Characterization of Spray Drying Nozzles at Industrially Relevant Conditions

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IFPRI International Fine Particle Research Institute

Project Objectives

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1. **Develop benchmark data for spray characteristics at different:**
   - Fluid properties: viscosity and polymeric effects
   - Pressures
   - Orifice diameters
   - Nozzle types:

     (1) Pressure Swirl Nozzles and

     (2) Twin-Fluid Nozzles

2. **Develop correlations for spray characteristics**
   - Physics based models based on observation and classification of the near nozzle primary atomization processes at different operating conditions.
     - Sheet preformation-based model for swirl nozzles
     - Droplet breakup-based model for twin fluid nozzles

3. Develop correlations for the effect of ambient temperature

(1) Pressure Swirl Nozzle

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Testing Facility

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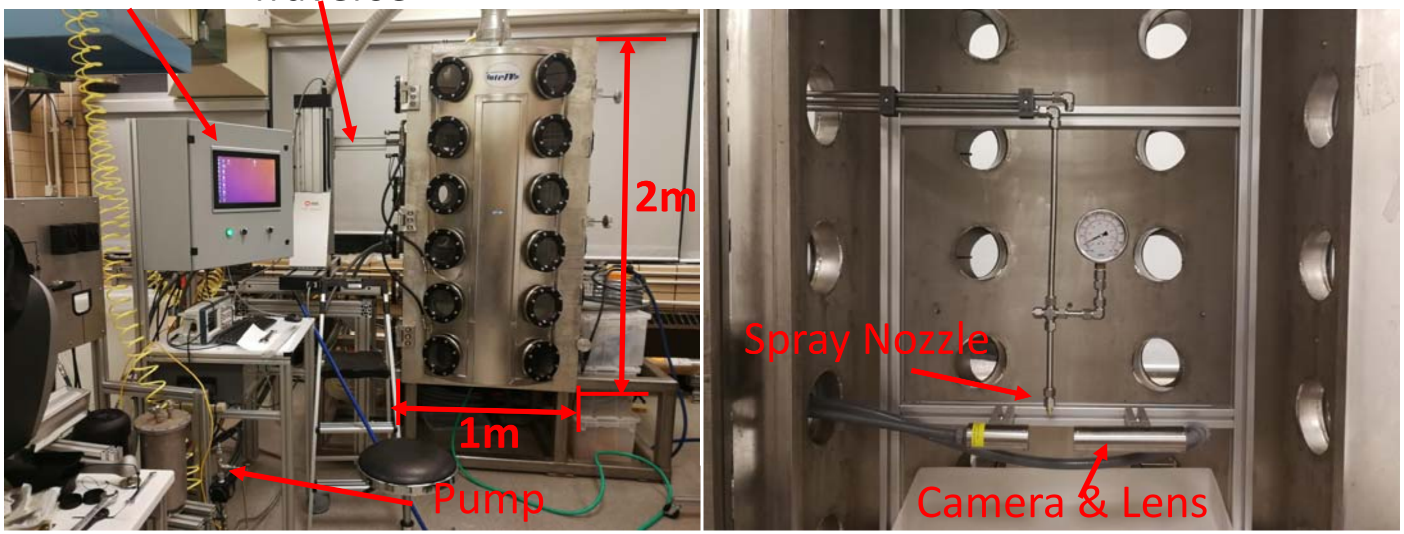
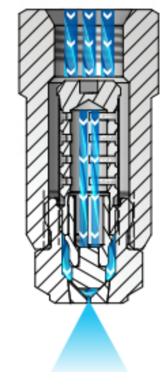
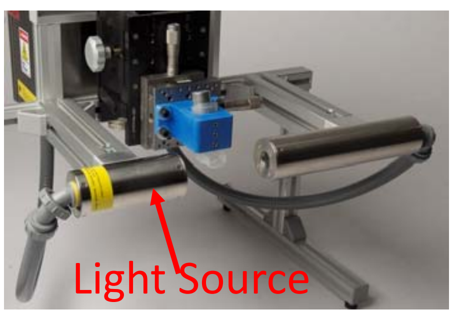
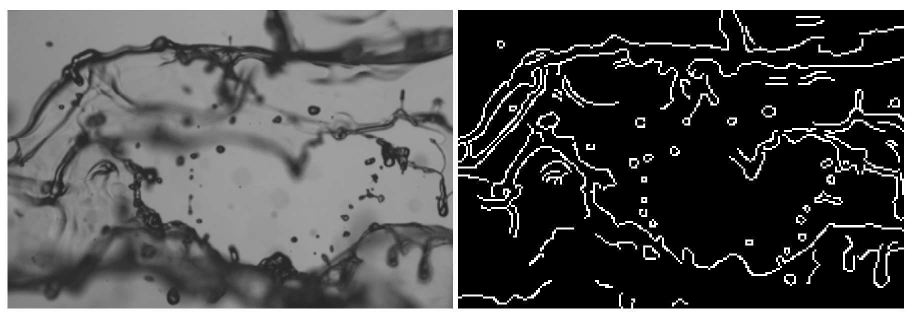


Swirl Nozzle with Swirl Insert





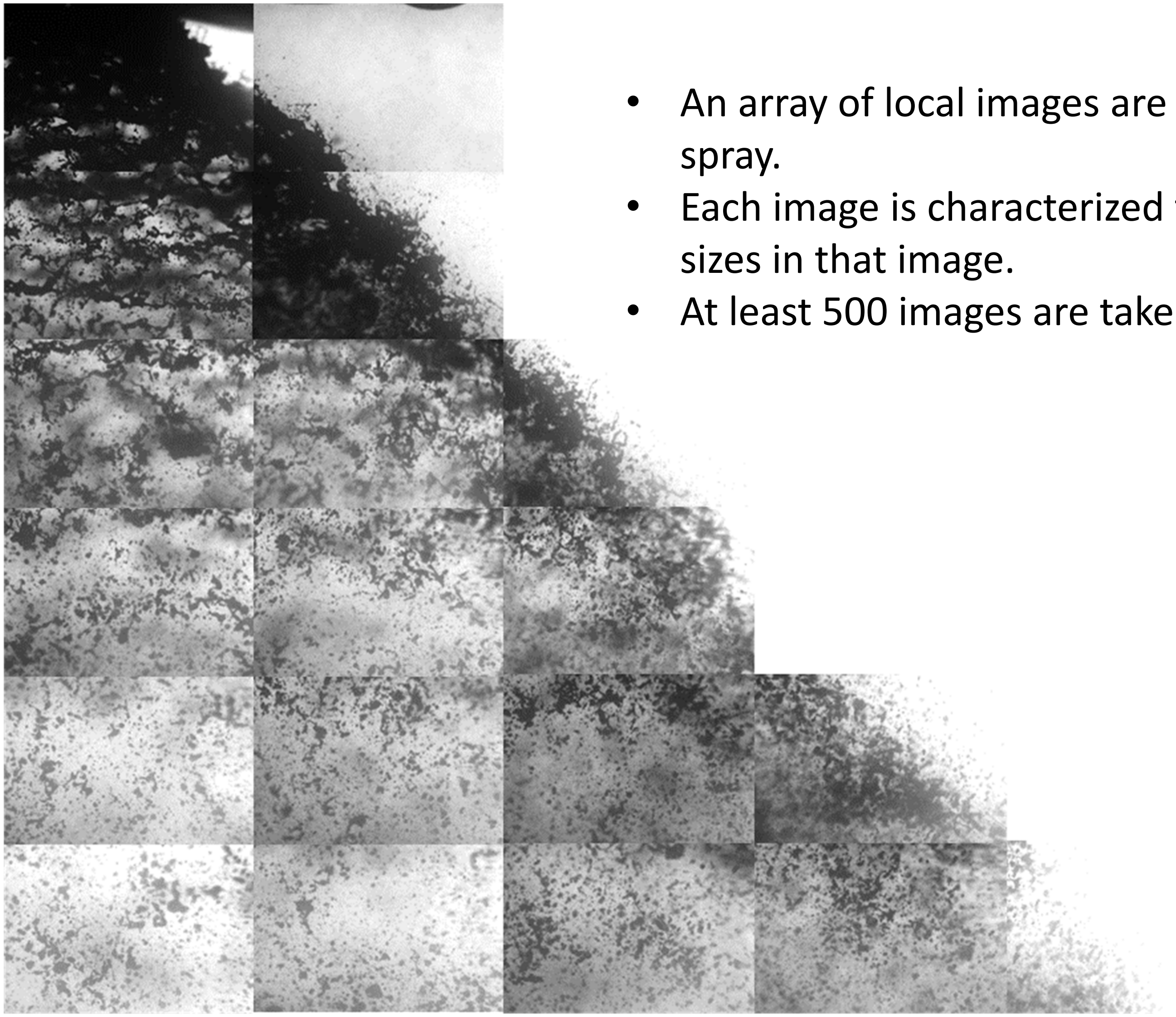
Imaging System
$5\mu m$ resolution,
50 nanosecond flash



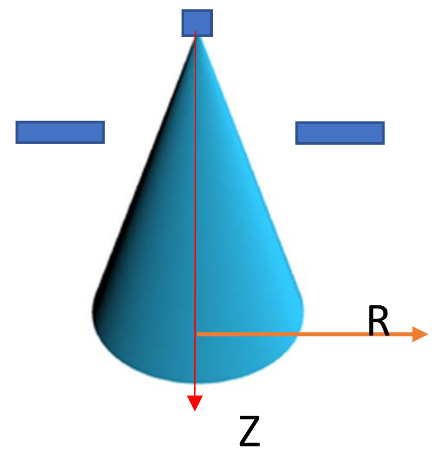
Imaging & image processing to determine droplet sizes and ligament thicknesses.

Swirl Nozzle with Tangential Inlet

Image based Characterization



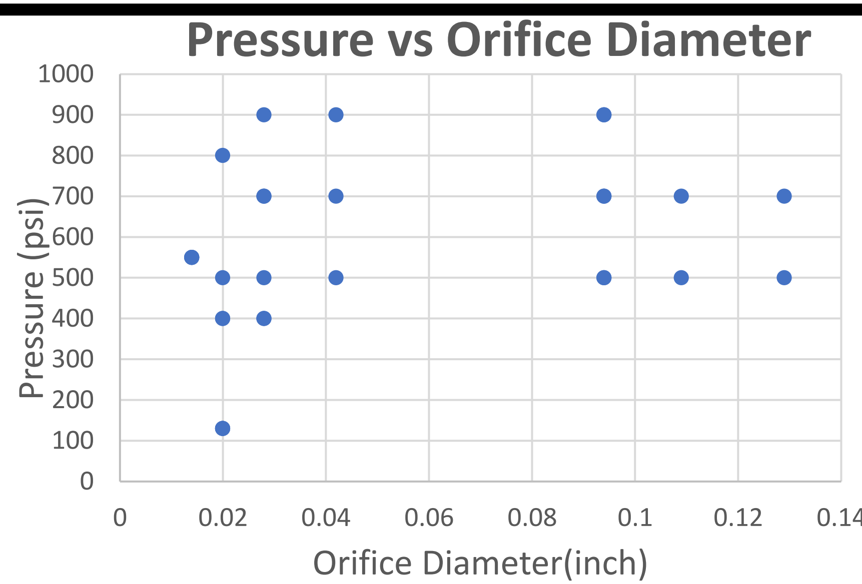
- An array of local images are taken to form the whole spray.
- Each image is characterized to determine the droplet sizes in that image.
- At least 500 images are taken for each position.

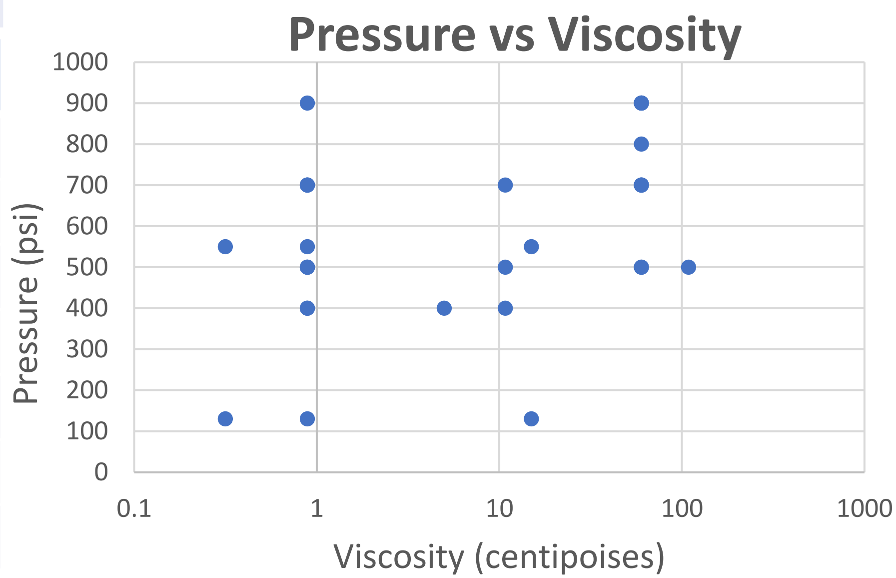


Testing Parameters

Nozzle Type (Orifice size)	Orifice Diameter
Spraying Systems Fine Spray Nozzle (FSN) (Swirl Insert)	0.02“ (0.5mm), 0.028” (0.7mm), 0.042” (1.1mm)
Spraying Systems SKH Nozzle (Swirl Insert)	0.02“ (0.5mm), 0.028” (0.7mm)
Spraying Systems WhirlJet Nozzle (WJN) (Tangential Inlet)	0.094“ (2.39mm), 0.109” (2.77), 0.129” (3.28mm)
Schlick 121V Nozzle (S121VN) (Swirl Insert)	0.014“ (0.36mm) 0.02” (0.5mm)

Fluid	Viscosity (cp)
Water	0.89
Acetone	0.316
60% glycerine	10.8
80% glycerine	60.1
5% HPMCAS/Acetone Solution	~5
10% HPMCAS/Acetone Solution	~30
Maltodextrin/Water Solution	60 to 308



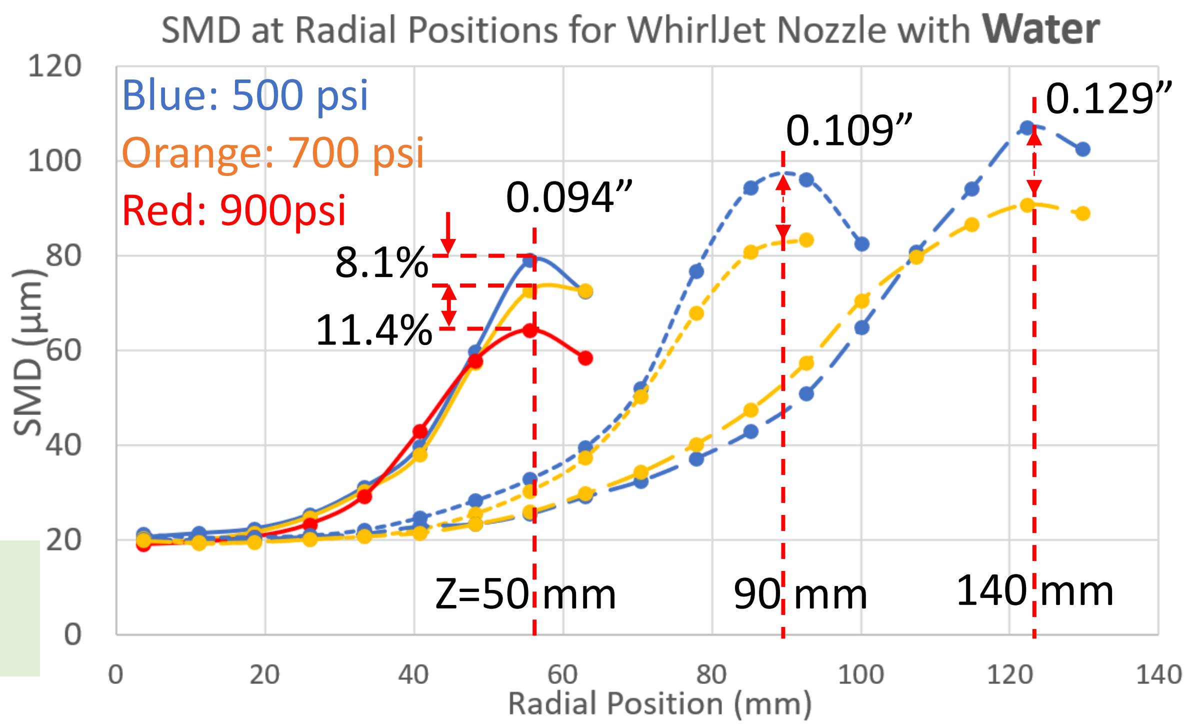


SMD in Radial Direction-WhirlJet Nozzle

$$\boldsymbol{SMD \downarrow \& \alpha \downarrow as\ P \uparrow}$$
$$\boldsymbol{SMD \uparrow \& \alpha \downarrow as\ D_{nozzle} \uparrow}$$

For the same nozzle and the same fluid, $SMD_{\max}$ reduces with increase in pressure, and the reduction is more at higher pressures.

Spray angle does not provide the location of $\boldsymbol{SMD_{\max}}$.



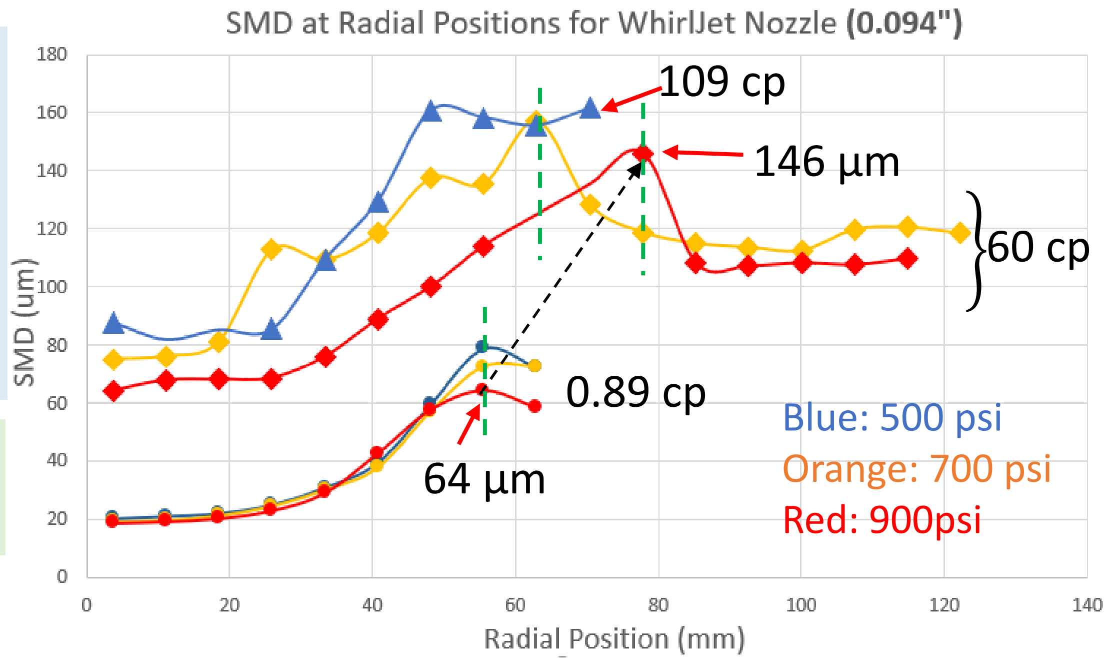
Orifice \ Pressure	$SMD_{\max}$ 500psi	700psi	900psi	Spray Angle 500psi	700psi	900psi
0.094”(2.39 mm)	79.1µm	72.7µm (-8.1%)	64.4µm (-11.4%)	89	82.2	75.4
0.109”(2.77 mm)	96.2µm	83.5µm (-13.2%)		81	77.4	
0.129”(3.28 mm)	107.3µm	90.8µm (-15.4%)		80	76	

Effect of Viscosity in WhirlJet Nozzle

$SMD \uparrow$ *as* $\mu \uparrow$

At 900 psi,
SMD_{max} 64.4µm at μ=0.89cp to 146.09µm at μ= 60cp, (126%)
SMD_{global} 41µm at μ=0.89cp to 98µm at μ= 60cp (140%).

For high viscosity fluids, the location of SMD_{max} can change significantly



$\boldsymbol{SMD}_{\mathbf{max}}$ and % of $\boldsymbol{SMD}$ reduced (in brackets) from the previous pressure level.

Orifice \ Pressure	Measuring Position	500psi	700psi	900psi
0.094”(0.89cp)	50 mm	79.1µm	72.7µm (-8.1%)	64.4µm (-11.4%)
0.094”(60.1cp)	200 mm		157.21µm	146.09µm (-7.1%)
0.094”(109cp)	135 mm	160.75µm		

Effect of Nozzle Diameter -FSN Nozzles

Whereas for low μ fluids:

$SMD \uparrow$ as $D_{nozzle} \uparrow$

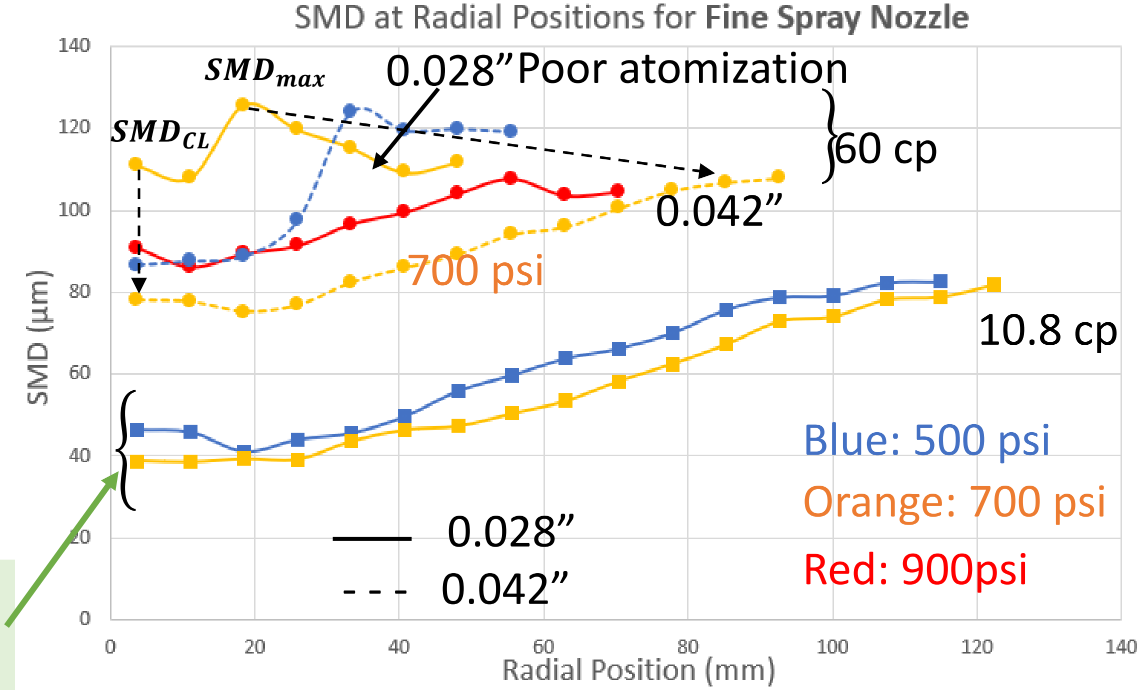
For high μ fluids:

$SMD \downarrow$ as $D_{nozzle} \uparrow$

Poor atomization at **60 cp**		
700 psi	SMD_{max}	SMD_{CL}
0.028”	112.3µm	110 µm
0.042”	108µm	76µm

For small nozzles & low μ, SMD_{max} does not reduce significantly as $P \uparrow$:
For 0.028” & 10.8cp: SMD_{max} reduces by 1% when P increases from 500 to 700psi, and SMD_{global} reduces from 58.39µm to 53.15µm, by 9%.

For high viscosity liquids, increase in pressure, reduces SMD_{max} more significantly, and more so for larger orifice nozzles.

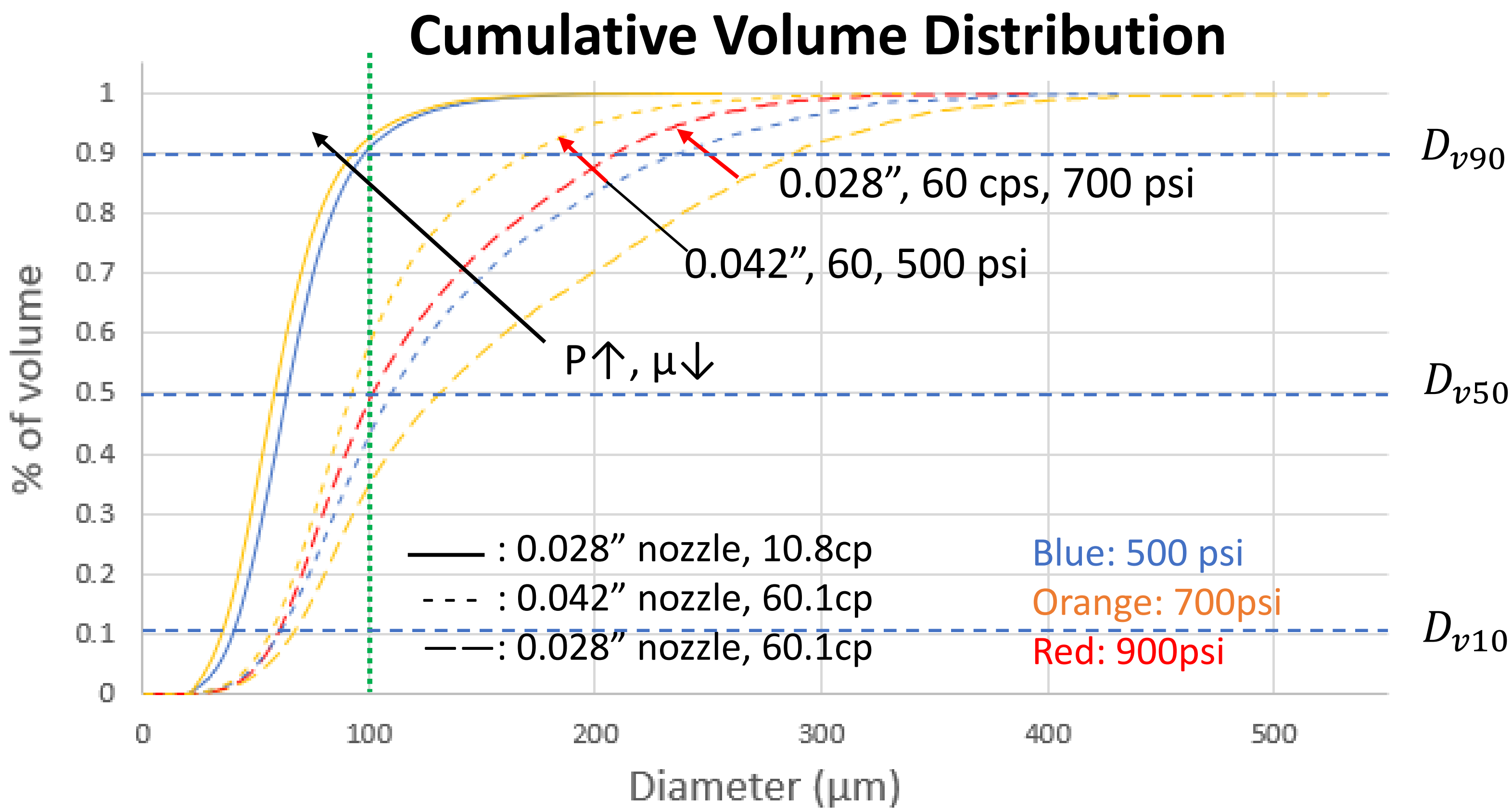


Measurements are at Z=200 mm

SMD_{max}

Orifice \ Pressure	500psi	700psi	900psi
0.028”(10.8cp)	82.5µm	82µm (-0.85%)	
0.028”(60.1cp)		112.3µm	108µm(-4.2%)
0.042”(60.1cp)	120µm	108µm (-12%)	

Atomization Quality

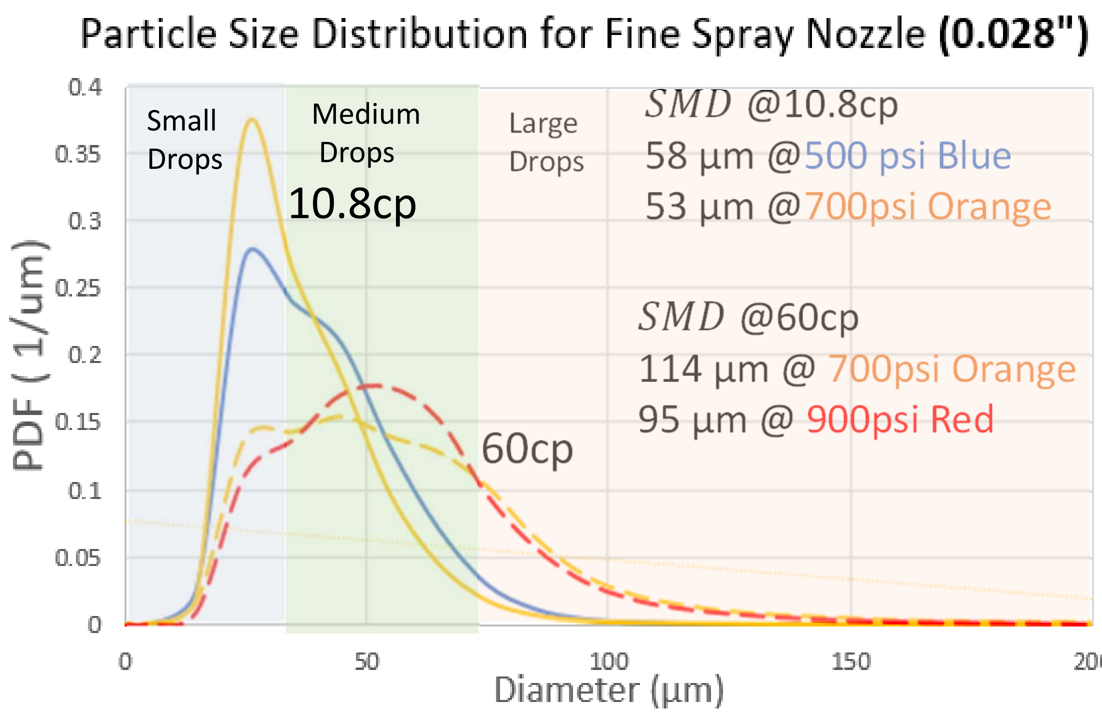


- Increase in pressure makes the droplet size distribution more uniform: More smaller droplets.
- For 0.028 nozzle with 10.8 cp fluid, droplets less than 100 μm take up 90% of the total volume, indicating a good atomization quality.

Particle Size Distribution

Viscosity influences the form of the size distribution function.

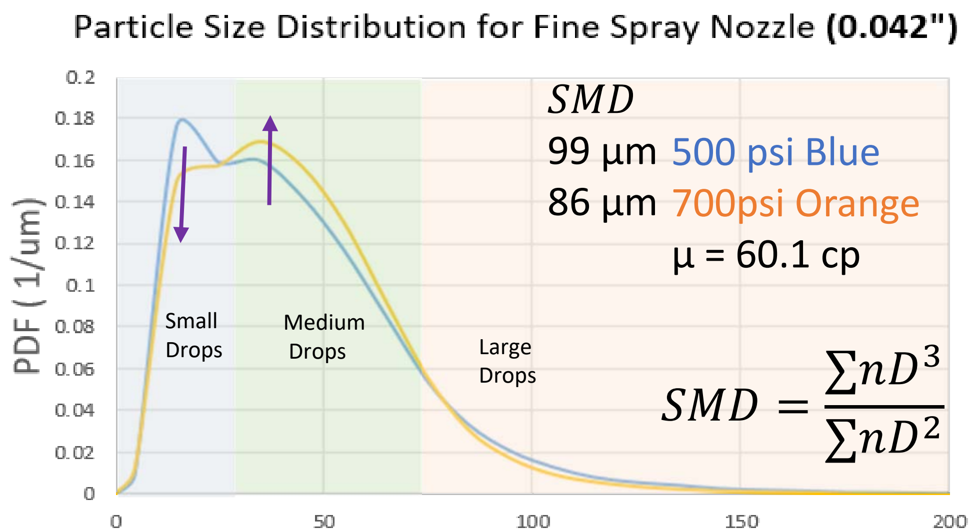
If the droplet sizes are categorizes as small, medium and large, as pressure increases, the number of large droplets decreases and number of small droplets increase. This is observed for curves for 10.8 cp fluids atomized at 500 psi and 700 psi, respectively.
The span of the PDF curve decreases as well.



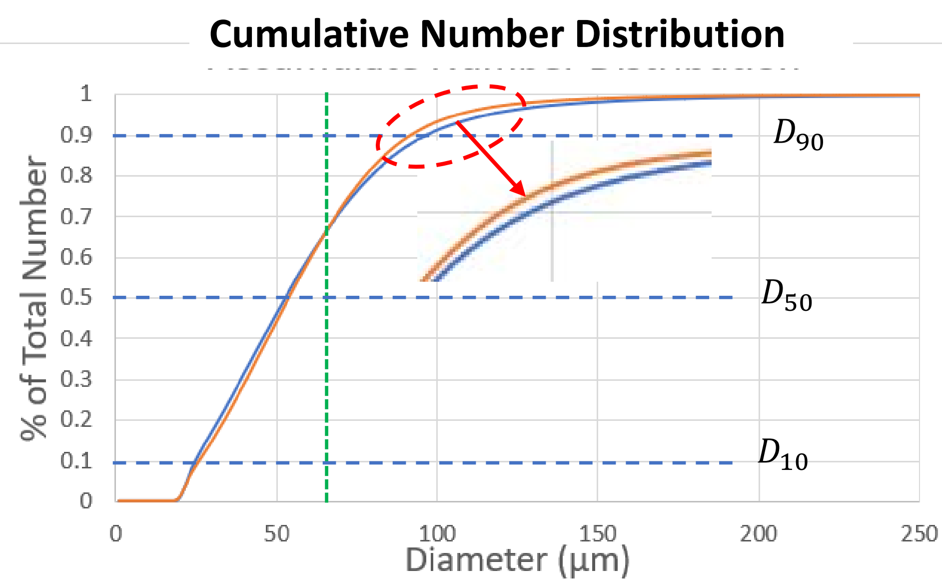
As viscosity increases, the number of large and medium size droplets increase, and the number of small droplets decreases (shown for 60.1 cp fluids atomized at 700 psi and 900 psi).

Effect of Pressure in high Viscosity Fluid Atom…

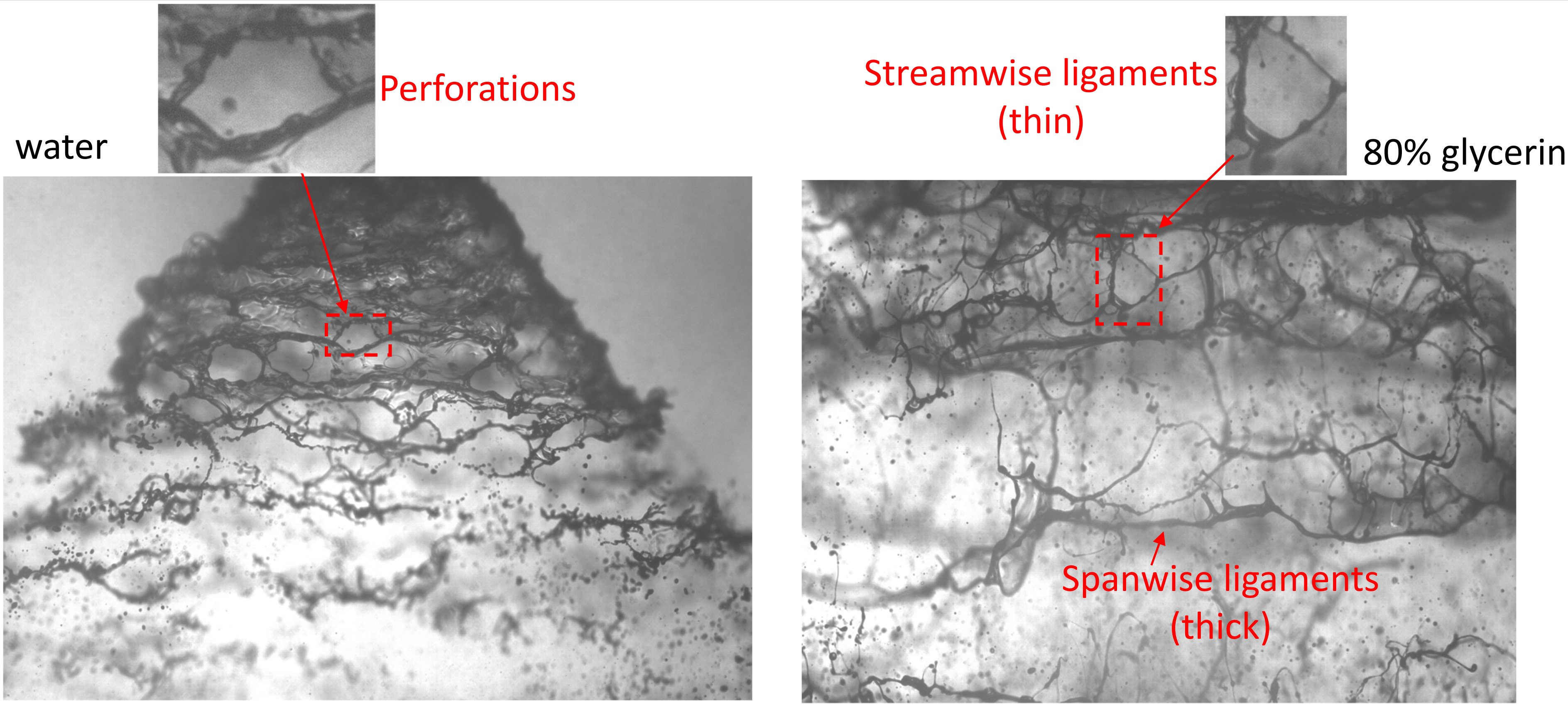
- Generally, $\boldsymbol{SMD \downarrow as\ P \uparrow}$
- However, size distribution change is not monotonic.
- The span of the distribution decreases at higher pressures: Span = $\left(\frac{D_{90}-D_{10}}{D_{50}}\right)$:
- For 0.042" with 60.1 cp fluid, the span reduces from 1.42 to 1.12 as pressure increases from 500 psi to 700 psi.



- The cumulate number distribution shows that the number of droplets below 64 µm are the same under both pressures. Above that, the curve for 700 psi increases faster than that of 500 psi.
- Since large droplets have much larger effect on the volume distribution and SMD, the SMD of 700 psi becomes smaller.



Breakup Mechanism



- Images show formation of surface waves; fluid accumulation at the wave crests and troughs, and a thin liquid sheet in between them.
- The liquid sheet thins out and eventually perforates.
- The wave crests and troughs form spanwise ligaments and collapse of thin sheets form streamwise ligaments.

Sheet Perforation-Based Model

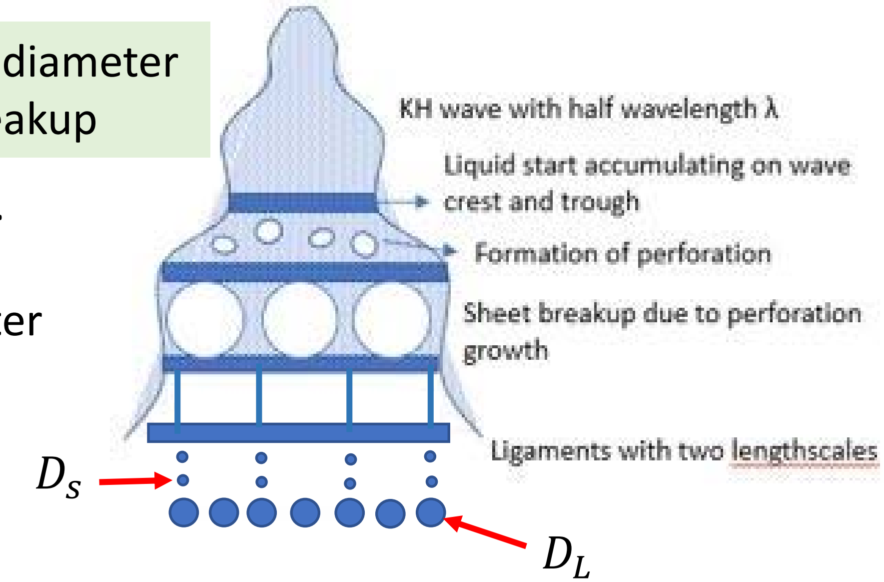
- Kelvin-Helmholtz waves are generated on the conical sheet.
- Liquid accumulates on the wave crests and troughs, whose mass at the breakup is m_c, which will generate large ligaments and droplets with diameter:

$$D_L = \sqrt{\frac{4m_c}{\pi^2 D_b}}$$

D_b=Cone diameter at the breakup

- Thin sheets form in between crests and troughs.
- Perforations occurs on these thin sheets.
- Perforations grow and form ligaments, which later breakup forming small droplets with diameter

$$D_s = \sqrt{\frac{4(m - m_c)}{\pi n \lambda}}$$



- Therefore, there are two different characteristic sizes in the spray. Each size is used to form a Gamma distribution. The overall PDF of droplets is the addition of both distributions:

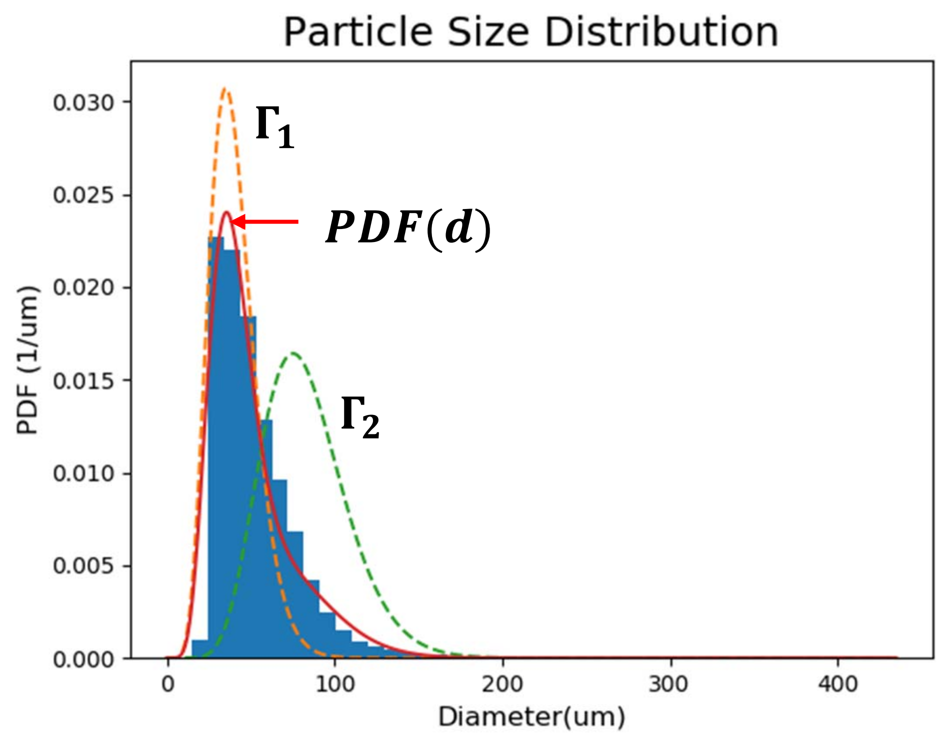
Compound Distribution Model

$$PDF(d) = \underbrace{\frac{m_c}{m}\frac{1}{\kappa D_L}\frac{\nu^\nu}{\Gamma(\nu)}\left(\frac{d}{\kappa D_L}\right)^{\nu-1}\exp\left(-\nu\frac{d}{\kappa D_L}\right)}_{\boldsymbol{\Gamma_1}} + \underbrace{\left(1-\frac{m_c}{m}\right)\frac{1}{\kappa D_s}\frac{\nu^\nu}{\Gamma(\nu)}\left(\frac{d}{\kappa D_s}\right)^{\nu-1}\exp\left(-\nu\frac{d}{\kappa D_s}\right)}_{\boldsymbol{\Gamma_2}}$$

$\nu = \mathrm{f(We, Re, based\ on\ sheet\ thickness)}$,
κ =f(wavelength of disturbance)

m_c, mass in the crests and troughs
n is the number of perforations.

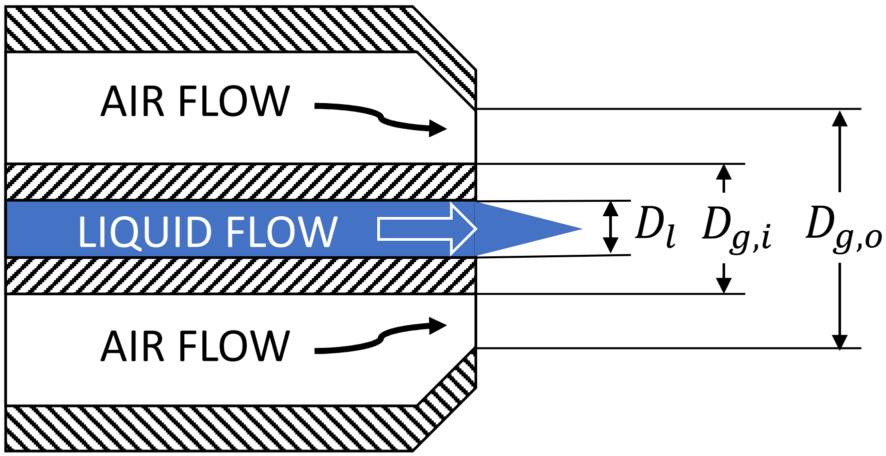
The maximum number of perforations is given by $n_{max} = floor\left(\frac{\pi D_b}{\lambda}\right)$

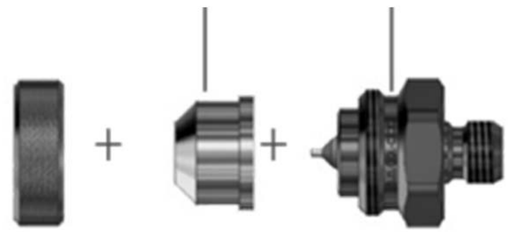


(2) Twin Fluid Nozzle

Isaac Jackiw

Testing Parameters





214 test points

Nozzle	D_l [mm]	$D_{g,i}$ [mm]	$D_{g,o}$ [mm]
Spraying Systems, ¼ J 2050-70	0.51	1.27	1.78
Spraying Systems, ¼ J 2850-70	0.71	1.27	1.78

Spraytec system

Nozzle	$\dot{m}_g$ [g/s]	$\dot{m}_l$ [g/s]	ALR	Distance from nozzle tip, Z [mm]	Liquids tested (viscosity)
SS-2050-70	0.22 – 1.28	0.33 – 1.0	0.2 - 4	80	Water and Glycerin mixtures
SS-2850-70	0.22 – 1.28	0.33 – 1.67	0.13 – 3.8	20, 40, 60, 80, 100	

Two-Fluid Nozzle

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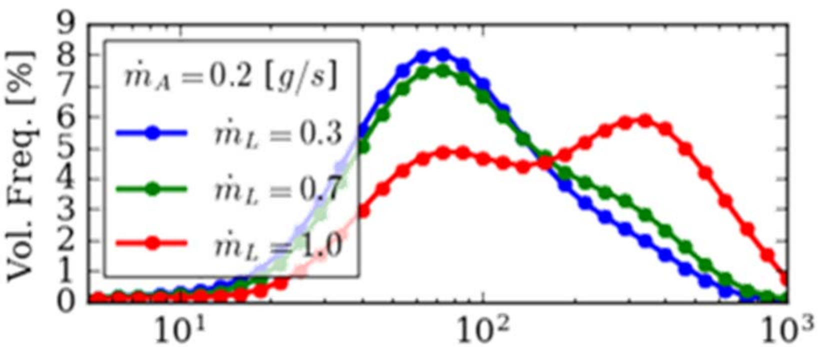
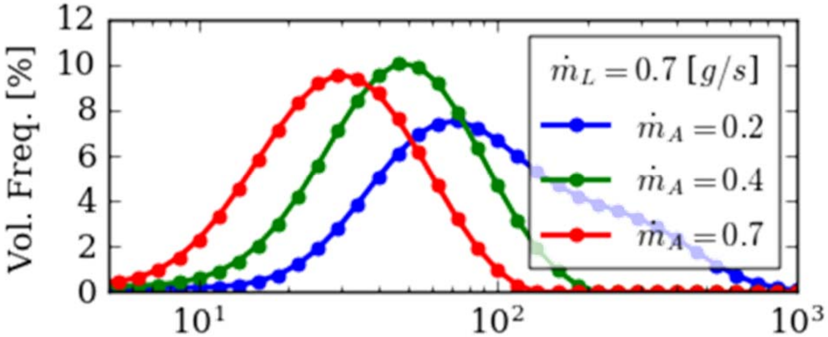
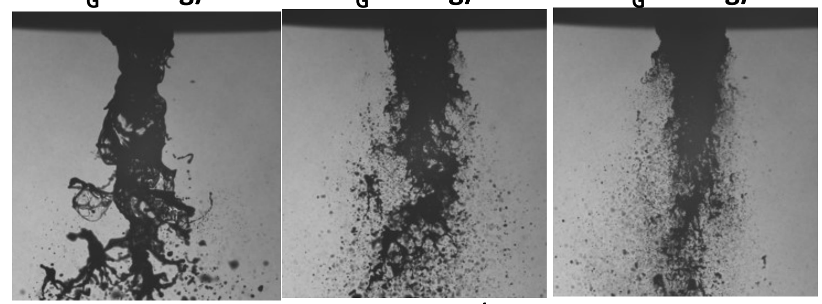


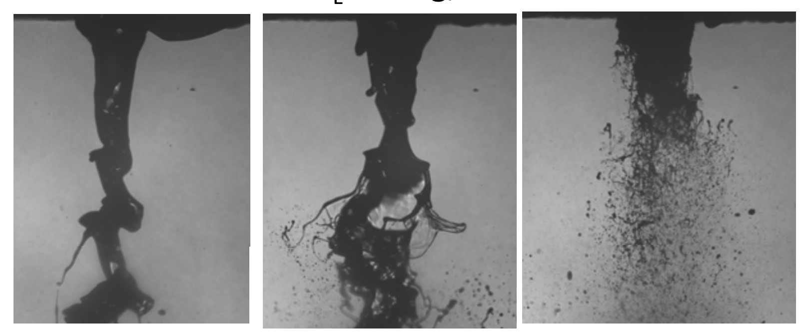


water

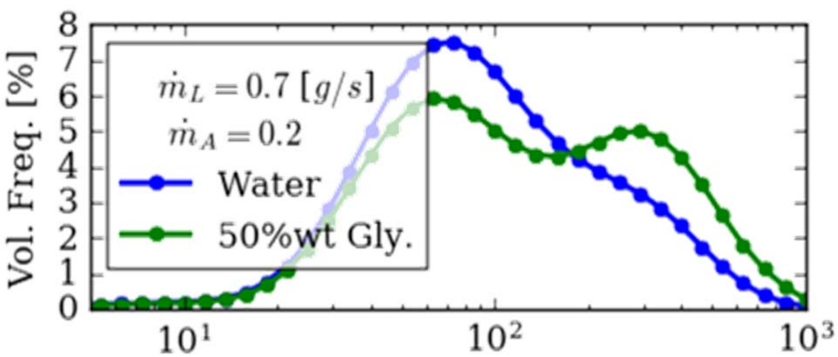
$\dot{m}_G$ = 0.2 g/s | $\dot{m}_G$ = 0.4 g/s | $\dot{m}_G$ = 0.6 g/s

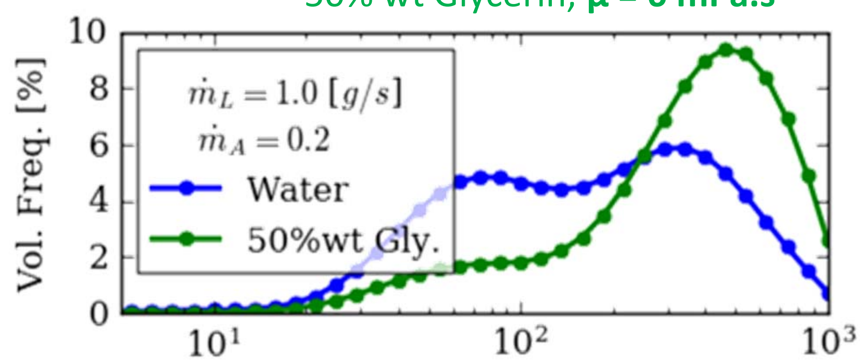


$\dot{m}_L$ = 0.7 g/s

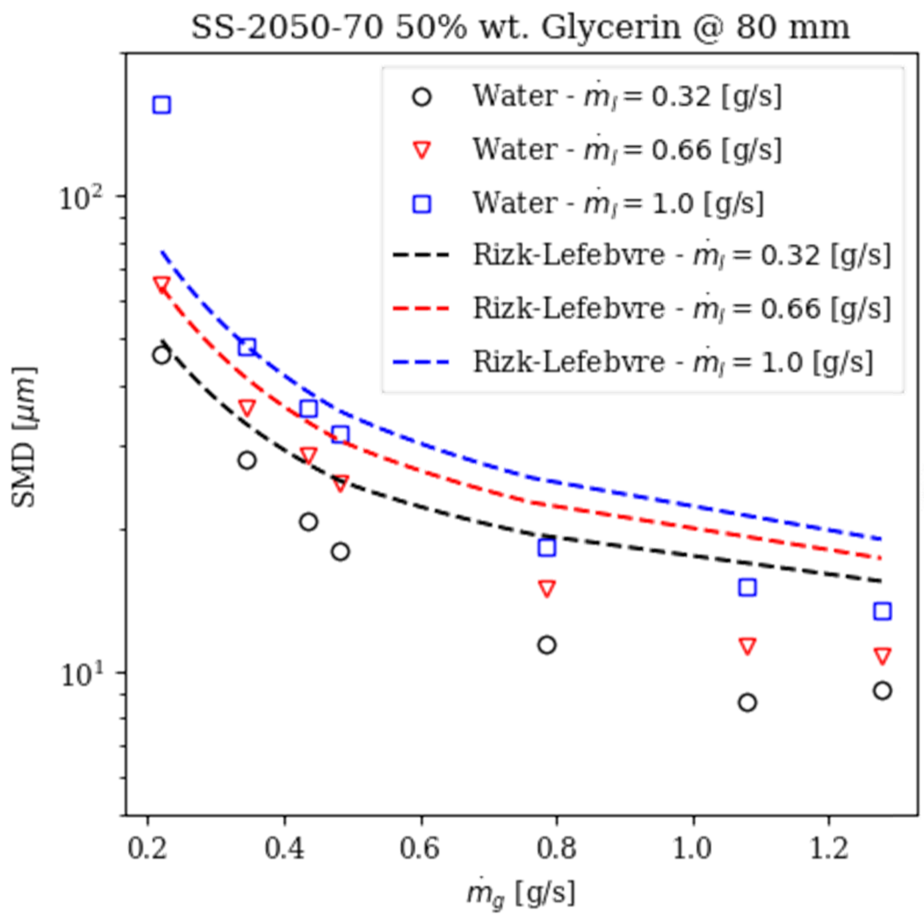


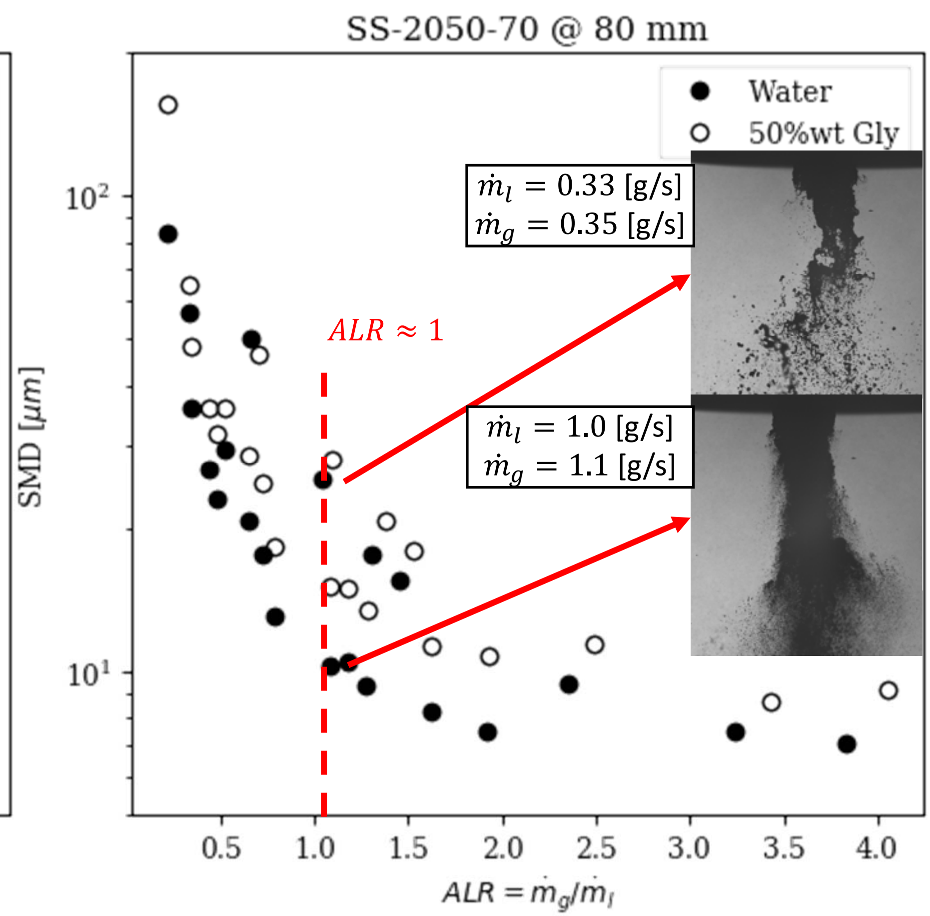
50% wt Glycerin, **μ = 6 mPa.s**





Comparison with Rizk-Lefebvre





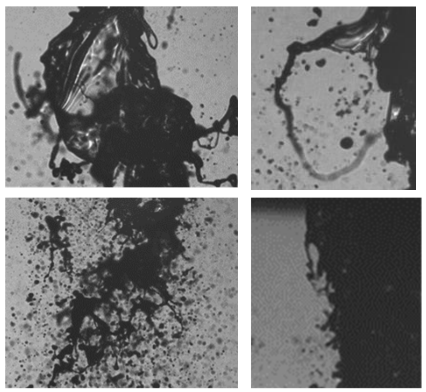
$$\frac{SMD}{D_l} = 0.48\left(\frac{\sigma}{\rho_a U_R^2 D_L}\right)^{0.4}\left(1+\frac{1}{ALR}\right)^{0.4} + 0.15\left(\frac{\mu_l^2}{\sigma \rho_l D_l}\right)^{0.5}\left(1+\frac{1}{ALR}\right)$$

Modelling the atomization physics

Breakup morphologies depend on flow conditions, liquid viscosity, atomizer scale, etc.

Membrane breakup

Shear breakup

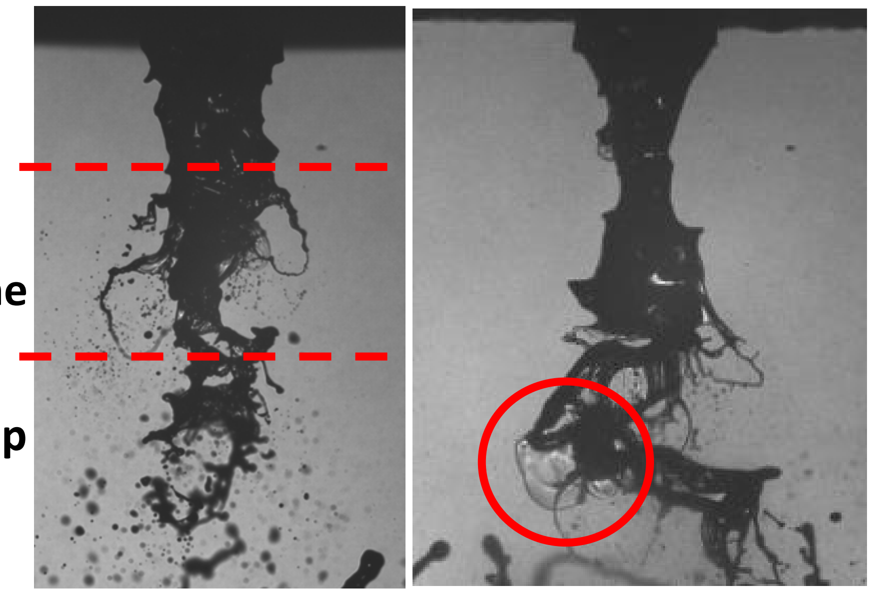


Spray morphology is **not global**

- Different types of **local breakup** can occur

Surface breakup zone

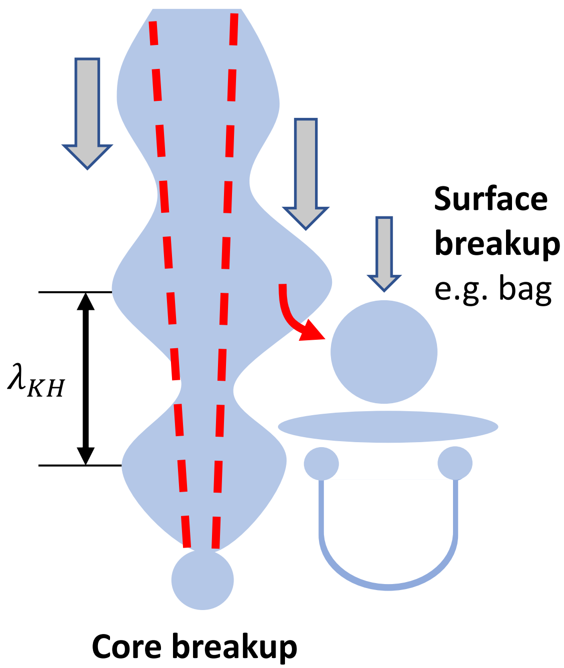
Core breakup zone



50% wt Glycerin,
μ = 6 mPa.s

Different local breakup morphologies result in distinct breakup sizes, leading to multi-modal PSD.

Droplet Breakup-Based Model



Surface breakup

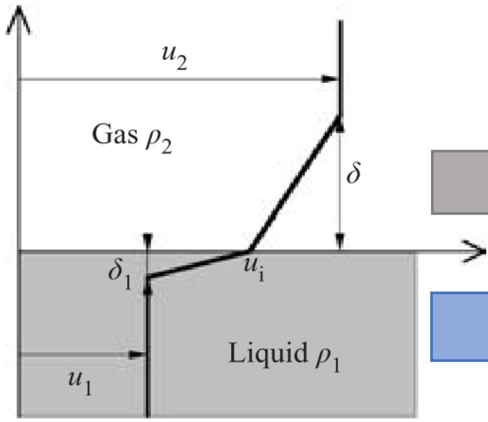
- Kelvin-Helmholtz (KH) waves form on the liquid
- Each wave forms an *'effective droplet'*
- The effective droplets breaks by a described model

Core breakup

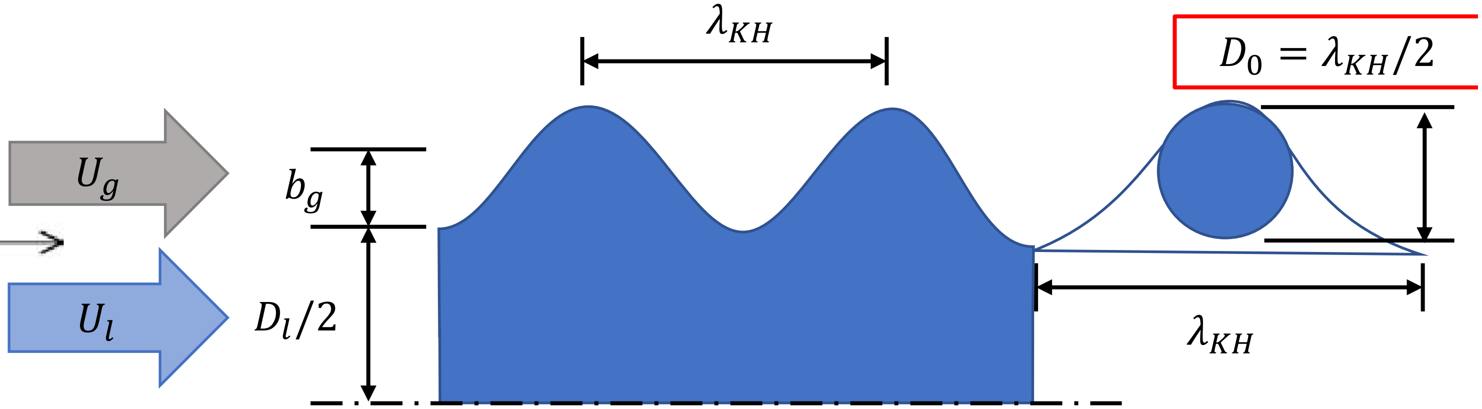
- The remainder of the liquid after surface breakup goes through Rayleigh-Plateau capillary pinching to generate core droplet sizes.

Kelvin-Helmholtz surface waves

Kelvin-Helmholtz surface waves (Finite vorticity thickness derivation)



Marmottant & Villermaux (2004)



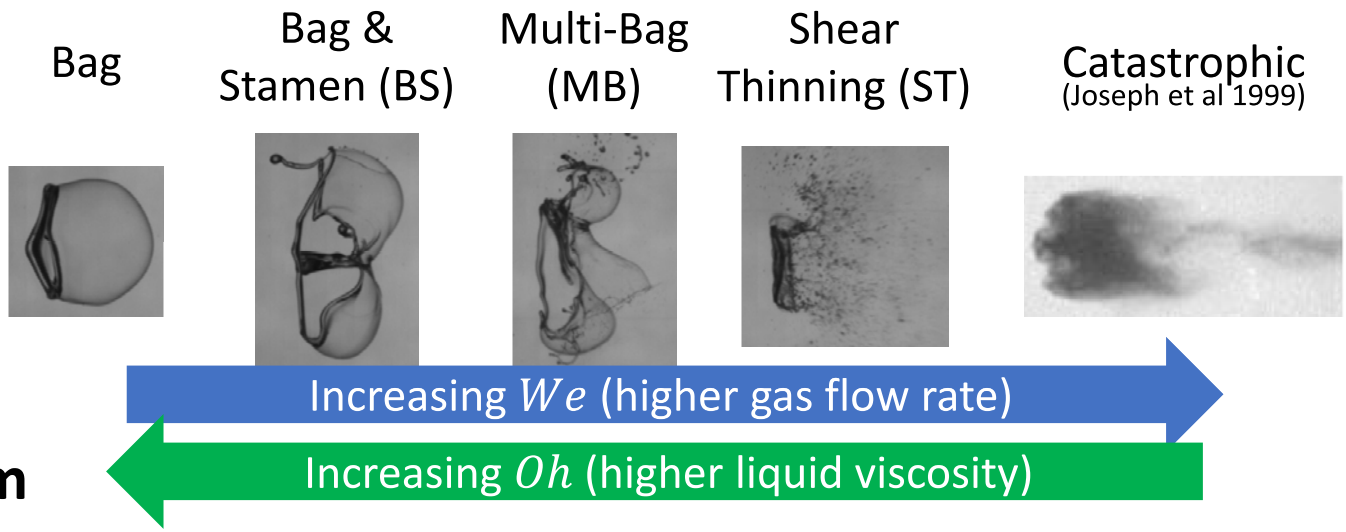
$$\lambda_{KH} = \frac{2Cb_g}{Re_{bg}^{0.5}}\left(\frac{\rho_l}{\rho_g}\right)^{0.5}, \qquad C \approx 1$$

C is a constant relating to the convergence of the nozzle

A portion of the wave is exposed to the airstream and deforms/breaks as an *'effective droplet'* as per our model described earlier

Droplet breakup Modes

Morphologies



Problem

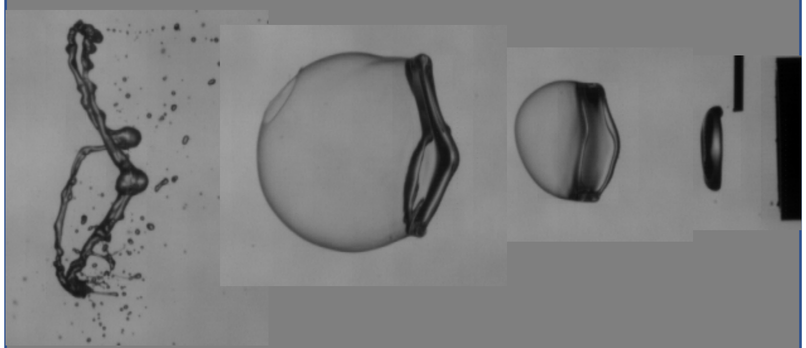
- Only ST and catastrophic breakup have been modelled well
- Highly viscous fluids tend to break by bag-type morphologies (Bag, BS, MB)
- Breakup of bag morphologies not modelled

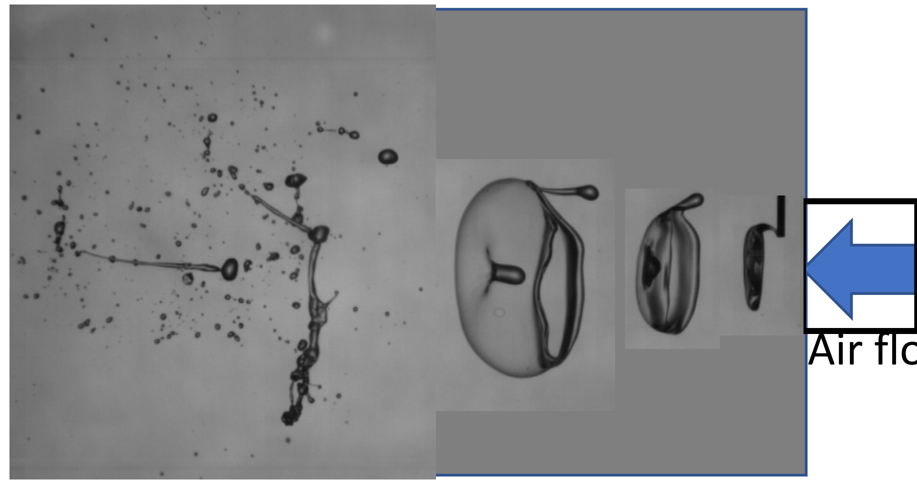
Weber number	$We = \frac{\rho_a U^2 D}{\sigma}$	Inertia of surrounding gas flow vs. surface tension
Ohnesorge number	$Oh = \frac{\mu_l}{\sqrt{\rho_l \sigma D}}$	Viscous vs. liquid inertia & surface tension

Bag Breakup Movies

Bag $We = 11$ Bag & Stamen (BS) $We = 16$

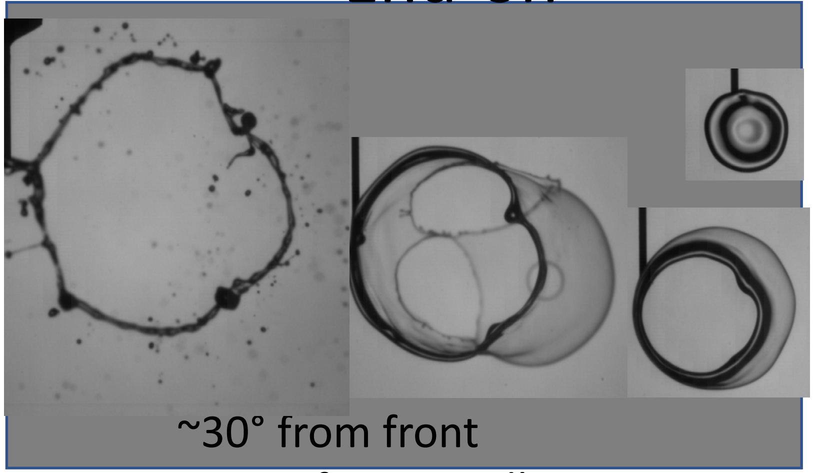
Side-view

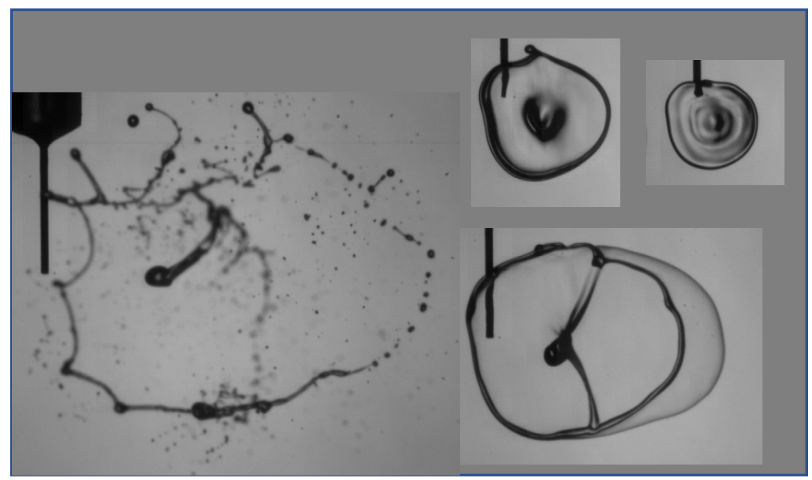




Air flow

End-on





~30° from front
10mm from needle tip

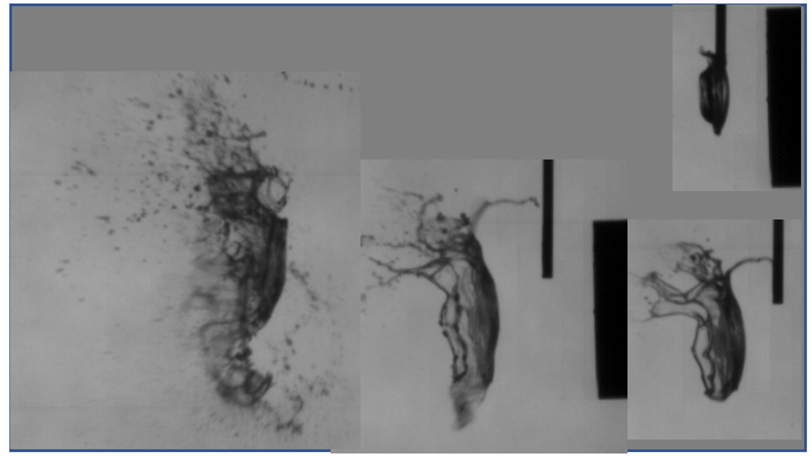
Droplet Breakup Movies

Multi-Bag (MB)

Shear-thinning (ST)

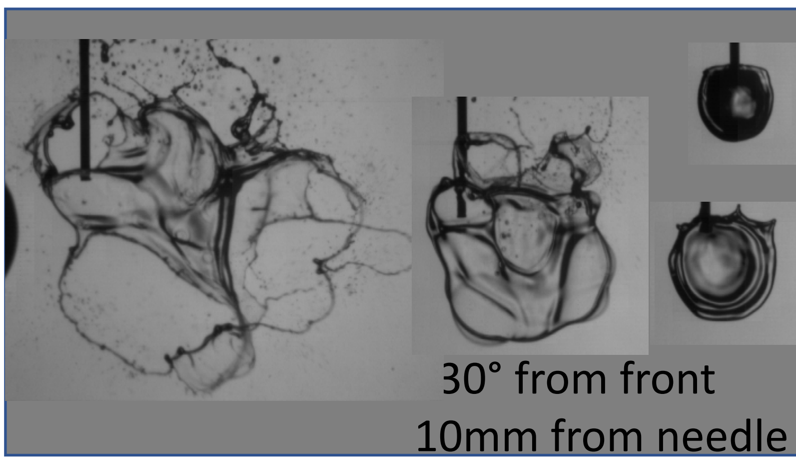
Side-view

$We = 40$

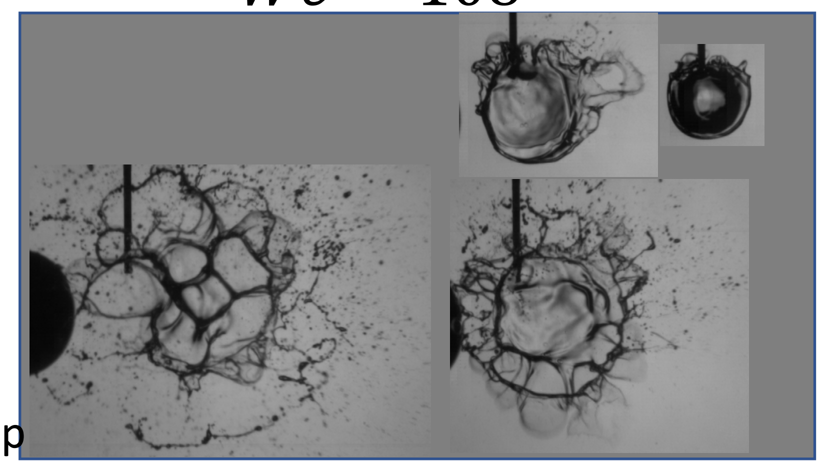


$We = 108$

End-on



30° from front
10mm from needle tip



Droplet Breakup-Based Atomization

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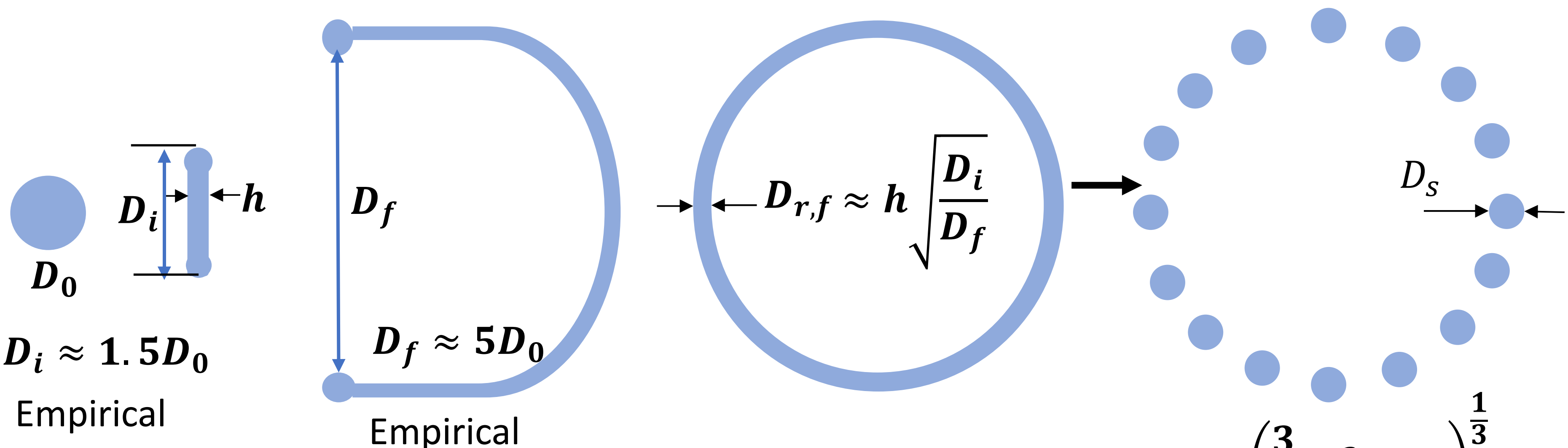
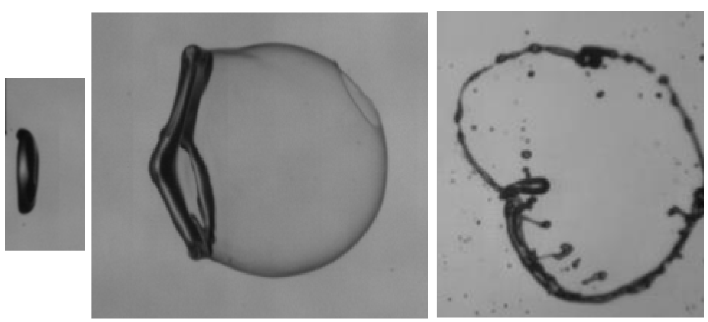




$$D_s = \left(\frac{3}{2}\,D_{r,f}^2\lambda_{RP}\right)^{\frac{1}{3}}$$

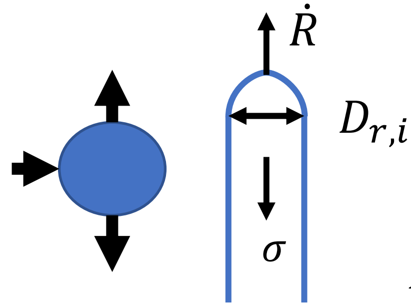
$$\lambda_{RP} = \frac{\pi}{0.69}D_{r,f}$$

Final Droplet Size:

$$D_s \sim h$$

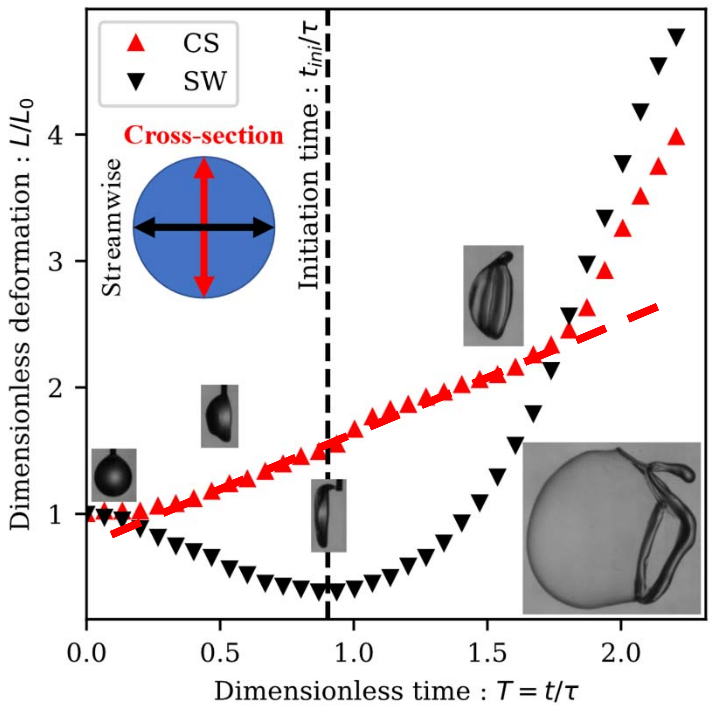
Droplet Deformation Rate

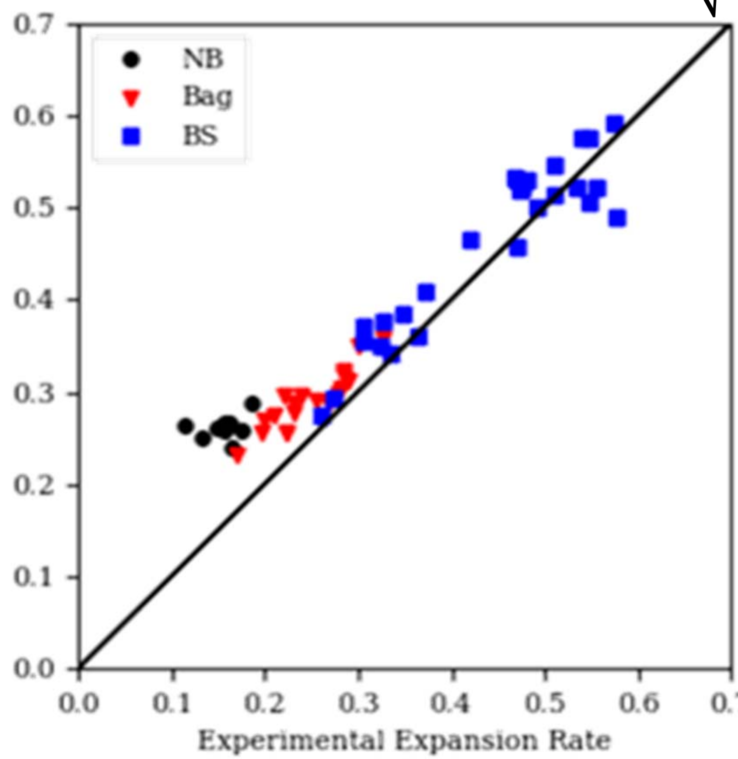
- Find $\boldsymbol{h}$ based on $\dot{R}$, the expansion rate of the droplet, which is found based on surface tension and inertia balance at the rim.



$$h = D_{r,i} \approx \frac{\sigma}{\rho_l \dot{R}^2}$$

$$\dot{R} = \frac{9}{8} U \sqrt{\frac{\rho_g}{\rho_l}} \left(1 - \frac{24}{9We}\right)$$





A model for the Spray Droplet Size

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- Two modes of breakup; Surface and core
  - Surface breakup by Kelvin-Helmholtz results in droplets of D_s.
  - Core jet thinned by mass loss from surface breakup, breaks by capillary pinch-off mechanism to result in droplets of D_c.

$$\mathrm{SMD} = \frac{\sum nD^3}{\sum nD^2} = \frac{fD_s^3 + D_c^3}{fD_s^2 + D_c^2}, \qquad f = n_s/n_c$$

- Our model will predict relative frequencies, f, as well as D_s and D_c to give SMD (or PSD).

$$f = C\, ALR\, We_{bg}^{n}\, Re_{bg}^{m}$$

$$ALR = \dot{m}_g/\dot{m}_l$$

$$C = 0.158, \qquad n = 1.3, \qquad m = 0.87$$

(empirically from a small set of our data)

Large f → High probability of **small** droplets
Small f → High probability of **large** droplets

SMD Prediction

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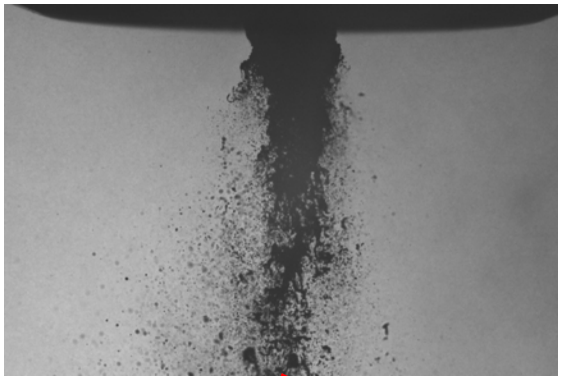
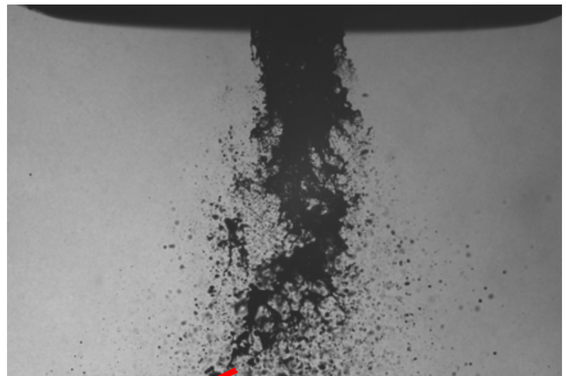
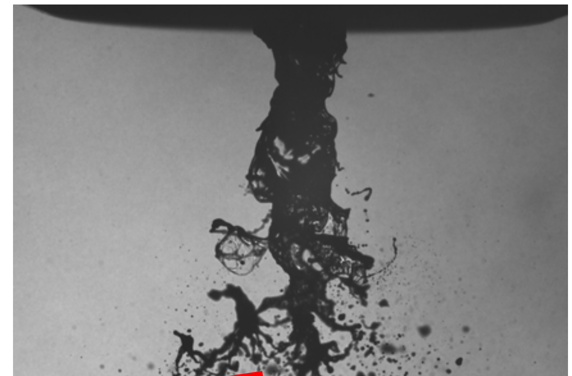
U_L = 3.3 m/s, **U_G = 216 m/s**

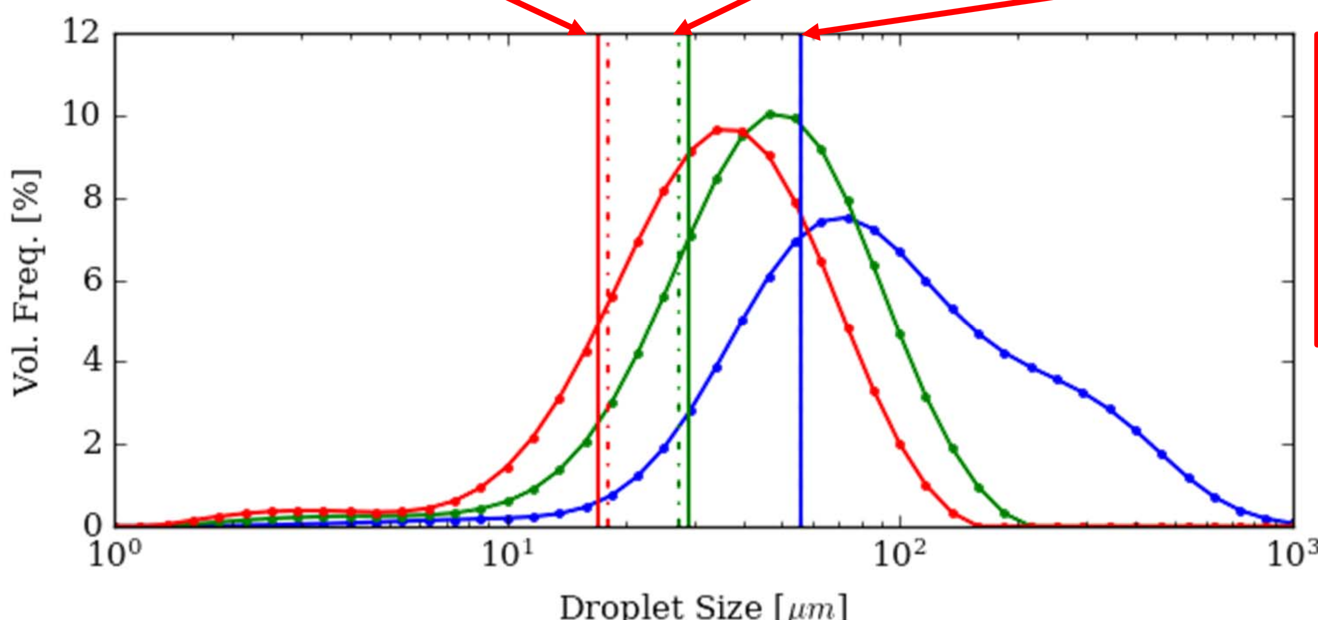


U_L = 3.3 m/s, **U_G = 168 m/s**



U_L = 3.3 m/s, **U_G = 109 m/s**





Measured SMD (Solid)
56 µm, 29 µm, 17 µm

Predicted SMD (Dashed)
56 µm, 28 µm, 18 µm

Summary

- A compressive data base for the spray characterization of pressure swirl and twin fluid nozzles for a wide range of viscosities and at high pressures is being developed.
  - Local size distribution and SMD are being measured for all sprays.
- The near nozzle images of the atomization process in pressure swirl nozzles have revealed two different size scales at high pressures.
  - The atomization process is dominated by: formation of waves on the swirling liquid sheet; accumulation of liquid on the wave crests and troughs and thin sheet in between them; breakup of the thick liquid in crests and troughs forming relatively large droplets (the 1st scale); and perforation of the sheet and formation of relatively small droplets (the 2nd scale).
- A sheet preformation-based model is developed for the atomization of pressure swirl nozzles.
- The near nozzle images of the atomization process in twin fluid nozzles have revealed multiple breakup modes.
- A droplet breakup-based model is proposed for the atomization process in twin-fluid nozzles.

END

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