Injector Dynamics and Atomization Behaviors of Liquid Monopropellants in Pintle Injectors

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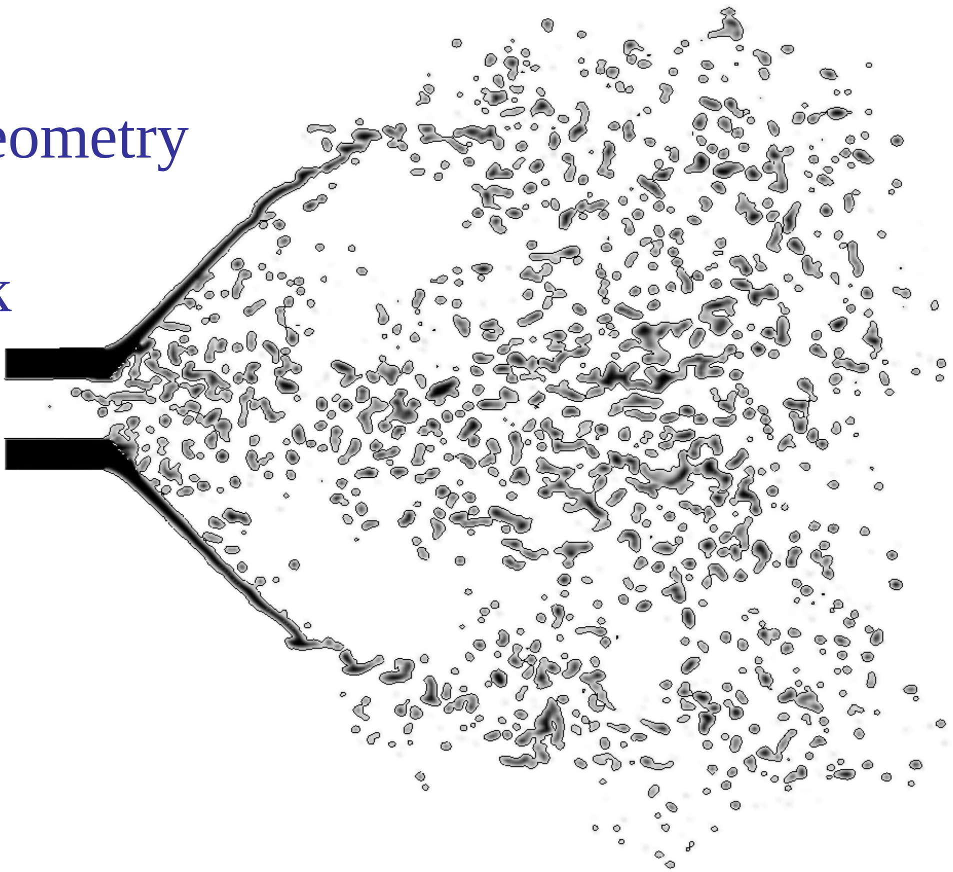
Acknowledgements: CEAS, University of Cincinnati

Outline

- Background
- Current Research and Objectives
- Theoretical formulation
- Model Validation
- Operating conditions and Geometry
- Analysis
- Conclusions and future work



Background/Motivation

Google images

Mark 48 Torpedo

Lunar Excursion Module

SpaceX Merlin Rocket Engine

Garden Hose, Monopropellant pintle injector

SpaceX raptor engine bipropellant pintle injector cold flow test

Current Status and Objectives

Current Status and unresolved research issues:

- Limited research exists on the fundamental mechanisms underlying the monopropellant pintle injector dynamics and atomization behaviors

- Most research is dedicated to bipropellant engines.

Objectives:

- Identify the fundamental mechanisms underlying the injector dynamics and atomization behaviors of liquid monopropellants in pintle injectors

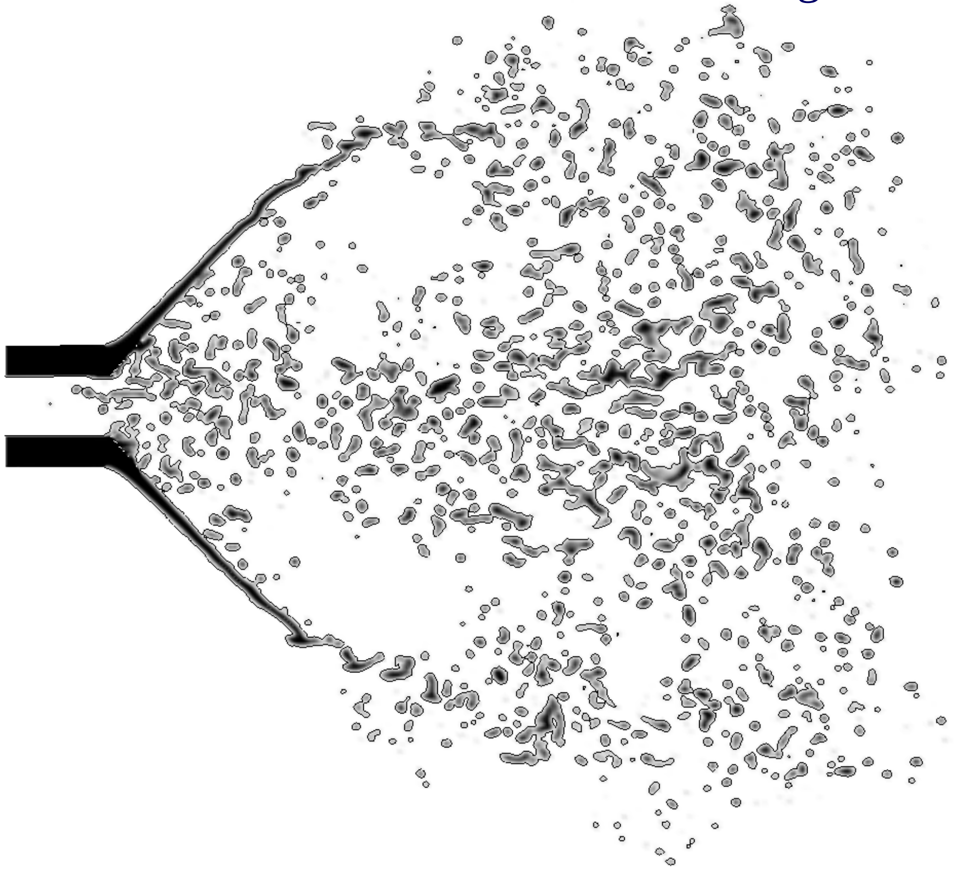
- Quantitatively investigate the droplet size distributions and their temporal and spatial evolution

- Conduct parametric studies to investigate these behaviors at a wide range of Weber numbers and operating pressures

Multiphase & Multiscale Challenges

multiphase
- Discontinuity of material properties at the interface
- Surface tension singularity force active only at the interface
- Frequent topology changes

multiscale
- Time and length scales vary over several orders of magnitude



Weber number, *We*	$\frac{\rho_g U^2 D}{\sigma}$
Reynolds number, *Re*	$\frac{\rho_g U D}{\mu_g}$
Density ratio	$\frac{\rho_l}{\rho_g}$
Viscosity ratio	$\frac{\mu_l}{\mu_g}$

Governing Equations: Volume-of-Fluid Method (VOF)

- **Incompressible, variable-density, Navier-Stokes equations:**

$$\rho(\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u}) = -\nabla p + \nabla \cdot (2\mu \boldsymbol{D}) + \sigma \kappa \delta_s \boldsymbol{n}$$

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

$$\nabla \cdot \boldsymbol{u} = 0$$

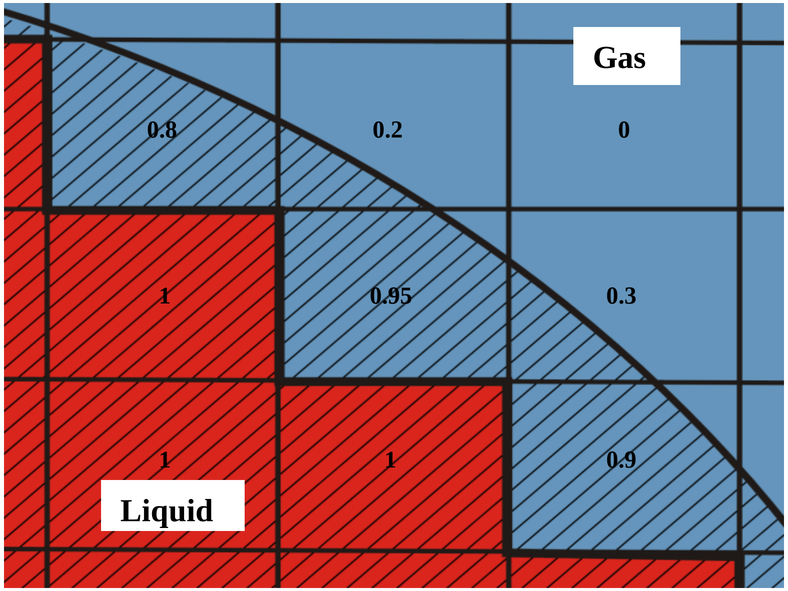
- **Volume fraction, two-phase fluid density and viscosity:**

$$\rho(c) \equiv c\rho_1 + (1-c)\rho_2$$

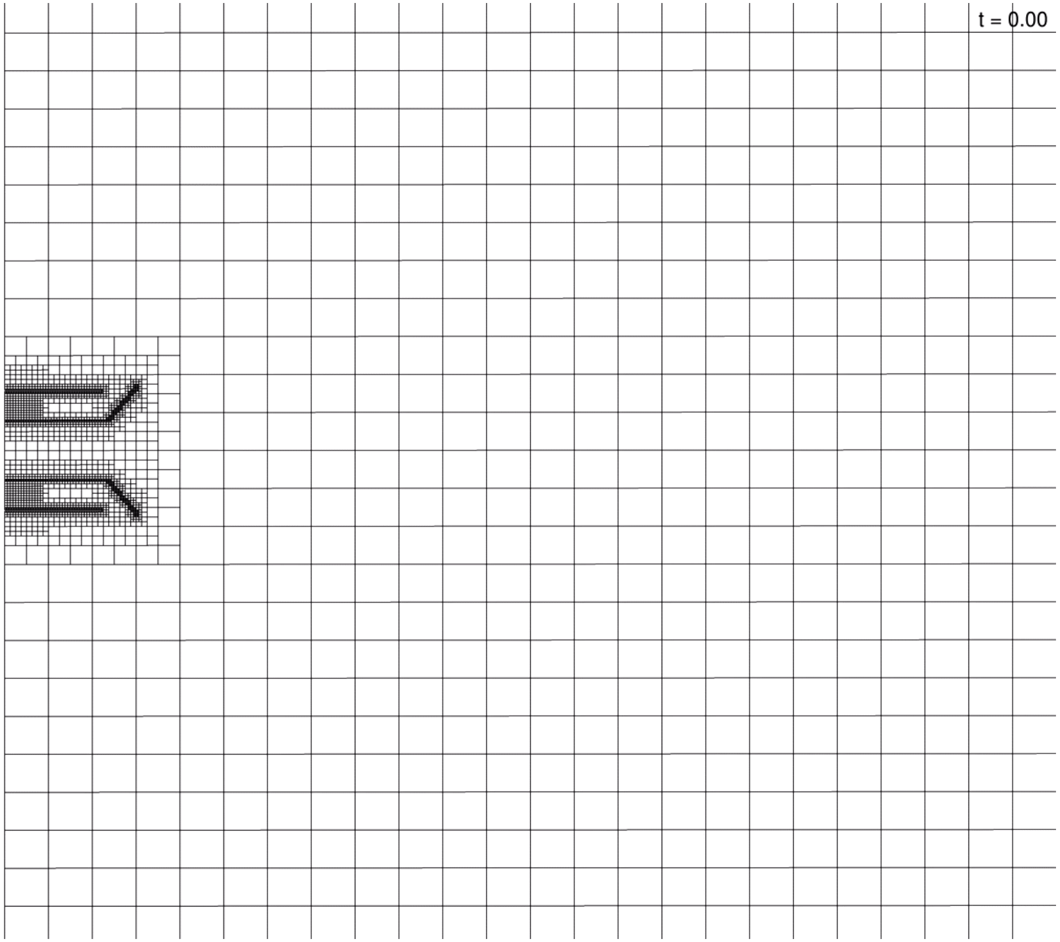
$$\mu(c) \equiv c\mu_1 + (1-c)\mu_2$$

- **Advection for volume fraction:**

$$\partial_t c + \nabla \cdot (c\boldsymbol{u}) = 0$$



Adaptive Mesh Refinement (AMR)



Adaptive Mesh Refinement (AMR)

- Gradient and value based refinement
- Cells without AMR 5.49×10^{12}
- Cells with AMR = 28.623 million
- Total reduction = 99.47%
- Min. cell size = 0.305µm

Validation Of The Model

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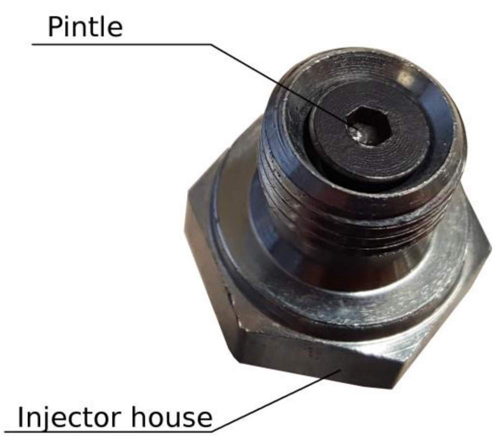
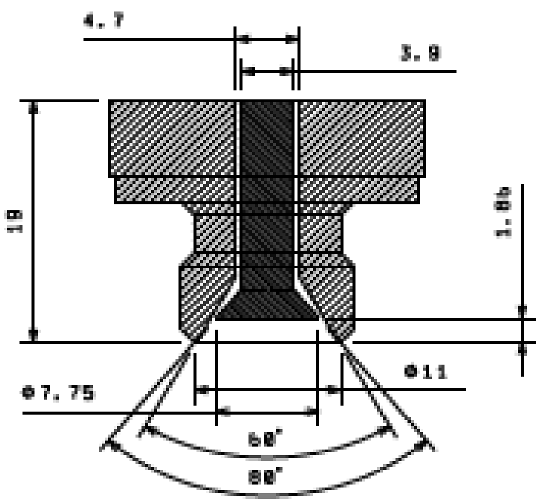
- Model validation will be based upon the work of Vlad Petrescu
- The model validation will be three faceted comparing
  - Spray Angle
  - Sauter mean diameter
  - Physical inspection

Physical Properties	Water (1.6psi)	Chamber gas (air atmospheric)
Density, ρ (kg/m^3)	1000	1.28
Viscosity, μ (Pa·s)	9.532×10^{-4}	1.822×10^{-5}
Surface Tension, σ N/m)	0.07275	

Experimental geometry





Model geometry

Qualitative comparison with experimental measurements

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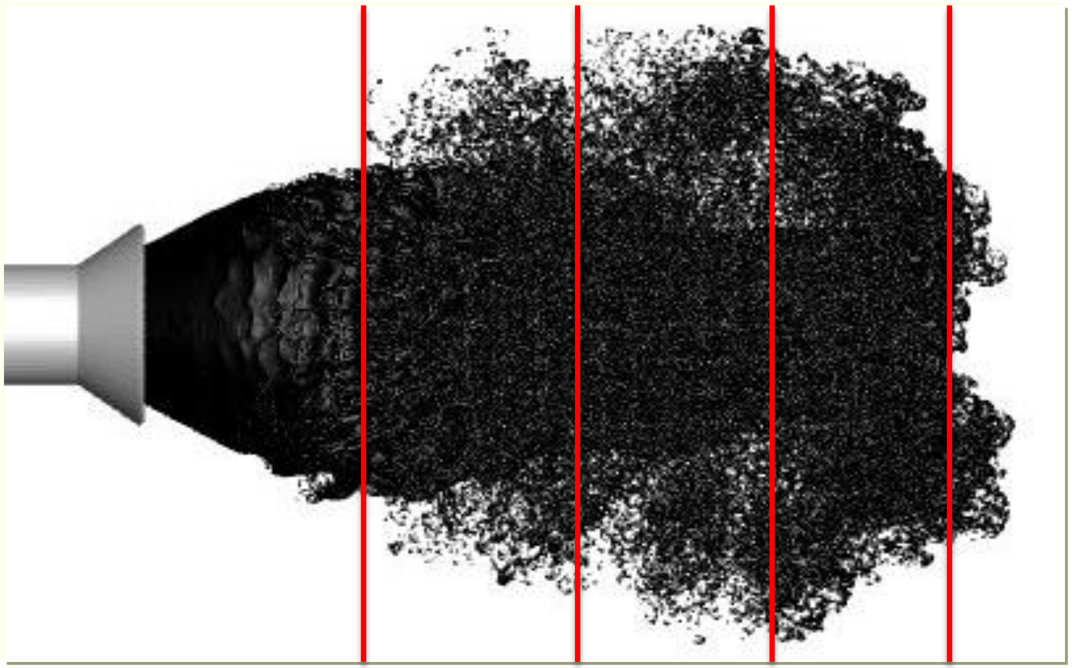
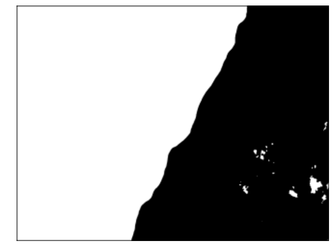
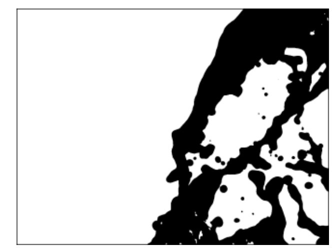


20mm 40mm 55mm 70mm

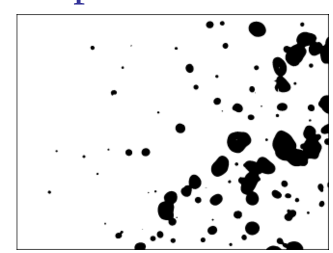
Liquid sheet



Ligaments



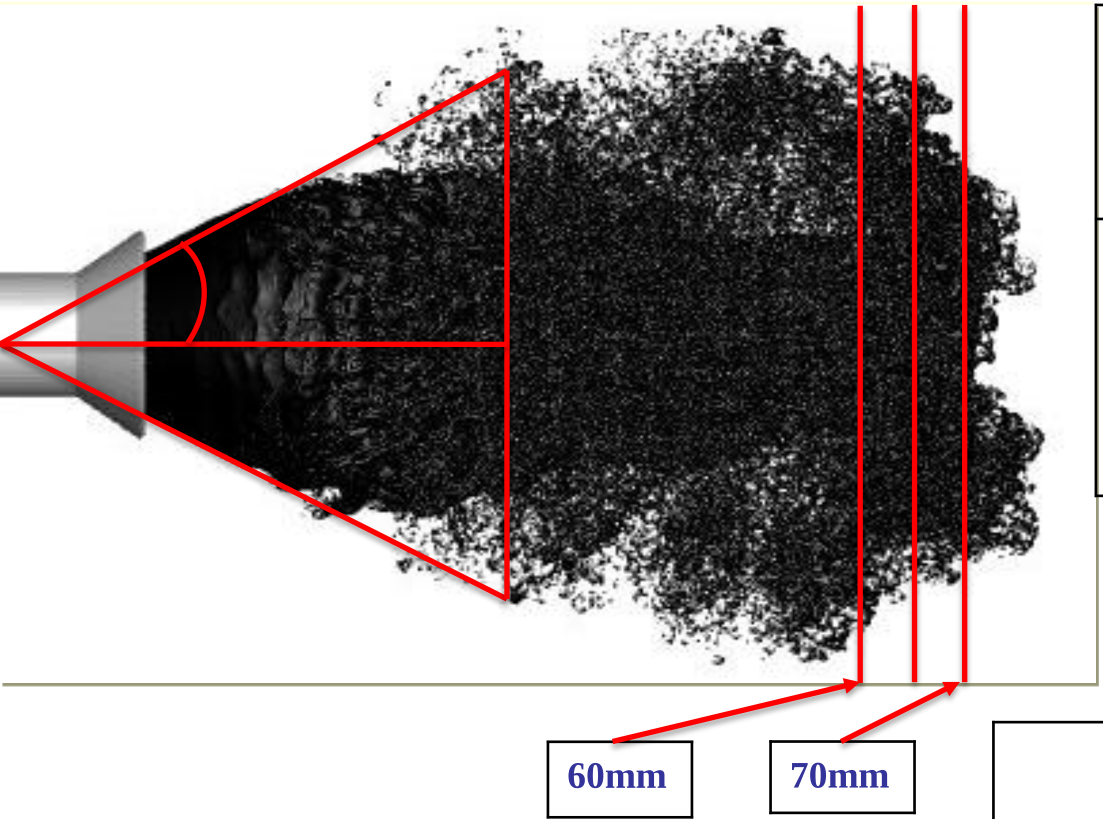
Droplet formation



From the Experiment

	Height			
Pressure (p_2)	10 - 25 mm	40 mm	55 mm	70 - 160 mm
1.6 bar	liquid sheet	liquid sheet	*ligaments*	**droplets**

Validation: SMD and spray angle comparison with experiment



Location from injector	SMD from experiment (µm)	SMD from present calculations (µm)	% error
60 mm	1291.32	1273.74	1.36%
65 mm	1194.56	1242.79	-4.04%
70 mm	1104.14	1101.92	0.20%

	Experimental	Present Calculations	% error
Spray angle	31.0	29.7	4.2%

Atomized spray properties in pintle injection , Petrescu, Schrijer and Zandbergen

Physical Properties and Geometry

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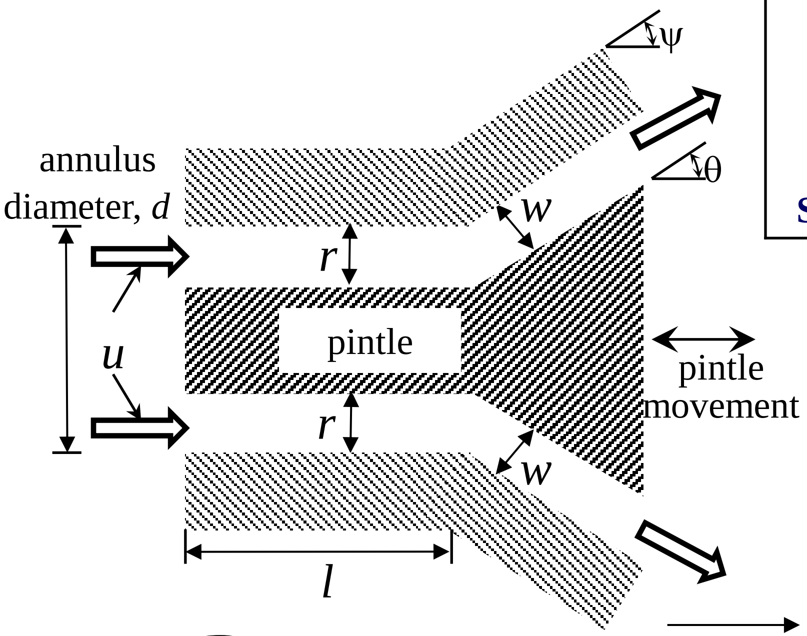
	Otto Fuel II	Chamber gas
Density, ρ (kg/m^3)	1232	123.2
Viscosity, μ (Pa·s)	0.44	2.0764 x 10^{-7}
Surface Tension, σ N/m)	0.03445	



ρ_g

μ_g

constant
inflow

ρ_l

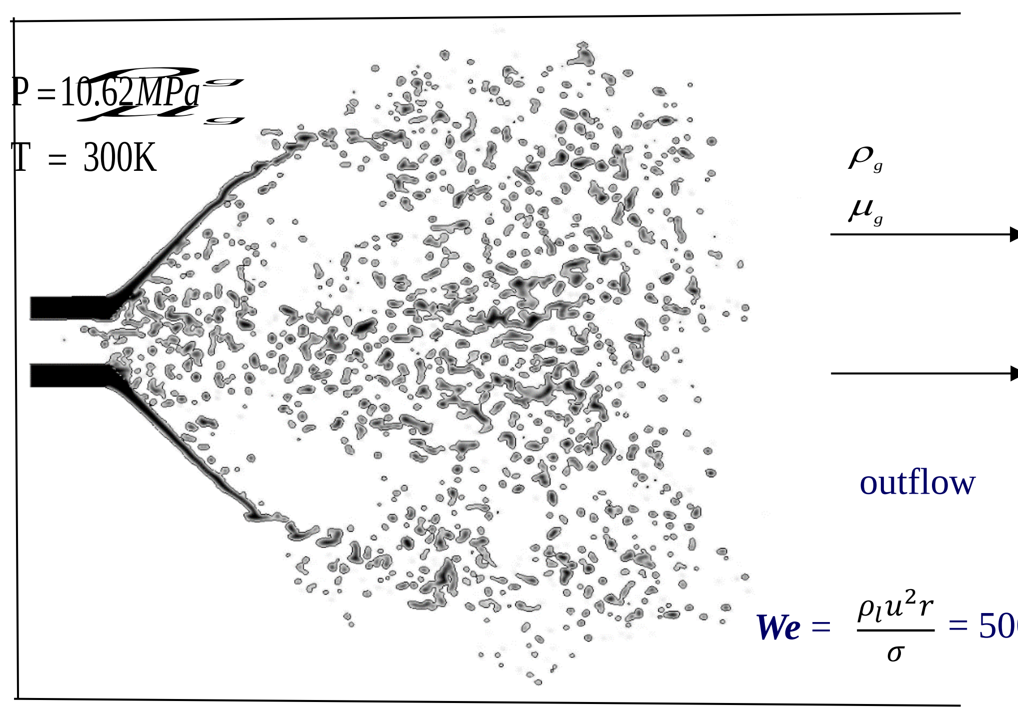
μ_l

σ

$u = 3.34\text{m/s}$

$d = 5\text{mm}$

no-slip boundary condition



$$We = \frac{\rho_l u^2 r}{\sigma} = 500$$

Pintle Injector Atomization at We=20

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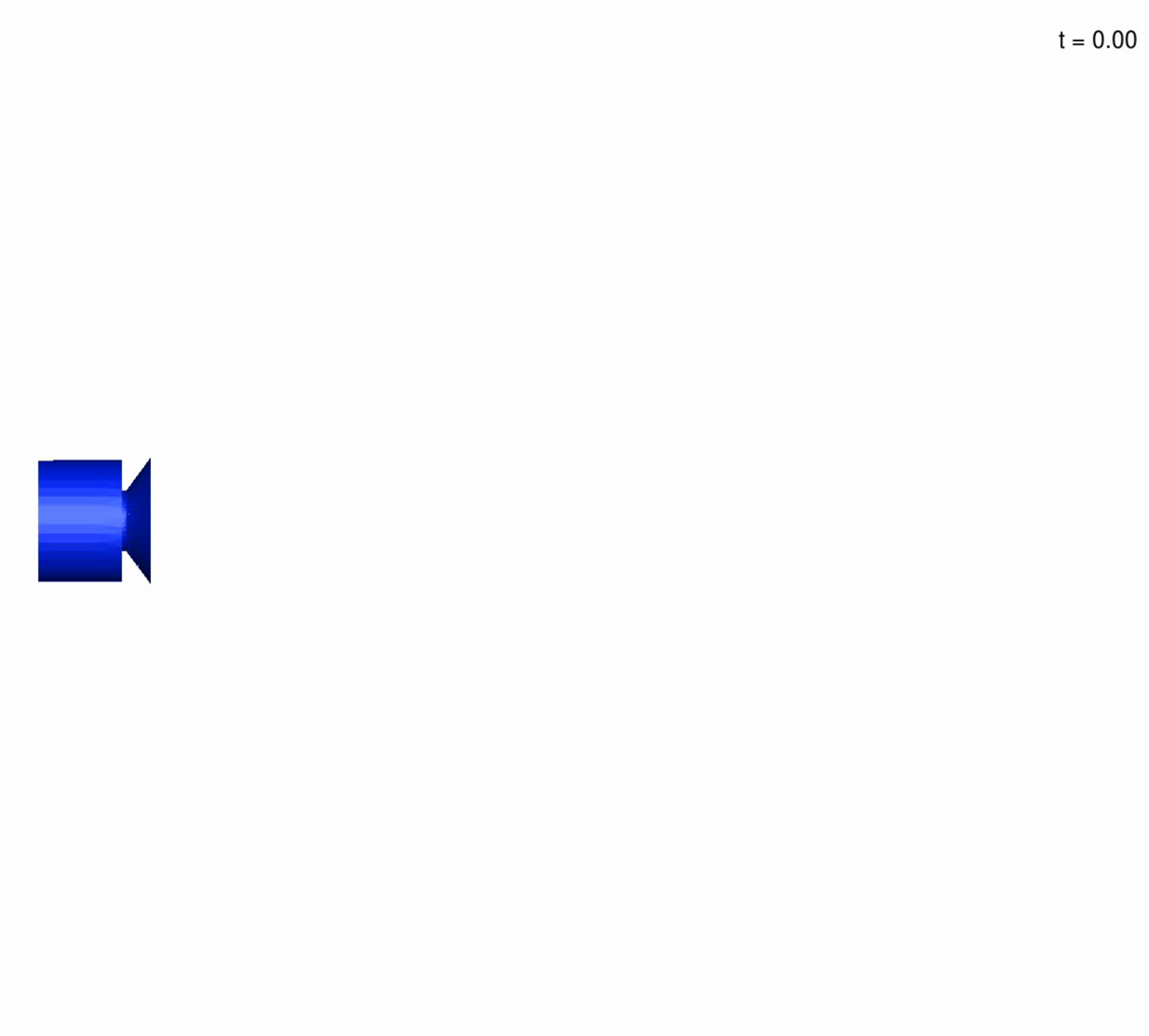
3-D VOF



Pintle Injector Atomization at We=20

Detailed Physics: Ligament Formation 3-D

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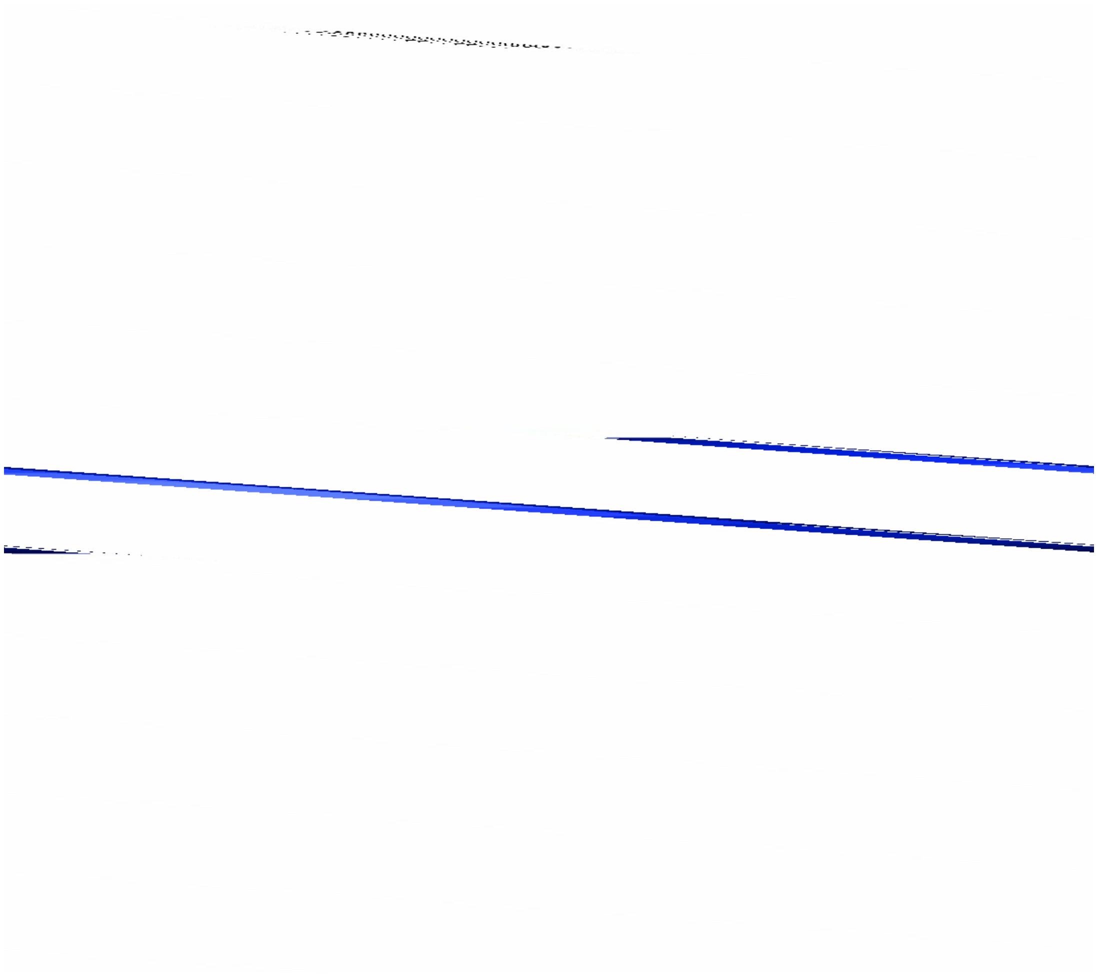
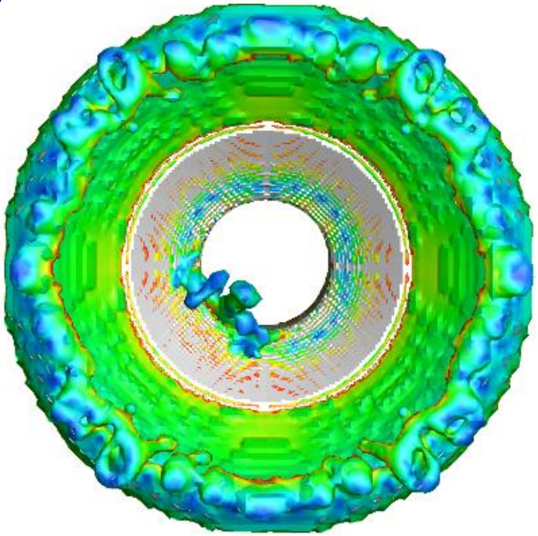
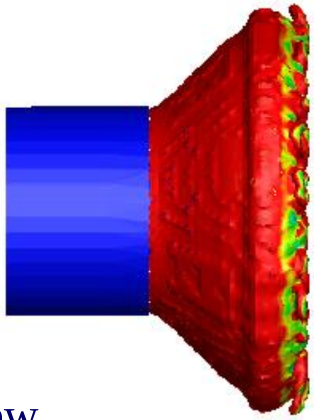
Side View



Axial view





Side View

non-dimensionalized time, t = t*/(d/Uj) = 0.0 - 0.11

Detailed Physics: Ligament Formation 2-D

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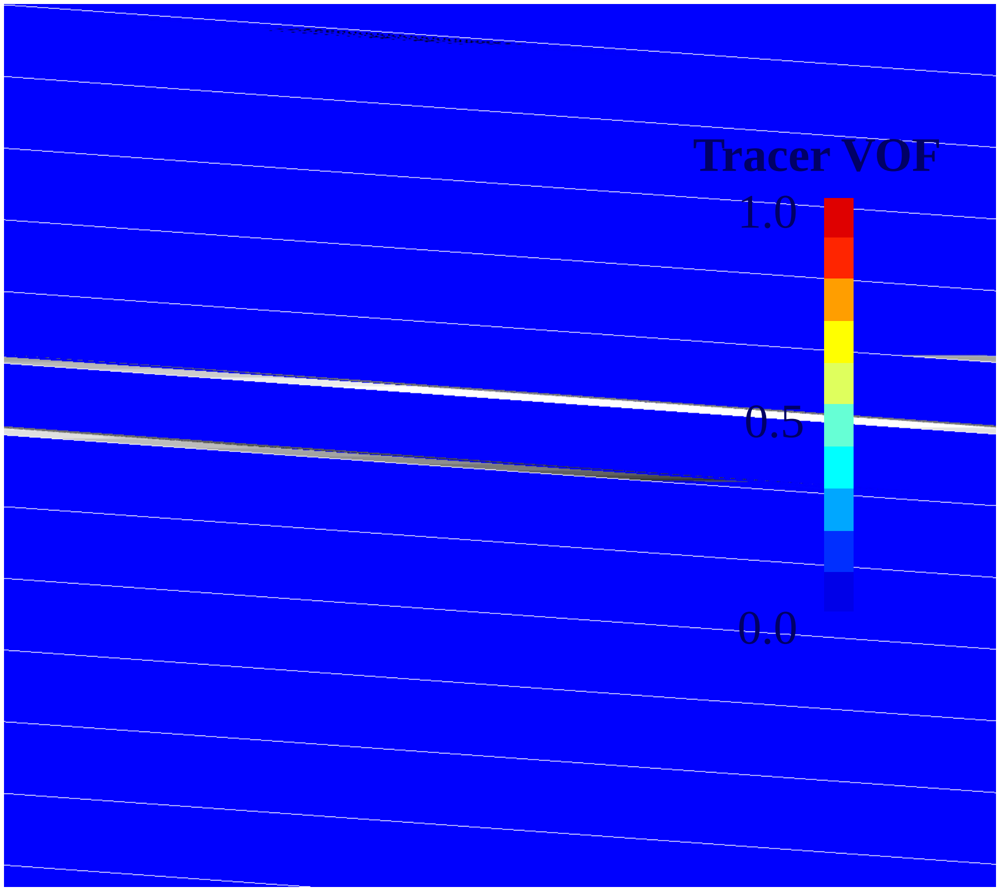
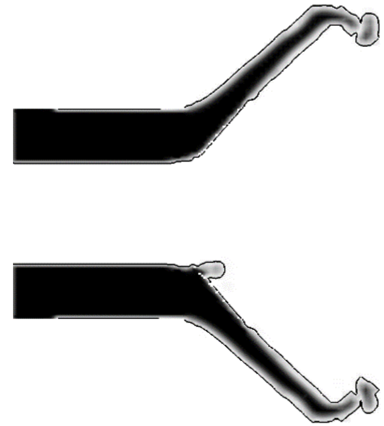
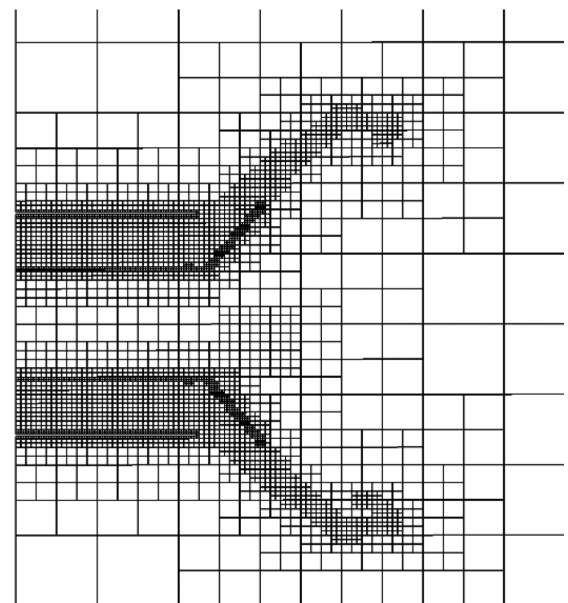
2-D center plane slice

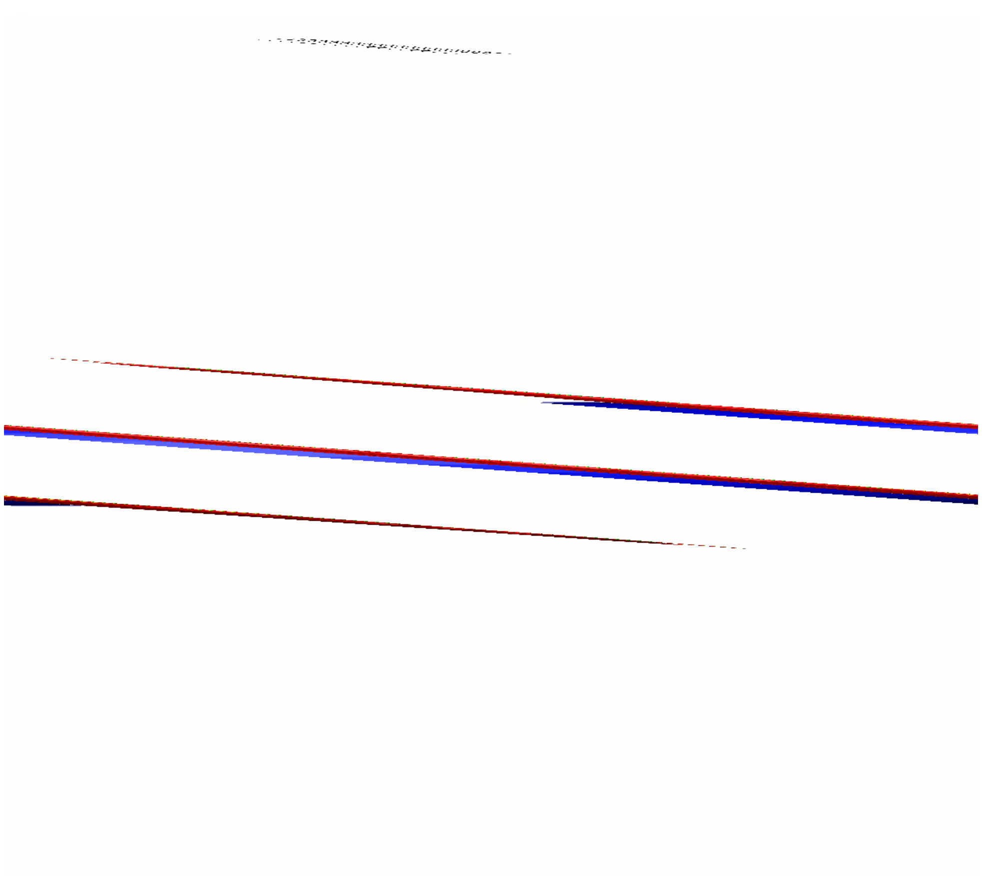




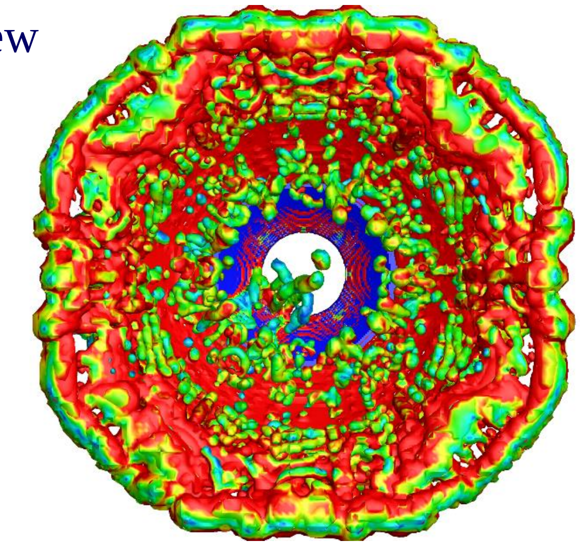


non-dimensionalized time, t = t*/(d/Uj) = 0.0 - 0.11

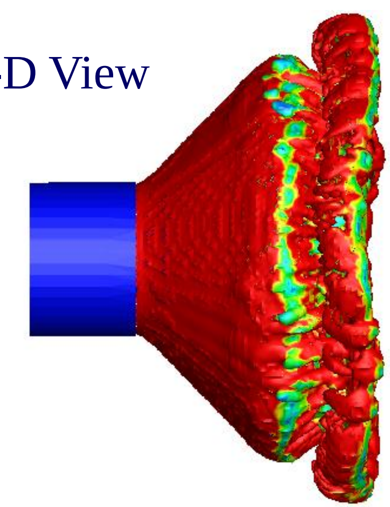
Detailed Physics: First break-up 3-D



Axial view



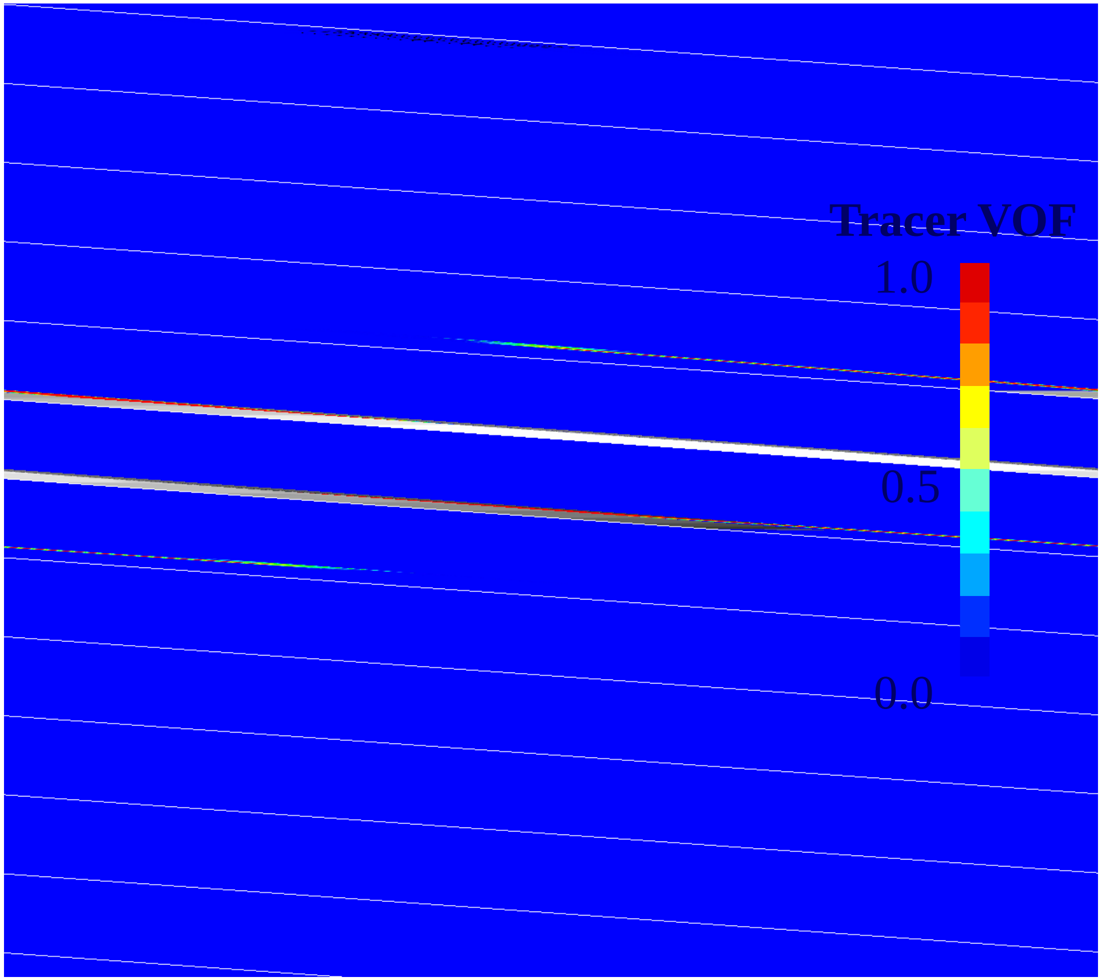
3-D View

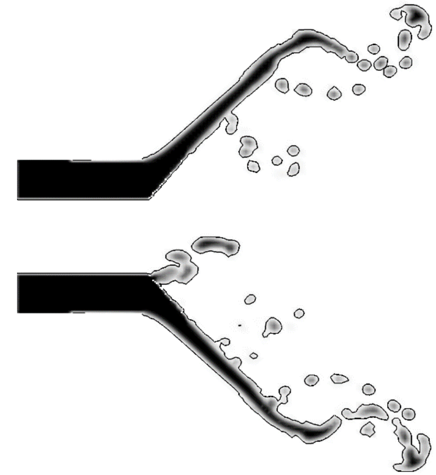


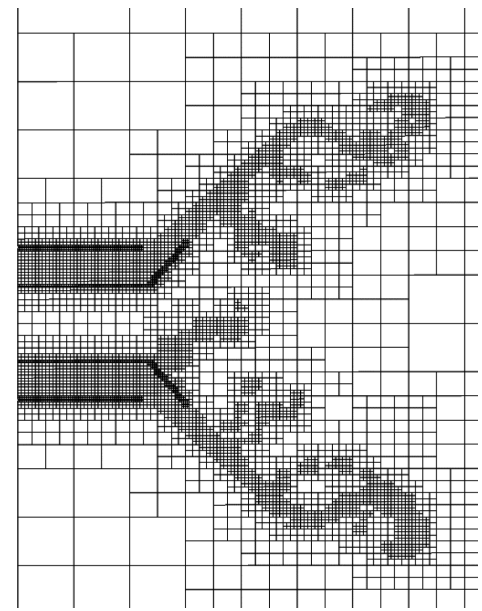
non-dimensionalized time, t = t*/(d/Uj) = 0.11- 0.21

Detailed Physics: First break-up 2-D

2-D center plane slice







non-dimensionalized time, t = t*/(d/Uj) = 0.11- 0.21

Detailed Physics: Sheet Sheering and Break-up

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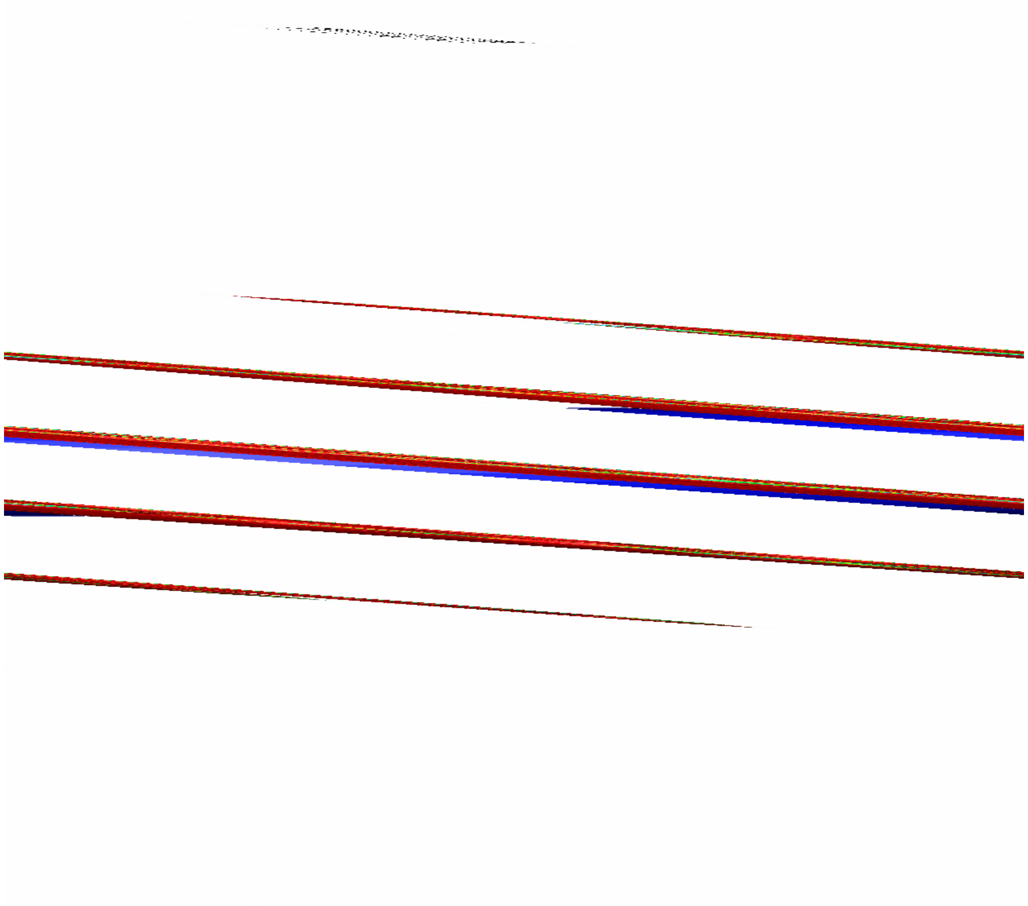
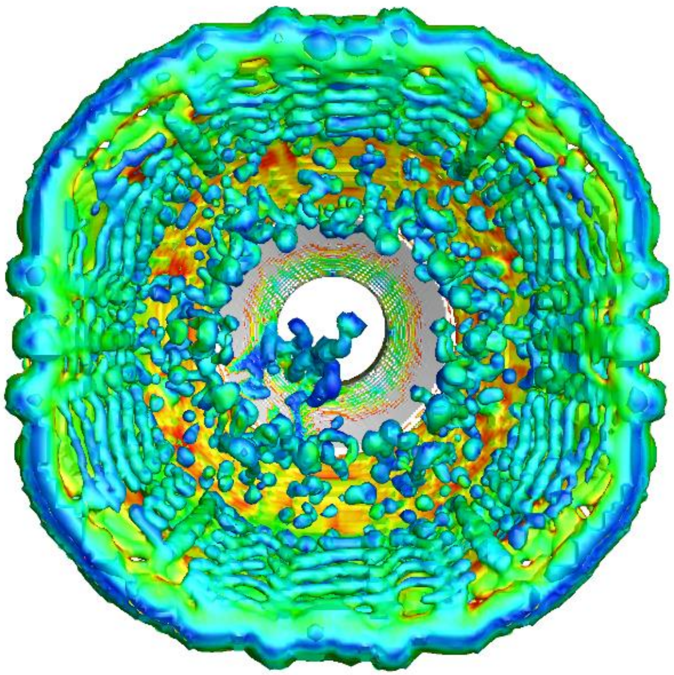
3-D VOF - Outside



non-dimensionalized time
$t = t^*/(d/U_j) = 0.22 - 0.90$

3-D VOF -Inside



non-dimensionalized time
$t = t^*/(d/U_j) = 0.19$

Detailed Physics: Appearance of Kelvin-Helmholtz Instabilities

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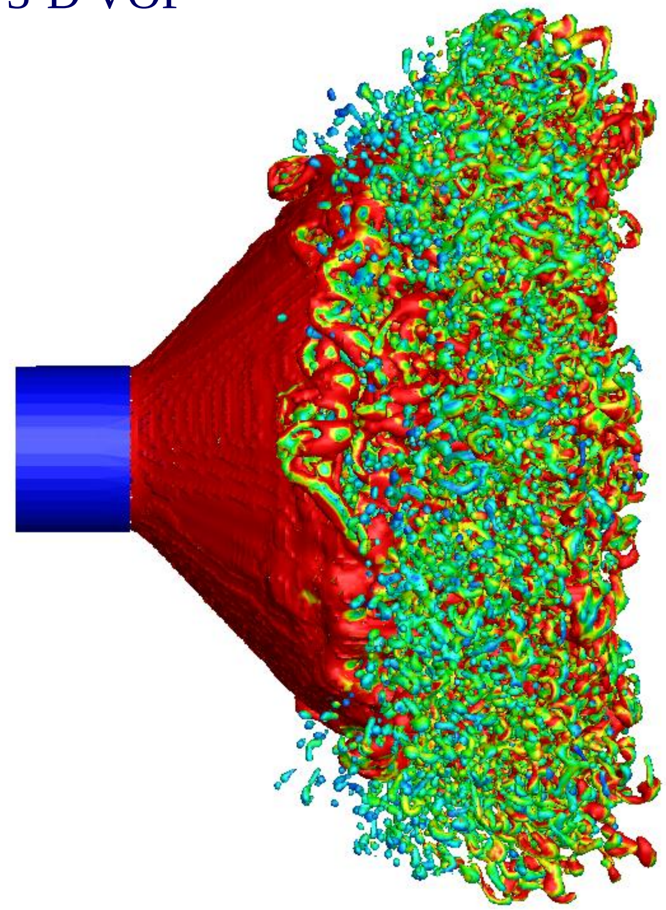
2-D Center Plane Slice

3-D VOF



non-dimensionalized time, t = t*/(d/Uj) = 0.50 - 1.00

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Detailed Physics: Droplet Recirculation Vortex Formation

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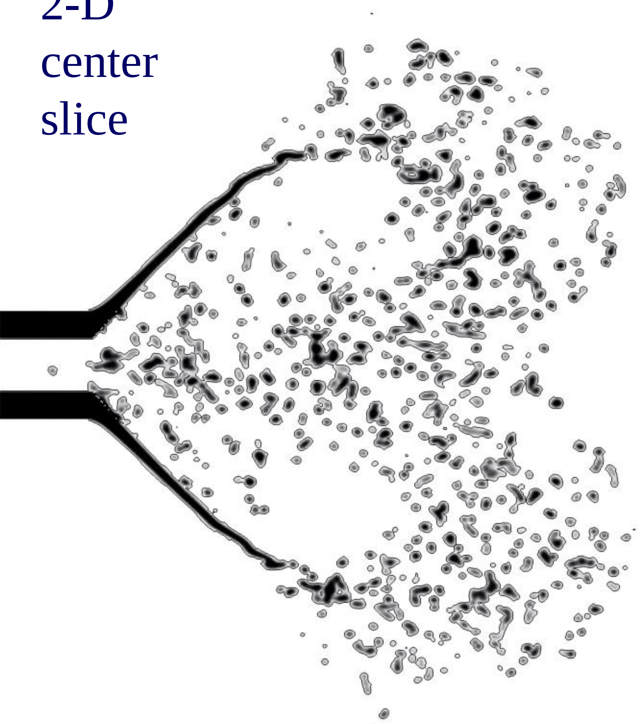
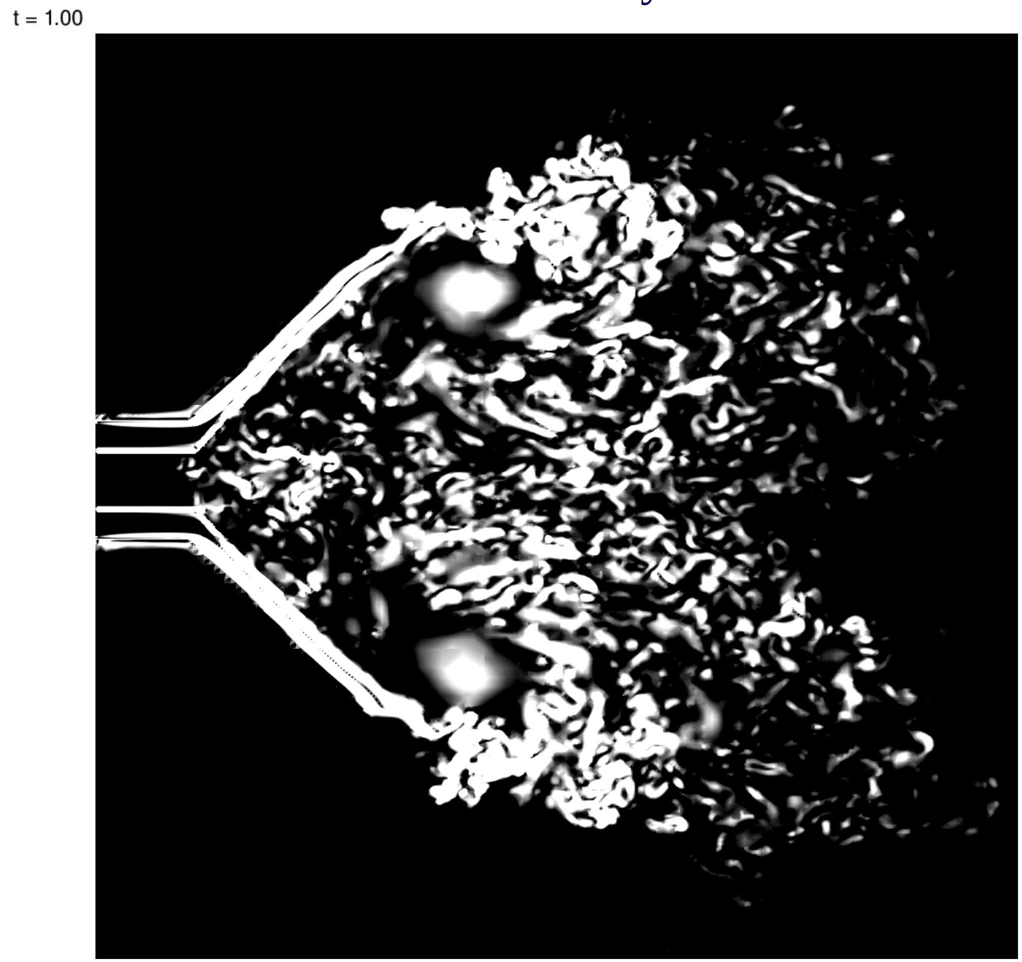
2-D Vorticity slice

2-D center slice

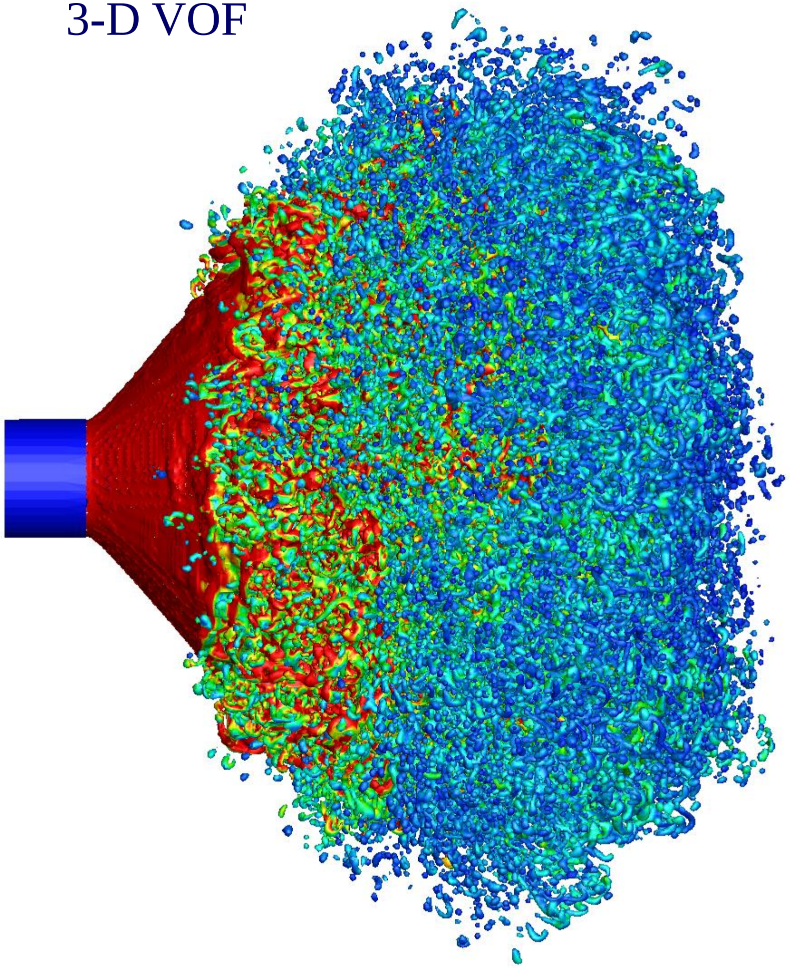




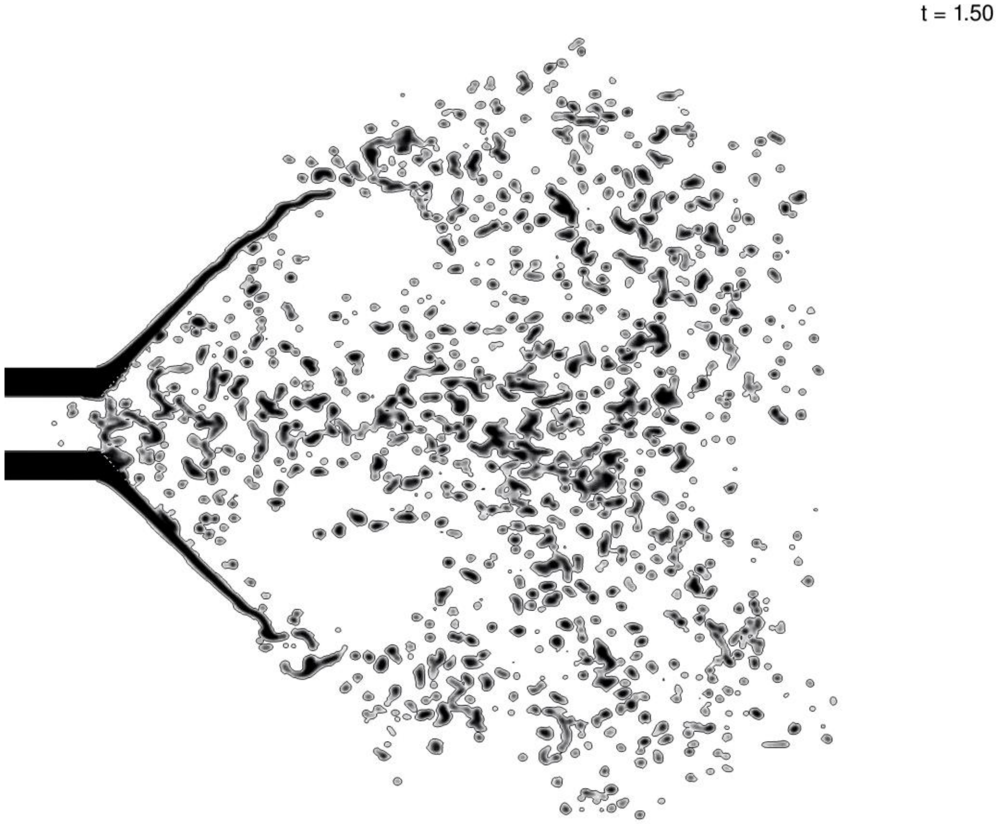
non-dimensionalized time t = t*/(d/Uj) = 1.24 – 1.40

Detailed Physics: Clumping and Droplet Coalescence Hinders Atomization

3-D VOF

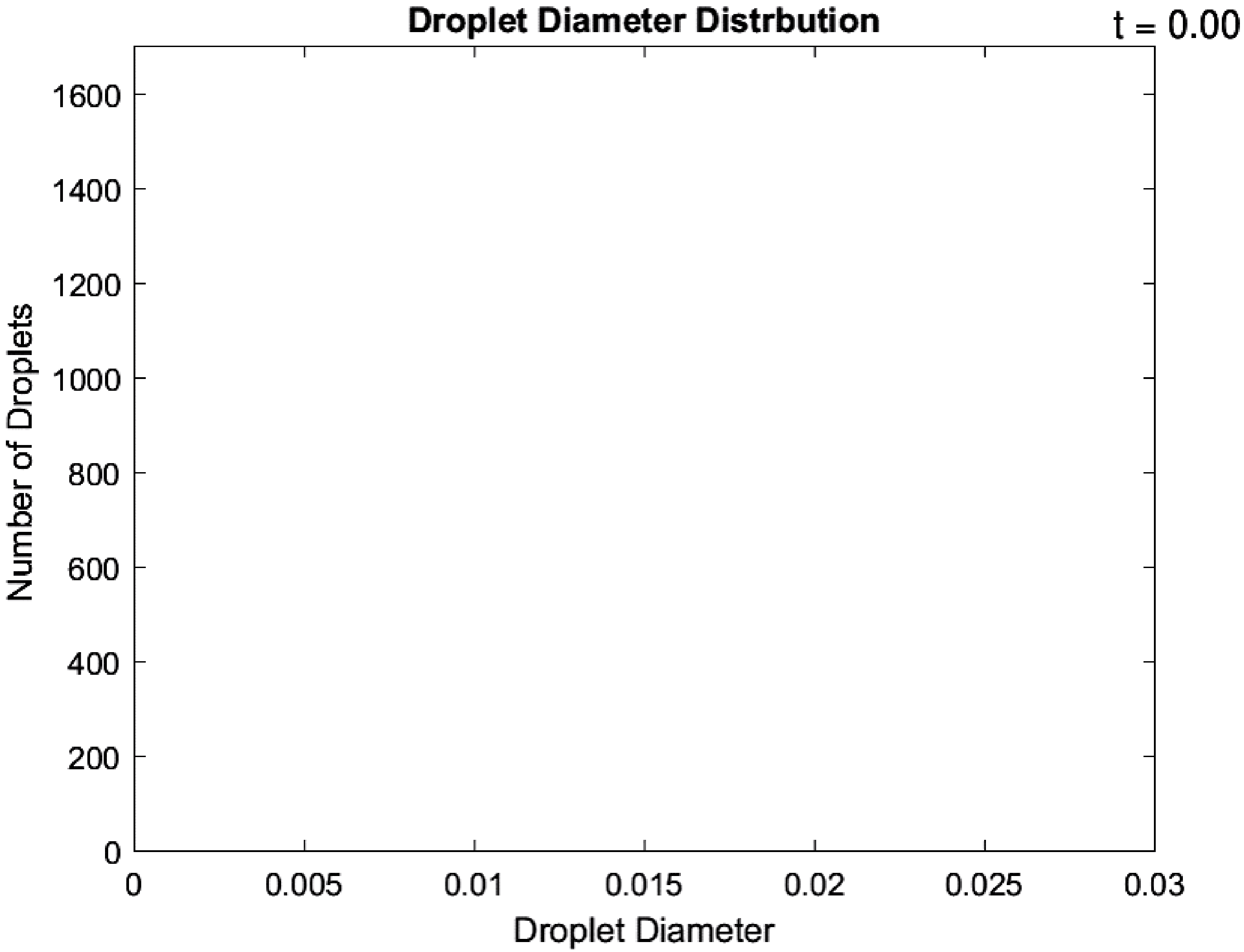


2-D Tracer Iso-line

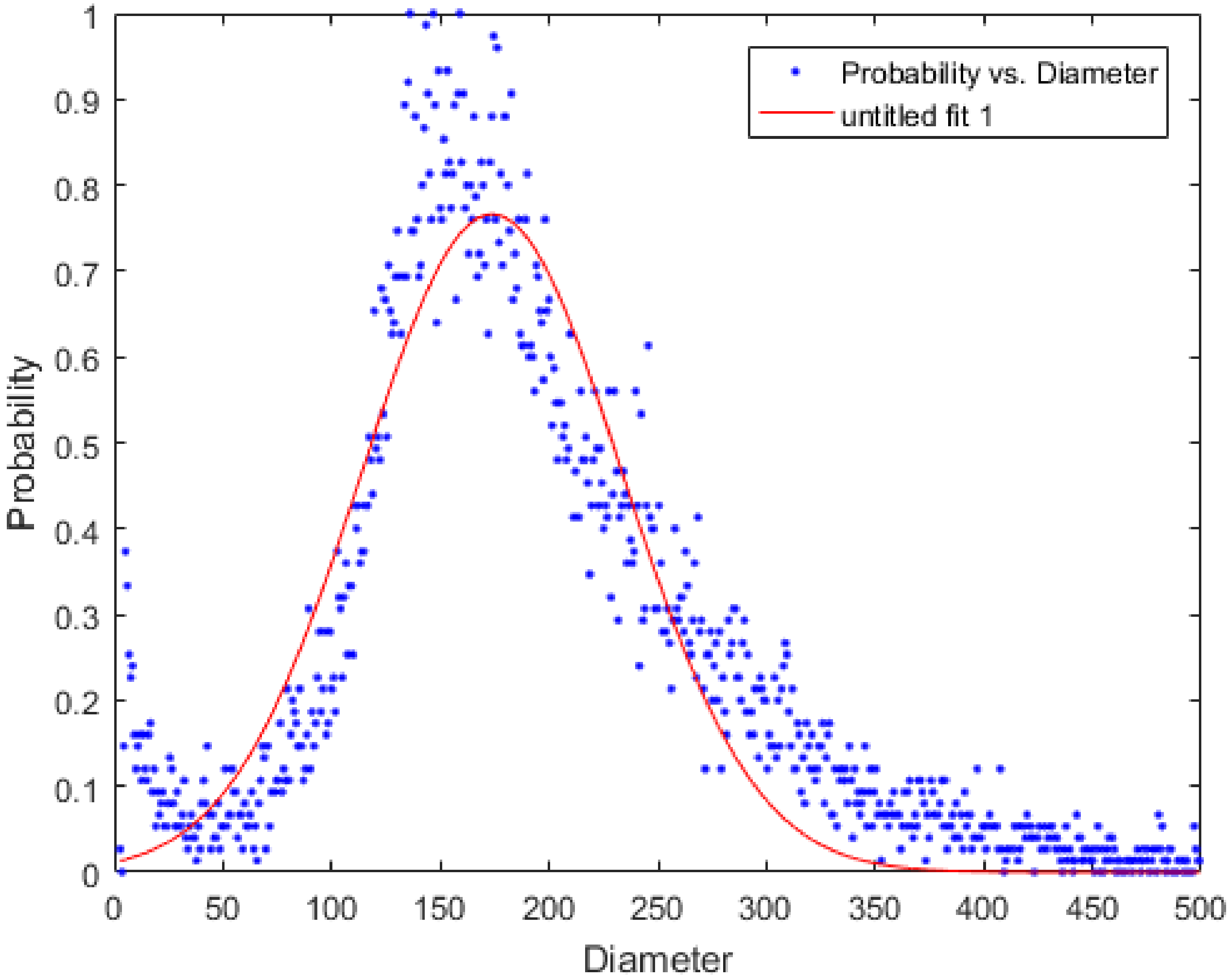


non-dimensionalized time,
t = t*/(d/Uj) = 1.64

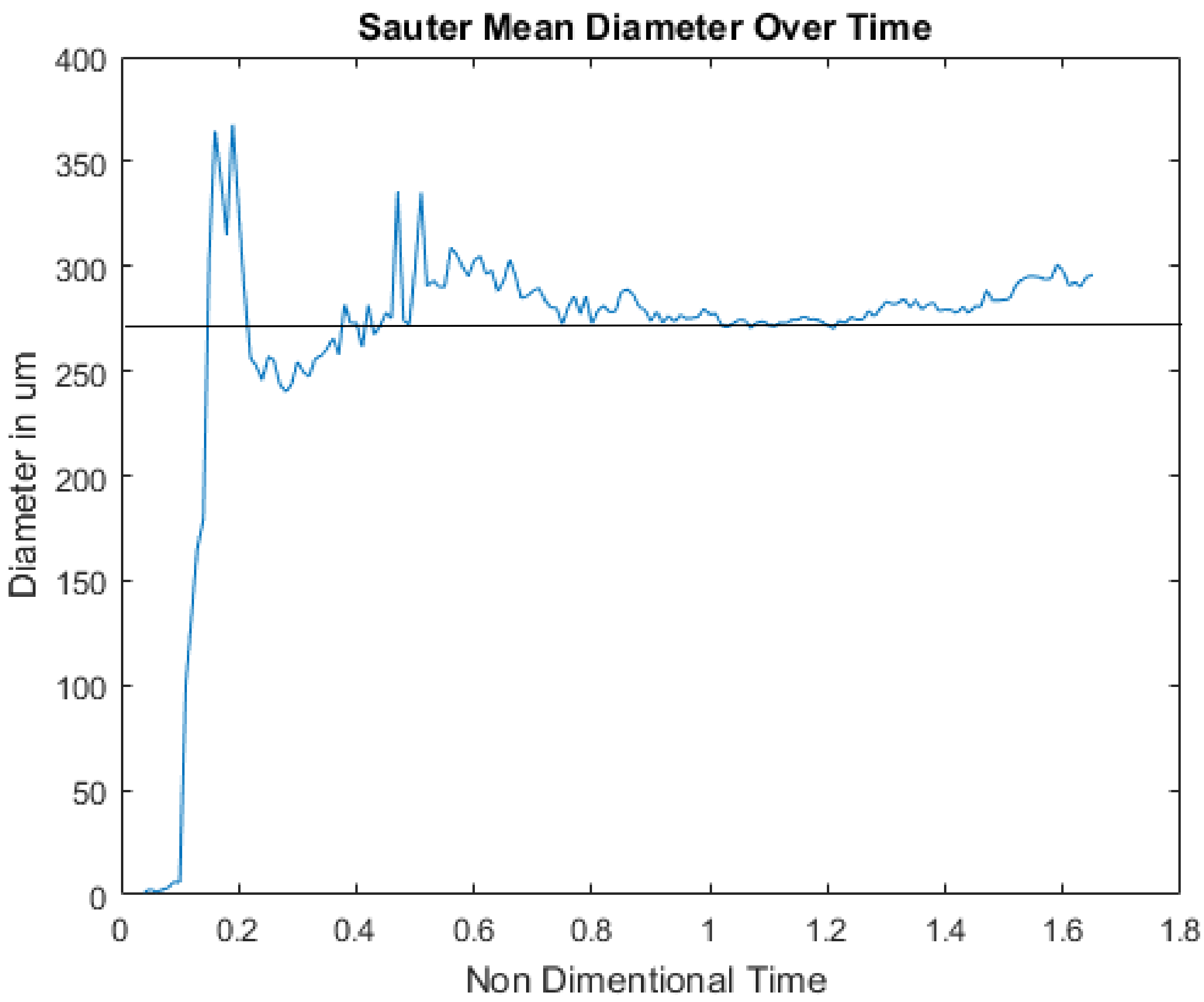
Droplet Production Changes with Time



Droplet Production in terms of Probability



Sauter Mean Diameter



$$D_s = \frac{1}{\sum_i \frac{f_i}{d_i}}$$

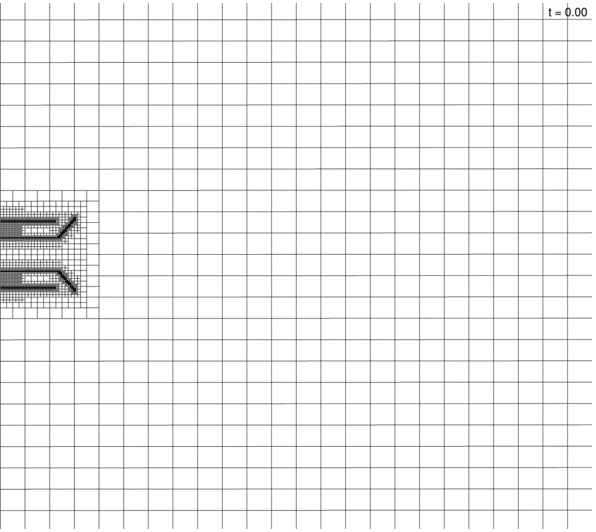
Conclusion

- High-fidelity numerical simulations were conducted to quantitatively identify the atomization of monopropellant pintle injectors was investigated
- By the formation of recirculation zones slowing the flow in the U direction.
- By the ligaments breaking inwards leading to formation of larger droplets
- Droplet distribution analysis shows that droplet coalescences increaces the overall sauter mean diameter
- Droplet distribution analysis also shows an Gaussian droplet distribution with a slowing production rate due to droplet coalescence

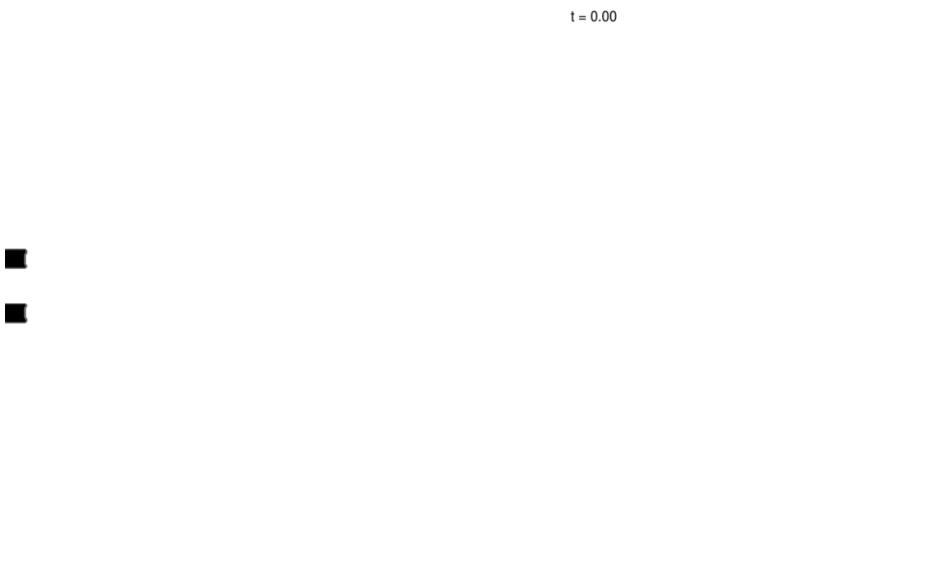
Future Investigations

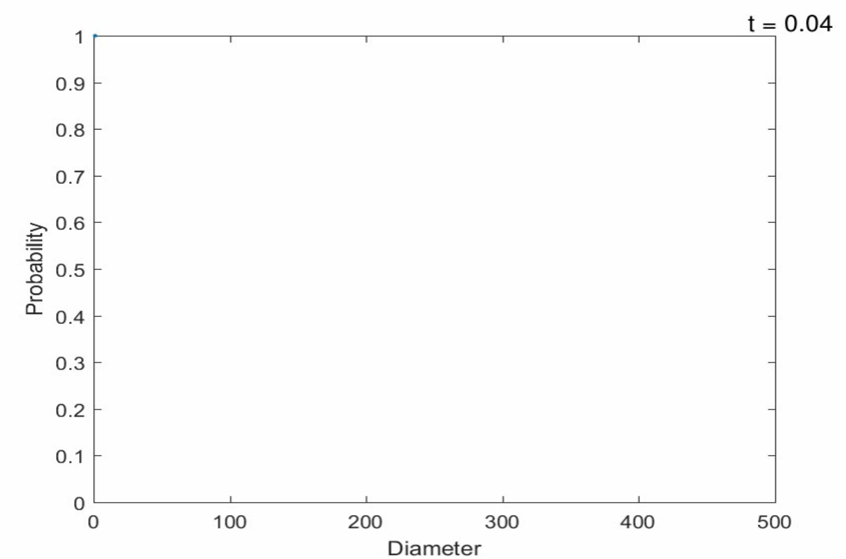
- Investigate and quantify the differences in breakup and droplet distribution for different Weber numbers and operating pressures
- Determine the effect of pintle angle and location on droplet distribution

Questions?


t = 0.00

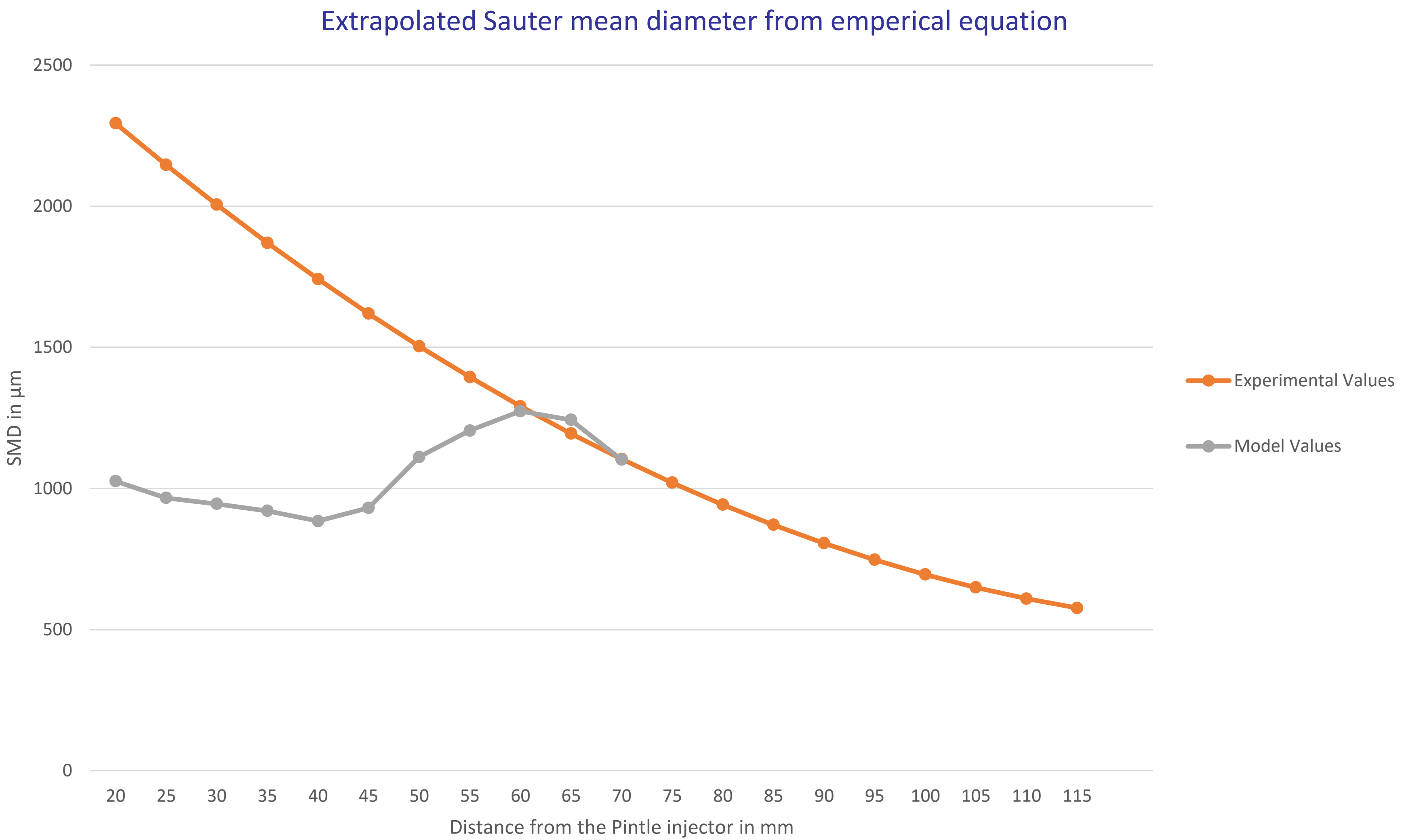

t = 0.00


t = 0.00


t = 0.04
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Probability
0
100
200
300
400
500
Diameter

Back-up

Sauter Mean diameter Comparison



Spray Angle Comparison

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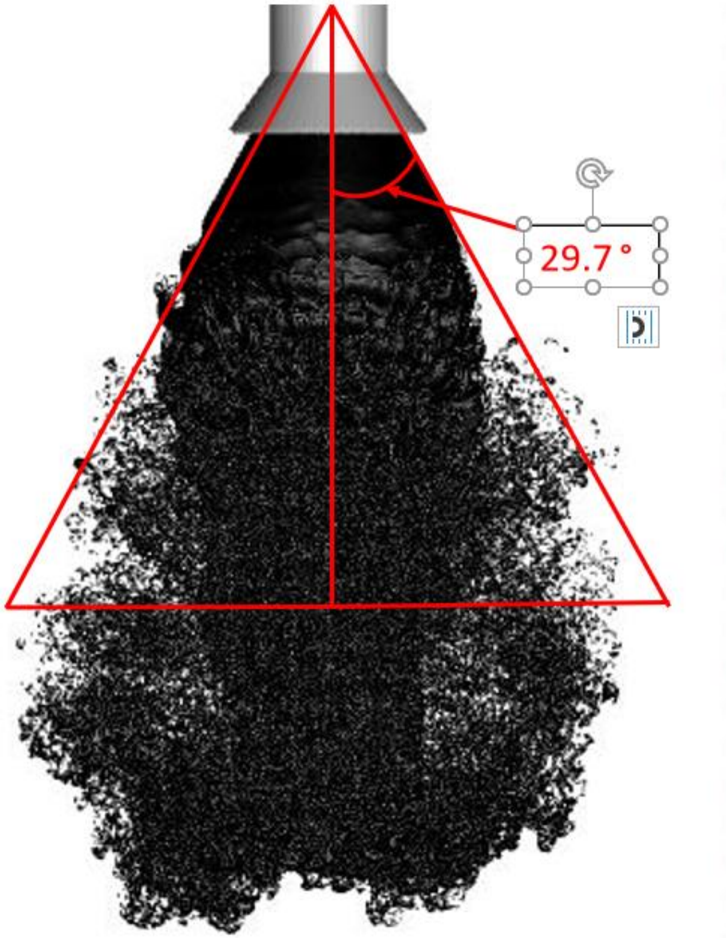

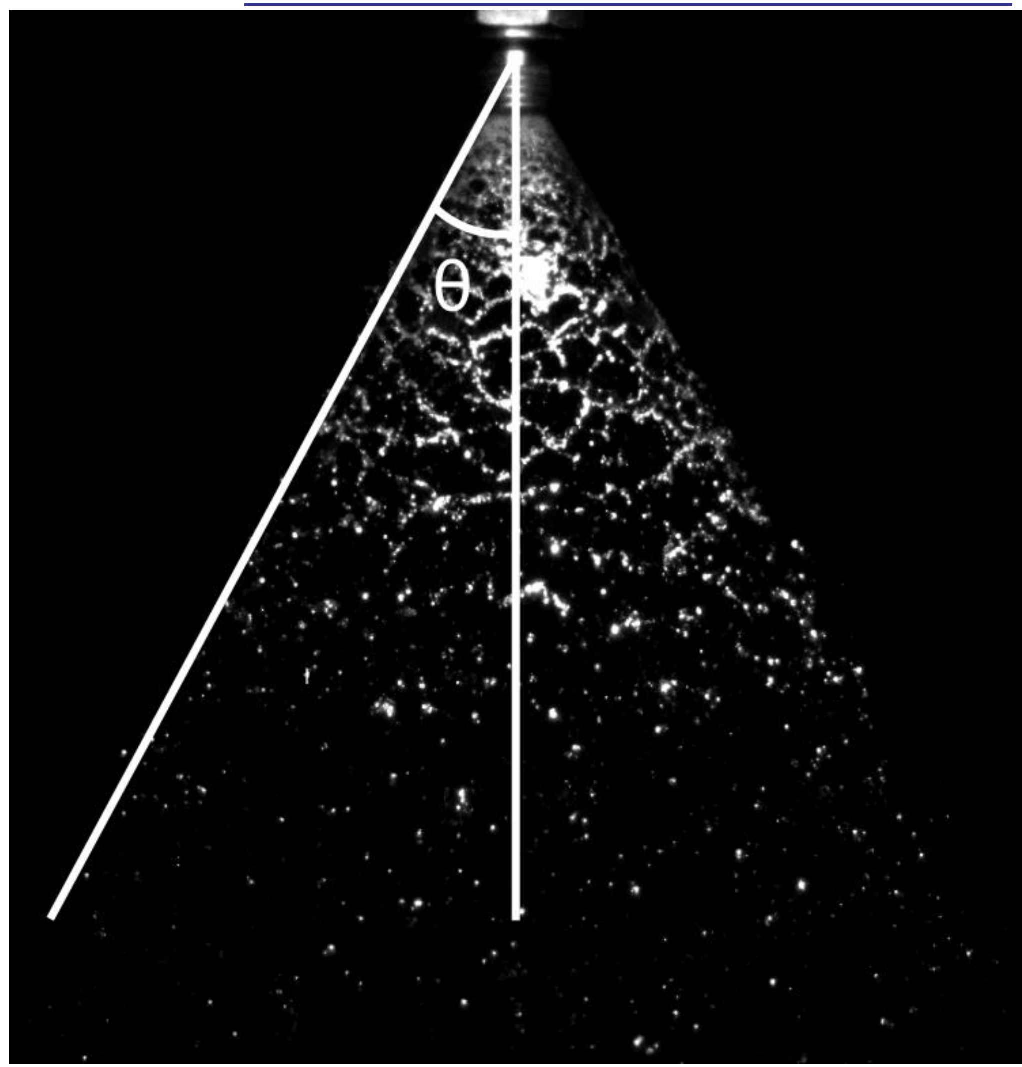

Model had a 31 degree half spray angle measured at 10mm