Internal Injector Flow Session

Group Leaders: Marco Arienti (SNL), Chris Powell (ANL), David Schmidt (UMass)

Contributors: Alan Kastengren (ANL), Thomas Furlong and Caroline Genzale (GA Tech), Sukanta Rakshit (UMass)

Progress Summary:

X-Ray tomography measurements by Argonne and Caterpillar have produced updated assessments of the nozzle geometry that reveal a more irregular nozzle exit for Spray A than previously indicated by silicone molding. Argonne's X-ray phase-contrast measurements have also documented the transient needle motion for Spray A injection. Argonne's X-ray measurements were used to assess the spray-H geometry as well.

All existing geometry characterizations produce nozzle surfaces with some degree of noise while also reflecting the irregular as-built shapes of the nozzles. Georgia Tech has developed an algorithm to smooth small irregularities in the measured nozzle shape while preserving larger scale shape information. This filtered geometry can then be used as the basis for generating computational meshes.

Modeling was performed using a simplified geometry based on the silicon mold shape. Modeling was performed using two compressible models and static geometry (UMass and Georgia Tech). Simulation results by Sandia with moving boundaries is forthcoming.

Findings:

- The transition from experimentally-measured geometry to computational geometry is a significant barrier to producing simulation results.
- Modeling results show no indication of cavitation in Spray-A. The absence of cavitation is due to two factors: the large degree of conicity of the nozzle shape and the assumed smooth walls. Modeling groups have expressed interest in Spray A, even if non-cavitating.
- Compressibility effects and nozzle convergence in Spray-A cause significant density drop and acceleration of the liquid as it transits the nozzle.
- Spray-H was found to cavitate, but the predicted nozzle discharge was very sensitive to the assumed inlet corner radius.
- The existing uncertainty in the measured inlet nozzle corner is a dominant error in the prediction of sharp nozzle discharge, such as in Spray-H

Recommendations and Future Directions:

- Spray-H is obsolete and its geometry is inadequately characterized. The workshop participants indicated that a 2X larger, transparent nozzle would provide a future target to replace Spray-H.
- Future modeling will test the efficacy of the proposed computational geometry process being developed at Georgia Tech.

- Experimentalists are hoping to find time to study Spray B, but continued interest in Spray A is the priority for most. It is suggested that a sharp-edged versions Spray A nozzles be obtained to study cavitation.

Engine Combustion Network

ECN2: Nozzle Geometry and Internal Flow

Session organizers:
Chris Powell
David Schmidt
Marco Arienti

Second Workshop of the Engine Combustion Network,

Heidelberg, Germany, September 2012

Outline

- Experimental Results
  Chris Powell
- 3D Reference Geometries of ECN Nozzles
  Caroline Genzale
- Internal Flow Modeling – Static Geometry
  David Schmidt
- Internal Flow Modeling – Moving Mesh
  Marco Arienti

Engine Combustion Network

Nozzle Geometry and Internal Flow: Experimental Results

Alan L. Kastengren, F. Zak Tilocco, Christopher F. Powell
Argonne National Laboratory

Tim Bazyn
Caterpillar Inc

Raul Payri, Jaime Gimeno
CMT Motores Termicos

Julien Manin, Lyle M. Pickett
Sandia National Laboratories

Second Workshop of the Engine Combustion Network,

Heidelberg, Germany, September 2012

Outline

- Publication of Spray A results submitted to Atomization & Sprays
  - Coordinate system
  - Turning angle, radius of curvature
  - Nozzle diameter and shape
  - Needle lift and velocity
  - Needle off-axis motion
  - Spray momentum, mass flow, discharge coefficients
- Web-based tool for Rate-of-Injection
- Images of Spray H Geometry
- Density measurements of Spray A for validation
- Data available for mesh development

Results from ECN1 Submitted to A&S

Engine Combustion Network (ECN): Measurements of Nozzle Geometry and Hydraulic Behavior

Alan L. Kastengren
X-Ray Science Division
Argonne National Laboratory
Bldg. 362, Room C240A; 9700 S. Cass Ave.
Argonne, IL 60439 USA
akastengren@anl.gov

F. Zak Tilocco, Christopher F. Powell
Center for Transportation Research
Argonne National Laboratory
powell@anl.gov

Julien Manin, Lyle M. Pickett
Combustion Research Facility
Sandia National Laboratories
jmanin@sandia.gov; lmpicke@sandia.gov

Raul Payri
CMT Motores Termicos
Universitat Politecnica de Valencia, SPAIN
rpayri@mot.upv.es

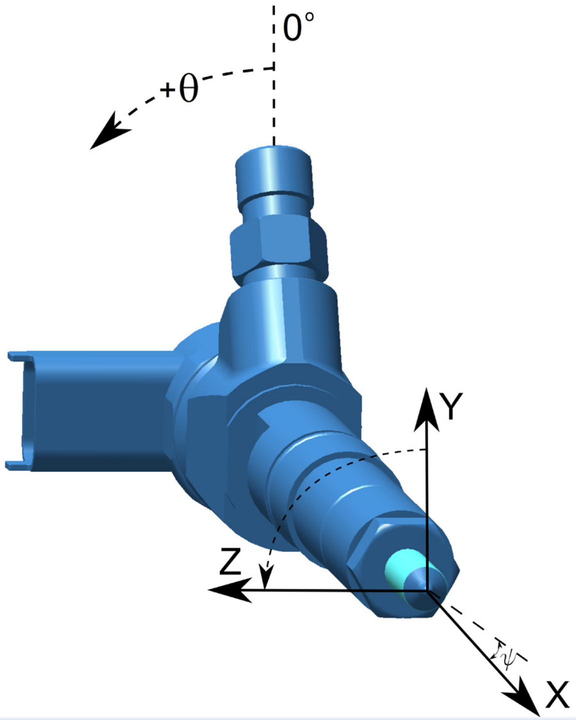
Tim Bazyn
Caterpillar Inc.
bazyn_tim@cat.com

Abstract

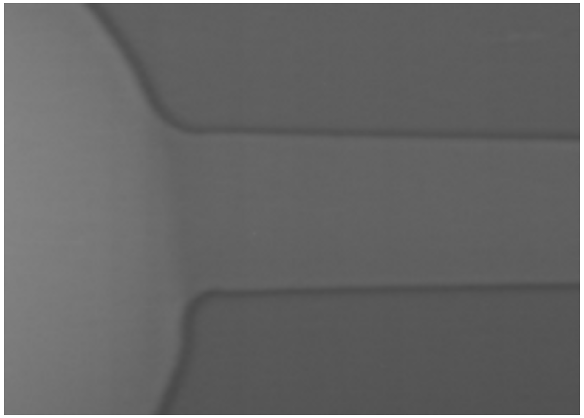
Despite the importance of sprays to engine combustion, understanding has been hampered by the sensitivity of spray behavior to unknown nozzle geometry effects. The Engine Combustion Network (ECN) collaboration has focused on overcoming this impediment to spray research by focusing on a set of nominally identical diesel injectors. Detailed measurements of the nozzle geometry for the four ECN Spray A injectors (90 μm diameter, axial single-hole nozzles) have been performed using x-ray tomography, x-ray phase-contrast imaging, silicone molding, and optical microscopy. Measurements of the needle motions (axial and lateral) and hydraulic performance of the nozzles have also been performed. Measurements of the nozzle geometry show that all of the nozzle holes are offset from the axis of the needle and sac. This offset creates an asymmetry in the inlet condition of the nozzle hole, which varies from nozzle to nozzle. The nozzle profile deviates significantly from the nominal specification, with an abrupt convergence of the nozzle holes near the nozzle exit seen in all of the injectors. Nozzle diameter measurements show a smaller diameter than the nominal specification, with significant differences between the injectors. Needle lift measurements show oscillatory behavior in both the axial and lateral motions of the needle. The hydraulic characterization of the nozzles demonstrates the impact of internal geometry (outlet diameter) on momentum and mass flow rate.

Key Words: diesel sprays, nozzle geometry, x-ray tomography, microscopy, silicone molding, needle motion

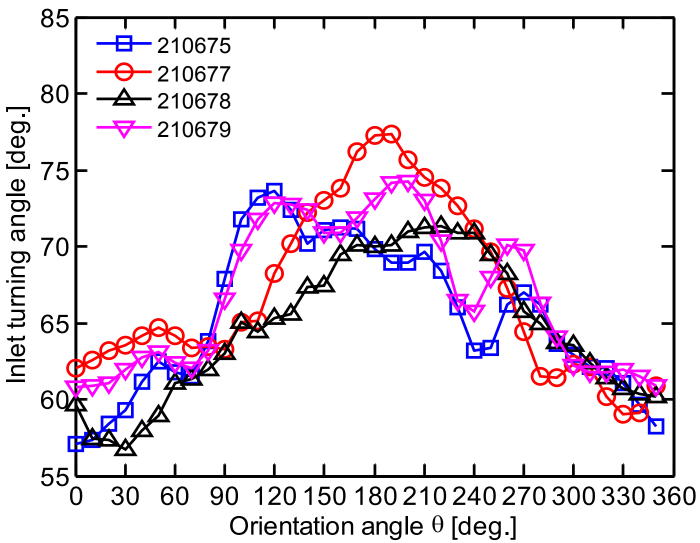
- 30 pages of knowledge
- “Spray A” geometry
- Discussion of accuracy of each techniques

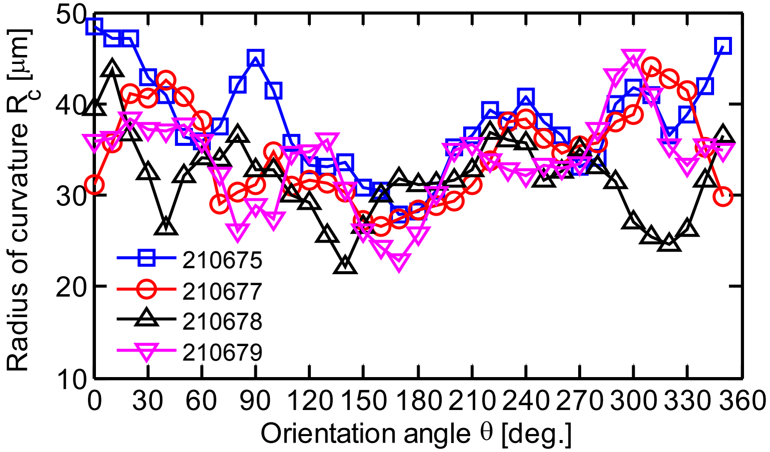


Shape of the Inlet to the Orifice

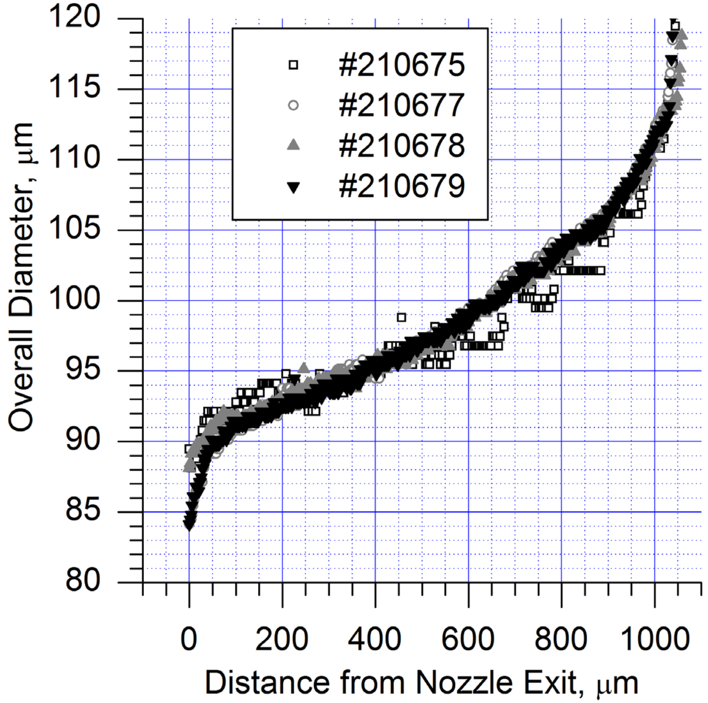


- Holes are off-center
- Inlet Turning Angle and Inlet Radius vary significantly with rotation angle
- Four nozzles follow similar trends

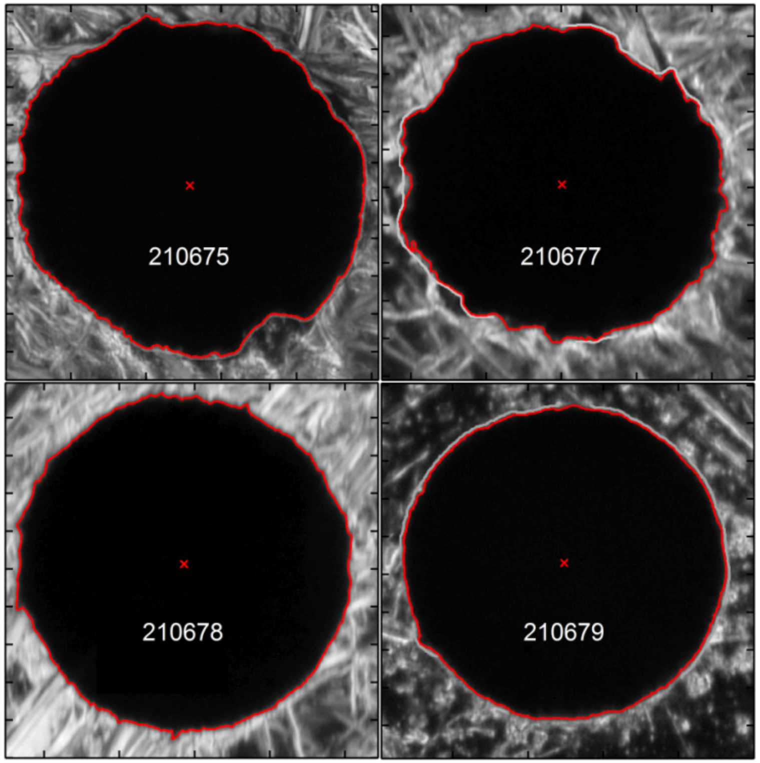




Diameter and Shape of Nozzle

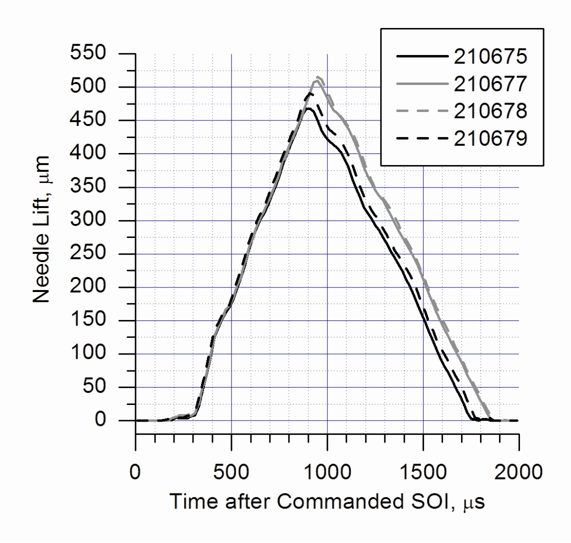


- Nozzles holes are tapered, but not linear
- Holes narrow abruptly near the outlet

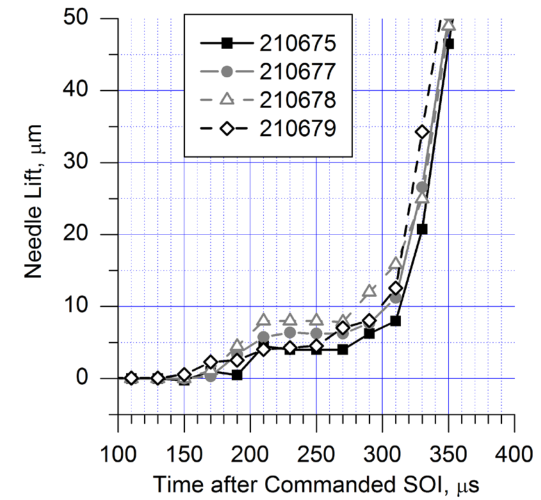


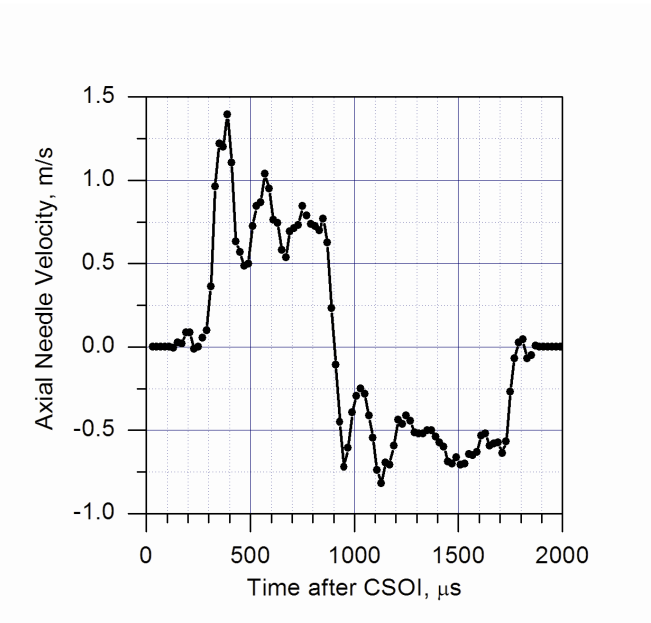
- Holes are elliptical at the outlet, not round (2-7 µm)
- Results in elliptical sprays

Needle Lift and Speed



- All four nozzles nearly identical
- Needle never reaches mechanical limit

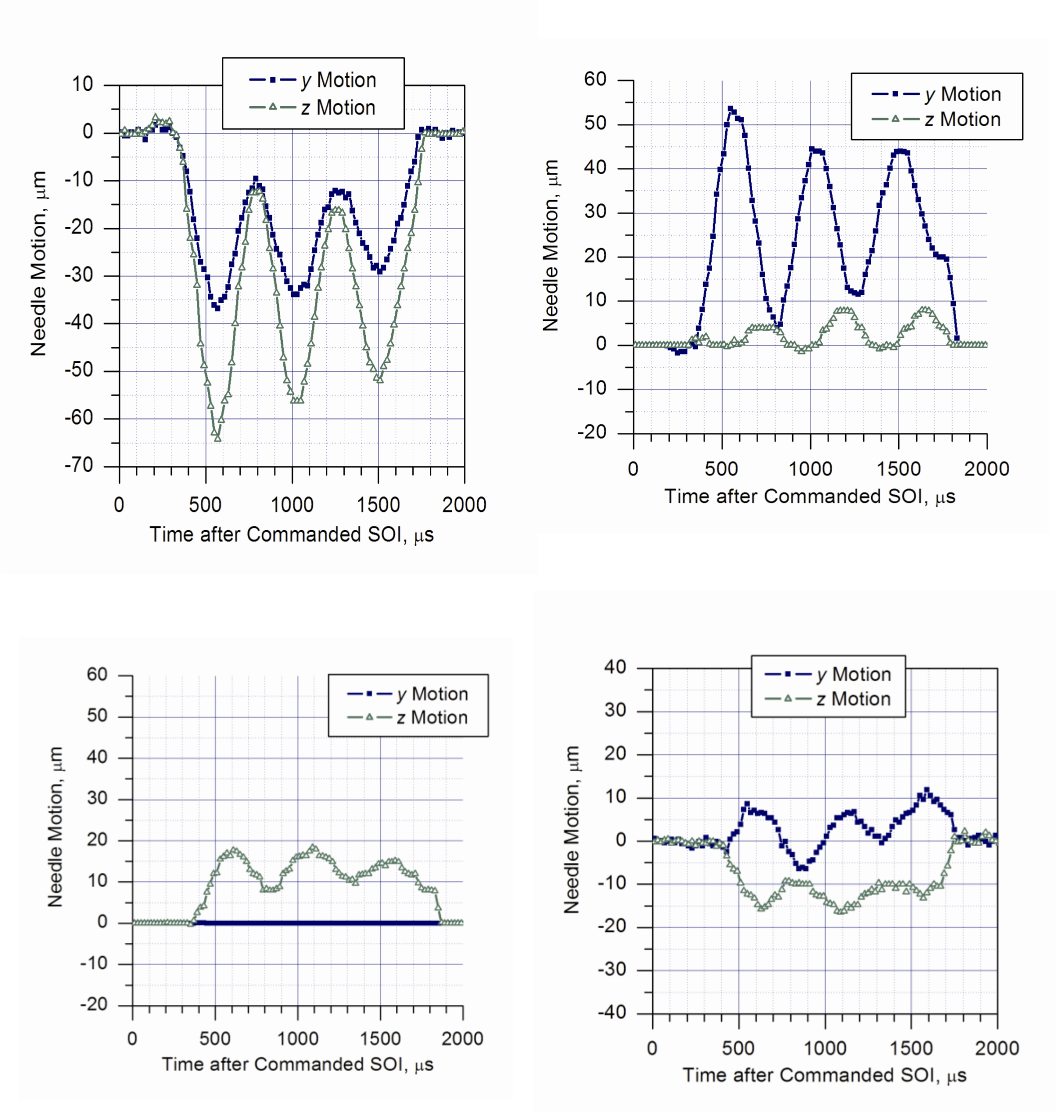




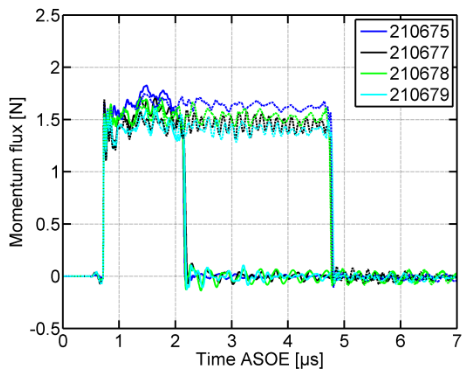
- Opening speed ~0.75 m/s
- Closing speed ~0.5 m/s
- Oscillations

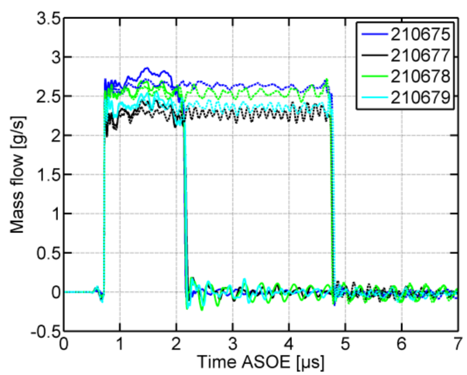
Eccentric Motion of the Needle

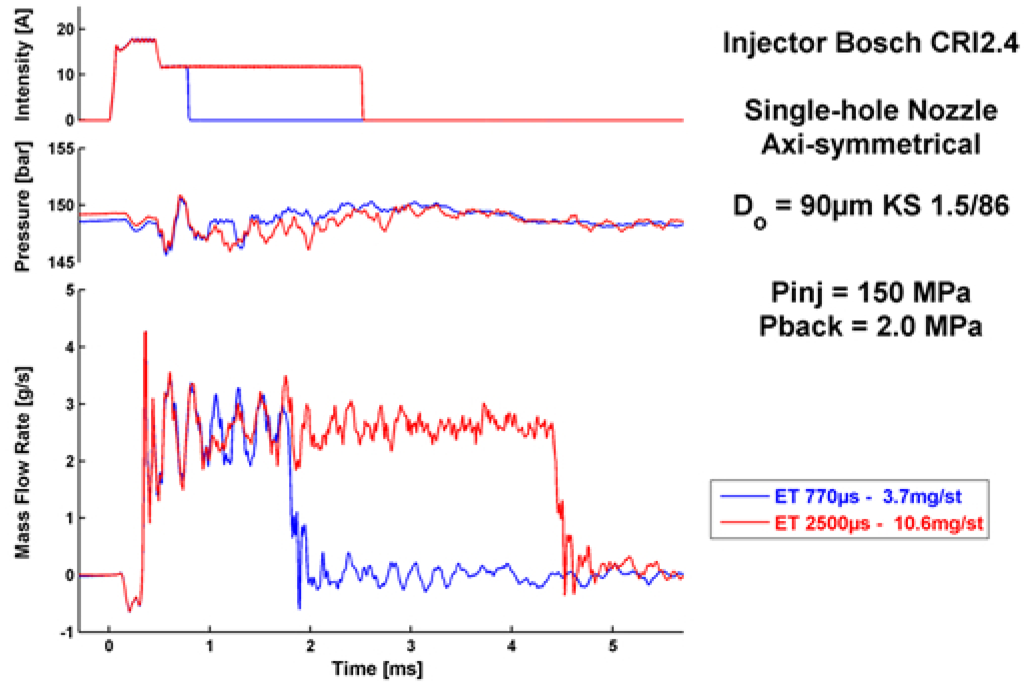
- Some nozzles have large off-axis motions of the needle
- Huge differences between the four nozzles



Spray Momentum and Rate of Injection



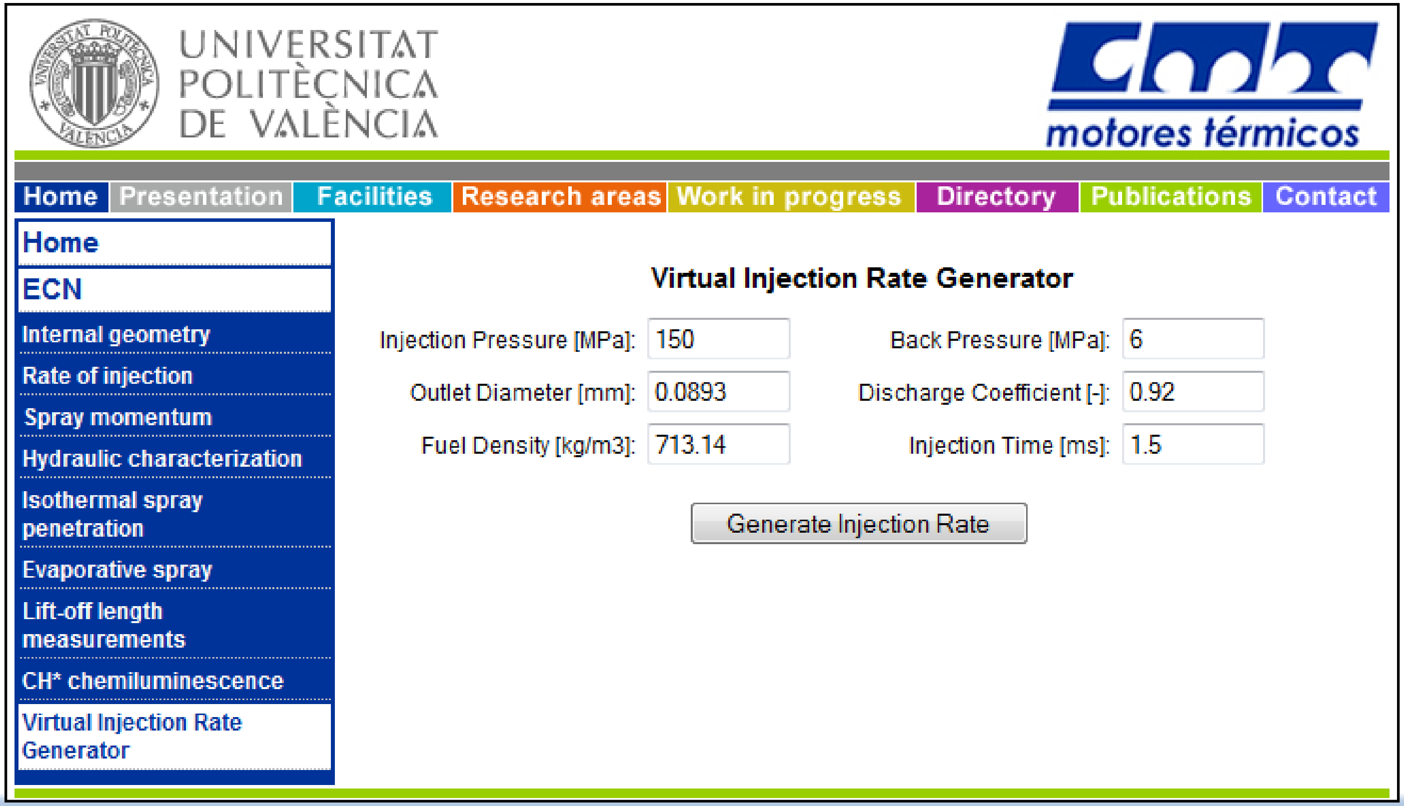




- CMT has calculated flow rate based on discharge coefficients for 675, 677, 678

Virtual injection rate generator

- A web application has been created for facilitate and easy virtual injection rate generator http://www.cmt.upv.es/ECN09.aspx
- The needed inputs are: Injection pressure, back pressure, outlet diameter, discharge coefficient, density and injection duration.
- The output is a standard comma-separated values file (csv) with time and mass flow columns.

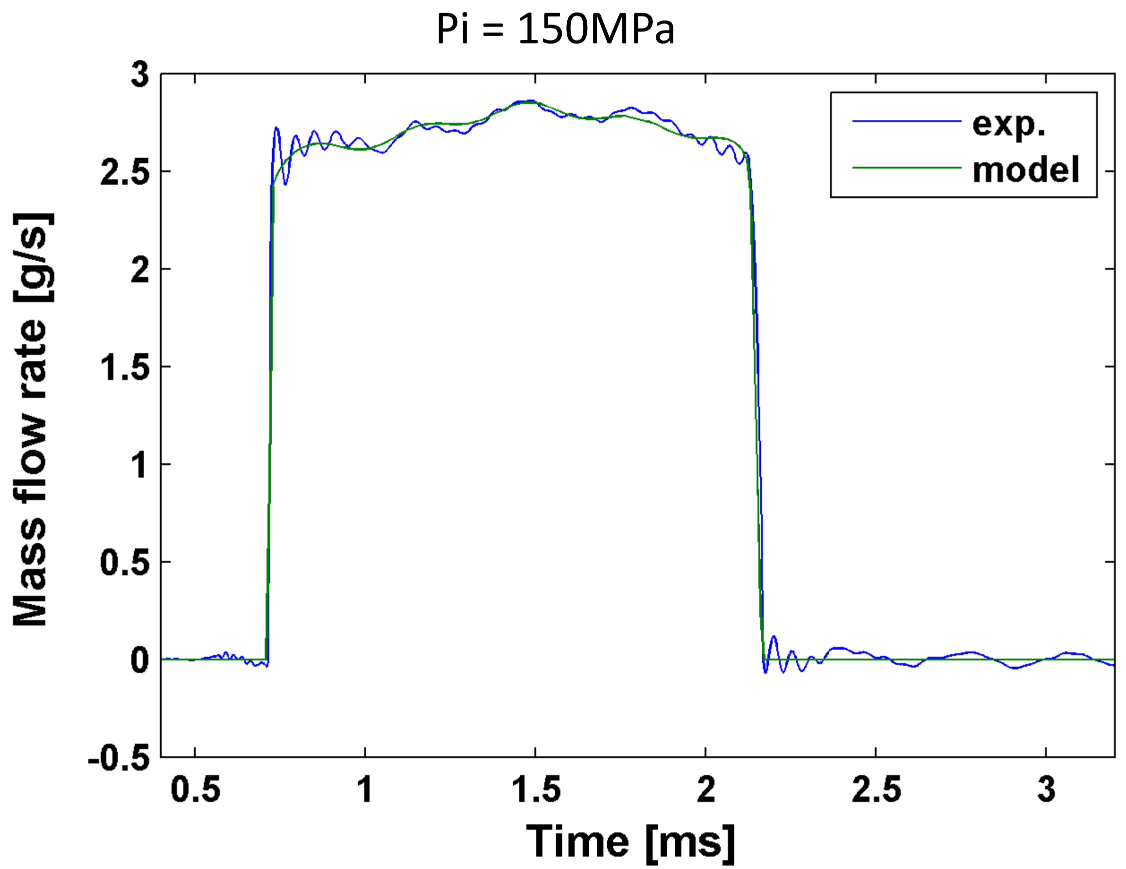


Virtual injection rate

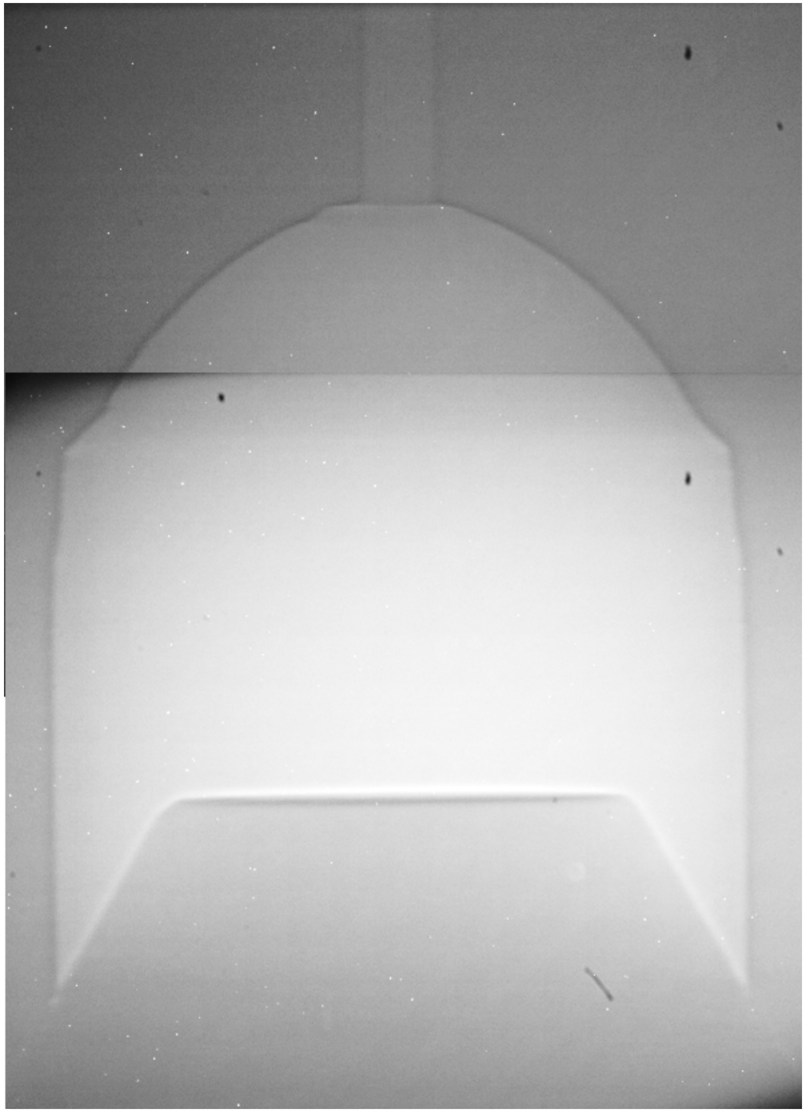
- The virtual injection rate the model is based on:
  - The quasi-steady mass flux
  - A shape function. Mainly defined by start and end slopes
  - A wave function taking into account the fluctuation due to pressure waves, needle, etc. This wave function will be different if injection system changes.
- Shape and wave functions are based in nozzle 675 and are calculated in the same way independently of the nozzle to simulate. They only depend on injection pressure.
- For modeling different nozzles stationary mass flux should be changed according the nozzle modifying the parameters that configures this one: Pi, Pb, D, Cd
- For a better injection modeling a bigger valid test matrix including different Pi, ET, nozzles, etc. should be done

Virtual injection rate example

- Experimental-Model comparison: Nozzle 675, Spray A Sandia test



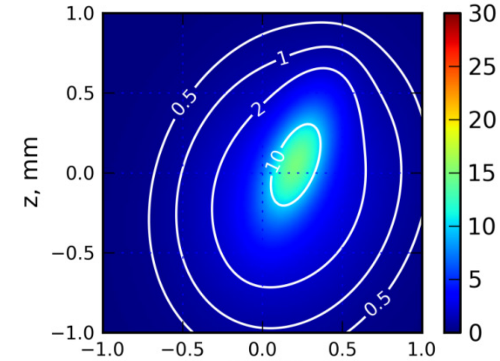
“Spray H” Nozzle Geometry

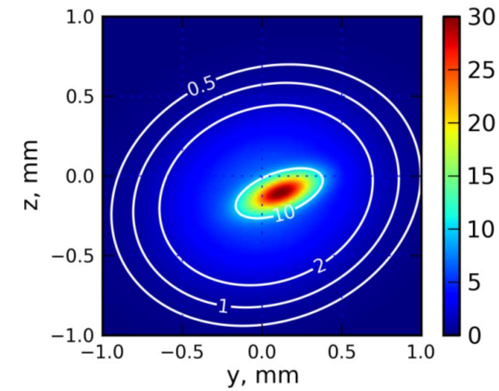


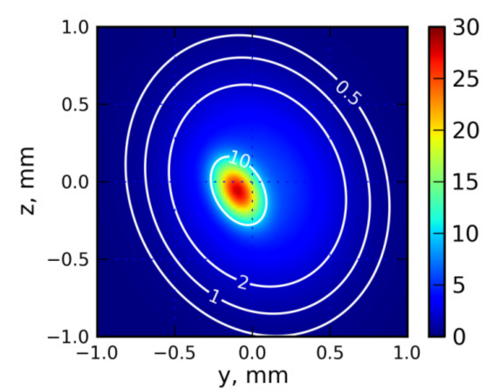
- Argonne has completed x-ray imaging of the Spray H nozzle
  - 4 micron resolution
- Nozzle shows significant asymmetries, abrupt features
- Very sharp inlet to orifice

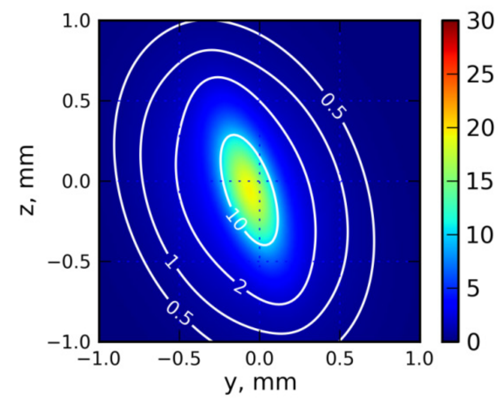
Radiography Measurements of Spray A

- Radiography measurements of the 3D, time-resolved fuel density distribution
  - Completed for all four Spray A nozzles
  - Cold conditions, representative of Spray A only near-nozzle
- As close as 100 microns from the exit
- Some data now on the ECN web site, more to come







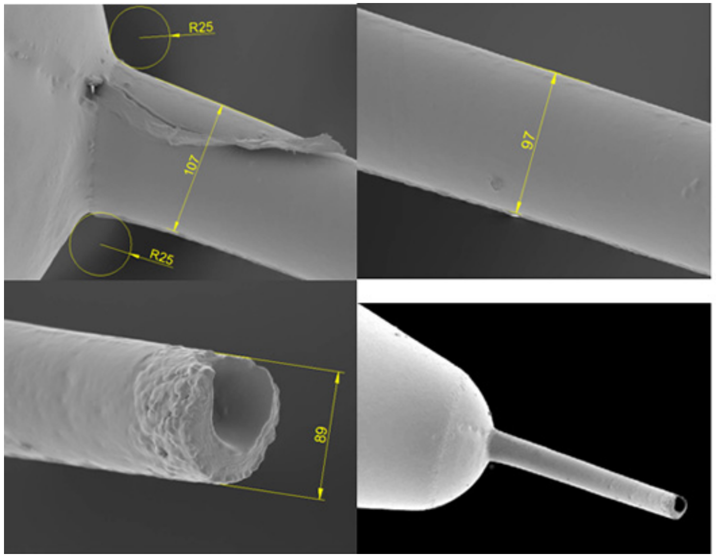


Future Work

- High resolution x-ray tomography of nozzle geometry
  - Infineum has arranged for high resolution (0.6 μm) 3D measurement of all (A&B) ECN diesel nozzles
  - Scheduled for July 2012, but equipment failure prevented measurements
  - Will be rescheduled.
- Spray B
  - Fuel density distributions
  - Reference geometries

Nozzle Geometry for Mesh Development

- CMT Geometry
  - Available now
  - Measurements only for Nozzle 210675, only at a few specific locations



http://www.cmt.upv.es/ECN01.aspx

- Caterpillar Tomography
  - Full 3D Geometry for all nozzles
  - STL files available now (ECN web site)
  - Measurement artifacts, non-realistic surface irregularity
- Schmidt Mesh
  - Available now (ECN web site)
  - Only available for 210675, based on CMT geometry
- Georgia Tech
  - Utilizes the CAT tomography results, smoothing the surface artifacts
  - 2 nozzles, STL format, Released soon, includes nozzle and sac

Generating CFD Nozzle Geometries from Experimental Measurements: Spray A Injectors

Caroline Genzale

Thomas Furlong

ECN2 Workshop

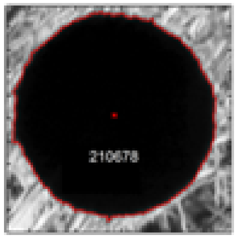
Heidelberg, Germany

September 7, 2012

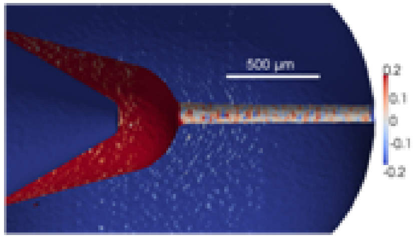
Georgia Institute of Technology

What geometry information should I use if I want to model nozzle flows for Spray A or B?

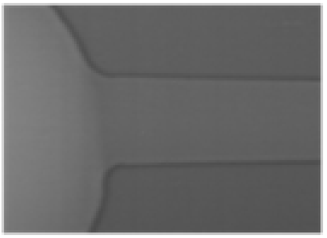
Optical microscopy, x-ray tomography, and x-ray phase contrast derived data



Optical microscopy



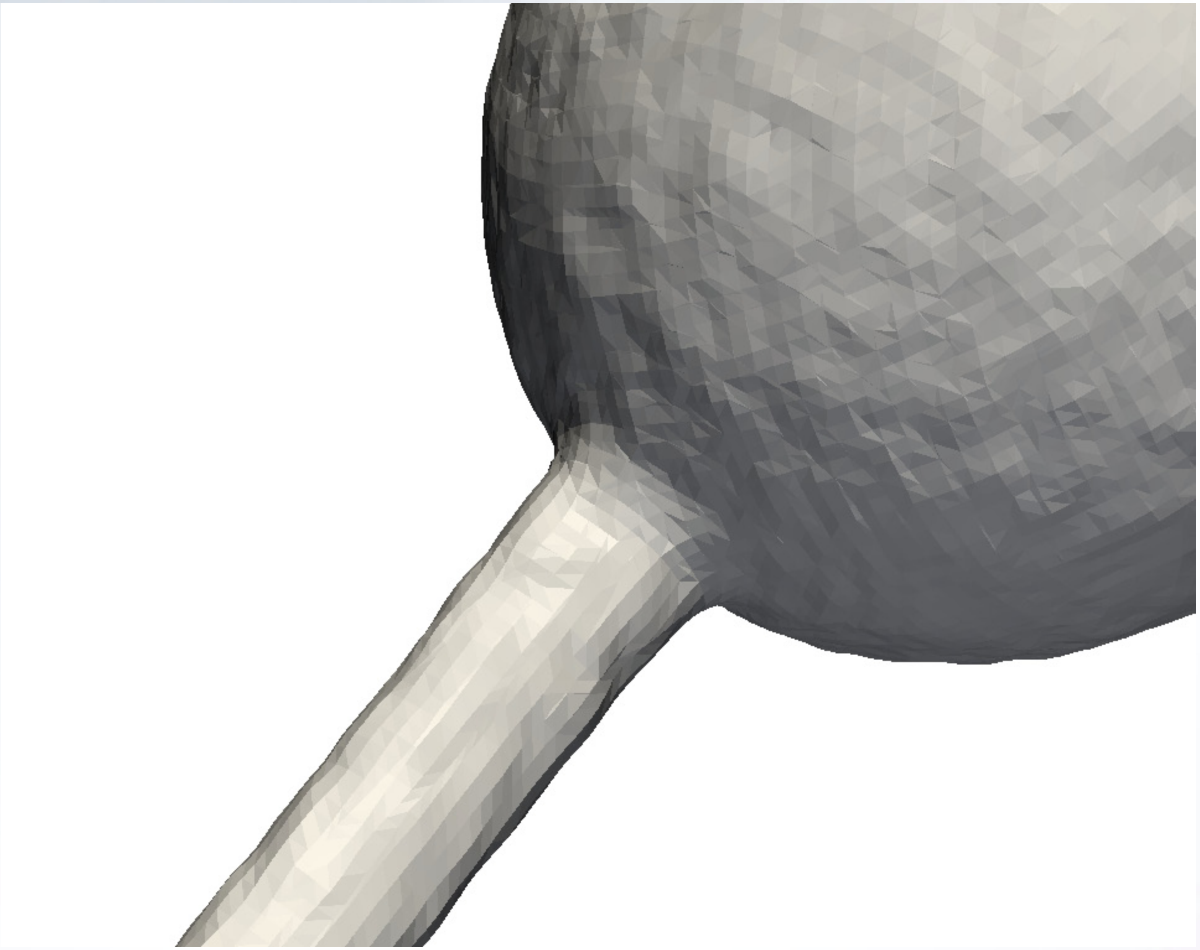
X-ray tomography surface



X-ray phase contrast projection

Injector Serial #	Exit diameter [µm]	Exit boundary [µm]	θ [deg.]	Surface file .stl	Exit offset [µm]	Axial diameter profile [mm]	K-factor	Inlet radius [µm]	Axial diameter profile [µm]	K-factor
210370	90.8	B1	-90	stl	50	P1	1.5	23	-	-
210675	89.4	B1	9	stl	53	P1	1.3	25	-	-
210677	83.7	B1	32	stl	37	P1	1.8	20	P2	1.8
210678	88.6	B1	36	stl	39	P1	1.8	19	P2	1.7
210679	84.1	B1	-22	stl	22	P1	1.8	17	P2	1.8

Tomography .stl files contain the most 3-D information, but they are not directly meshable.

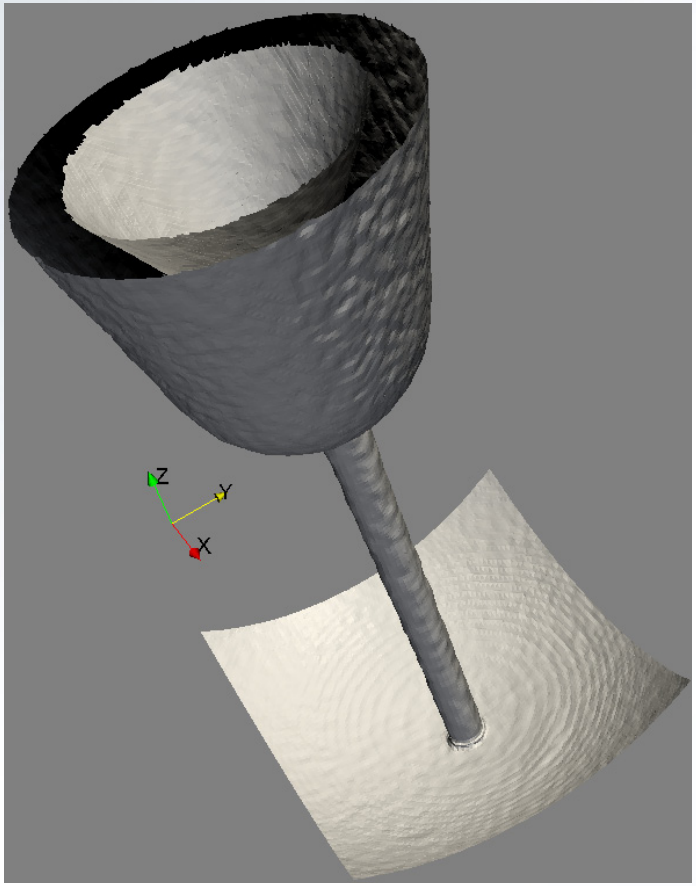


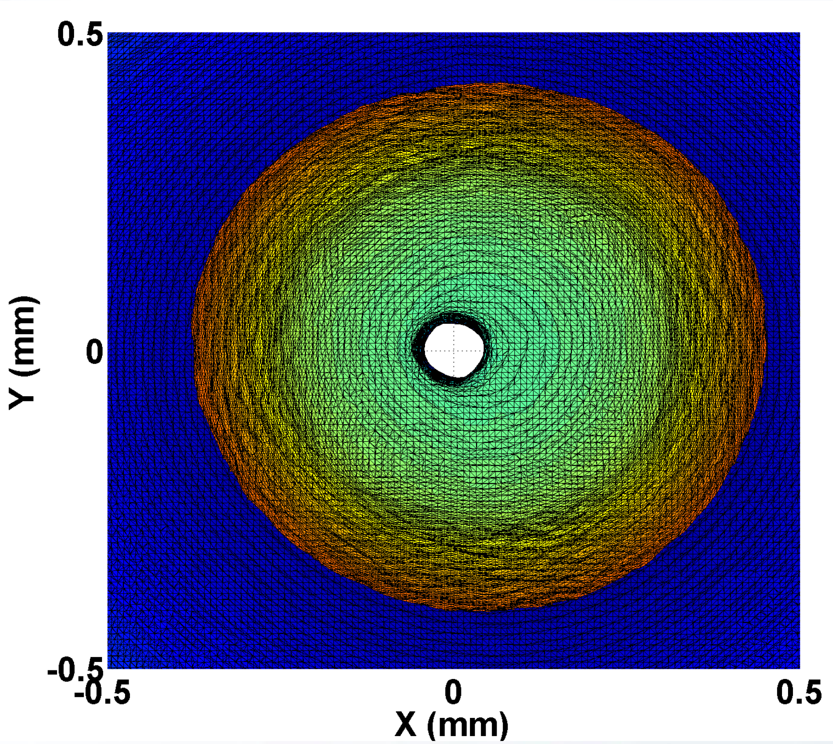
X-ray tomography .stl file for nozzle 675

- Which features are real?
- Which ones are important for accurately modeling the nozzle flow?
- How do I get from this to a geometry that I can mesh?

Orienting the nozzle axis

- The nozzle orifice axis is defined by rotating and centering the .stl geometry to align the centers of the inlet and outlet of the nozzle.

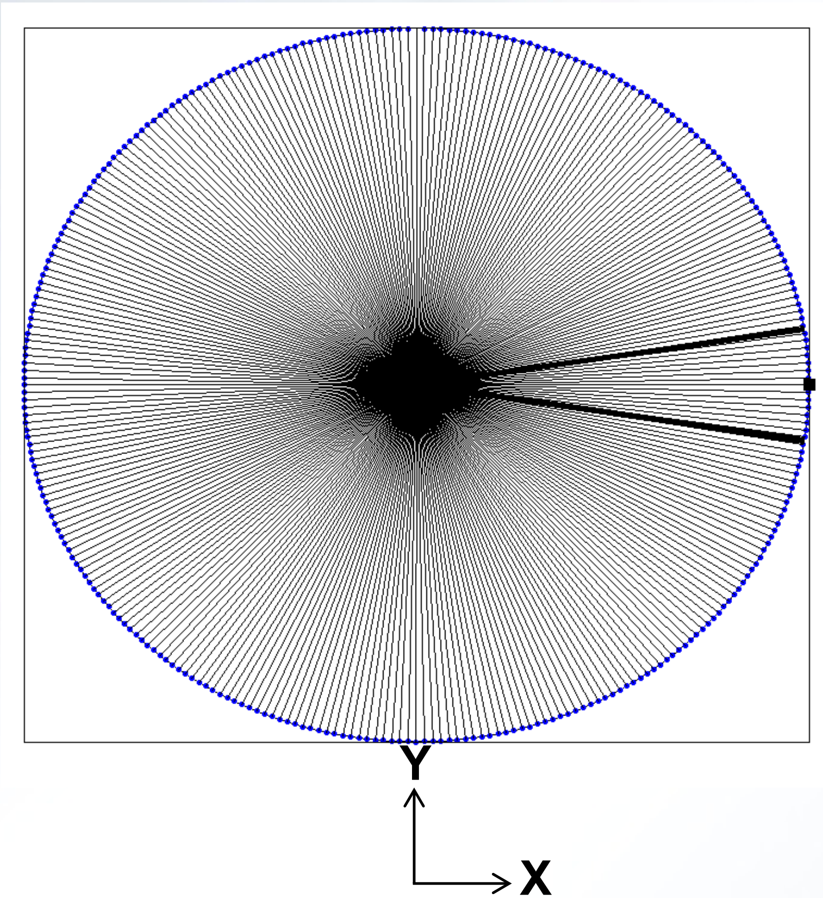




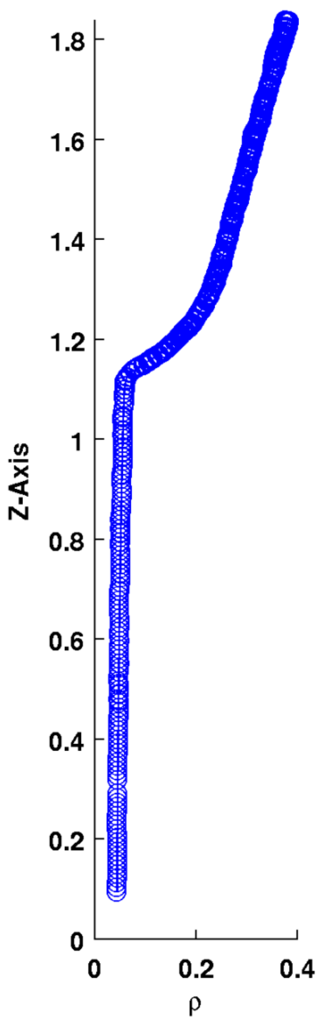
Georgia Tech

Because the tomography points are not uniformly spaced, and have limited resolution, we employ a curve fitting approach.

- The STL file is cut into discrete theta regions of size $\pi/150$ to stipulate 300 splines that will define the axial curvature.
  - Due to non-uniform spacing of measurement points, a larger discrete theta region of size $\pi/10$ is necessary to produce each spline fit
  - A vertical spline curve is created through all points within each sector



Because of the complex curvature of the sac, nozzle, and orifice, we piece together splines for each region.

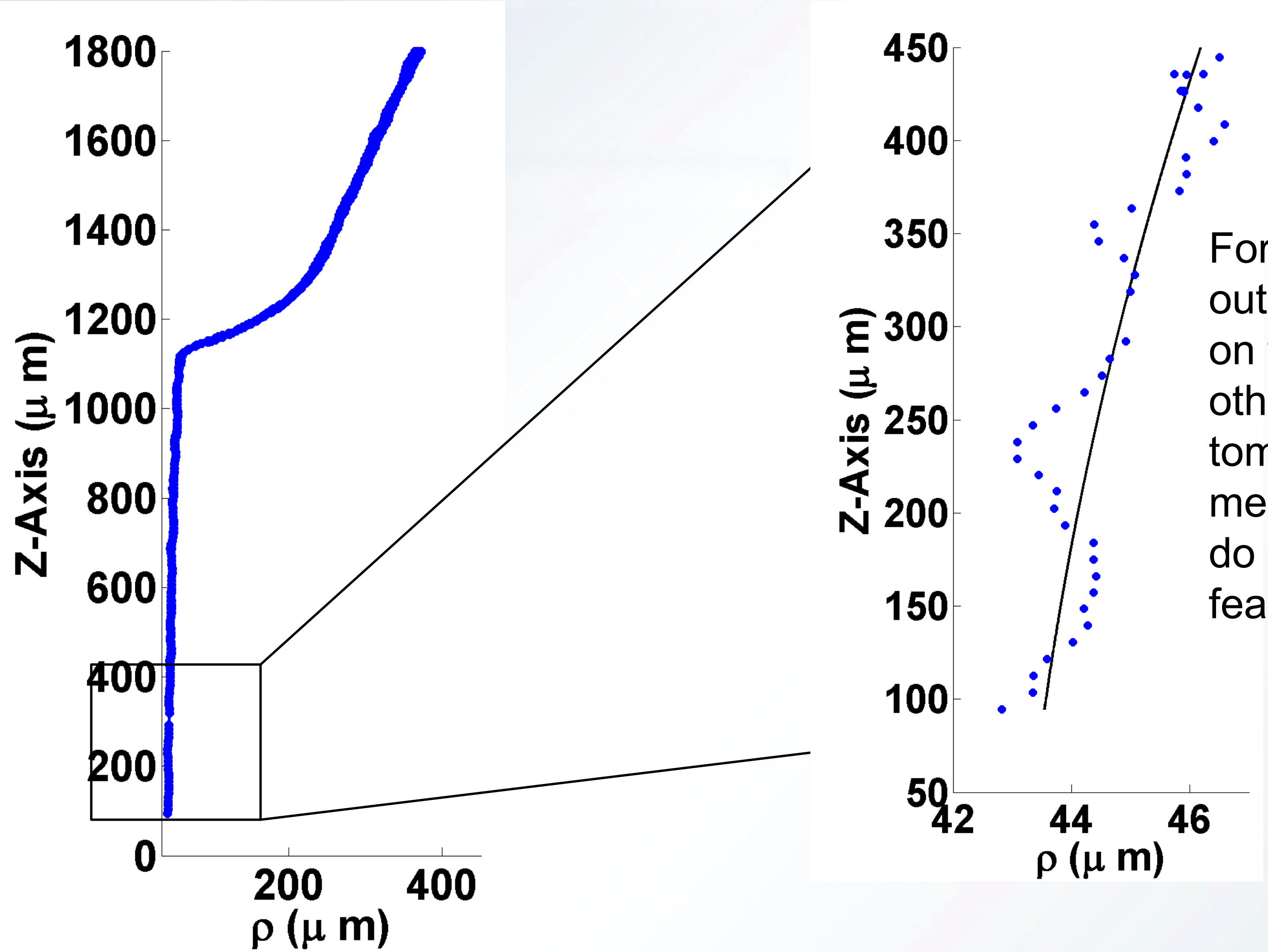


- Nozzle, orifice, and sac splines are generated separately using the function spap2
- Knots are first defined utilizing the matlab splinetool and hardcoded
- The knot locations are iterated using the ‘newknt’ function to minimize spline fit errors with the current theta slice

Georgia Tech

The splines essentially filter the noise in the tomography measurement points, but still follow the curvature.

- The outlet region

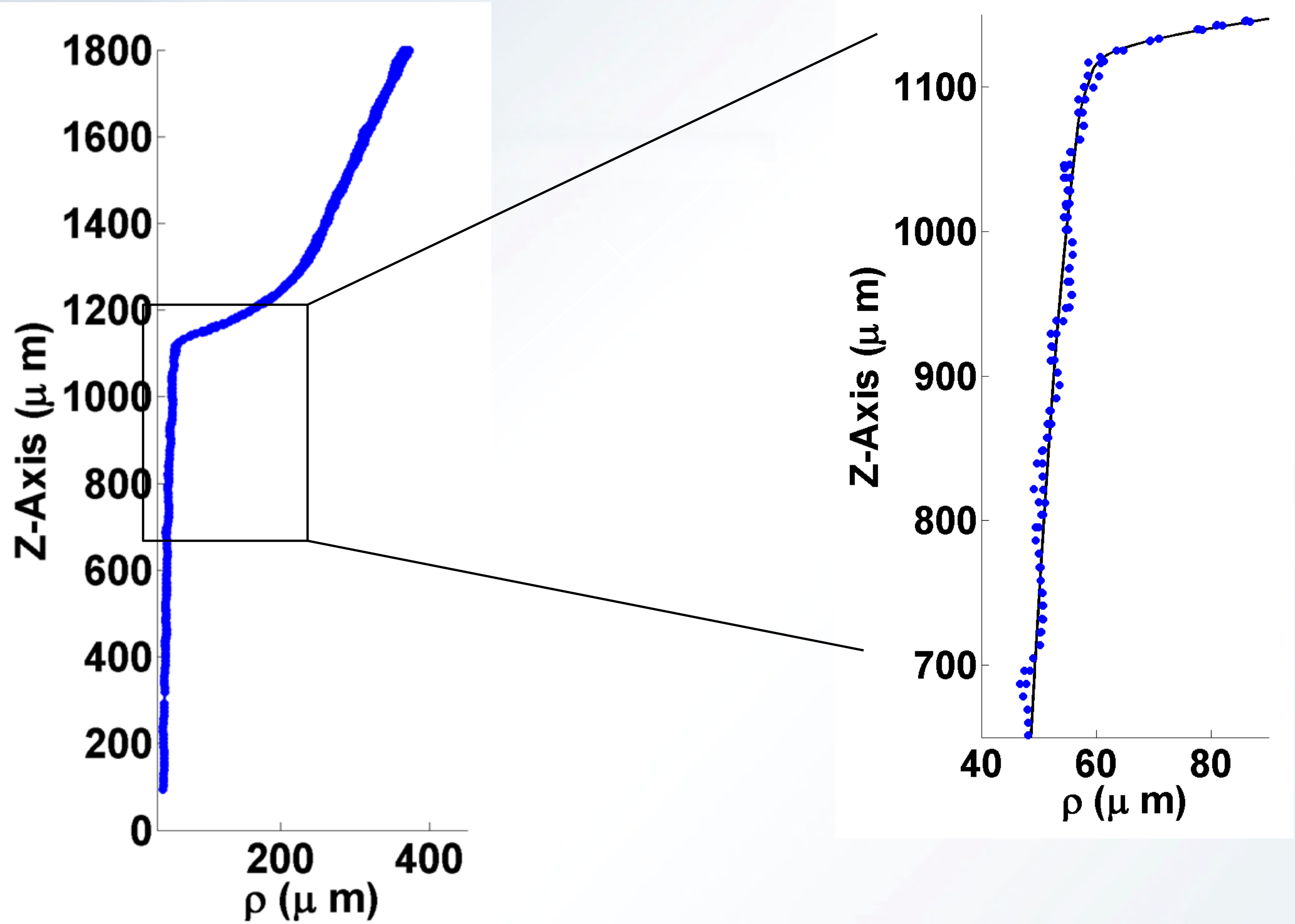


For nozzle 675, the outlet convergence is on the same order as other noise in the tomography measurement, so we do not capture this feature.

Georgia Tech

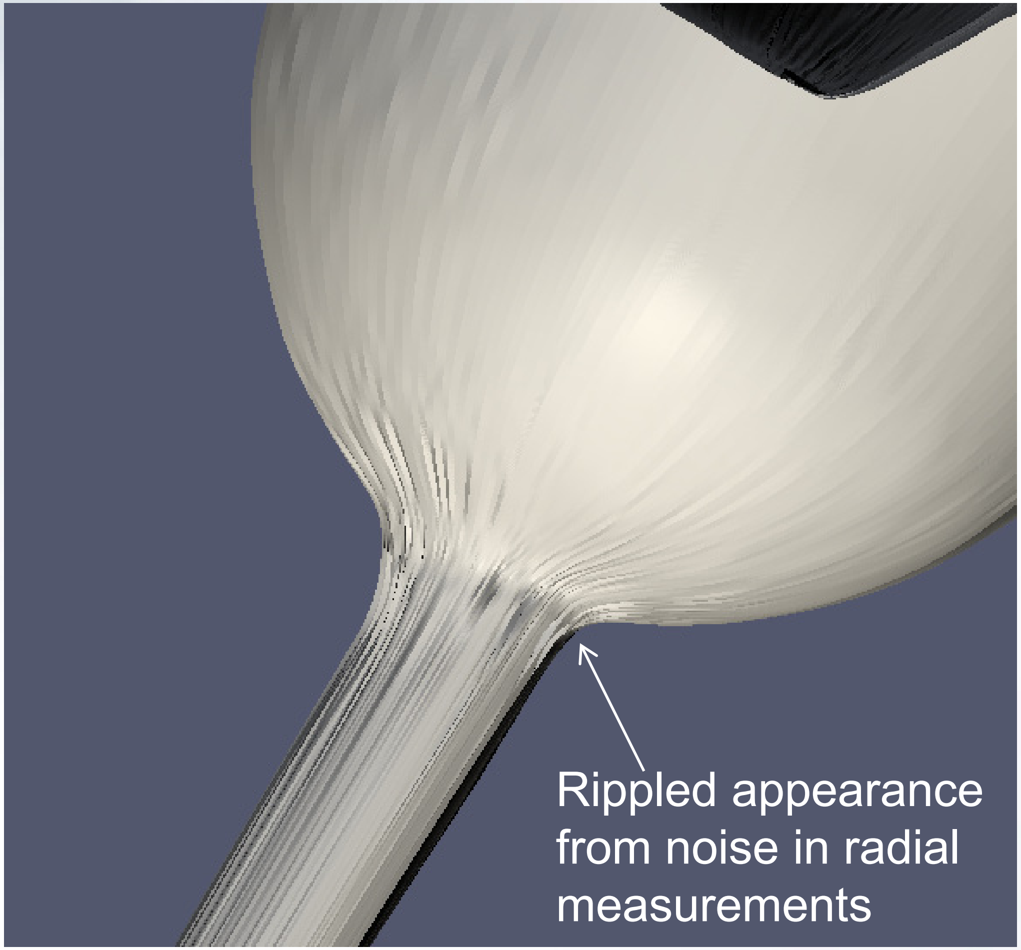
The splines essentially filter the noise in the tomography measurement points, but still follow the curvature.

- The turning region



Georgia Tech

Fitting of axial splines is insufficient for creating a meshable geometry. Noise in radial measurement must also be smoothed.

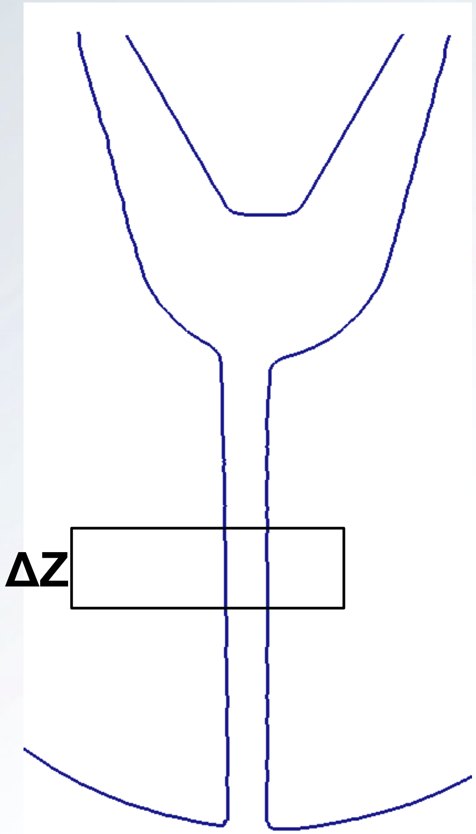


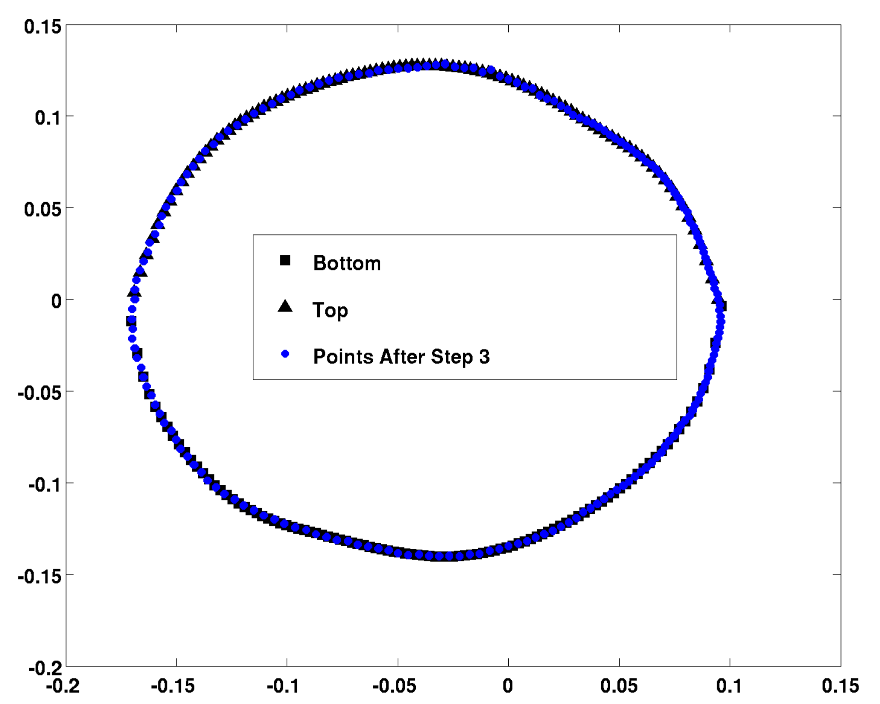
- Interior of the STL file after axial spline smoothing near the sac/orifice turning junction

Georgia Tech

To establish smooth connections between the axial splines, we fit a second set of circumferential splines.

- The second geometry fit is done utilizing vertical slices (instead of theta slices) to populate a circumferential spline fit
    - Select a region of data of size ΔZ (0.1 micron)
    - Create a spline fit around the data (300 nodes
    - To allow for asymmetry, we utilize two splines to define the circumference.

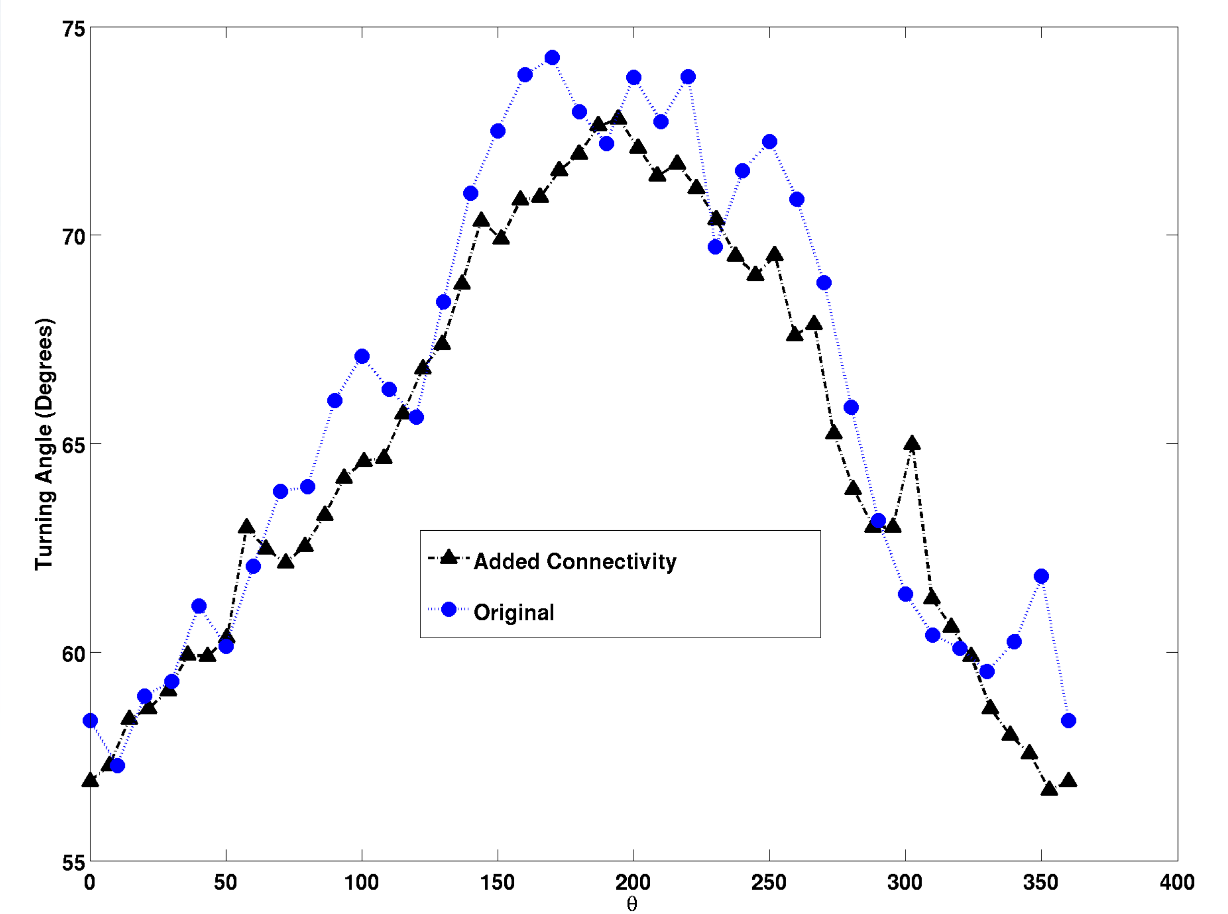




Georgia Tech

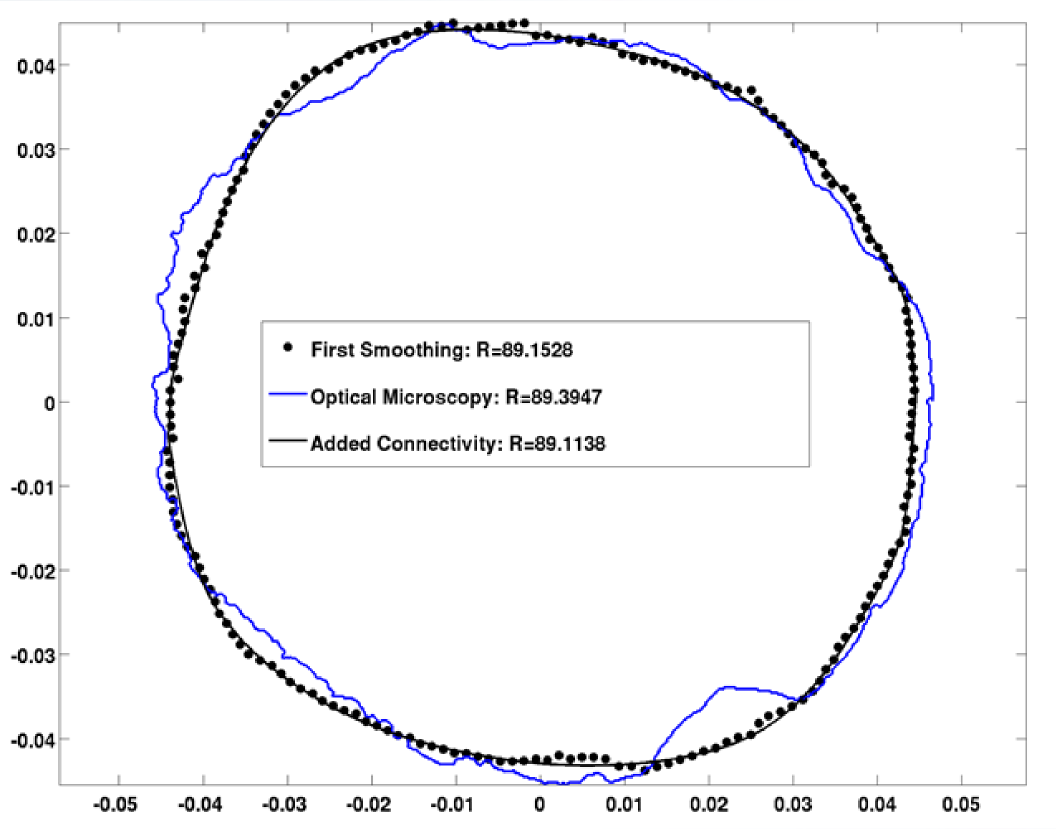
The final result is a smooth geometry that captures large scale geometry features and asymmetries in the tomography data.

The circumferential turning angle trend measured by the tomography measurements is retained.



The outlet diameter of the smoothed geometry is close to that measured by optical microscopy.

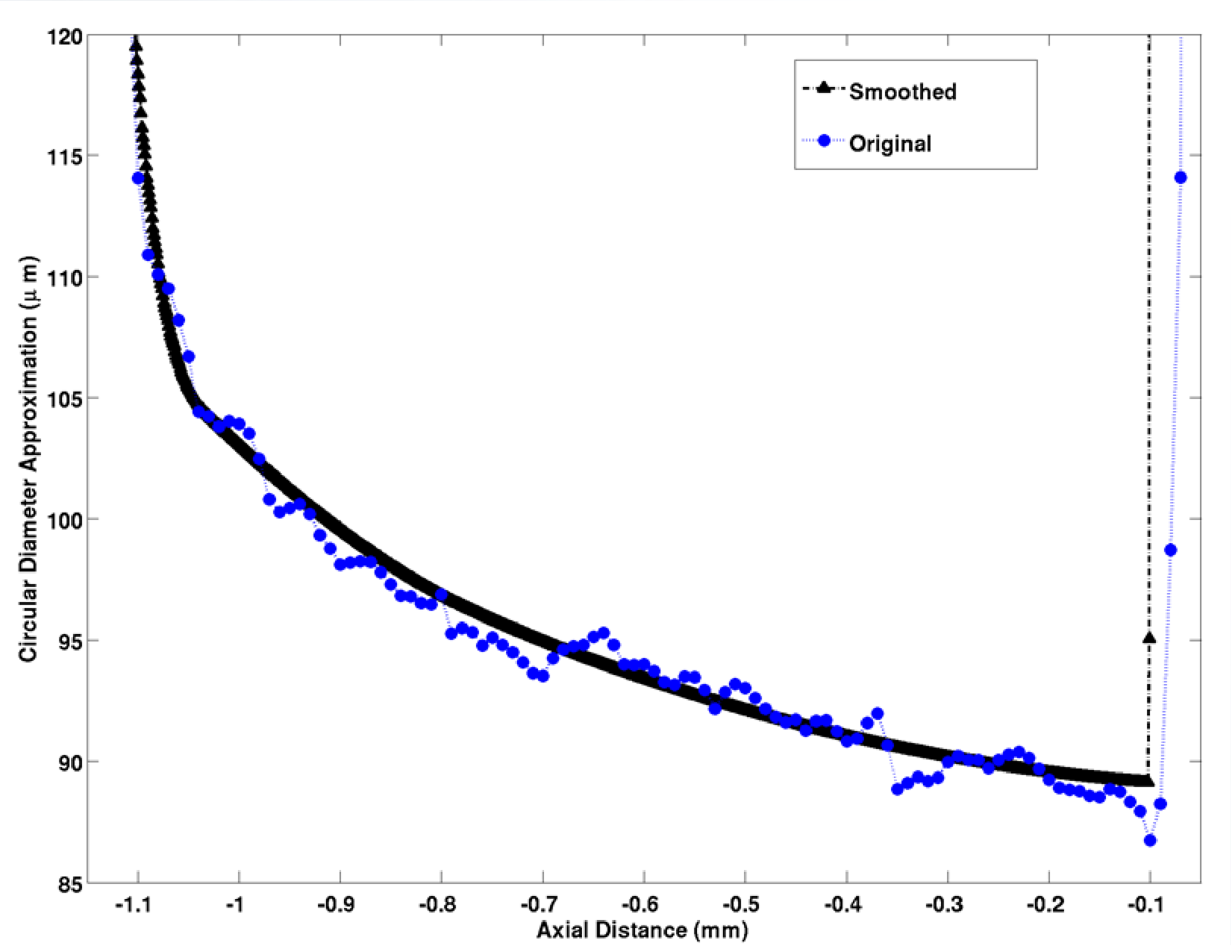
- Using a circle fit function (assumes circular orifice) we compare the representative outlet diameters



- Optical microscopy
  - 89.4 μm
- Smoothed geometry
  - 89.11 μm

Georgia Tech

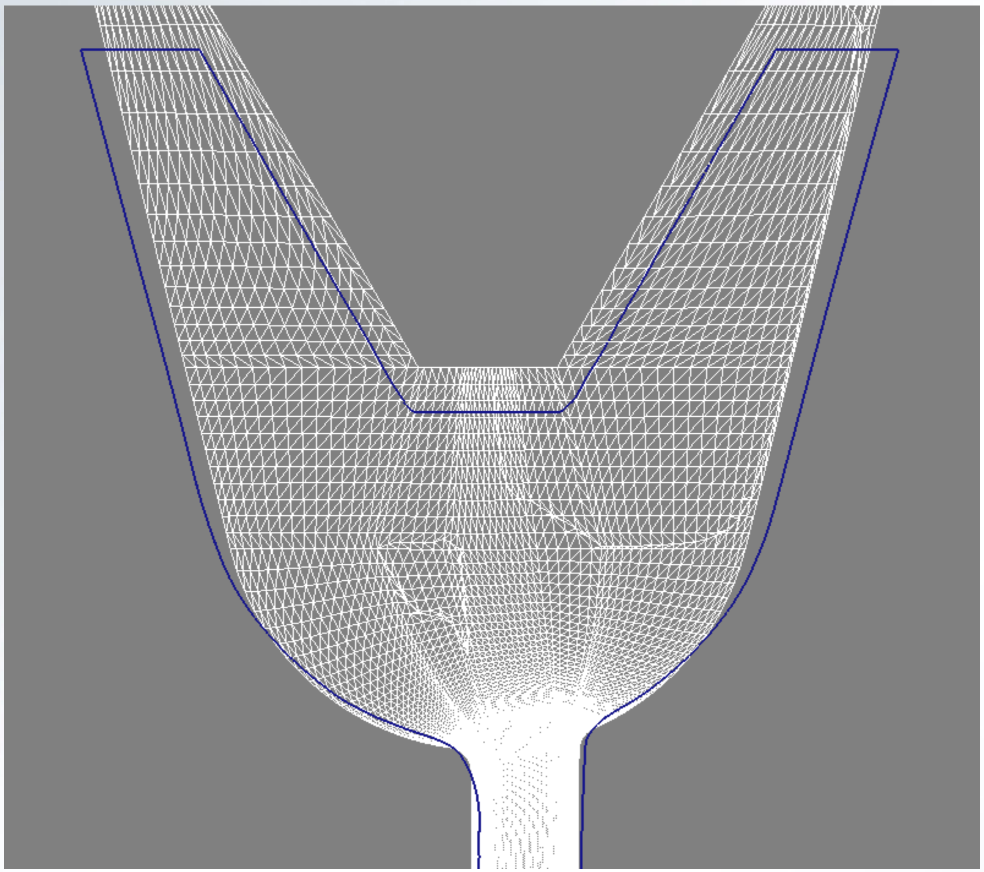
Orifice diameters along the nozzle axis are also retained in the smoothing process, but not necessarily near the orifice exit.

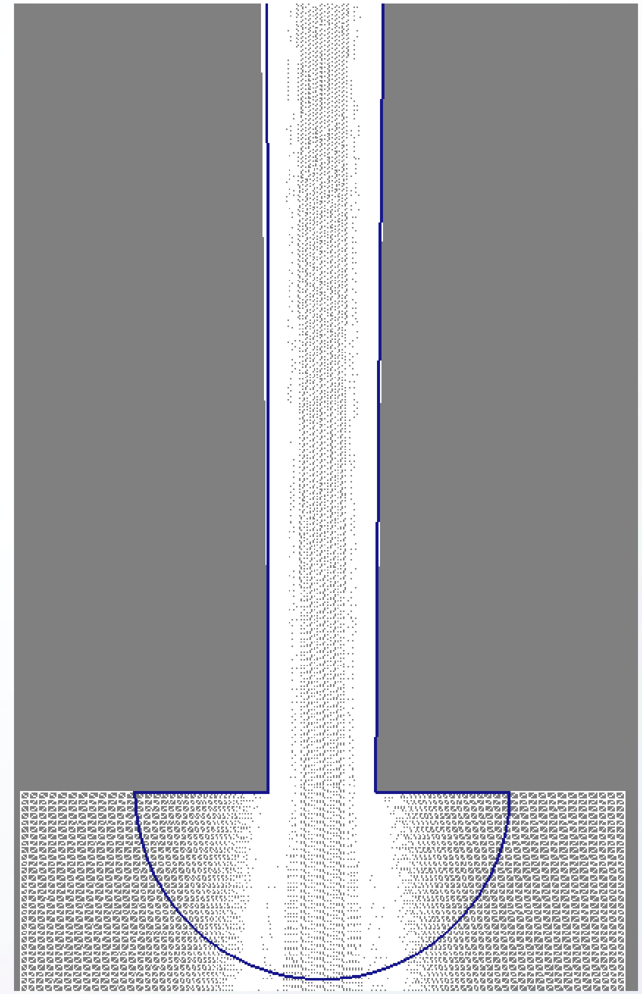


- This 2-dimensional representation assumes a circular orifice

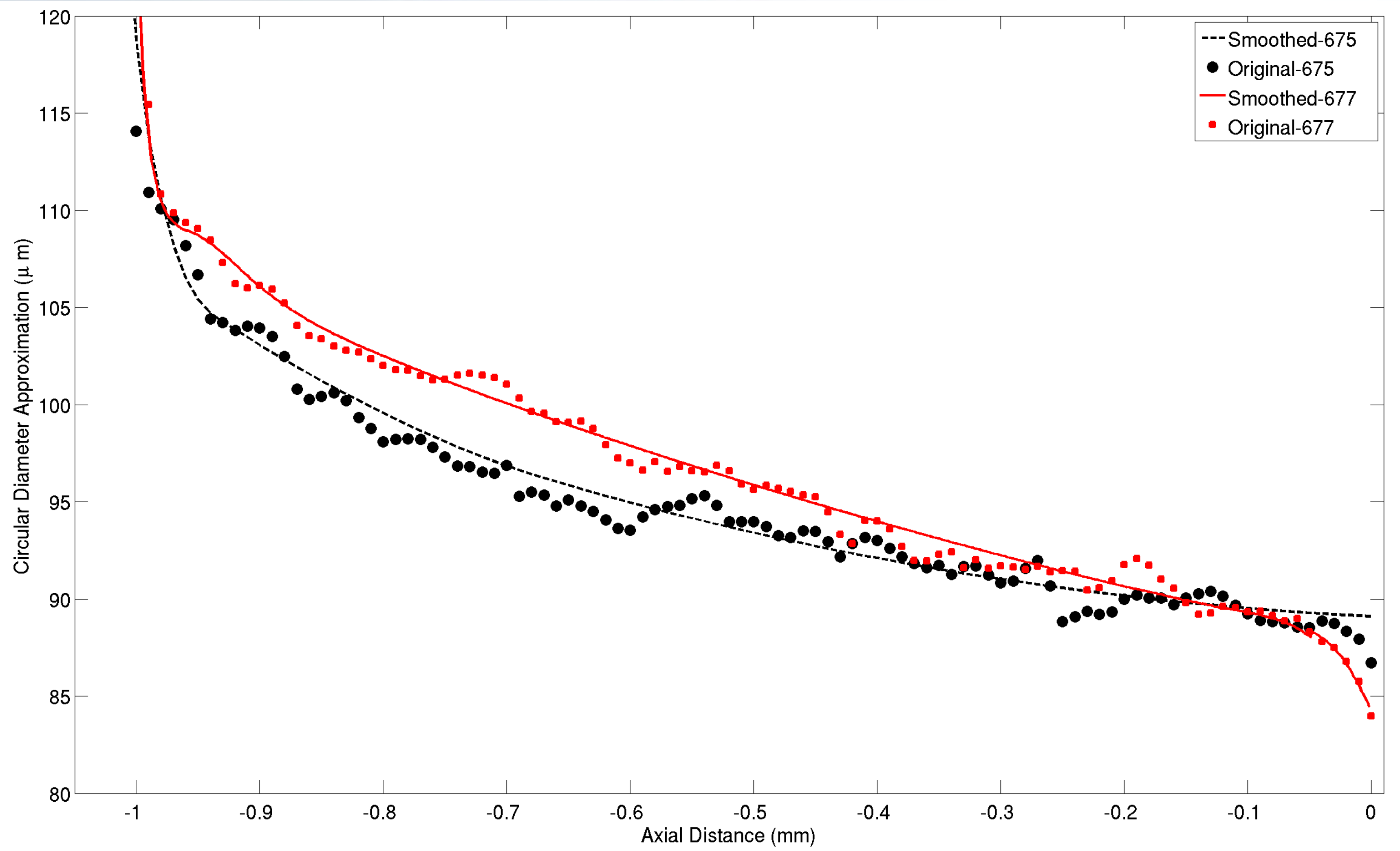
Georgia Tech

A comparison of our smoothed geometry to the 675 mesh currently posted on the ECN website:





We have applied this same processing method to the 677 nozzle.



Georgia Tech

Summary and discussion items

- Currently, the x-ray tomography .stl files are the best measurement suited for CFD geometry generation because they contain the most 3-D information.
- Spline smoothing technique does a good job at filtering out noise, while retaining global geometry features and asymmetries, and generates a solid model ready for meshing.
- Tomography measurements are noisy and have poor resolution, so some of the features and asymmetries may not be real.

- To mesh or not to mesh?
- How can we incorporate information from other measurement techniques (phase contrast, silicon molds, optical microscopy)?
- How important is it to capture every real twist and turn?

ECN2: Internal flow

Contributor:

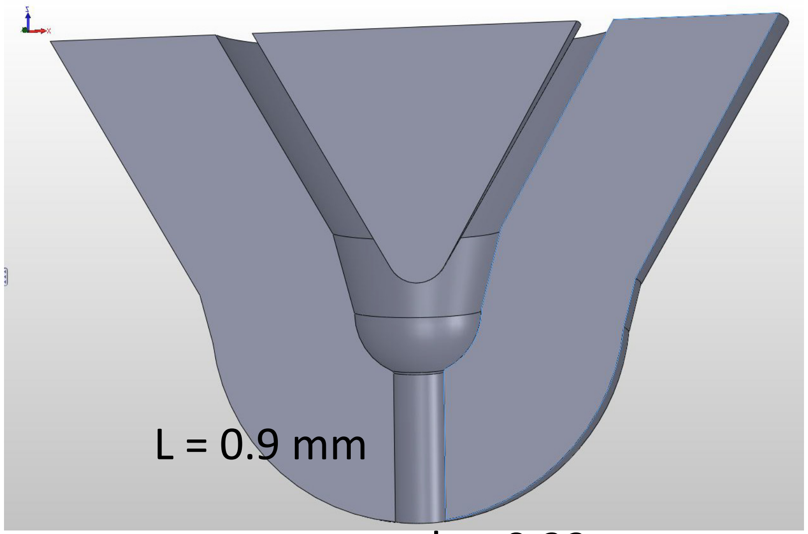
Marco Arienti

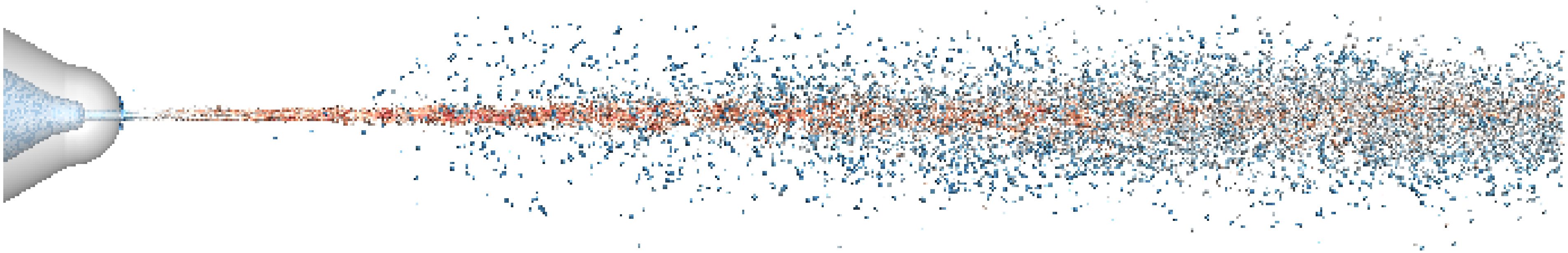
Sandia National Laboratories, Livermore, CA, USA

Second Workshop of the Engine Combustion Network,

Heidelberg, Germany, September 2012

Injection simulation capability

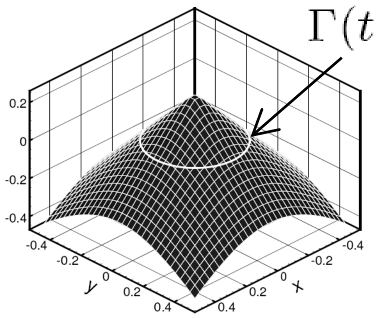




Snapshot at t = 0.37 ms: liquid surface colored by velocity (0 to 240 m/s)

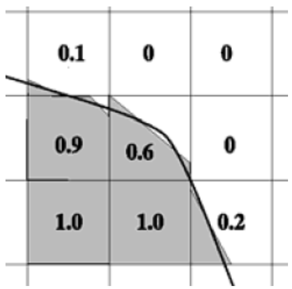
Sharp-interface method for primary atomization

Gas-liquid interface updated by coupled level-set / volume-of-fluid technique (CLSVOF)



$$\Gamma(t) = \{\mathbf{x} \,|\, \phi(\mathbf{x}, t) = 0\}$$

- LS: interface slope; height fraction; velocity extrapolation from liquid phase



$$F_t + \nabla \cdot (UF) = (\nabla \cdot U)F$$

$$F_{ij} = \frac{1}{\Delta x \Delta y} \int_{\Omega_{ij}} H(\phi(x, y, 0))\, dx\, dy$$

- VOF: local correction for volume preserving distance; curvature

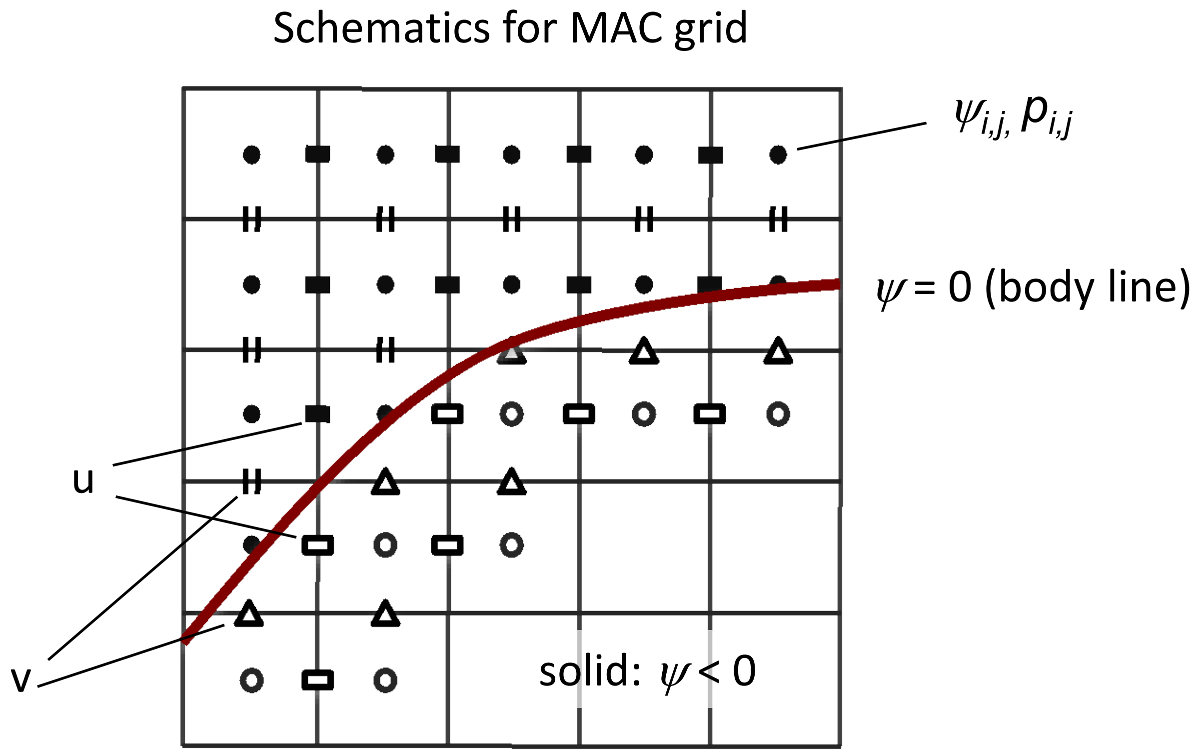
- Velocity extrapolation from the liquid phase recovers the limit case of zero gas viscosity and density
- Incompressible flow solver stable under wide range of parameters: density ratio 1000:1; viscosity ratio 50:1
- Separate treatment of liquid velocity → gas solution can be sub-cycled → higher accuracy for the same cost

[Sussman et al., *A sharp interface method for incompressible two-phase flows*, JCP 2007]

3

Embedded solid boundary for injector

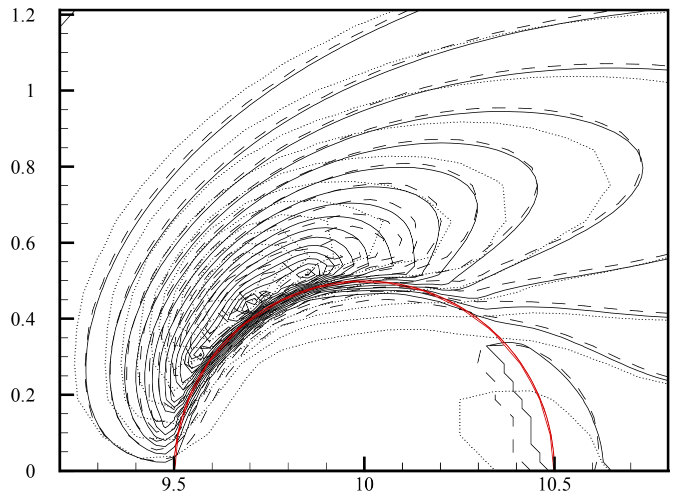
Simple staircase implementation on narrow-band ghost region

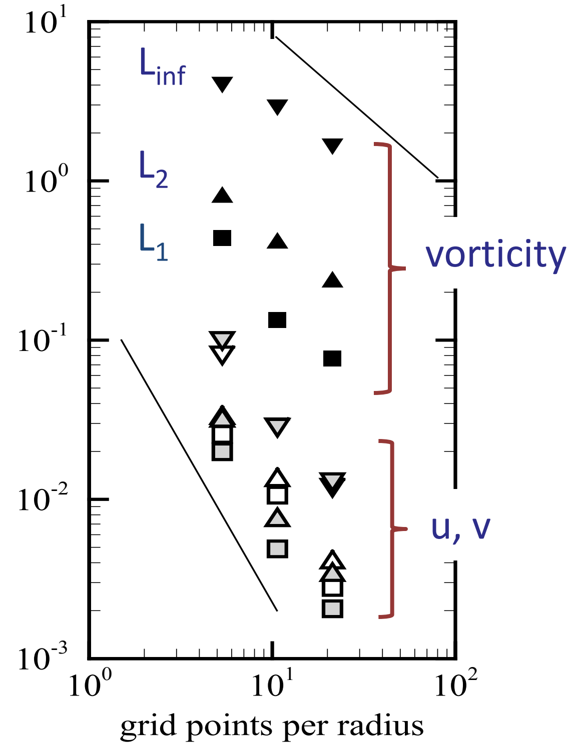


Test: half-cylinder in crossflow (low Re)

Demonstrates first-order convergence

Contours of vorticity at Re = 20





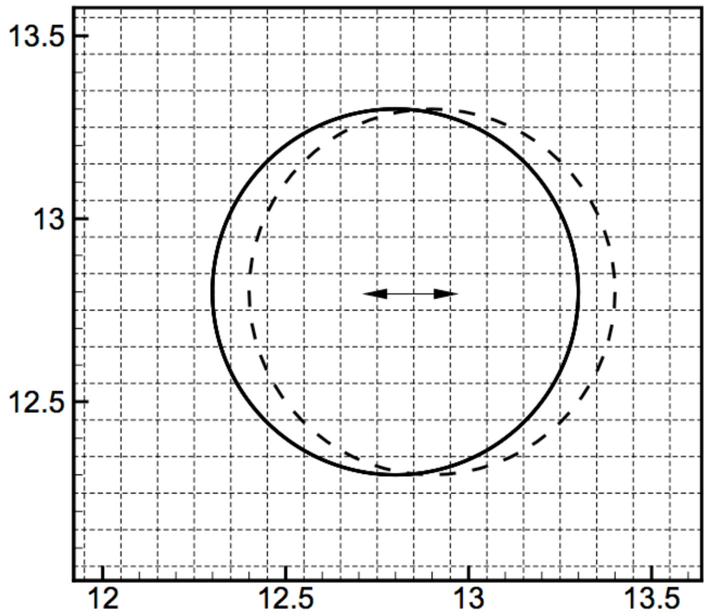
Re-attachment length

	⊗x=0.0937	0.04688	0.02344	0.01172	Dennis & Chang, 1977	Calhoun 2002
L (Re=20)	0.825	1.076	0.990	1.008	0.94	0.91
L (Re=40)	2.130	2.633	2.419	2.458	2.35	2.18

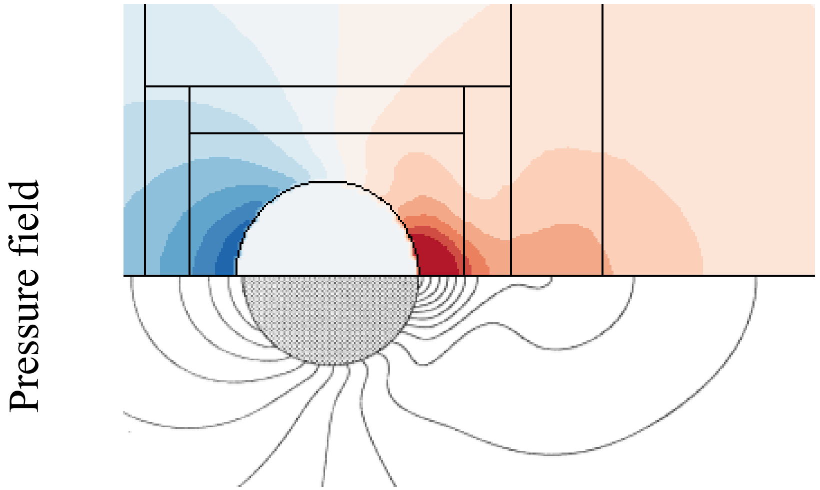
5

Test: oscillating cylinder

Satisfactory match reached with 60 grid points across cylinder



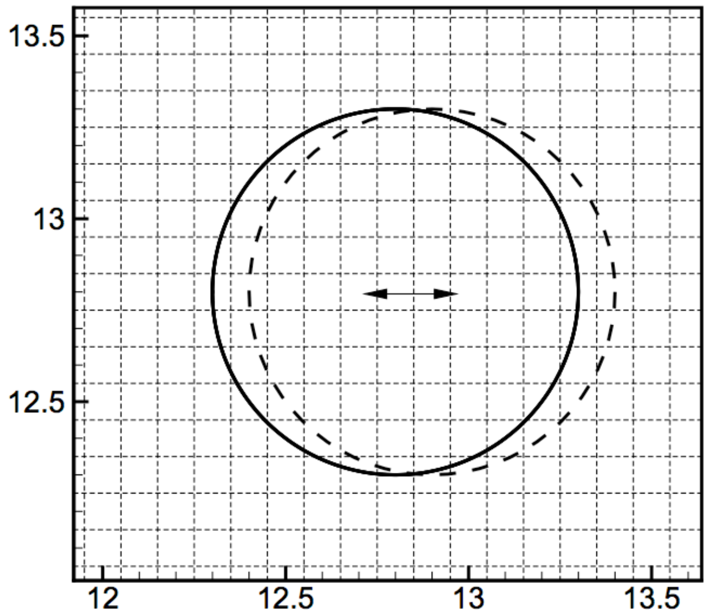
$$x_1(t) = -A \sin(2\pi f\, t)$$



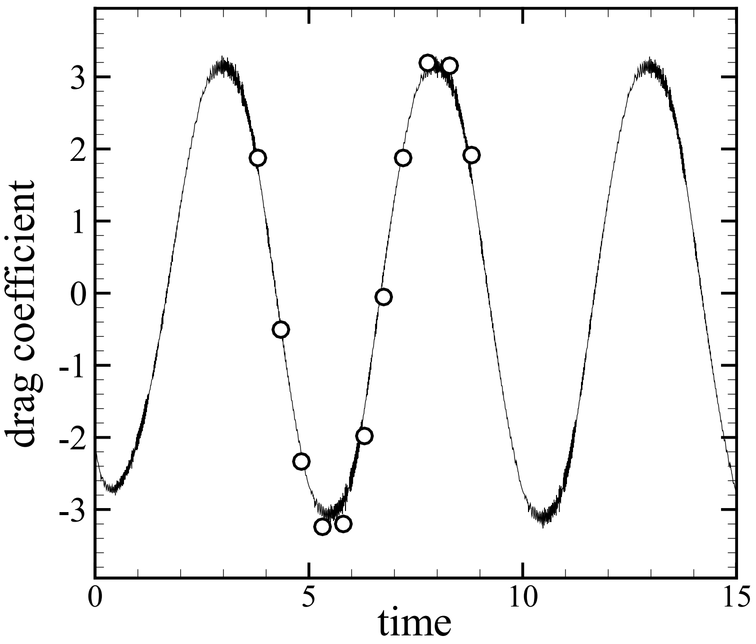
Body-fitted simulation by Dütcsh et al., J. Fluid Mech. 360 (1998)

Test: oscillating cylinder

Satisfactory match reached with 60 grid points across cylinder



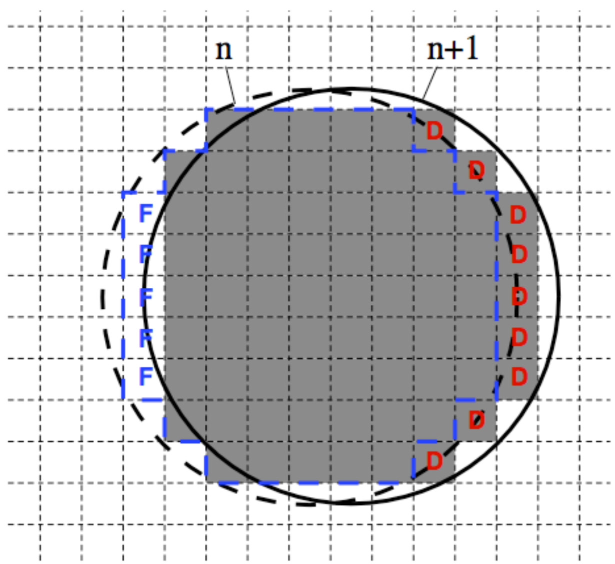
$$x_1(t) = -A\ \sin(2\pi f\ t)$$

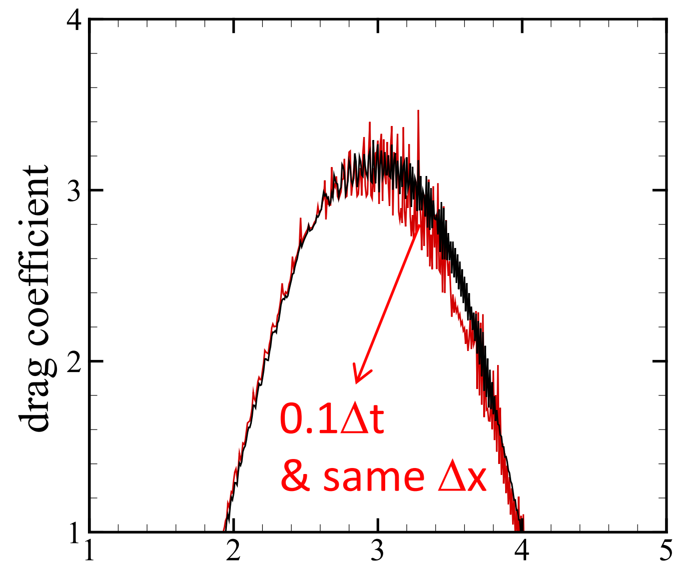


○ Data by Dütcsh et al.,
J. Fluid Mech. 360 (1998)

Artifacts of the staircase approach

Undesired pressure oscillations due to abrupt inclusion/exclusion of cells





Error analysis by Seo and Mittal, J. Comp. Physics 230 (2011):

$$\underbrace{\frac{\Delta V}{\Delta t}\left(q^{n+1}-q^{n}\right)}_{S_V} - \underbrace{\Delta A\sum\nolimits_{face}\vec{U}_b\left(\vec{n}_f-\vec{n}_b\left(\vec{n}_f\cdot\vec{n}_b\right)\right) - \Delta A\sum\nolimits_{face}(\vec{d}\cdot\vec{\nabla})\vec{U}\cdot\vec{n}_f}_{S_\sigma}.$$

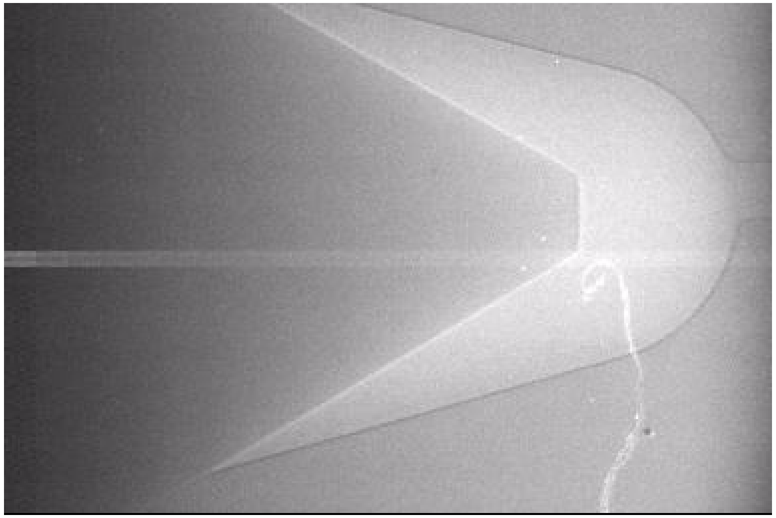
Spurious source of fluid volume due to fresh (F) and dead (D) cells

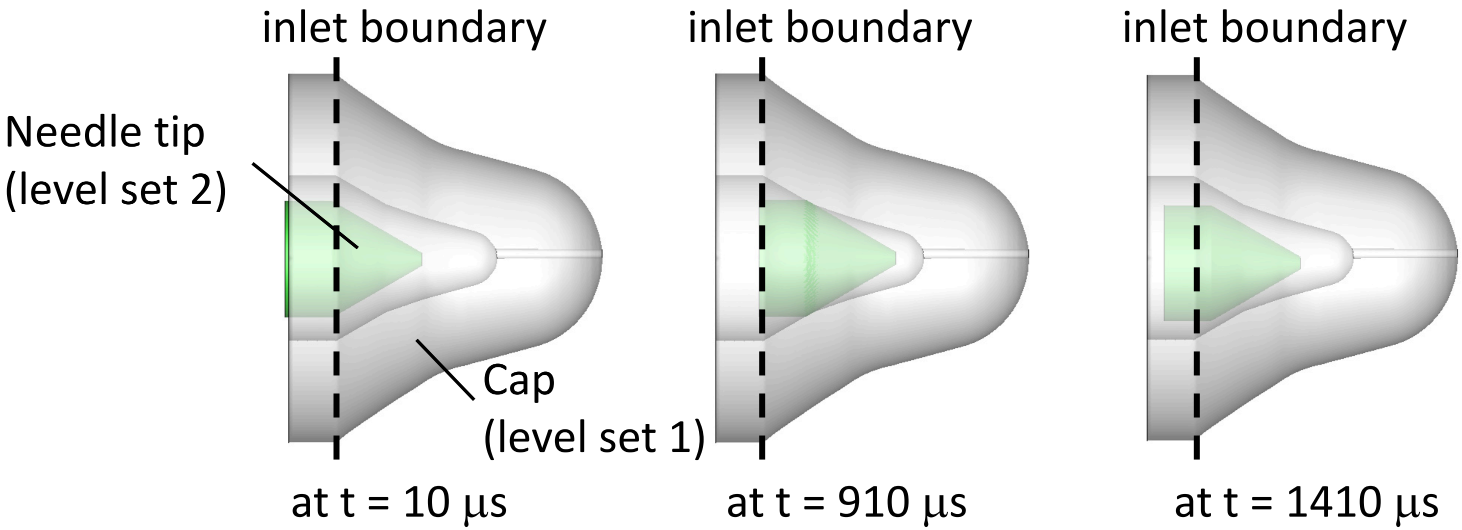
Shape difference

Flux location

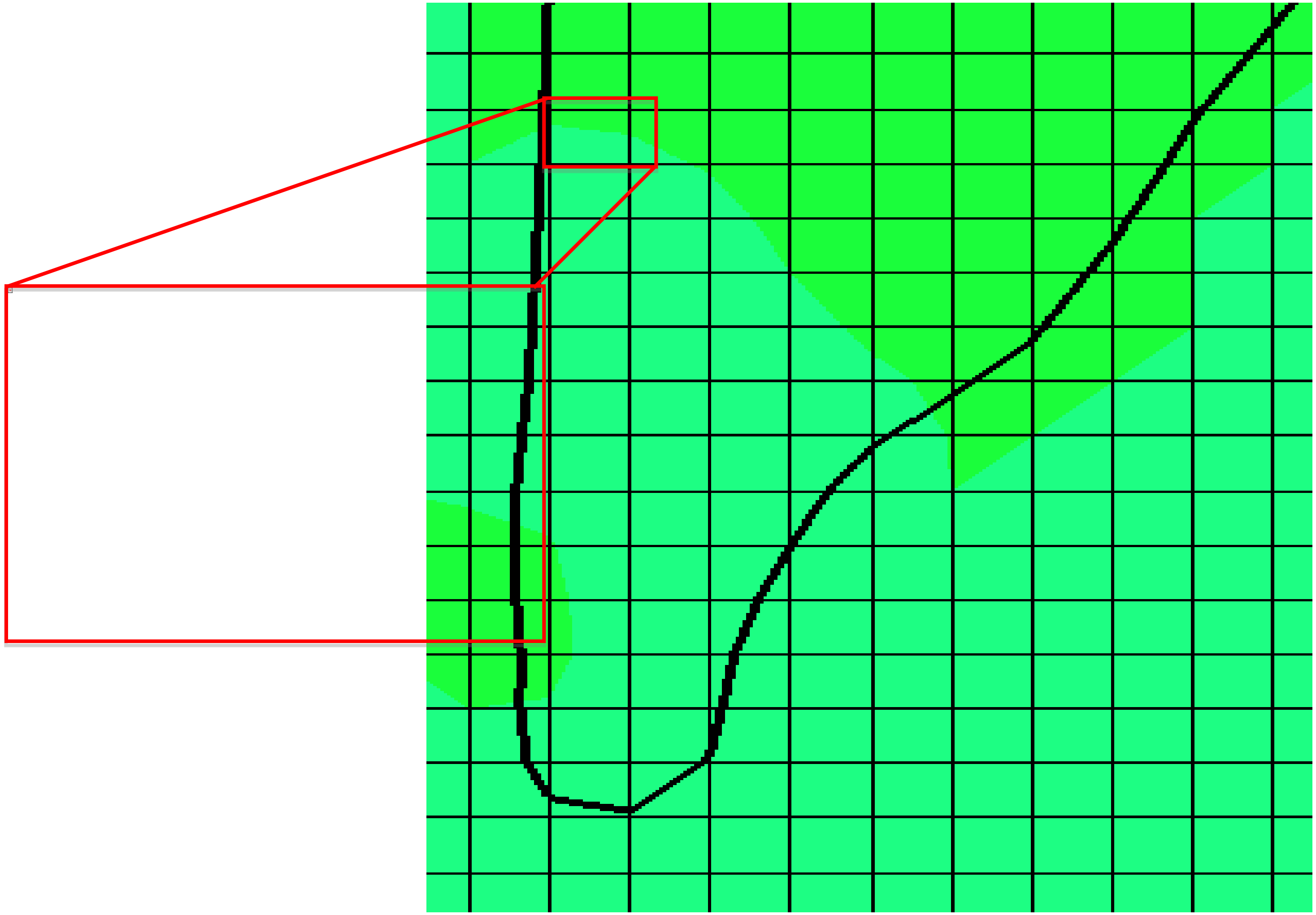
Spray A: needle motion

Use combination of distinct level set functions for each injector part



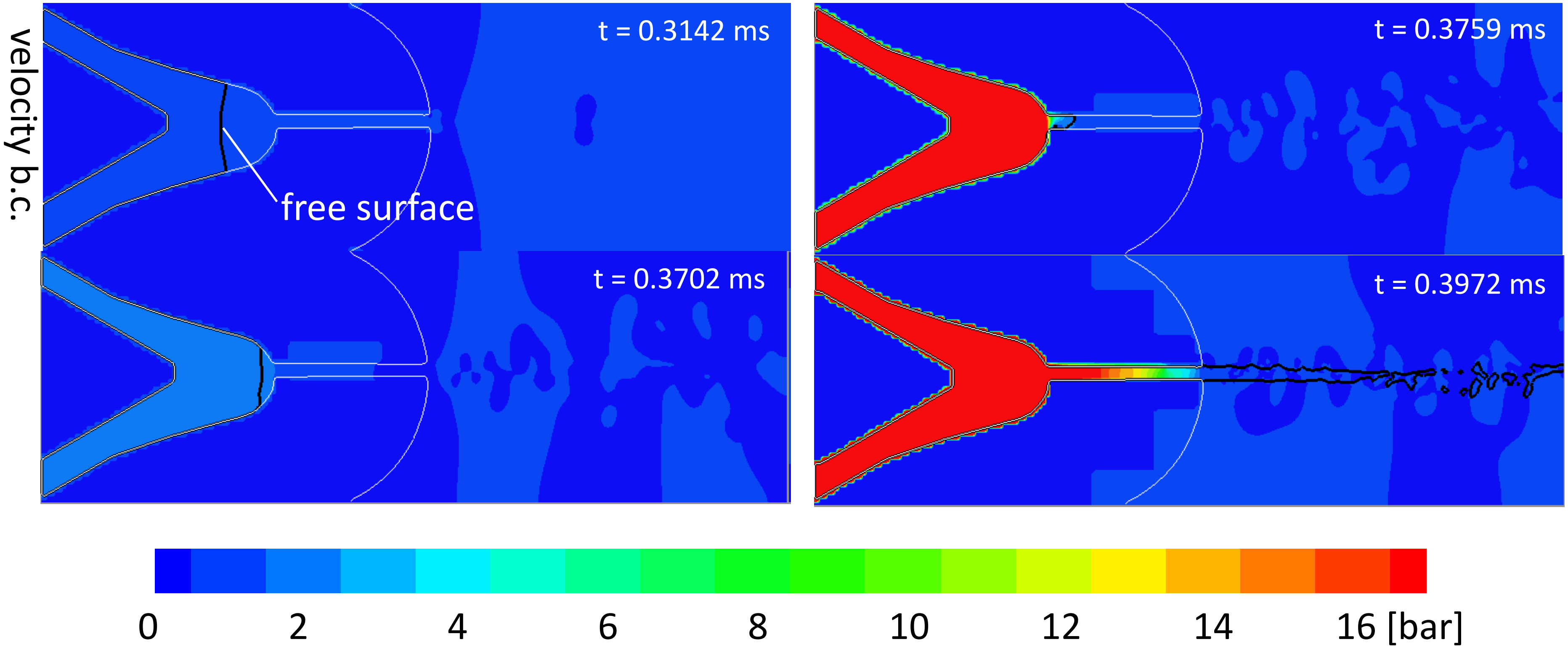


Grid resolution is critical to resolve sharp corners



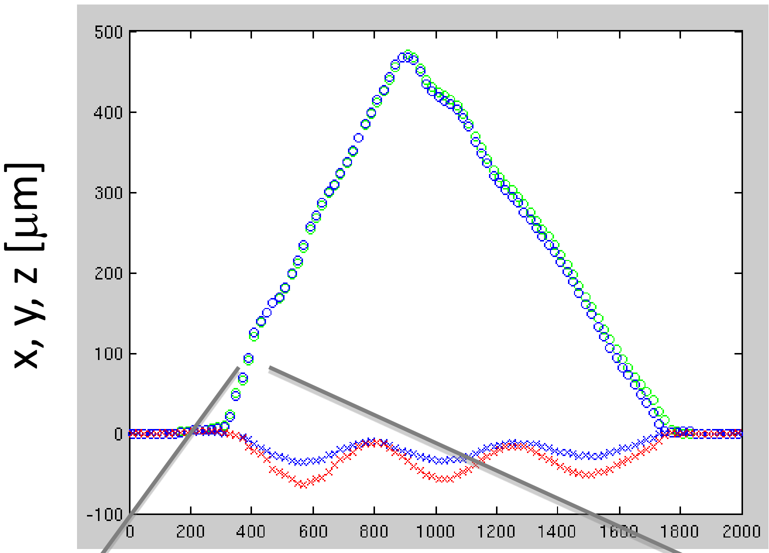
Partially filled sac and needle displacement

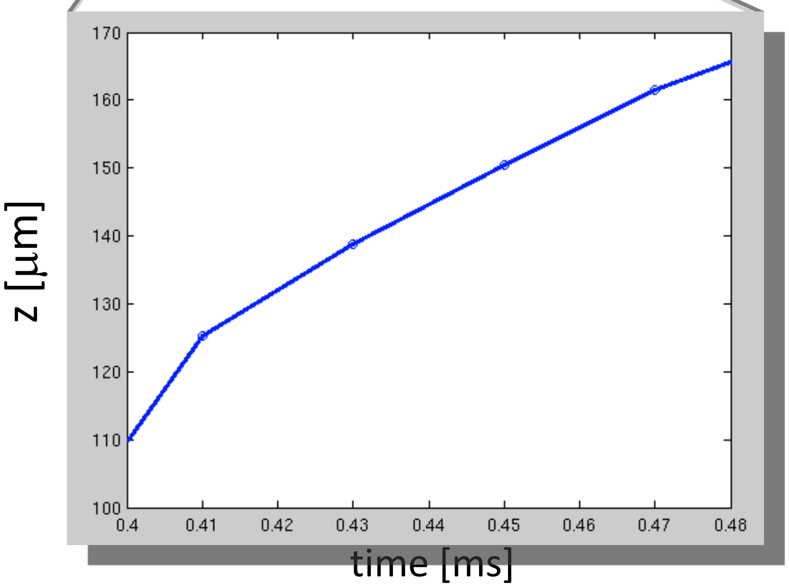
Toy problem with near zero inlet velocity

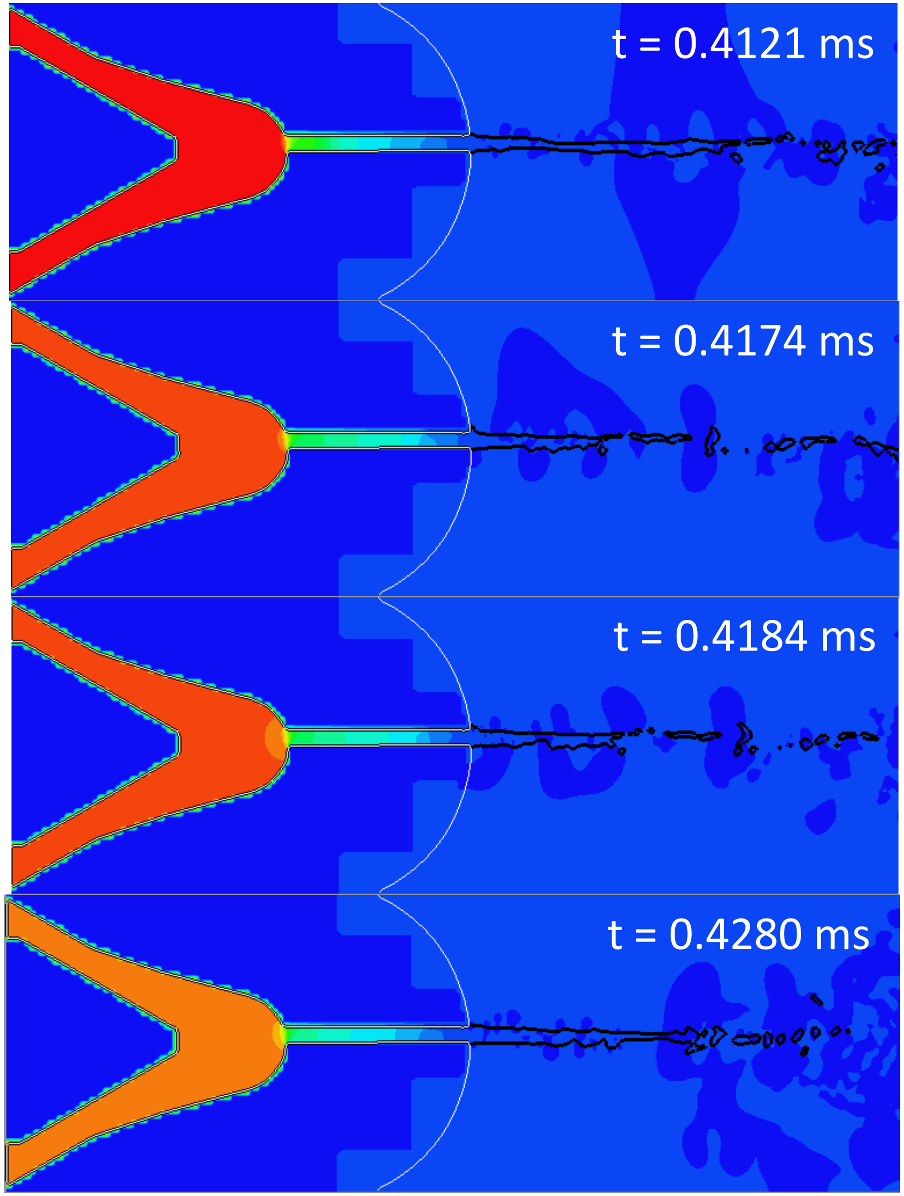


Test: Needle deceleration

Needle trajectory

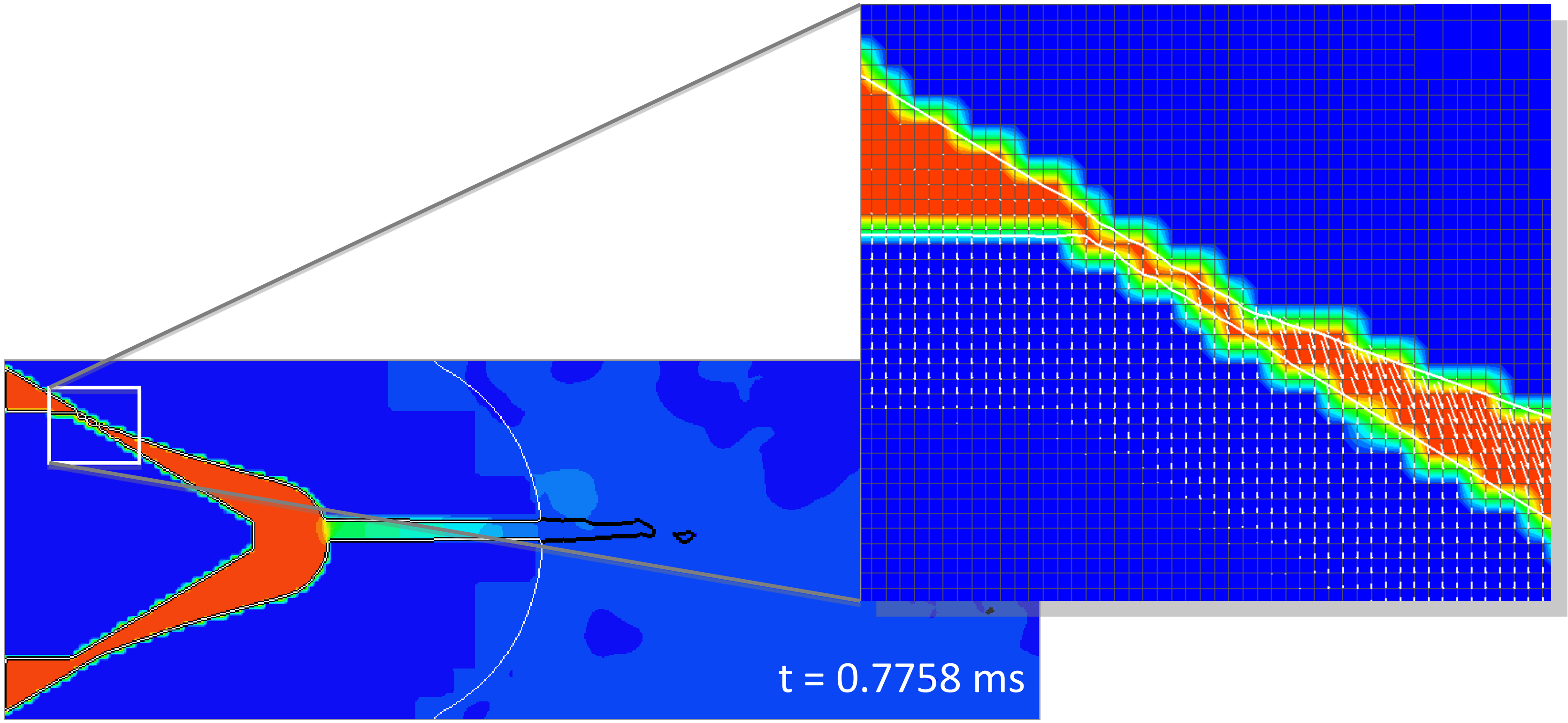






Achieved partial injector closure

Completion requires the implementation of inlet pressure boundary conditions



Final remarks

- Embedded boundary method is a simple alternative to body-fitted re-meshing for the existing multiphase capability in CLSVOF
  - Improve wall boundary treatment by wall functions?
- Straightforward staircase implementation may be sufficient for moving parts if $\Delta x/\Delta t$ is not too large
  - A method to avoid pressure oscillations is under development
- Problem stiffness and injection duration cause very long simulation times
  - Use more recent Boxlib library
  - Improve scalability of embedded boundary algorithm
- Substantial amount of physics is still missing for a realistic Diesel injection
  - Cavitation,
  - Compressibility of the liquid phase
  - …

"Science is long, life is short…"

Engine Combustion Network

ECN2: Internal Injector Modeling

Session organizers:

David Schmidt

Chris Powell

Marco Arienti

Second Workshop of the Engine Combustion Network,

Heidelberg, Germany, September 2012

Introduction and background

- Targets
- Approaches
- Results
- Future Work

Targets

- Spray A
  - This year's target
  - Converging, resembles a common, modern diesel fuel injector hole
  - Well-characterized by CMT and ANL
  - Minimal, if any, cavitation
- Spray H
  - This year's second target
  - Less characterization than Spray A
  - Cavitates readily
- Spray B
  - Multi-hole
  - Next year's target
  - Computational shape being determined by Georgia Tech

Proposed Metrics for Comparison

- Global metrics
  - Cd: Coefficient of discharge
  - Cv: Velocity coefficient
  - Ca: Area coefficient
  - No consensus for which density to use, so be verbose
- Pressure drop across the orifice (may be different than nominal pressure difference across the injector)
- Momentum and fluctuation distribution at the nozzle exit
- Vapor fraction at the exit plane.
- Axial slices showing a longitudinal variation of momentum, vapor fraction, and temperature.
- Spatial position and timing ASI of these quantities (e.g. radial profile at exit, extent of vapor bubbles, swirl)
- Temperature is also a factor in injector flows, especially if they are experiencing minimal cavitation, and should be noted

Contributors

- Thomas Furlong and Caroline Genzale, Georgia Tech.
- Sukanta Rakshit and David P. Schmidt, UMass
- Marco Arienti, SNL

Summary of Approaches

Cavitation modeling

Sub-grid Bubble Dynamics

- Kubota et al.[1989]
- Chen and Heister [1995]
- Gavaises et al.[1998]
- Alajbegovic [1998]
- Schnerr et al.[2001]
- Singhal [2002]

Thermal Equilibrium

- Delannoy and Kueny [1990]
- Schmidt et al. [1996]
- Kärrholm et al. [2001]
- Habchi et al. [2003]
- Lee and Reitz [2010]

Thermal Non-Equilibrium

- Avva et al. [1995]
- Neroorkar et al.[2011]

- Georgia Tech & UMass used thermal equilibrium approaches
- Marco used bubble dynamics approach

Thermal Equilibrium Approach

- Phase change is fast compared to flow times
- Inertial equilibrium: the two phases move at the same velocity
- Permits creation of an equation of state and use of a single velocity field

Other comparisons

- Both implemented in OpenFOAM
- Georgia Tech used the cavitatingFoam solver based on the work of Fabian Peng-Kärrholm
- UMass used an in-house solver, minMod flux limiter
- Different compressibility models and numerical methods
- UMass included turbulence

cavitatingFoam

- Homogenous Flow Model
- Barotropic Equation of State
  - $\rho = (1-\gamma)\rho_l^0 + (\gamma\psi_v + (1-\gamma)\psi_l)p^{sat} + \psi(\gamma)(p - p^{sat})$
- Continuity (Solve for ρ)
  - $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$
- Momentum (Solve for U, not ρU)
  - $\frac{\partial \rho U}{\partial t} + \nabla \cdot (\rho U U) = -\nabla p + \nabla(\mu_f \nabla U)$
- Pressure
  - $\frac{\partial \psi\rho}{\partial t} - \left(\rho_l^0 + (\psi_l - \psi_v)\right)p^{sat}\frac{\partial \gamma}{\partial t} - p^{sat}\frac{\partial \psi}{\partial t} + \nabla \cdot (\rho U) = 0$

[1] Kärrholm et al., Modelling Injector Flow Including Cavitation Effects for Diesel Applications, FEDSM2007-37518

Numerical Settings

- Interpolation Schemes – Linear
- Divergence Schemes – Gauss Upwind
- Laplacian Schemes – Gauss Linear Uncorrected
- Gradient Schemes – Gauss Linear
- Solvers
  - All Gauss Seidel
  - Except Pressure – Precondition Conjugate Gradient
    - Diagonal Incomplete-Cholesky Preconditioner
- Pimple Algorithm

Mesh and Fuel Properties

- Mesh Settings
  - Sharp Edged Orifice
    - 831,572 Hexahedral Cells
  - 10 mm Rounded Inlet
    - 778,447 Hexehedral Cells

- Fuel Properties
  - ψ_v=3.42827083e-5 s^2/m^2
  - ψ_l=1.45928011e-6 s^2/m^2
  - $\rho_{l,sat}$=612.82 kg/m^3
  - ρ_v=3.615 kg/m^3
  - Psat=105770 Pa
  - μ_l=0.00029233 Pa.s
  - μ_v=7.6299e-6 Pa.s

- The compressibility in the liquid phase is given by the Tait-Kirkwood equation as

$$a = \sqrt{N \frac{(B/N) - p_l^{sat} + p}{\rho}}$$

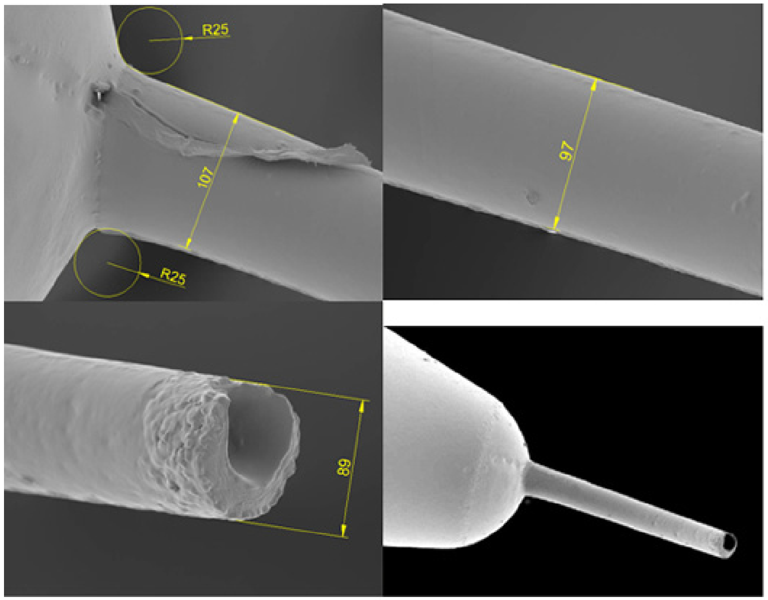
- And in the gas phase is derived from the ideal gas law

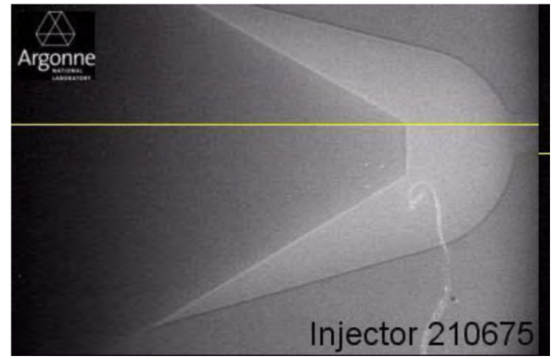
$$a = \sqrt{\gamma \frac{p}{\rho}}$$

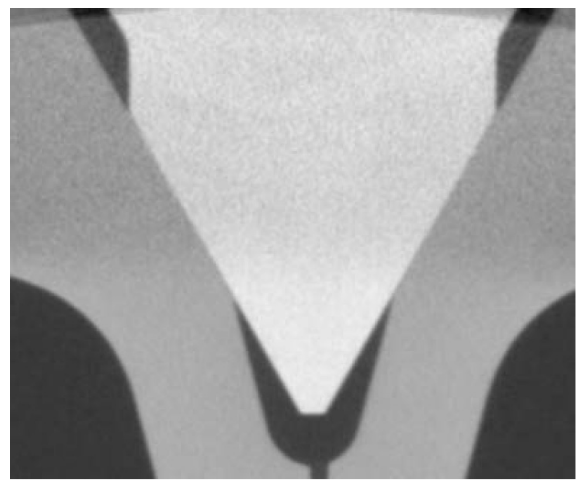
- The two-phase compressibility given by Wallis as

$$a = \sqrt{\frac{1}{(\alpha\rho_g + (1-\alpha)\rho_l)\left(\frac{\alpha}{\rho_g a_g^2} + \frac{(1-\alpha)}{\rho_l a_l^2}\right)}}$$

Results : Spray A Nozzle





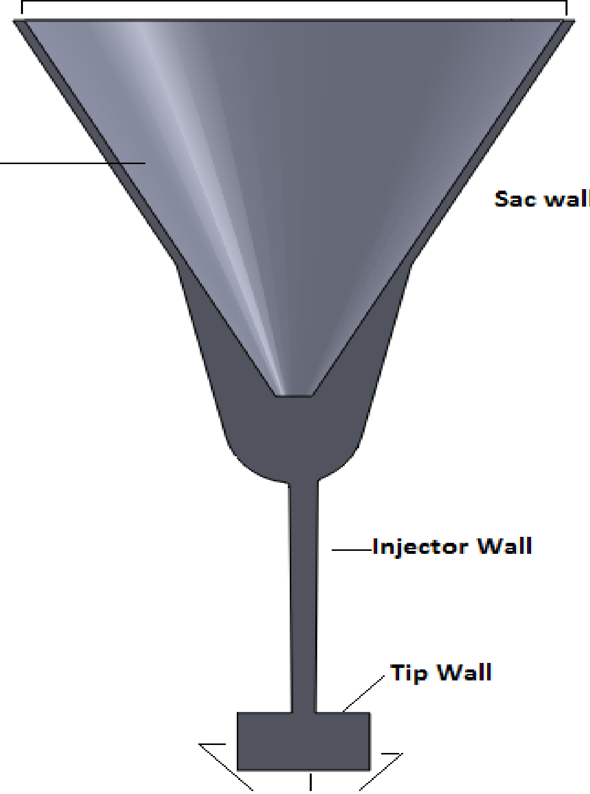


Internal geometry					
r_e [μm]	D_i [μm]	D_m [μm]	D_o [μm]	*k-factor*	AR [%]
25	107	97	89	1.8	16.8
Dimensionless parameters					
L/D_o		r_e/D_i		D_i/D_o	
11.3		0.23		1.20	

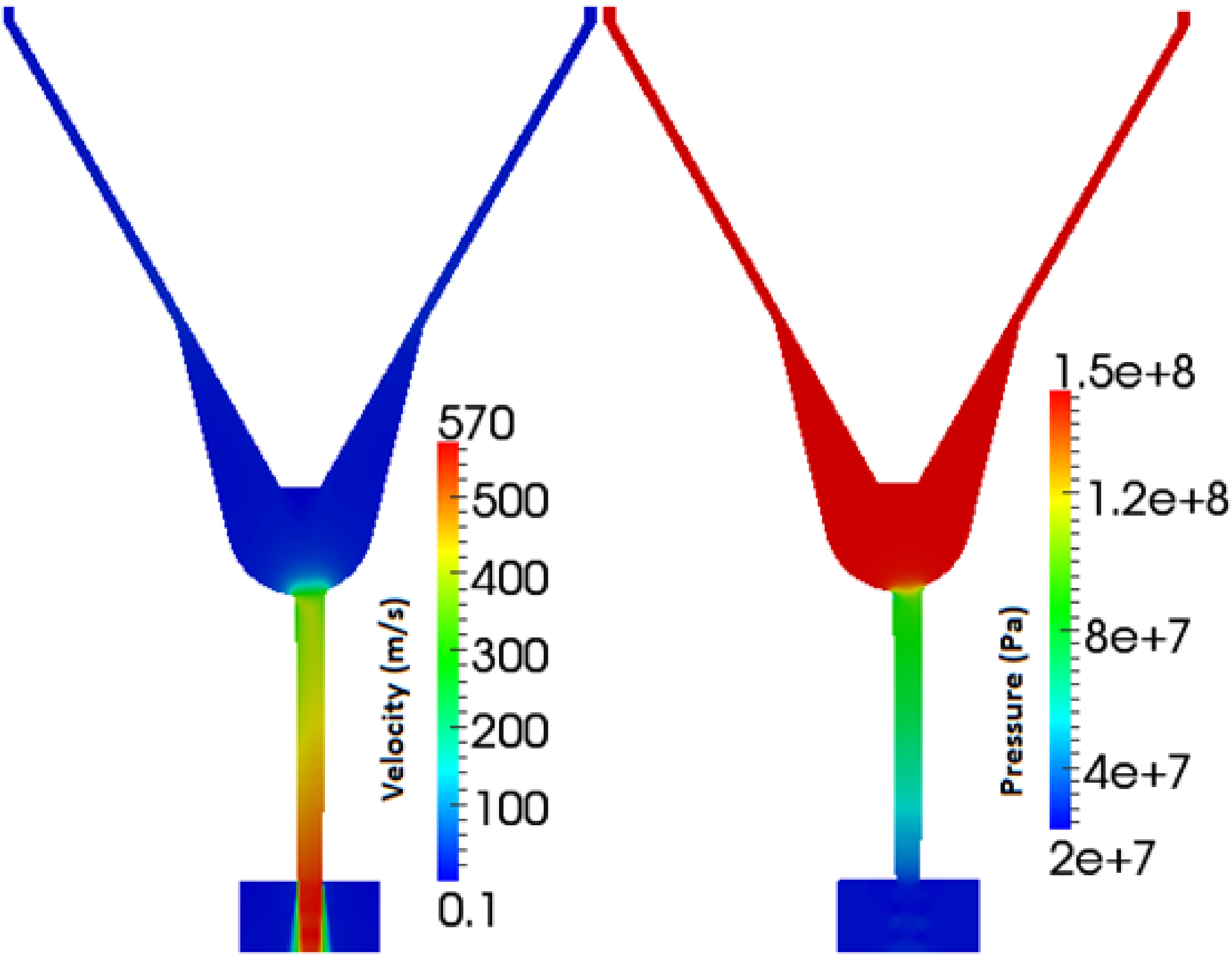
Nozzle # SN 210675 used from Engine Combustion Network 'spray A' condition*

*V. Macian, V. Bermúdez, R. Payri, J. Gimeno, New technique for the determination of the internal geometry of Diesel nozzle with the use of the silicone methodology, *Experimental Techniques, Vol 27 (2), pp. 39-43, 2003.*

Setup : Spray A Nozzle



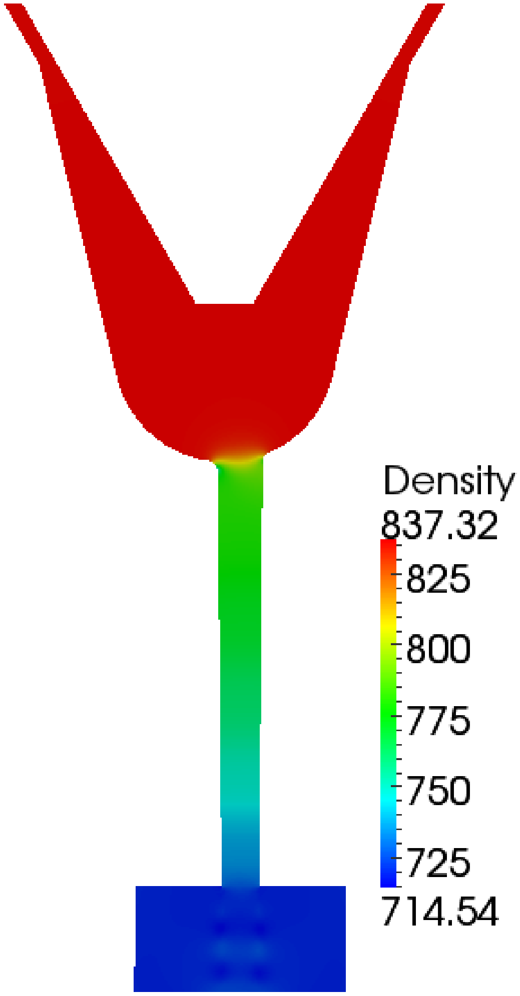
- 3D hex mesh, with off-center hole
- Total Cells : 686K
- Inlet Pressure : 150 MPa
- Outlet Pressure : 6 MPa
- Fuel used : n-dodecane
- Fuel Temperature : 363 K
- Nozzle Inlet Diameter : 0.107 mm
- Nozzle Outlet Diameter : 0.089 mm
- Nozzle L/D : 11.3
- Nozzle r/D : 0.025
- Standard k-ε Turbulence model
- Boundary conditions
  - **Inlet** : Total Pressure
  - **Outlet**: waveTransmissive (pressure)
  - **Wall** : slip wall



Sectional view

Compressibility : Spray A Nozzle

Sectional view



Note the large decrease in density, even in the absence of phase change

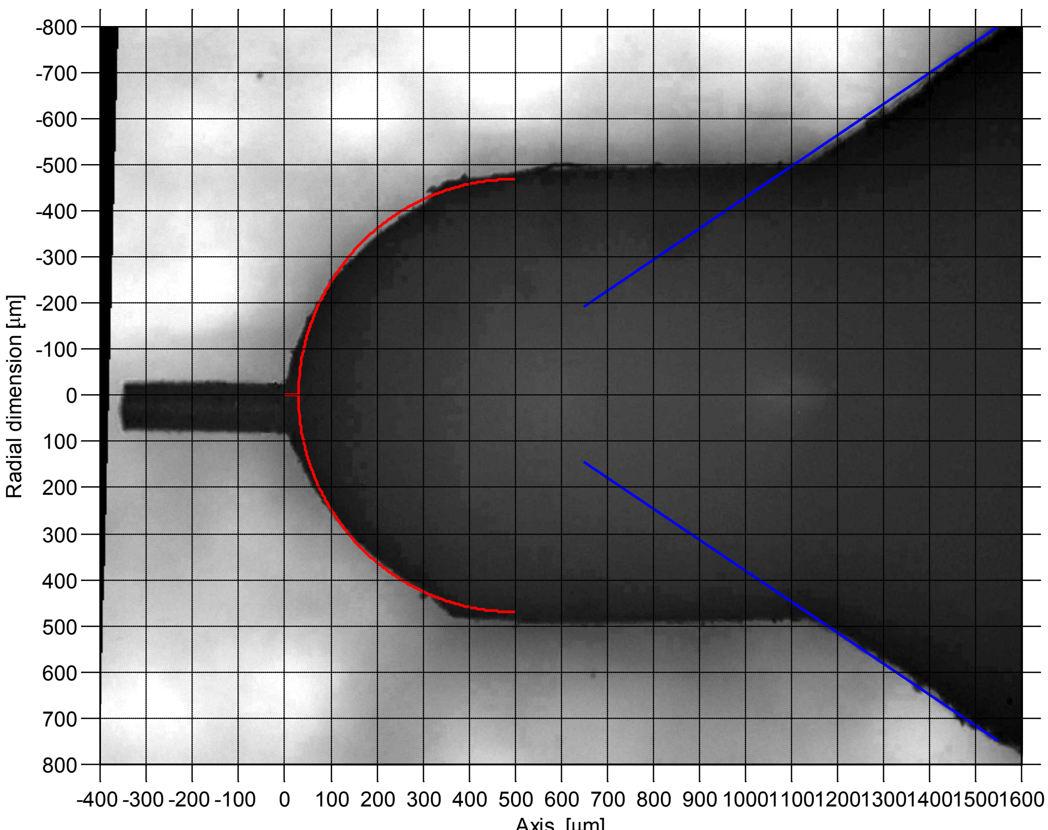
Metrics

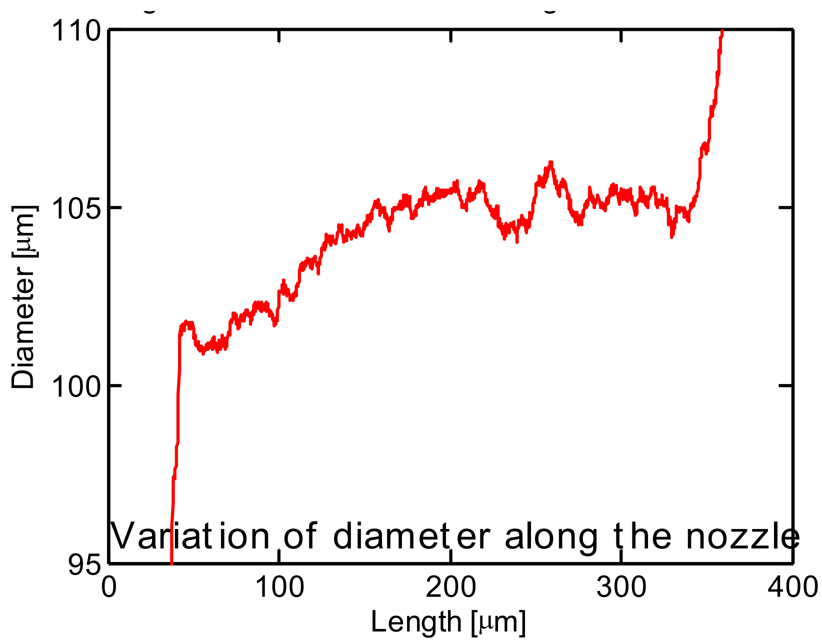
	Experiment*	Simulation	% error	Units
Mass flux	2.62	2.56	2.3	g/s
Momentum flux	1.52	1.58	3.9	N
C_d	0.9	0.89	2.2	
C_v	0.92	0.96	4.34	
C_a	0.98	0.93	5	

- Data used for calculations
  - Density (exit) = 702.5 Kg/m^3
  - Nominal Diameter = 90 μm
  - Inlet Pressure = 150 MPa
  - Exit Pressure = 6 MPa

* R. Payri, J. Manin, "Injector's hydraulic characterization" ECN Workshop, Ventura, Ca 2011

Mesh Construction: Spray H Nozzle



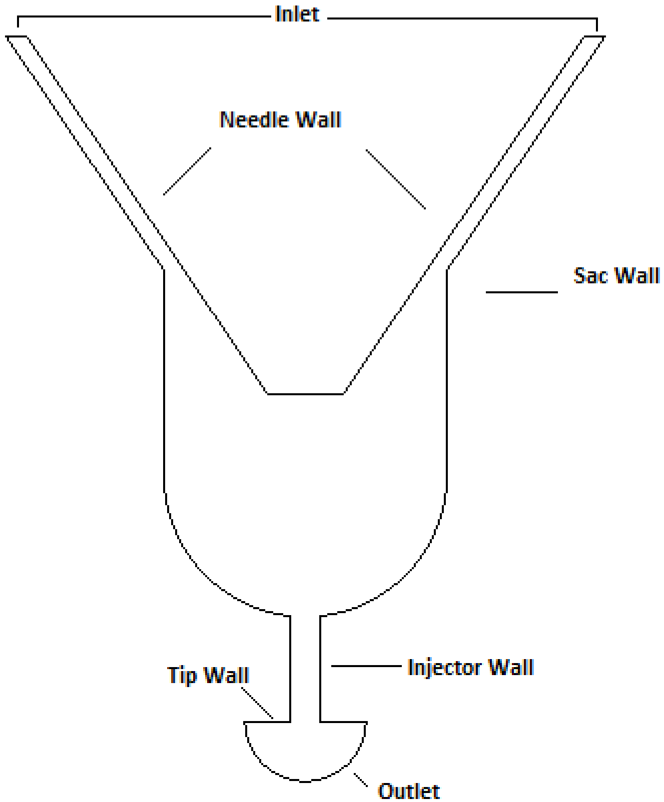


Variation of diameter along the nozzle

Nozzle data from Engine combustion network*

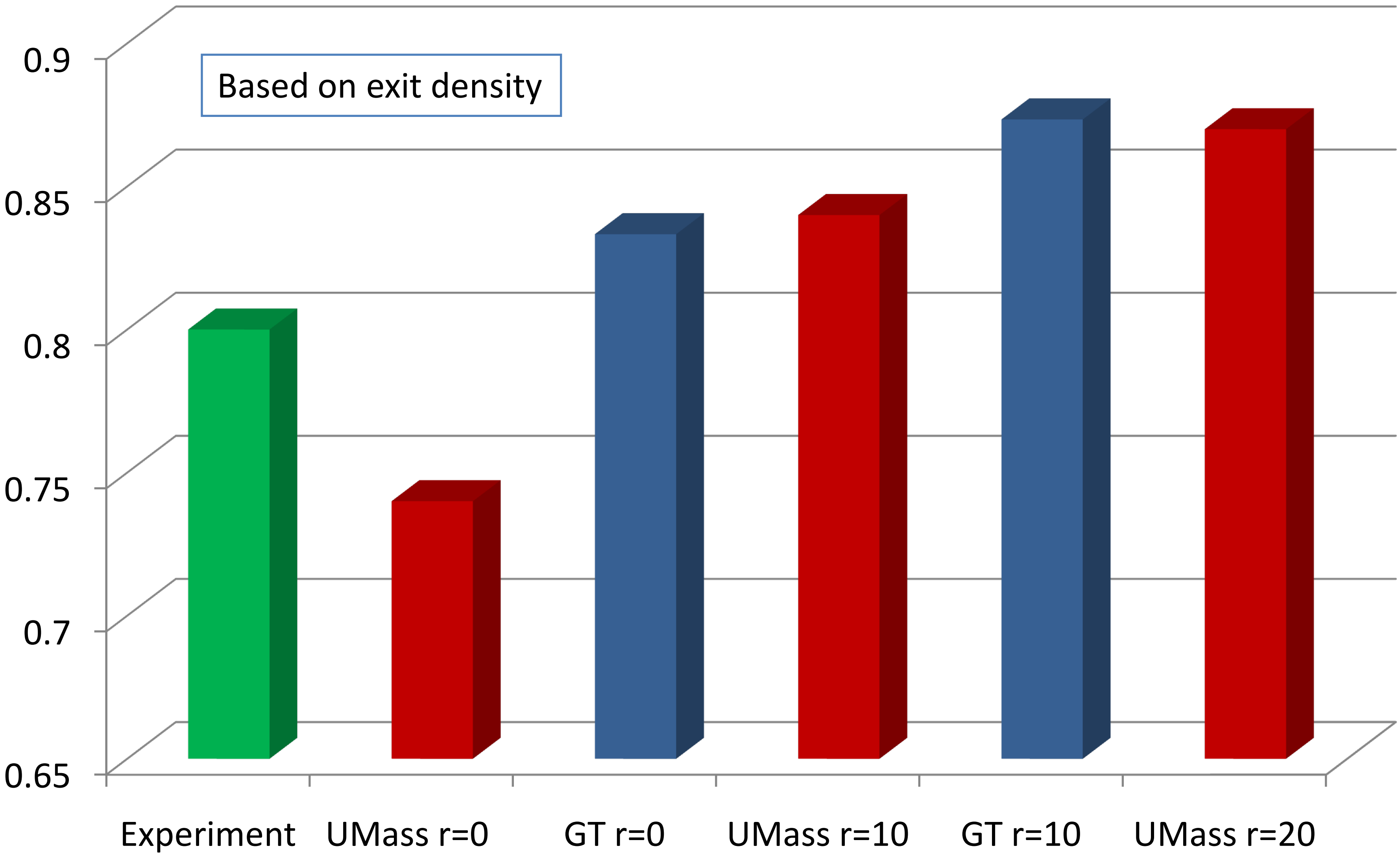
*n-heptane baseline nozzle : Dr. L. Pickett's presentation

Run parameters : Spray H Nozzle

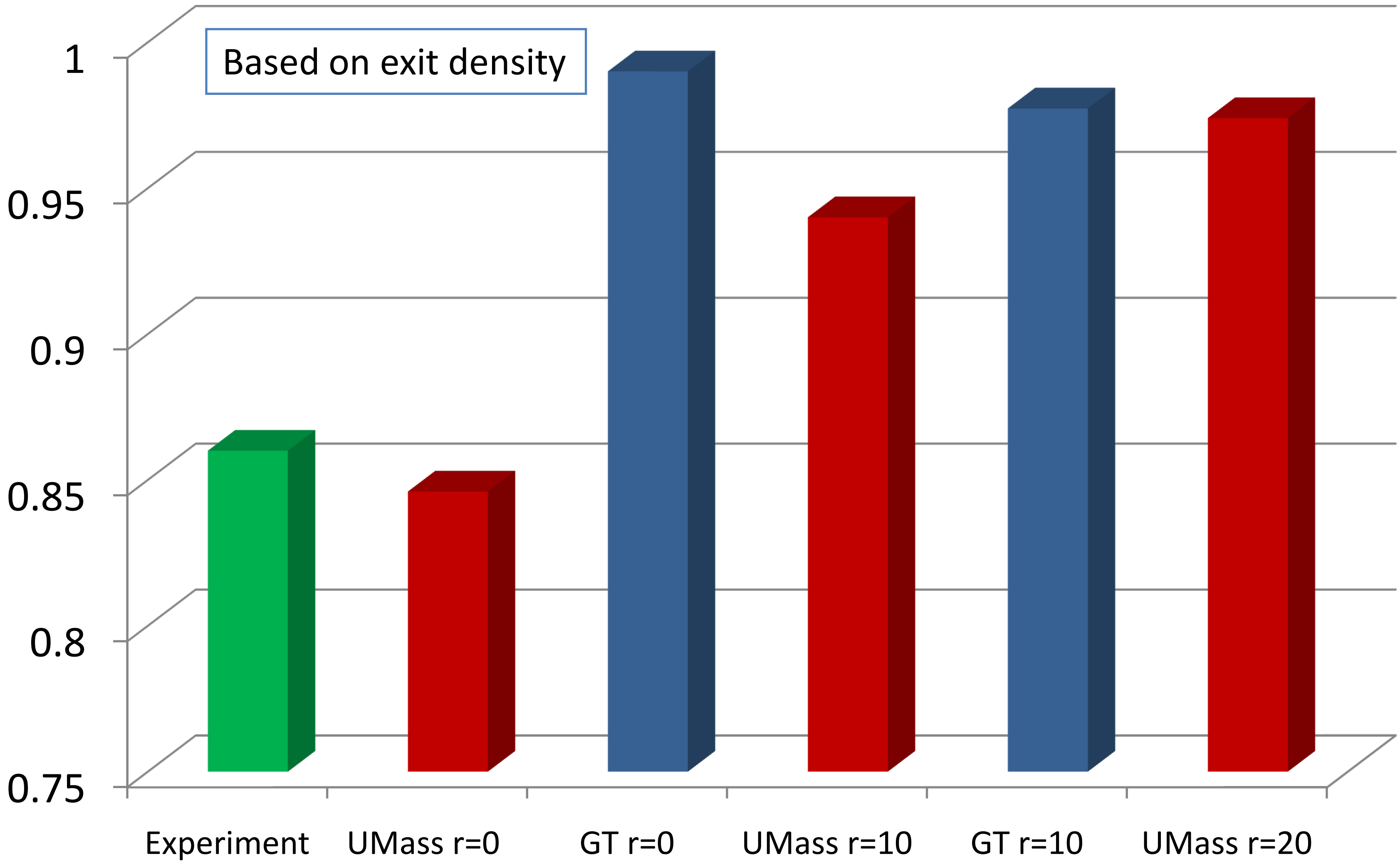


- 3D, hex mesh
- Total Cells : 0.9 million cells
- Inlet Pressure:154.3 MPa
- Outlet Pressure: 4.33 MPa
- Fuel used : n-heptane
- Inlet Diameter : 0.105 mm
- Outlet Diameter : 0.1 mm
- L/D : 3.5
- Fuel Temperature : 373 K

Spray-H Coefficient of Discharge

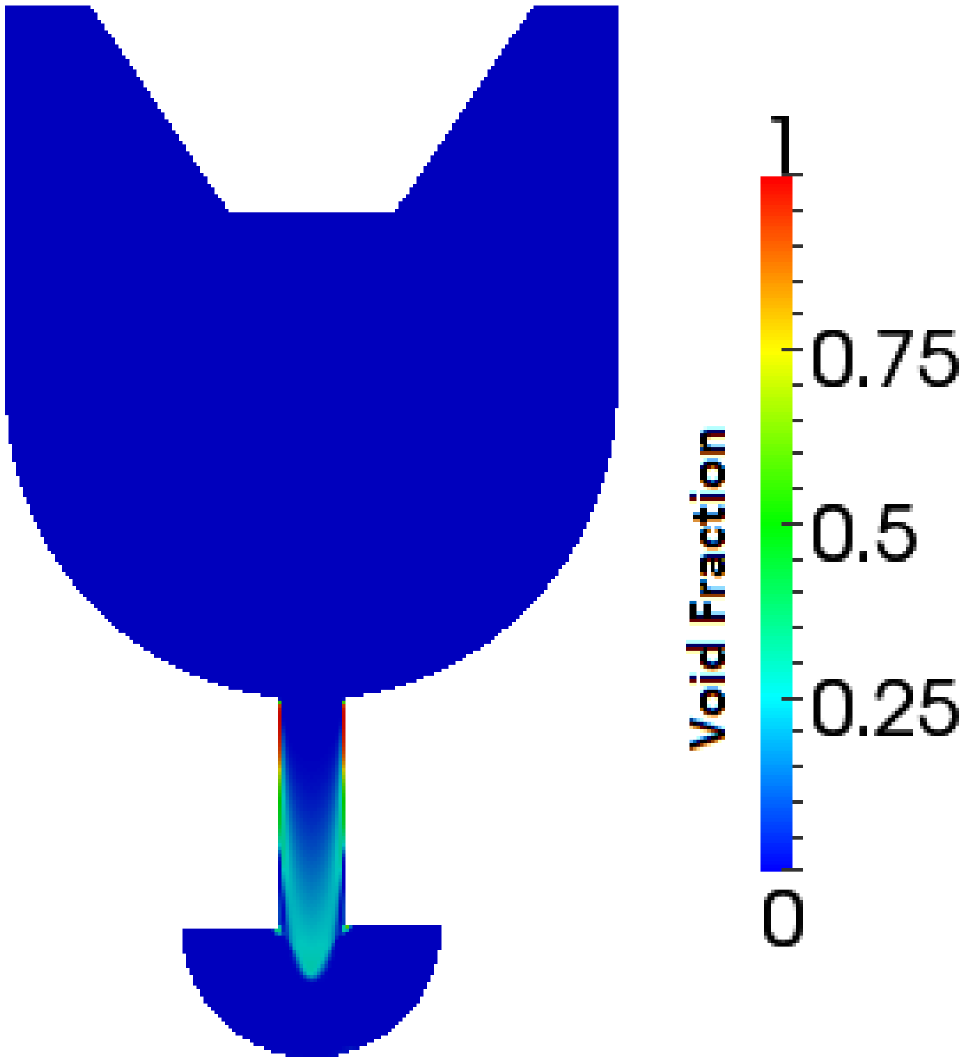


Spray-H Coefficient of Area

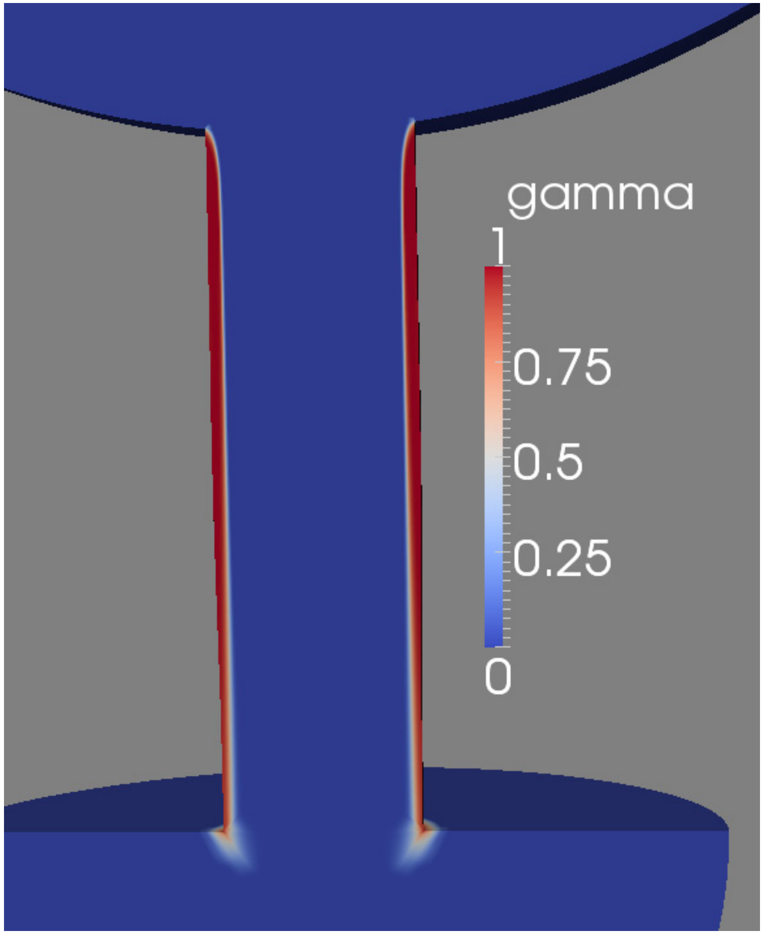


Inner Flow Details: Void Fraction

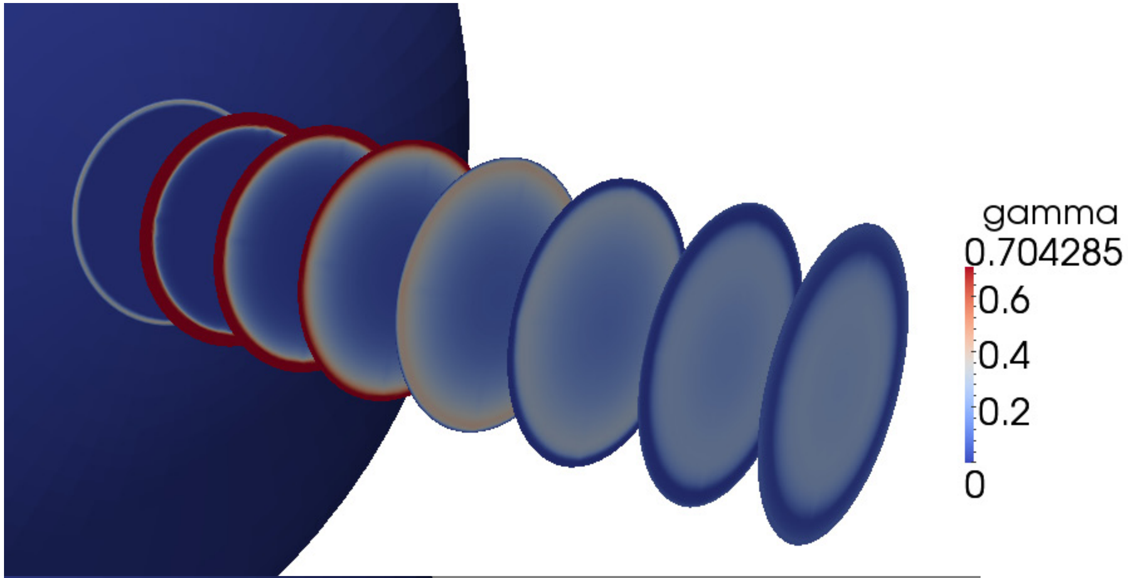
UMass



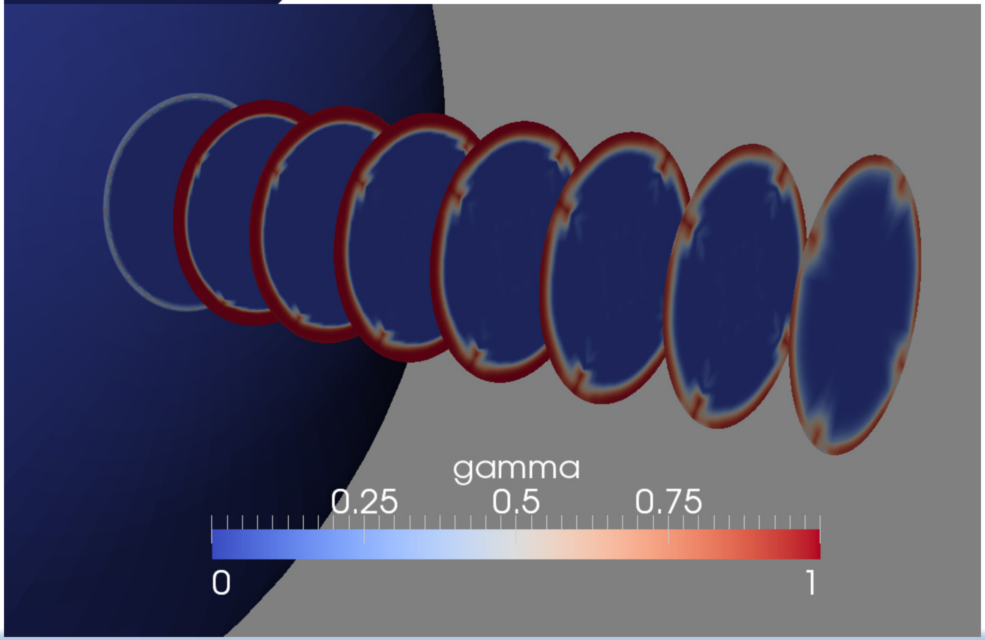
GT



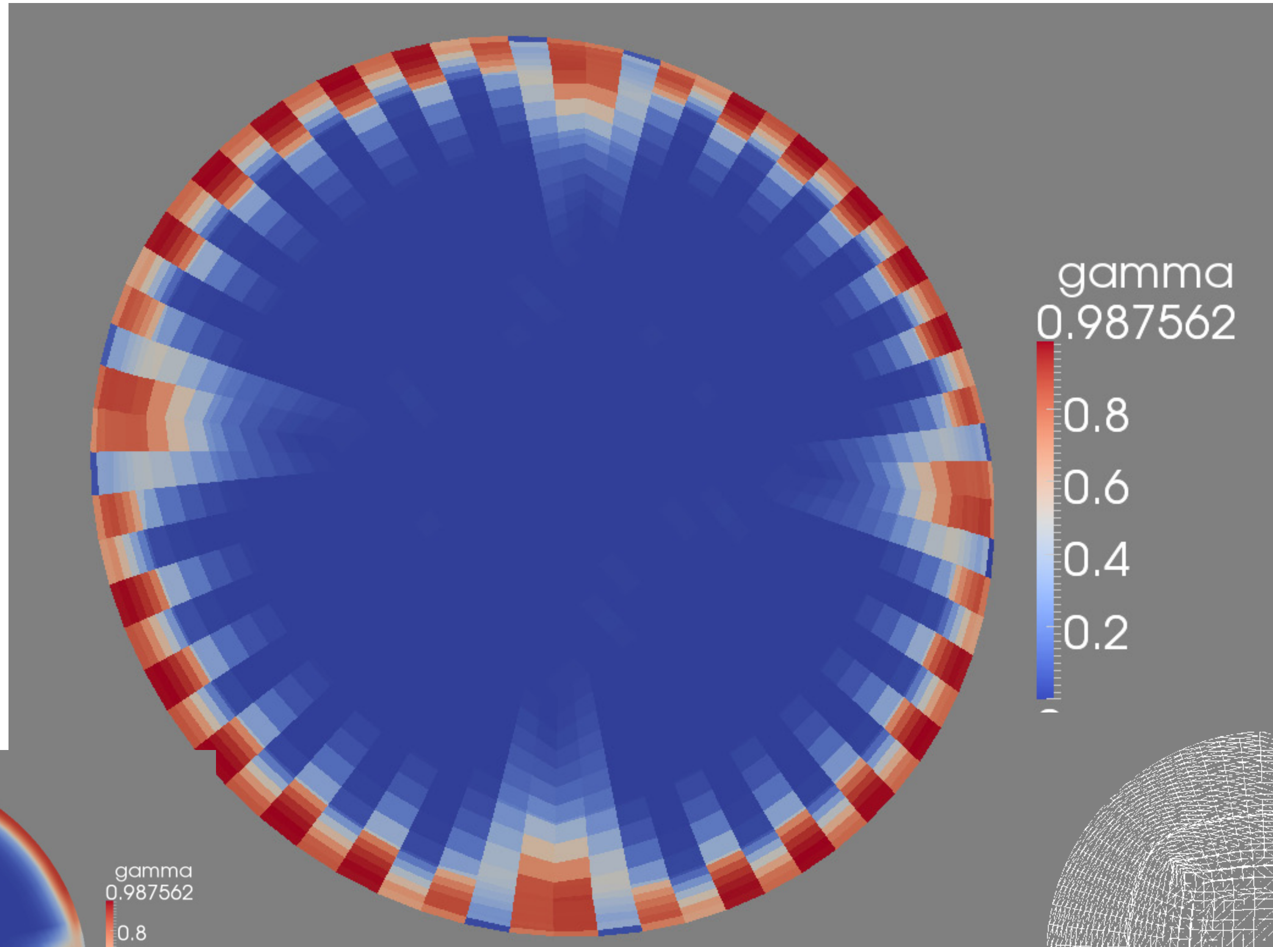
UMass

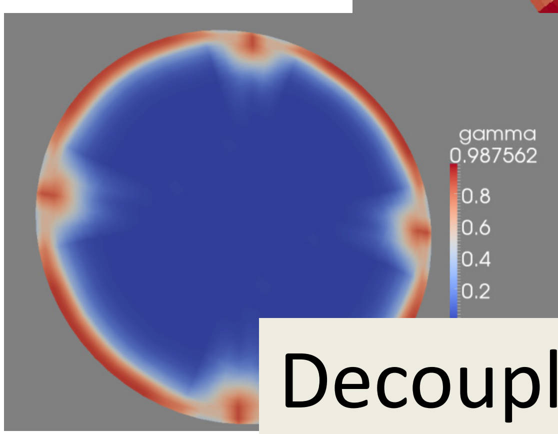


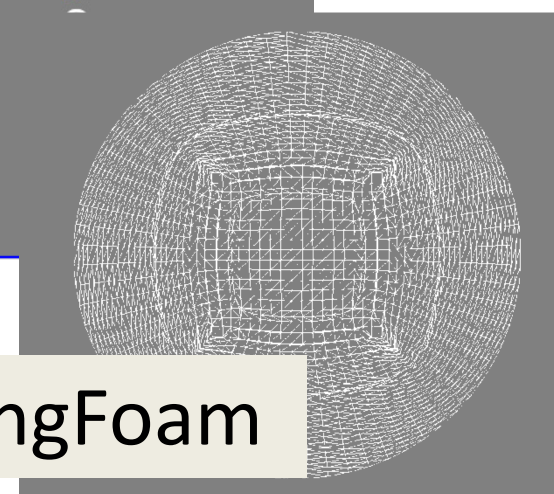
GT



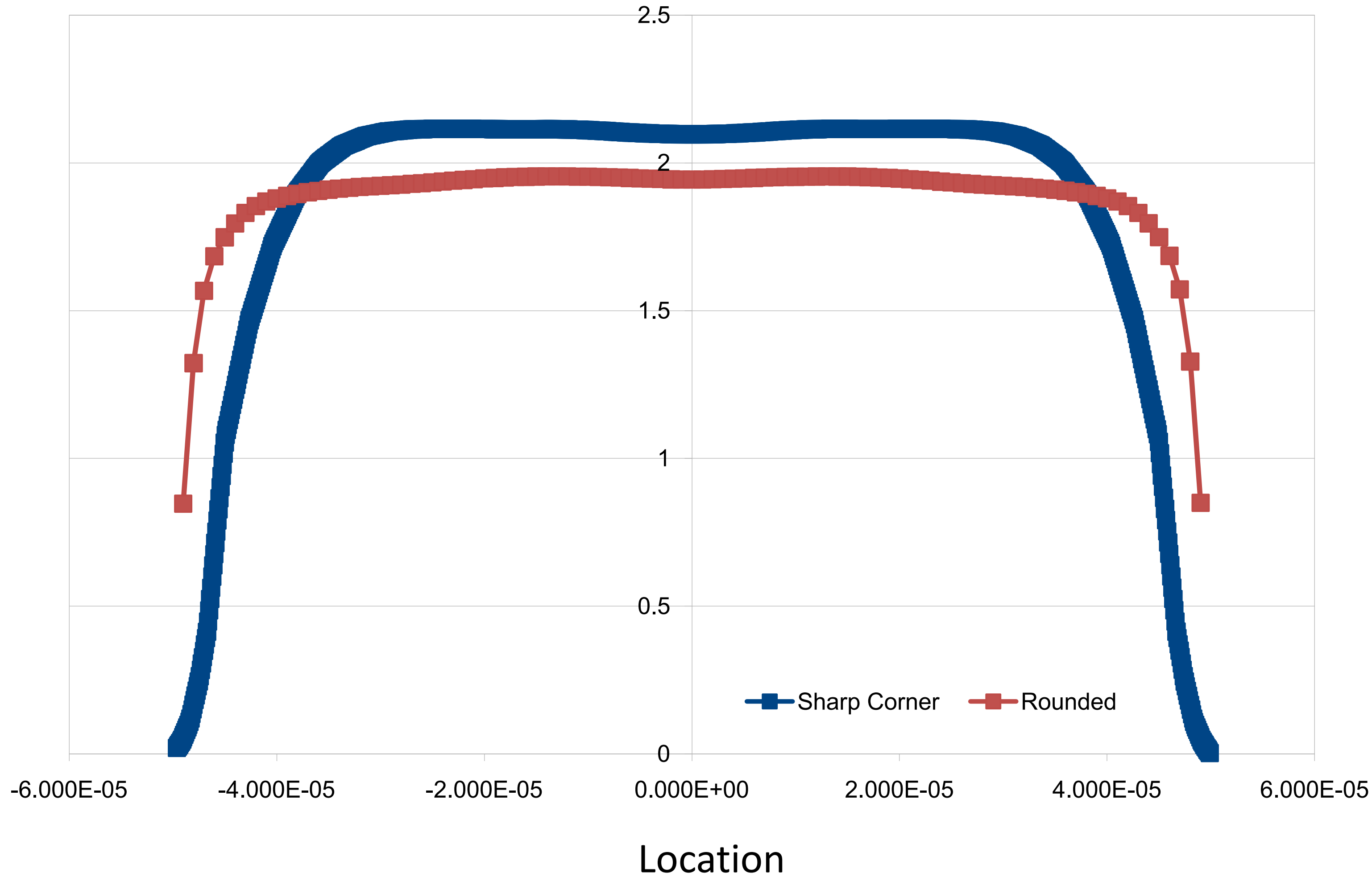
Decoupling Issue







Decoupling issue with cavitatingFoam


2.5
2
1.5
1
0.5
0
-6.000E-05
-4.000E-05
-2.000E-05
0.000E+00
2.000E-05
4.000E-05
6.000E-05
Sharp Corner
Rounded
Location

Summary and Conclusions

- Spray A
  - No cavitation predicted
  - Effects of compressibility clear
  - Agrees with experimental measurements fairly well

- Spray H
  - Preliminary results from UMass & GT
  - Shows geometrically induced cavitation
  - Great sensitivity to inlet corner radius
  - For predictive results, we need to know r within +/- 3 microns