ECN 5 Topic 8: Internal & Near Nozzle Flow Modeling Spray G

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UMass,Amherst

Presentation Contents

- Modelling Approaches
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  - Boundary Conditions
  - Meshing
- ECN 5 Simulation Results
  - Injector coefficients and ROI comparison
  - Representative contour plots
  - Comparison with Experimental LVF.
- Next Steps for Spray G
  - Updated geometry
  - Needle closure, multiple injections
  - Encouraging more contributors!

Contributors

- Three institutions contributed simulation results
  - University of Massachusetts-Amherst and General Motors
    - Eli Baldwin, Chinmoy Mohapatra, David Schmidt (UMass)/Ronald Grover (GM)

    * Results published in International Journal of Multiphase Flow, **87** (2016) 90-101
  - CD-Adapco, A Siemens Business,UK
    - Samir Muzaferija, Kshitij Neroorkar , Dimitrios Papoulias
  - Argonne National Laboratory and Convergent Science Inc.
    - Kaushik Saha, Sibendu Som, Michele Battistoni (ANL)/ Yanheng Li, Eric Pomraning, and P.K. Senecal (Converge)

    *Results published in SAE International Journal of Engines, SAE 2016-01-870
  - New Geometry Results
    - Dan Duke et al., SAE 2017-01-0824, to be presented Thursday morning
  - Acknowledgement
    - GridPro

Spray G and G2 Nominal Operating Conditions

Condition	SprayG	SprayG2
Fuel	Isooctane	Isooctane
Injection Pressure	20 MPa	20Mpa
Fuel Temperature	90° C (363.15 K)	90° C (363.15 K)
Ambient Temperature	300° C (573.15 K)	60° C (333.15 K)
Ambient Density	3.5 kg/m^3	0.5 kg/m^3
Back Pressure	600 kPa (N_2)	50 kPa (N_2)
Injected Quantity	10 mg	
Injection Duration	780 µs ("actual")	780 µs ("actual")

Modelling Approaches

Internal Modeling Codes

Institution	UMass/GM	CD-Adapco	ANL/Converge
Code	HRMFoam	STAR-CCM+	Converge
Origin	UMass	CD-Adapco	Convergent Science
External Coupling	Eulerian	Eulerian	Eulerian
Modelled	Both (Spray G and Spray G2)	Spray G2	Both (Spray G and Spray G2)

Approaches

Institution	UMass/GM	CD-Adapco	ANL/Converge
Liquid fuel	Iso-Octane	Iso-Octane	Iso-Octane
Equation of State	Compressible	IC fuel, IG N2	Compressible
Cavitation Enabled?	Yes	Yes	Yes
Model For Phase change	Homogenous Relaxation	Homogenous Relaxation	Homogeneous Relaxation
Turbulence	RANS k-Omega SST	RANS K-Omega SST	RANS K-epsilon
Spatial Discretization	2nd order	2nd order	2nd order
Fuel Properties	REFPROP (input table)	NIST	CONVERGE, Dymond et al. 1985
Ambient Properties	Ideal Gas	Ideal Gas	Ideal Gas
Liquid/Gas interface	Eulerian, diffuse-interface (i.e., pseudo-fluid)	VOF	Eulerian, Mixture Model
Heat Transfer Enabled?	No; fuel is isenthalpic	Yes	Yes

Computational Domain

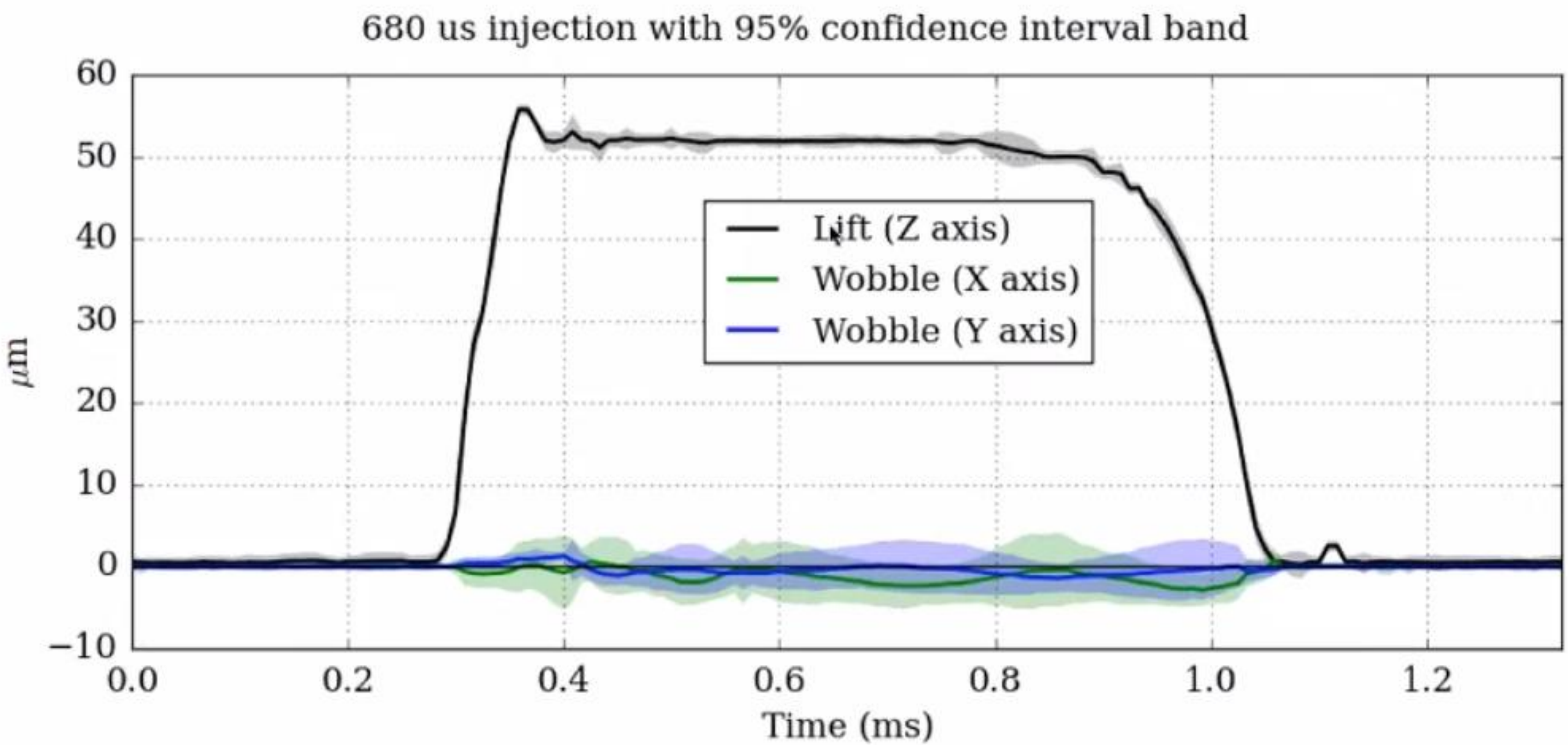
Institution	Umass/GM	CD-Adapco	ANL /Converge
Dimensionality	3	3	3
Cell Type	Hexahedral with anisotropic refinement between needle and wall	Hex & prism cells + wall layers	Cut-cell Cartesian Cubic Types
Meshing Tool	Grid Pro	STAR CCM+	Converge Meshing
Cell count (total interior and exterior)	1.5 million	8 million	2.8 & 4.5 million
Adaptive or Static Refinement?	Static	Static	Static
Needle motion?	Yes	No	No
Initial Needle lift	5 µm	Full needle lift	10%,50%, 100% of full needle lift
Geometry	"Ideal" geometry with 9mm plenum	"Ideal" geometry with 9mm plenum	"Ideal" geometry with 18mm plenum

Boundary Conditions

Institution/Code	UMass	CD-Adapco	ANL/Converge
Time Accurate ROI Profile?	Predicted	No	No
Inlet	Constant Pressure	Constant Pressure	Constant Pressure
Wall BCs	L.O.W.	L.O.W.	L.O.W.
Needle motion?	Yes (Needle motion in all three directions)	No	No

Needle Lift Measurements for Spray G #28

680 μs commanded injection at 190 bar/300K into N_2 at STP



Data and figure provided by Dan Duke at Argonne National Lab

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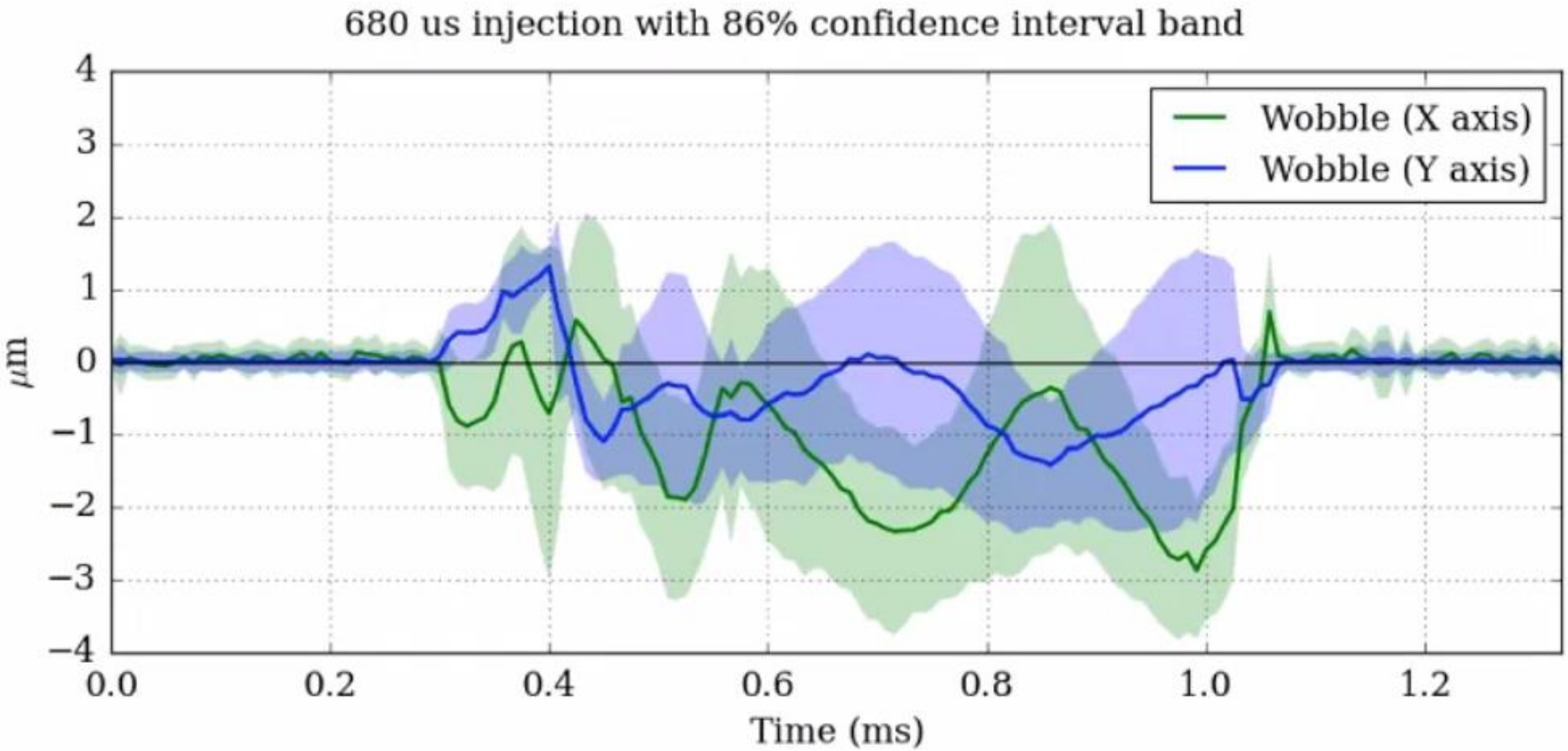
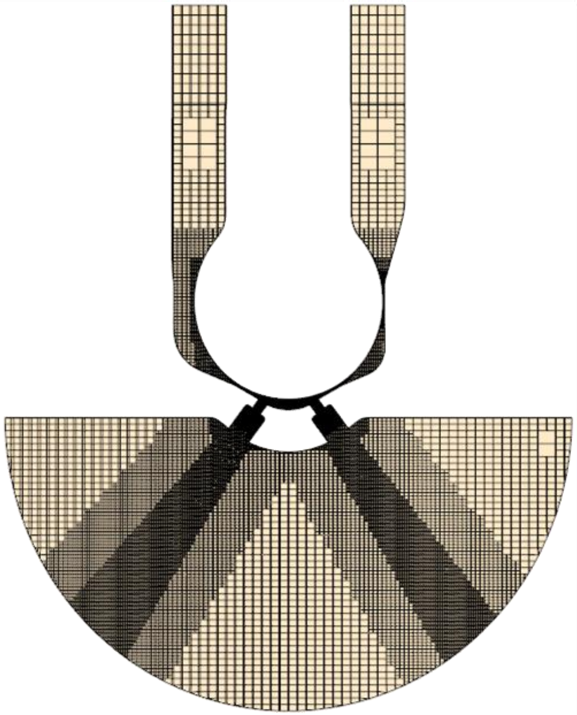
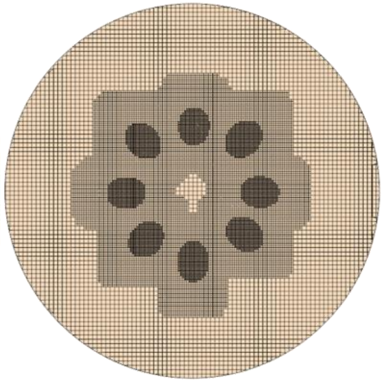


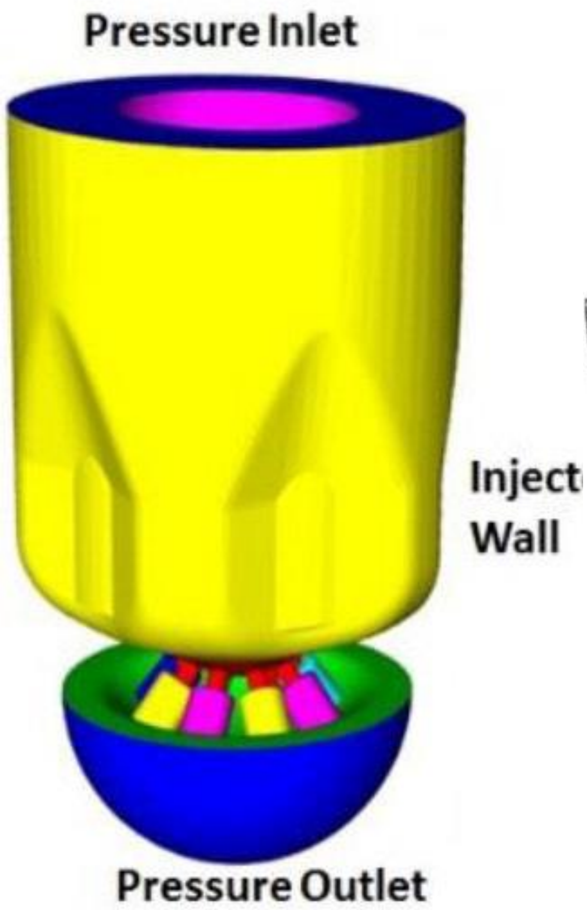
Data and figure provided by Dan Duke at Argonne National Lab

Computational Mesh

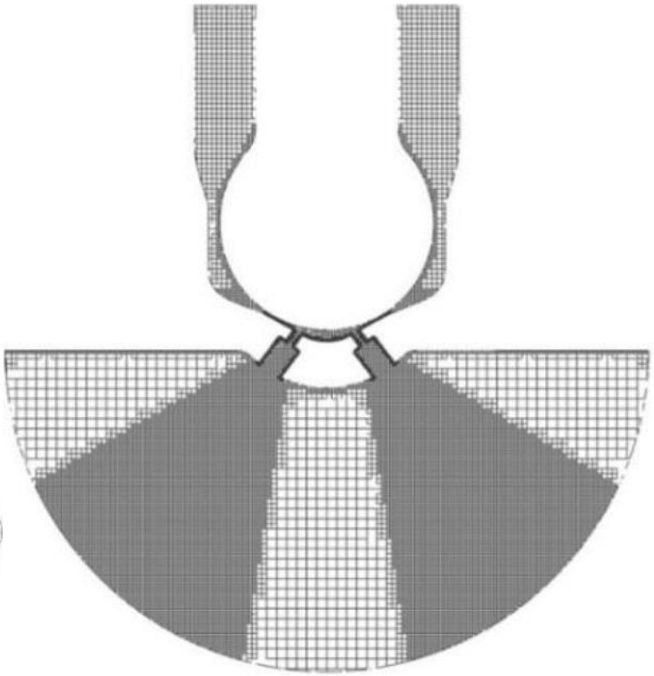
CD-Adapco







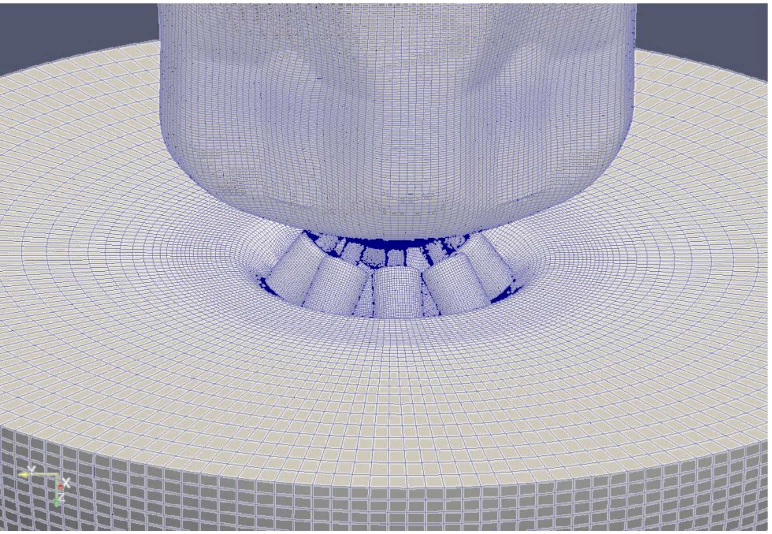
ANL/CONVERGE

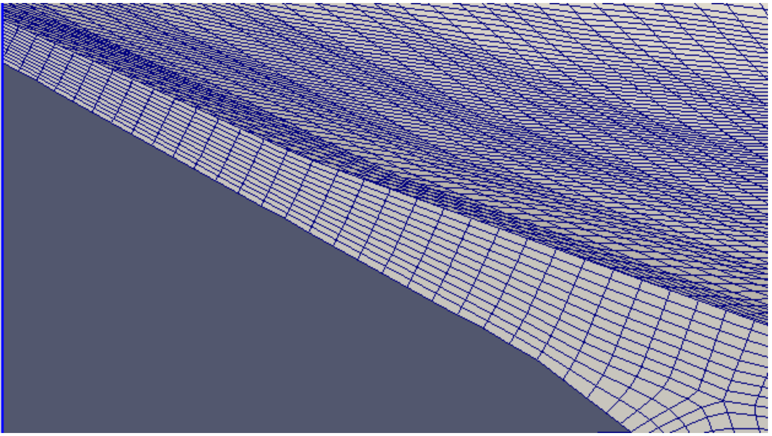


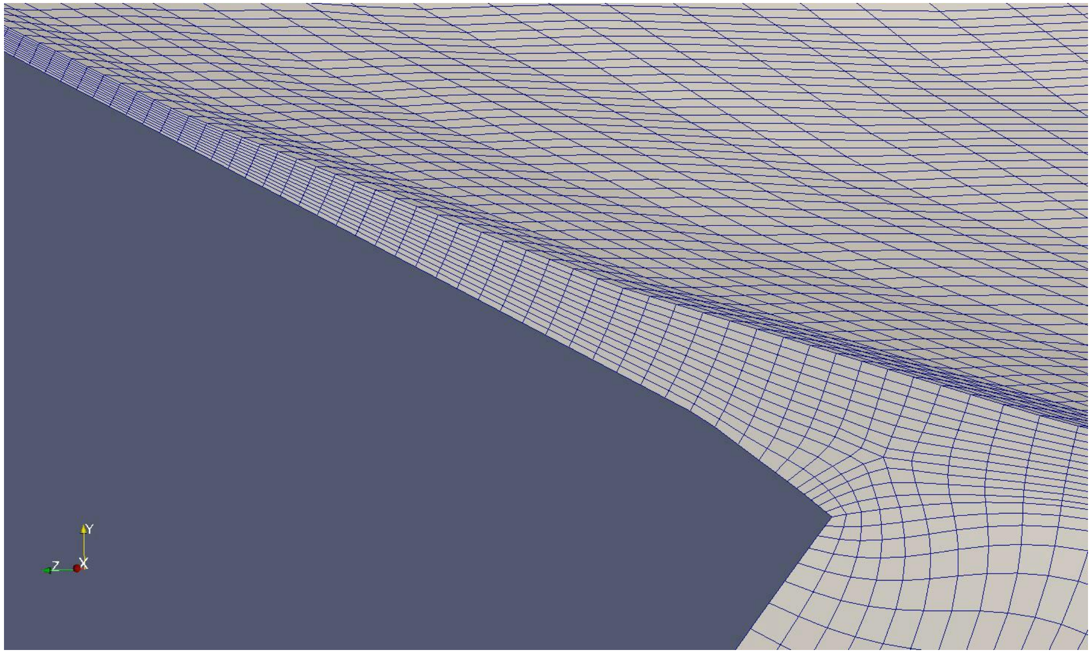
- 17.5 μm minimum grid size with 9-mm diameter outlet plenum

Computational Meshes

UMass/GM





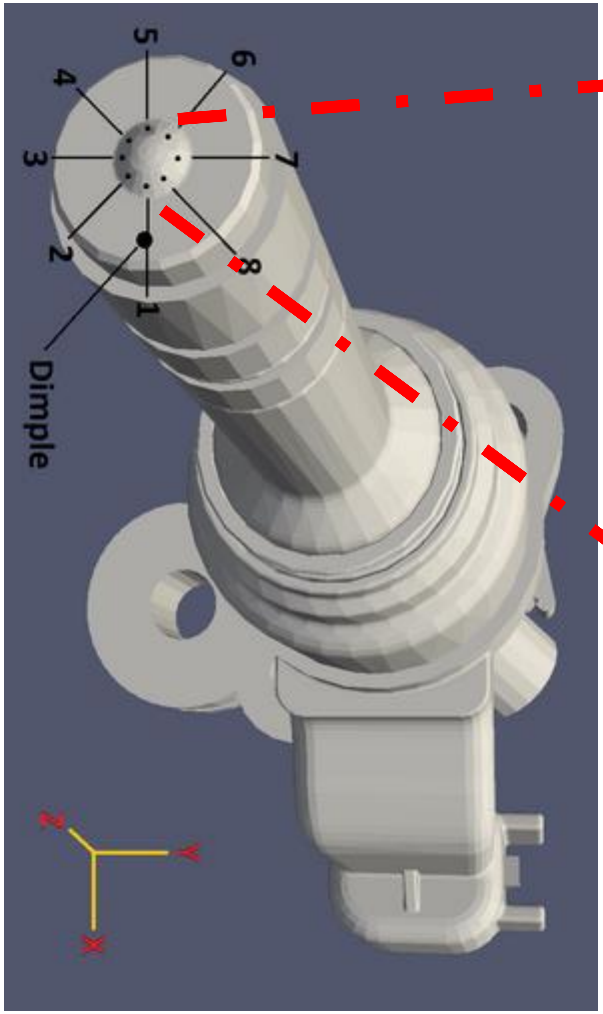


- Transient lift and wobble based upon ensemble averaged Argonne measurements
- Laplacian smoothing for mesh motion
- 10 µm and 7 µm grid spacing in the sac and nozzle hole

Simulation Results

Hole Orientation & Numbering

Spray G Convention



CAD Geometry

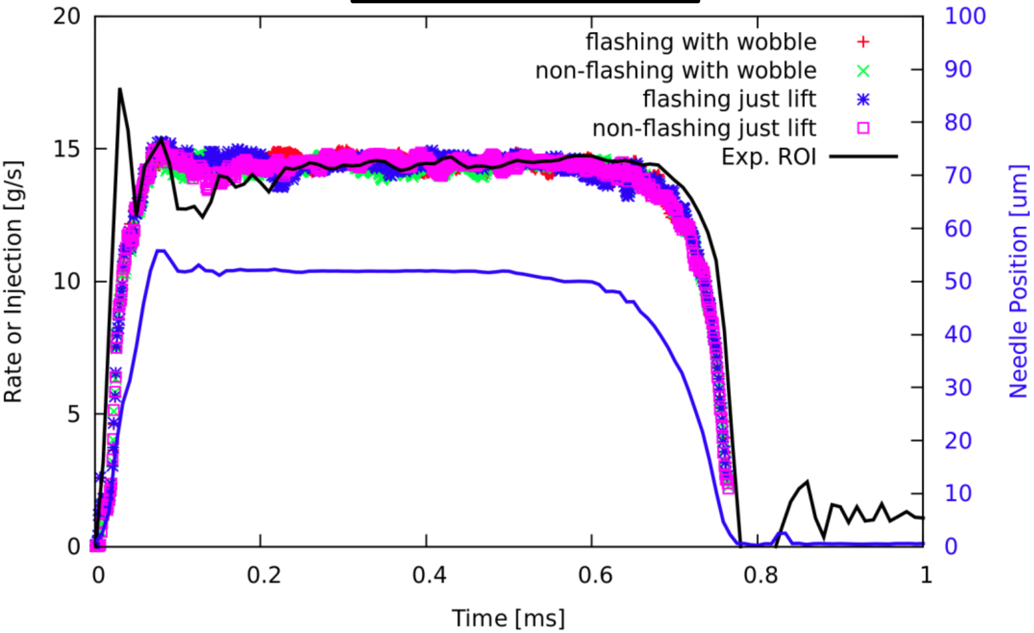
Summary of Submissions

1. Terminology
    - Fuel → liquid + vapor
    - Ambient → non-condensable gas
2. Injector Coefficients
    - C_D (individual hole & injector averaged)
3. Rate Of Injection
    - Individual hole and overall
4. 2-D Contour plots and animations for both flashing and non flashing condition
    - Z= 2 mm (downstream of the nozzle)
    - Spherical cut plane at the nozzle exit and counter bore exit

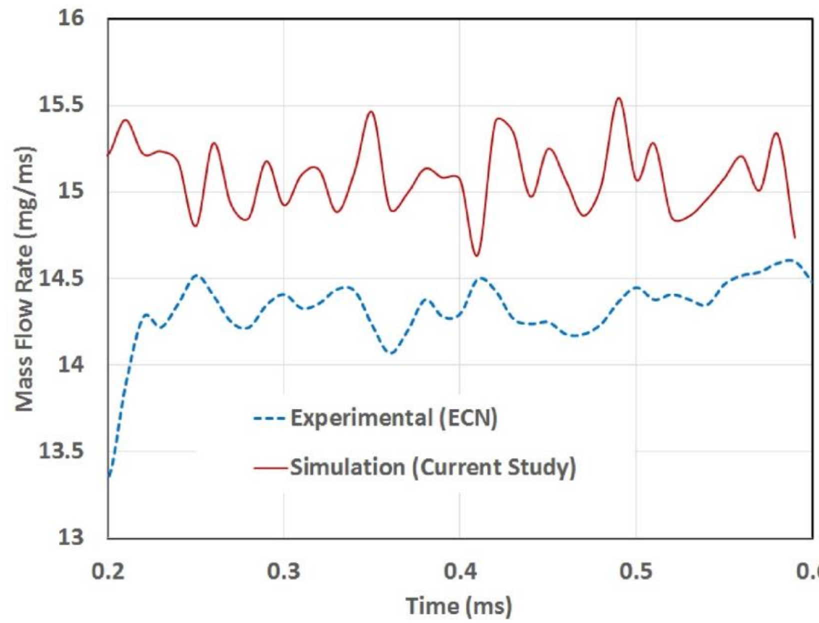
Hole to hole variation in C_D and ROI

ROI Prediction

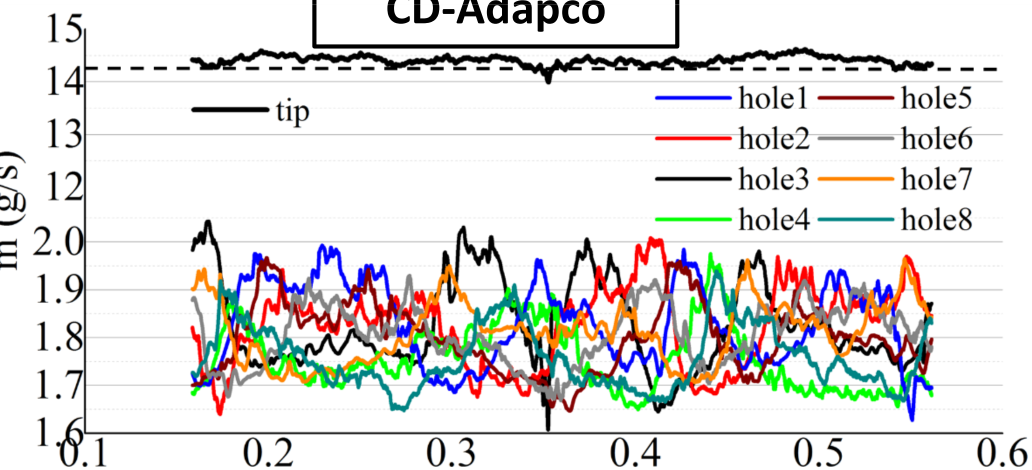
UMass/GM



ANL/CONVERGE



CD-Adapco



Injector coefficients

	Hole #	UMass/GM (SprayG)	UMass/GM (SprayG2)	CD-Adapco (SprayG2)
Individual hole C_D	1	0.51	0.51	0.53
	2	0.50	0.50	0.53
	3	0.49	0.51	0.51
	4	0.52	0.52	0.53
	5	0.52	0.53	0.52
	6	0.49	0.50	0.53
	7	0.50	0.50	0.53
	8	0.51	0.51	0.51
Overall Injector	C_D	0.51	0.51	0.52

Highest flowing holes

Lowest flowing holes

GM Measurement(ECN4) C_D ~ 0.52

* To calculate C_D UMass has taken time average of mass flow rate over the period of 0.2ms-0.6ms

Total Injected Mass

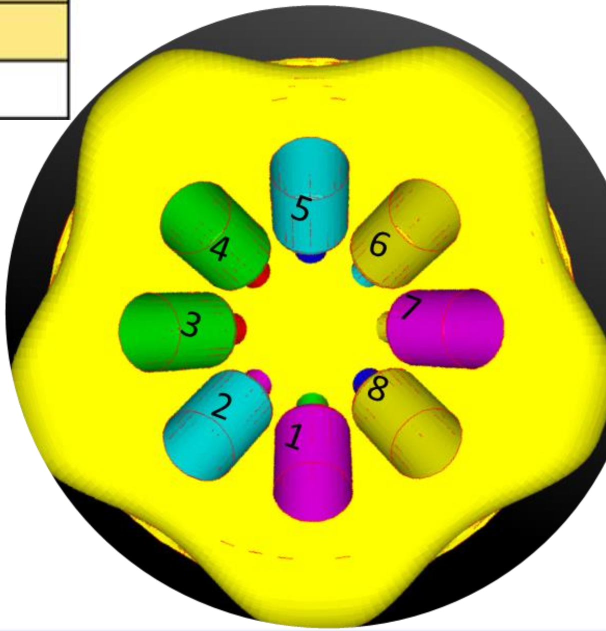
UMass/GM

	Spray G Just Lift [mg]	Spray G w/ Wobble [mg]	Spray G2 Just Lift [mg]	Spray G2 w/ Wobble [mg]
Hole 1	1.29	1.30	1.28	1.29
Hole 2	1.25	1.25	1.31	1.27
Hole 3	1.26	1.25	1.29	1.28
Hole 4	1.29	1.27	1.27	1.29
Hole 5	1.27	1.29	1.25	1.31
Hole 6	1.27	1.27	1.28	1.29
Hole 7	1.29	1.26	1.27	1.28
Hole 8	1.32	1.29	1.28	1.28
Total	10.24	10.17	10.24	10.29

high

low

- Agrees well with 10 mg injected mass target
- The hole to hole variation in total injected mass is the order of 1-2%
- Wobble does not effect in a consistent way

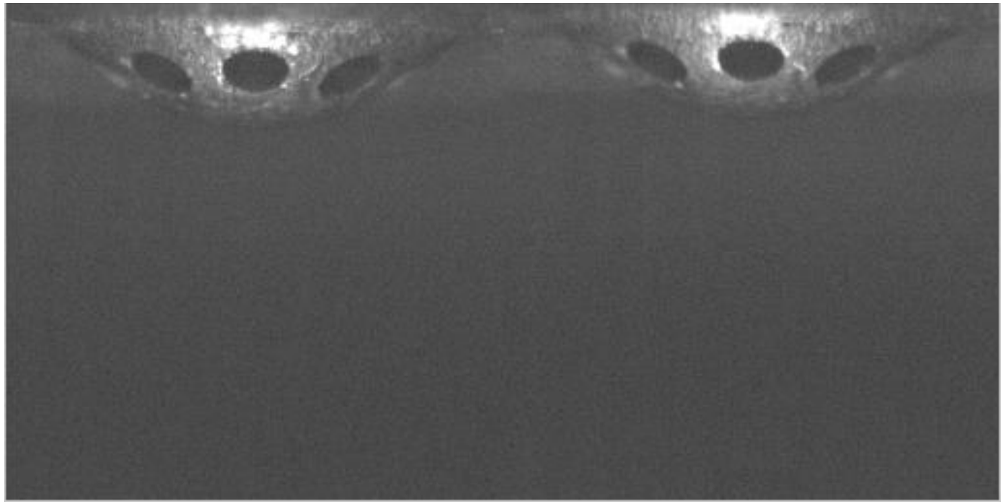


Total Injected Mass

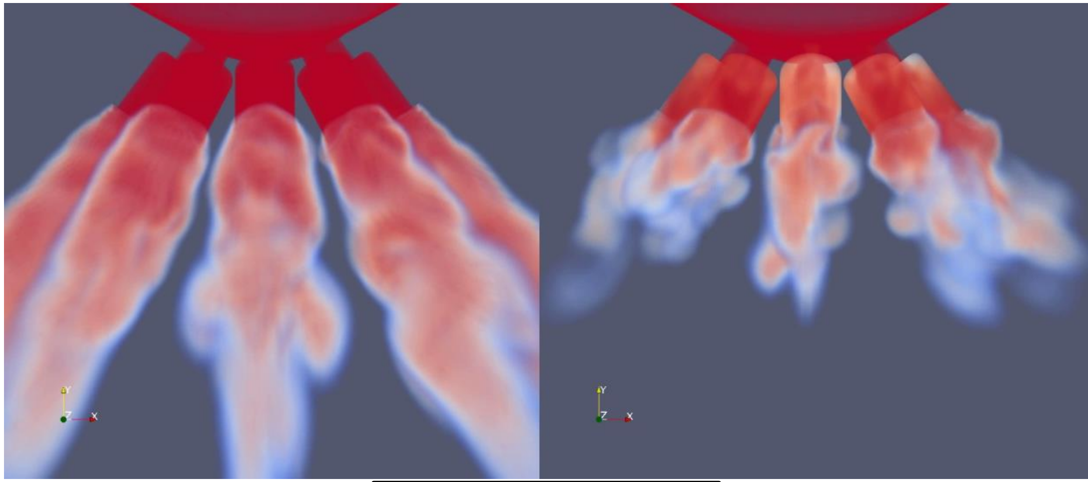
CD-Adapco

Flashing

GM



Flashing **Non-Flashing**

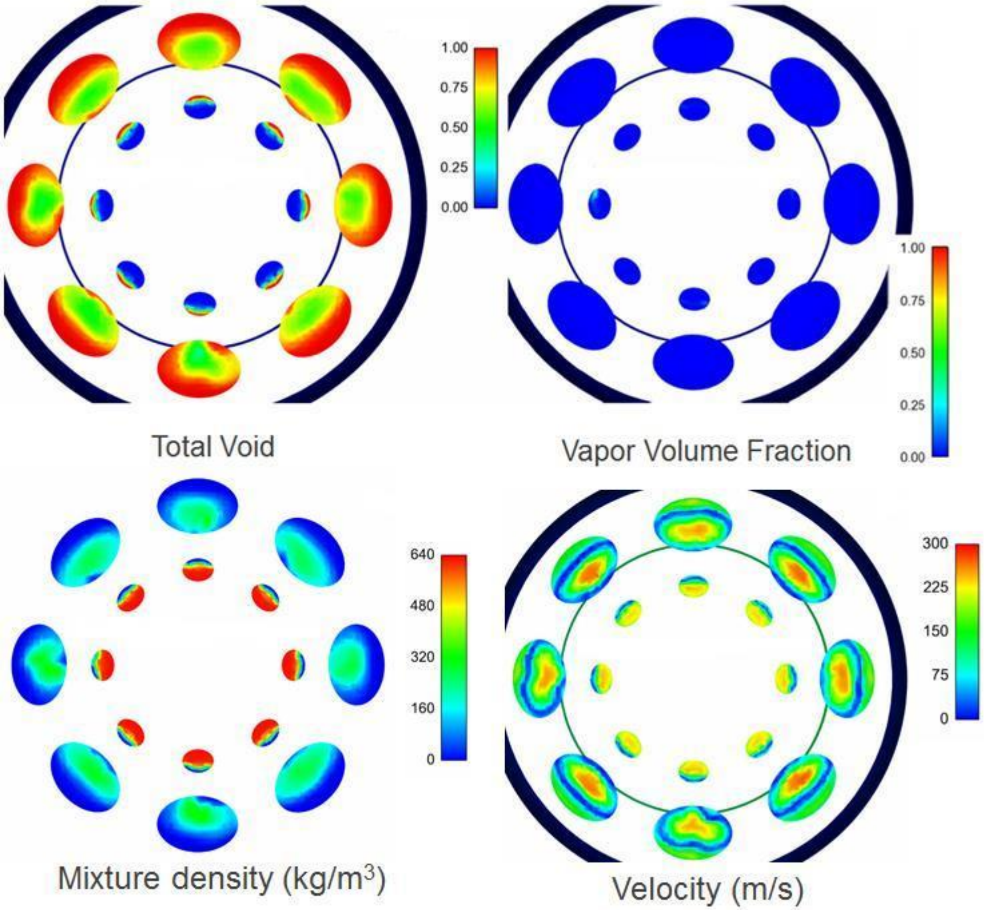


UMass/GM

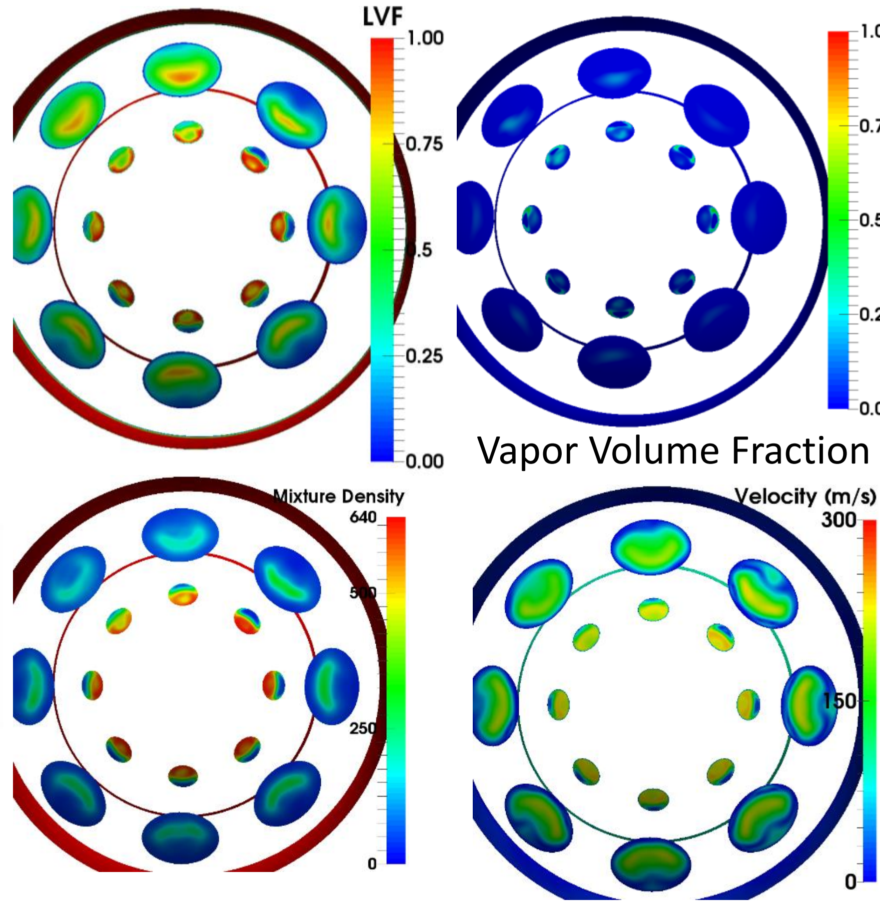
- Near-tip visualized with high-speed CCD camera with long-distance microscope (Parrish, GMRC)
- Volume-rendered simulations
- Fuel fills counter-bore in flashing case
- What is causing the oscillations in the spray???

Comparison of Spray G (Non-Flashing) results between different sources

Spray G (Spherical cut planes at nozzle and counterbore exit)



ANL



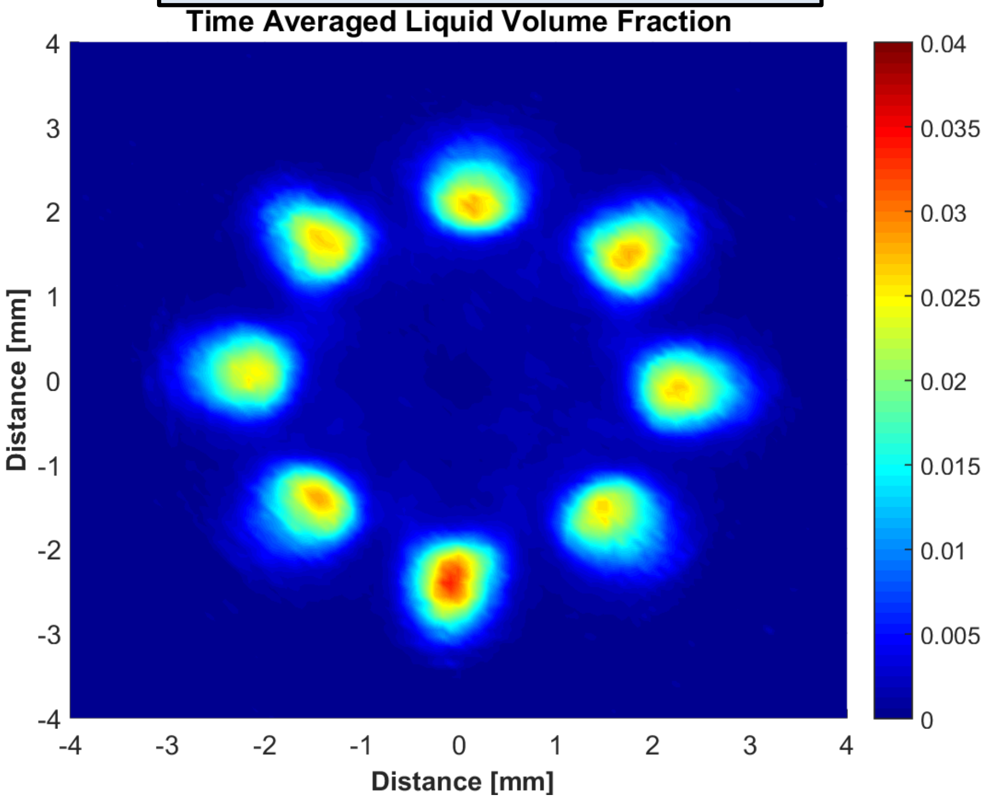
UMass/GM

The ANL contours represents the quantities at 0.2 ms.

The UMass data have been time averaged over the range 0.2ms -0.6ms(Maximum Lift) at an interval of 1µs.

Time averaged LVF at Z=2mm

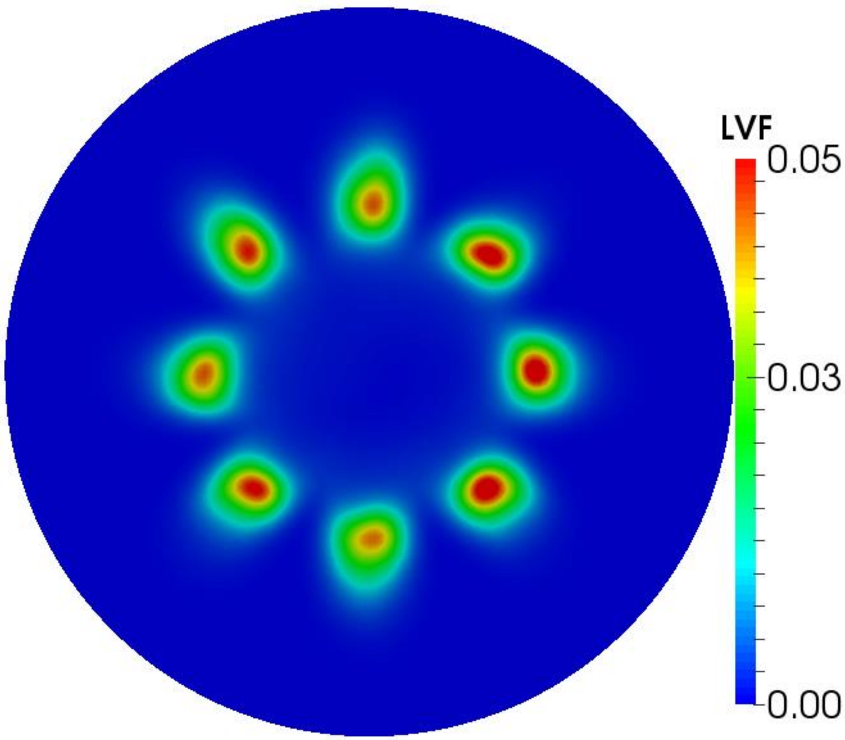
ANL X-Ray Thermography for SprayG#29



Experimental data provided by Katie Matusik at Argonne National Lab

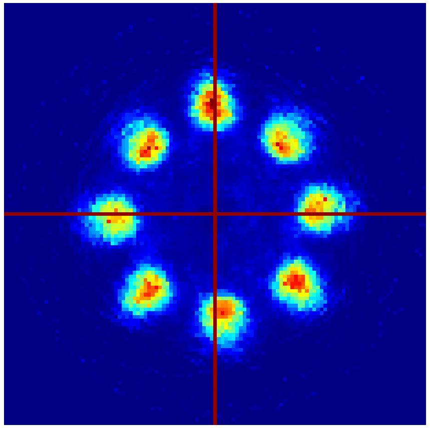
The ANL data has been time averaged in the range of 0.2ms-0.6ms.

The UMass data has been time averaged in the range of 0.2ms-0.6ms.

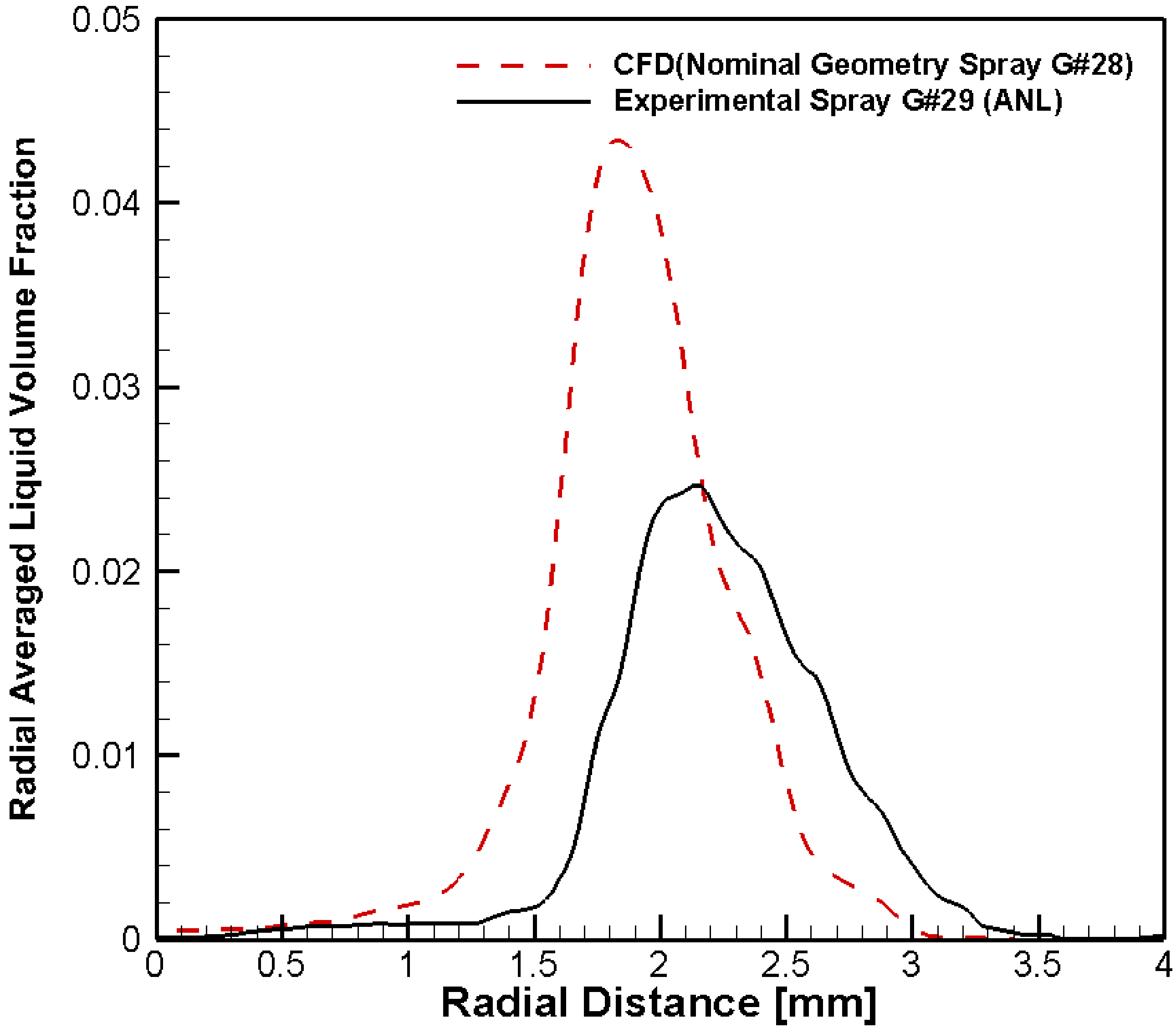


UMass/GM

Time averaged LVF v/s Radial Distance



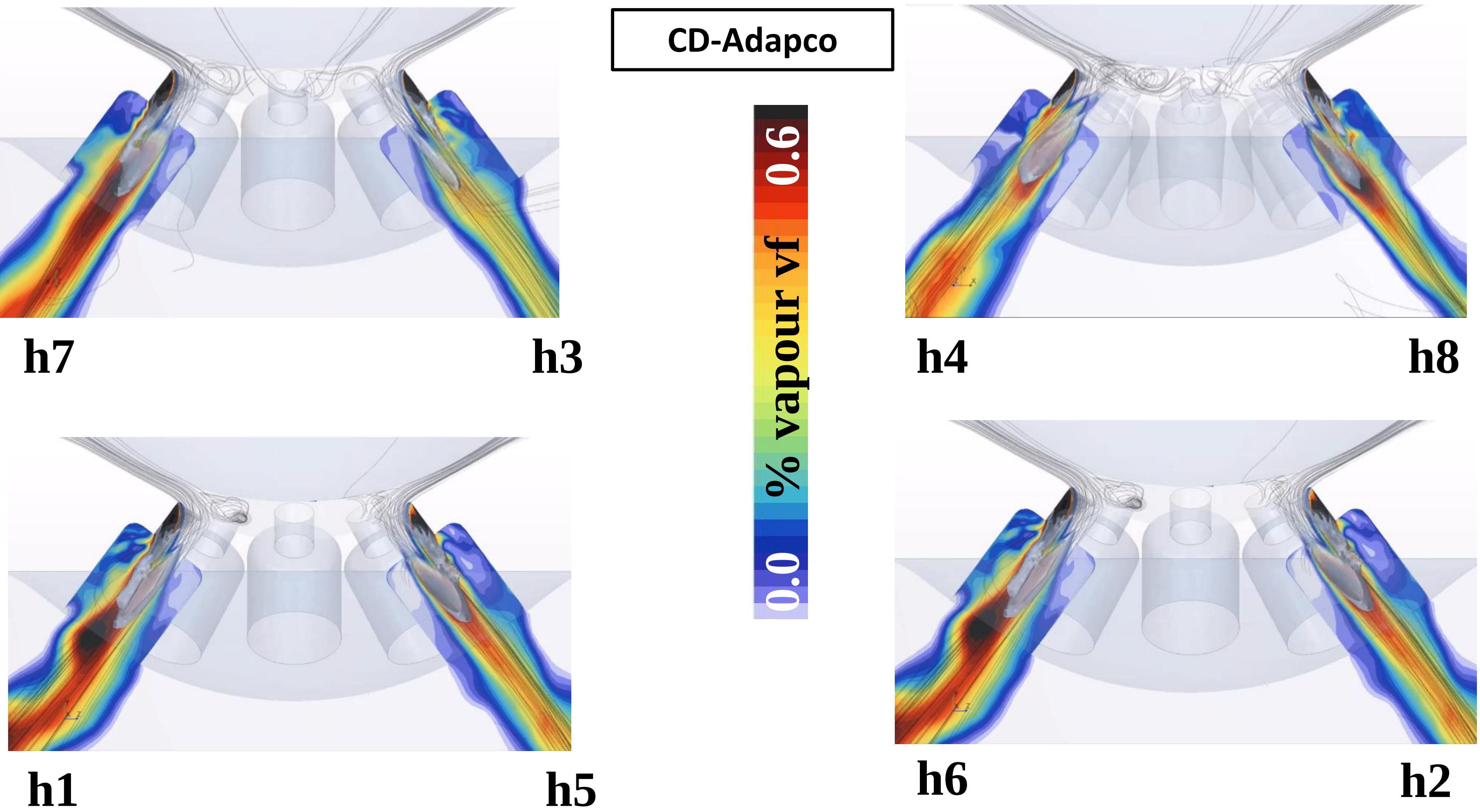
CFD studies have been performed by UMass



Experimental data provided by Katie Matusik at Argonne National Lab

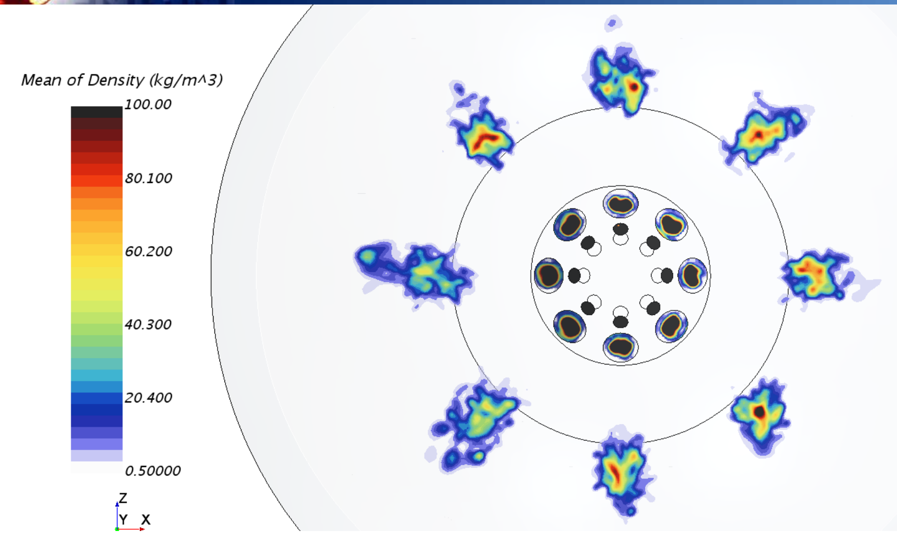
Comparison of Spray G2 (Flashing) results between different sources

Spray G2 hole – hole variation



The semi transparent iso surface represents pressure values below the vapor pressure

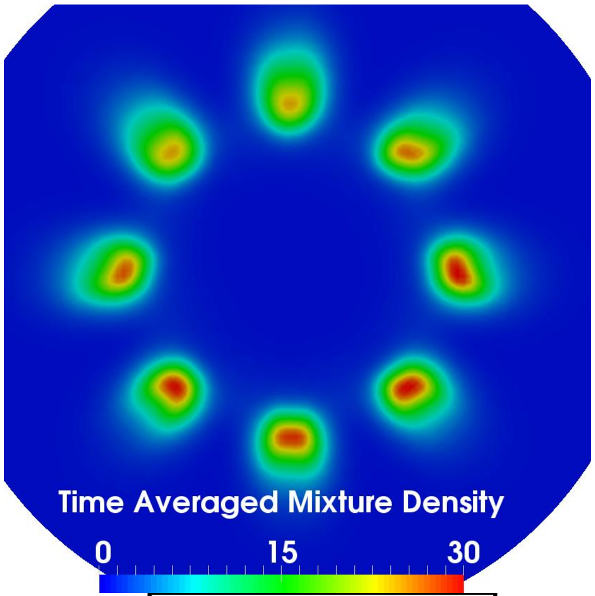
Spray G2 (Z= 2mm)



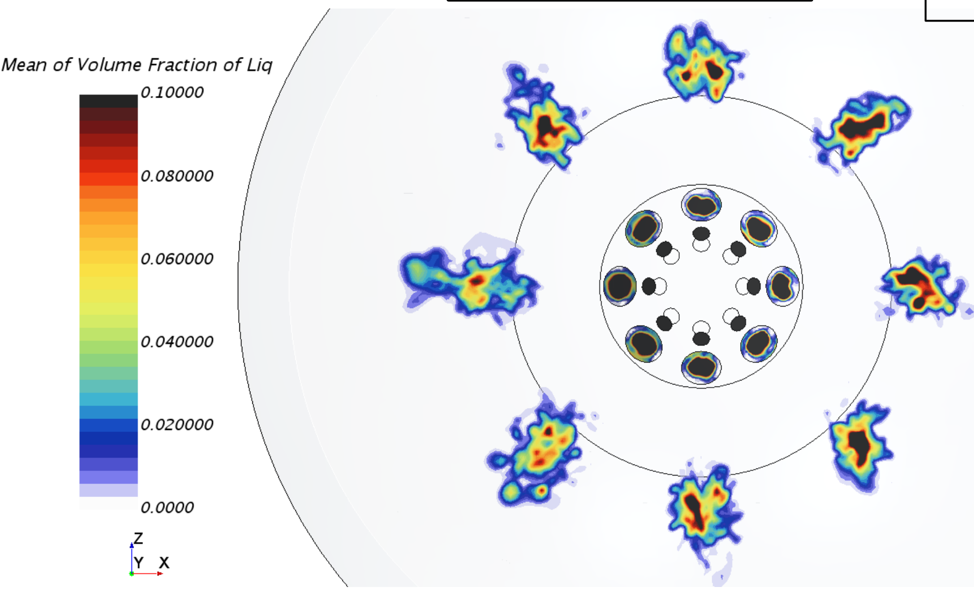
CD-Adapco

The Mixture density and the LVF are both time averaged

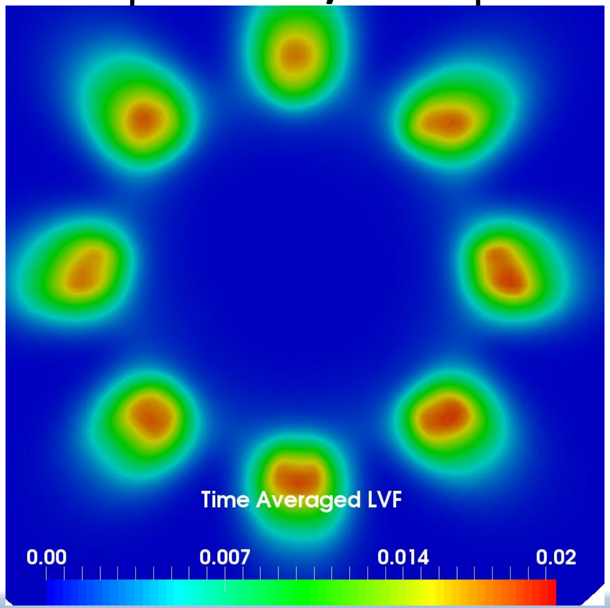
The averaging sample for CD-Adapco is 37µs.



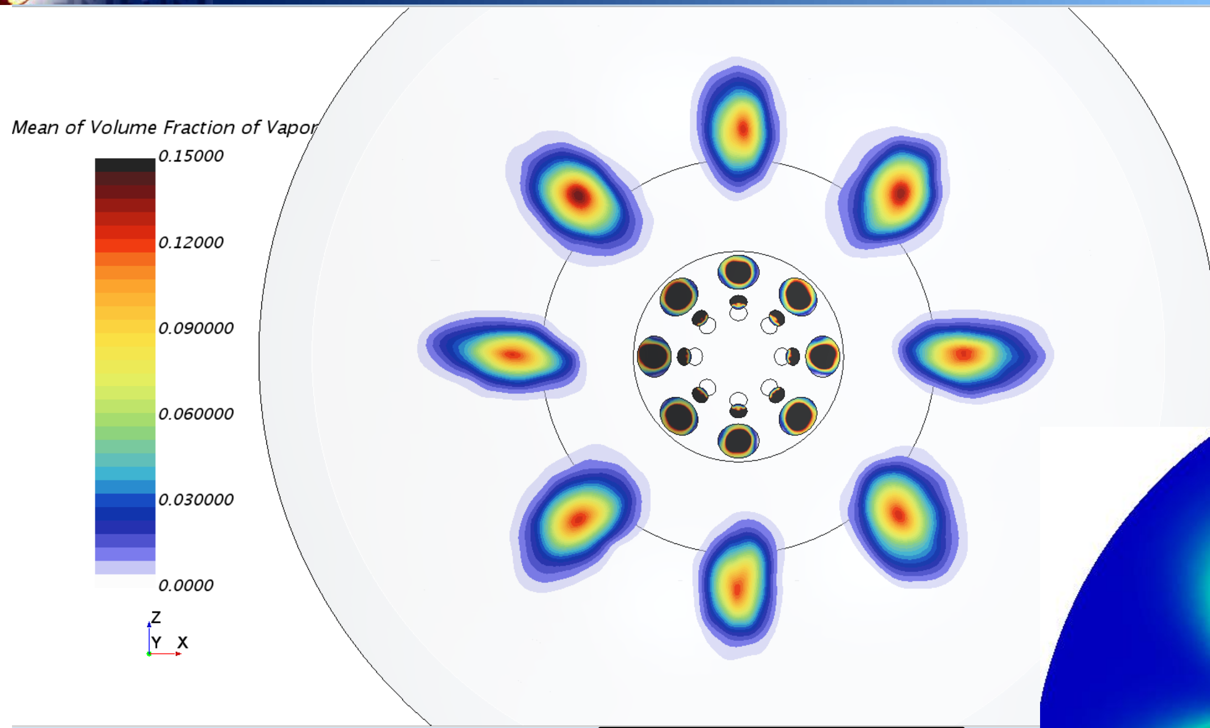
UMass/GM



The Umass data have been time averaged over the range 0.2ms - 0.6ms(Maximum Lift) at an interval of 1µs.

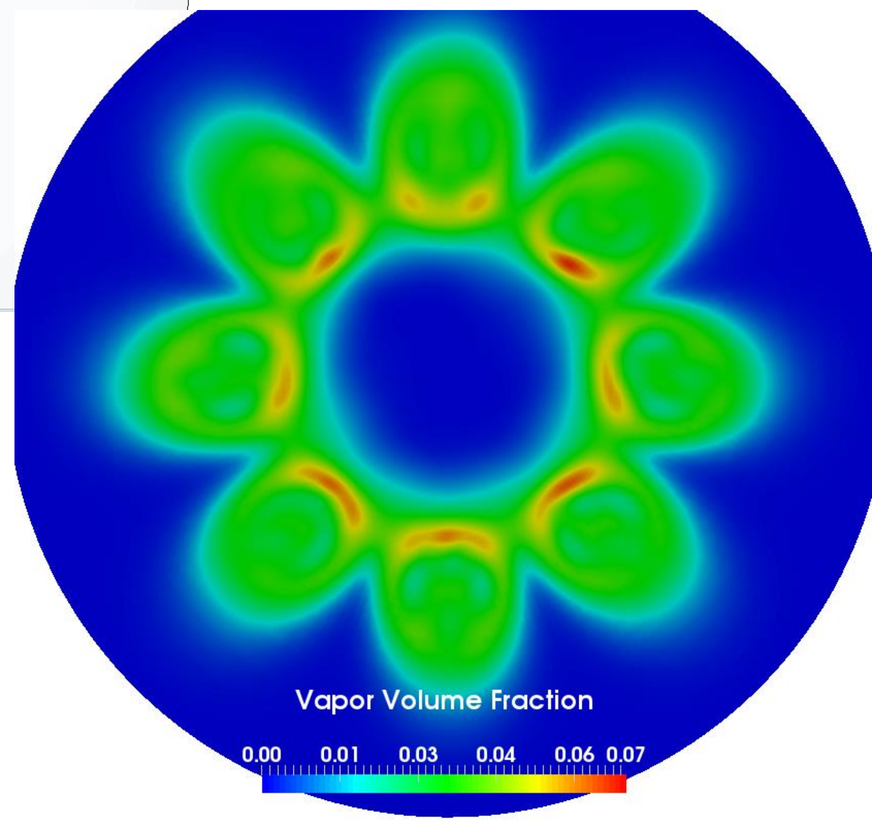


Spray G2 (Z=2 mm)



CD-Adapco

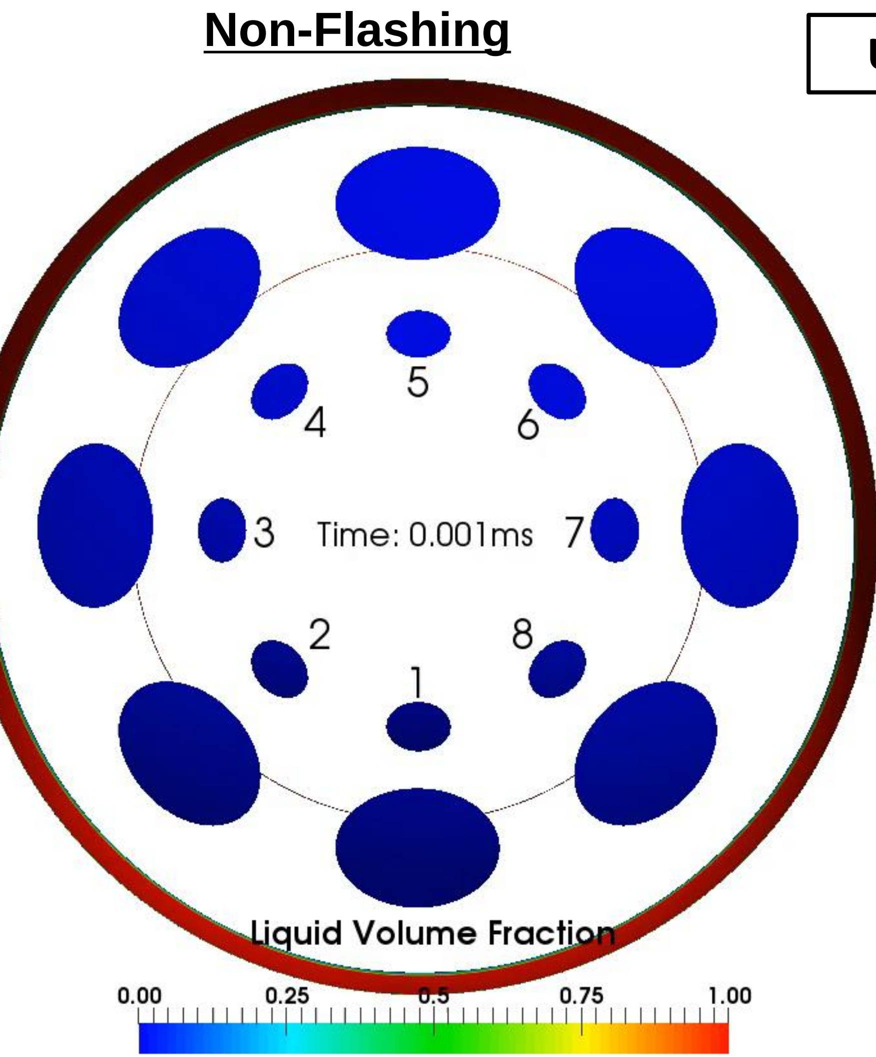
UMass/GM

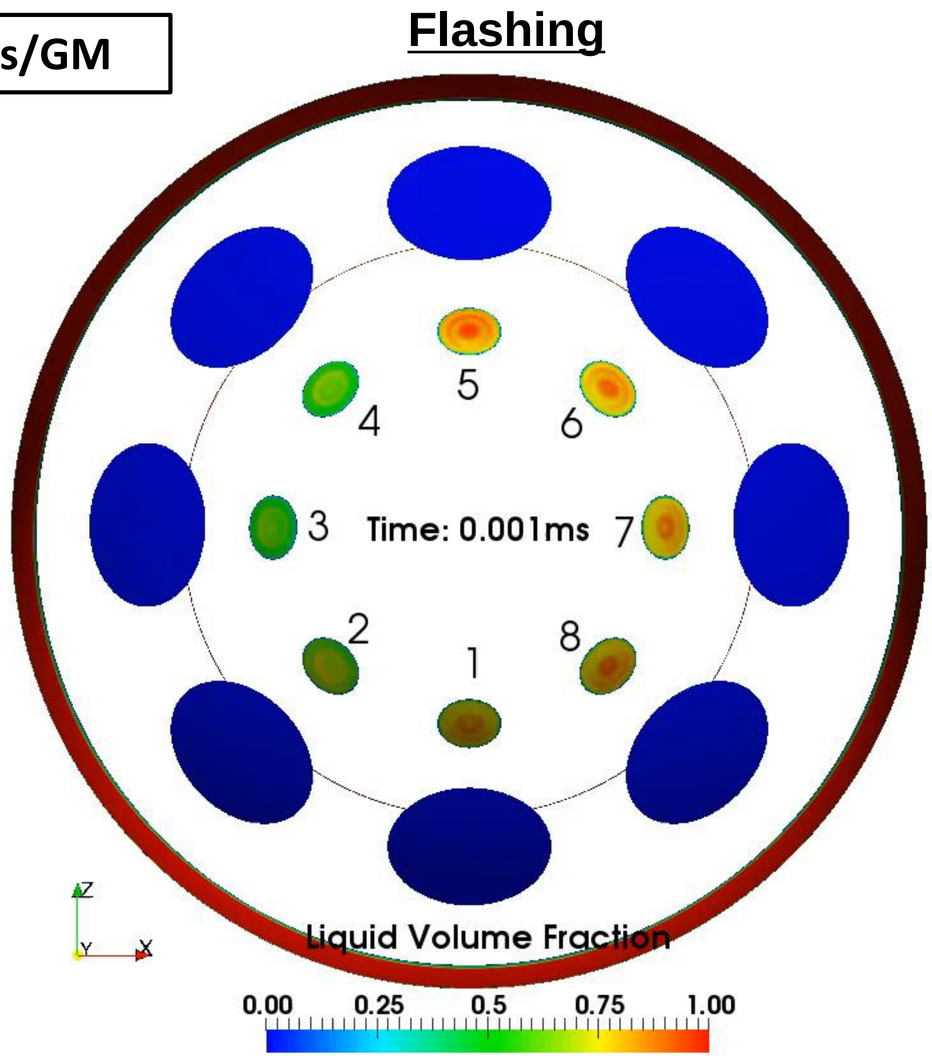


Flashing v/s Non-Flashing

Flashing v/s Non-Flashing (nozzle and counter bore exit)

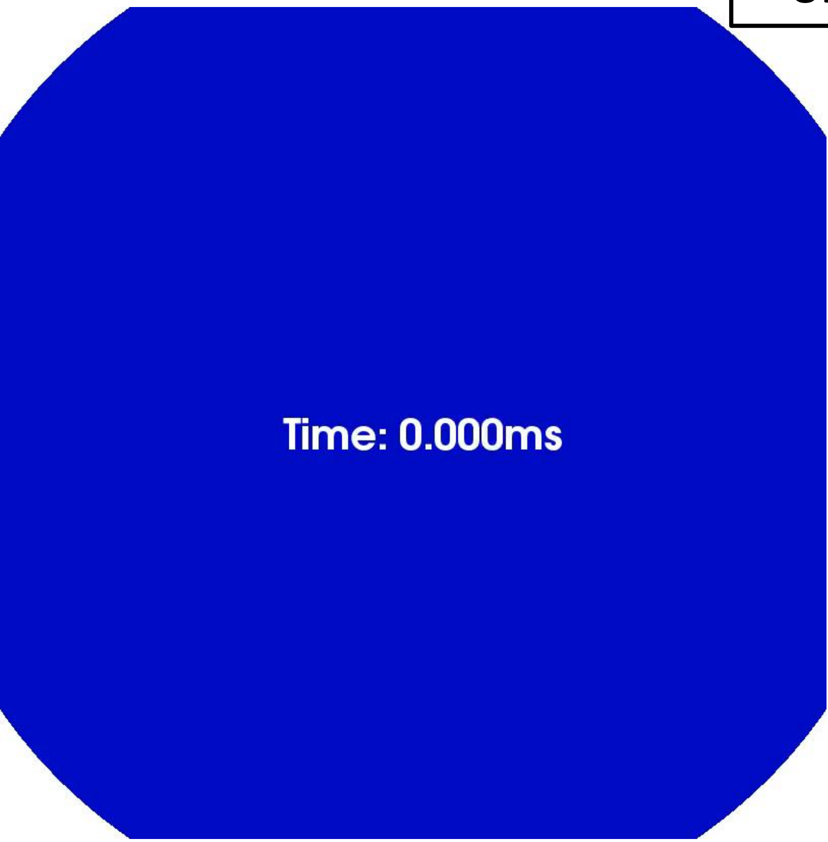
UMass/GM

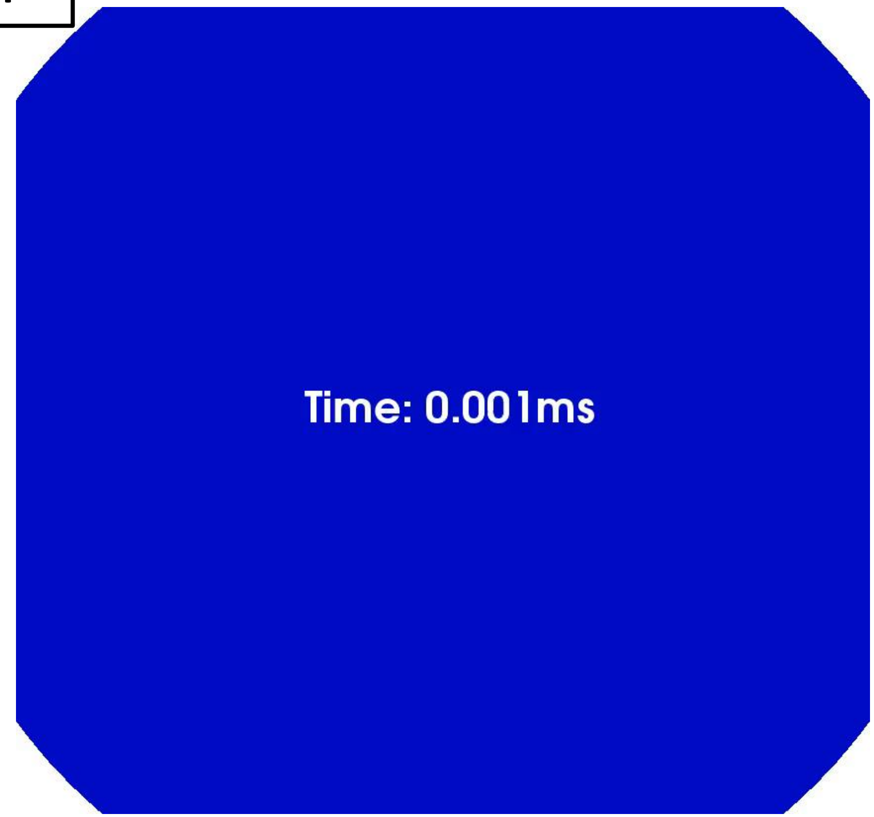




Flashing V/S Non-Flashing (Z=2mm)

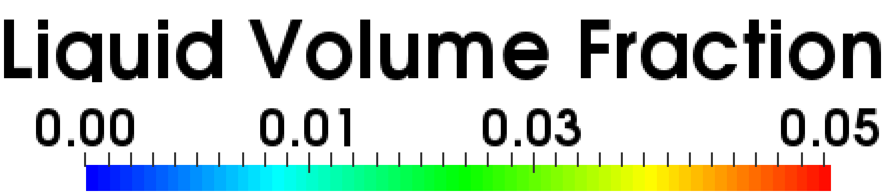
UMass/GM





Spray G

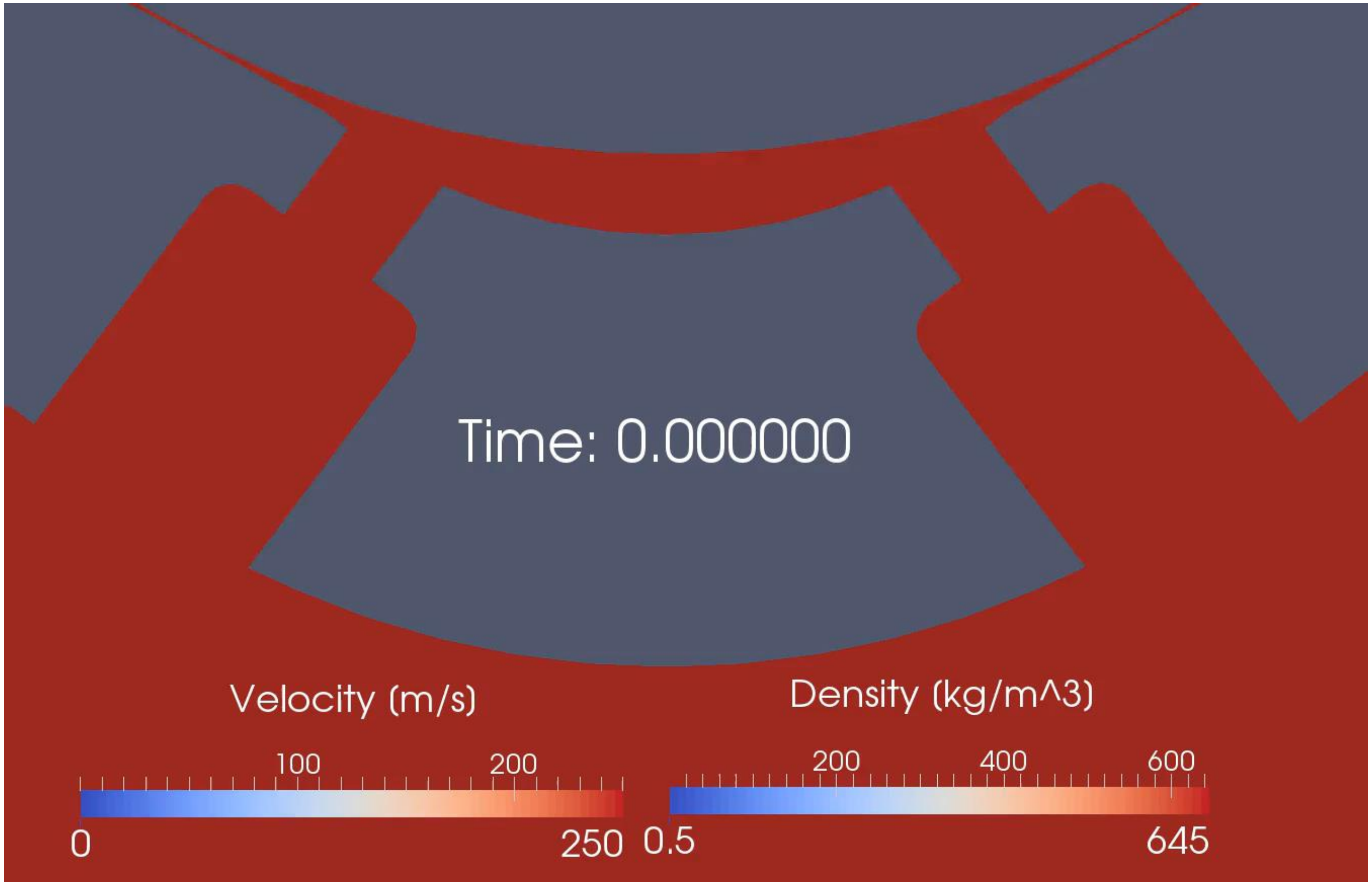
Spray G2



Sac Flow and Hole-hole variation

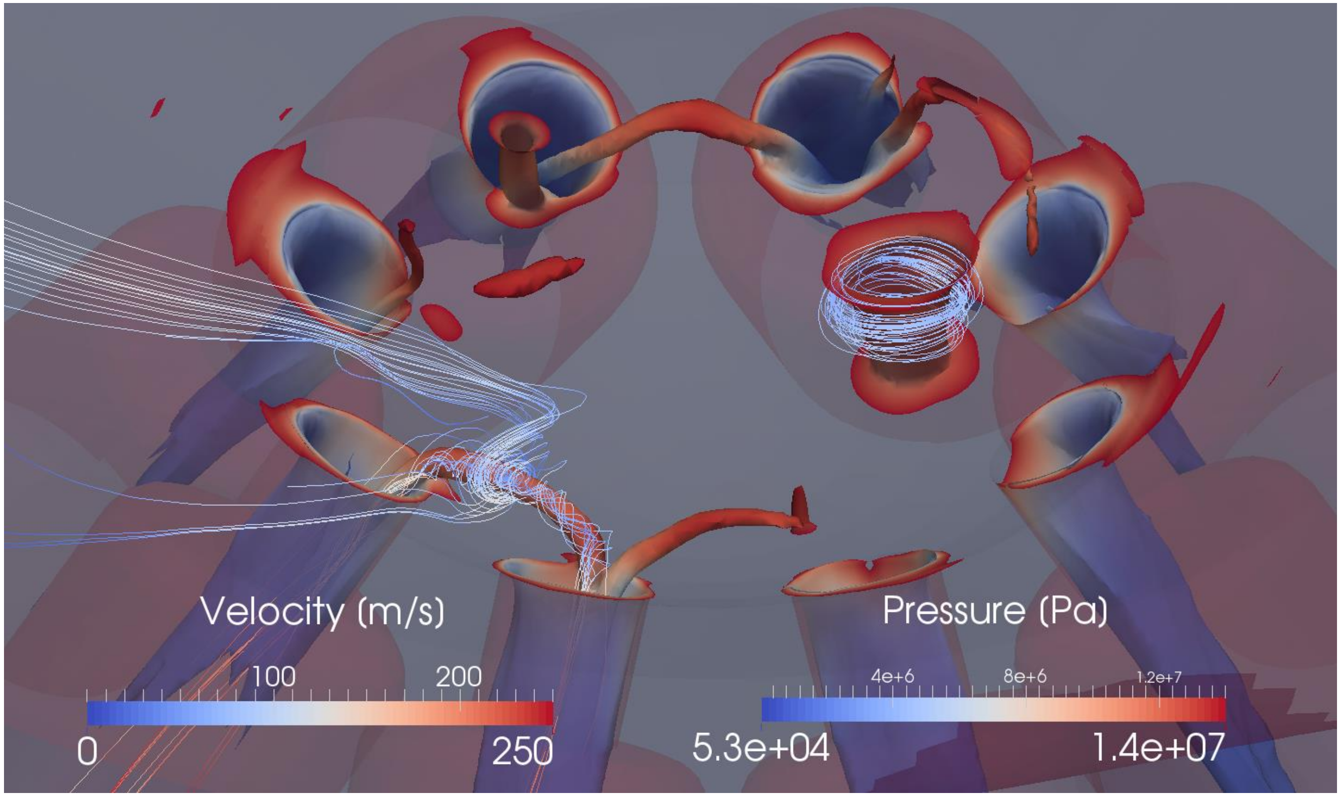
Exploration of hole to hole variation (Vorticity /Spray Connection)

UMass/GM



Vortical structure in SAC

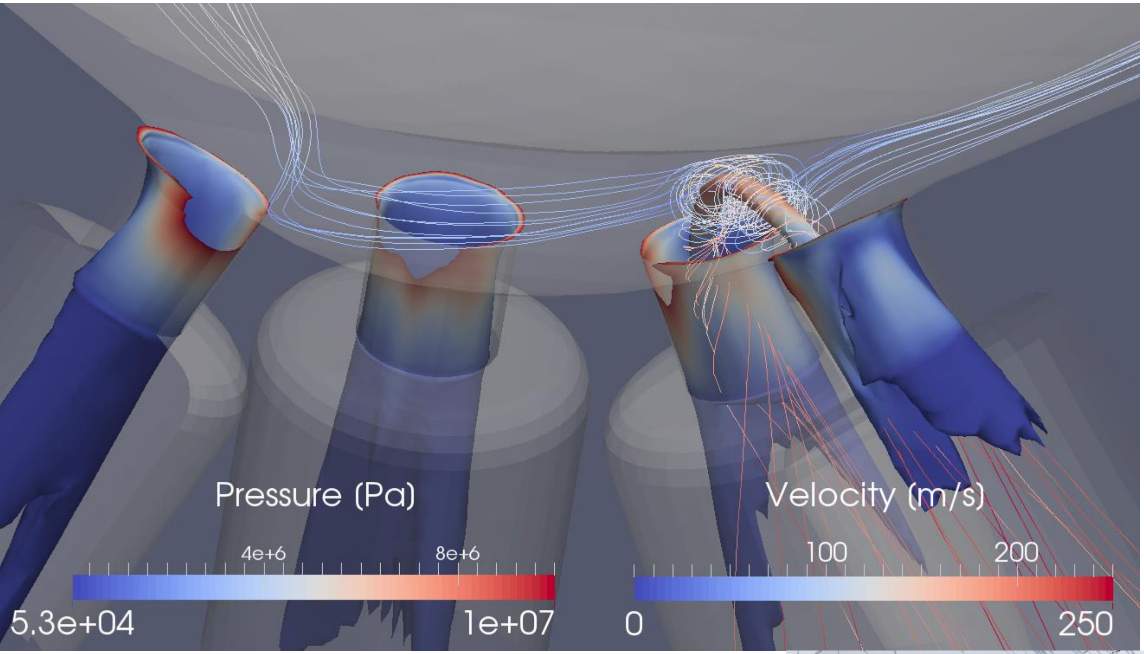
UMass/GM



1. Unterminated
2. Semi-terminated
3. Fully-terminated

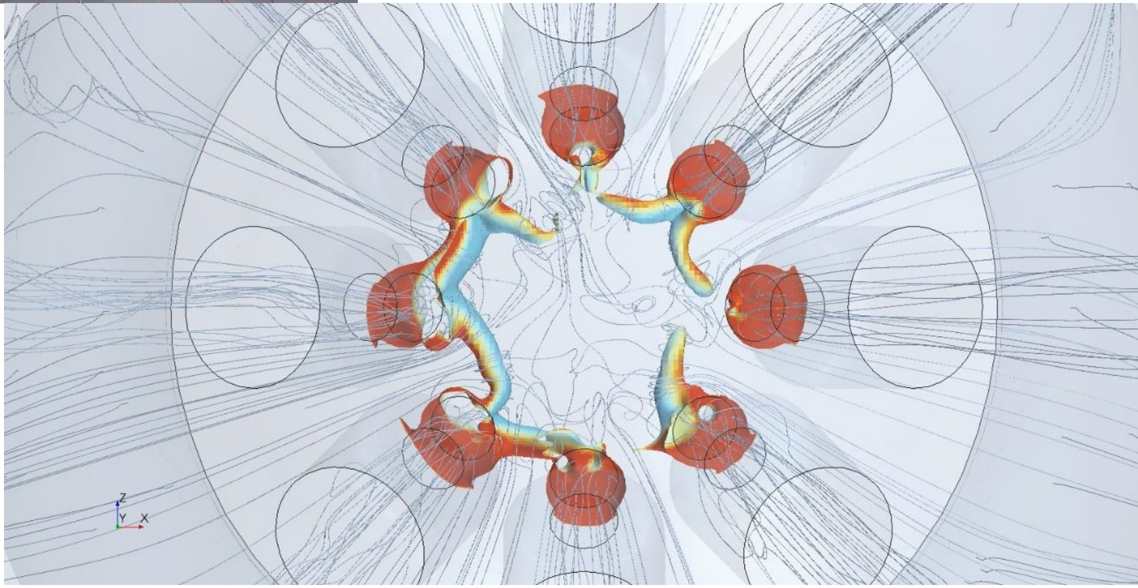
- Iso Surface of 14 Mpa total pressure colored by static pressure with velocity streamlines colored by velocity magnitude. Taken midway through flashing simulation. Vortices contained in the sac can be seen to terminate on a wall or they can be entrained into one or two nozzle holes

Flow crossing the SAC



UMass/GM

- Adverse pressure gradient induces vorticity into flow

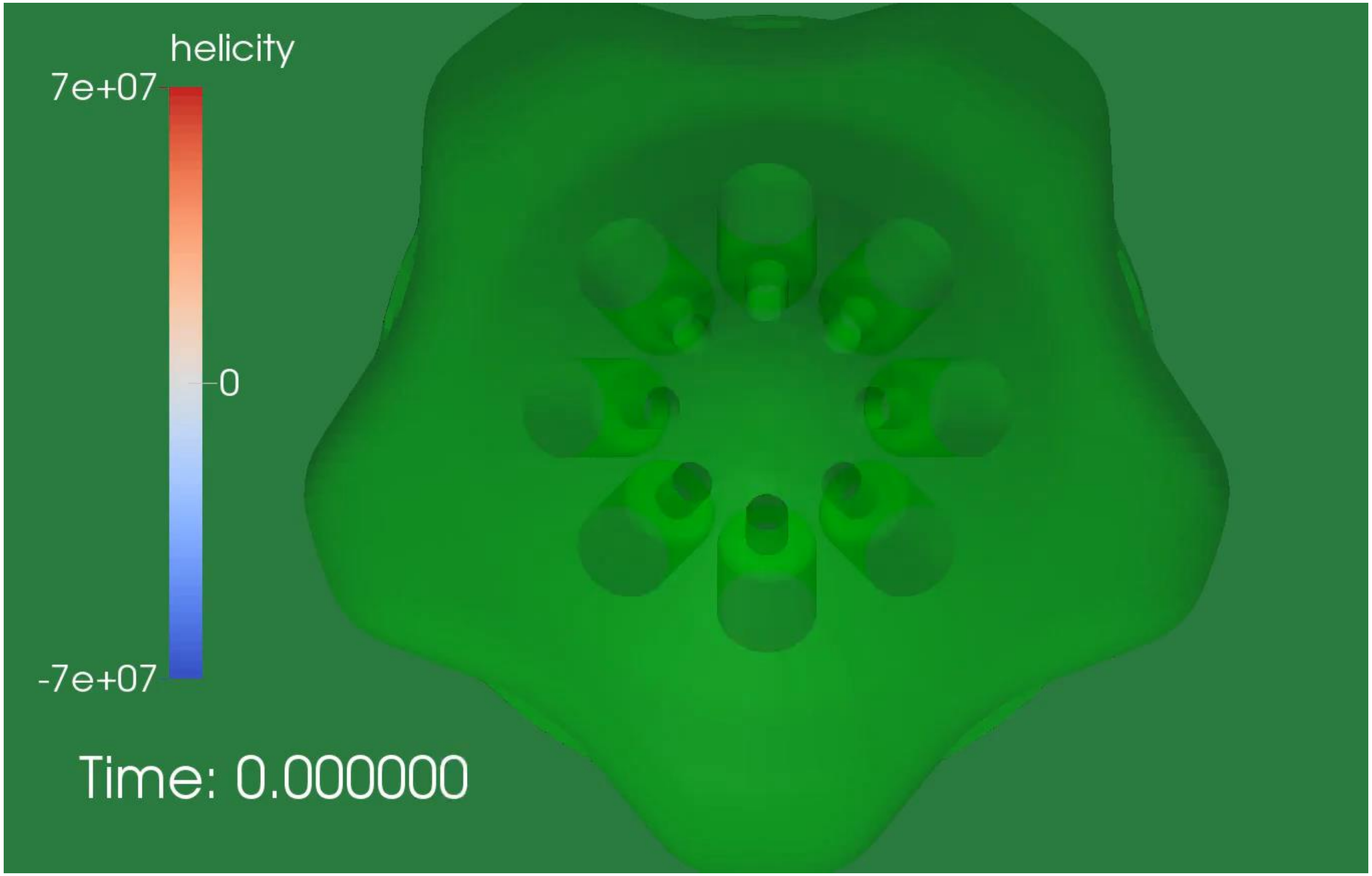


- The pressure range of the iso surface is 14 Mpa.

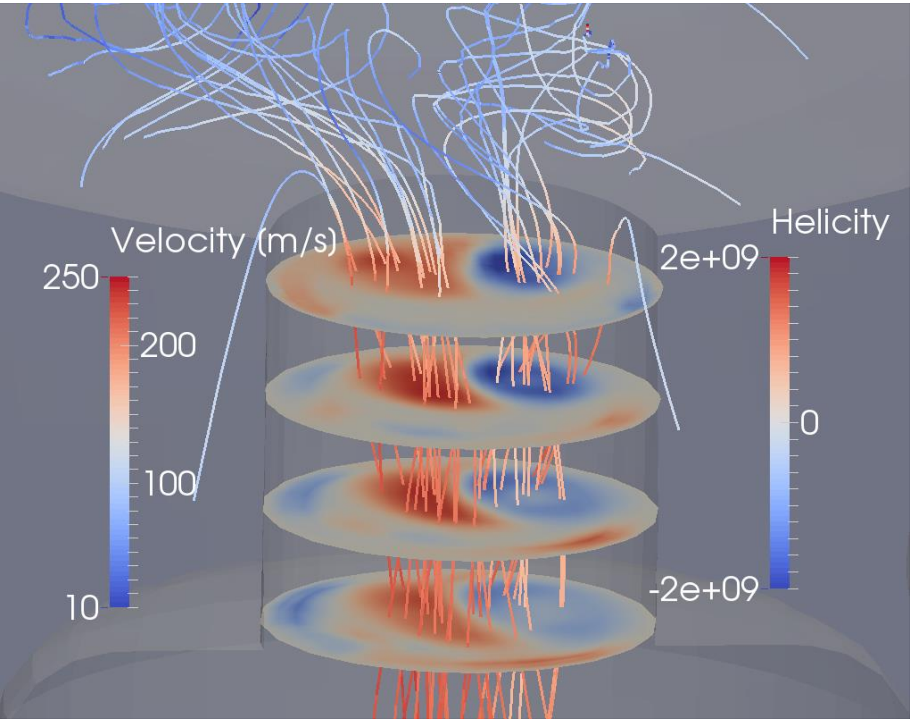
CD-Adapco

Where does it come from?

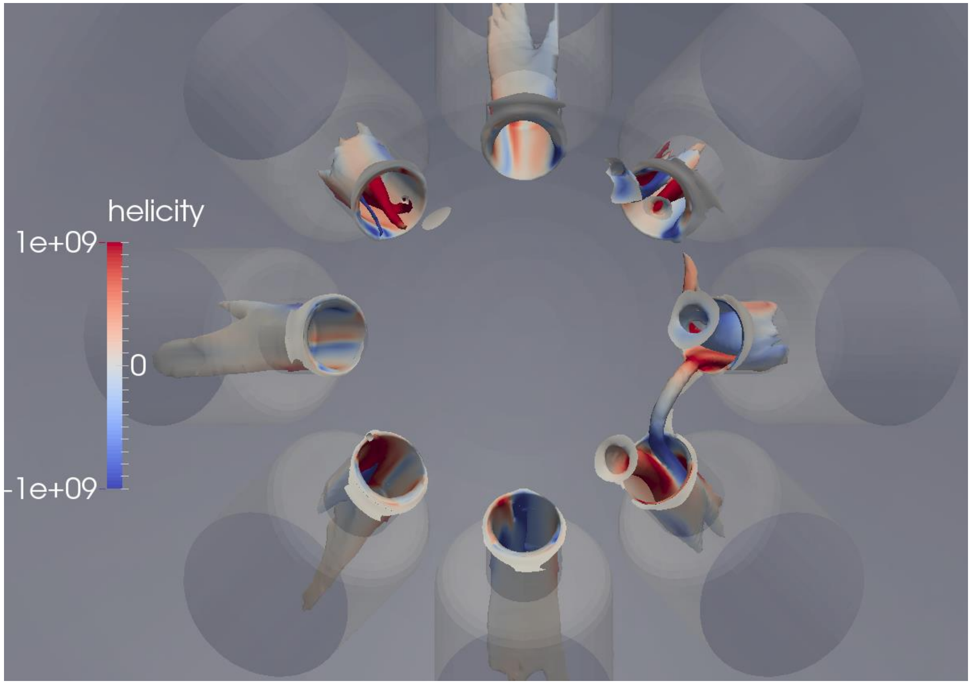
UMass/GM



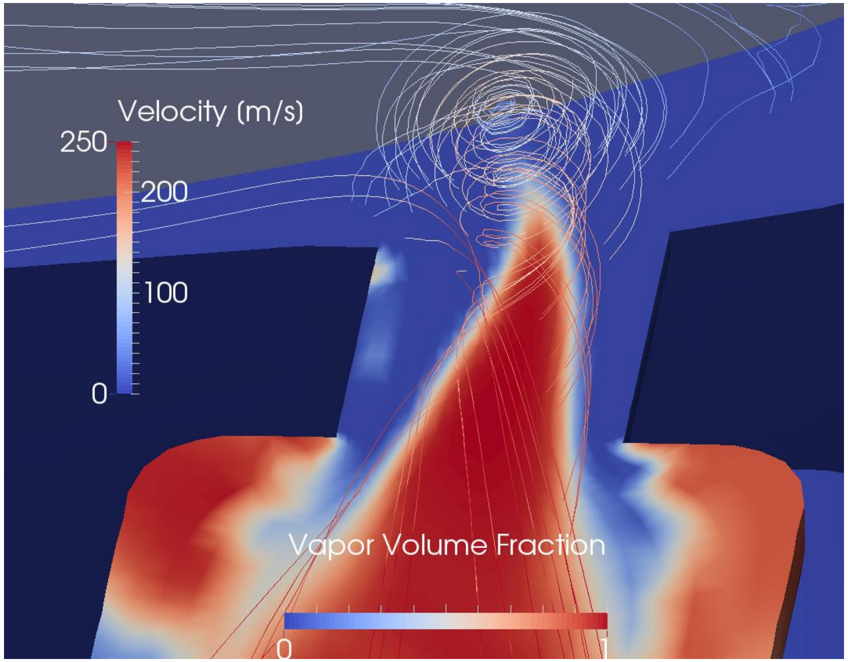
Vortices Sharing Hole



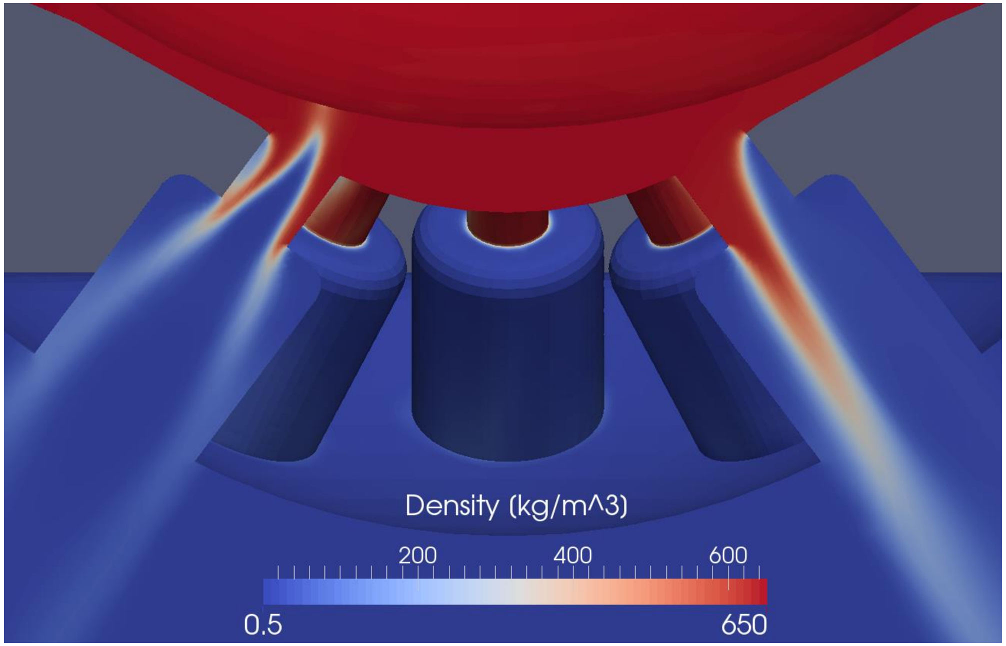
UMass/GM



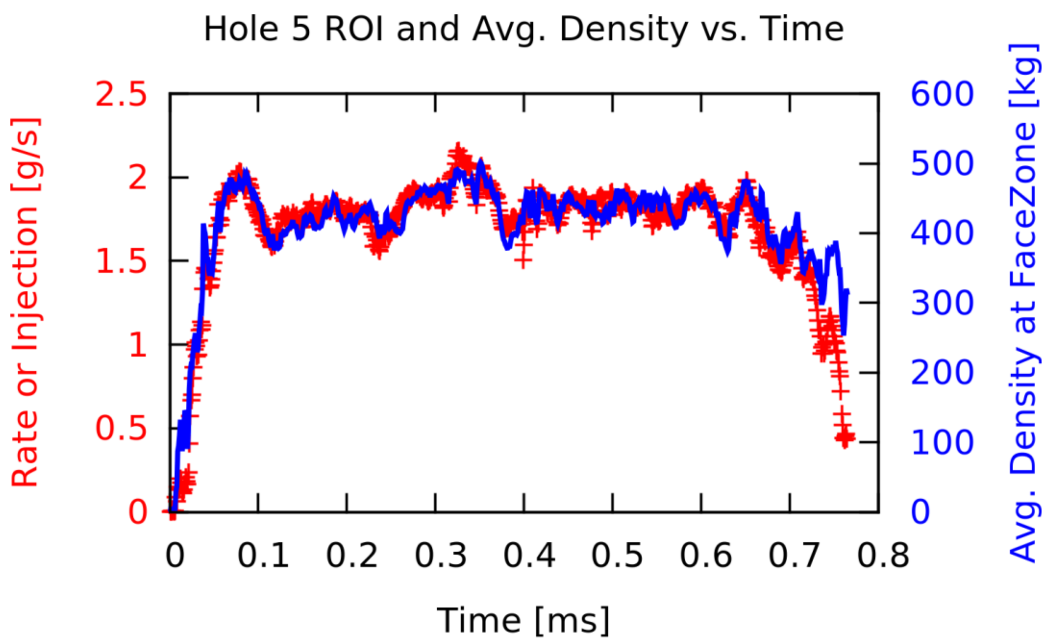
- Helicity = Vorticity dot U
- Counter-rotating vortices can share holes
- Co-rotating vortices are unstable



UMass/GM

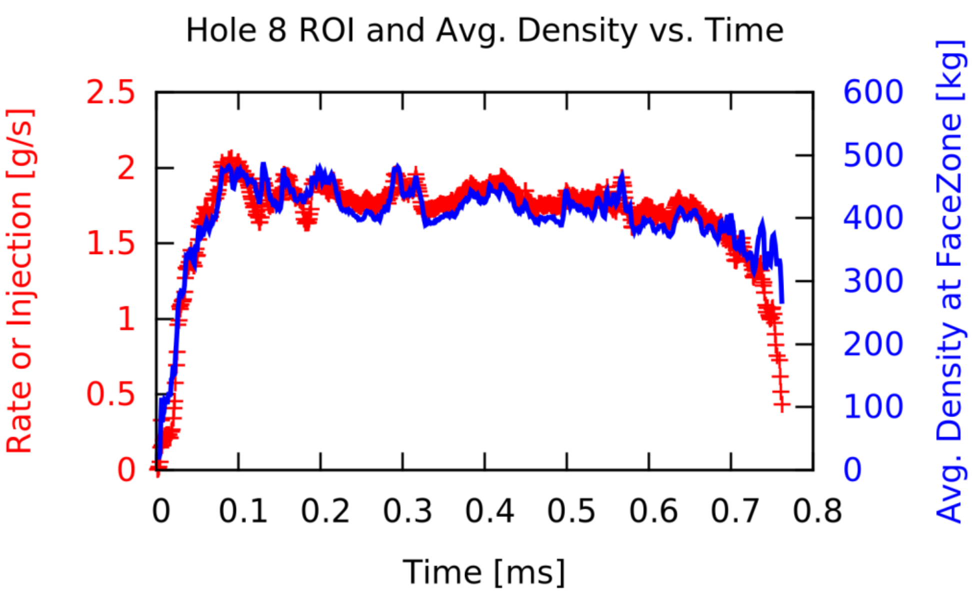


- String flash-boiling
- Perturbation of spray angle



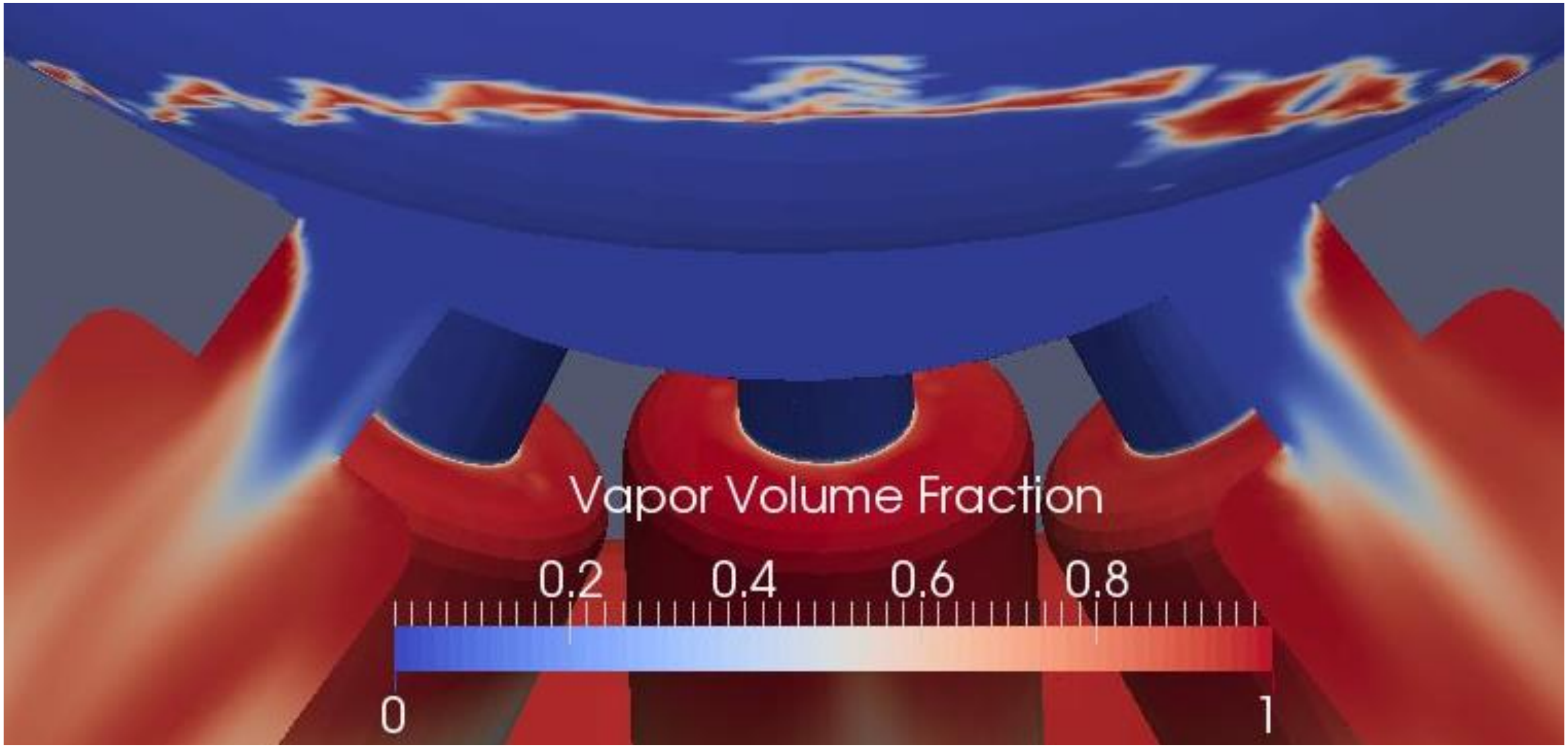
UMass/GM

Hole to Hole ROI variation follows the variation of Avg. Mixture Density.



Internal Vapor Generation

UMass/GM

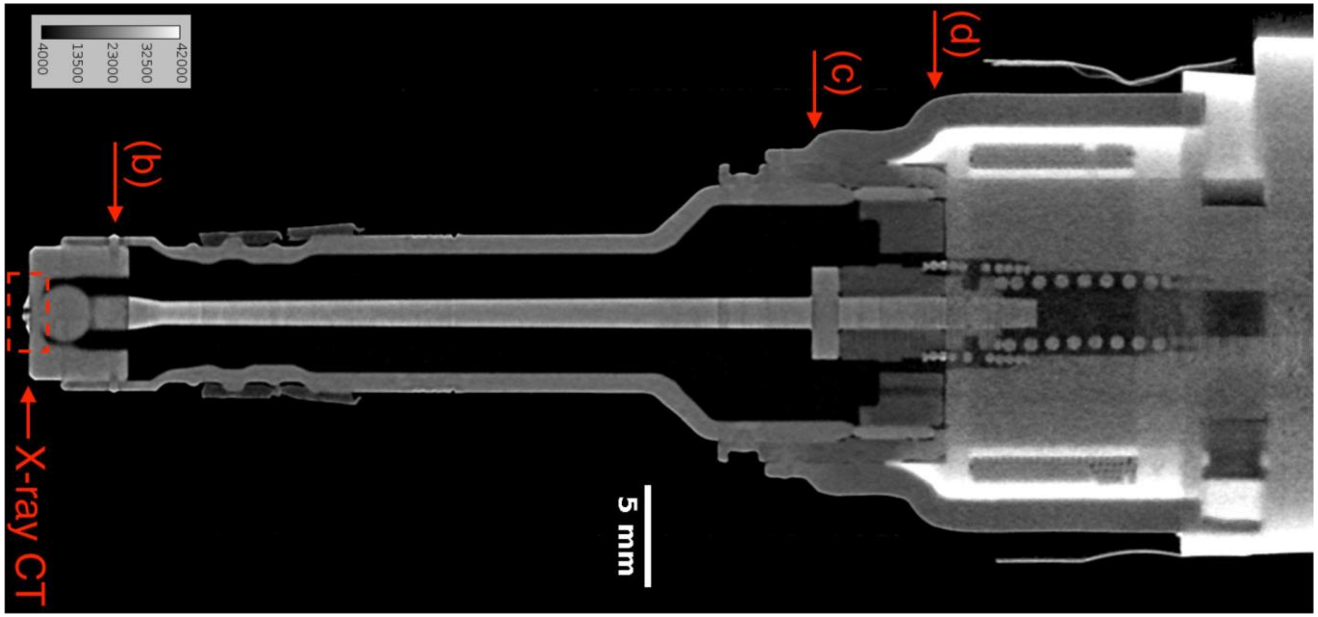


- Implications for IC of next injection event
- Could cavitation here degrade the needle/seat?

Computations with Updated Geometry

CFD With Scanned Geometry

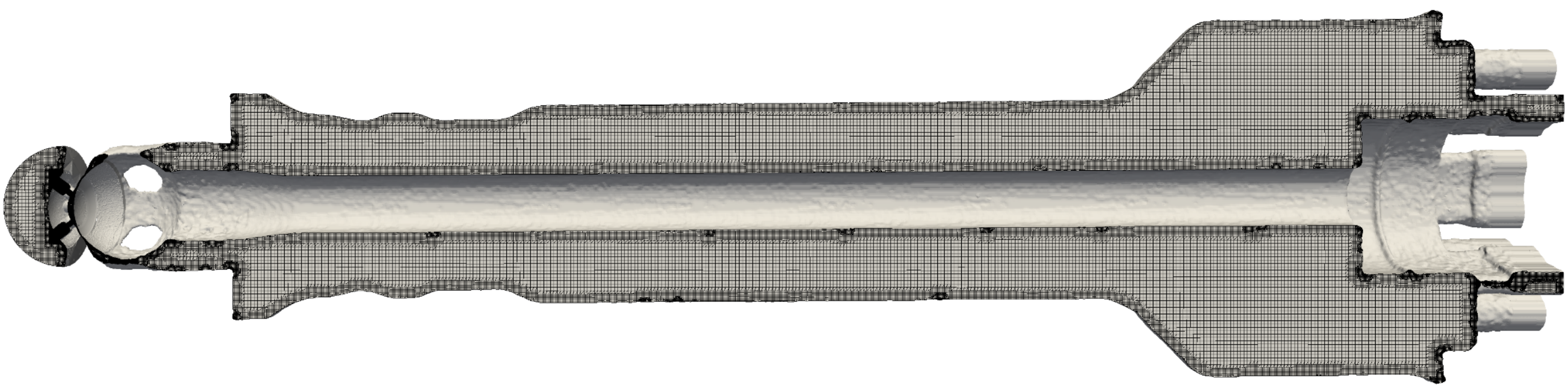
- Do the small-scale manufacturing defects and variabilities matter?
- 40 µm resolution from neutron imaging, 2 µm from x-ray imaging
- Non-flashing, submerged in iso-octane @ 5.8 bar



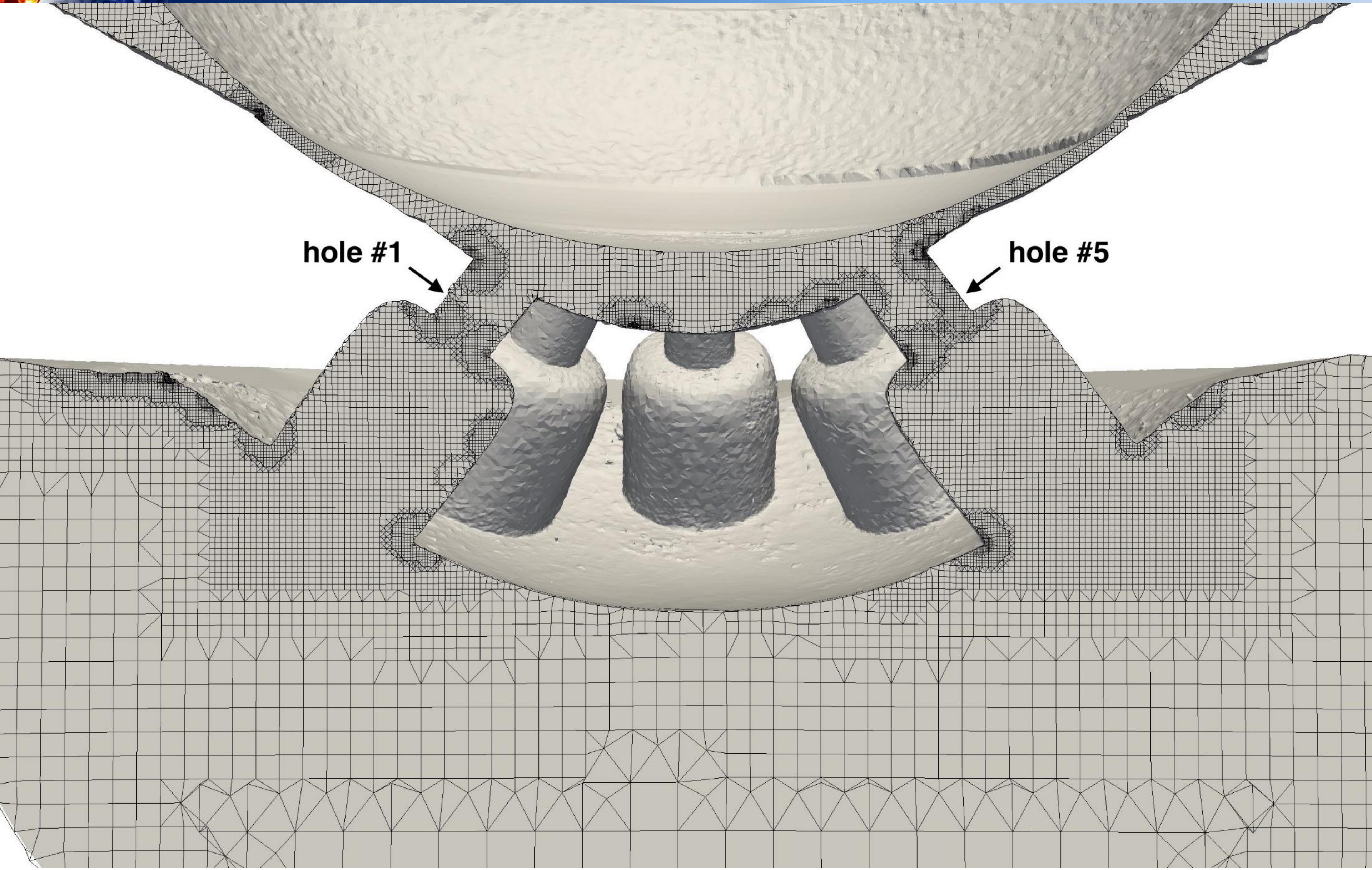
- *Duke et al / SAE Int. J. Fuels Lubr. / Volume 10, Issue 2 (June 2017)*

Modeling Details

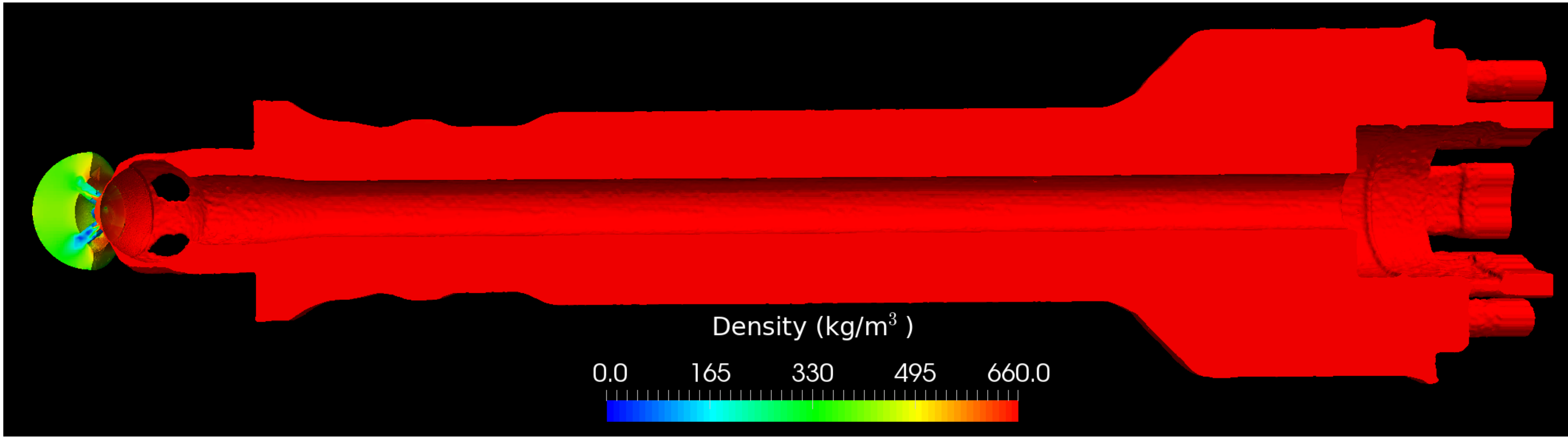
- HRMFoam (UMass)
- Static needle
- Time-varying upstream pressure
- Realizable k-eps turbulence model
- Using "snappyHexMesh" tool in OpenFOAM (hexahedral cut cells)
- Final mesh 13.7 M cells, minimum cell size 1.6 µm

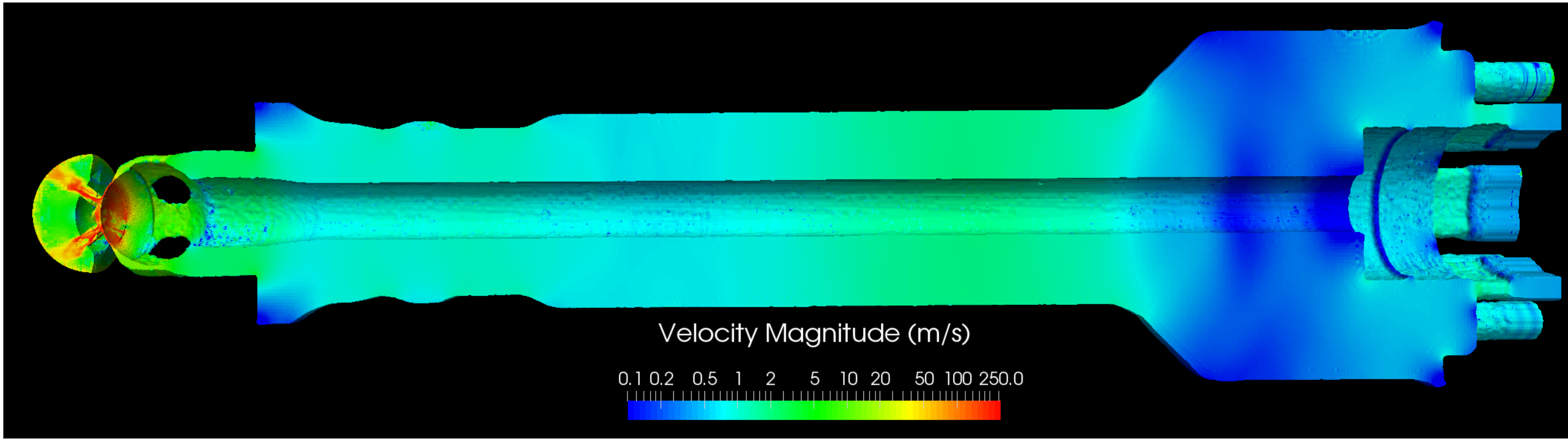


CFD Mesh



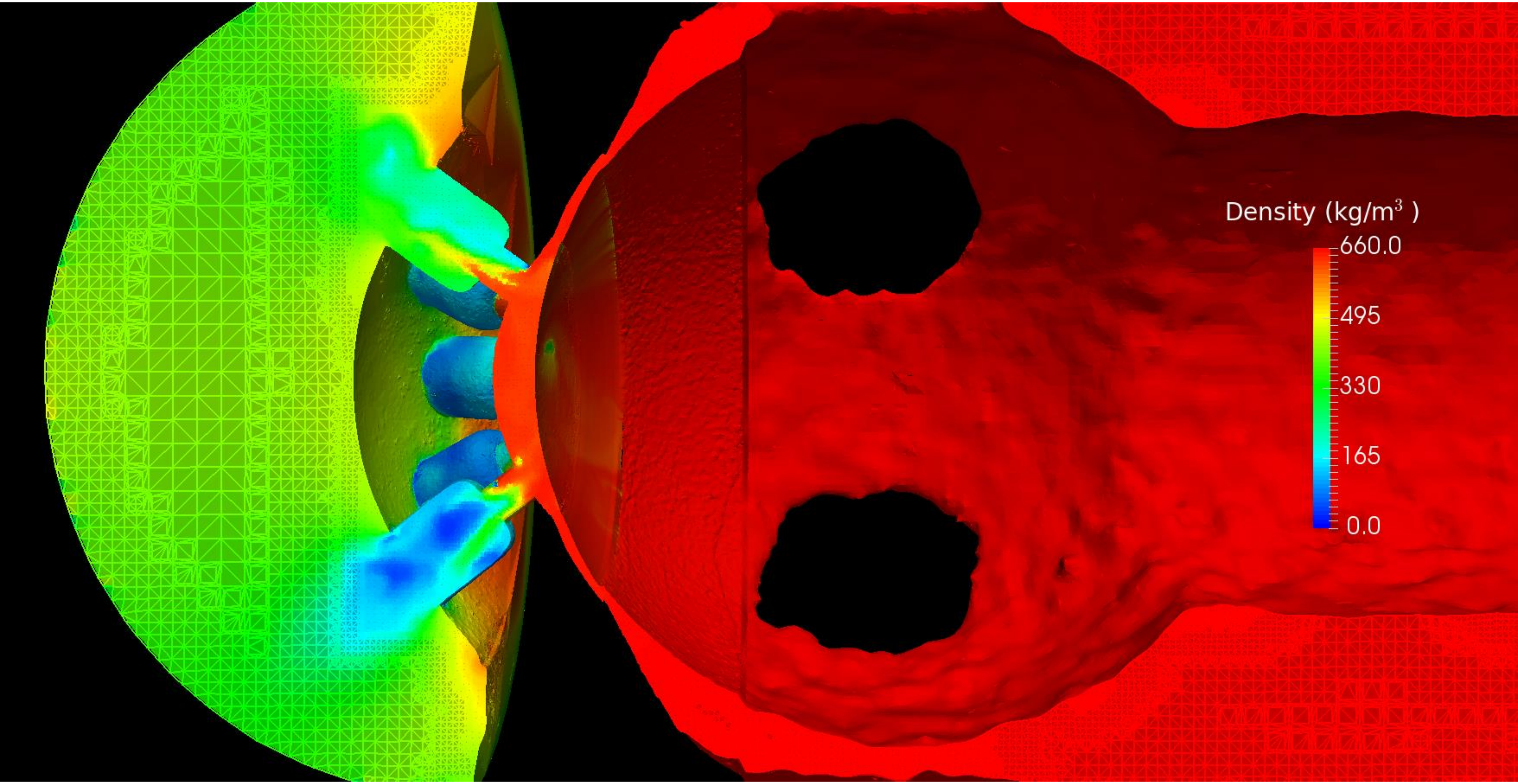
Cut plane of whole injector





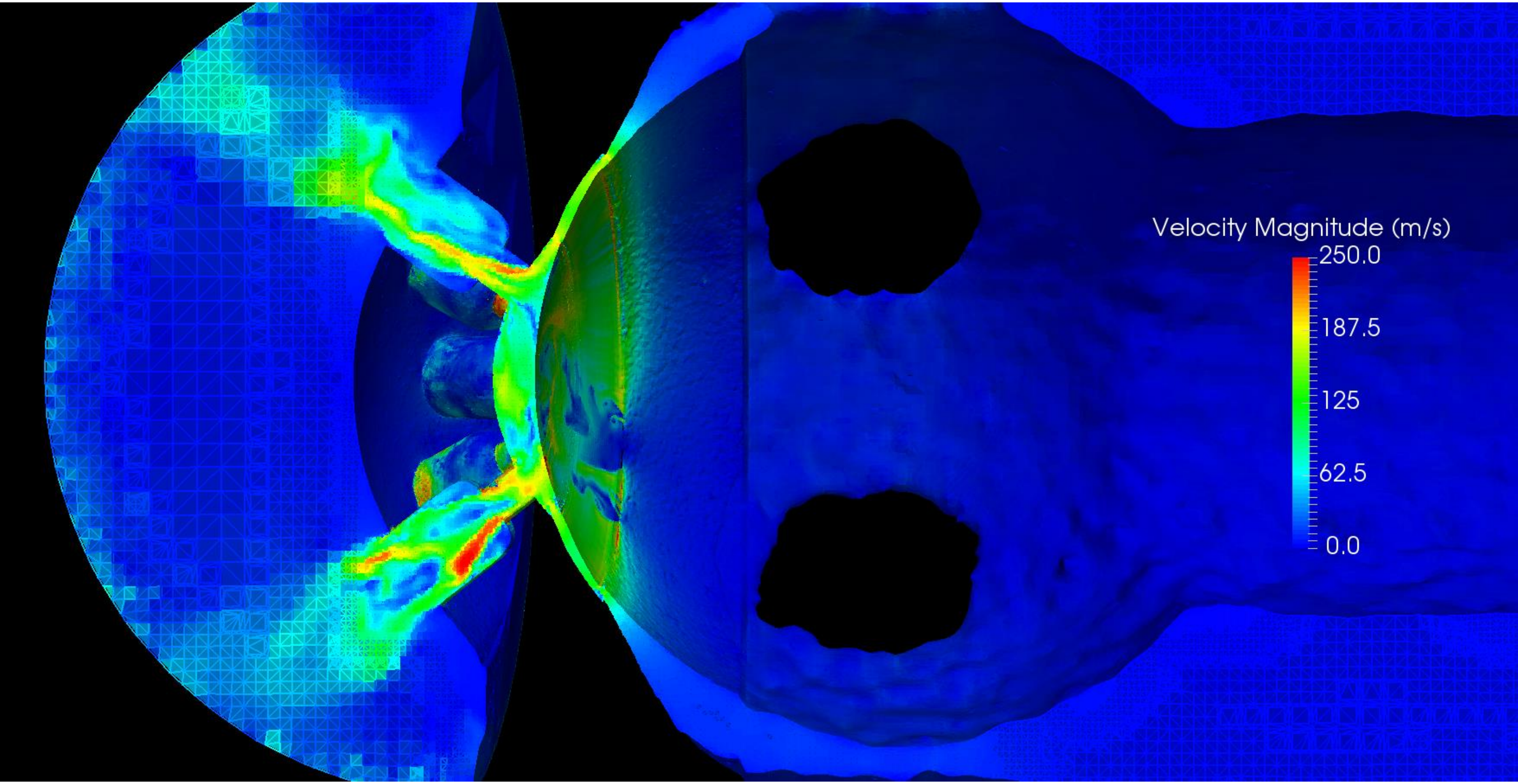
CFD Density Field

- T = +68 µs



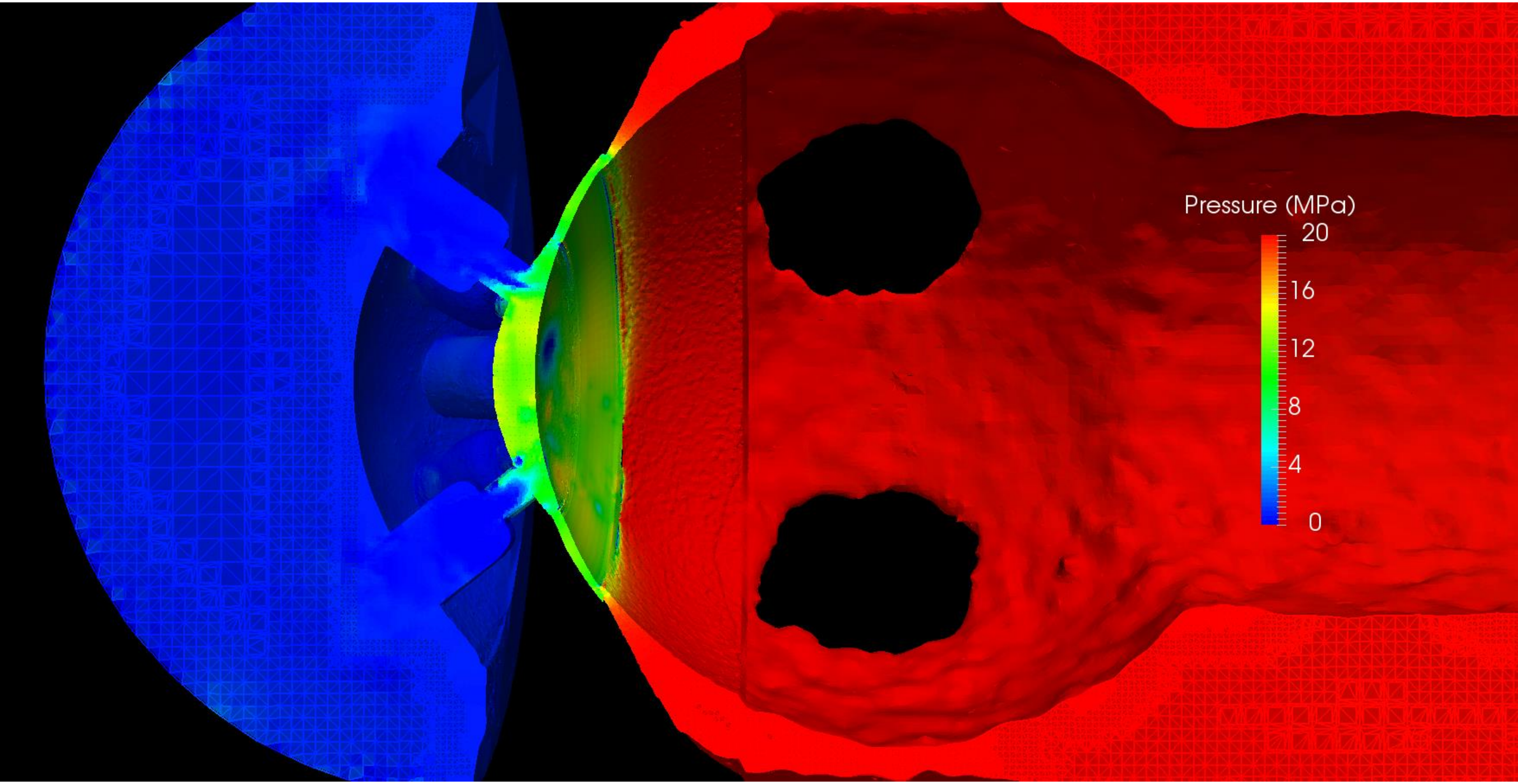
CFD velocity Field

- T = +68 μs



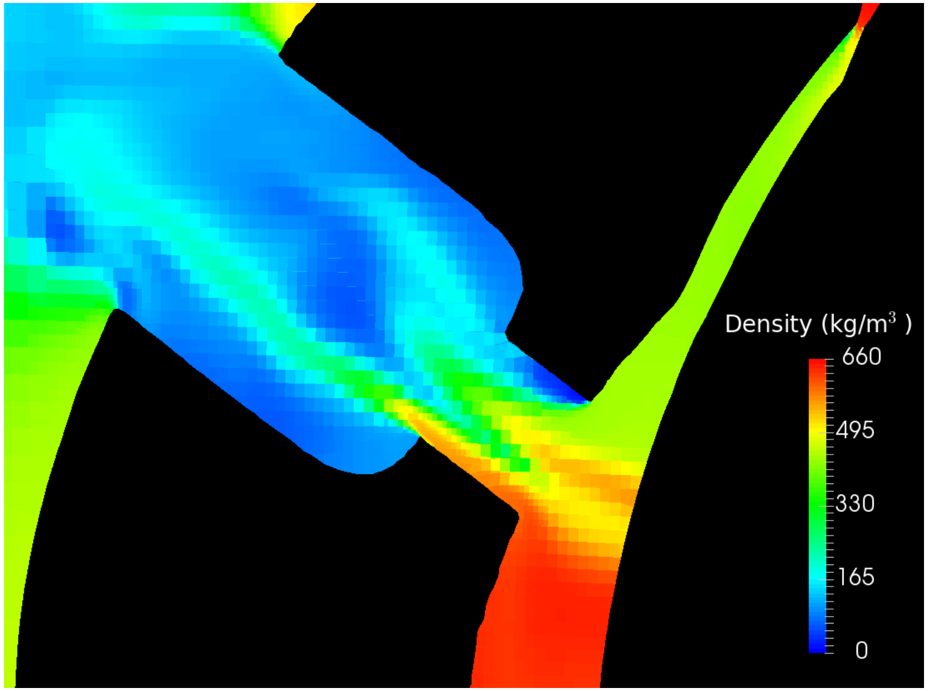
CFD pressure Field

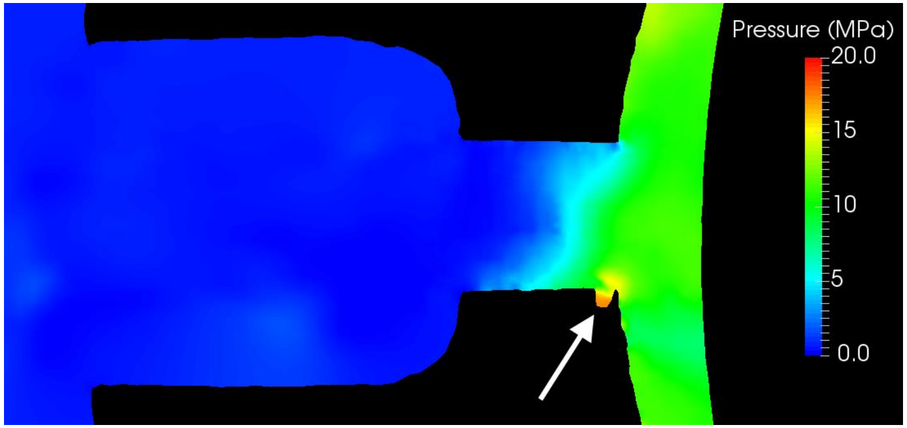
- T = +68 µs

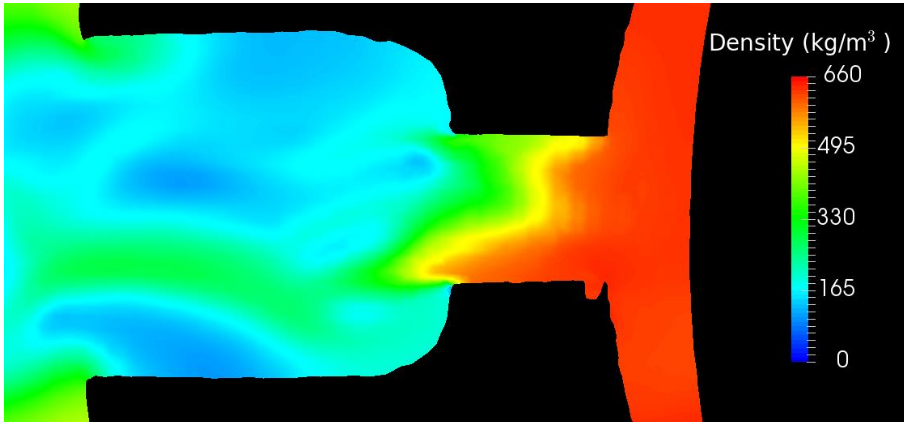


Zoom in on nozzle holes

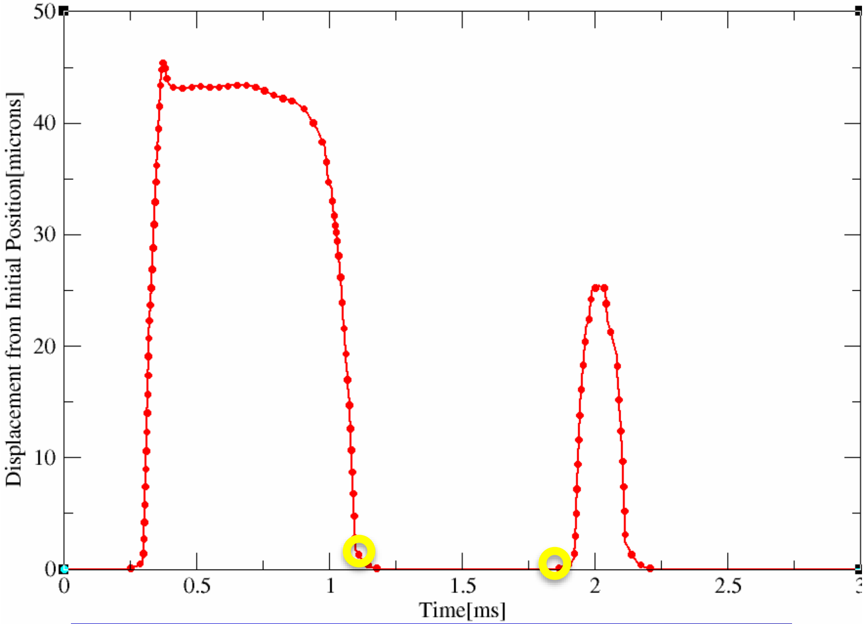
- Holes with nice sharp edges cavitate strongly
- Inclusions near the turning corner suppress cavitation!
  - High density, high pressure fluid recirculations inside the inclusion
    - This has an effect on hole discharge
- We have seen evidence in x-ray radiography data that Cd varies from hole to hole

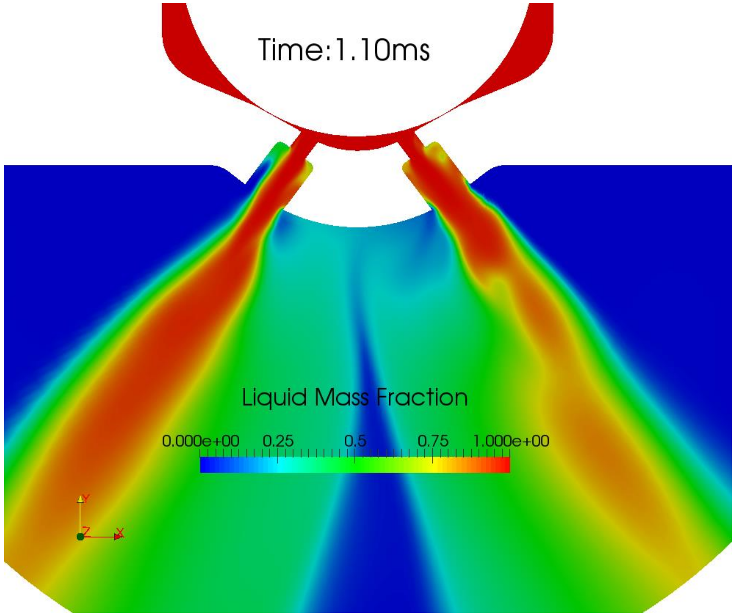


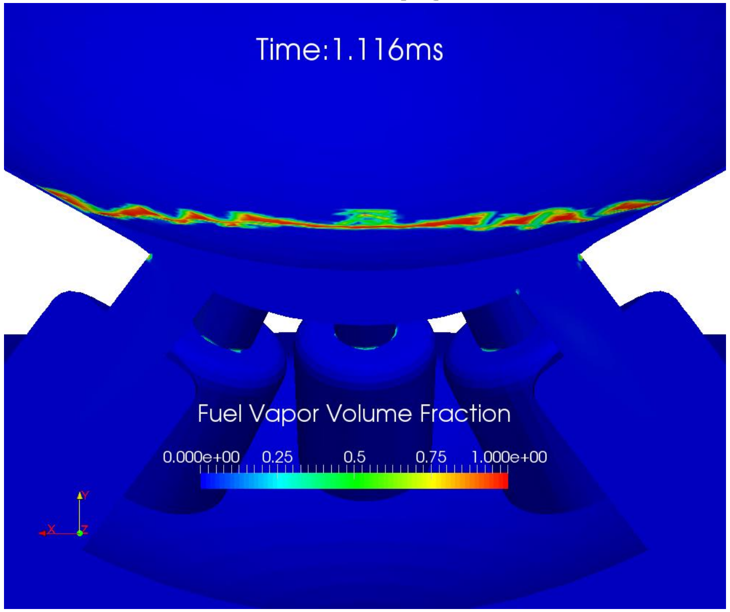




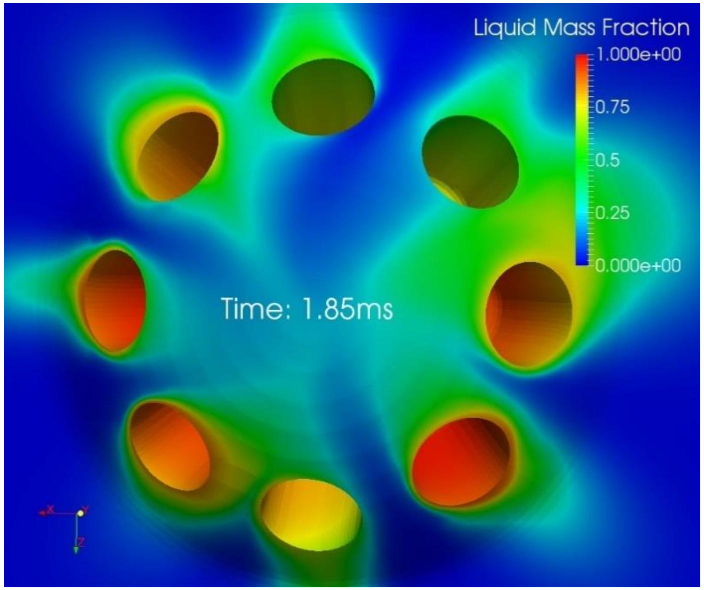
Foreshadowing … Needle Closure- Multiple Injection



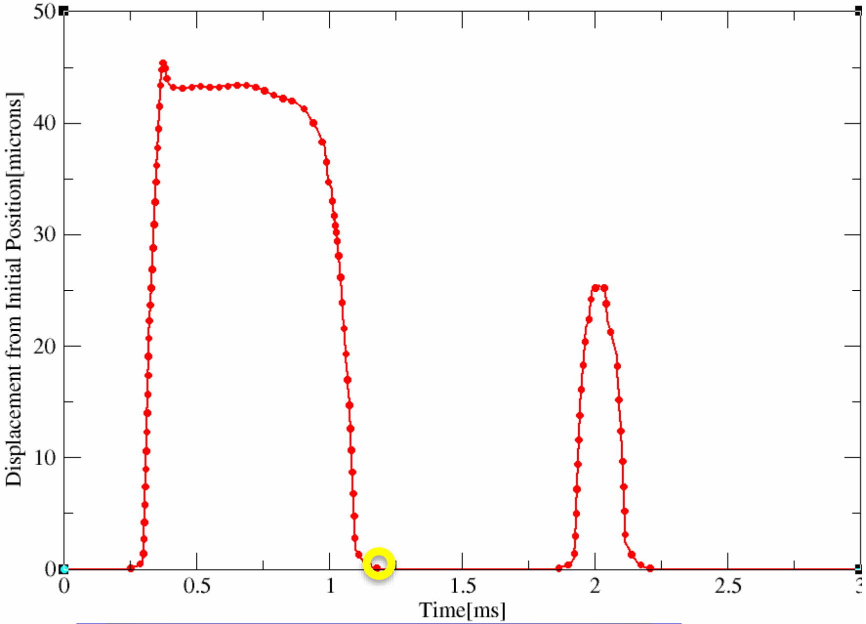


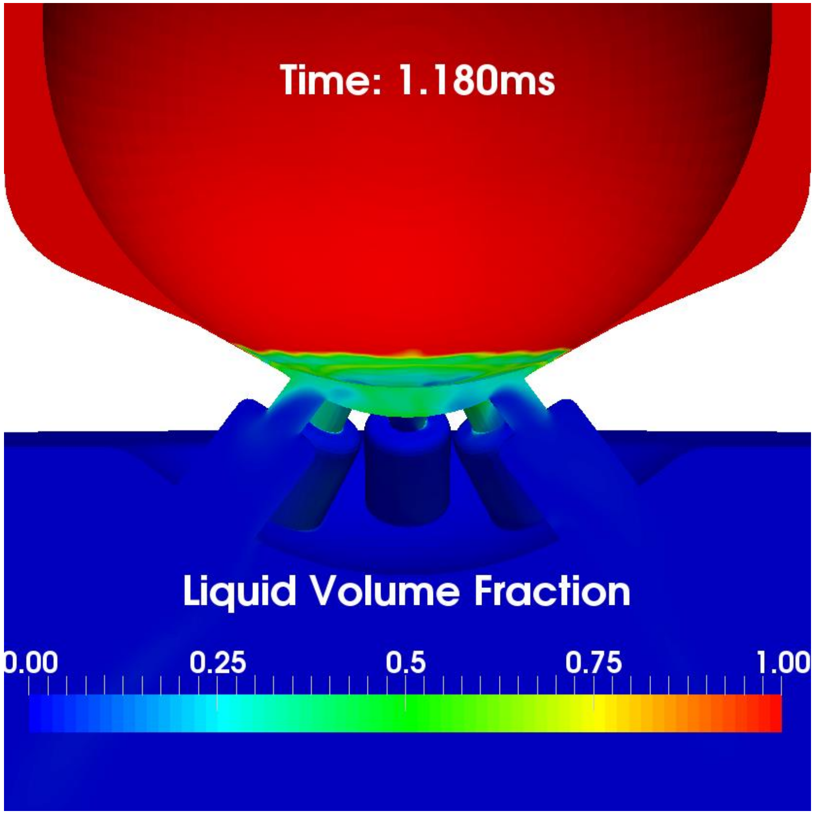


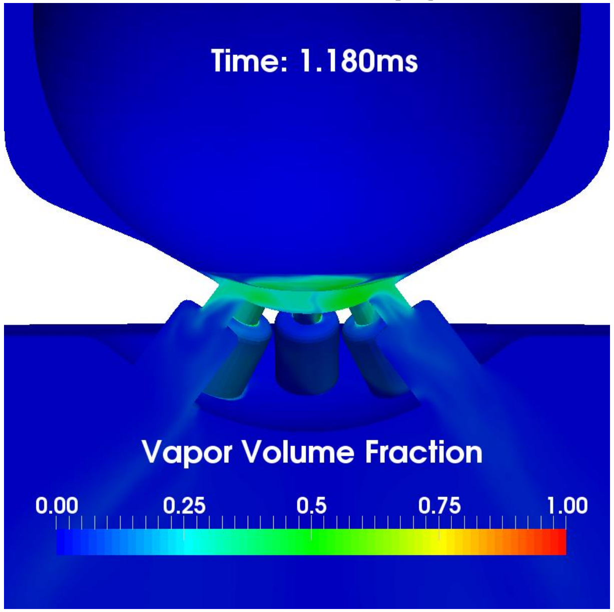
Spray G



Needle Closure- Multiple Injection(Flashing)







Spray G2

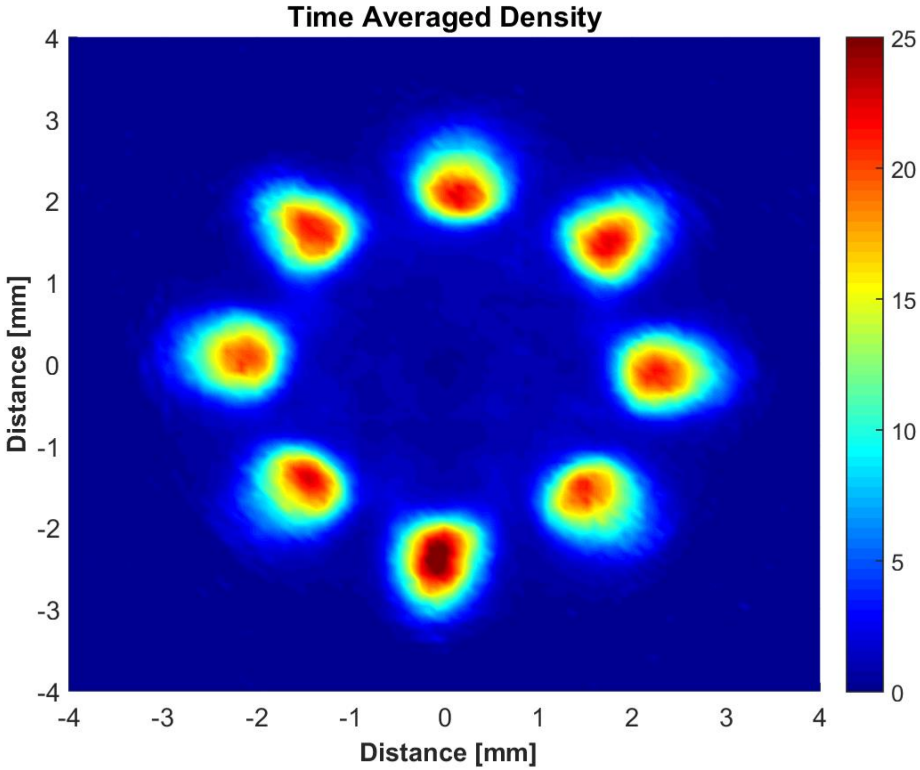
Summary

- Models can predict mass flow rate/Cd
- The sac is home to powerful vortices
- Highly transient variation, transition to swirl
- Need to include real geometry

- Bonus slides

Time averaged Density at Z=2mm

ANL X-Ray Thermography for SprayG#29

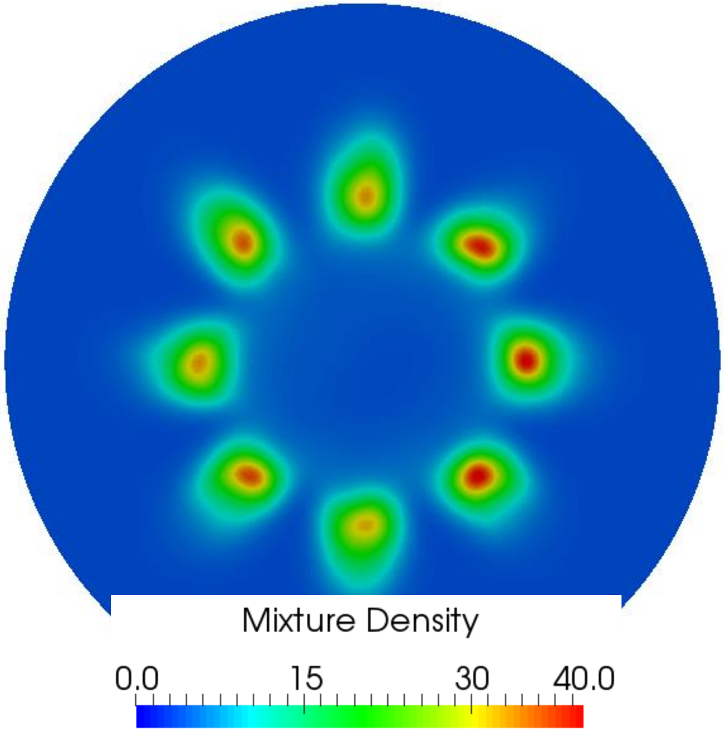


Experimental data provided by Katie Matusik at Argonne National Lab

*Note- The ANL contour represents X-Ray measured density

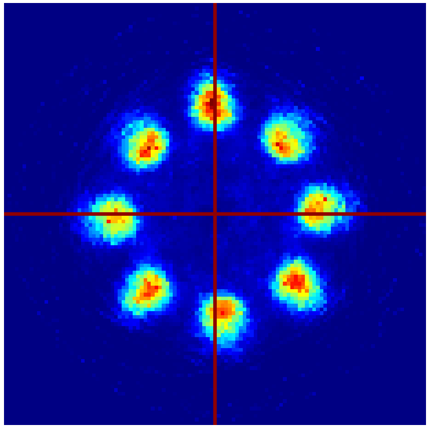
The ANL data has been time averaged in the range of 0.2ms-0.6ms.

The UMass data has been time averaged in the range of 0.2ms-0.6ms.

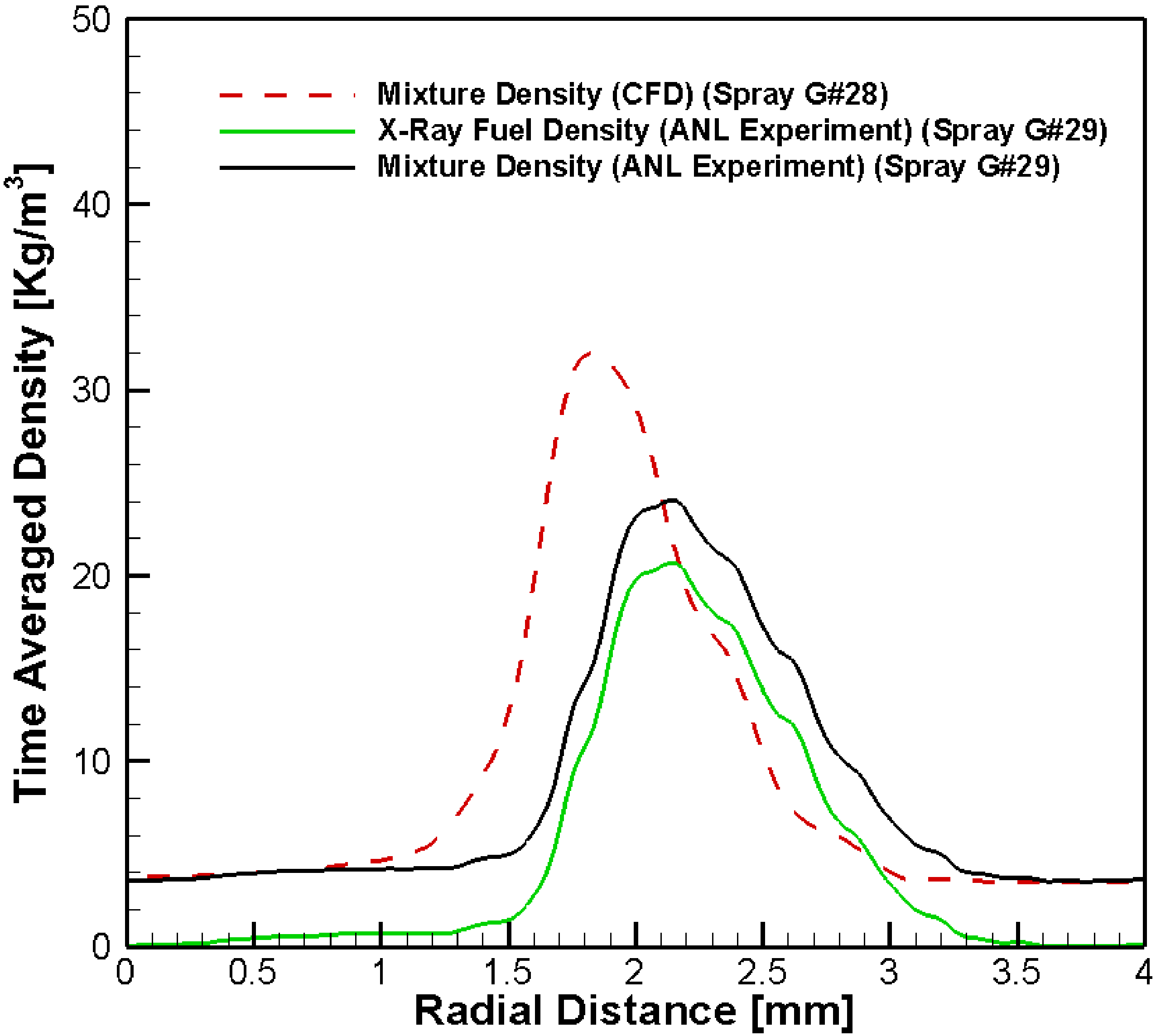


UMass/GM

Time averaged Mixture Density v/s Radial Distance



CFD studies have been performed by UMass



Experimental data provided by Katie Matusik at Argonne National Lab