ENGINE COMBUSTION NETWORK

ECN6 Topic 9 :
Internal and Near Nozzle Flow Gasoline Spray

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ENGINE COMBUSTION NETWORK

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PRESENTATION CONTENTS

- Modelling Approaches
  - Simulation Techniques
  - Boundary Conditions
  - Meshing
- ECN 6 Simulation Results
  - ROI comparison
  - Hole-Hole Rate of Injection comparison
  - Hole-Hole variation at Z = 2mm plane
  - Representative contour plots
- Next Steps for Gasoline sprays
  - Encouraging more contributors for experiments, new models for CFD

SPRAY G , G2 , G3 NOMINAL OPERATING CONDITIONS

Condition	SprayG	SprayG2	SprayG3
Fuel	Isooctane	Isooctane	Isooctane
Injection Pressure	20 MPa	20MPa	20MPa
Fuel Temperature	90° C (363.15 K)	90° C (363.15 K)	90° C (363.15 K)
Ambient Temperature	300° C (573.15 K)	60° C (333.15 K)	60° C (333.15 K)
Ambient Density	3.5 kg/m^3	0.5 kg/m^3	1.2 kg/m^3
Back Pressure	600 kPa (N_2)	50 kPa (N_2)	100 kPa (N_2)
Injected Quantity	10 mg	10 mg	10 mg
Injection Duration	780 μs (“actual”)	780 μs (“actual”)	780 μs (“actual”)

ENGINE COMBUSTION NETWORK

MODELING APPROACHES

INTERNAL MODELING CODES

Institution	UMass	CD-Adapco	CMT Converge	CMT CCM+	ANL	Chalmers	KAUST
Code	HRMFoam	STAR-CCM+	Converge	STAR-CCM+	Converge	SchnerrSauer	Converge
Origin	UMass	CD-Adapco	Convergent Science	CD-Adapco	Convergent Science	Chalmers	Convergent Science
External Coupling	Eulerian	Eulerian	Eulerian	Eulerian	Eulerian	Eulerian	Eulerian
Cases	Spray G, G2	G, G2	G,G2,G3	G	G	G	G

APPROACHES

Institution	UMass	CD-Adapco	CMT Converge	CMT	ANL	Chalmers	KAUST
Liquid Fuel	Iso-Octane	Iso-Octane	Iso-Octane	Iso-Octane	Iso-Octane	Iso-Octane	Iso-Octane
Compressibility	Yes	No	Yes	No	No	No	Yes
Cavitation	Yes	Yes	Yes	Yes	No	Yes	Yes
Phase Change Model	HRM	HRM	HRM	HRM	No	Rayleigh-Plesset	HRM
Turbulence	k-ω SST	k-ω SST	k-ε RNG	k-ω SST	LES dynamic structure	LES Smagorinsky	k-ε RNG (Cε1 = 1.1)
Spatial DIscretization	2nd order	2nd order	1st order	1st order	-	1st order	-
Fuel Properties	REFPROP	NIST	CONVERGE, Dymond et al. 1985	Star CCM+	CONVERGE	Dymond et al.,NIST	CONVERGE

APPROACHES

Institution	UMass	CD-Adapco	CMT Converge	CMT CCM+	ANL	Chalmers	KAUST
Ambient Properties	Ideal Gas	Ideal Gas	Ideal Gas	Ideal Gas	Ideal Gas	Liquid Fuel	Ideal gas
Liquid/Gas interface	Eulerian, diffuse-interface (Pseudo fluid)	Volume of Fluid - Mixture type approach	VOF	VOF	VOF-PLIC	HEM	VOF
Heat transfer	No, Isenthalpic	Adiabatic	Isothermal	Isothermal	Adiabatic	Isothermal	Isothermal

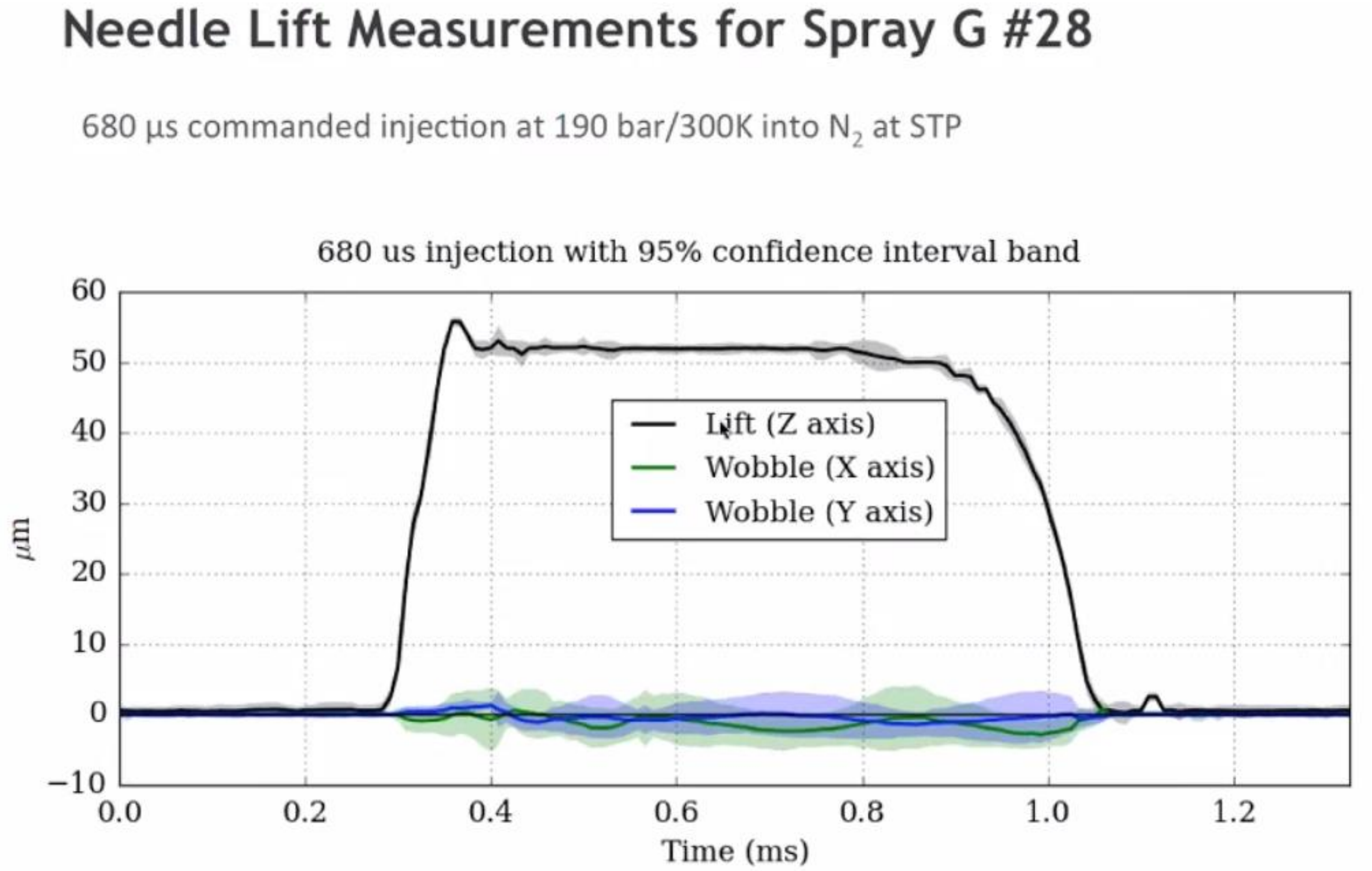
COMPUTATIONAL DOMAIN

Institution	UMass	CD-Adapco	CMT Conv.	CMT CCM+	ANL	Chalmers	KAUST
Dimensionality	3	3	3	3	3	3	3
Cell Type	Hexahedral with anisotropic refinement between needle and wall	Hex & prism cells+ wall layers	Hex + wall layers	Hex & poly hedra with wall layers	Hex + wall layers	Hexa-hedral cells	Hex + wall layers
Meshing Tool	Grid Pro	Star CCM+	Converge	Star CCM+	Converge	Grid Pro(refined)	Converge
Cell Count	1.5 million	8 million	1 million	11.4 million, 5.08 million	-	9.8 million	-
Adaptive or static refinement	Static	Static	AMR	Static	AMR	Static	AMR

GEOMETRY AND BOUNDARY CONDITION

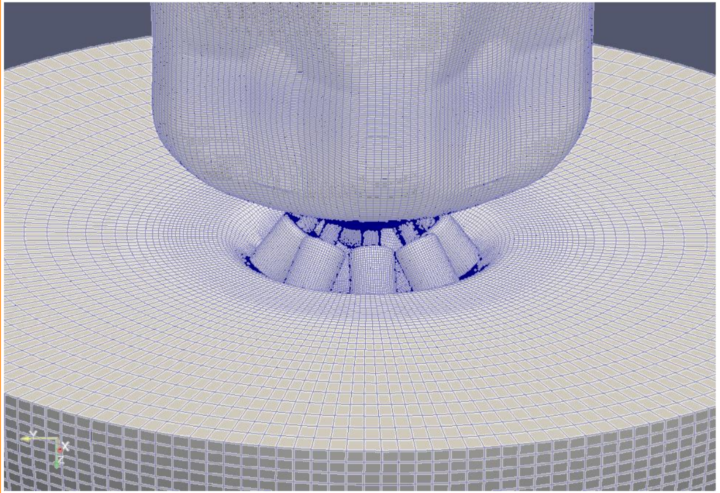
Institution	UMass	CD-Adapco	CMT Conv.	CMT CCM+	ANL	Chalmers	KAUST
Initial lift	5 µm	50 µm	2 µm	50 µm	5 µm	50 µm	2 µm
Needle Motion	Yes	No	Yes	No	Yes	No	Yes
Geometry	Gen 1 with 9mm plenum	Gen 1 with 9 mm plenum	Gen 1 with 6 mm plenum	Gen 1 with 9 mm plenum	Realistic geometry X-Ray	Gen1	Gen 2
Time Accurate ROI Profile?	Predicted	No	Predicted	No	Predicted	No	Predicted
Inlet	Constant Pressure	Constant Pressure	Constant Pressure	Constant Pressure	Constant Pressure	Constant Pressure	Constant Pressure
Wall BCs	L.O.W.	L.O.W.	L.O.W.	L.O.W.	L.O.W.	-	L.O.W.
Needle Closure	Yes	No	No	No	No	No	No

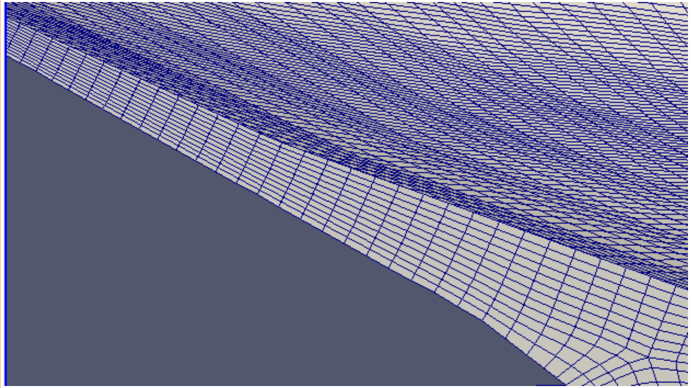
NEEDLE LIFT

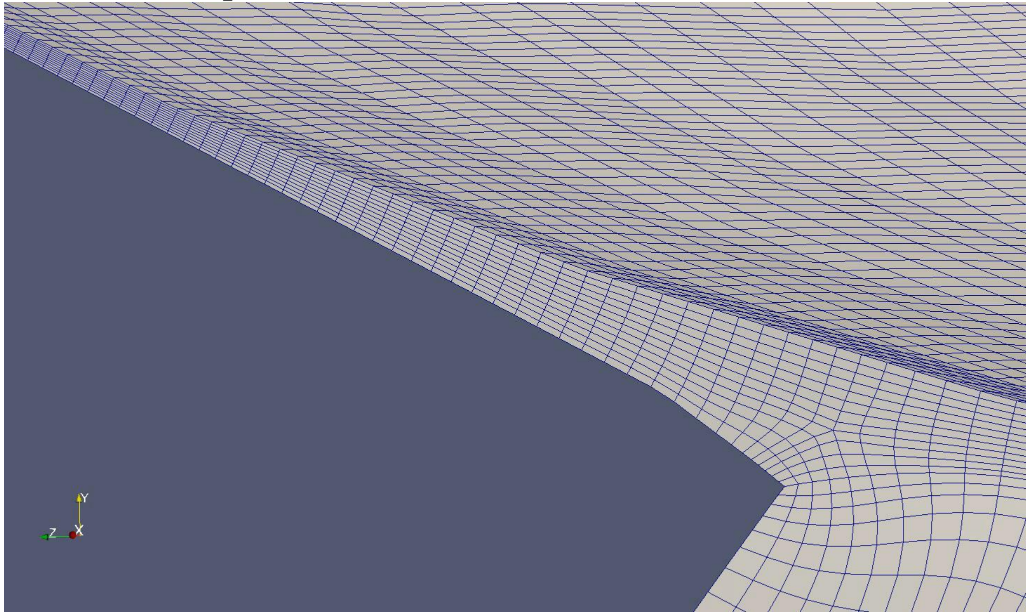


Data and figure provided by Dan Duke at Argonne National Lab

COMPUTATIONAL MESH (UMASS)

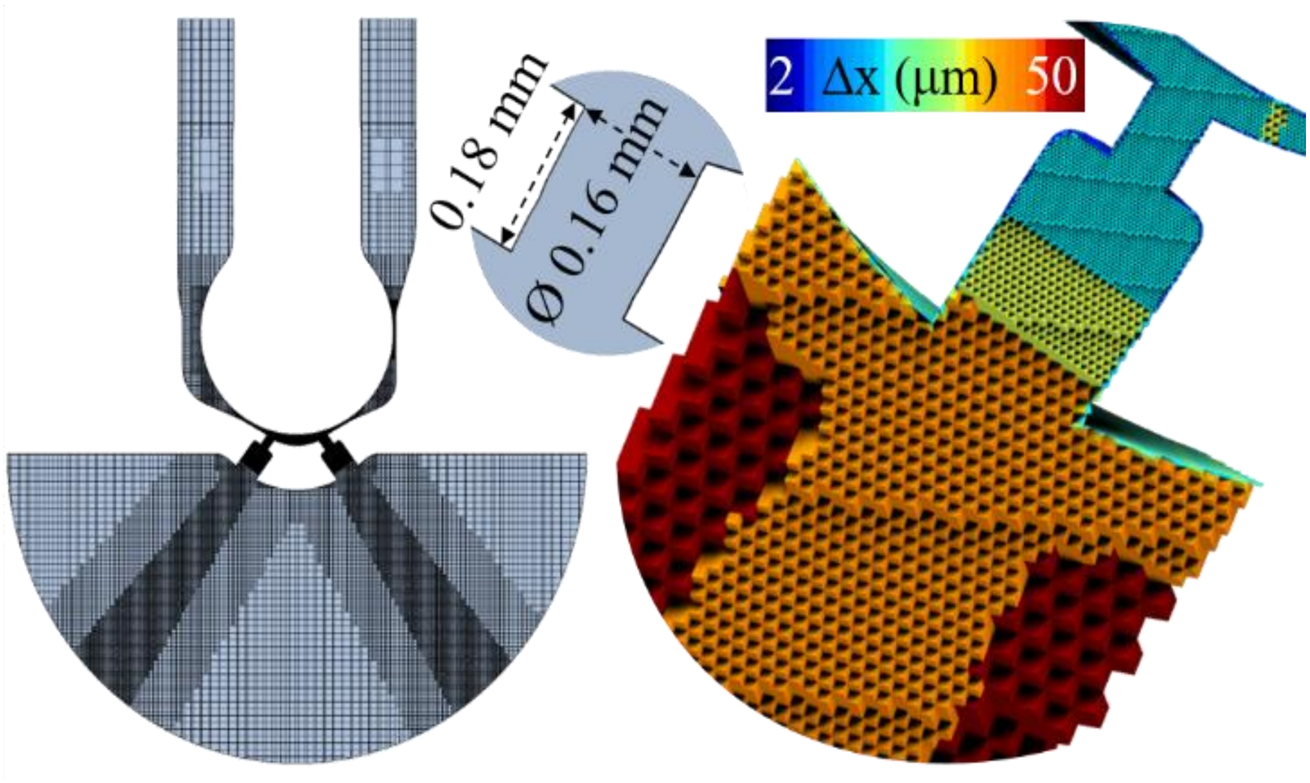






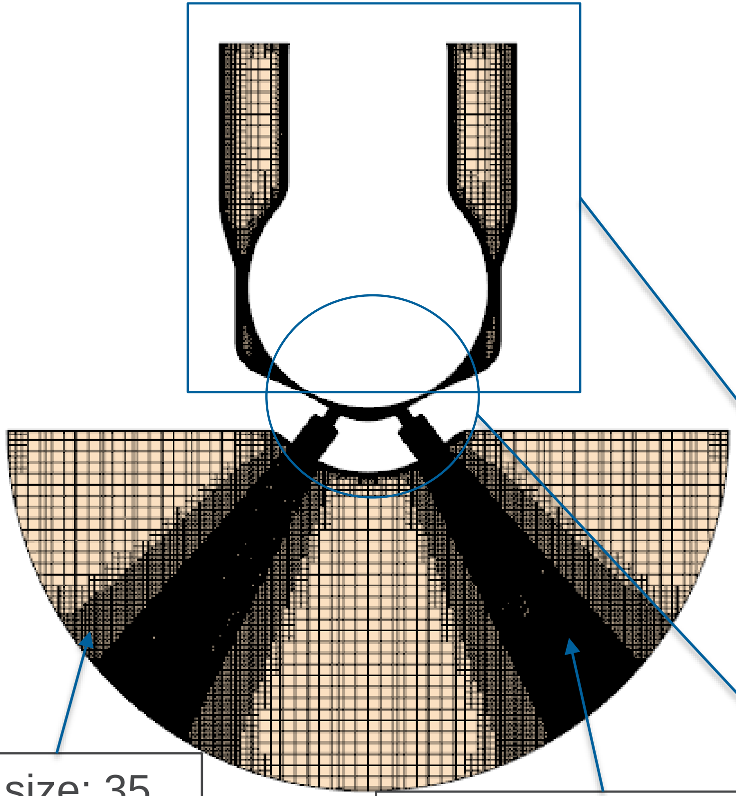
- Transient lift based upon ensemble averaged Argonne measurements
- Laplacian smoothing for mesh motion
- 10 μm and 7 μm grid spacing in the sac and nozzle hole

COMPUTATIONAL MESH (CD-ADAPCO)



Inside the nozzle holes, the sac-volume and along the vicinity of the spray jets the mesh is refined with cells which ranged from 5 to 25 μm in size, respectively

HEXAHEDRAL MESH (CMT- STARCCM+)



Cell size: 35 µm

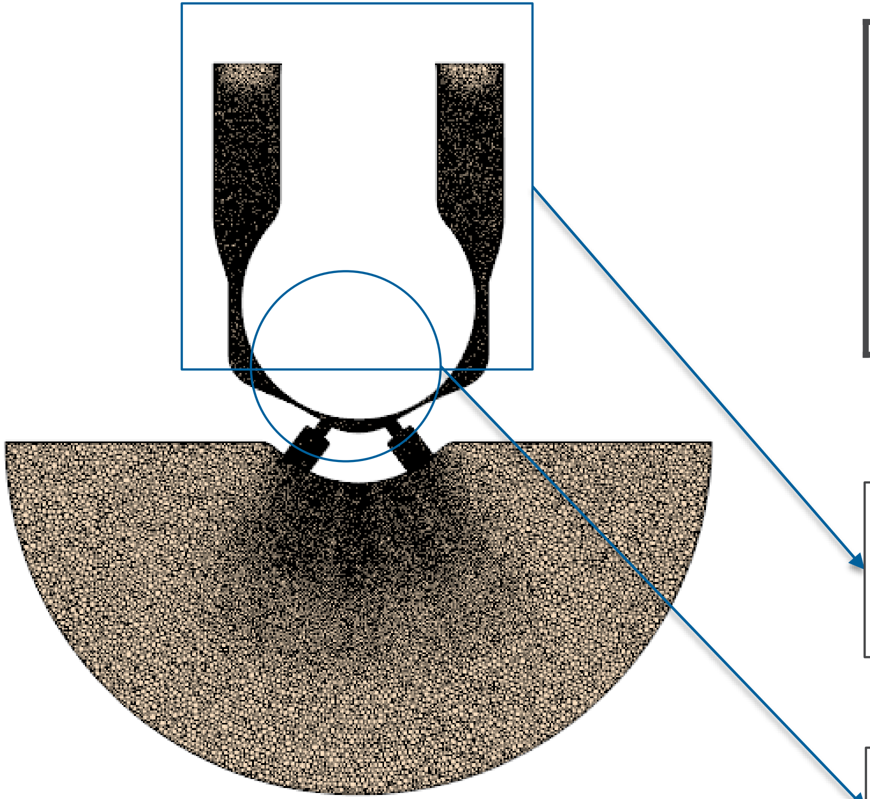
Cell size: 17.5 µm

Base size	140 µm
Cells	11.44 millions
Prism Layer	3
Layer Total Thickness	8.75 µm

Surface Control:
- Minimum cell size: 17.5 µm
- Surface Growth Rate: 1.05
- Trimmer Surface Growth Rate: Medium

Volumetric Control:
- Minimum cell size: 8.75 µm

POLYHEDRAL MESH (CMT- STARCCM+)

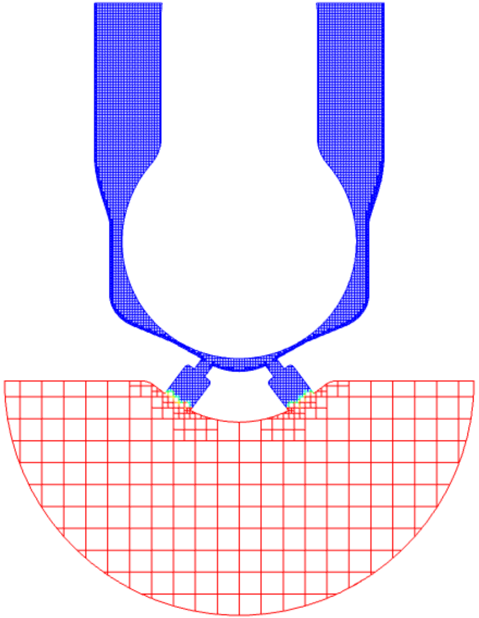


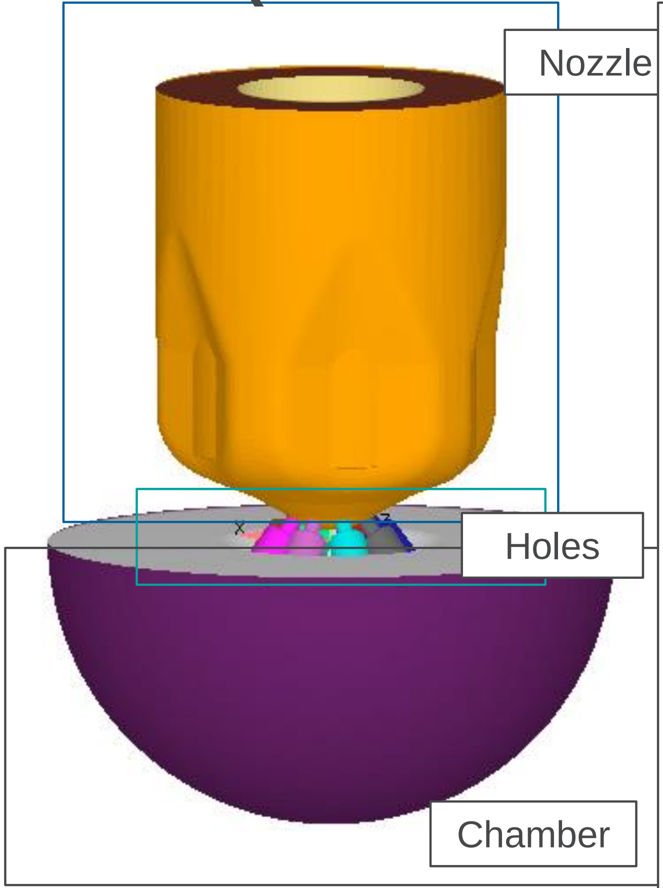
Base size	60 µm
Cells	5.08 millions
Prism Layer	3
Layer Total Thickness	8.625 µm

Surface Control:
- Minimum cell size: 18 µm
- Surface Growth Rate: 1.05

Volumetric Control:
- Minimum cell size: 18 µm

COMPUTATIONAL MESH (CMT- CONVERGE)



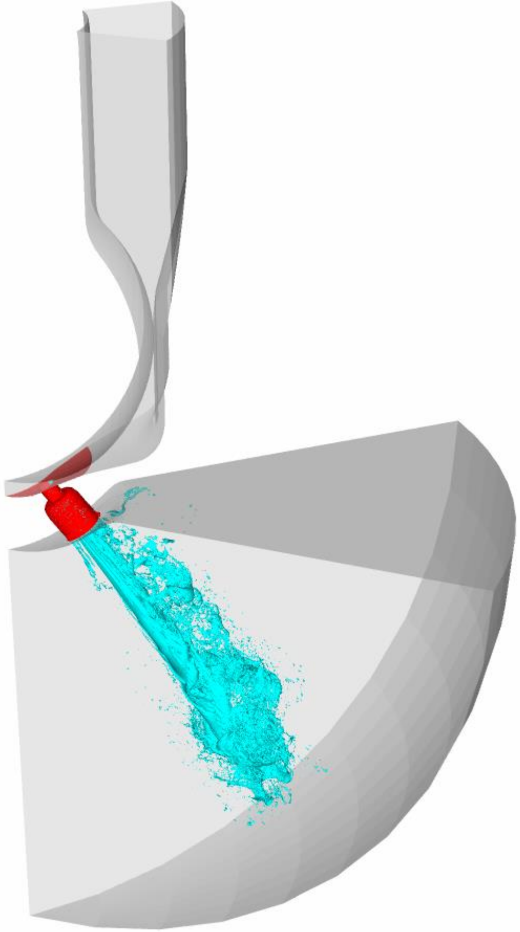


- Base Size: 140 µm
- Grid Scaling: -1
- Fixed Embedding:
  - Region (Nozzle & Holes)
    - Mode: Permanent
    - Scale: 3
  - Boundary (Nozzle)
    - Mode: Permanent
    - Scale: 4
    - Embed layers: 1
- AMR:
  - Chamber & Holes
    - Embedding: 4
    - Sub-grid criterion: 1.0
    - Timing control type: Permanent

Cell count at start of simulation: 1.018.865

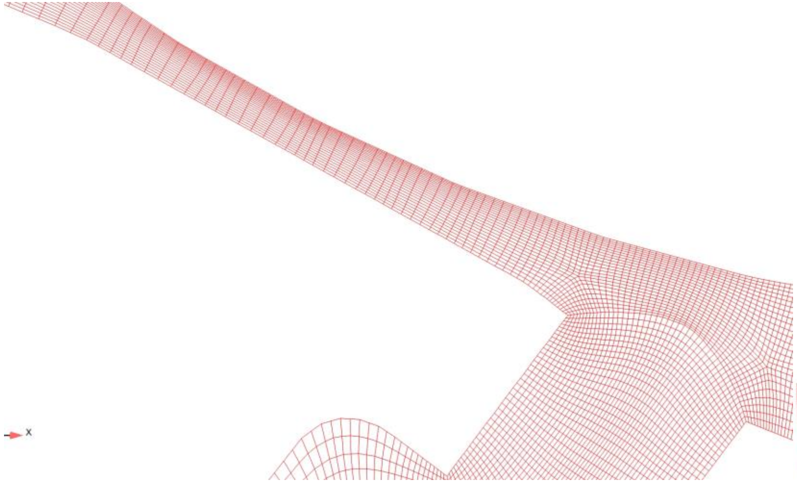
ANL CONVERGE

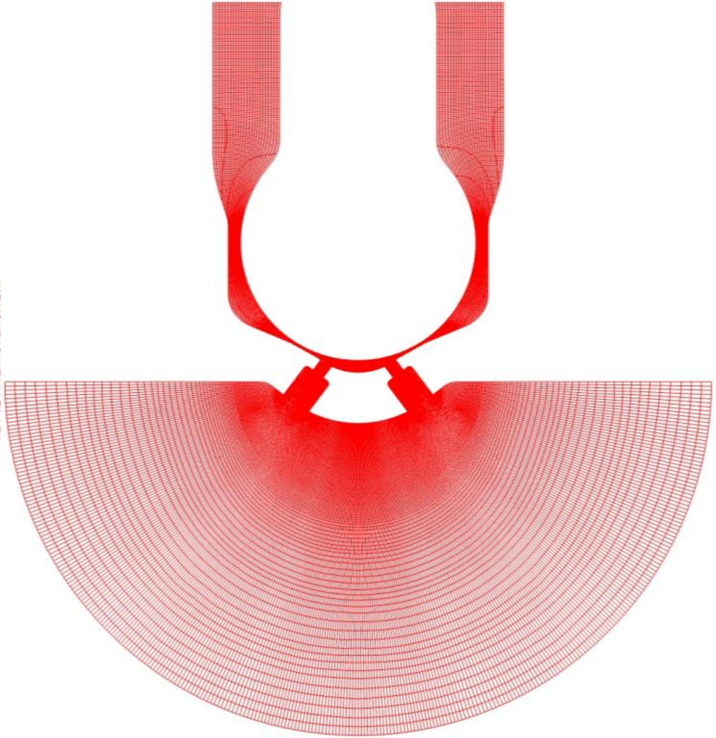
- Red surface: X-ray scanned realistic geometry (1.7 μm resolution)
- Immediately adjacent holes simulated at low resolution



ENGINE COMBUSTION NETWORK

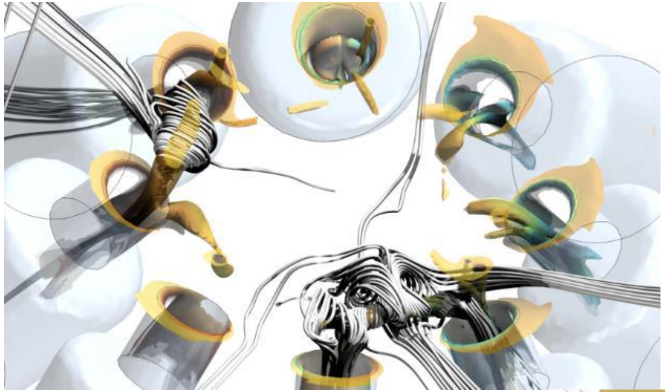
CHALMERS OPENFOAM



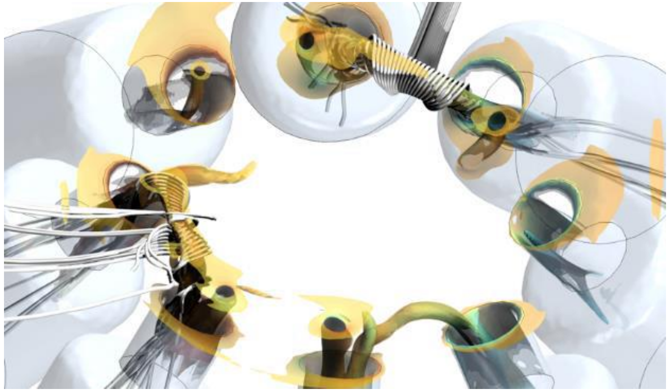


SIMULATION RESULTS

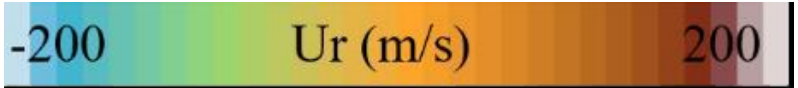
INTERNAL OBSERVATIONS



Iso-surface of 14MPa total pressure, streamlines

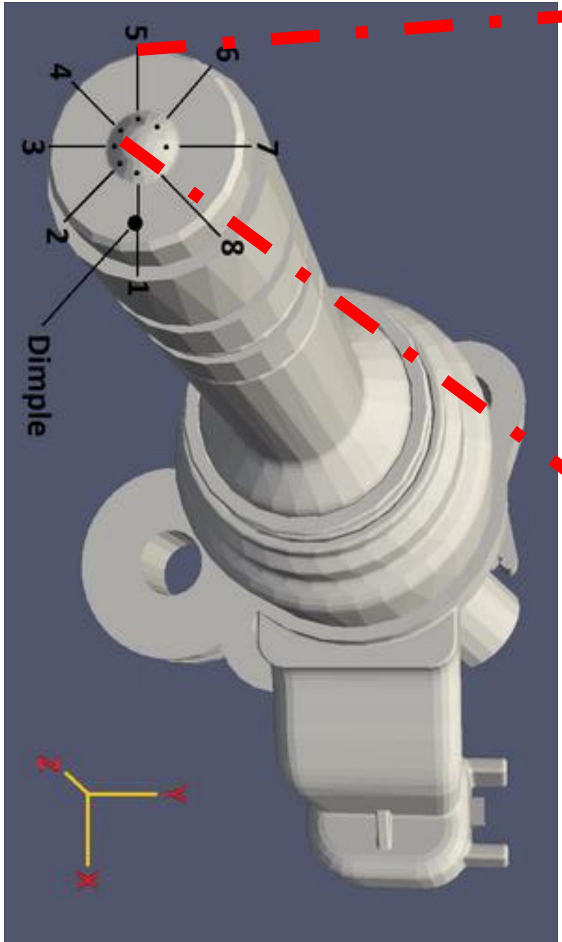


CCM+ CD Adapco



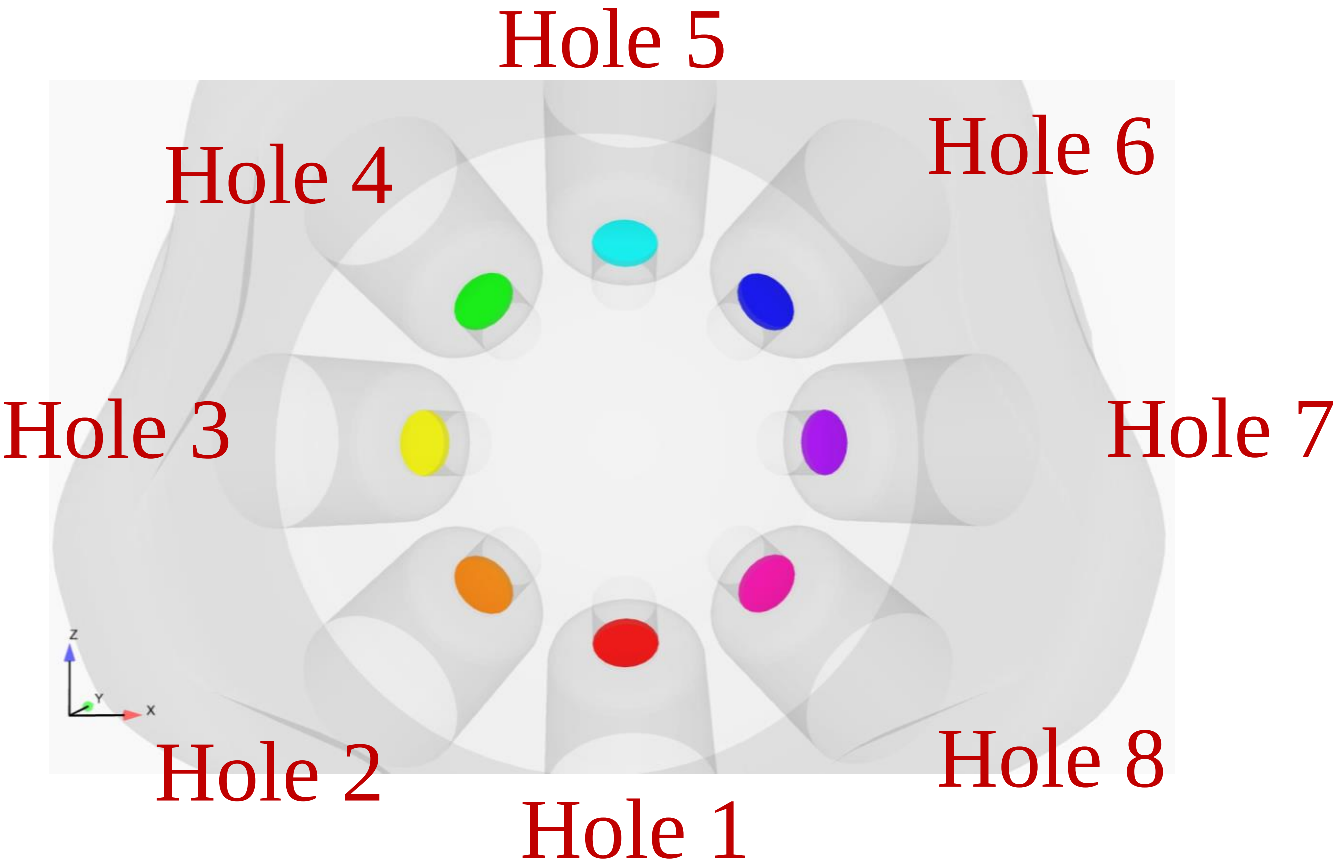
Similar to vorticity seen in Baldwin et al. 2016

HOLE ORIENTATION

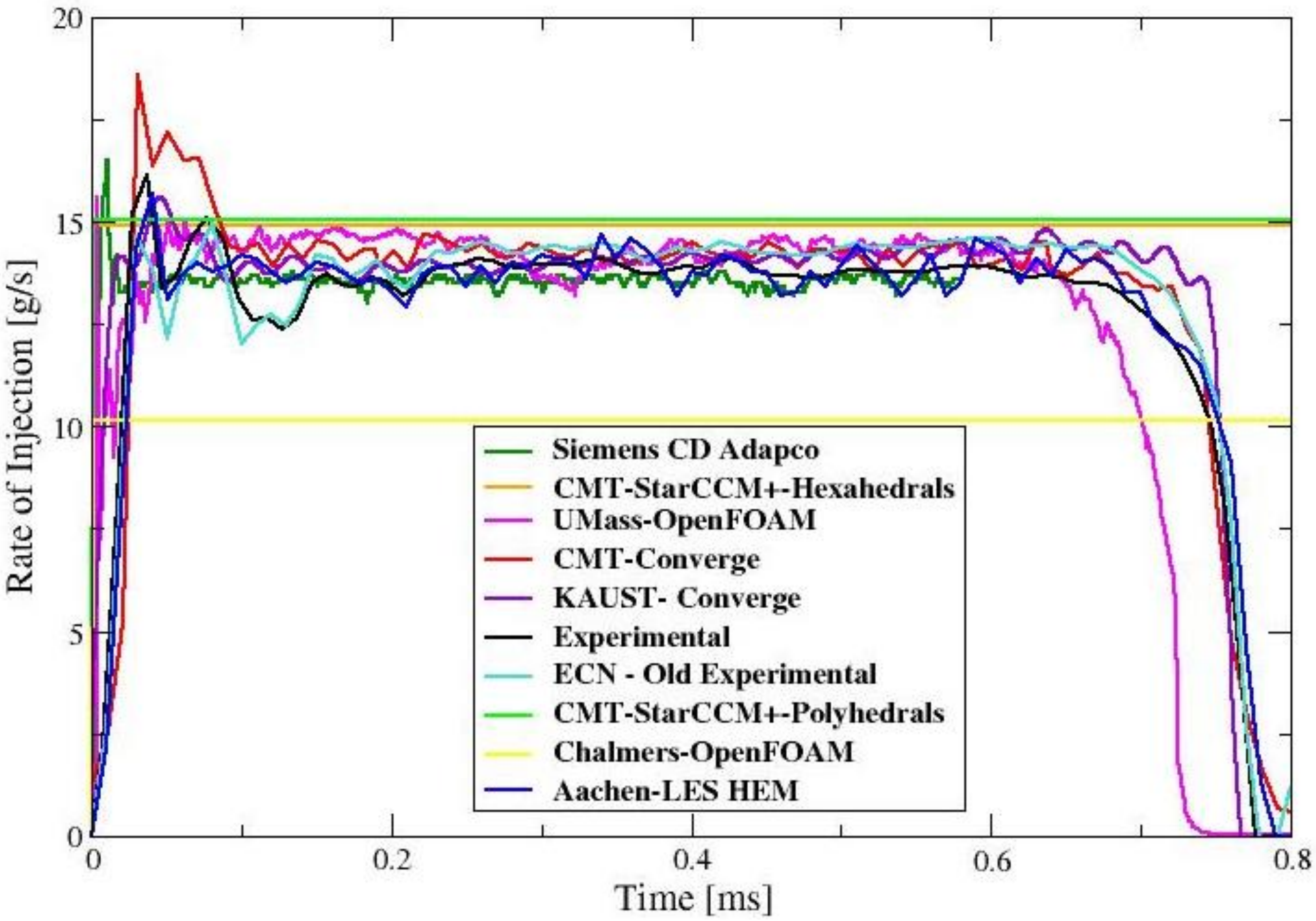


CAD Geometry

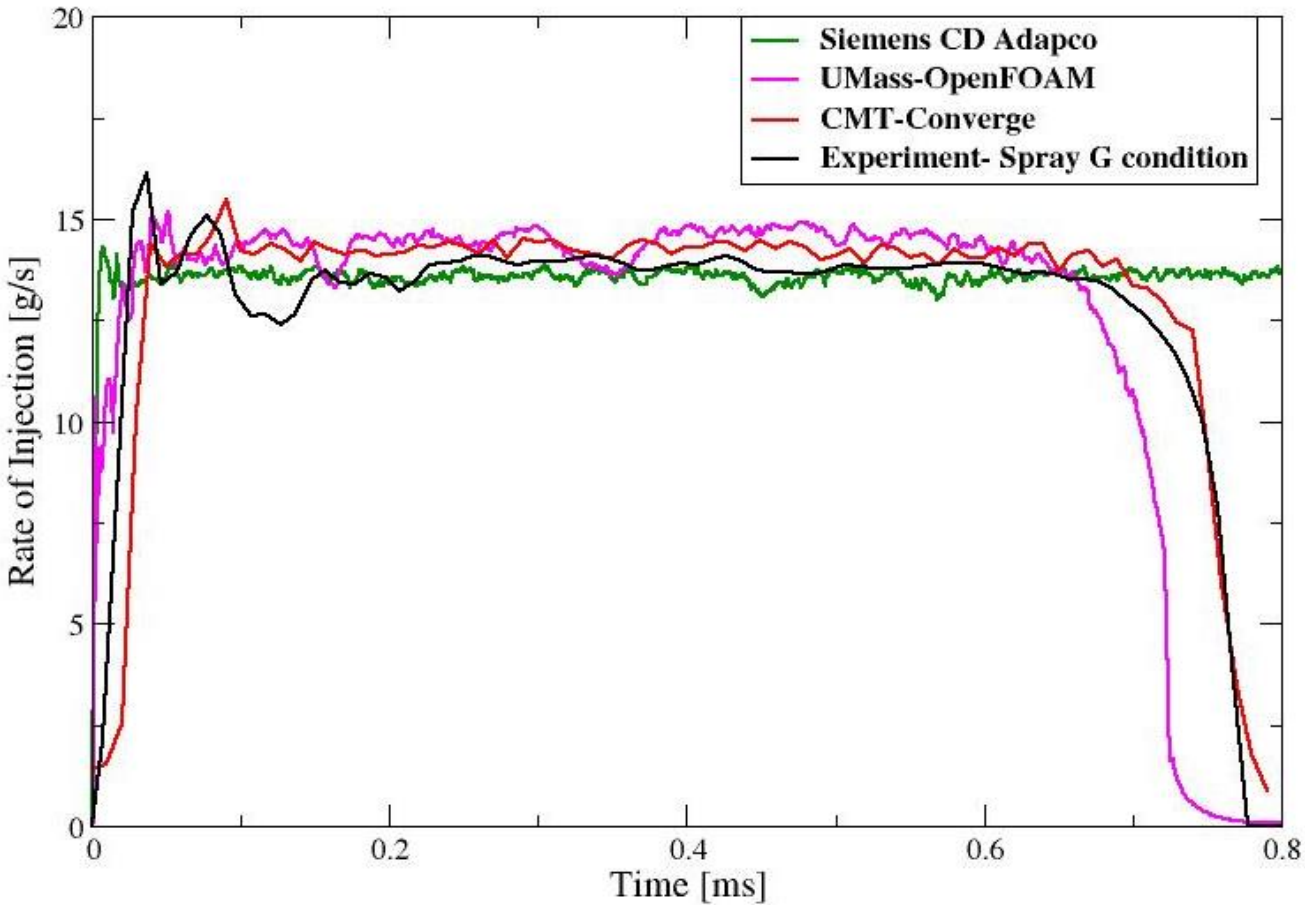
ROI, MOMENTUM RATE MEASUREMENT LOCATION (NOZZLE EXIT PLANE)



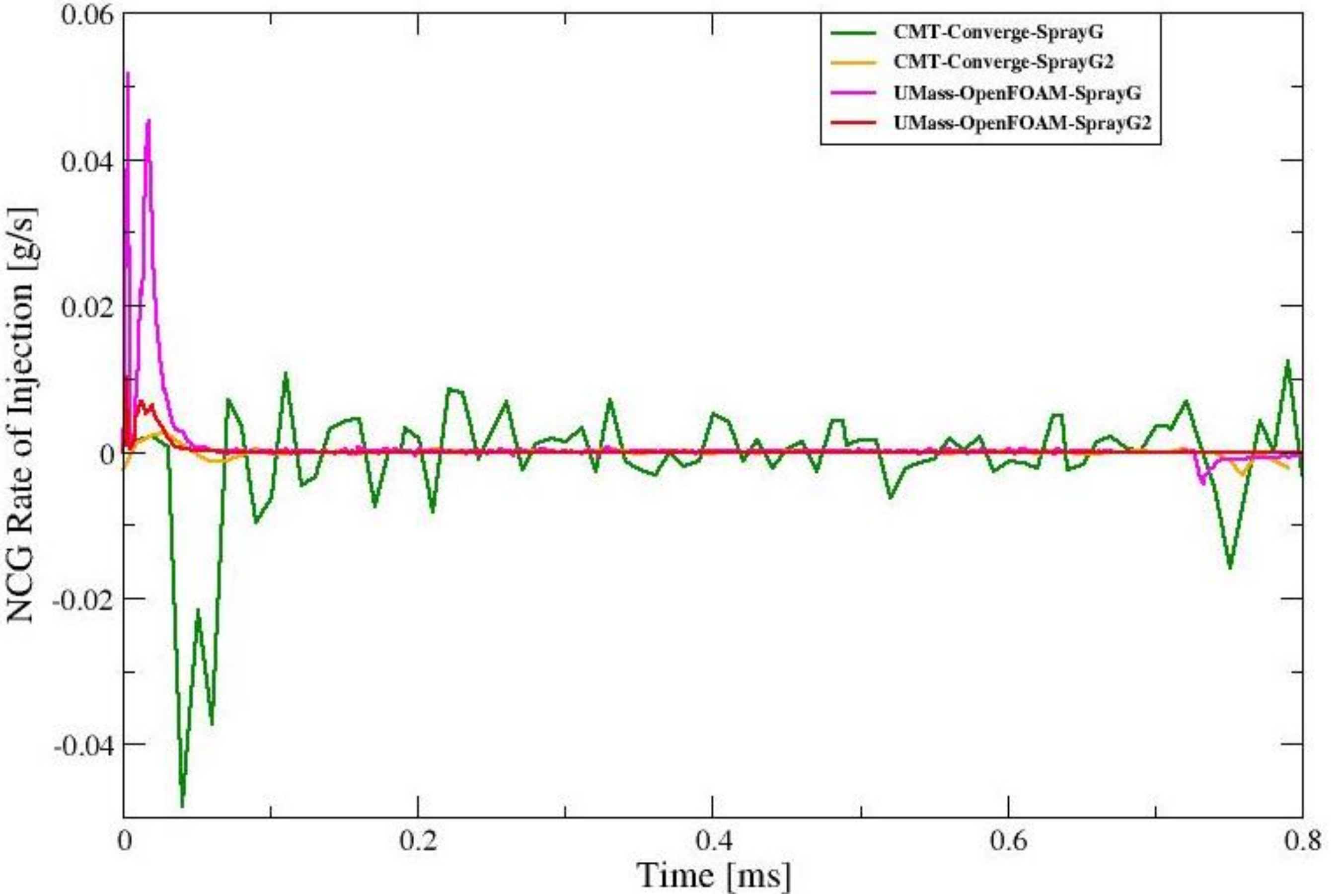
RATE OF INJECTION – SPRAY G



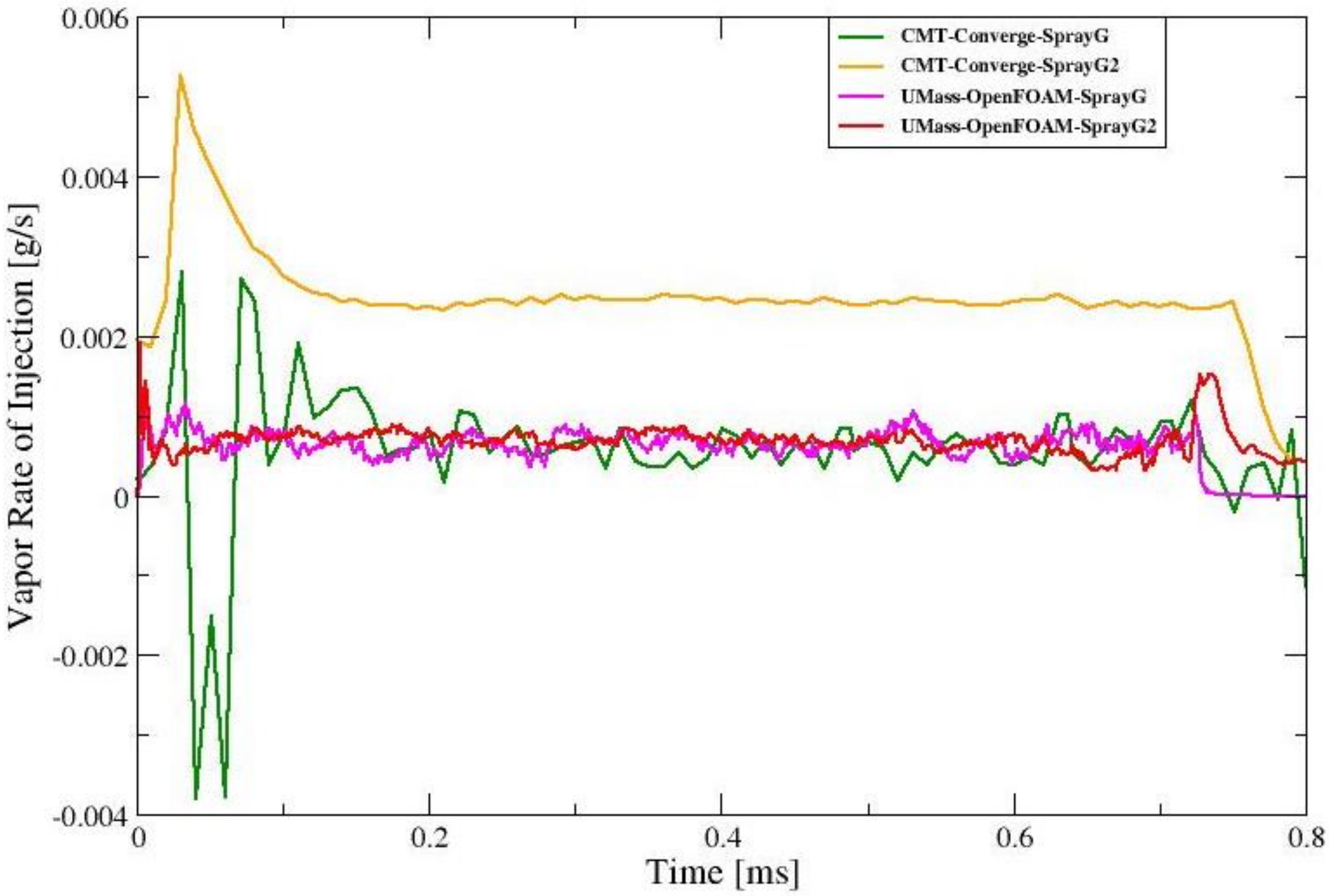
RATE OF INJECTION – SPRAY G2



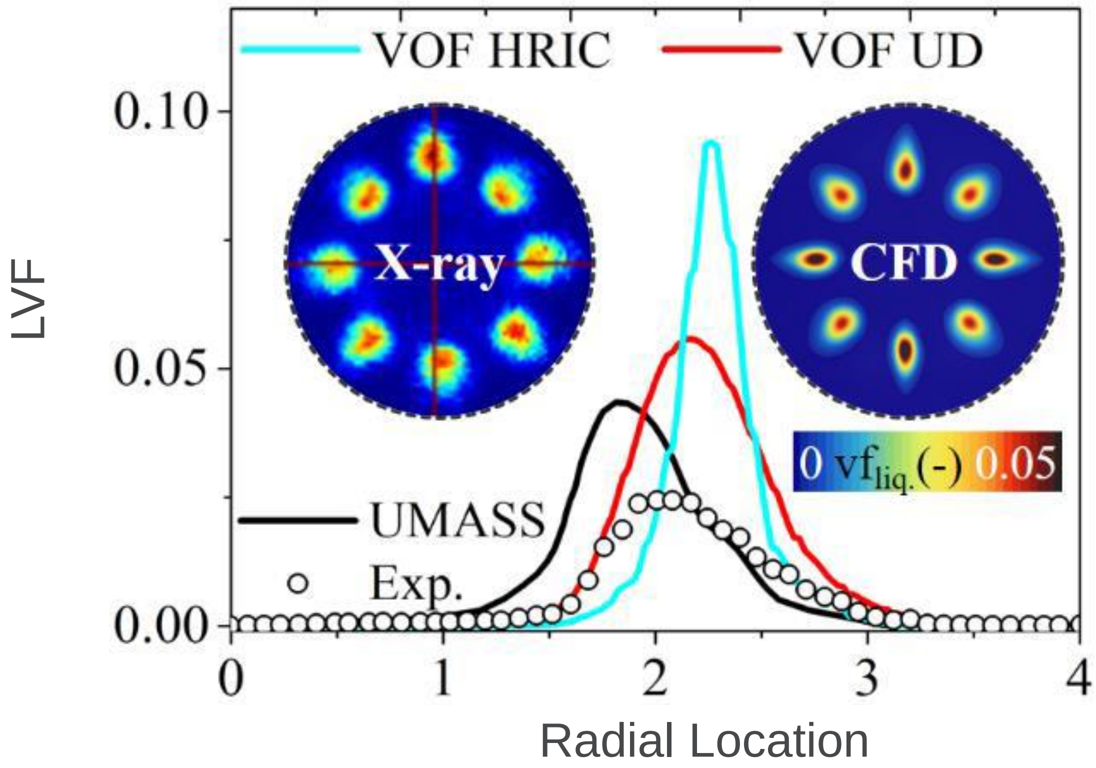
NCG RATE OF INJECTION



VAPOR RATE OF INJECTION



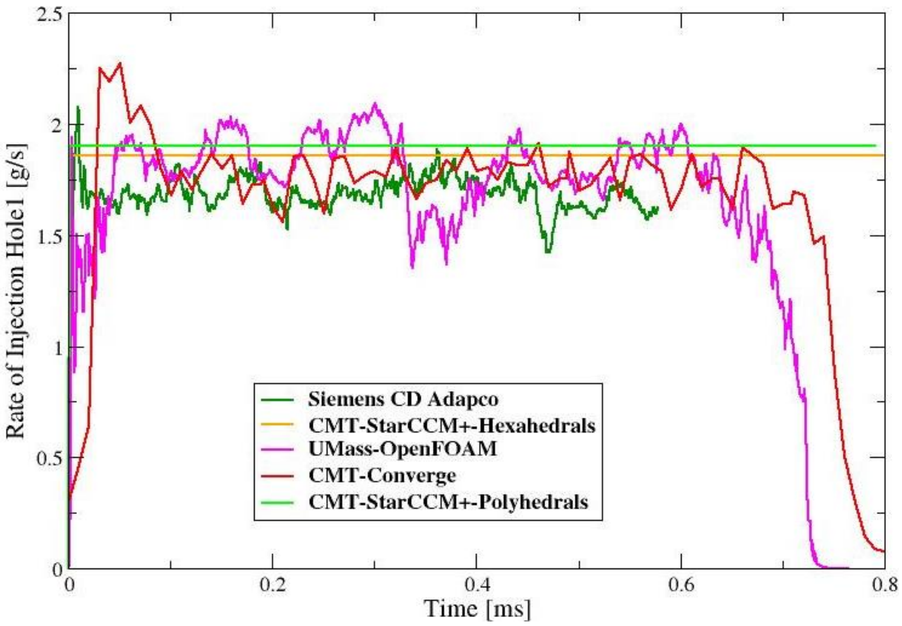
RADIALLY AVERAGED LVF AT 2MM COMPARED TO EXPT.



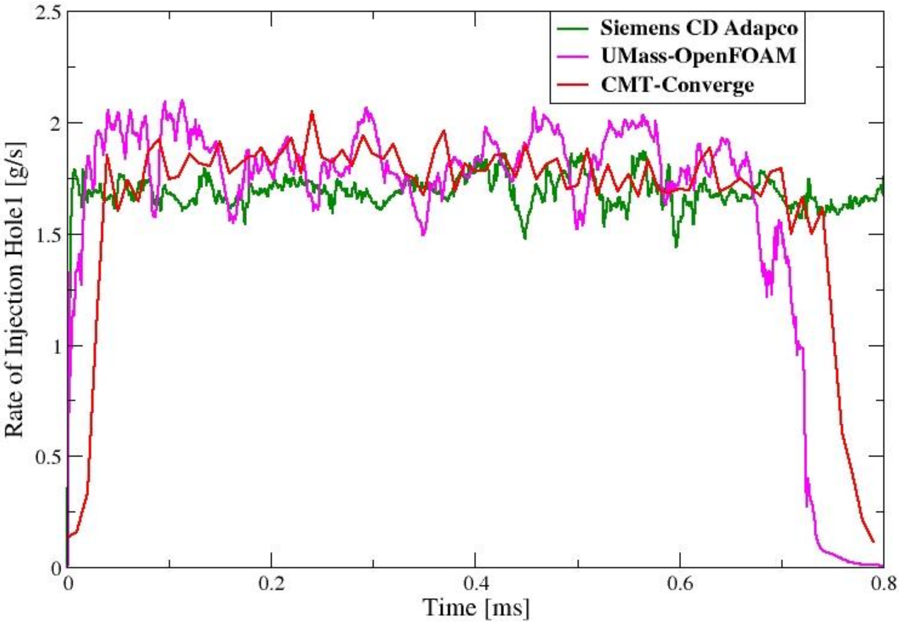
- Experiment is with viscor under non-flashing conditions
- Simulation is with flashing conditions

"Eulerian modeling of flash-boiling in multihole gasoline nozzles using the homogeneous relaxation model" by Papoulias et al. 2018

ROI – HOLE 1

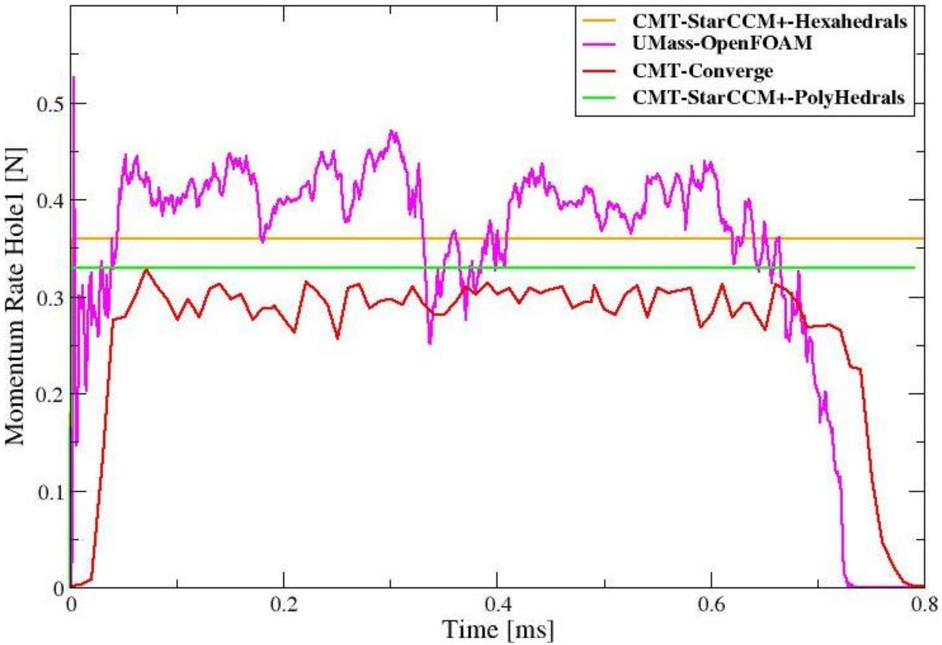


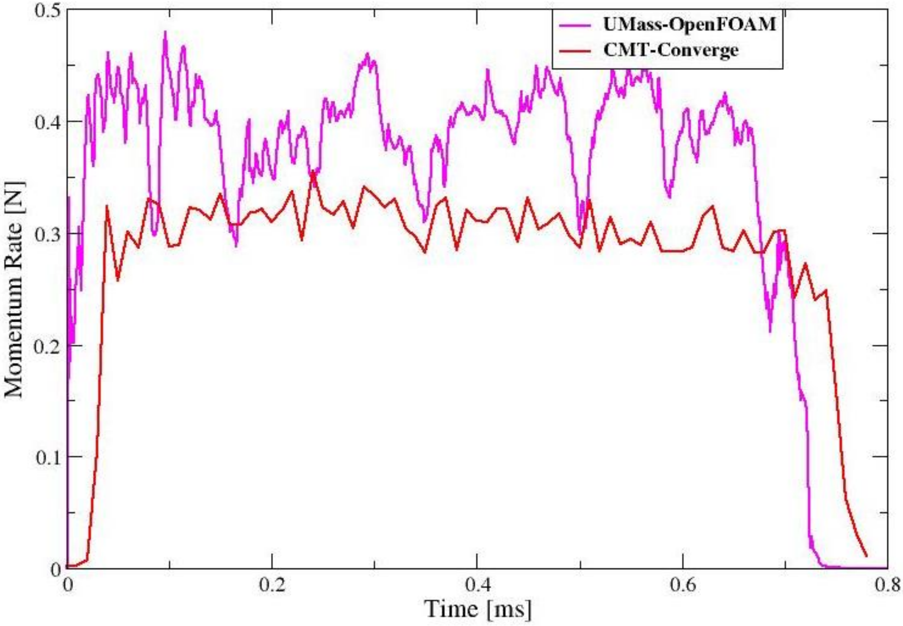
Spray G



Spray G2

MOMENTUM RATE – HOLE 1

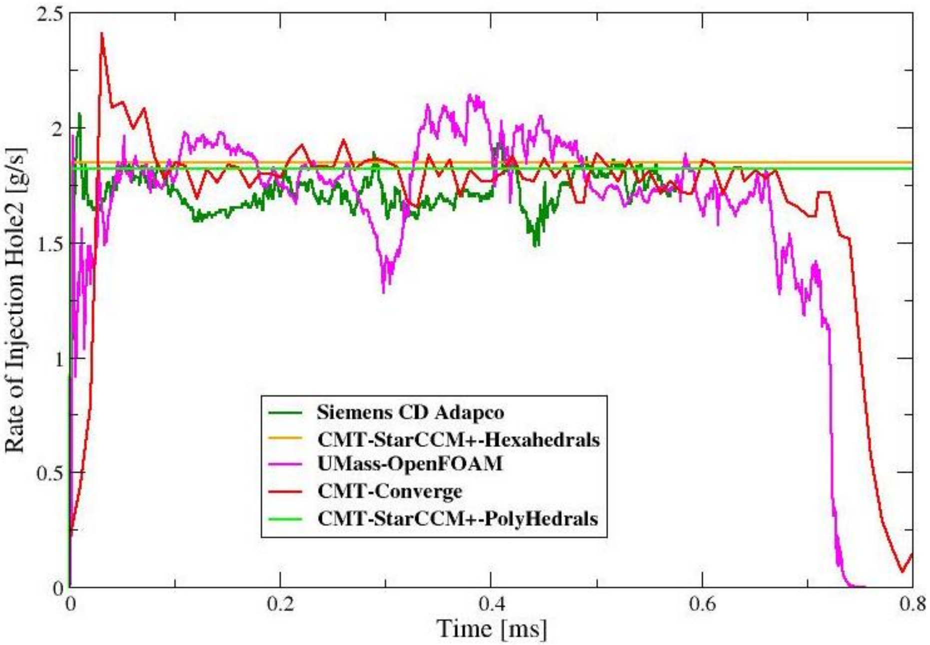




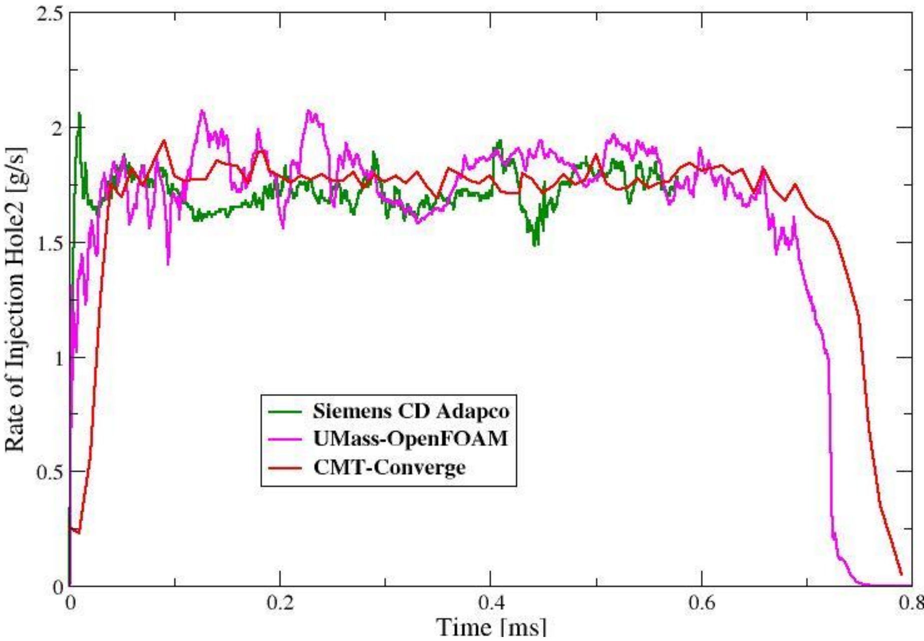
Spray G

Spray G2

ROI – HOLE 2

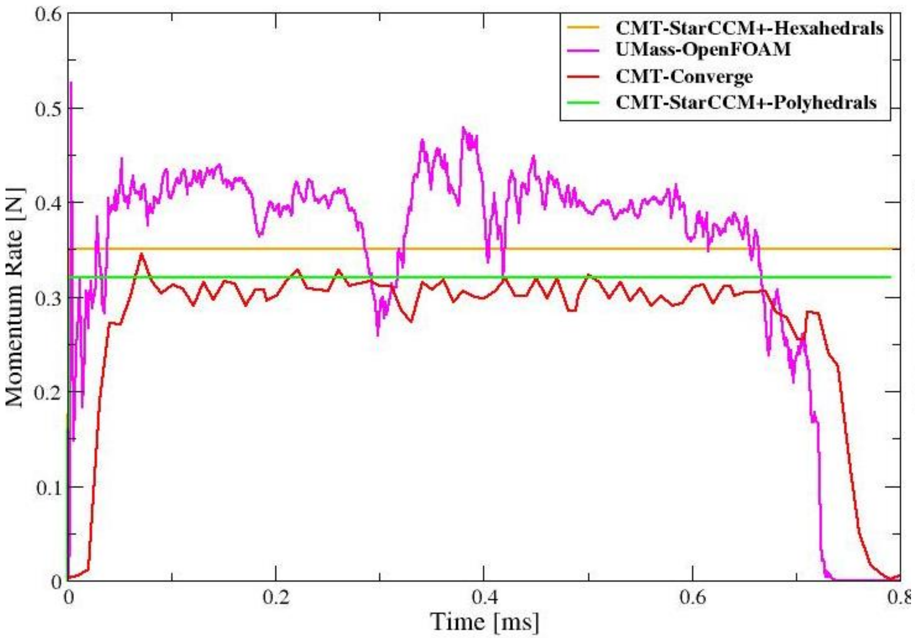


Spray G

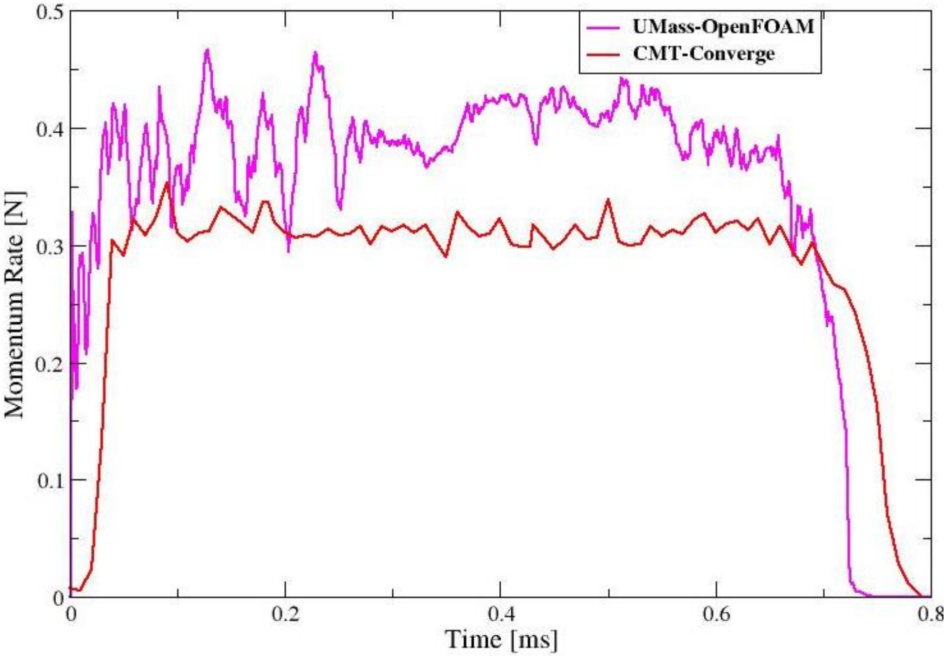


Spray G2

MOMENTUM RATE – HOLE 2

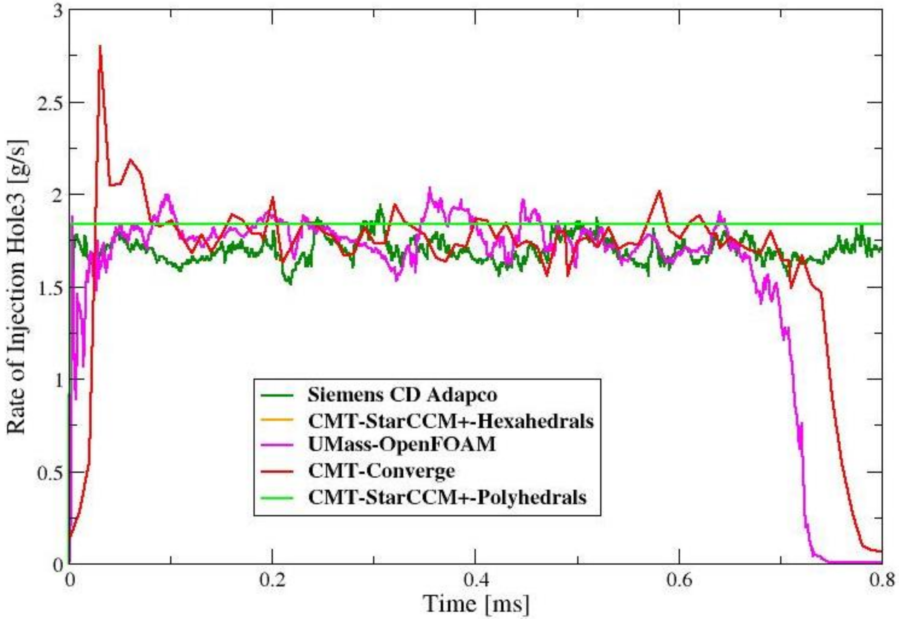


Spray G

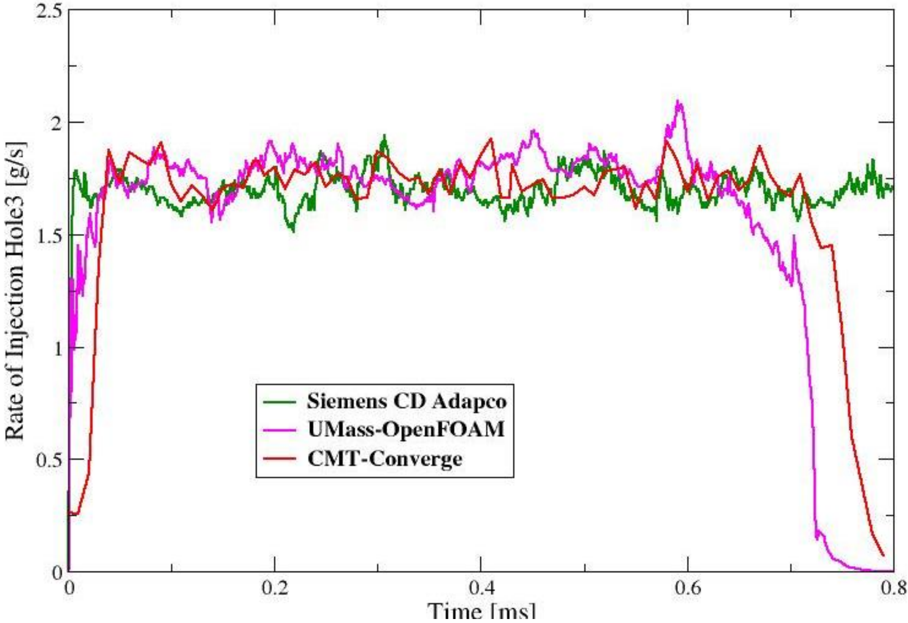


Spray G2

ROI – HOLE 3

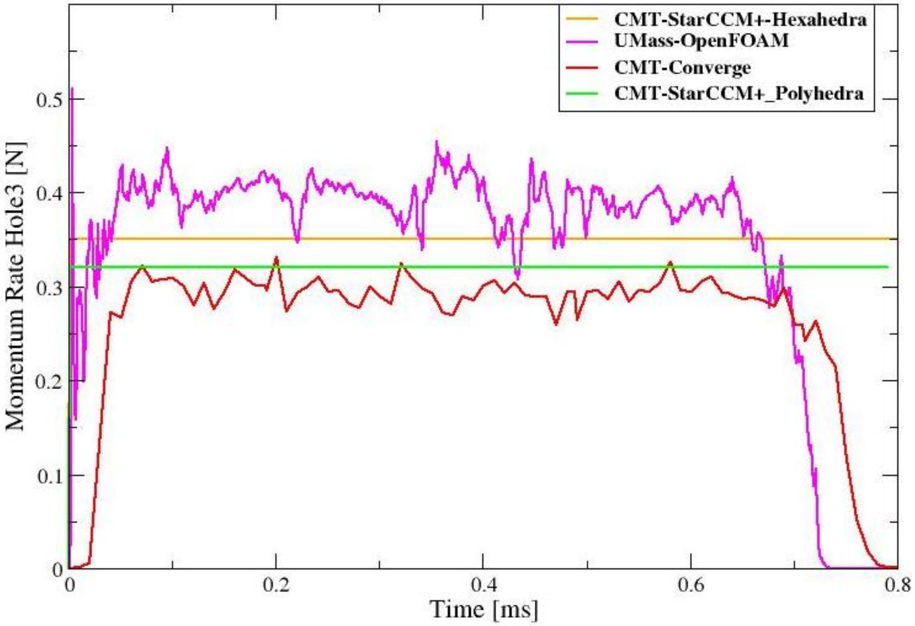


Spray G



Spray G2

MOMENTUM RATE – HOLE 3



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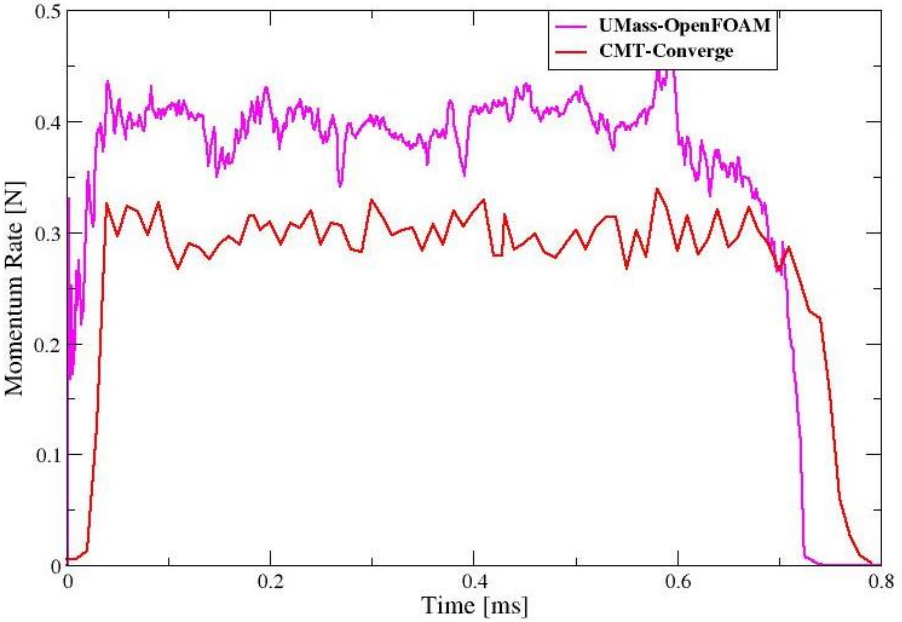
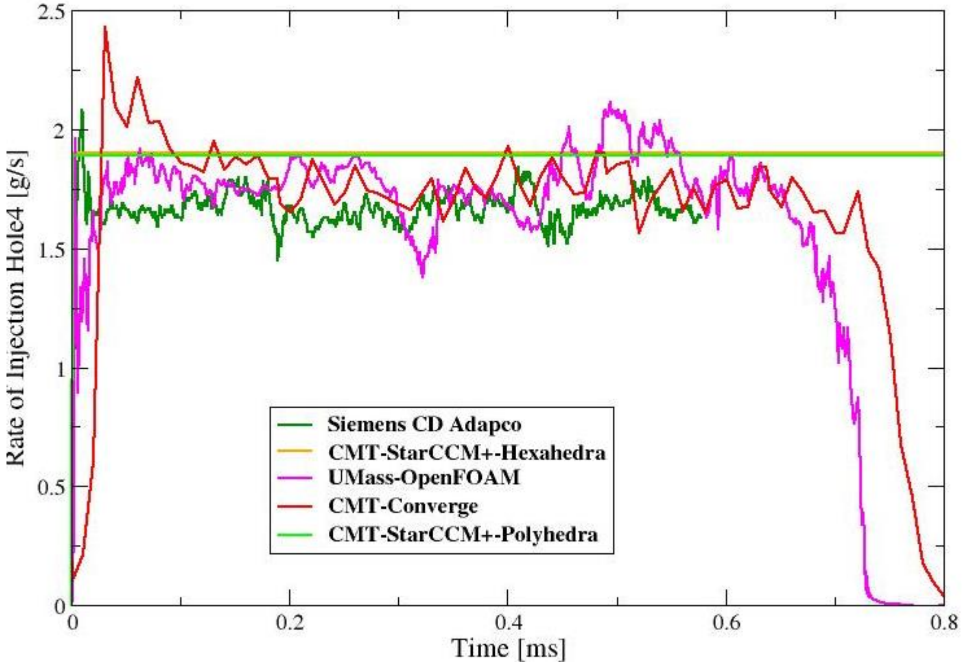
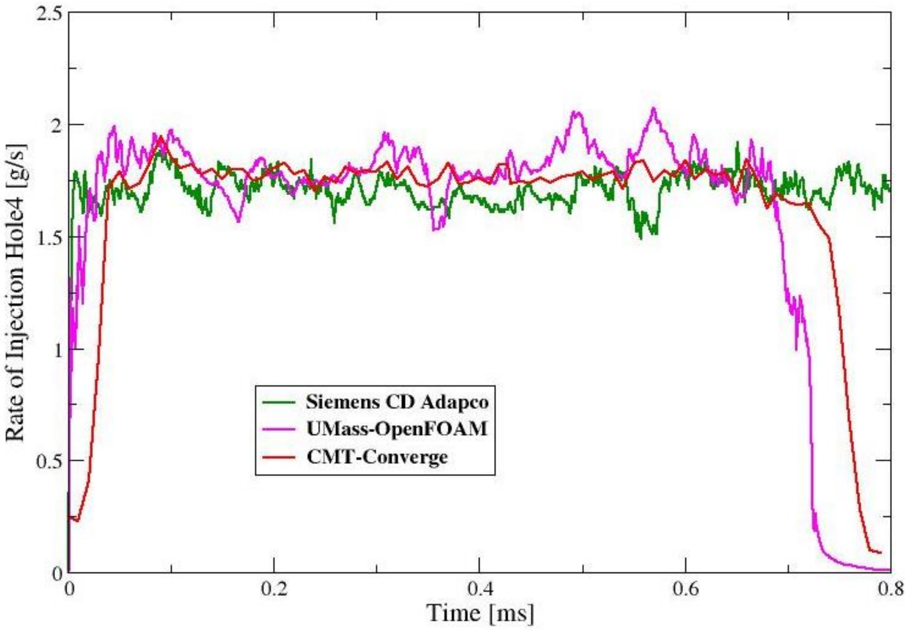


Spray G2

ROI – HOLE 4

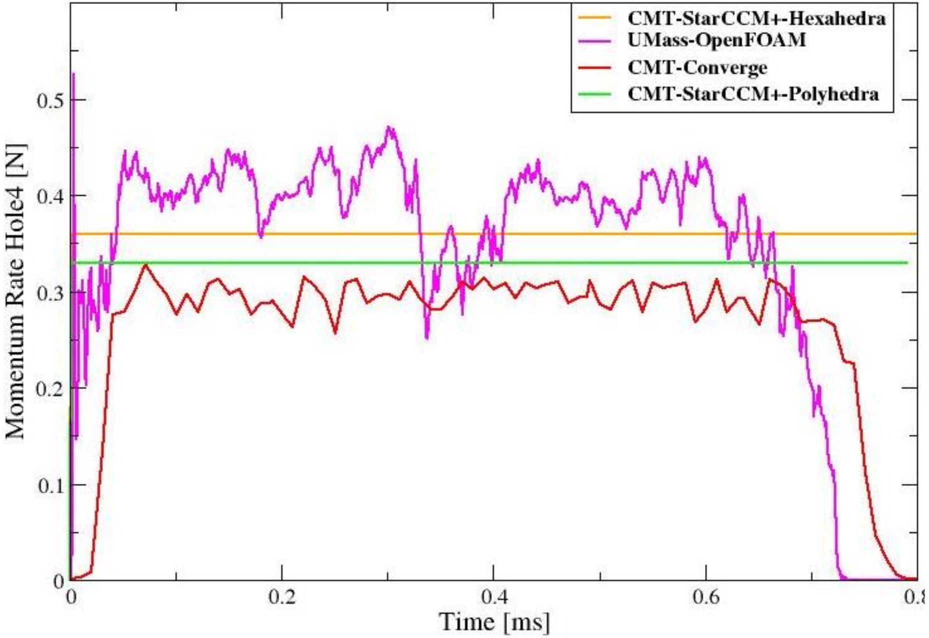


Spray G

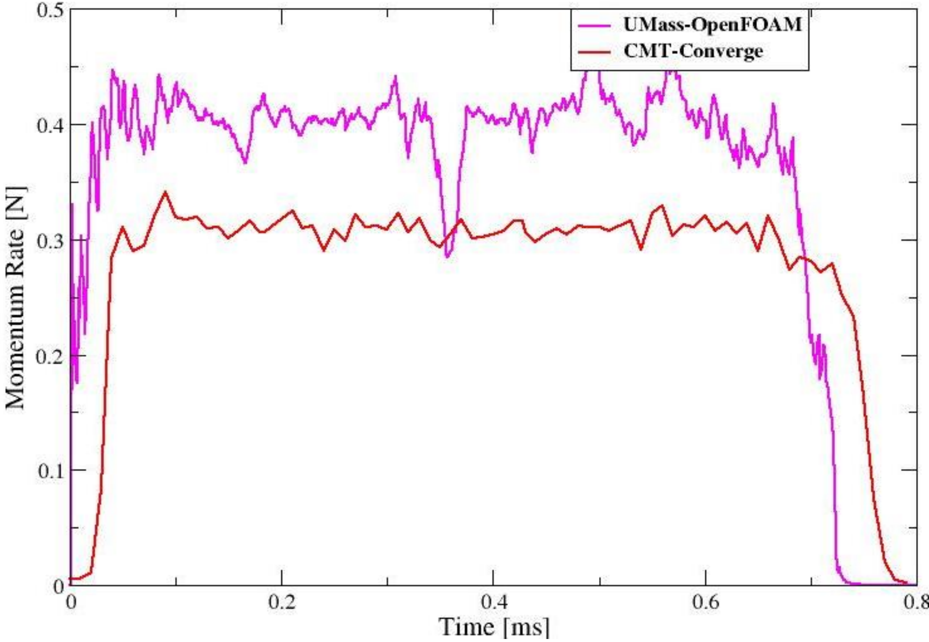


Spray G2

MOMENTUM RATE – HOLE 4

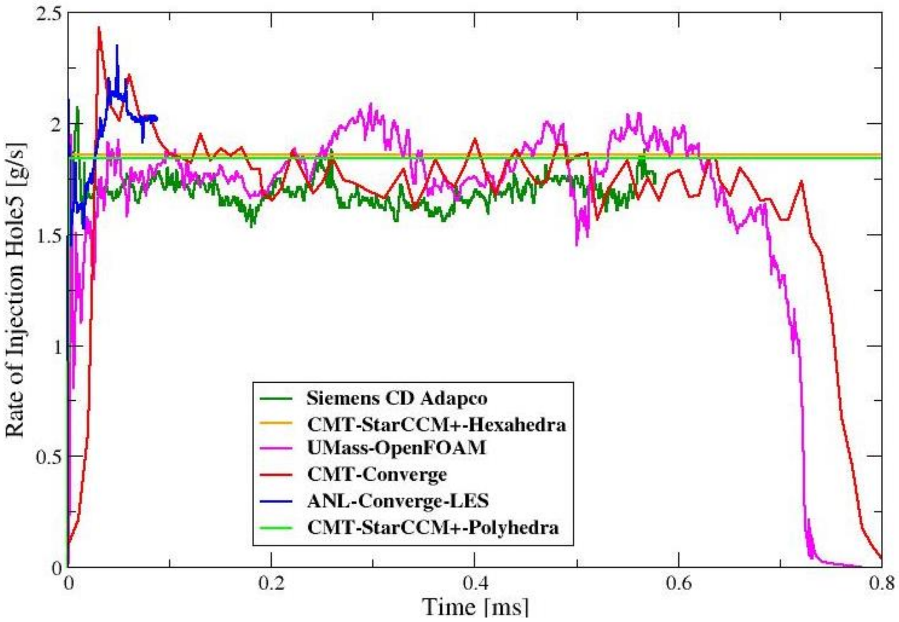


Spray G

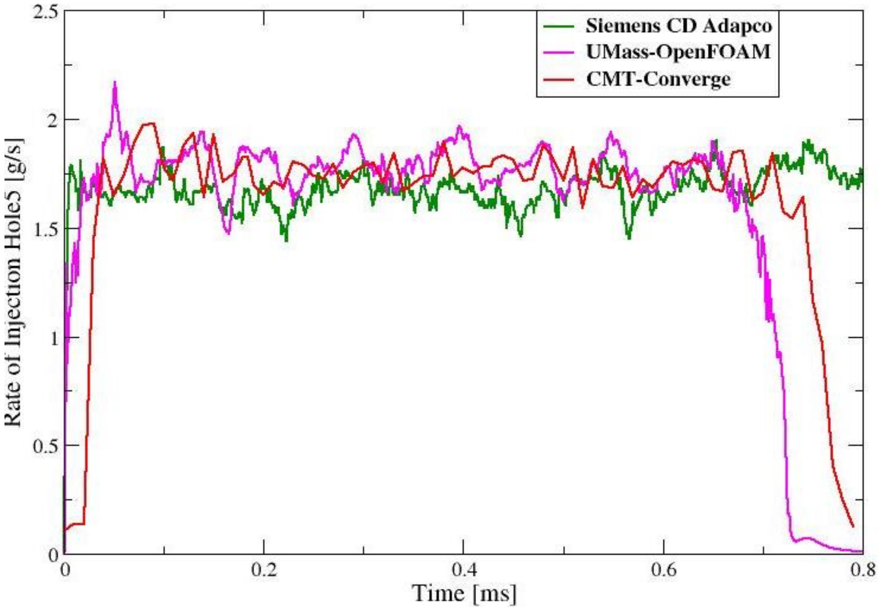


Spray G2

ROI – HOLE 5

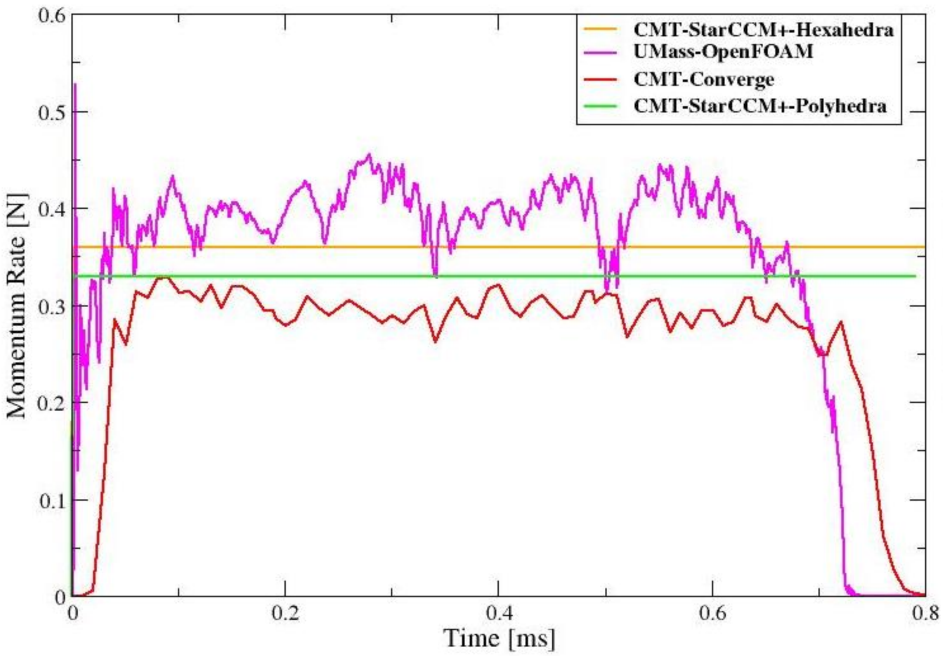


Spray G

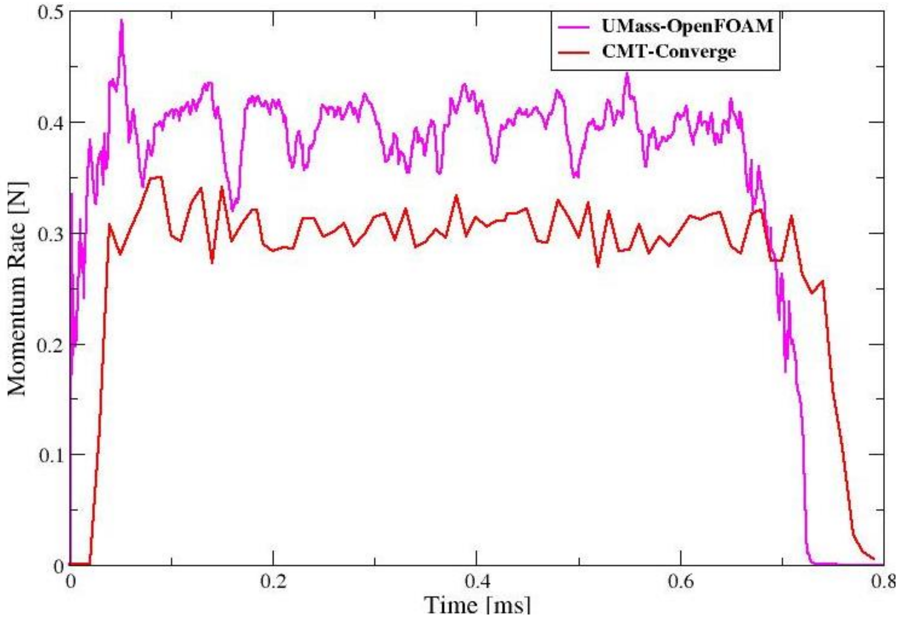


Spray G2

MOMENTUM RATE – HOLE 5

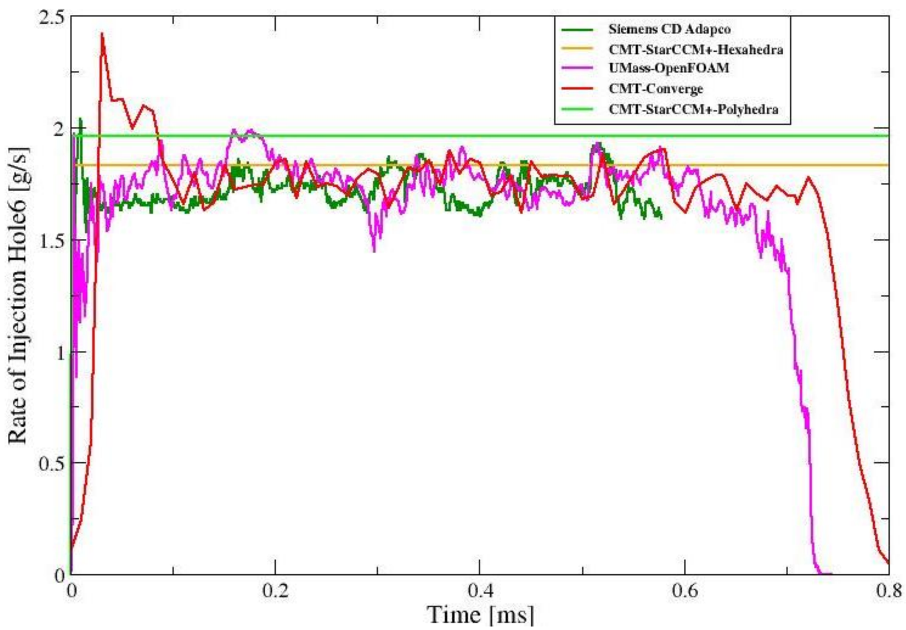


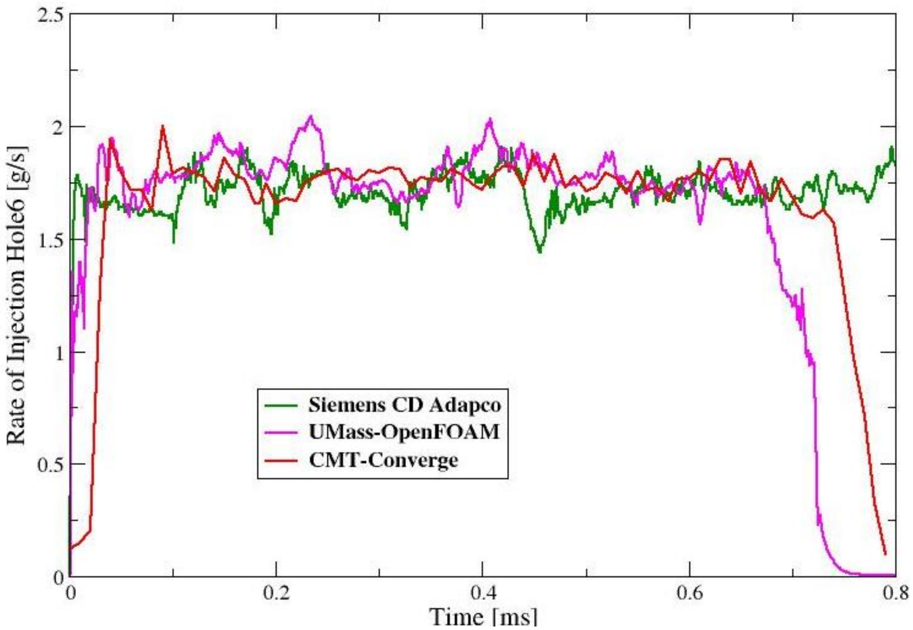
Spray G



Spray G2

ROI – HOLE 6

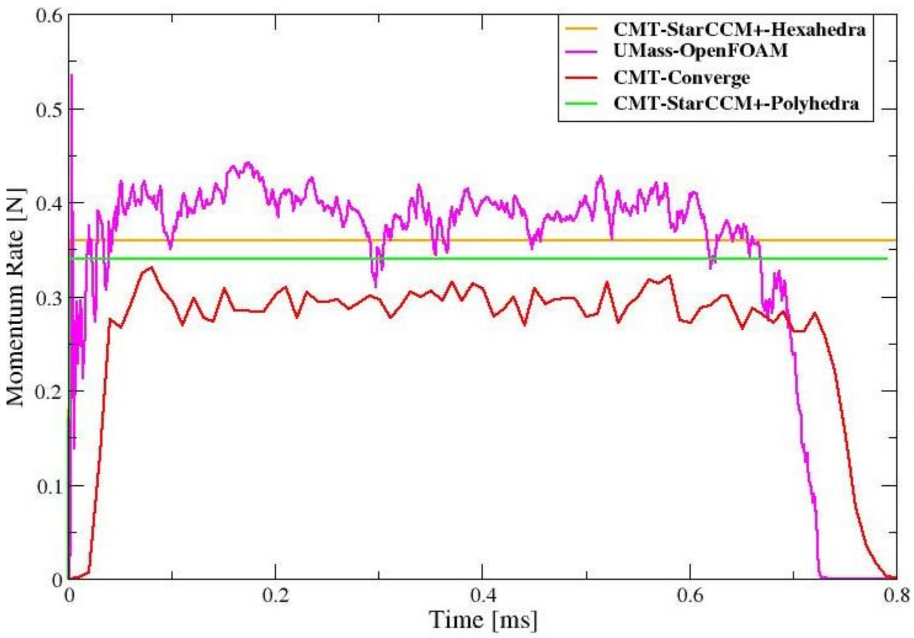




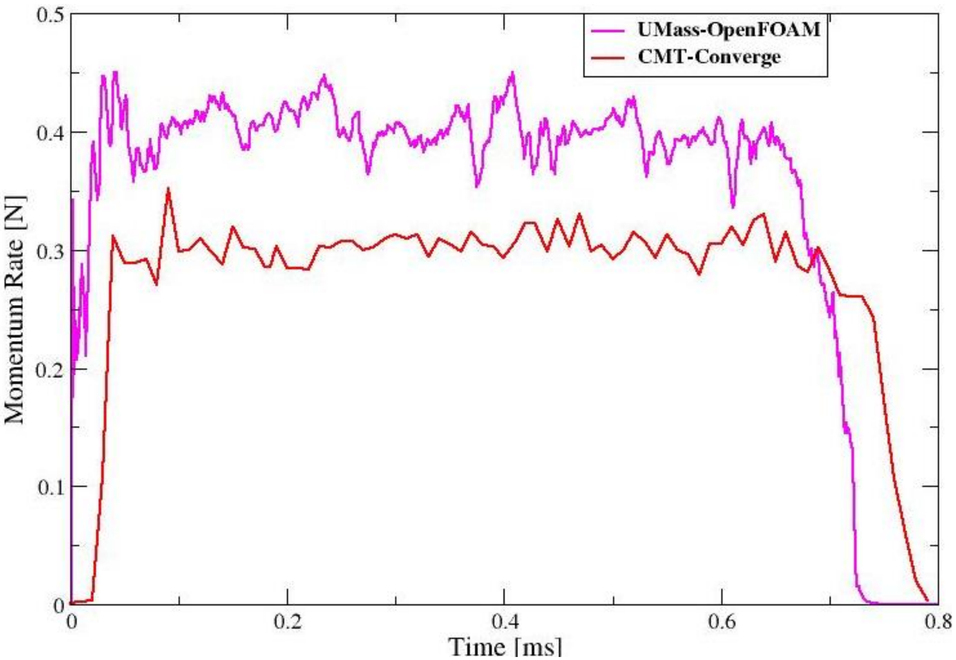
Spray G

Spray G2

MOMENTUM RATE – HOLE 5

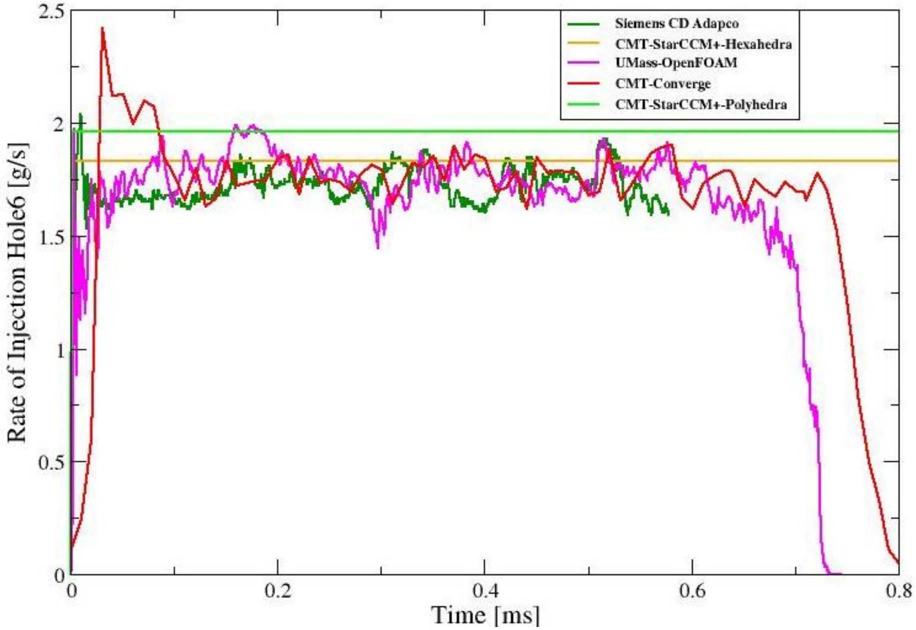


Spray G

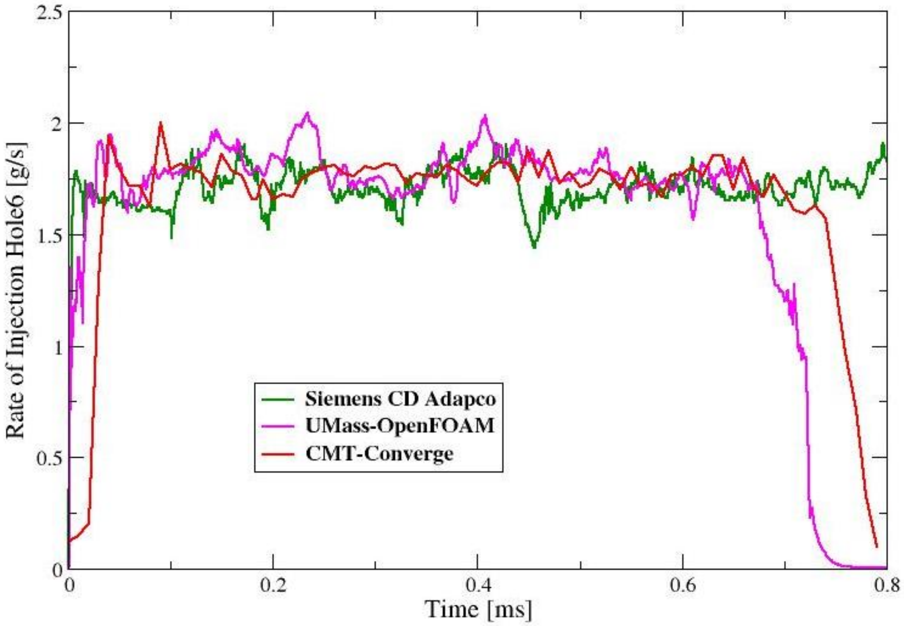


Spray G2

ROI – HOLE 6

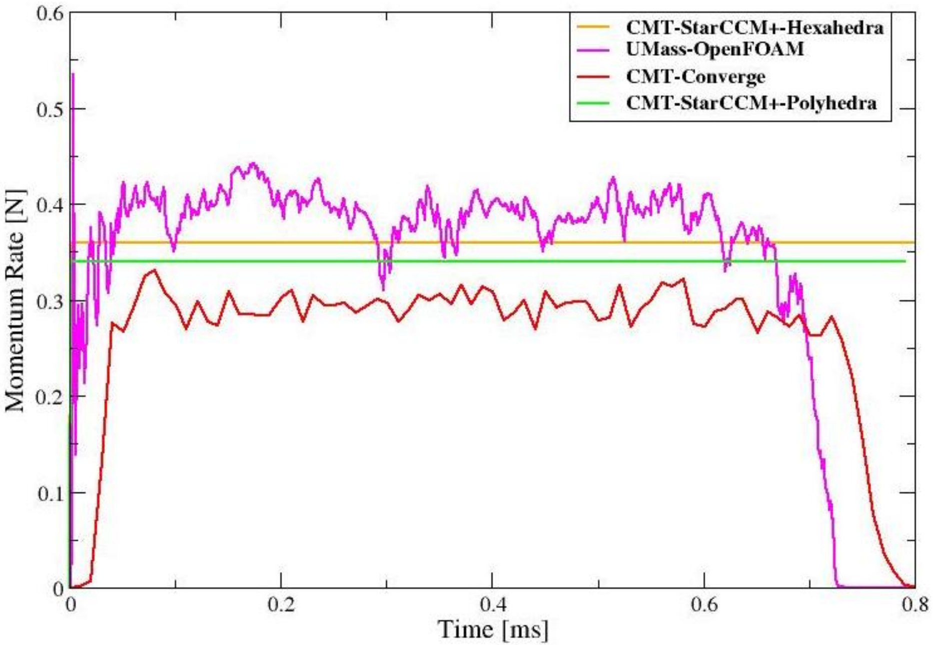


Spray G

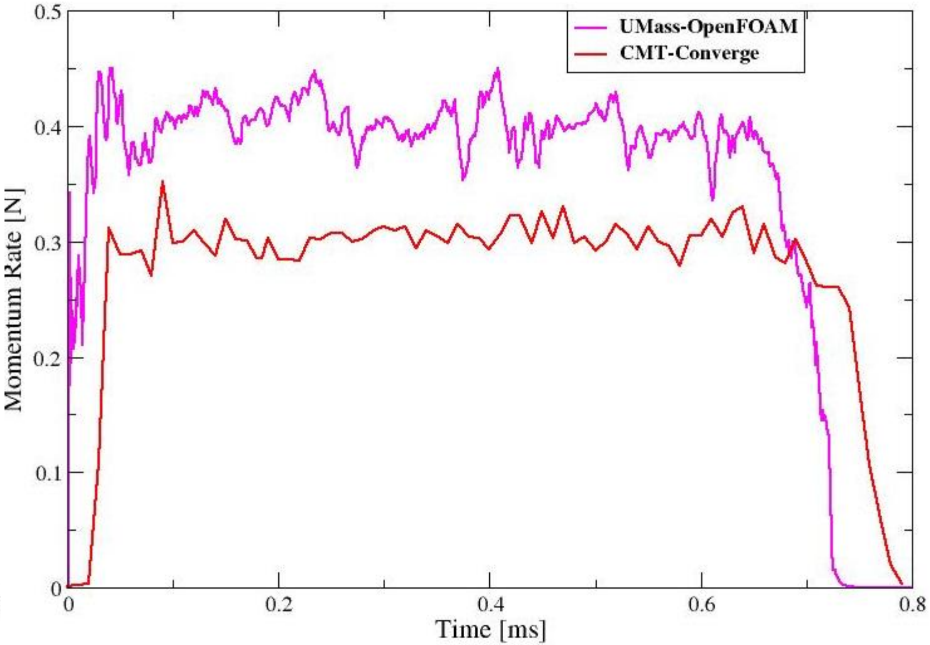


Spray G2

MOMENTUM RATE – HOLE 6

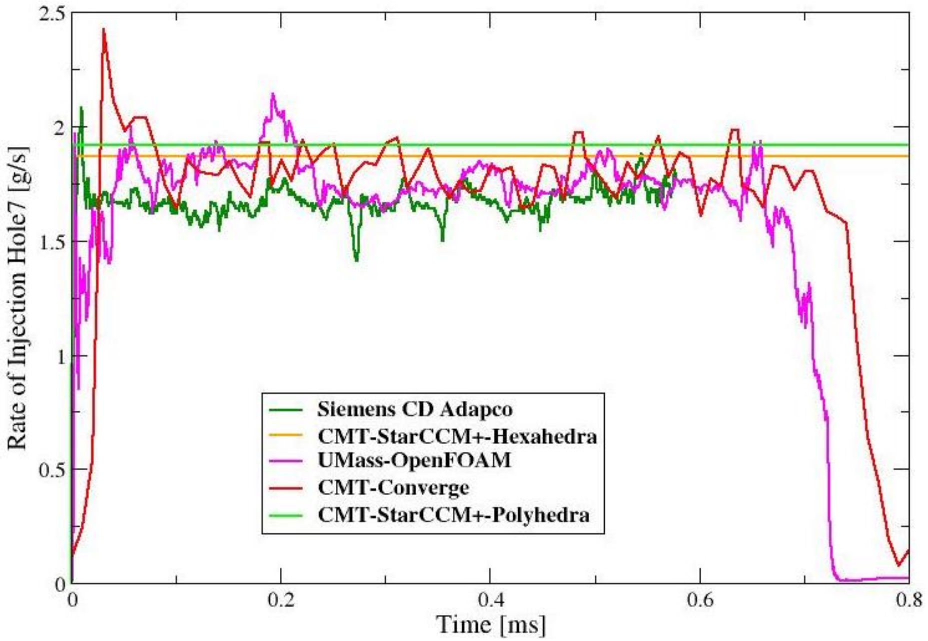


Spray G

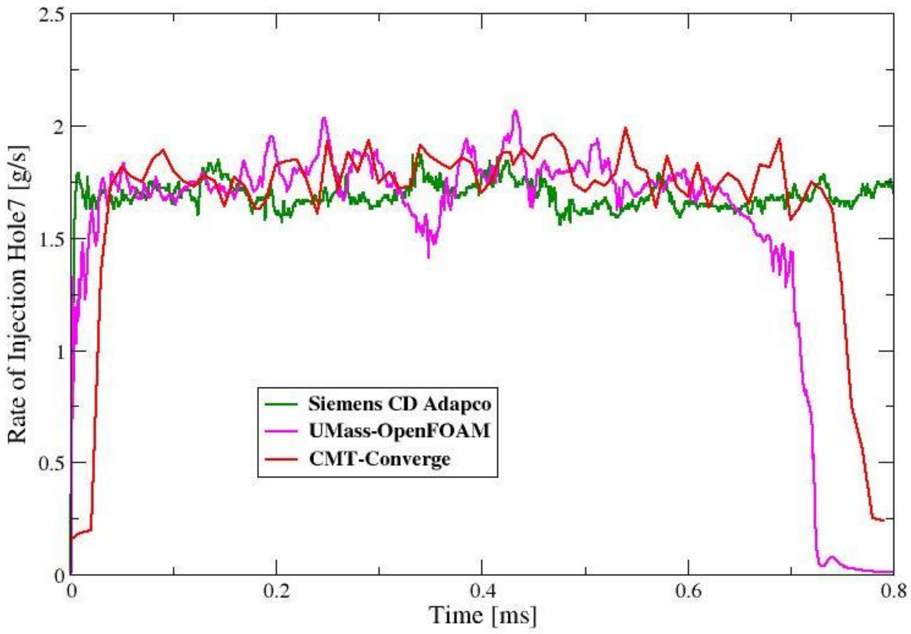


Spray G2

ROI – HOLE 7

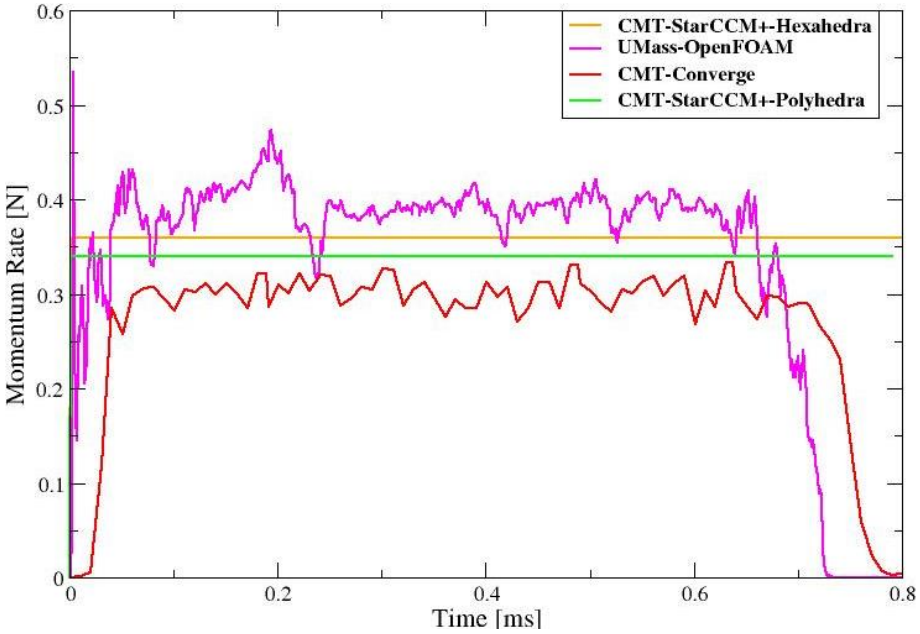


Spray G

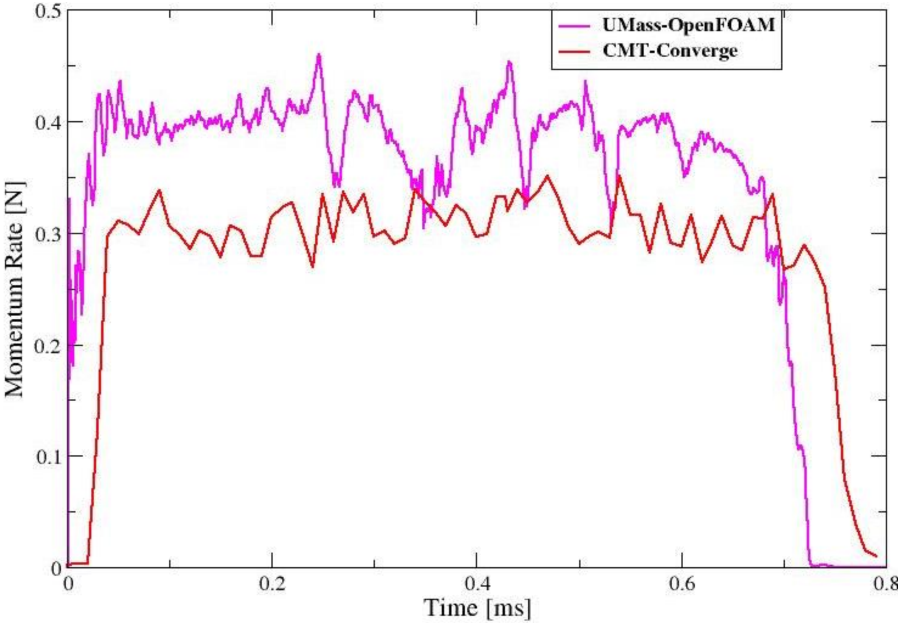


Spray G2

MOMENTUM RATE – HOLE 7

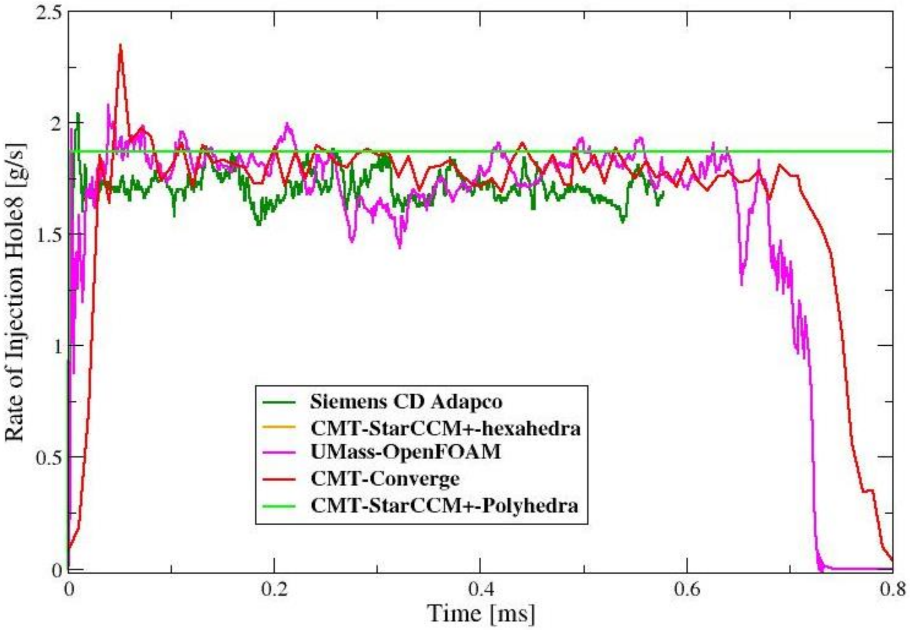


Spray G

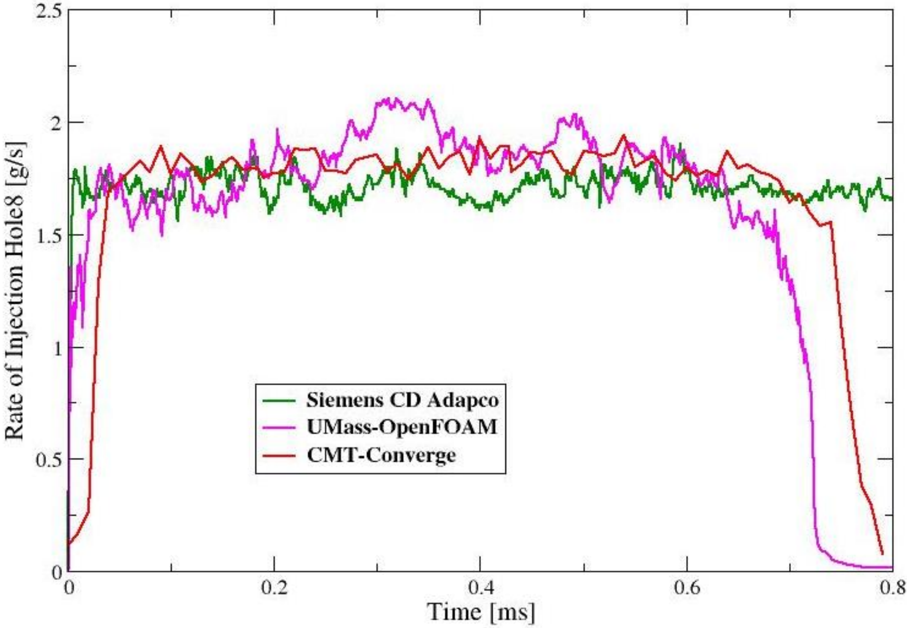


Spray G2

ROI – HOLE 8

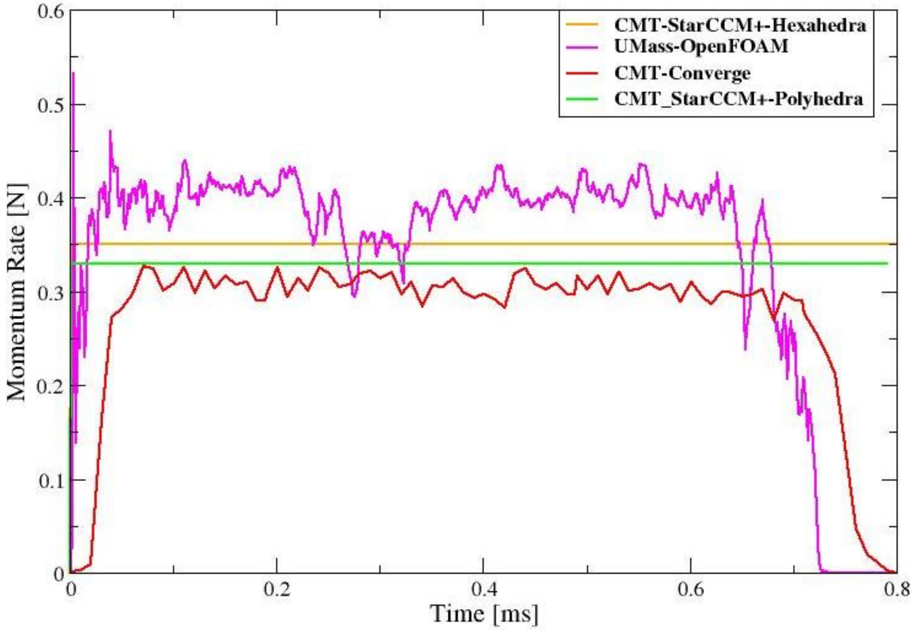


Spray G

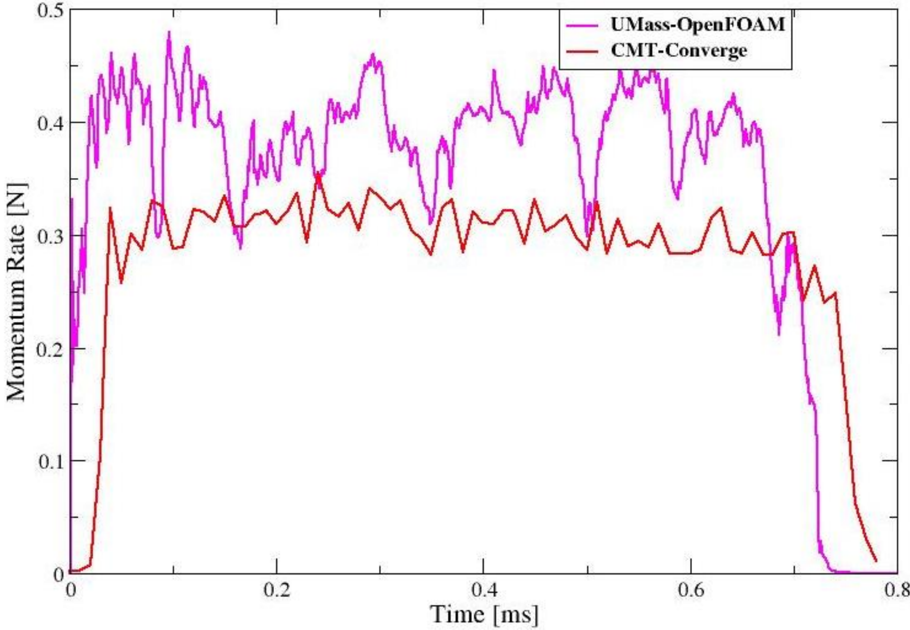


Spray G2

MOMENTUM RATE – HOLE 8

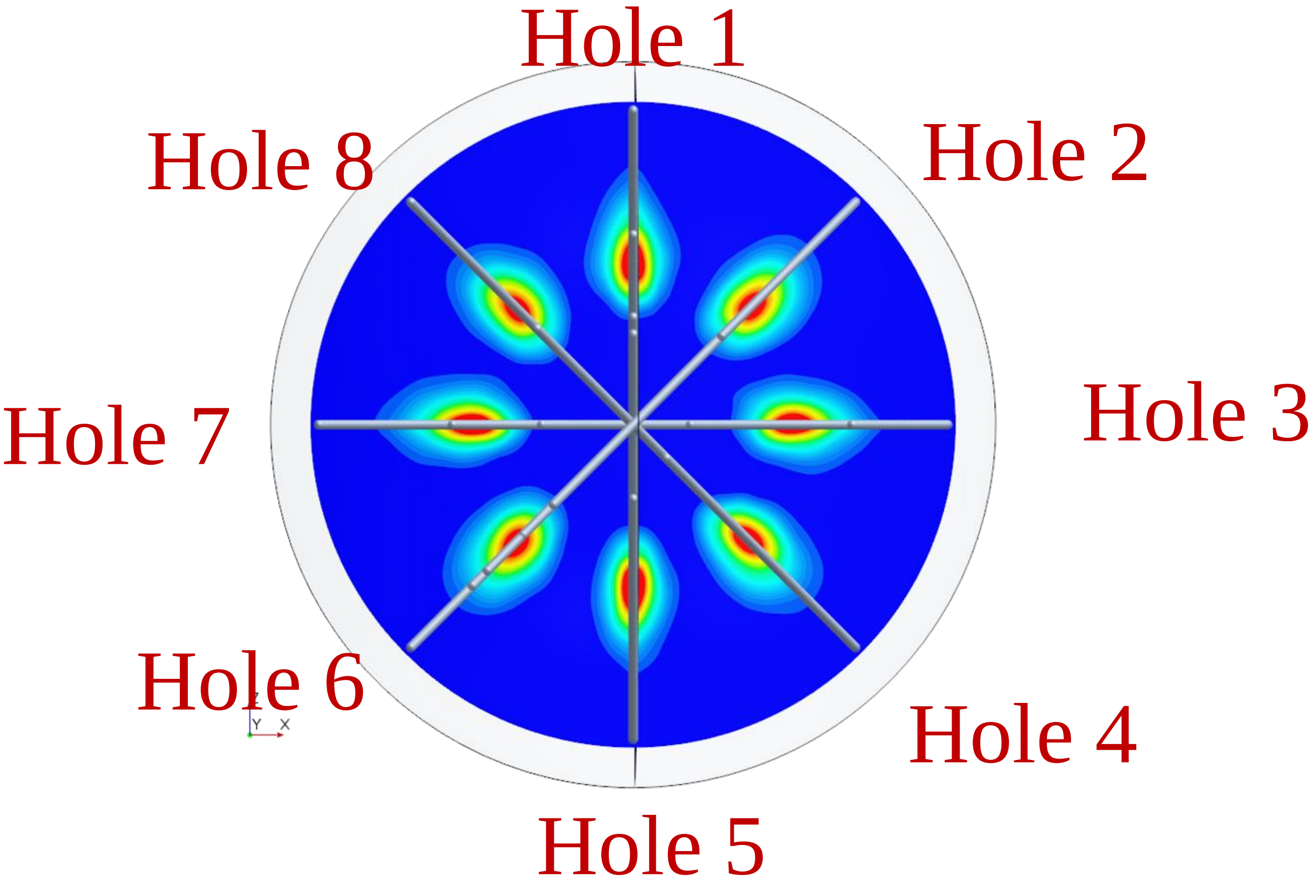


Spray G

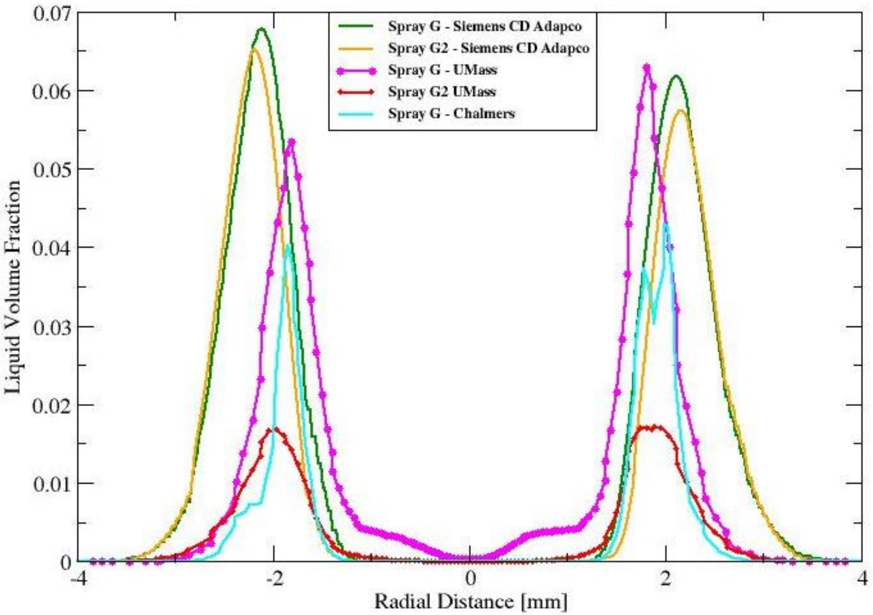


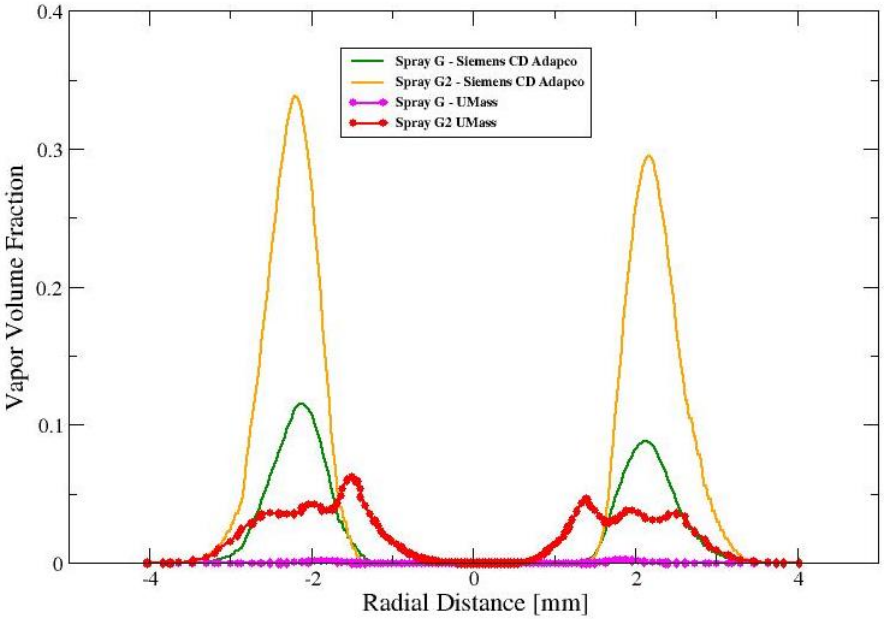
Spray G2

TIME AVERAGED QUANTITIES AT Z= 2MM



TIME AVERAGED QUANTITIES AT Z= 2MM (HOLE1-HOLE5)

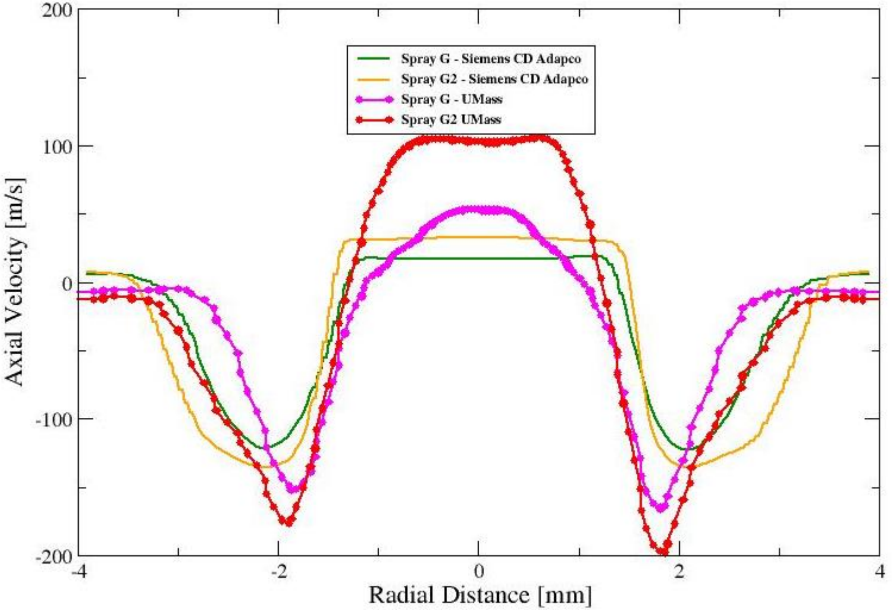


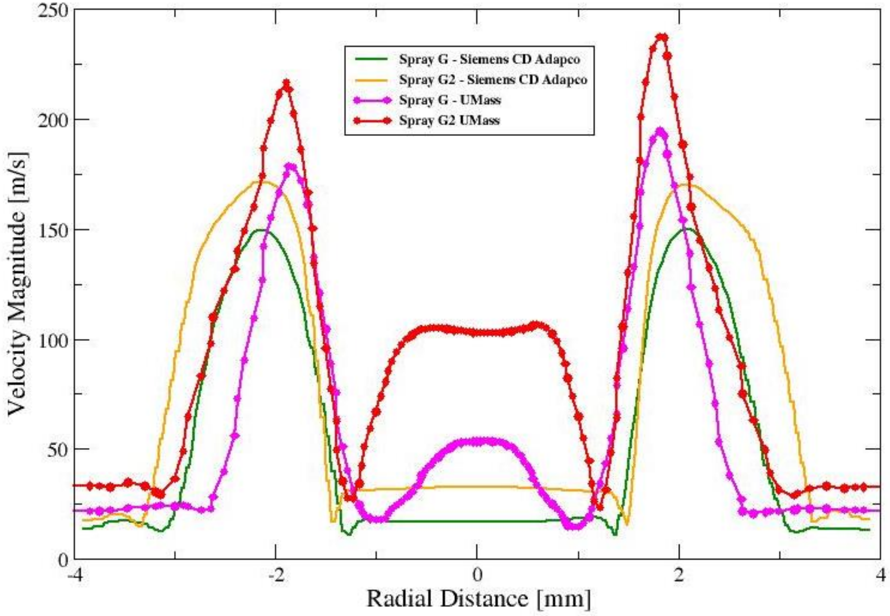


Hole1 Hole5

Hole1 Hole5

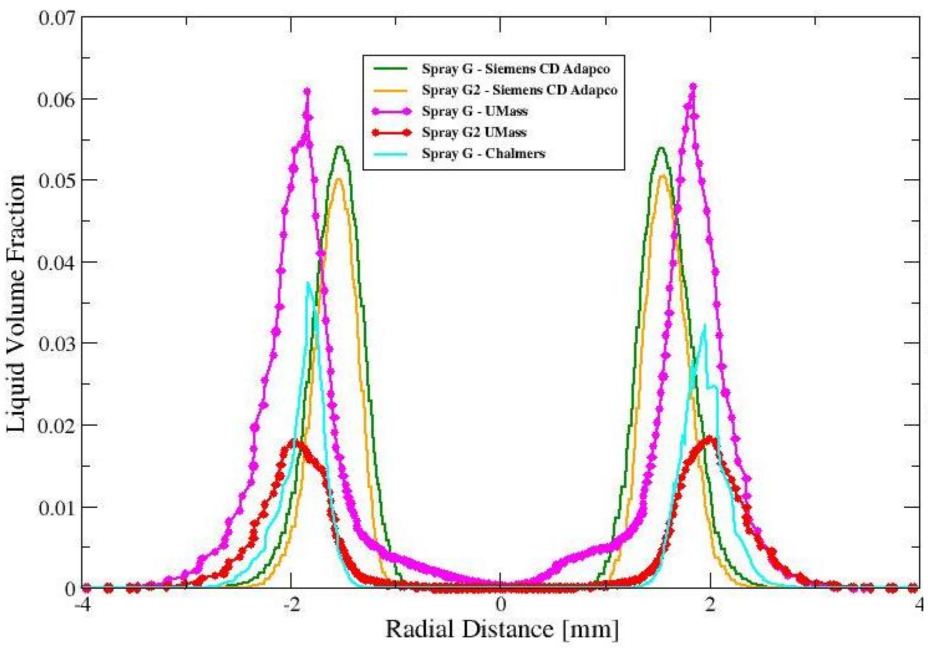
TIME AVERAGED QUANTITIES AT Z= 2MM(HOLE1-HOLE5)

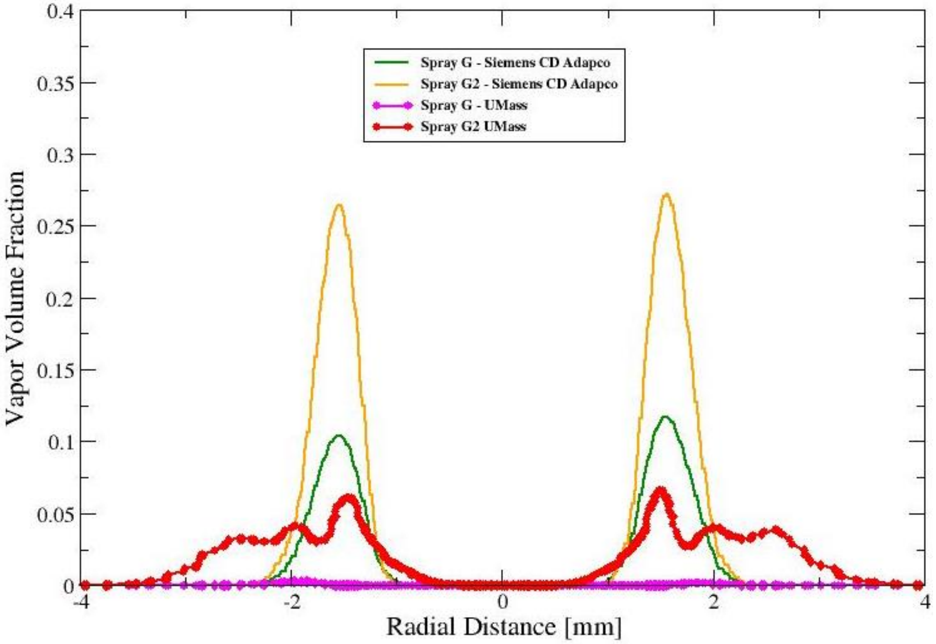




Hole1 Hole5 Hole1 Hole5

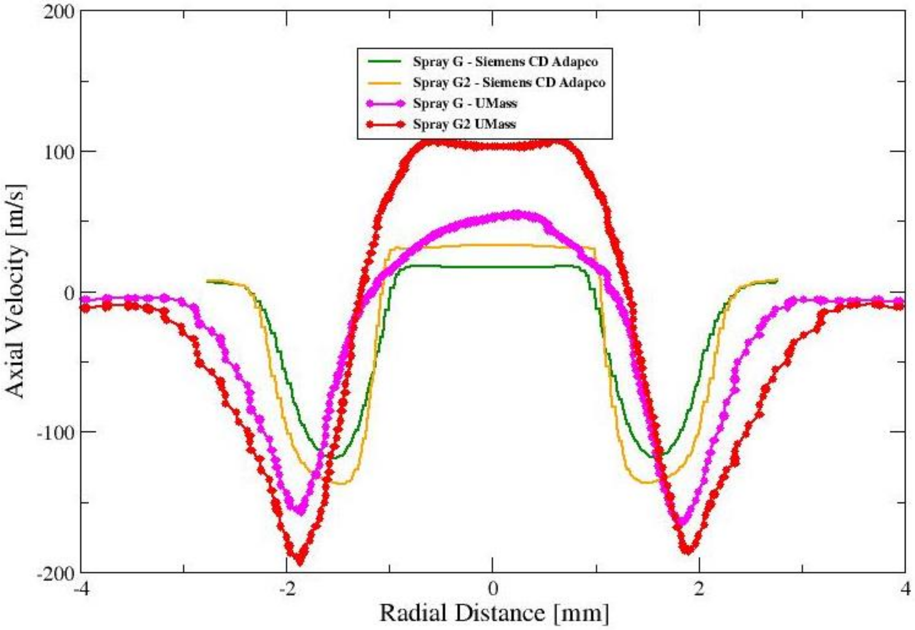
TIME AVERAGED QUANTITIES AT Z= 2MM(HOLE2-HOLE6)

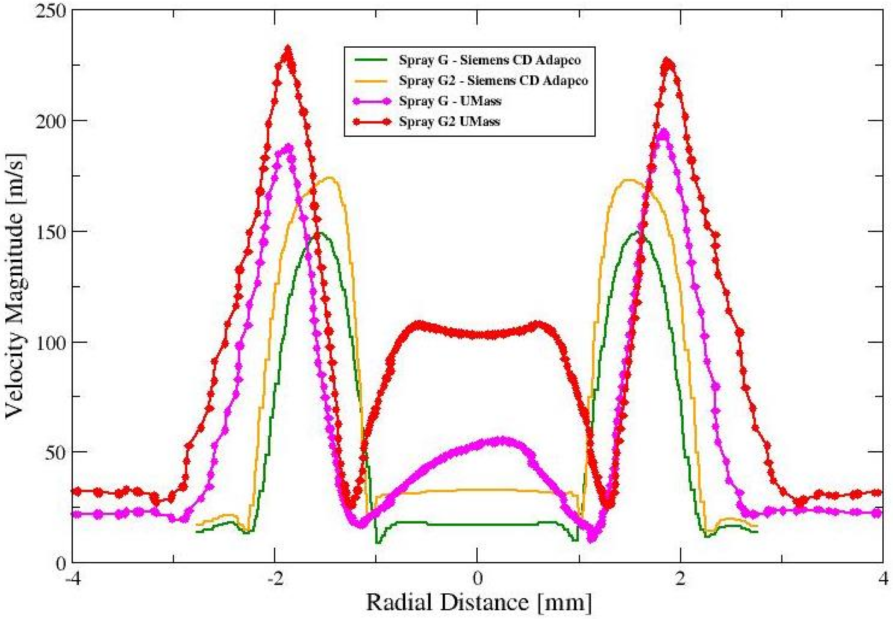




Hole2 Hole6 Hole2 Hole6

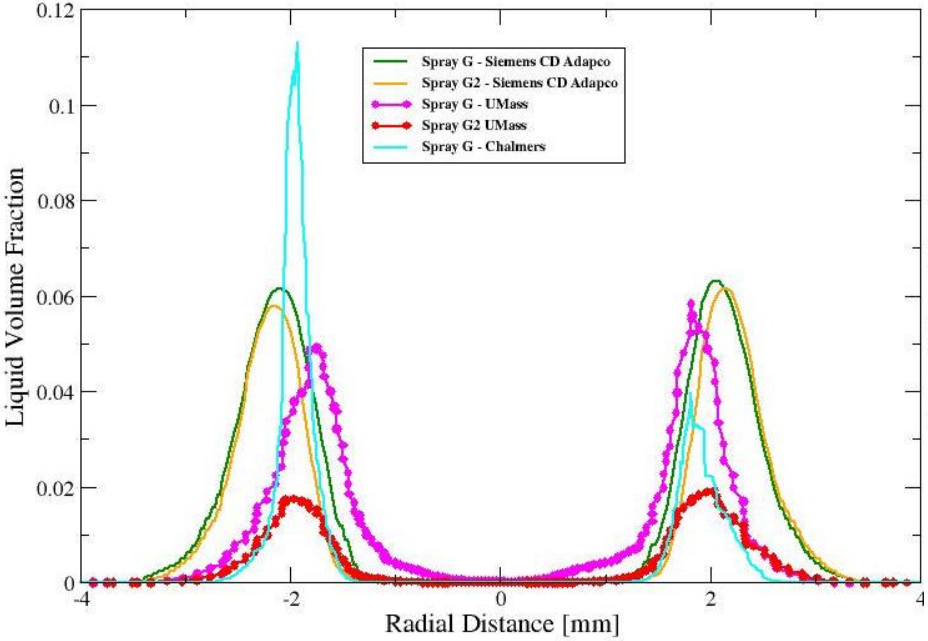
TIME AVERAGED OUANTITIES AT Z= 2MM(HOLE2-HOLE6)

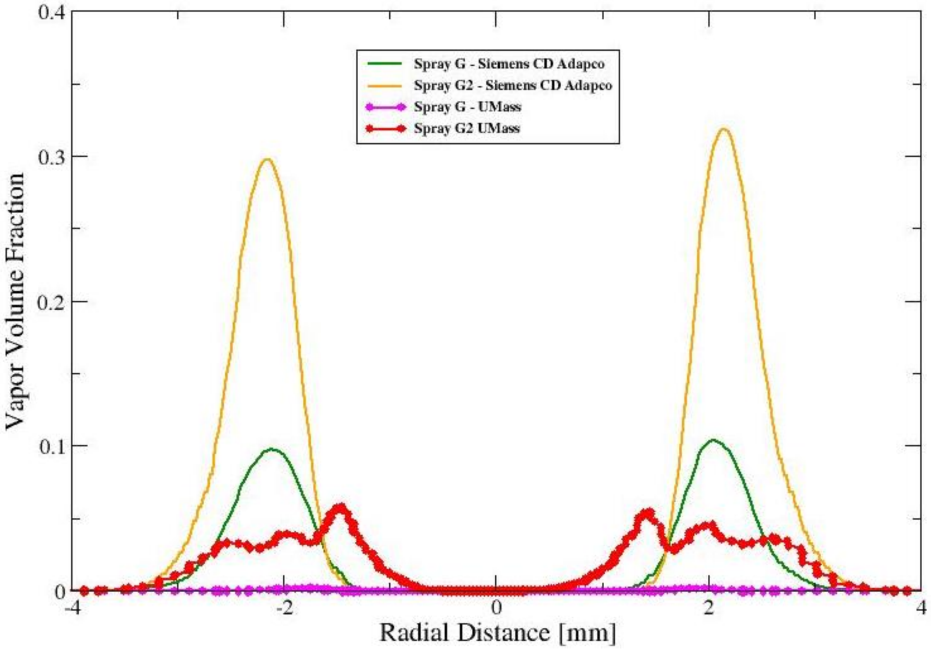




Hole2 Hole6 Hole2 Hole6

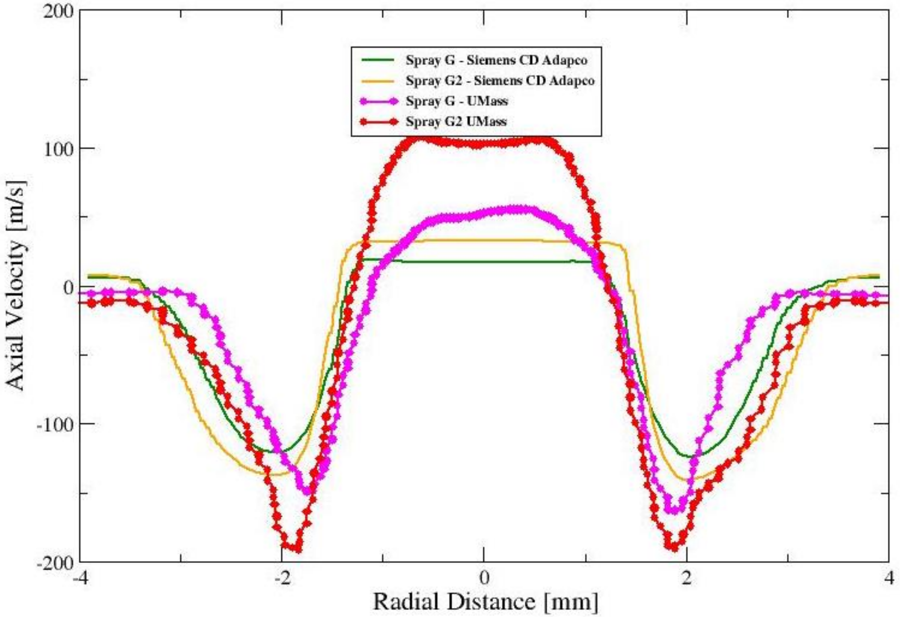
TIME AVERAGED QUANTITIES AT Z= 2MM(HOLE3-HOLE7)

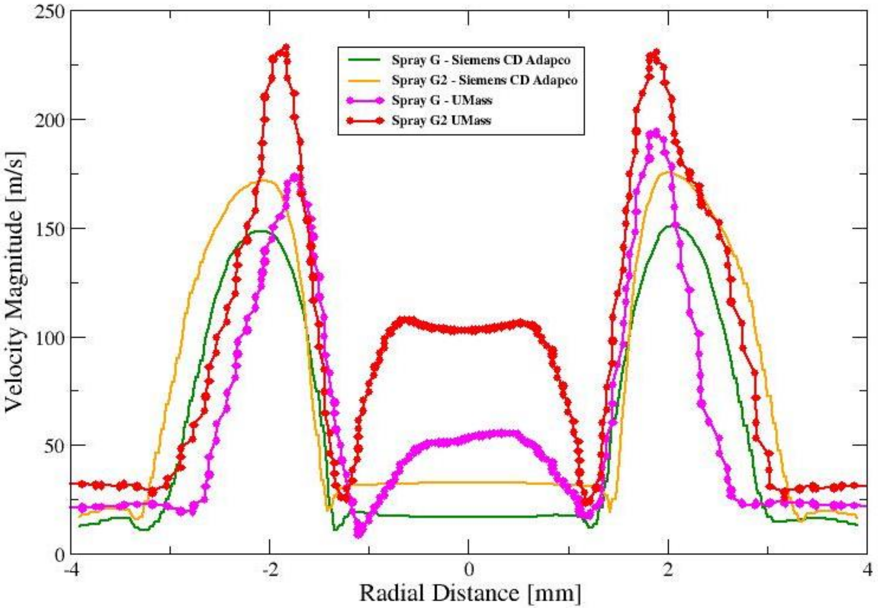




Hole3 Hole7 Hole3 Hole7

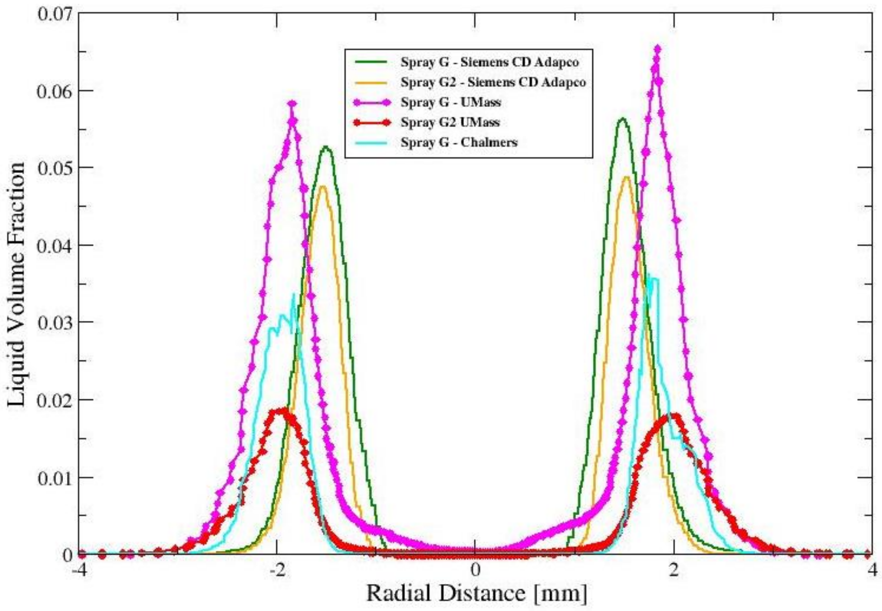
TIME AVERAGED QUANTITIES AT Z= 2MM(HOLE3-HOLE7)

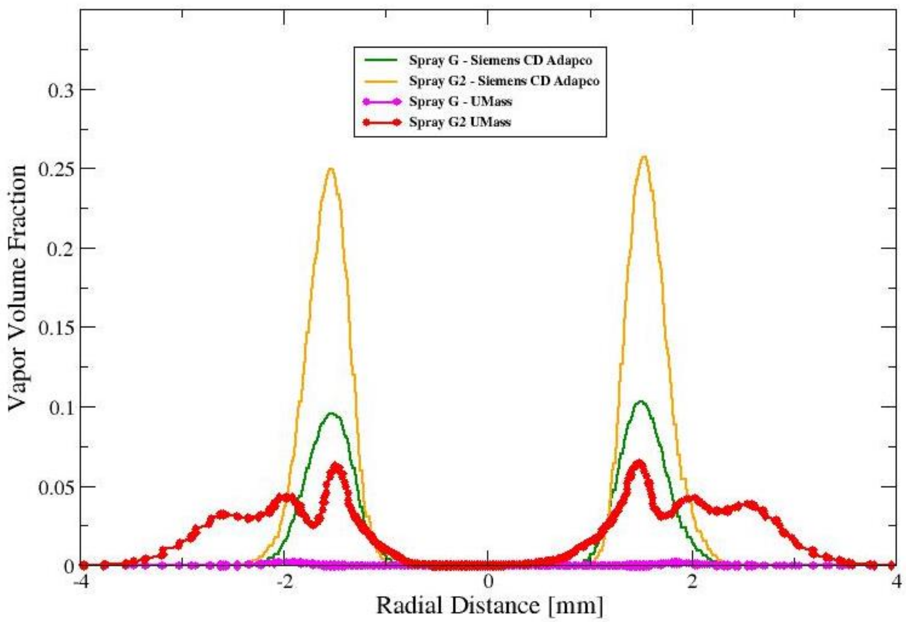




Hole3 Hole7 Hole3 Hole7

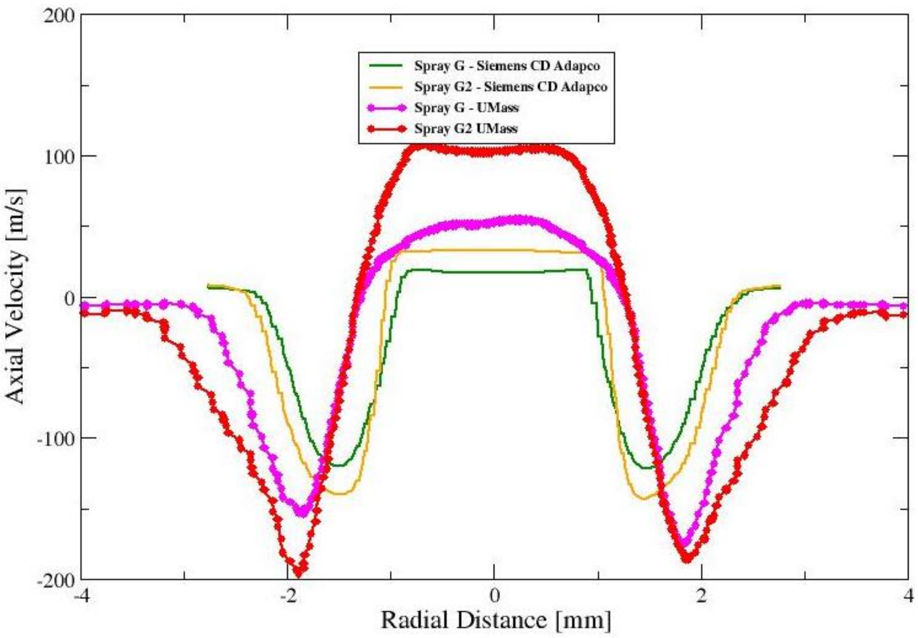
TIME AVERAGED QUANTITIES AT Z= 2MM(HOLE4-HOLE8)

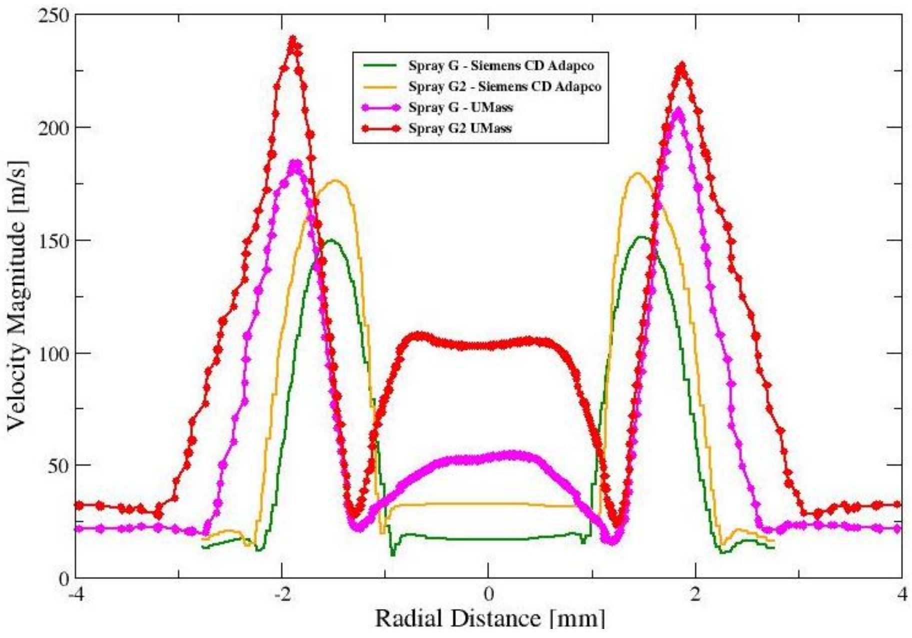




Hole4 Hole8 Hole4 Hole8

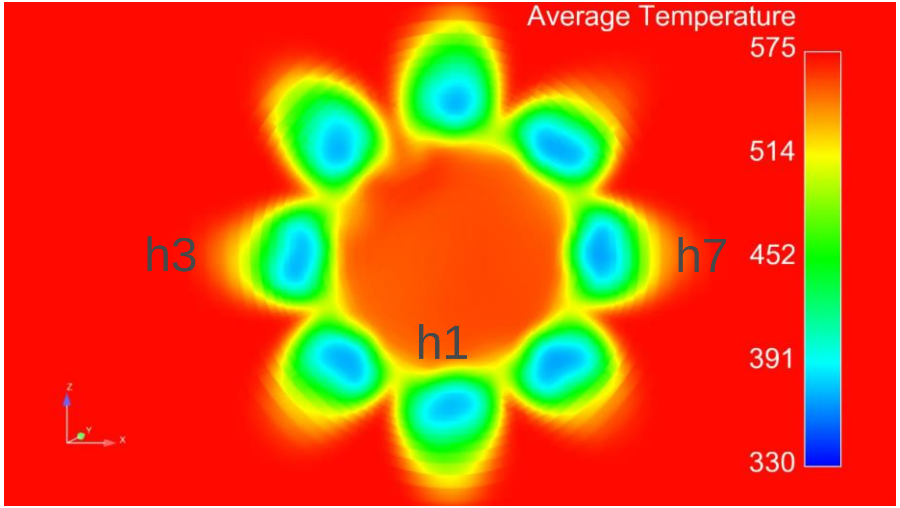
TIME AVERAGED QUANTITIES AT Z= 2MM(HOLE4-HOLE8)

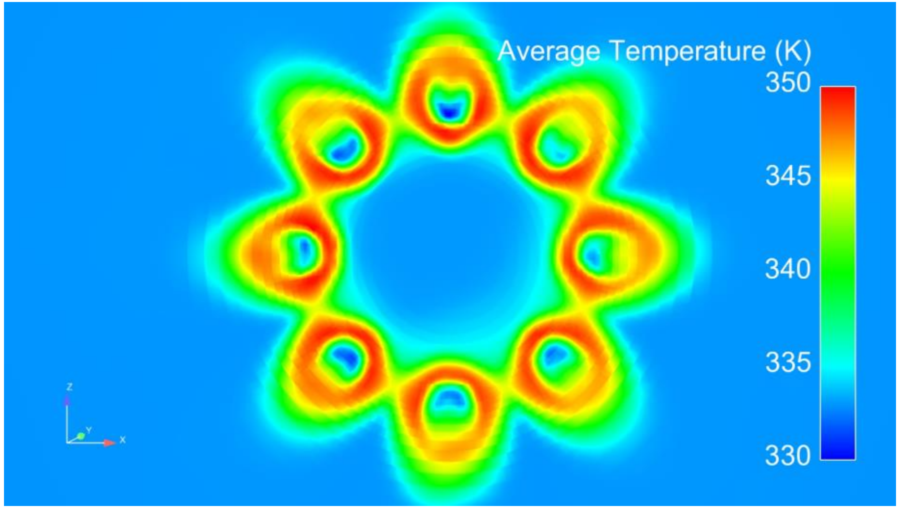




Hole4 Hole8 Hole4 Hole8

TIME AVERAGED TEMPERATURE (Z=1MM)-UMASS HRMFOAM

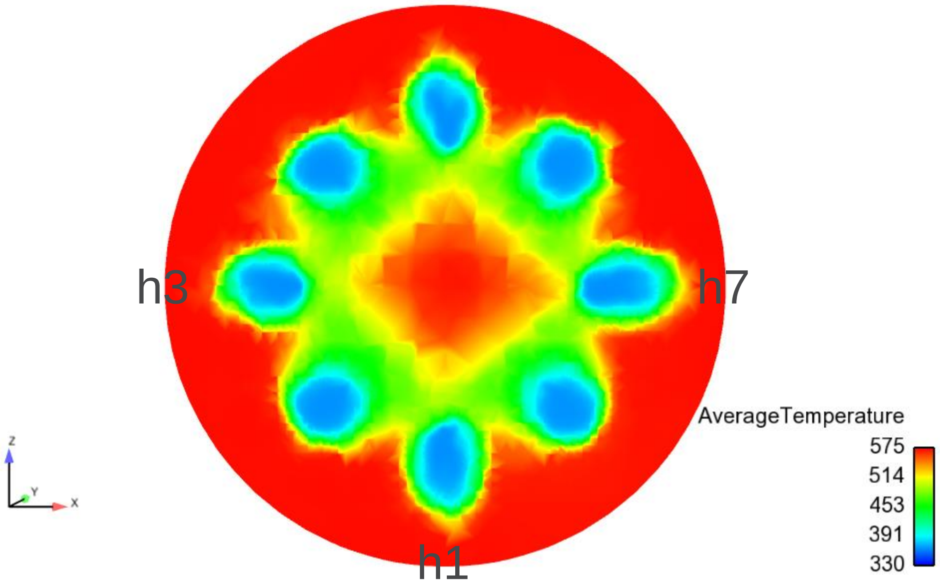




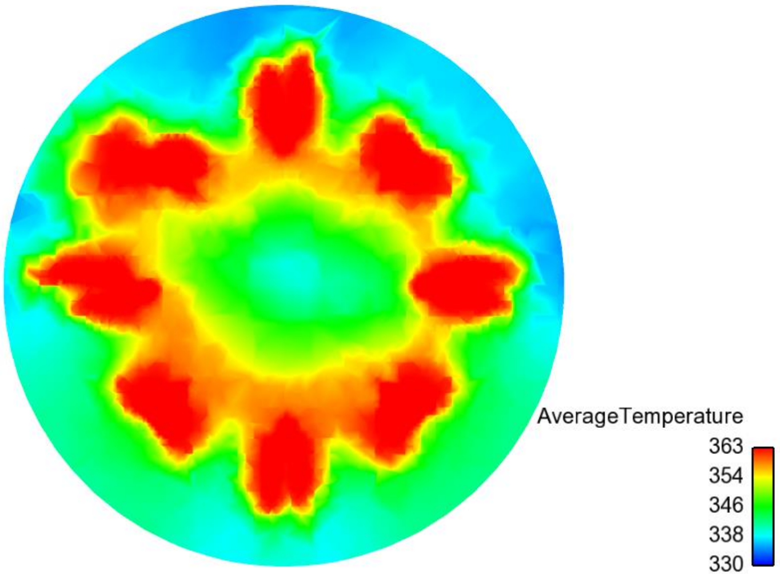
Spray G

Spray G2

TIME AVERAGED TEMPERATURE (Z=1MM)-CMT CONVERGE

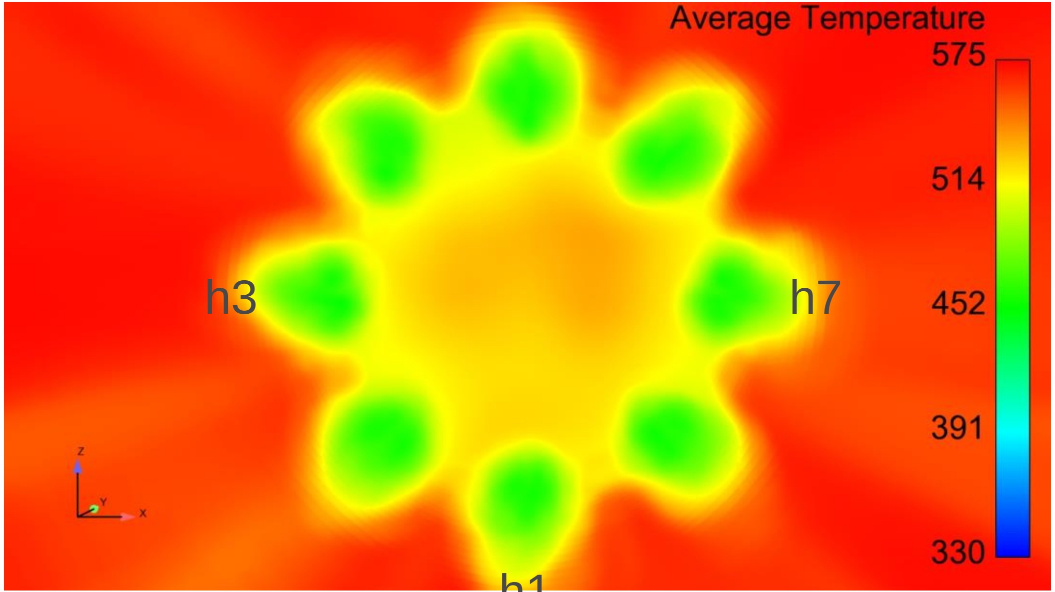


Spray G



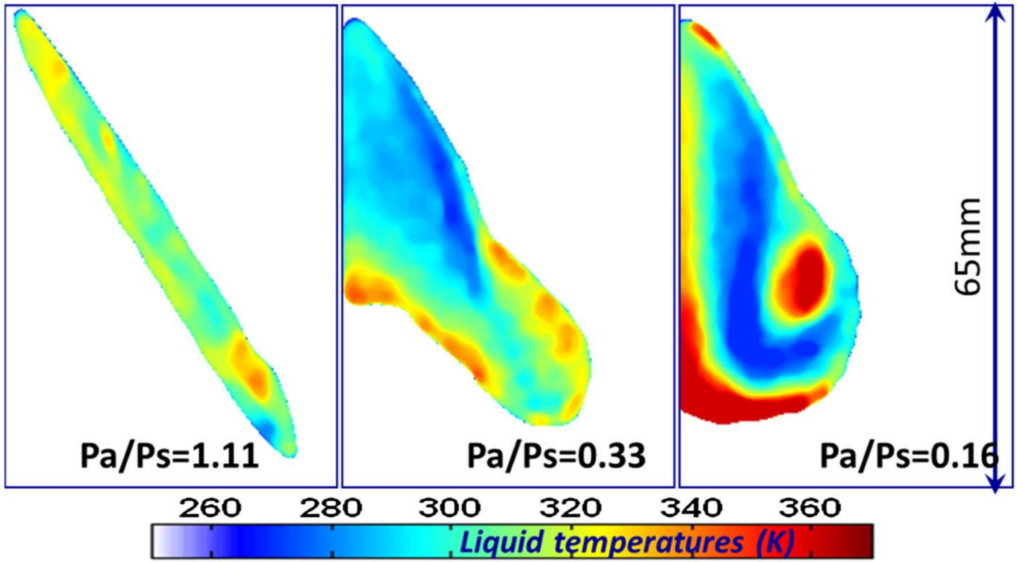
Spray G2

TIME AVERAGED TEMPERATURE (Z=1MM)-CHALMERS

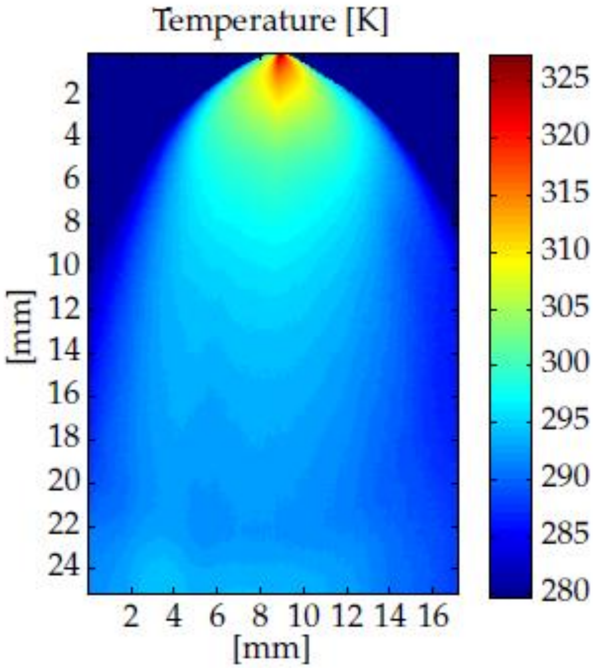


Spray G

WHAT IS THE RIGHT ANSWER?

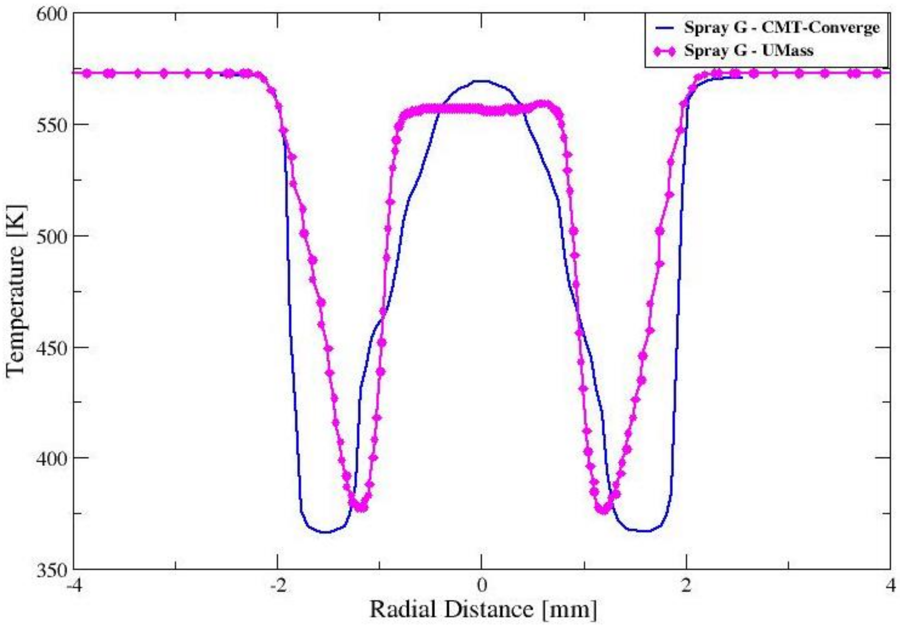


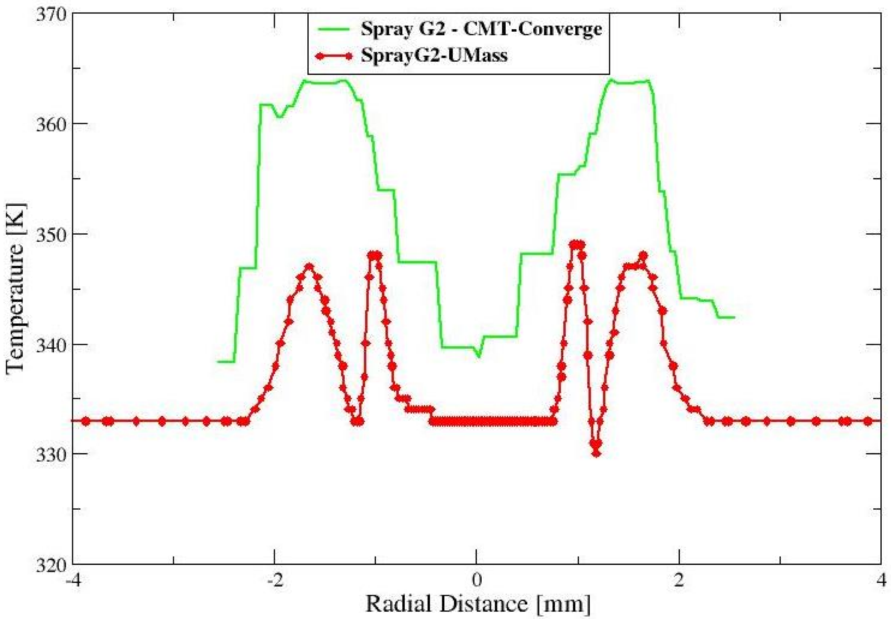
Zhang, Gaoming, David LS Hung, and Min Xu. "Experimental study of flash boiling spray vaporization through quantitative vapor concentration and liquid temperature measurements." Experiments in fluids 55.8 (2014): 1804



Kamoun, H., Lamanna, G., Ruberto, S., Komenda, A., Weigand, B., & Steelant, J. (2014). Experimental investigations of fully flashing jets.

TIME AVERAGED TEMPERATURE AT Z= 1MM (HOLE1-HOLE5)

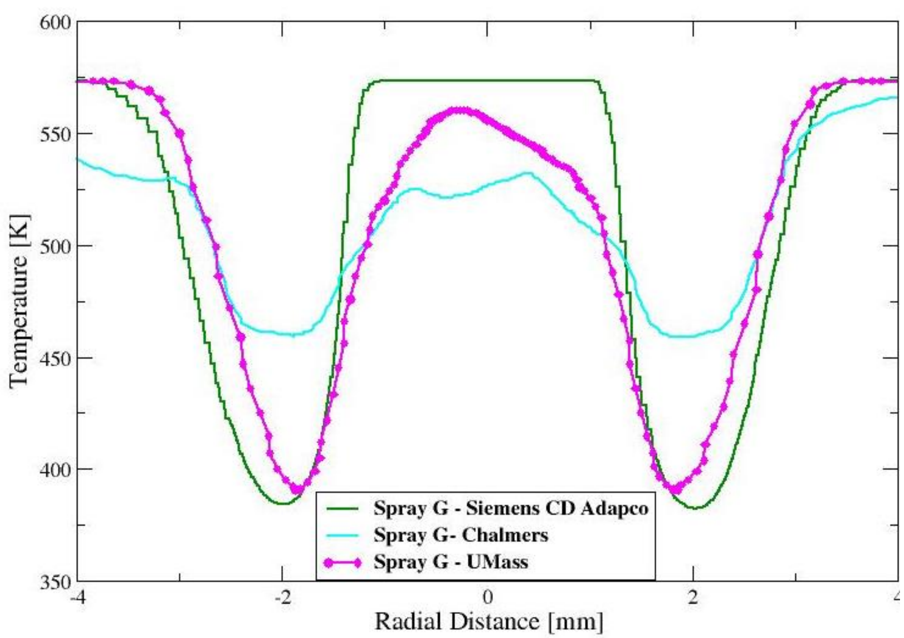


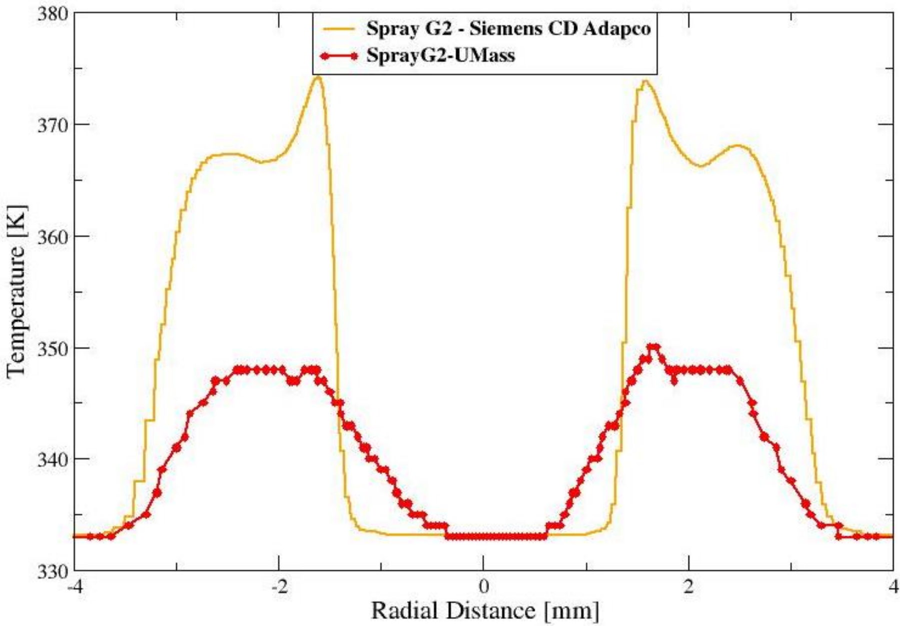


Hole1 Hole5 Hole1 Hole5

Spray G Spray G2

TIME AVERAGED TEMPERATURE AT Z= 2MM (HOLE1-HOLE5)





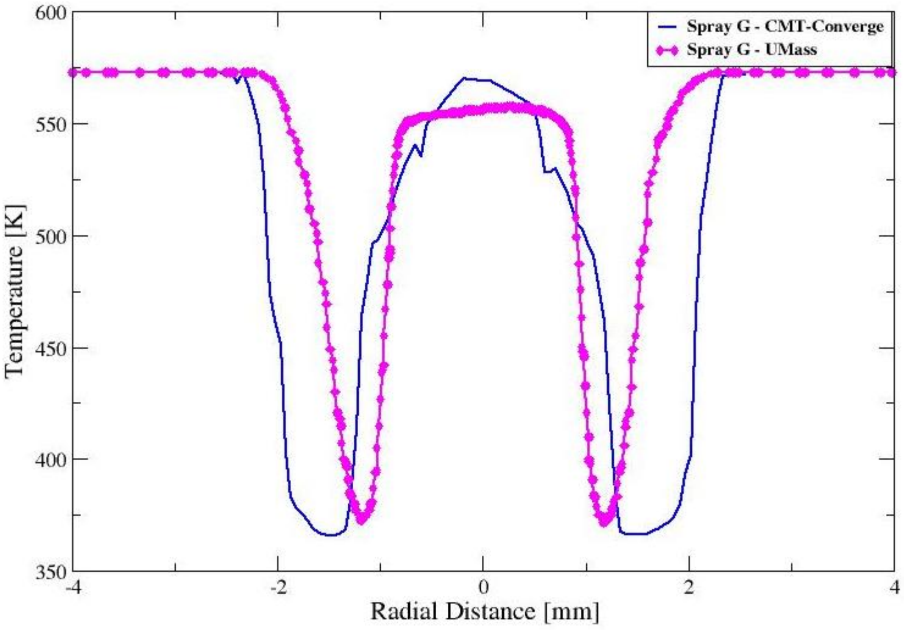
Hole1 Hole5

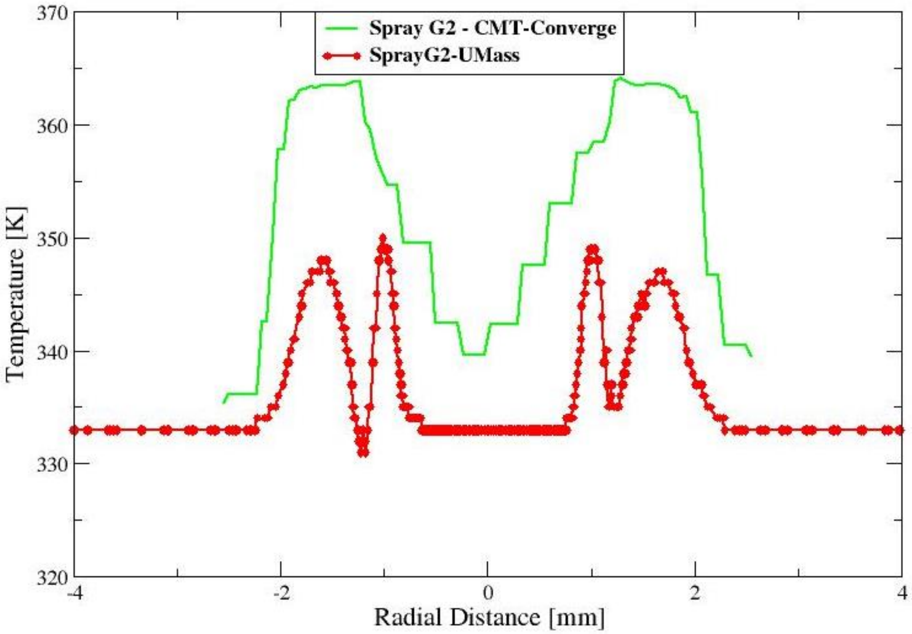
Spray G

Hole1 Hole5

Spray G2

TIME AVERAGED TEMPERATURE AT Z= 1MM (HOLE2-HOLE6)





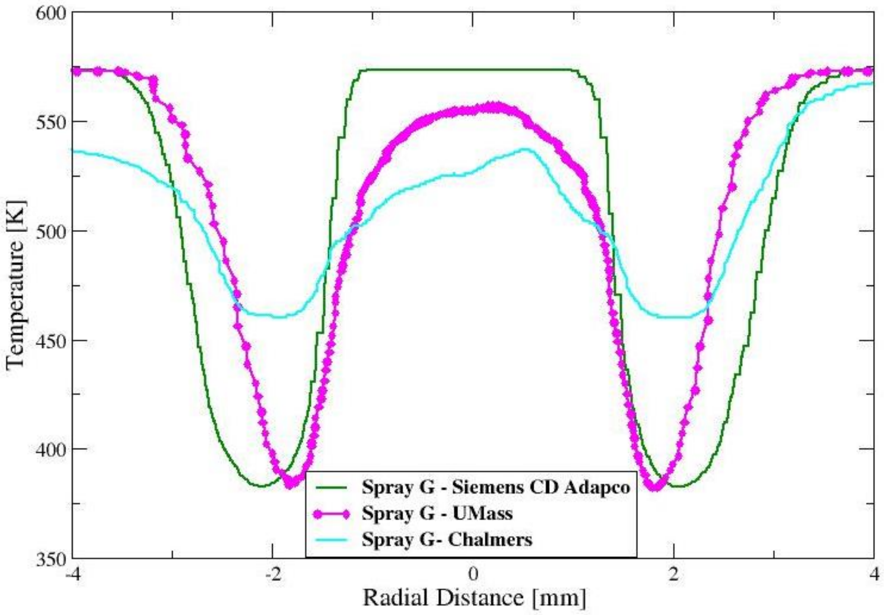
Hole2 Hole6

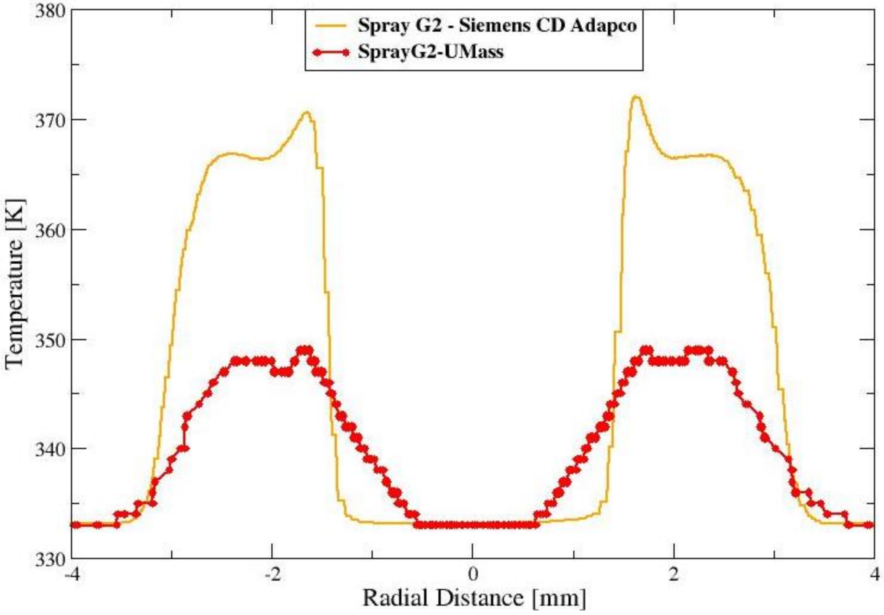
Spray G

Hole2 Hole6

Spray G2

TIME AVERAGED TEMPERATURE AT Z= 2MM (HOLE2-HOLE6)





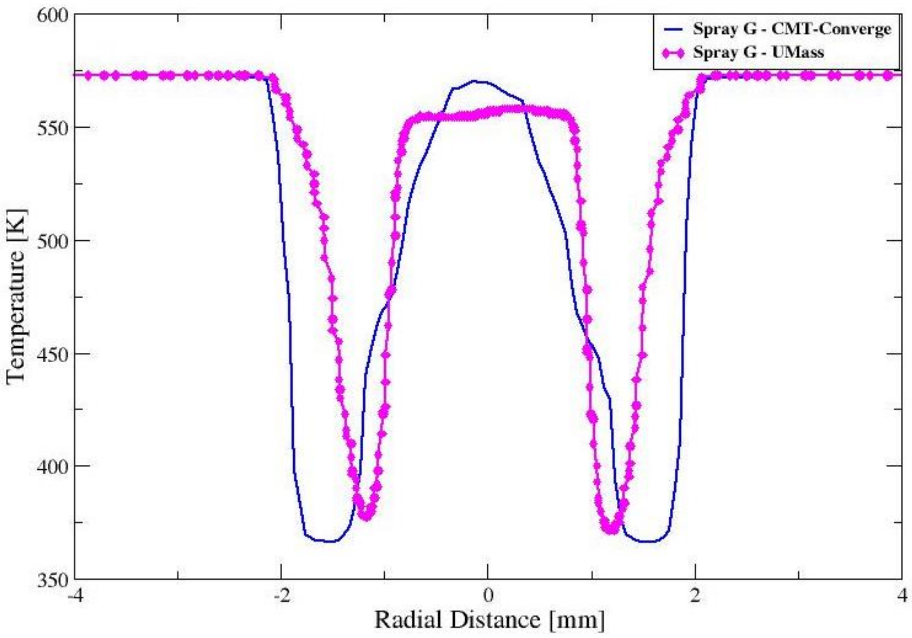
Hole2 Hole6

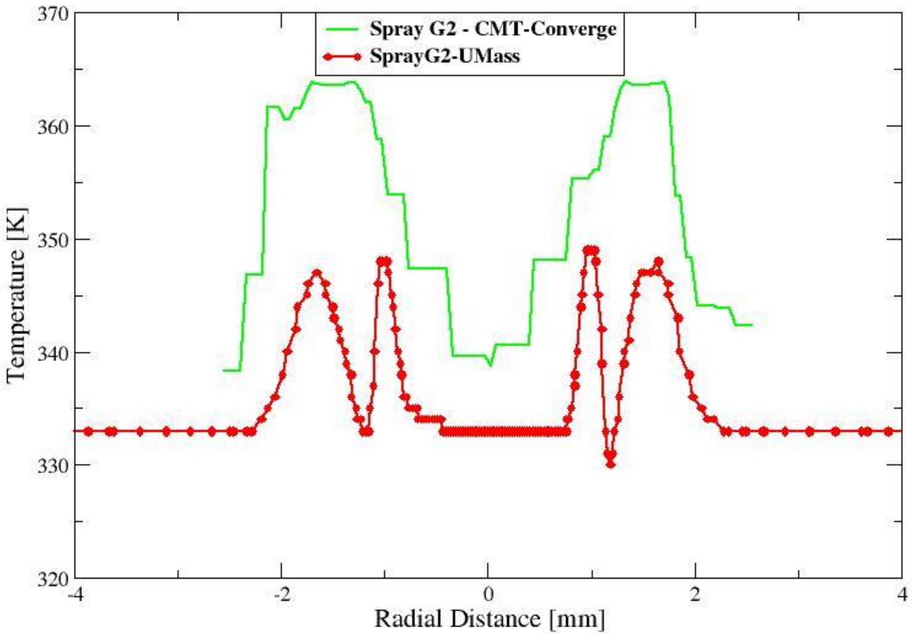
Spray G

Hole2 Hole6

Spray G2

TIME AVERAGED TEMPERATURE AT Z= 1MM (HOLE3-HOLE7)





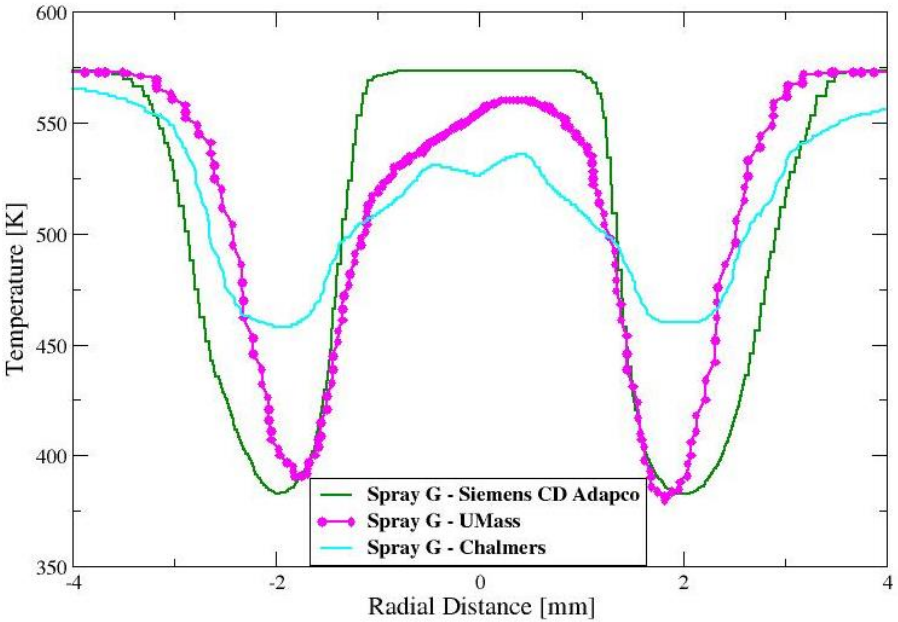
Hole3 Hole7

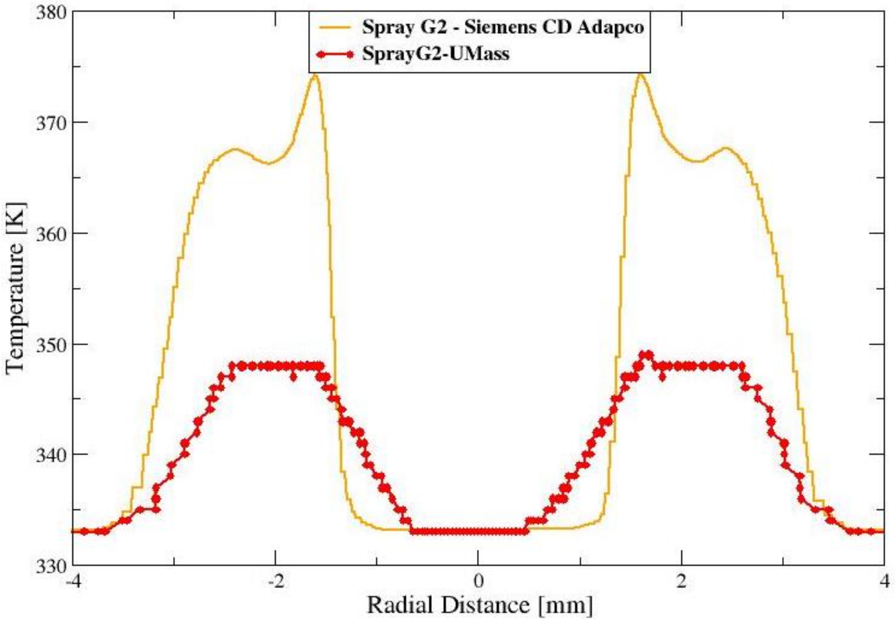
Spray G

Hole3 Hole7

Spray G2

TIME AVERAGED TEMPERATURE AT Z= 2MM (HOLE3-HOLE7)





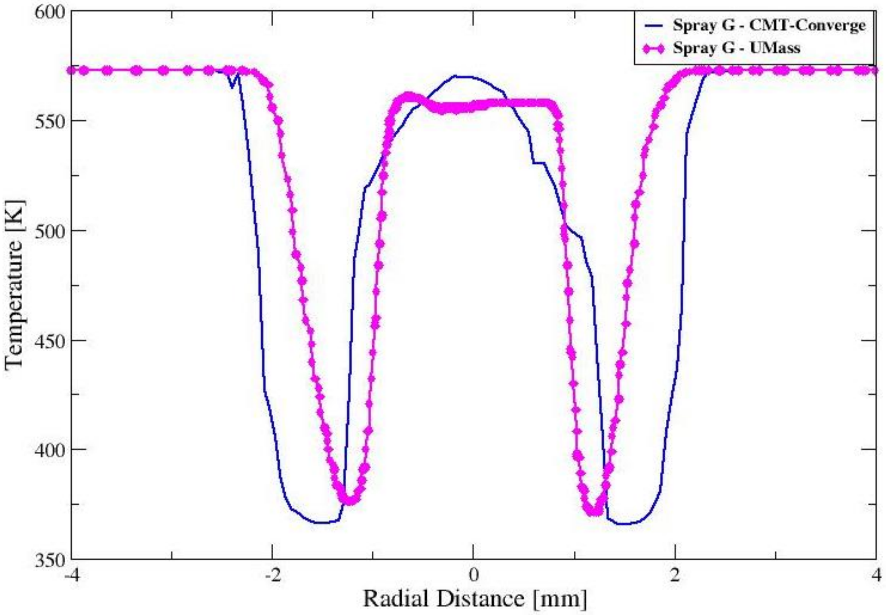
Hole3 Hole7

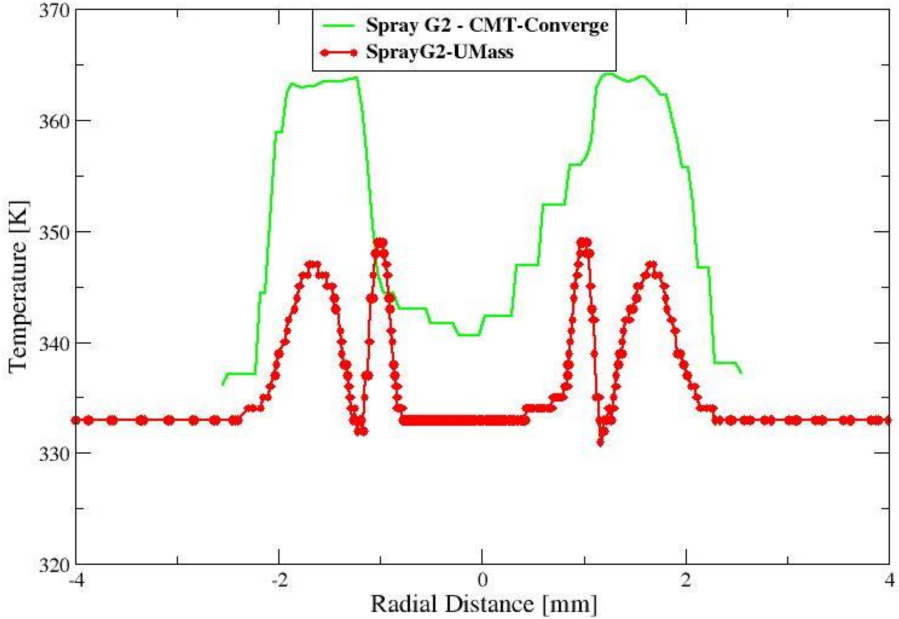
Spray G

Hole3 Hole7

Spray G2

TIME AVERAGED TEMPERATURE AT Z= 1MM (HOLE4-HOLE8)





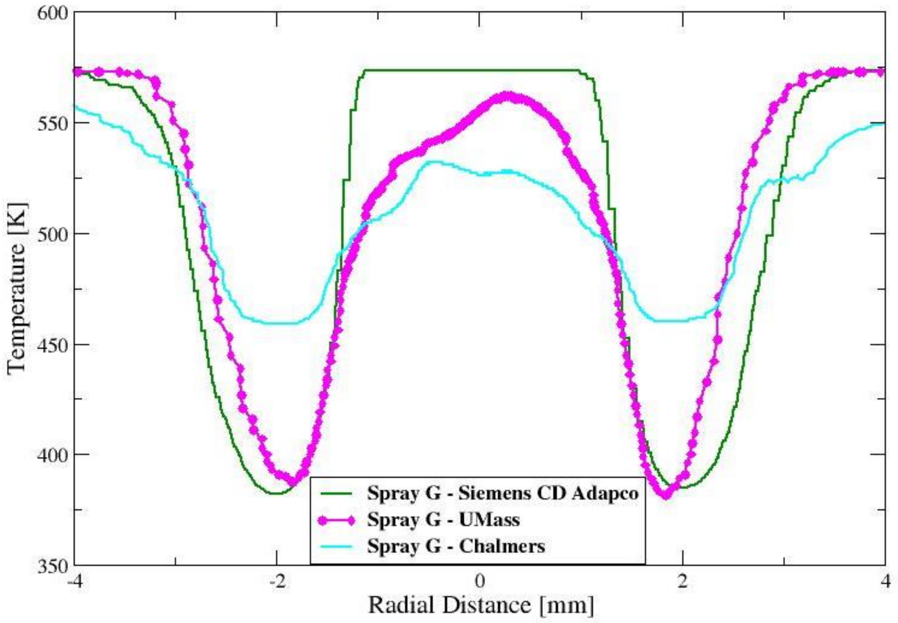
Hole4 Hole8

Spray G

Hole4 Hole8

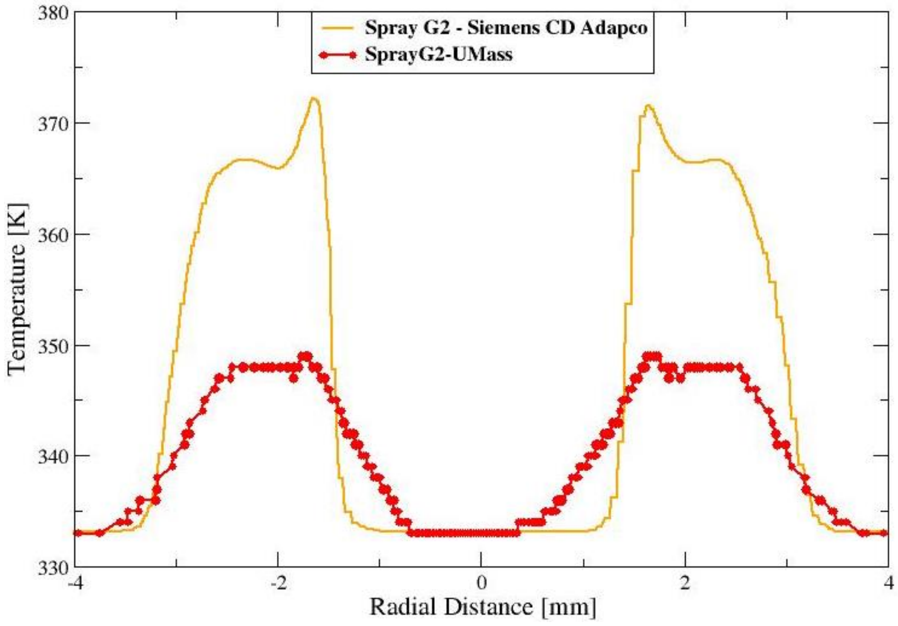
Spray G2

TIME AVERAGED TEMPERATURE AT Z= 2MM (HOLE4-HOLE8)



Hole4 Hole8

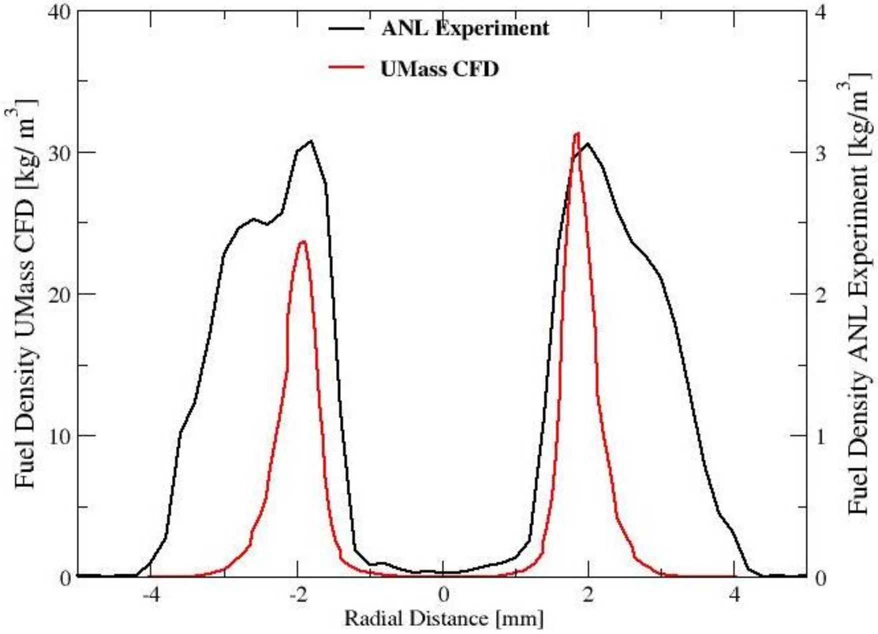
Spray G

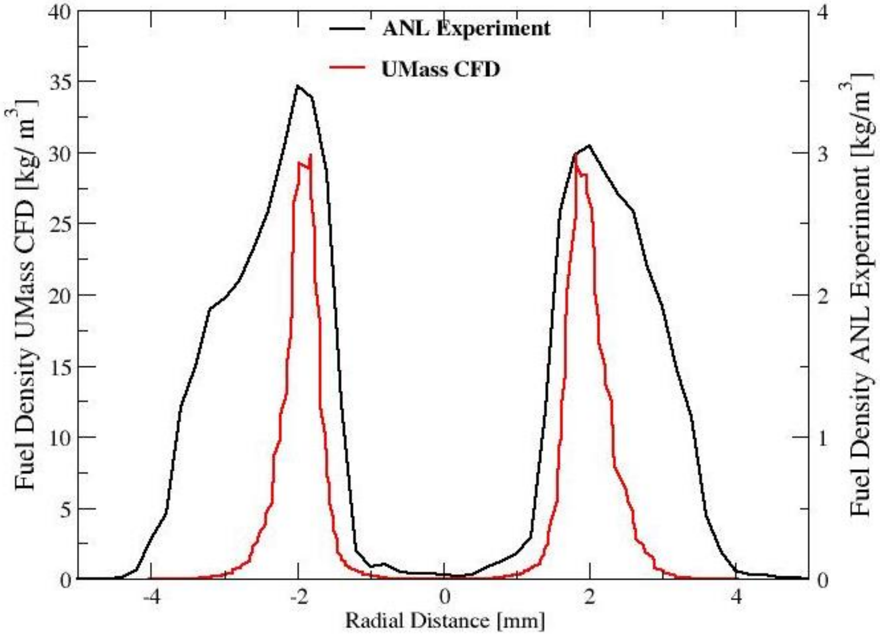


Hole4 Hole8

Spray G2

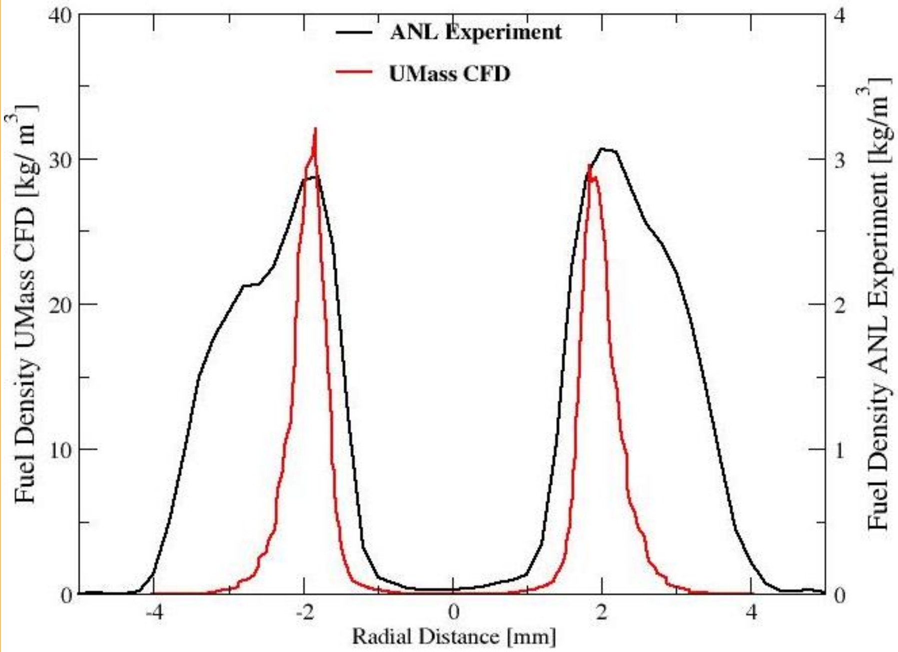
TIME AVERAGED DENSITY AT Z= 2MM (SPRAY G2)



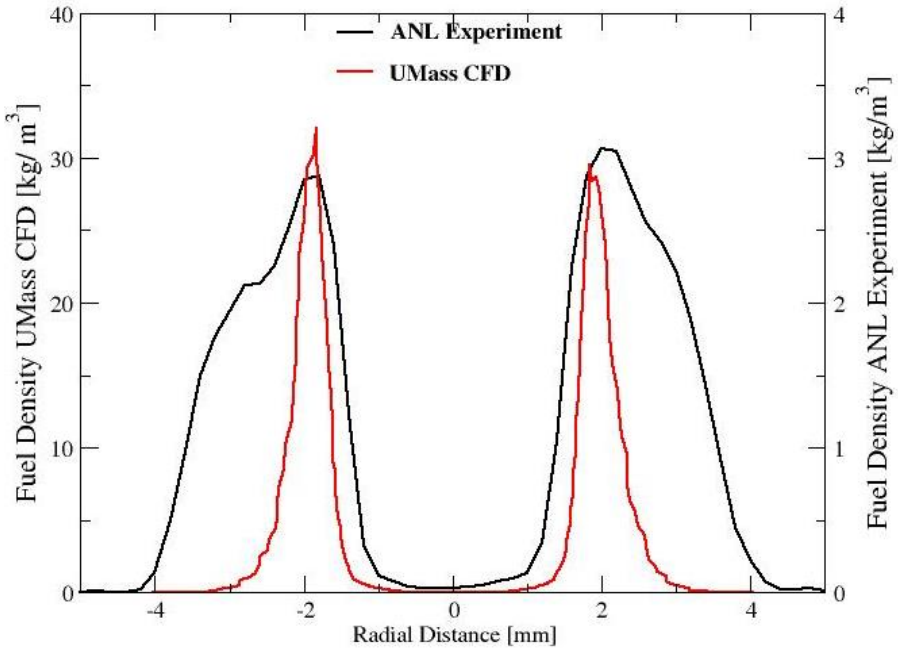


Hole1 Hole5 Hole3 Hole7

TIME AVERAGED DENSITY AT Z= 2MM (HOLE4-HOLE8)

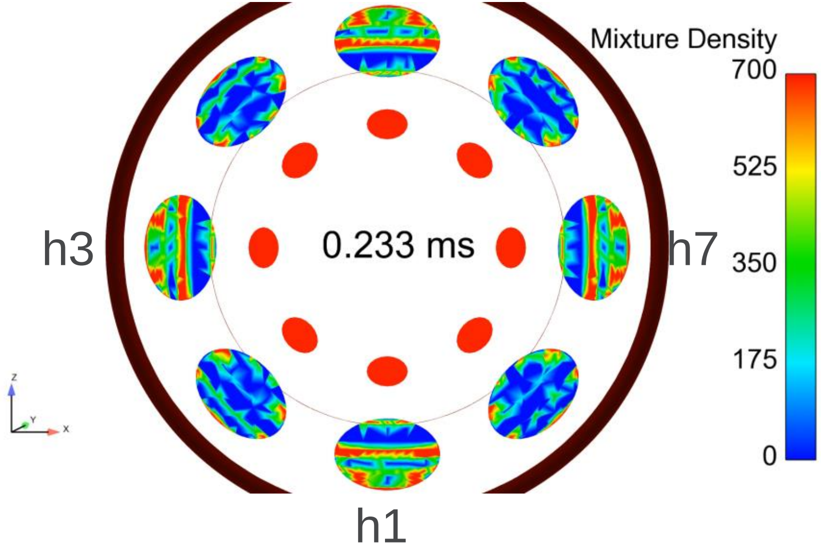


Hole2 Hole6

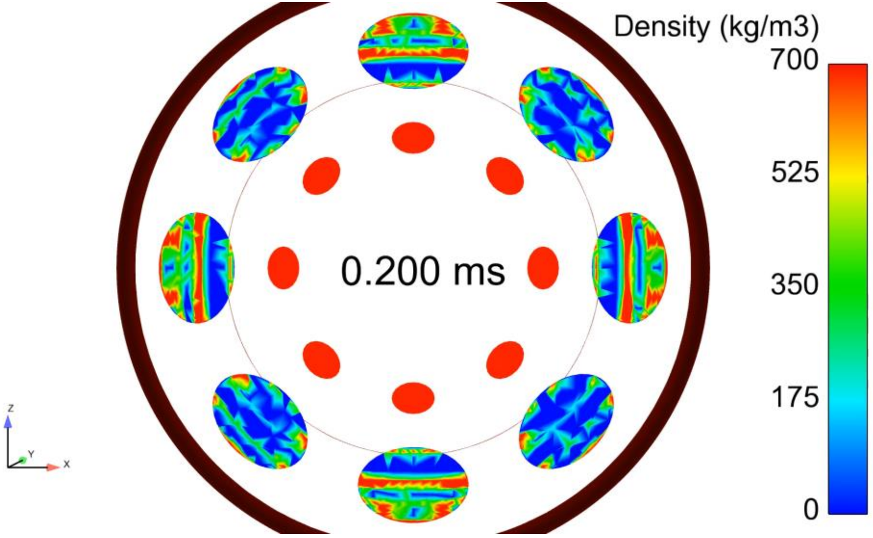


Hole4 Hole8

DENSITY (NOZZLE & CB EXIT)-CMT CONVERGE

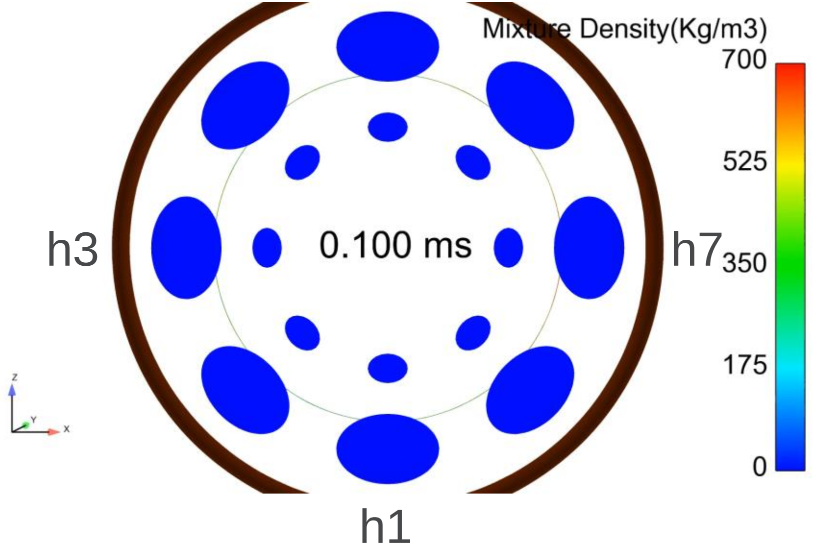


Spray G

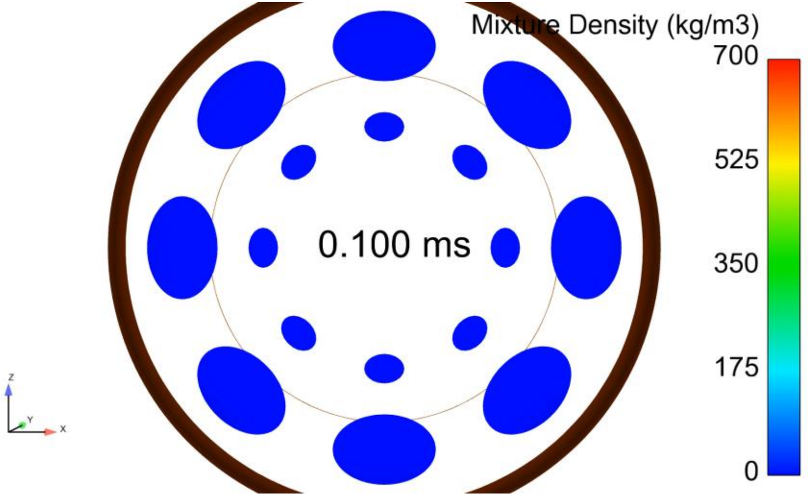


Spray G2

DENSITY (NOZZLE & CB EXIT)-UMASS HRMFOAM

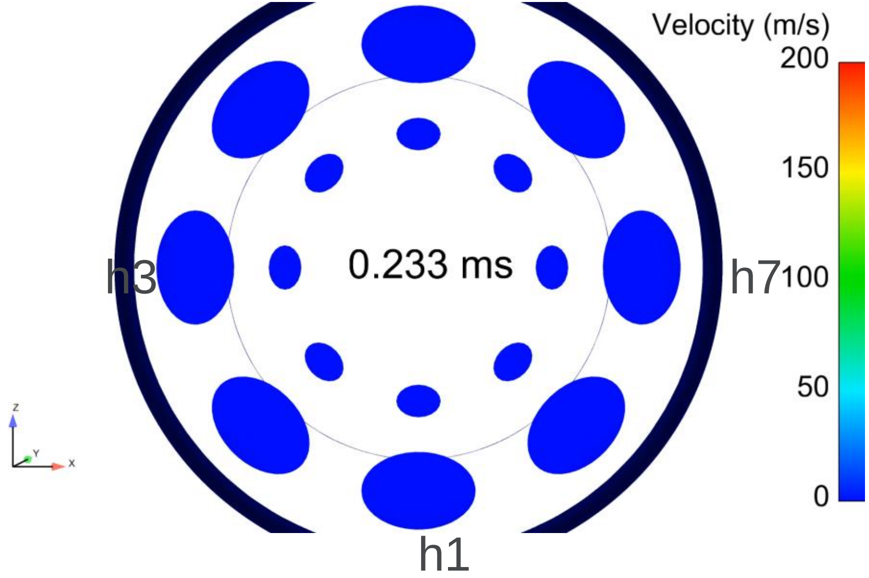


Spray G

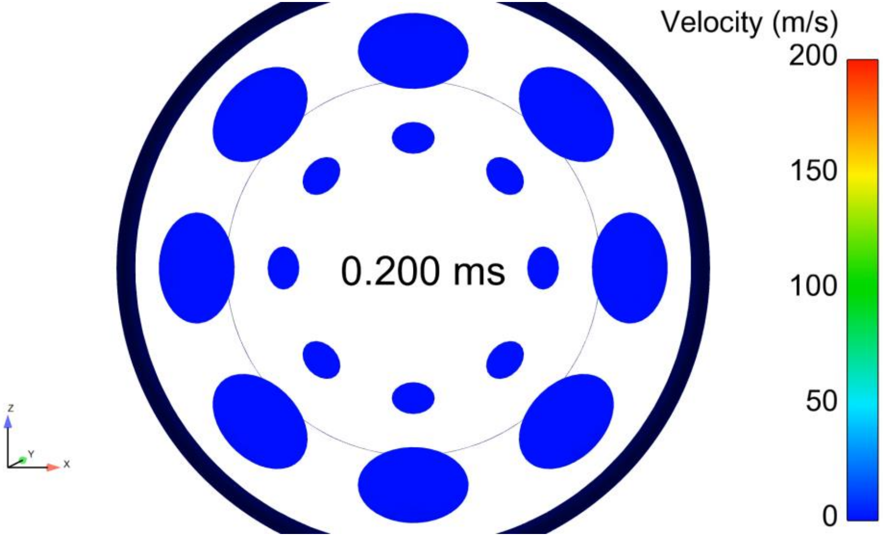


Spray G2

VELOCITY (NOZZLE & CB EXIT)-CMT CONVERGE

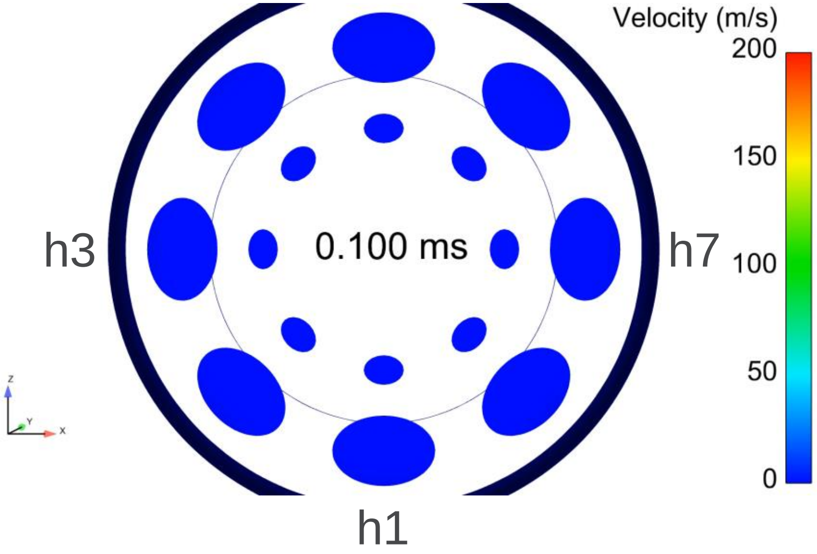


Spray G

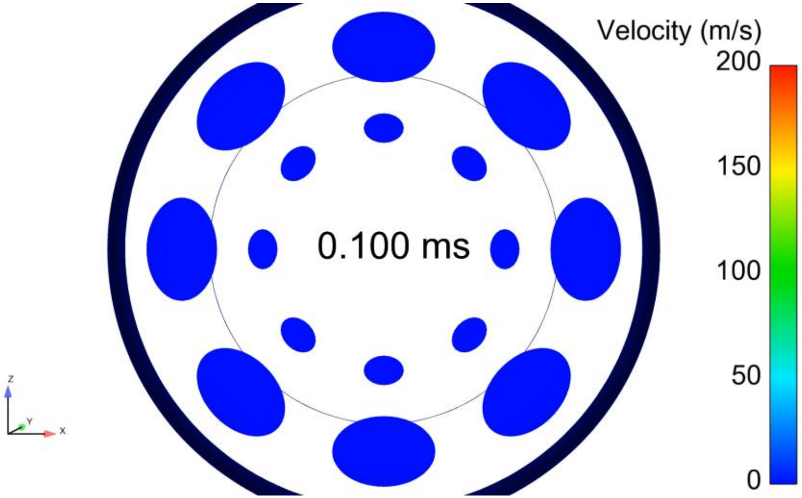


Spray G2

VELOCITY (NOZZLE & CB EXIT)-UMASS HRMFOAM

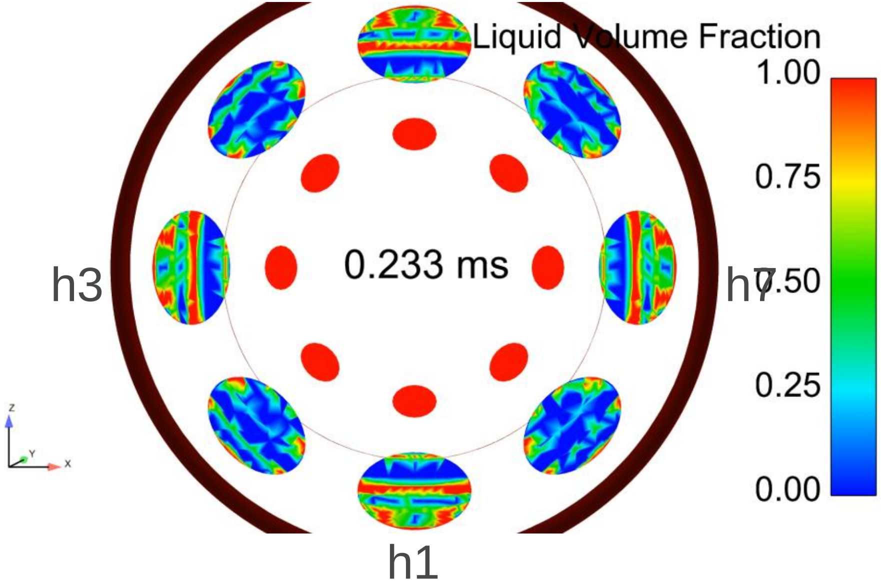


Spray G

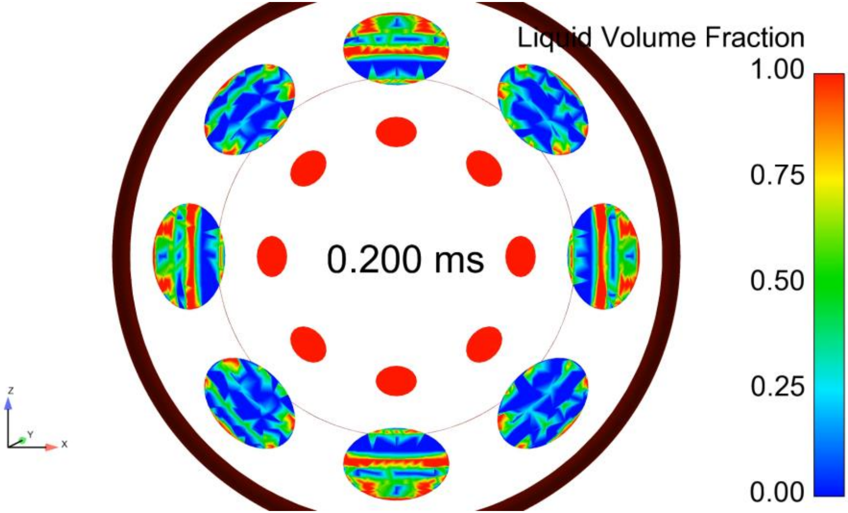


Spray G2

LIQUID VOLUME FRACTION (NOZZLE & CB EXIT)-CMT CONVERGE

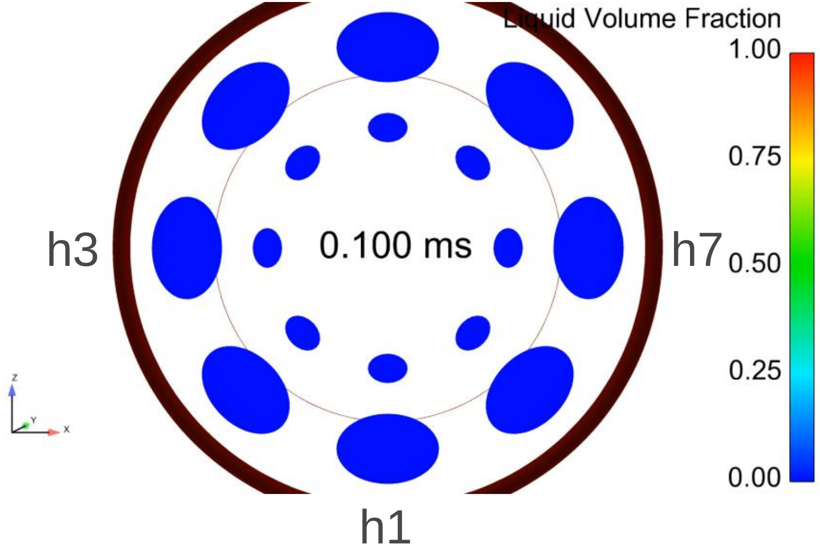


Spray G

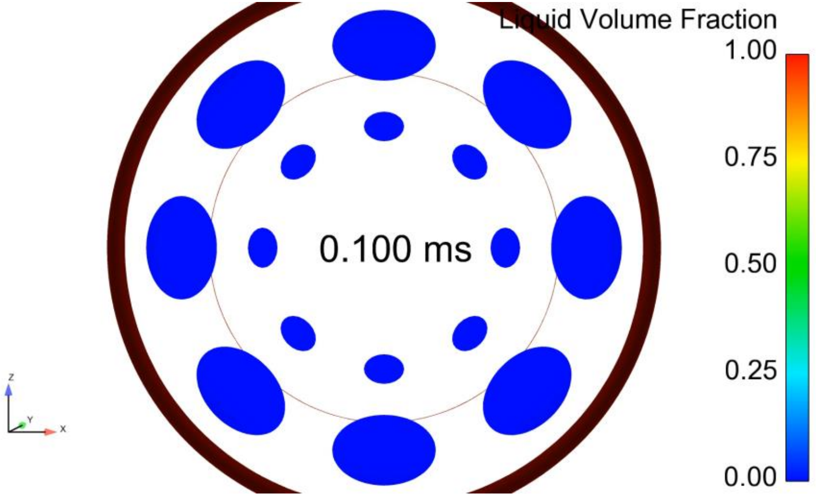


Spray G2

LIQUID VOLUME FRACTION (NOZZLE & CB EXIT)-UMASS HRMFOAM

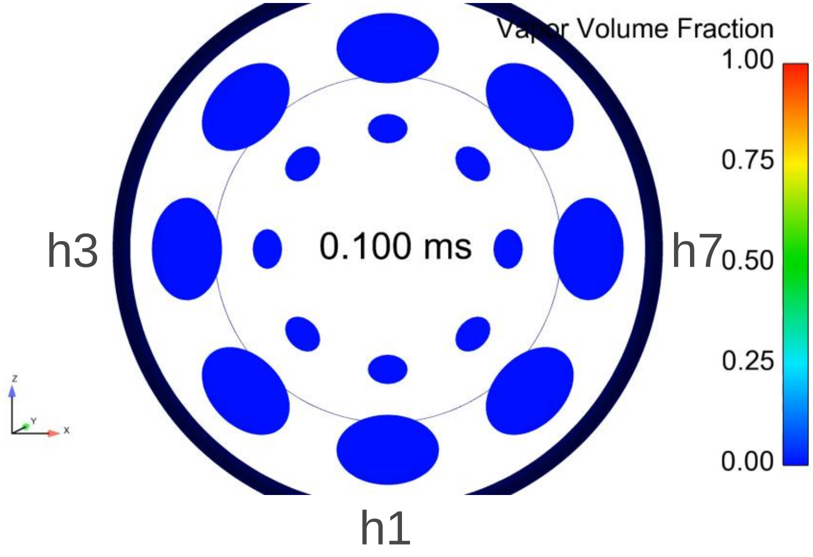


Spray G

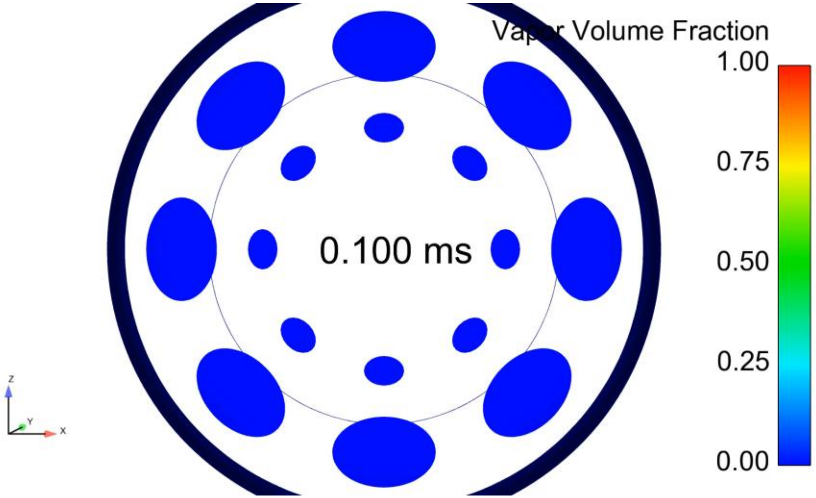


Spray G2

VAPOR VOLUME FRACTION (NOZZLE & CB EXIT)-UMASS HRMFOAM

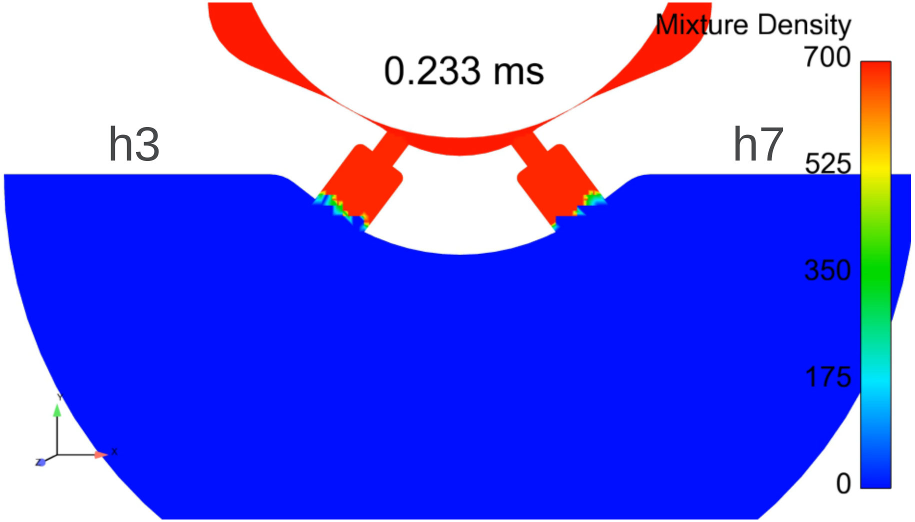


Spray G

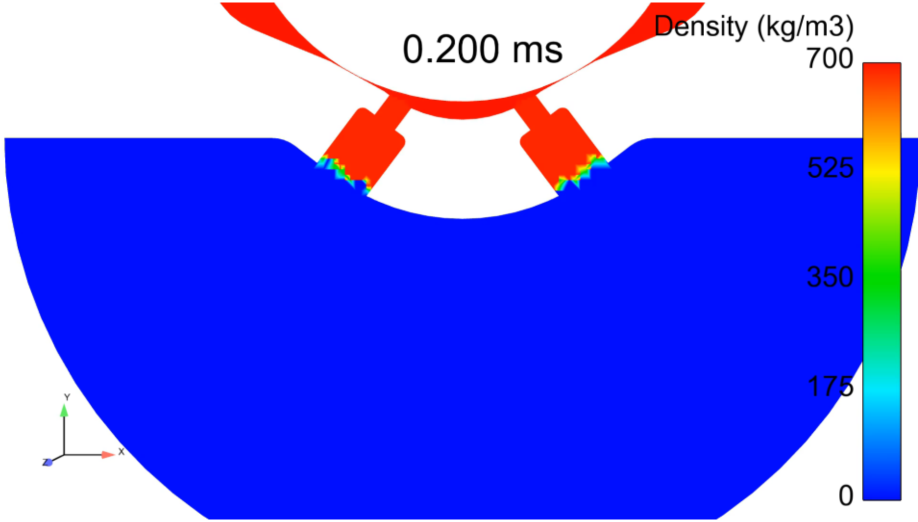


Spray G2

DENSITY (MID PLANE CLIP)-CMT CONVERGE

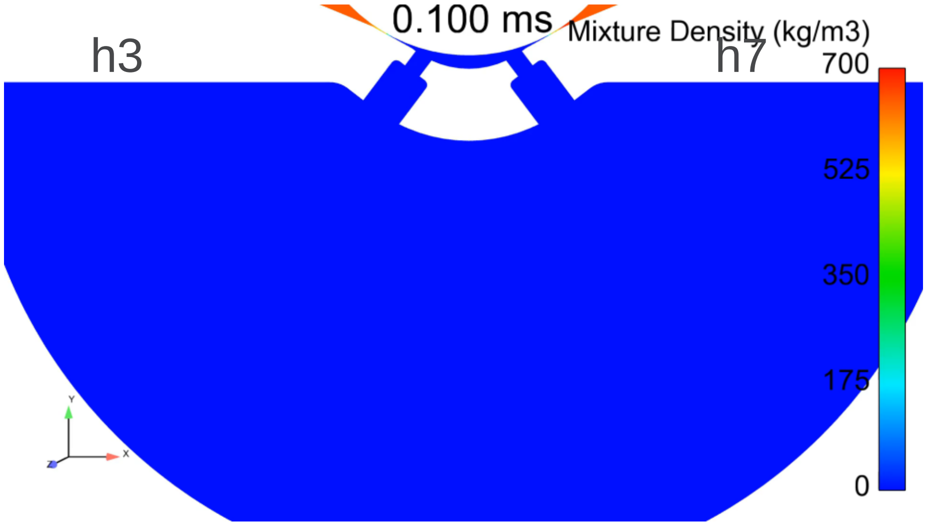


Spray G

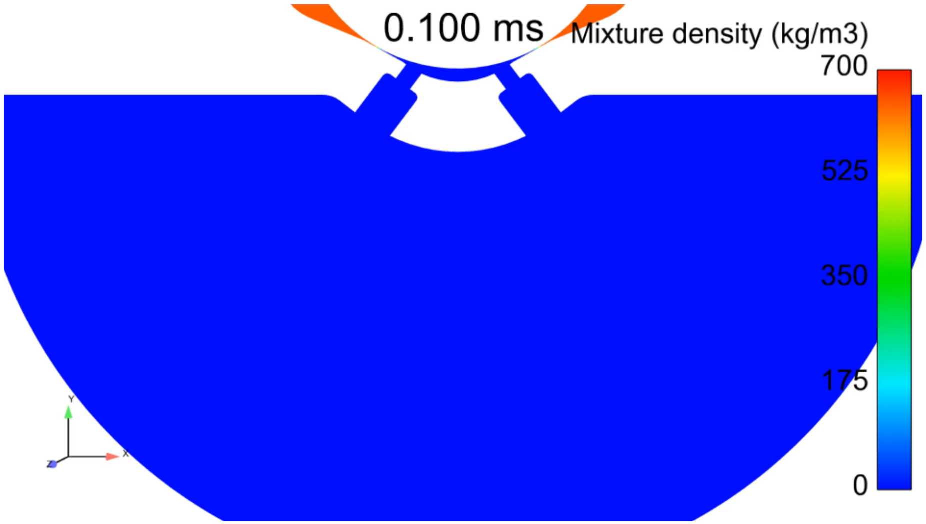


Spray G2

DENSITY (MID PLANE CLIP)-UMASS HRMFOAM

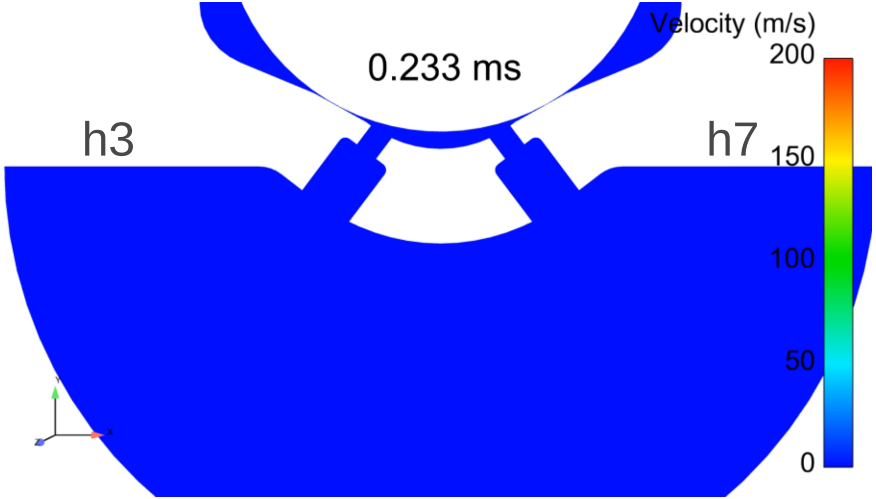


Spray G

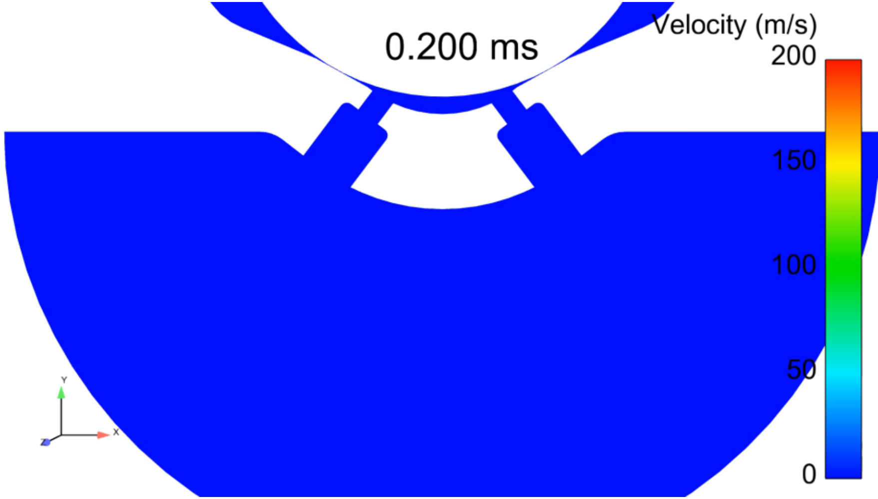


Spray G2

VELOCITY (MID PLANE CLIP)-CMT CONVERGE

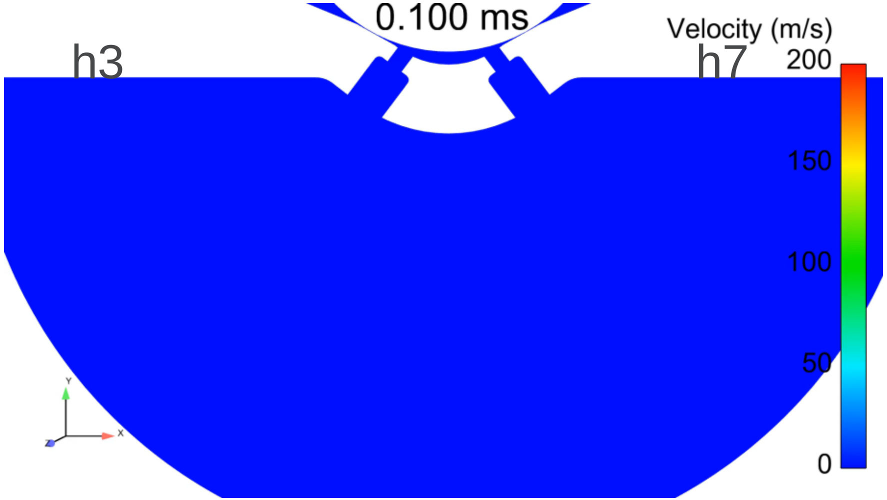


Spray G

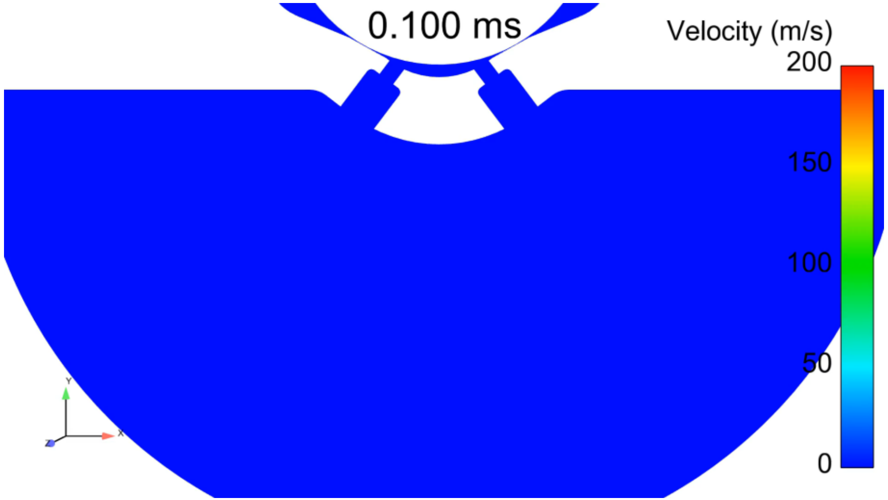


Spray G2

VELOCITY (MID PLANE CLIP)-UMASS HRMFOAM

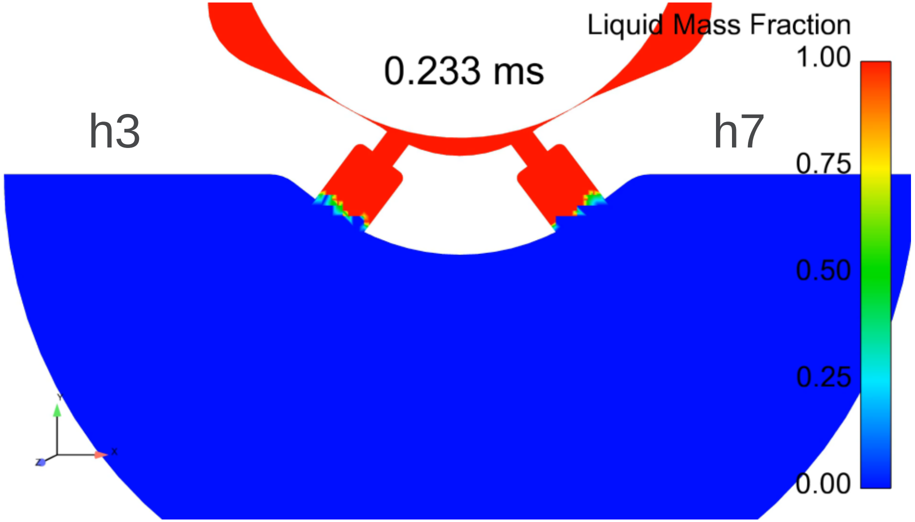


Spray G

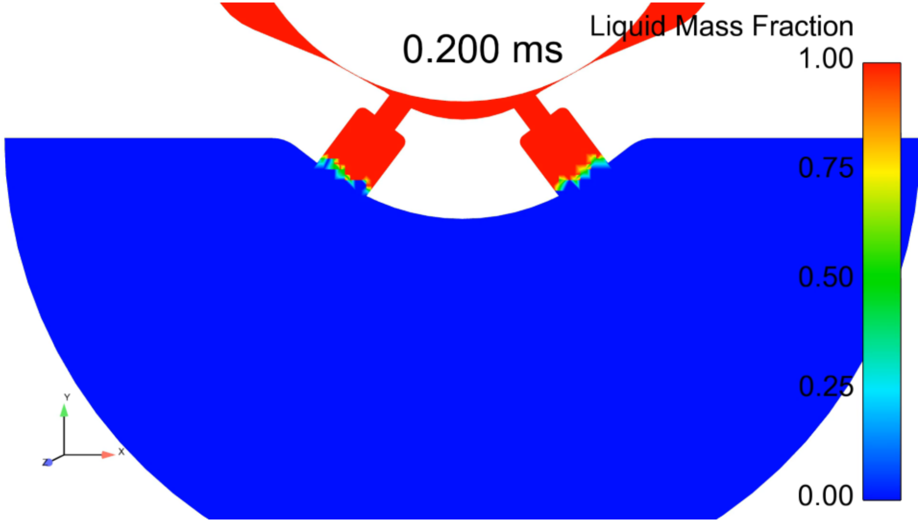


Spray G2

LIQUID MASS FRACTION (MID PLANE CLIP)-CMT CONVERGE

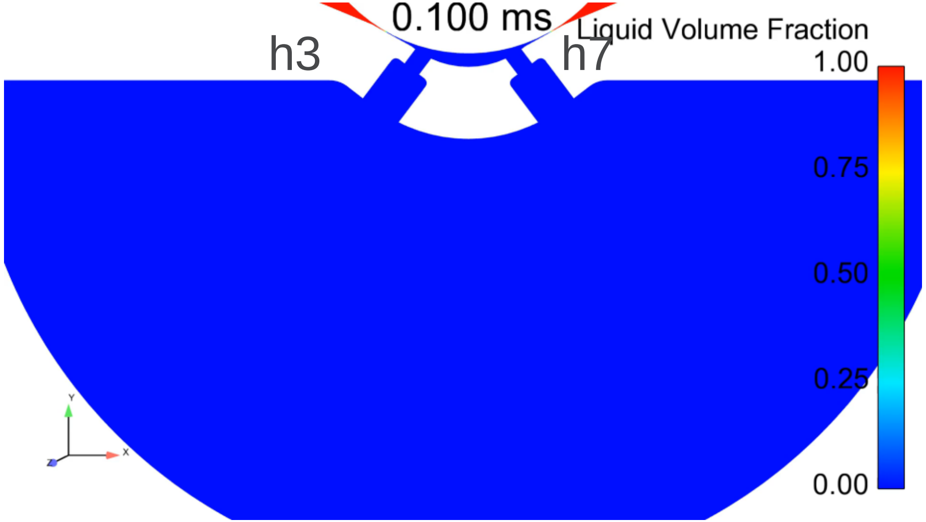


Spray G

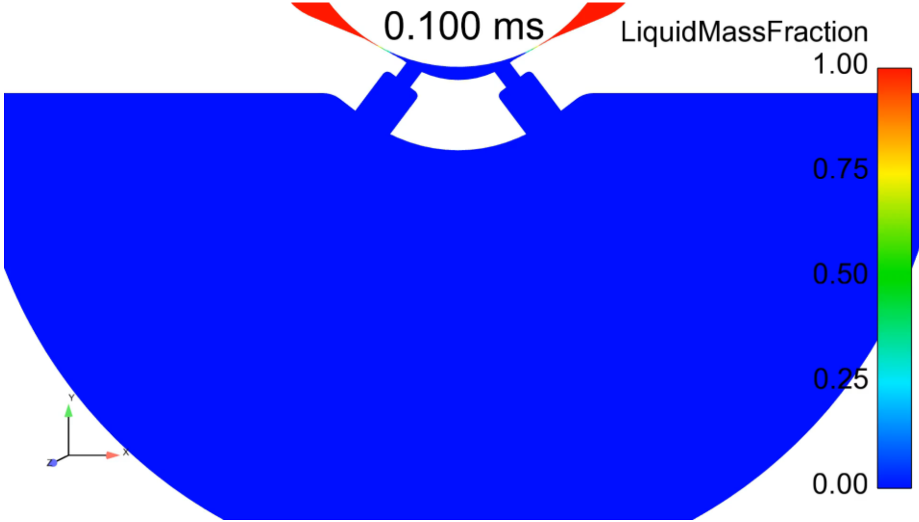


Spray G2

LIQUID MASS FRACTION (MID PLANE CLIP)-UMASS HRMFOAM

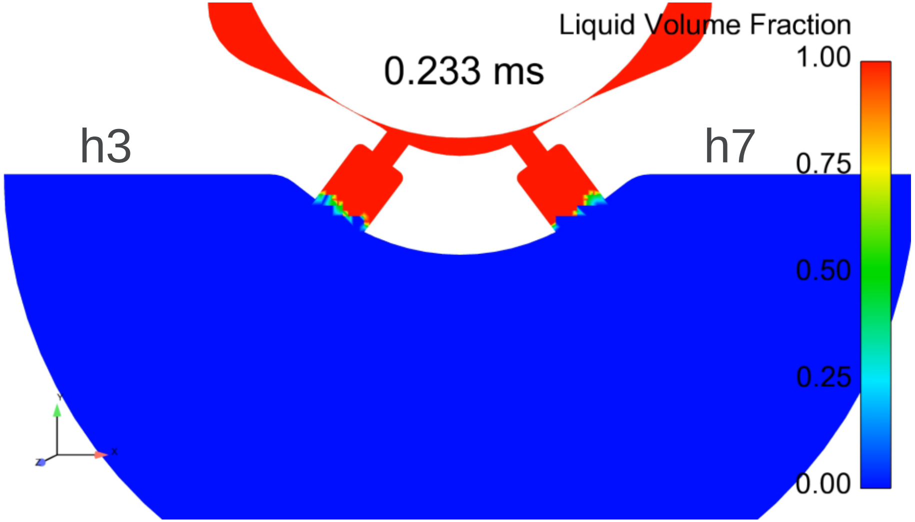


Spray G

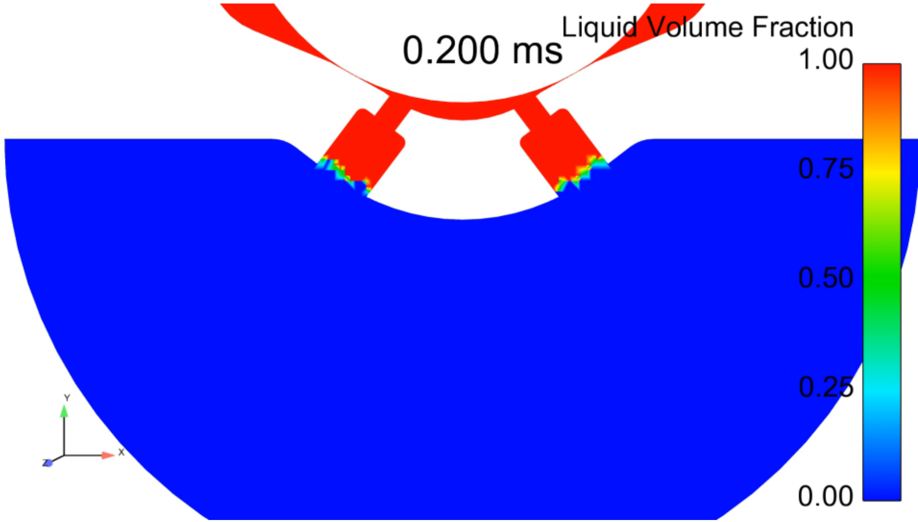


Spray G2

LIQUID VOLUME FRACTION (MID PLANE CLIP)-CMT CONVERGE

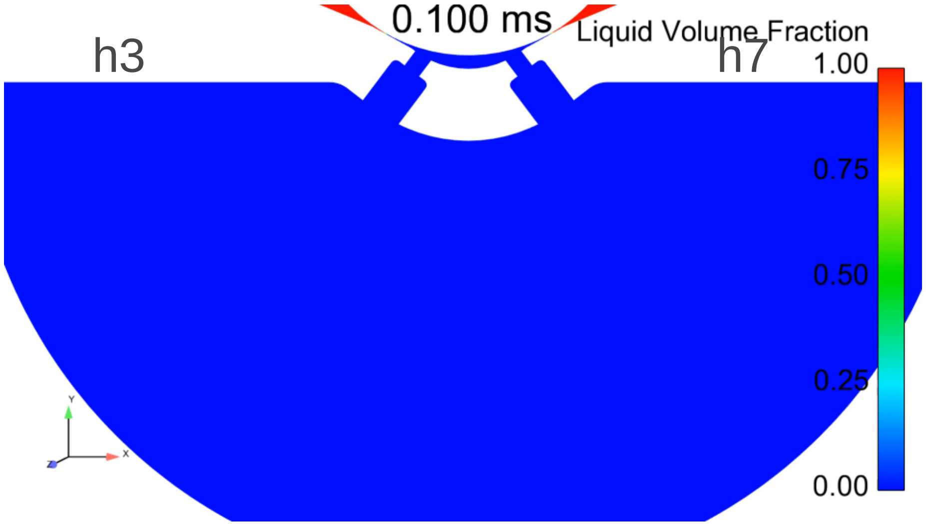


Spray G

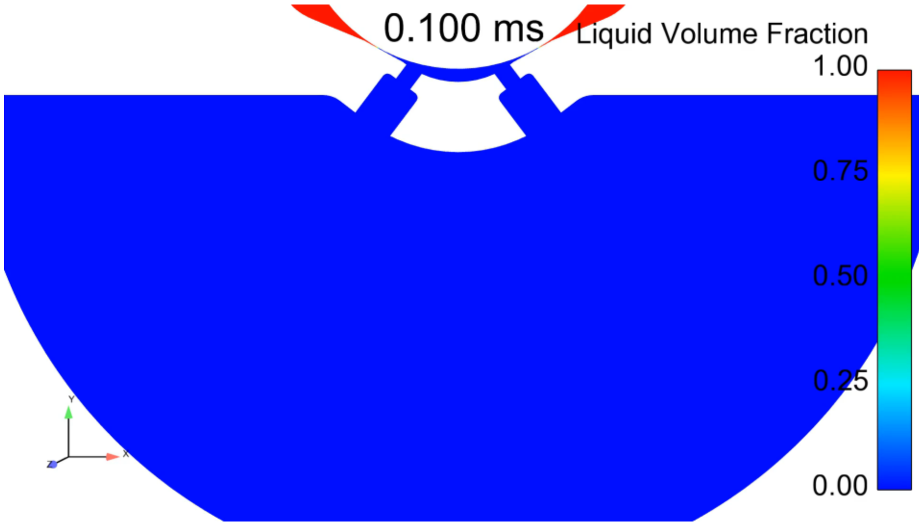


Spray G2

LIQUID VOLUME FRACTION (MID PLANE CLIP)-UMASS HRMFOAM

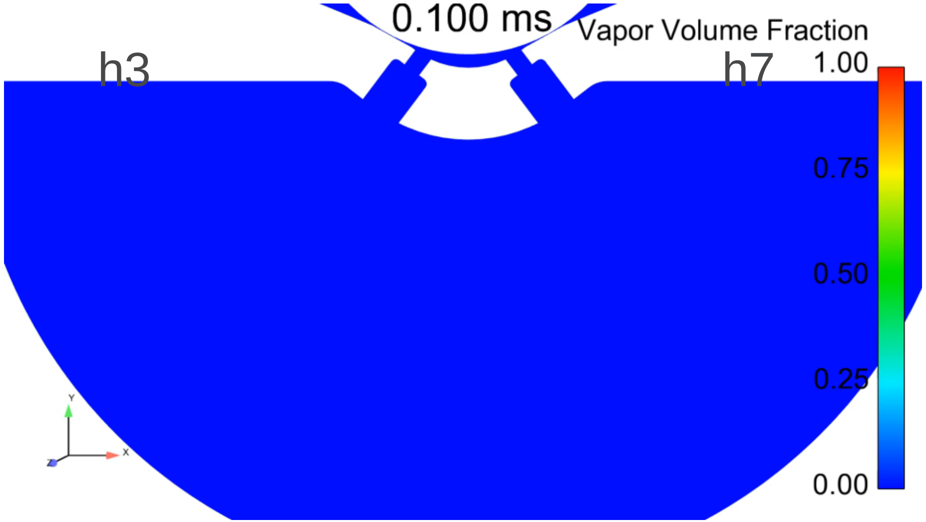


Spray G

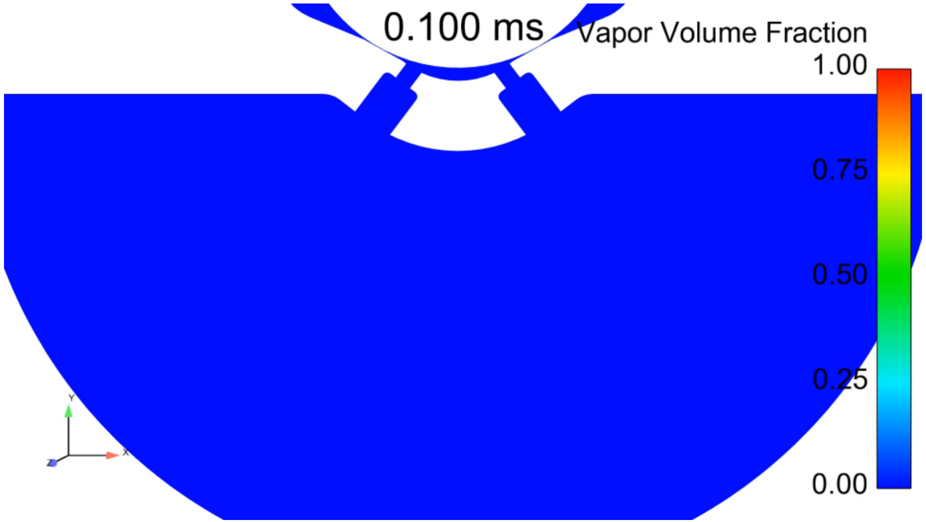


Spray G2

VAPOR VOLUME FRACTION (MID PLANE CLIP)-UMASS HRMFOAM

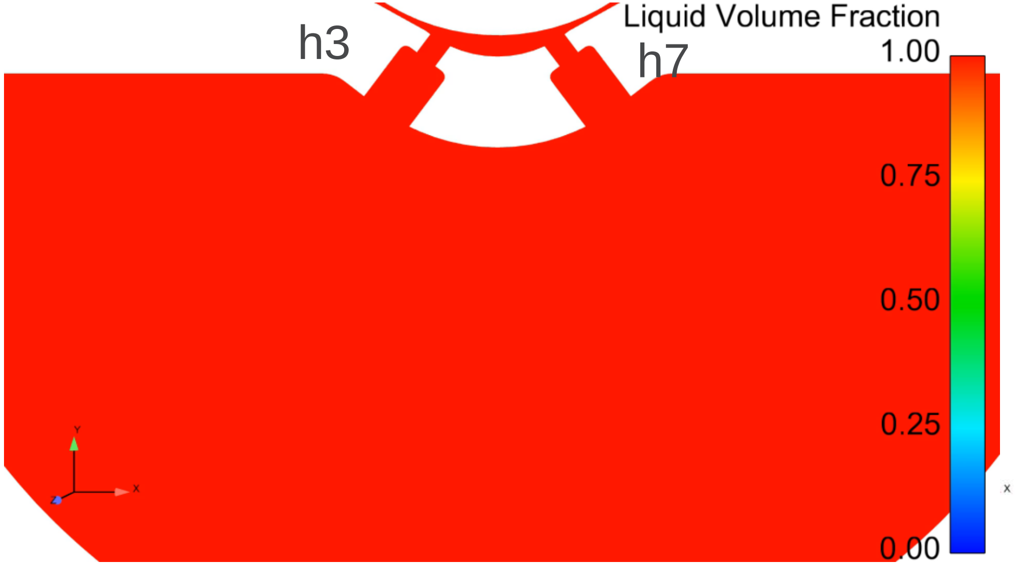


Spray G

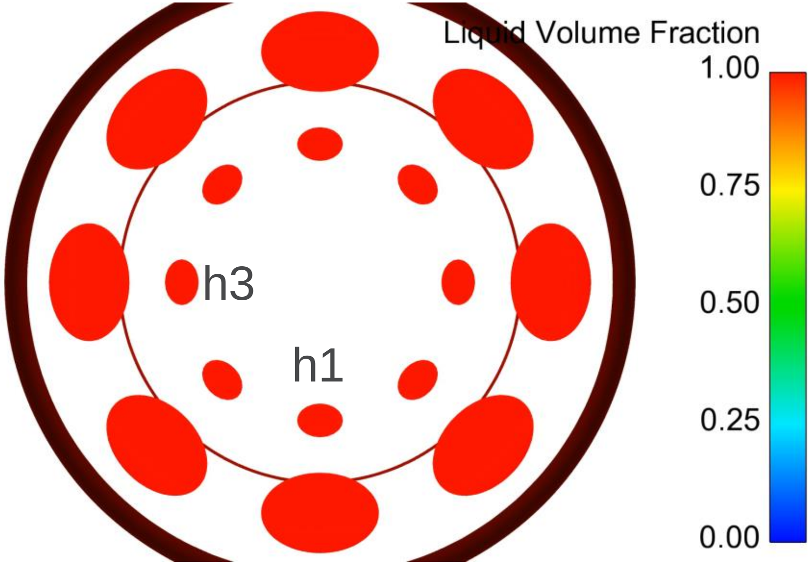


Spray G2

LIQUID VOLUME FRACTION (SPRAY G)-CHALMERS



Mid plane view



CB and Nozzle exit cut plane view

NEXT STEPS

- Get a Generation 3 file from ANL
    - “Stanford Bunnied”: a verb
    - Separated into separate parts

- Start paying a lot more attention to hole numbering convention

- G3 and other conditions

EXPERIMENT AND MODELING NEEDS

- Broken:
  - Eulerian liquid/gas exchange rates are broken--At the maximum bound of instantaneous transfer
  - Only ANL is contributing experimental data
  - HRM in different codes gives VERY different results

- Requisite modeling work:
  - Finite-rate momentum and energy exchange

- Requisite experimental work:
  - Geometry that is CFD-ready
  - Temperature measurements
  - Individual hole mass flow rates
  - Momentum rate measurements