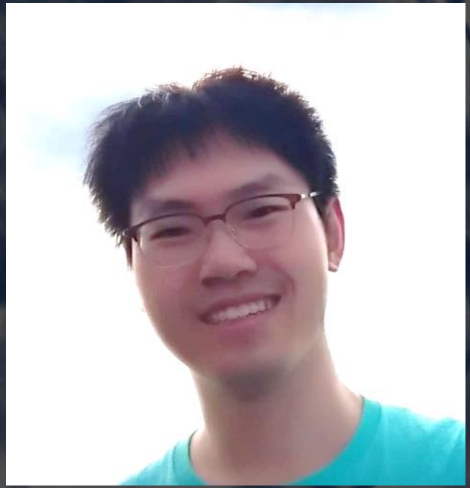

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UNIVERSITY OF TORONTO | Department of Mechanical and Industrial Engineering

IFPRI
International Fine Particle Research Institute

Summary of the Previous Term

- Atomization in swirl and twin fluid nozzles:
  - Developed benchmark database:
    - Measurement of **spray size distribution** and **near-nozzle images**
    - Tested several commercially used nozzles of varying scales
    - Tested high viscosity and polymeric fluids

  - Developed physics-based models with multi-modal distributions:
    - ADAM (Aerodynamic Droplet Atomization Model) for twin fluid nozzle.
      - Jackiw, I., and Ashgriz, N., "Aerodynamic droplet atomization model (ADAM)," Journal of Fluids Mechanics, (2023), vol. 958, A2.
      - Jackiw, I., and Ashgriz, N., "Prediction of the droplet size distribution in aerodynamic droplet breakup," Journal of Fluids Mechanics, Feb 2022, vol. 940, A17.
      - Jackiw, I., and Ashgriz, N., "On aerodynamic droplet breakup," Journal of Fluids Mechanics, Volume 913, 25 April 2021, A33.
    - A semi-empirical model for swirl nozzles for high viscosity Newtonian fluids.
      - Chen, S-Y. and Ashgriz, "Droplet Size Distribution in Swirl Nozzles," the International J. of Multiphase flows, Volume 156, November 2022, 104219.

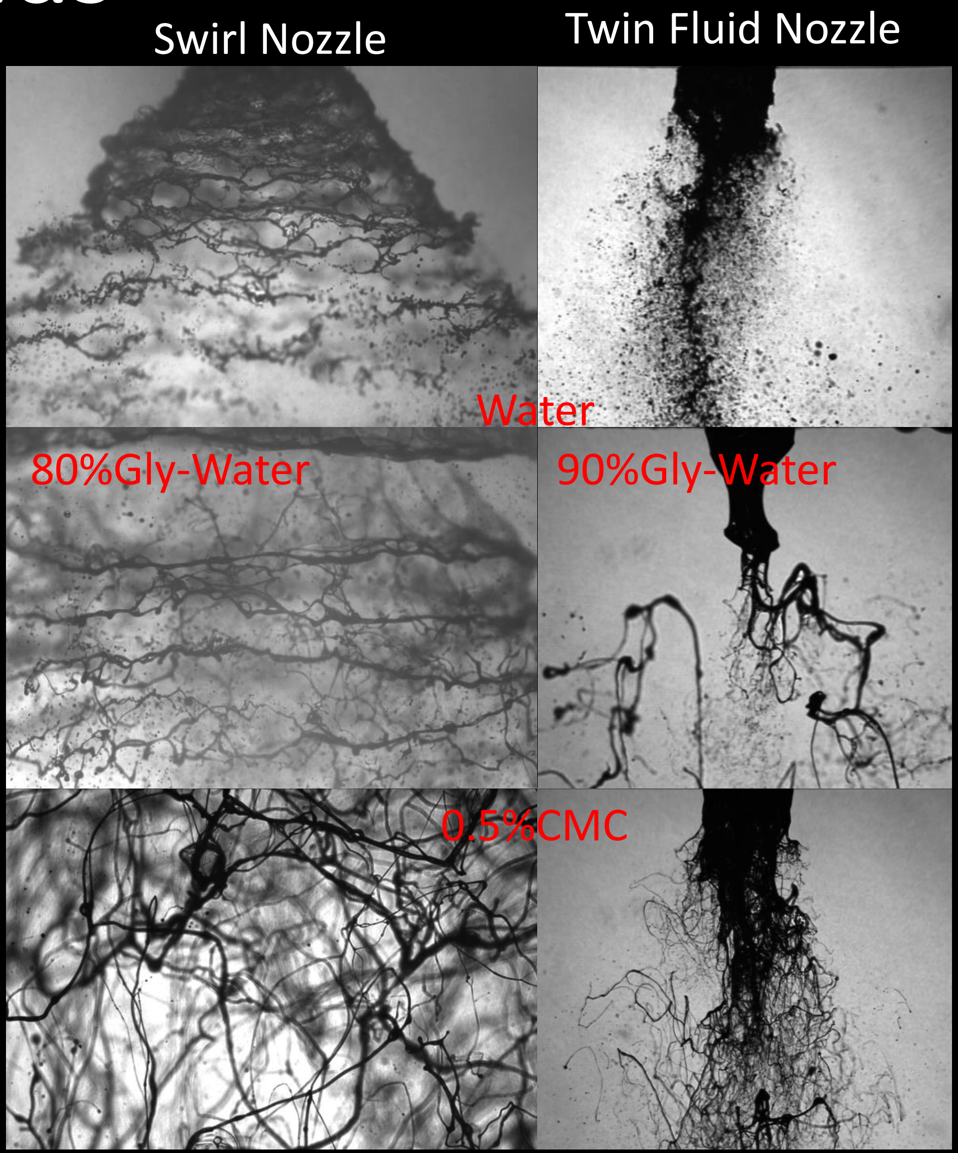
Atomization of High Viscous Fluids

- Ligaments of viscous and polymerics fluids are stretched thinner before they break up into droplets

- Applying Rayleigh-Plateau instability on initial thickness will overestimate droplet size:

$$d_{32} = 1.882 d_{lig}(1 + 3Oh)^{\frac{1}{6}} \approx 2.2 d_{lig}$$

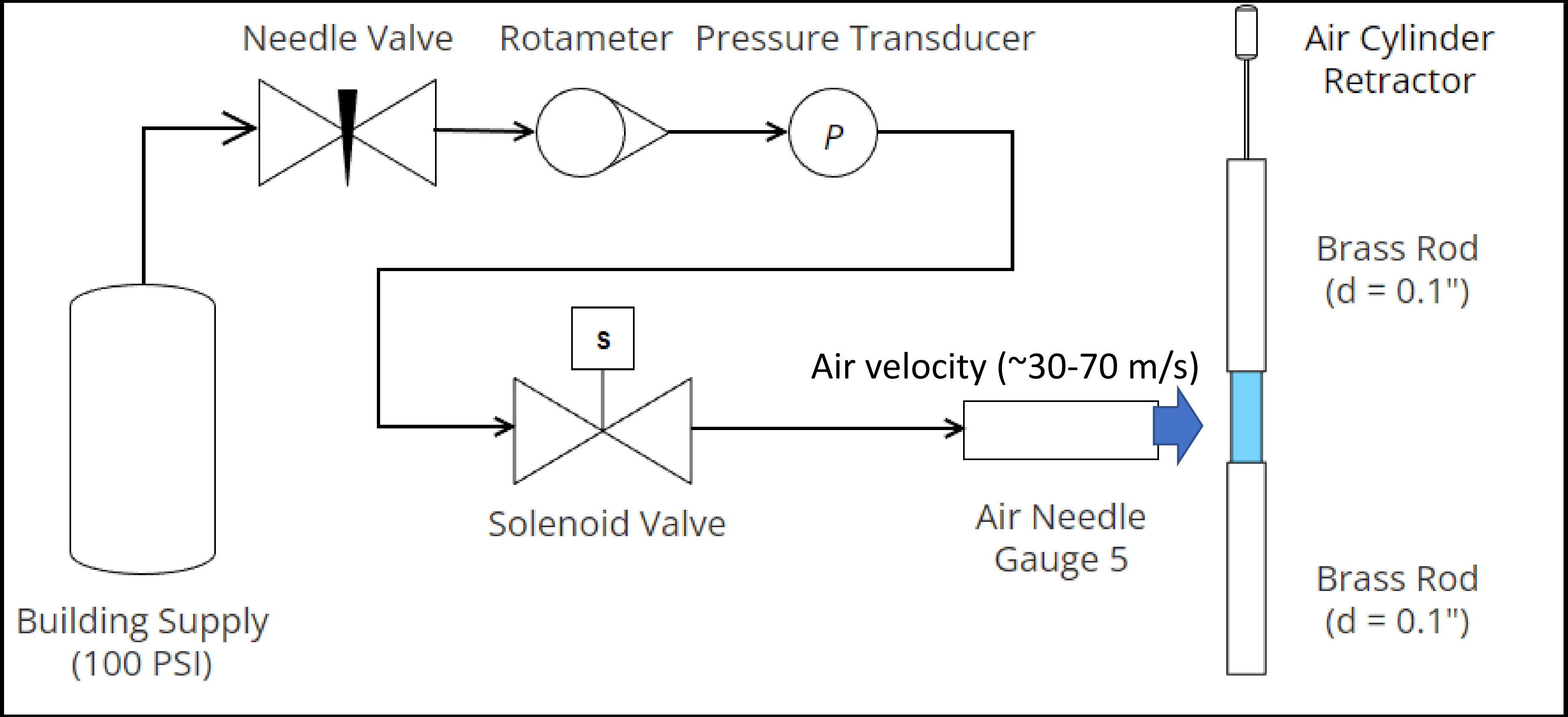
- This indicates that <u>thinning effect</u> on ligaments is crucial in determining droplet size



Objectives

1. Breakup of ligaments of fluids in cross flows.
2. Spray droplet size measurement of polymeric fluids and slurries.
3. Models for the atomization of high viscosity/polymeric fluids and slurries in swirl and twin fluid nozzles based on ligament dynamics.

Breakup of Liquid Ligaments in a Cross Flow

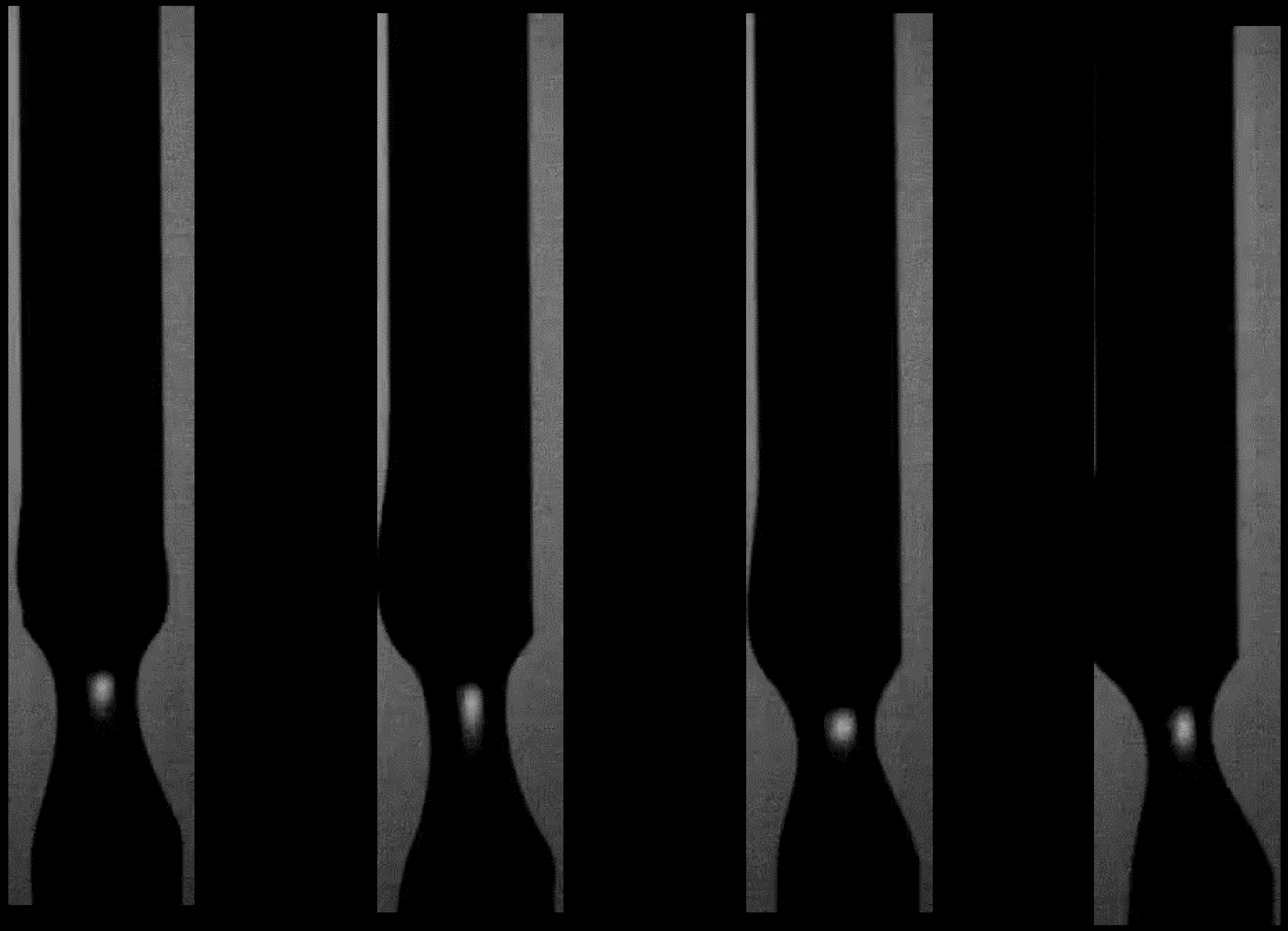


0.4m/s

$$We = \frac{\rho_g u_{gas}^2 d_{lig}}{\sigma}$$

80 % Glycerin	99.7% Glycerin
0.25% CMC	0.5% CMC
Neodol	Slurry with Neodol

Experiment Result – Pure Pulling



80% Gly.
60 cps

99.7% Gly.
1410 cps

0.25% CMC
1.5 cps

0.5% CMC
2.9 cps

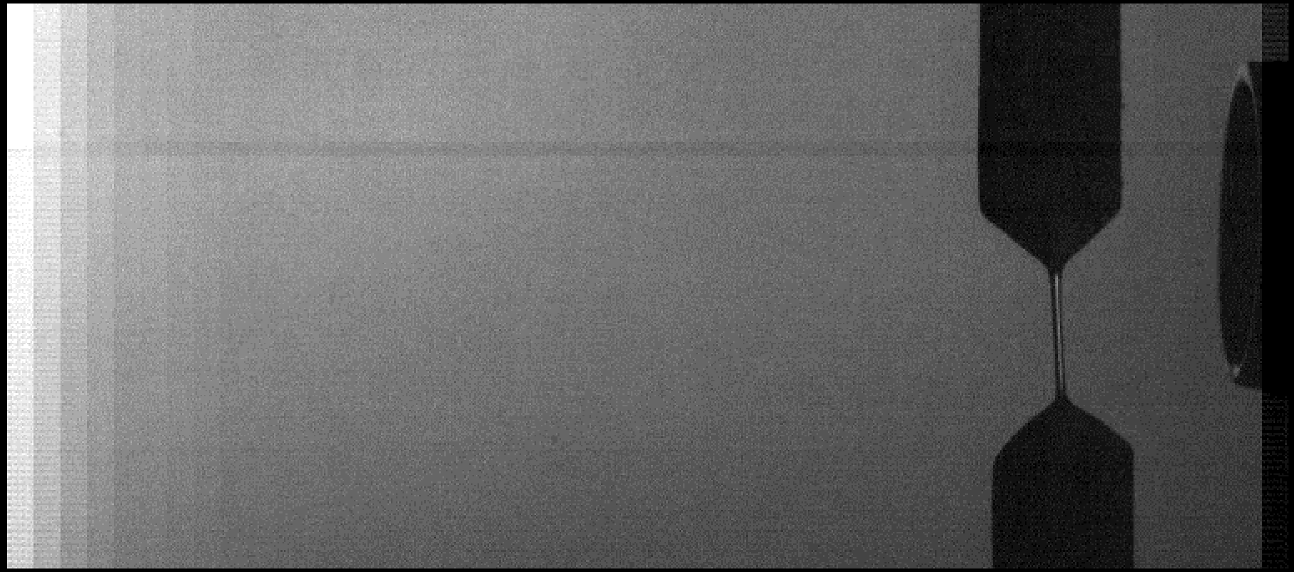
0.5% CMC

From swirl nozzle

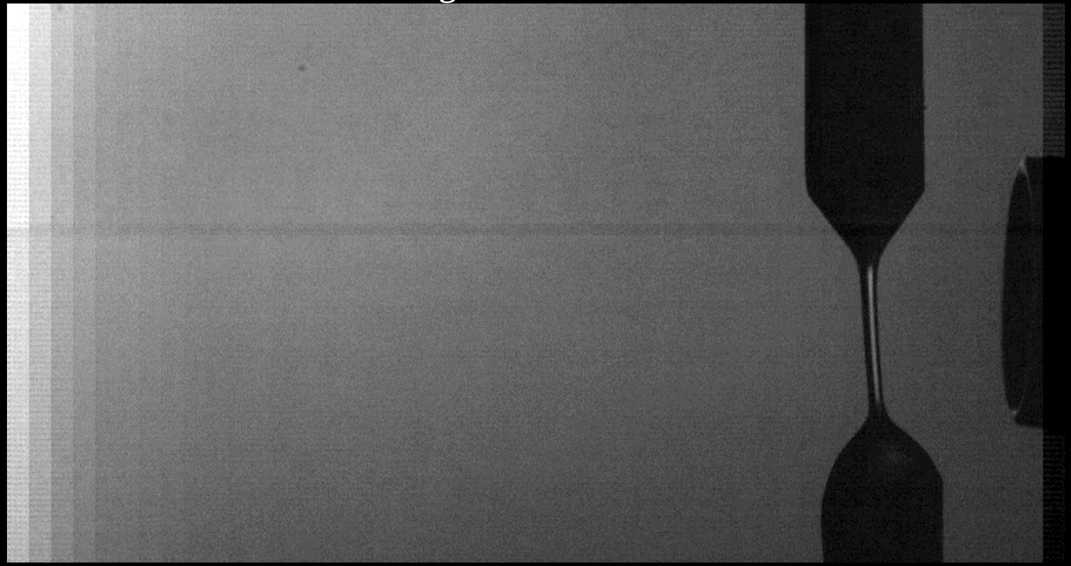
From twin fluid nozzle

Ligament in a cross flow

80% Gly-water, $u_g = 50m/s$, d_{lig}=210μm, We=10, $l_{lig} = 3mm$



80% Gly-water, $u_g = 72m/s$, d_{lig}=300μm, We=28, $l_{lig} = 3.3mm$



80% Gly-water, $u_g = 50m/s$, d_{lig}=390μm, We=18, $l_{lig} = 2mm$

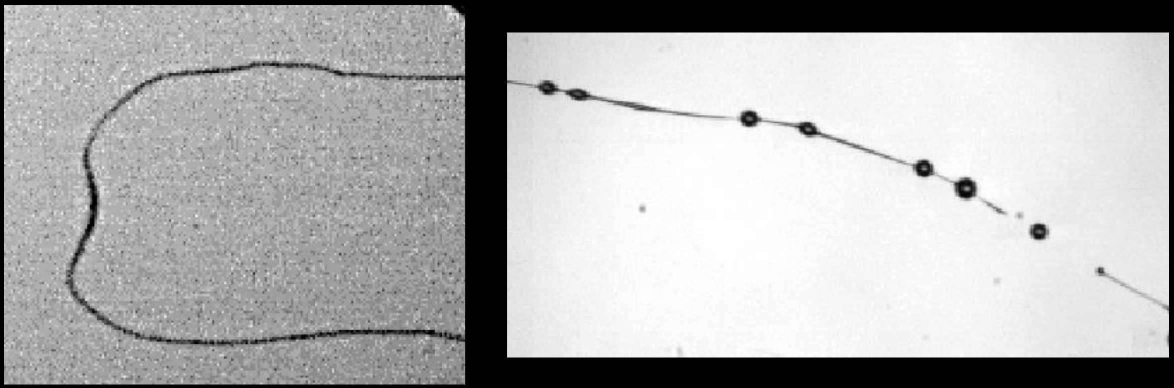
80% Gly-water, $u_g = 72m/s$, d_{lig}=480μm, We=46, $l_{lig} = 3mm$

Morphologies

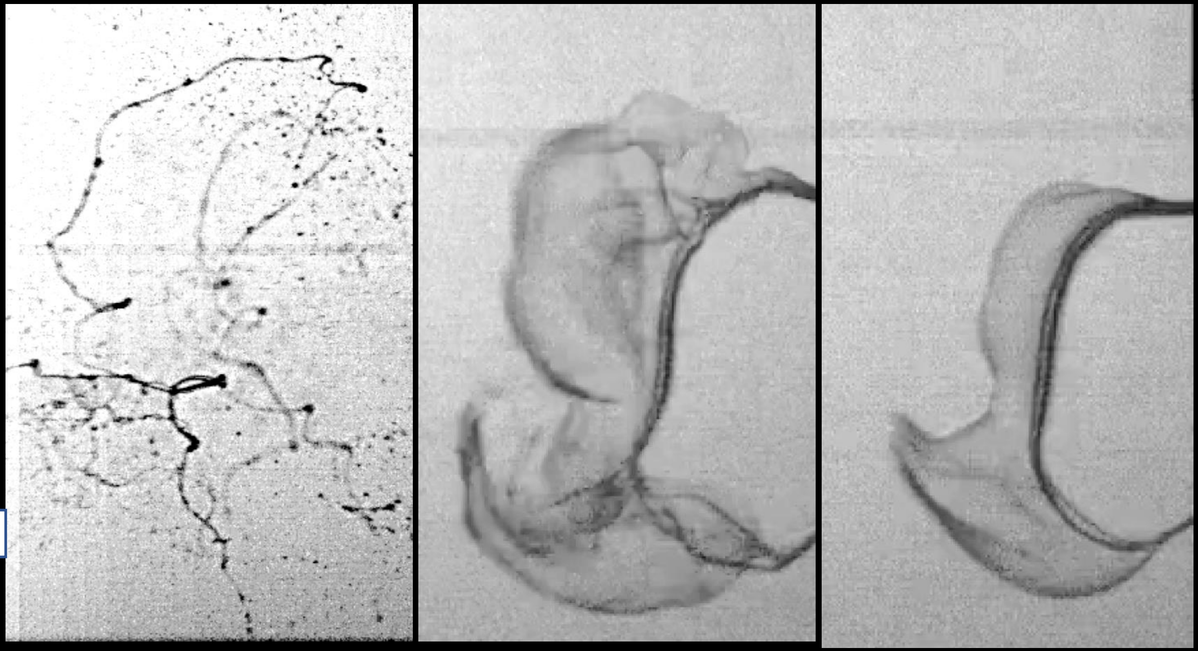
Ligament stretching and thinning, followed by bead and then droplet formation

Bag formation, followed by bag breakup and ligament formation from the rims of the bag, followed by ligament-stretching and breakup.

Ligament Stretching for We =10



Bag – Ligament - We=18

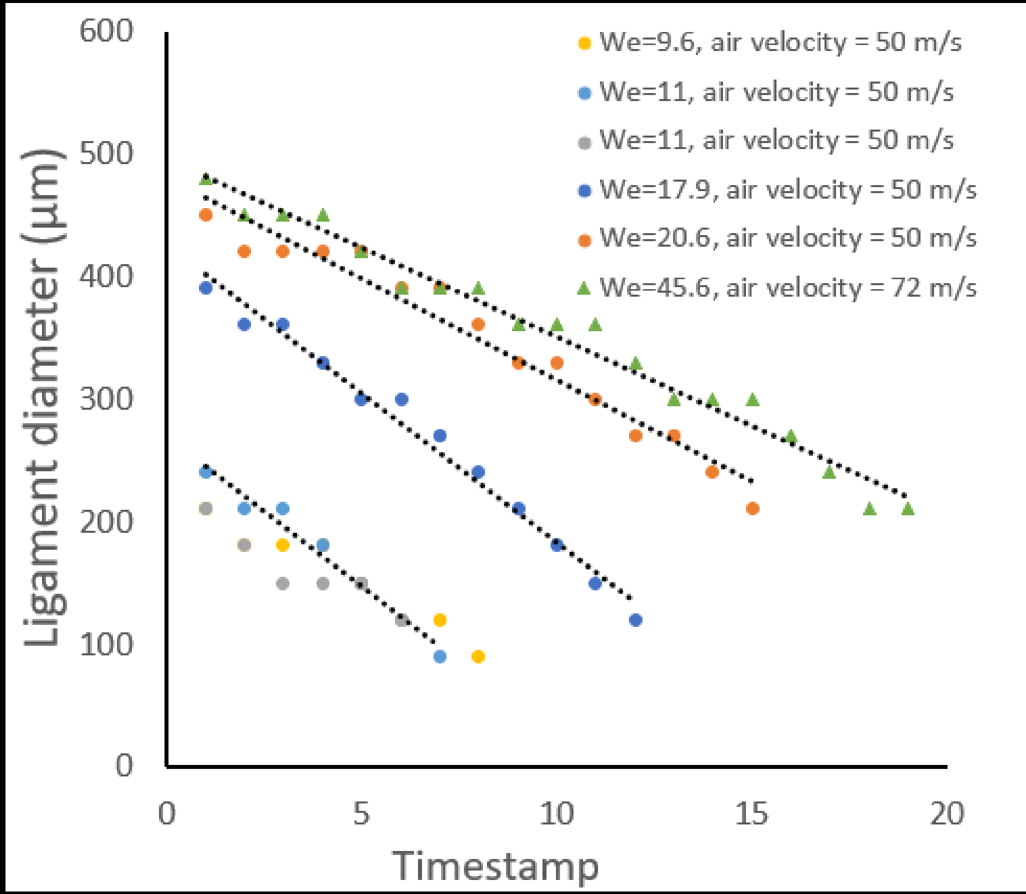


Drops generated by bag-membranes are generally smaller than drops generated by direct ligament stretching.

Measurement Procedure

1--Determine the conditions for the bag formation.
2- Determine bag rim/membrane diameters.
3- Correlation for the ligament thinning rate at different flow conditions.
4- Measure the bead/drop sizes for different ligaments.

$$\text{Critical } We_c = \frac{\rho_g u_{gas}^2 d_{lig}}{\sigma} \approx 11$$



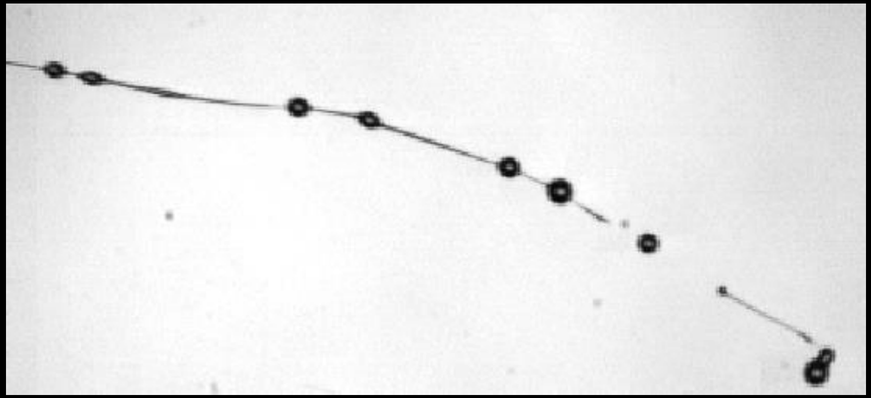
Process of undulation or bead formation on a ligament

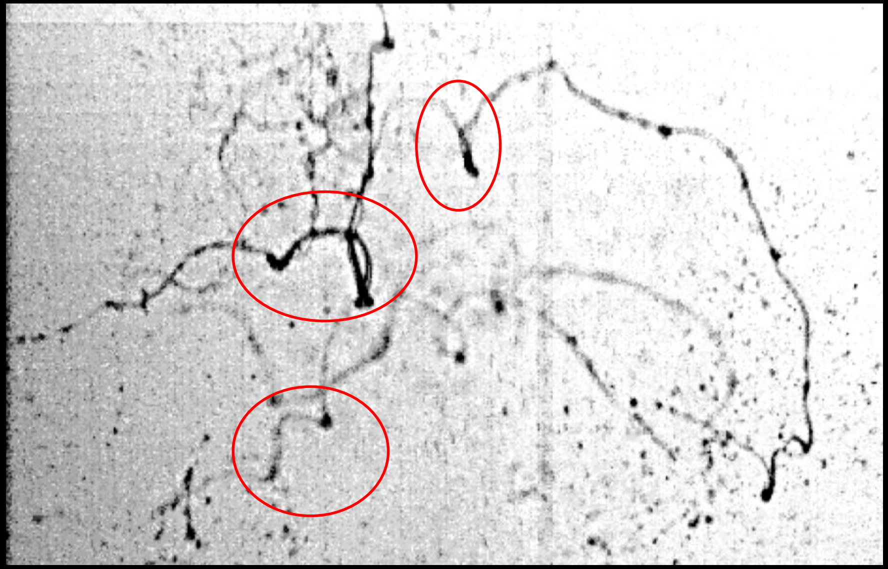
Two mechanism of bead formation are observed.

1- Classical Rayleigh-Plateau Instability – In this mechanism, small disturbances on a cylindrical liquid ligament grow, causing the breakup of the ligament.

The bead formation appear when the thinning rate of the ligament is smaller than the growth rate of the instability.

2- Undulations formed by a **flapping** ligament. Ligaments form bead as they go through large sinusoidal oscillation.



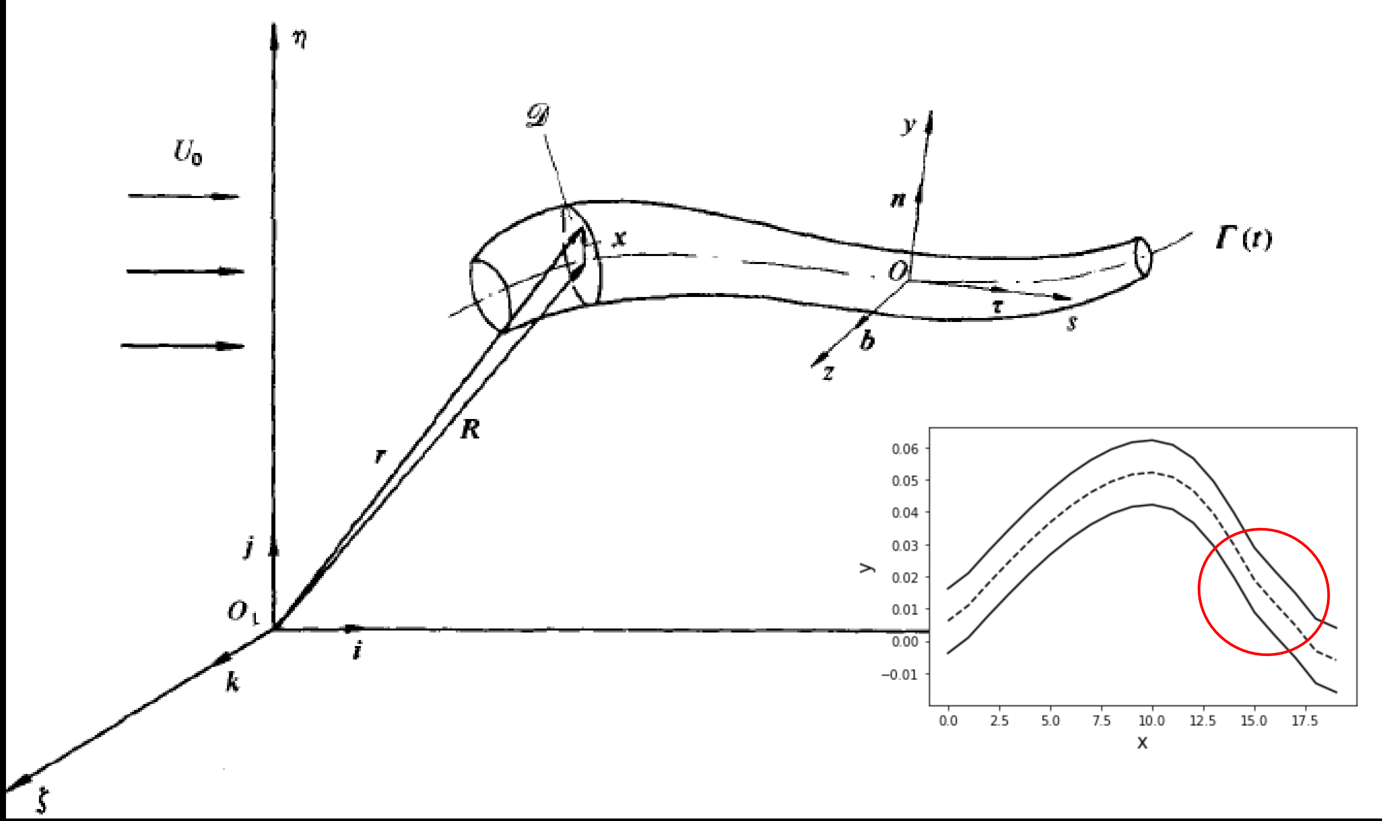


Modeling a flapping ligament

- A model by proposed by Yarin A.L. (1993), provides a set of equations for

  the movement of ligament central axis $\Gamma(r)$,

  the movement of a fluid particle in the cross section.



These equations are solved numerically to obtain the rate of thinning of a ligament in any type of flow.

$$\frac{\partial \lambda a^2}{\partial t} + \frac{\partial W a^2}{\partial s} = 0 \quad \text{(mass conservation)}$$

$$\frac{\partial \lambda a^2 V_n}{\partial t} + V_\tau \frac{a^2}{\lambda}\frac{\partial V_n \lambda}{\partial s} + \frac{\partial W V_n a^2}{\partial s} + a^2 W V_\tau \lambda k = \frac{1}{Re}\left(\frac{\partial Q_n}{\partial s} + \lambda P k\right) - J\frac{k a^2}{\lambda} \quad \text{(momentum)}$$

$$v = V + \Omega \times x + \delta x + v' \quad \text{(affine transformation in cross section)}$$

$$W = V_\tau - V_n \frac{\partial H}{\partial s}$$

Summary & Future Work

- Designed an experiment to study the breakup of liquid ligaments in cross flows.
- Initial experiments show
  - ligament stretching and thinning, followed by bead and then droplet formation or
  - bag formation, followed by bag breakup and ligament formation by the rims of the bag, followed by ligaments stretching and breakup.
  - Droplet sizes appear smaller in the bag-ligament-drop breakup mechanism.

- Future
  - More detailed ligament breakup experiments and measurement of droplet sizes after breakup, for polymeric, and slurry ligaments.
  - Identify effect of elongational viscosity on breakup mechanism and droplet size.

END

IFPRI Burlington, 2019