CFD Simulation of Injection Processes in OpenFOAM: Under-expanded Jets and Lagrangian Sprays

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a - Università degli Studi dell' Aquila

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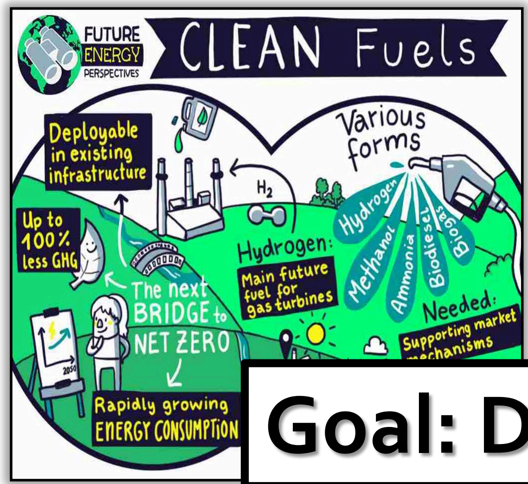
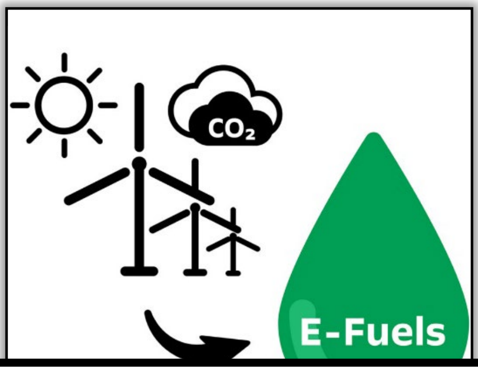
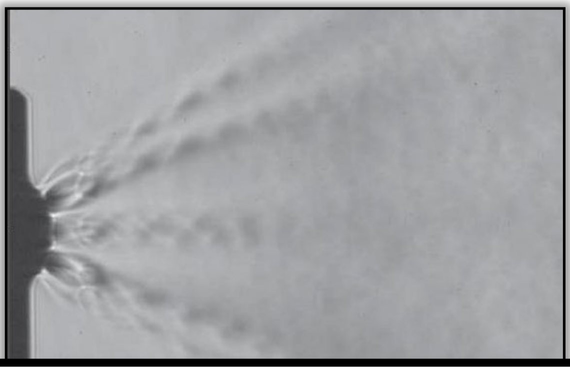
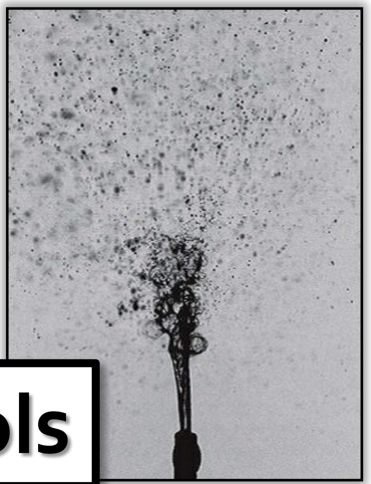
c - Aramco Americas: Aramco Research Center – Detroit

Motivations: Sprays & Innovative Fuels









Goal: Development of ad-hoc simulation tools

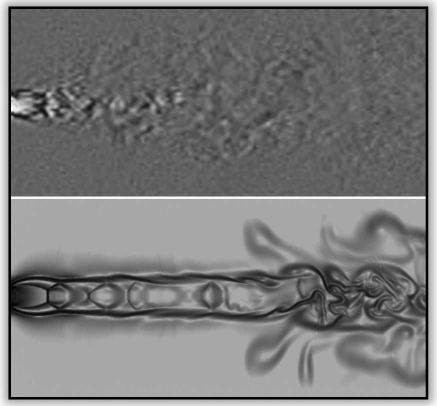
Poursadegh, F., Lacey, J.S., Brear, M.J., Gordon, R.L., Petersen, P., Lakey, C., Butcher, B., Ryan, S. and Kramer, U. On the phase and structural variability of directly injected propane at spark ignition engine conditions.

- ✓ H_2, MeOH, C_3H_8, NH_3, e-fuels, ..
- ✓ Sprays: different physical behavior
- ✓ Under-expanded jets

- ✓ Often injected in critical conditions or as gases
- ✓ Phase transition ruled by flash boiling

Challenges on Injection Processes CFD Simulation

Near Nozzle: Eulerian Approach



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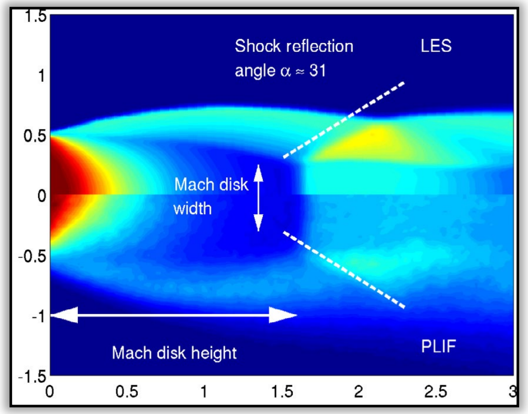
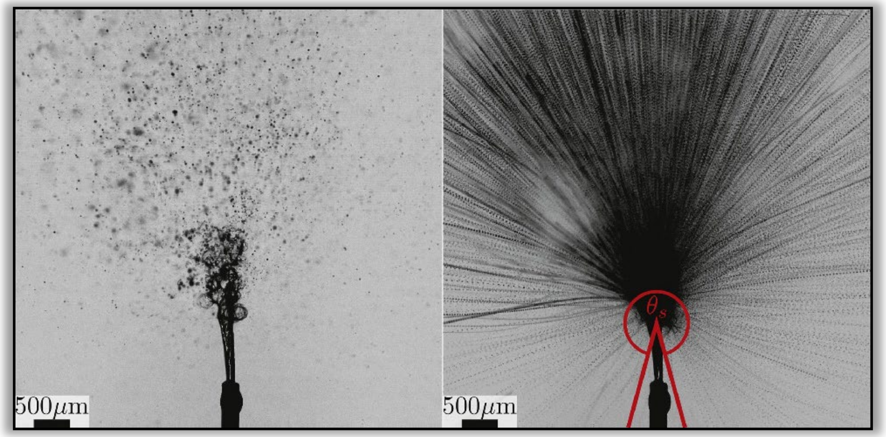


Yu J,Vuorinen V,Kaario O,Sarjovaara T,Larmi M. Characteristics of High Pressure Jets for Direct Injection Gas Engine

- ✓Strong compressibility effects and handle trans-critical fluids
- ✓Under-expanded jets
- ✓Limit numerical dissipation
- ✓Development of low order methods

Whole Spray: Eulerian-Lagrangian Approach

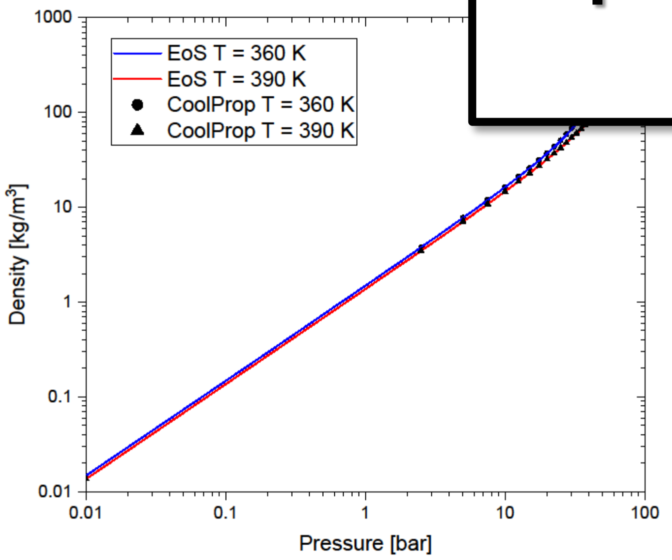


- ✓Flash boiling onset
- ✓Extreme tuning of:
  - Breakup model constants
  - Spray angles
- ✓Droplets sizing inaccurate
- ✓Difficulties in catching spray collapse

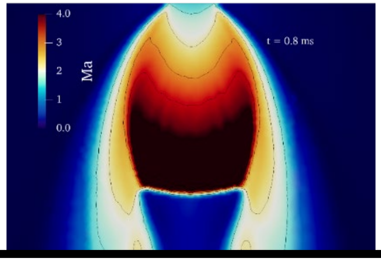
Simulation of Near-Nozzle Multi-phase Flow

Fluid Properties

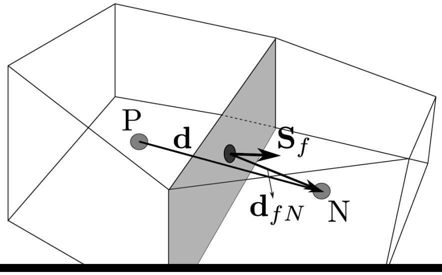
- ✓ **UniPG Real Fluid Pkg**
- ✓ Peng Robison EOS
- ✓ Cp, Cv: Modified Janaf
- ✓ Dyn Visc: Chung



Adequate Numerics

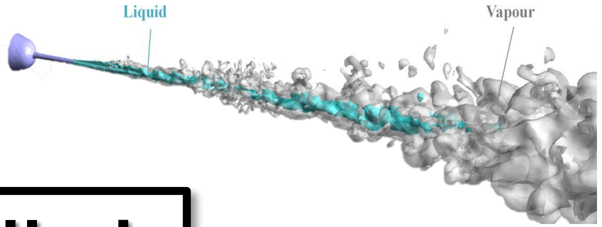


...nio, F., Montanaro, A., ...ca, L., Ranieri, S. and De ...A.. *Effects of ...modynamic Conditions and ...e Geometry in Gaseous Direct Injection Process for ...nced Propulsion Systems*



- ✓ Under-expanded jets
- ✓ **Low numerical dissipation!**
- ✓ Flux splitting: Kurganov Noelle Petrova
- ✓ Crank Nicholson 2°temporal int.
- ✓ MUSCL scheme for reconstruction

Phase Transition Model



...dal-Roncero, A., Rodriguez, C., Gavaises, M. ...o. High pressure/high temperature ...tions of dodecane injection to nitrogen: ...N Spray-A

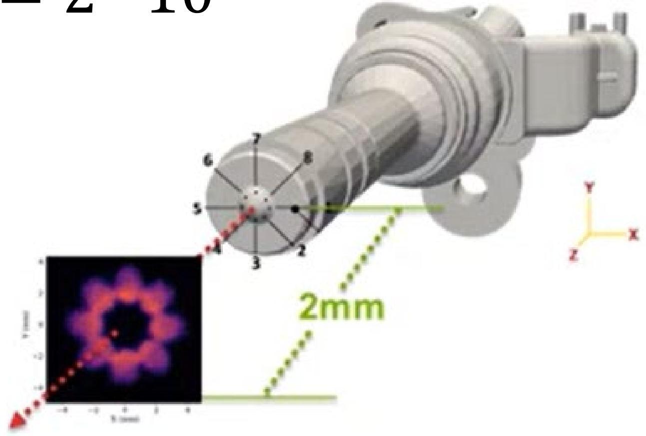
Thermal non-equilibrium

Homogeneous Relaxation Model

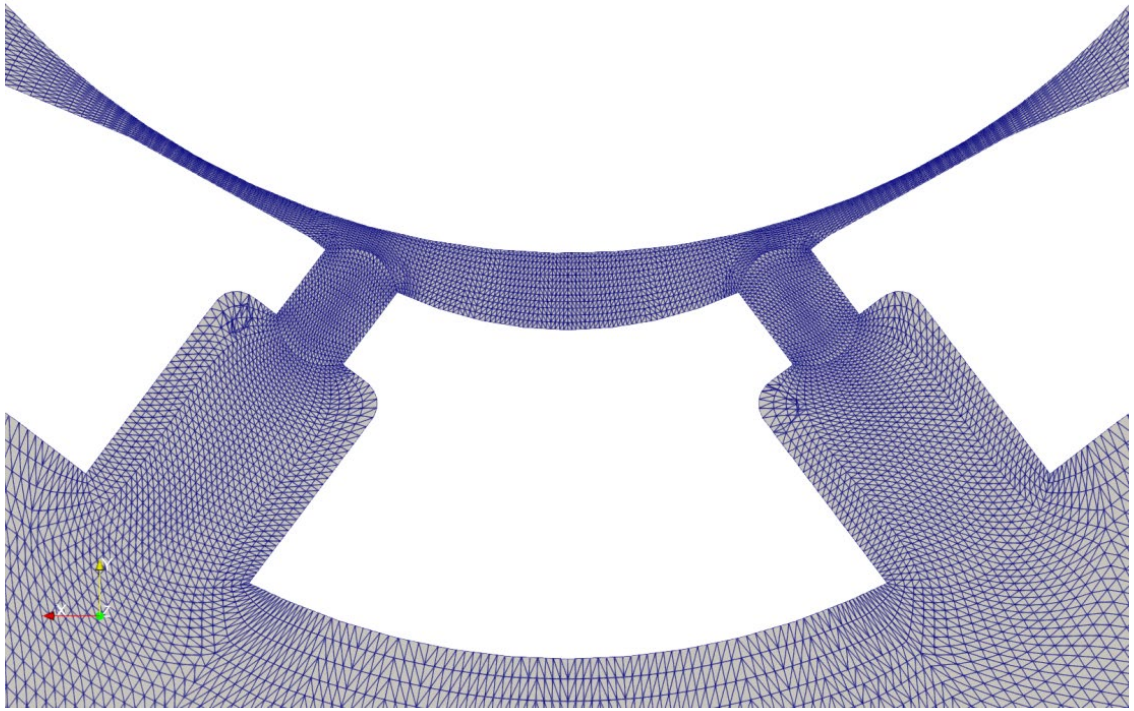
OpenFOAM developed solver was called
realCentralHRMFoam

Validation on G2 Injection (flashing case)

- ✓ECN Spray G condition G2:
  - ✓Fuel temp: 363 K
  - ✓Ambient temp: 333 K
  - ✓Ambient Pressure 0.5 bar
- ✓Argonne X-Ray data: density maps
- ✓Fuel: IC_8H_{18}
- ✓Turbulence: LES Dynamic kEqn
- ✓HRM: $\vartheta_0 = 2 \cdot 10^{-10}$



- ✓Mesh: GridPro provided @ ECN website, Structured up to 5 μm (refineMesh - 9 M)
- ✓Injector + 9 mm cap
- ✓Fixed Needle: 50 mm



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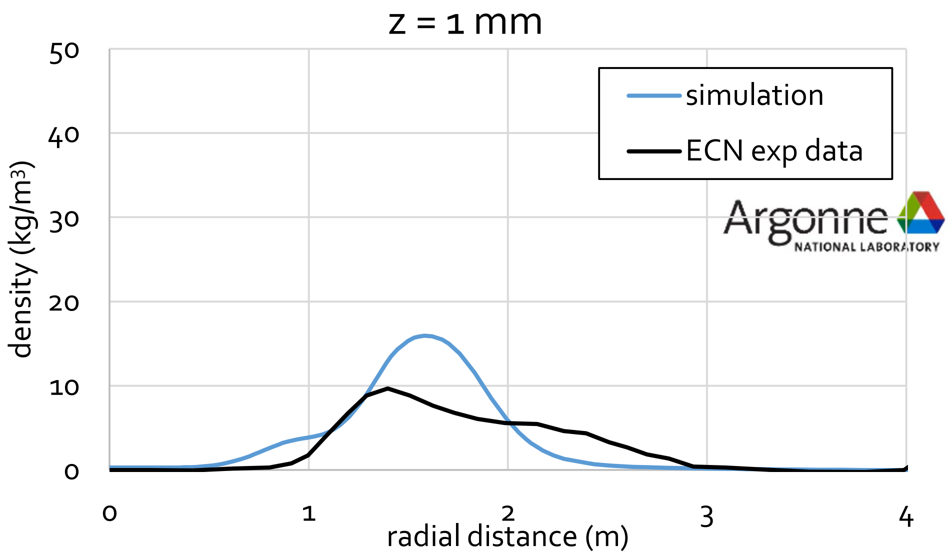

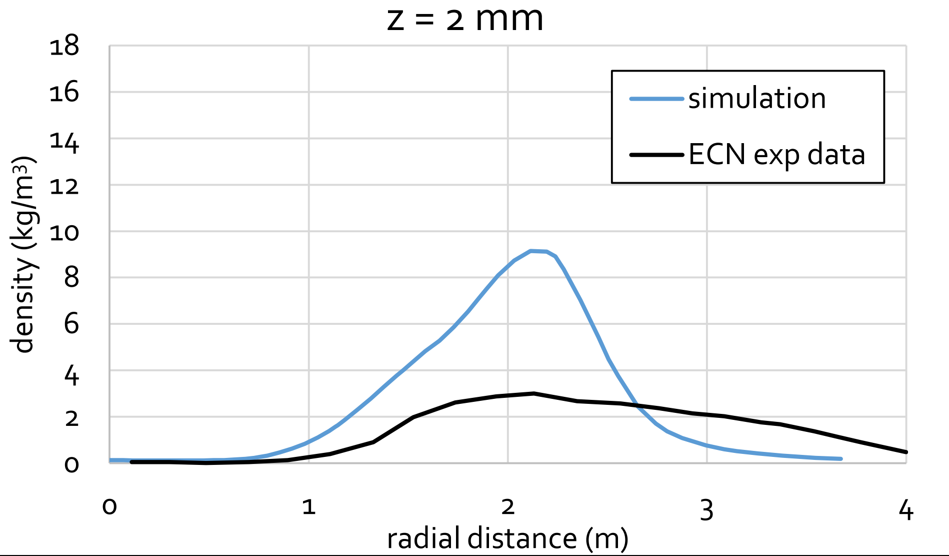

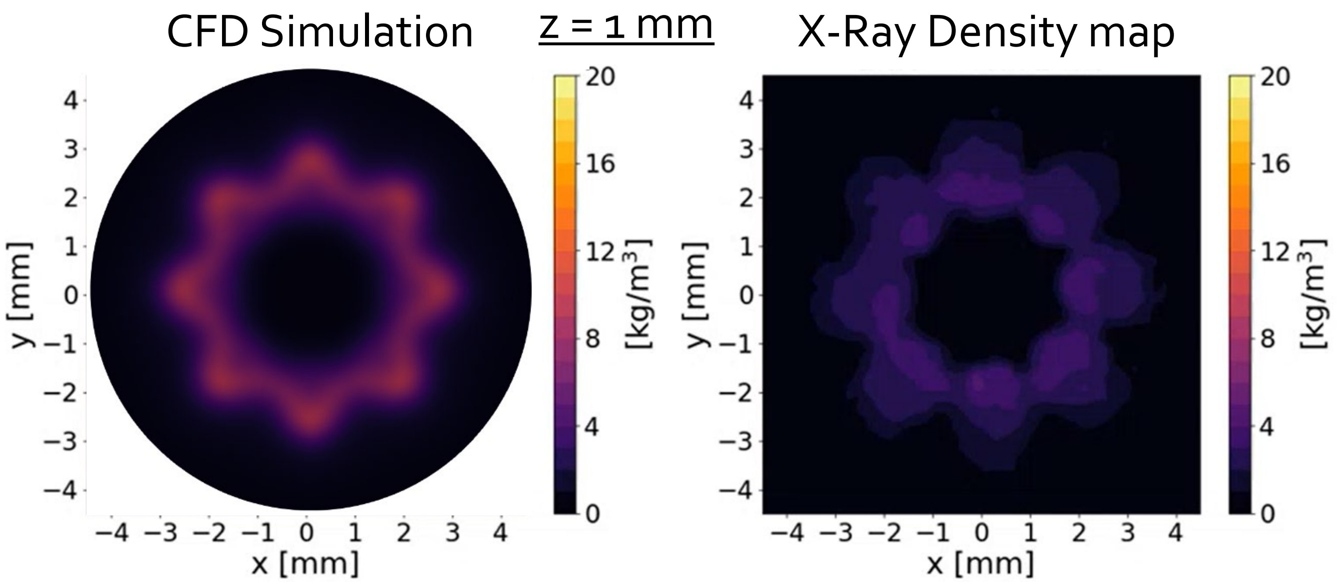

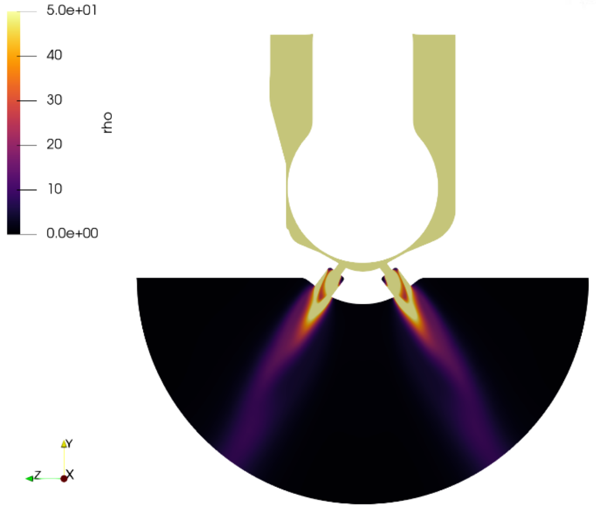

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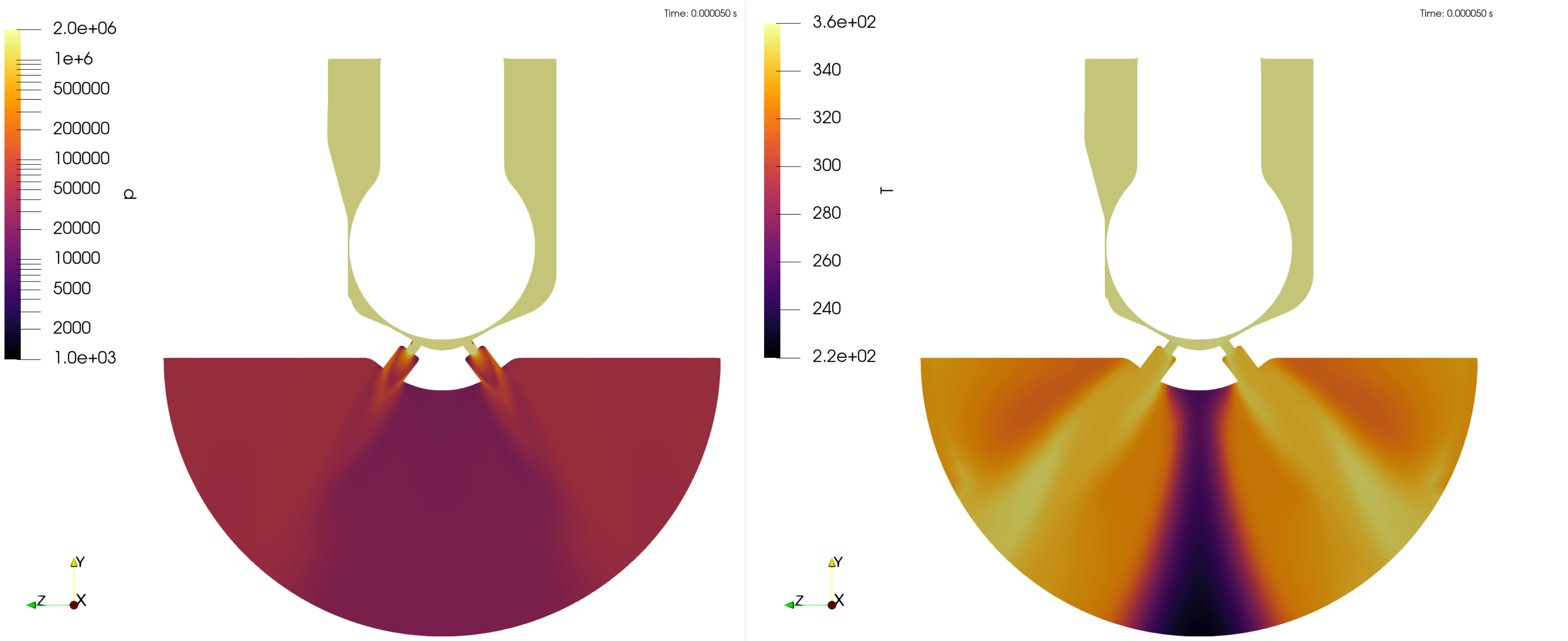
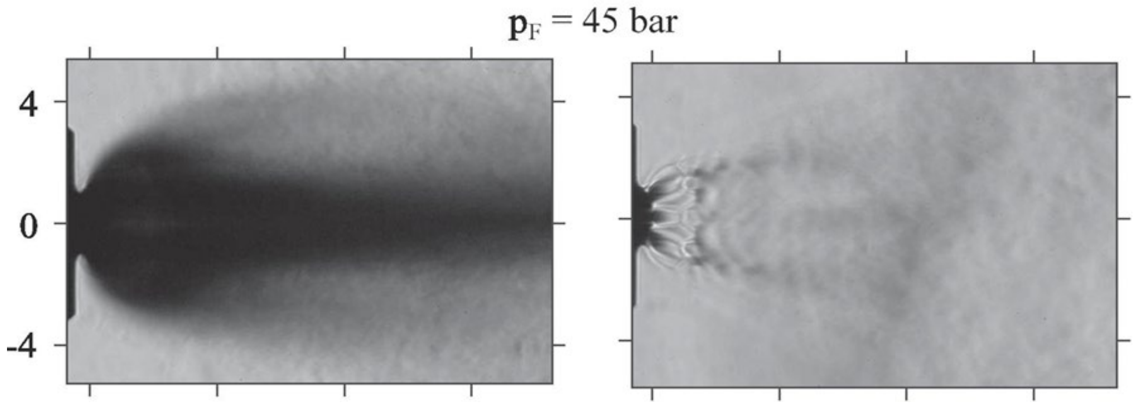


- ✓Pressure field shows a slight internal depressurization
- ✓Temperature field also shows a strong decrease in the internal region among jets

Case Study: Spray G - C3H8 Injection

- ✓Validation: Schlieren images of Poursadegh et al.
- ✓Fuel: C3H8
- ✓Turbulence: LES Dynamic kEqn
- ✓HRM: $\vartheta_0 = 3.84 \cdot 10^{-8}$



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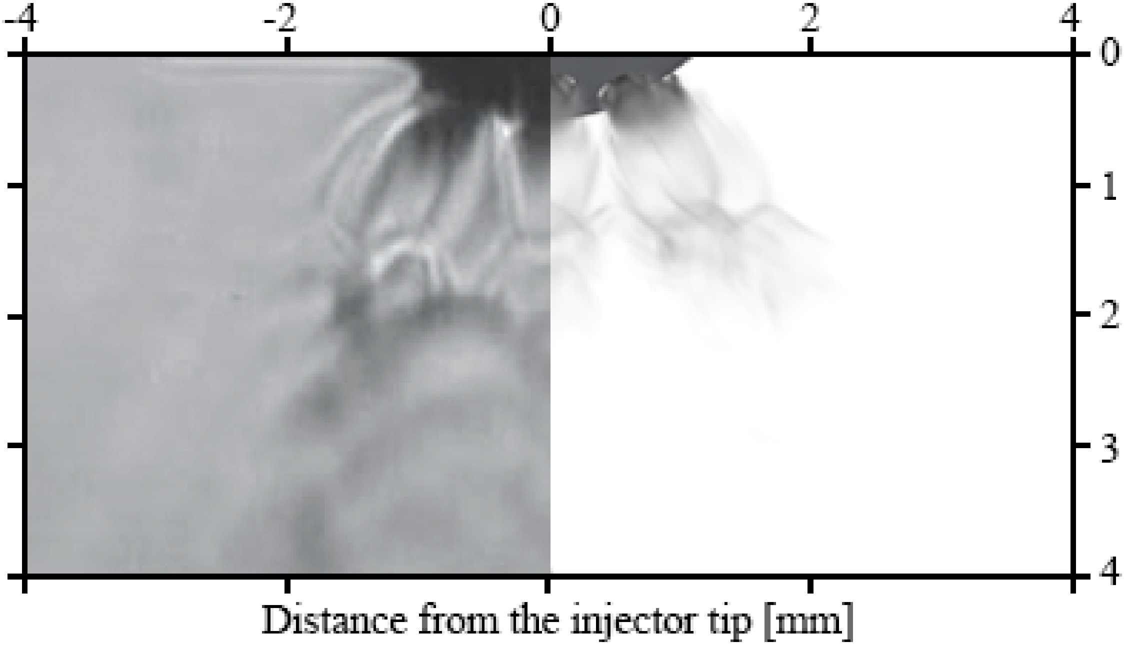
- ✓Mesh: GridPro provided @ ECN website, Structured
  - Base grid: up to 10 μm (1.5 M)
  - Fine grid: up to 5 μm (refineMesh - 9 M)
- ✓Injector + 9 mm cap
- ✓Fixed Needle: 50 mm

	Sub Critical	Super Critical
Inj Press. [bar]	45	
Ambient Press. [bar]	0.5	
Amb. Temp. [K]	390	
Fuel Temp. [K]	360	390

Comparison with Schlieren Images

Super-Critical Injection

Sx: Exp. / Dx: CFD - $log|\nabla\rho|$



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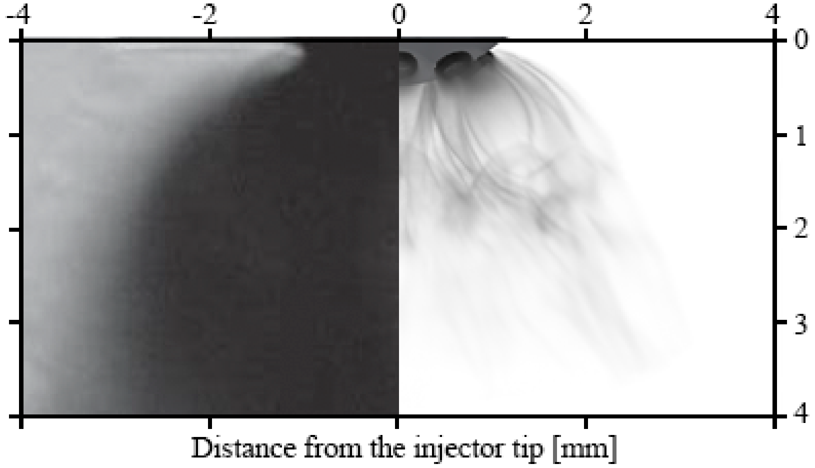
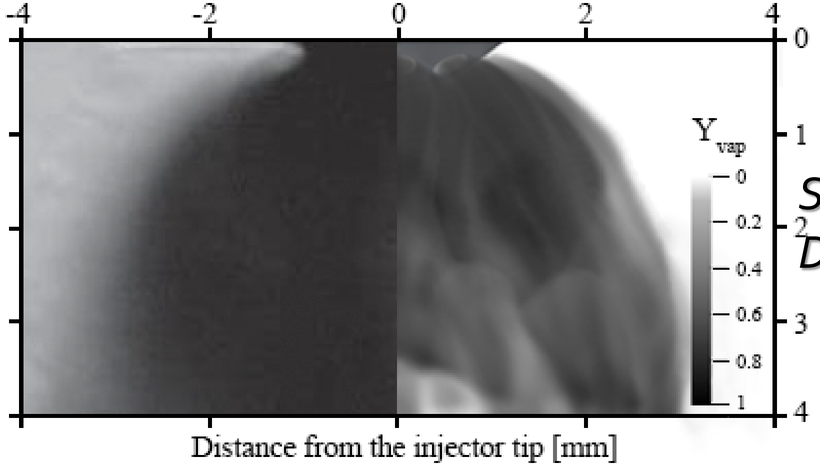
Sub-Critical Injection



Sx: Exp.
Dx: CFD - $log|\nabla\rho|$

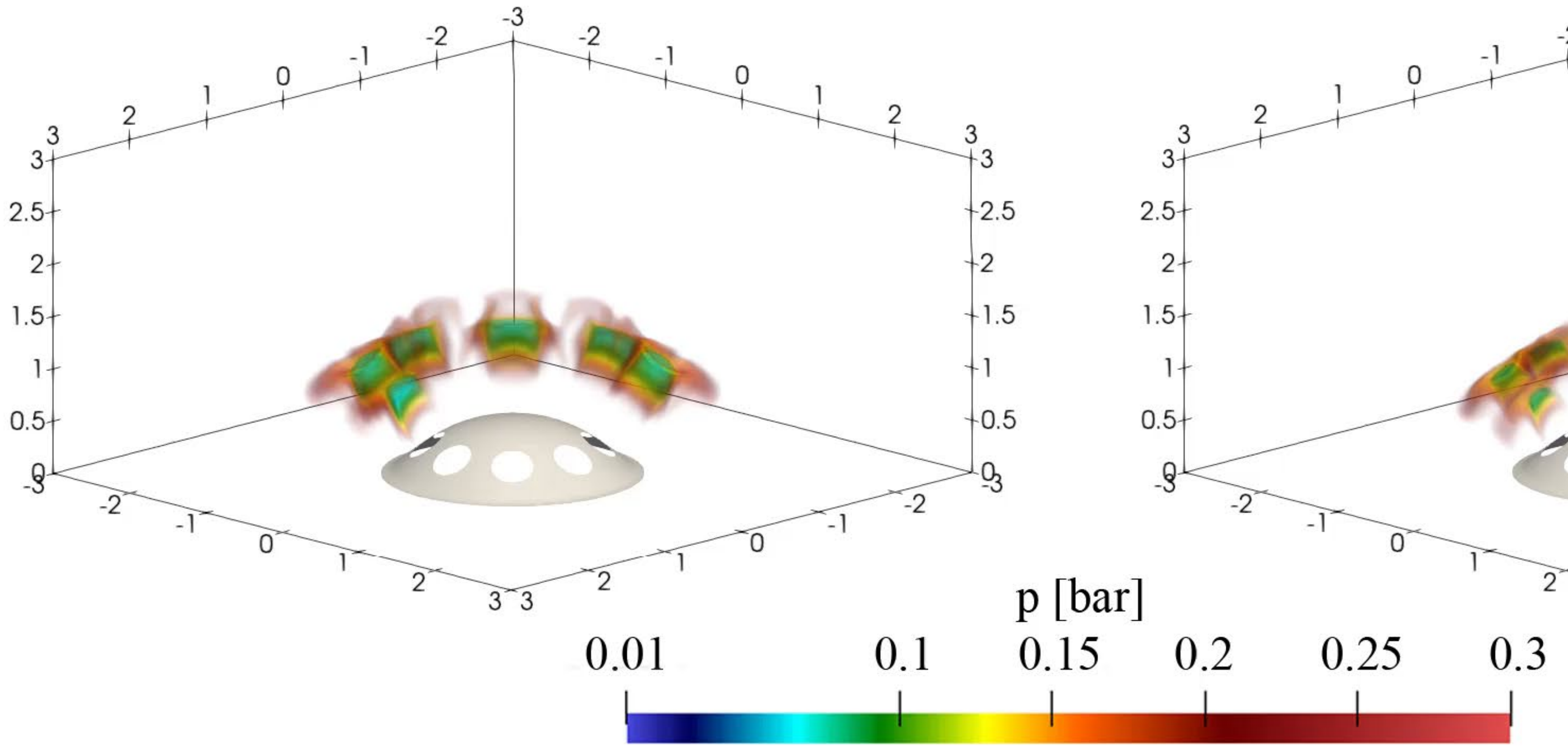


Sx: Exp.
Dx: CFD - Y_{vap}

Temporal Evolution

Super-Critical Injection

Sub-Critical Injection



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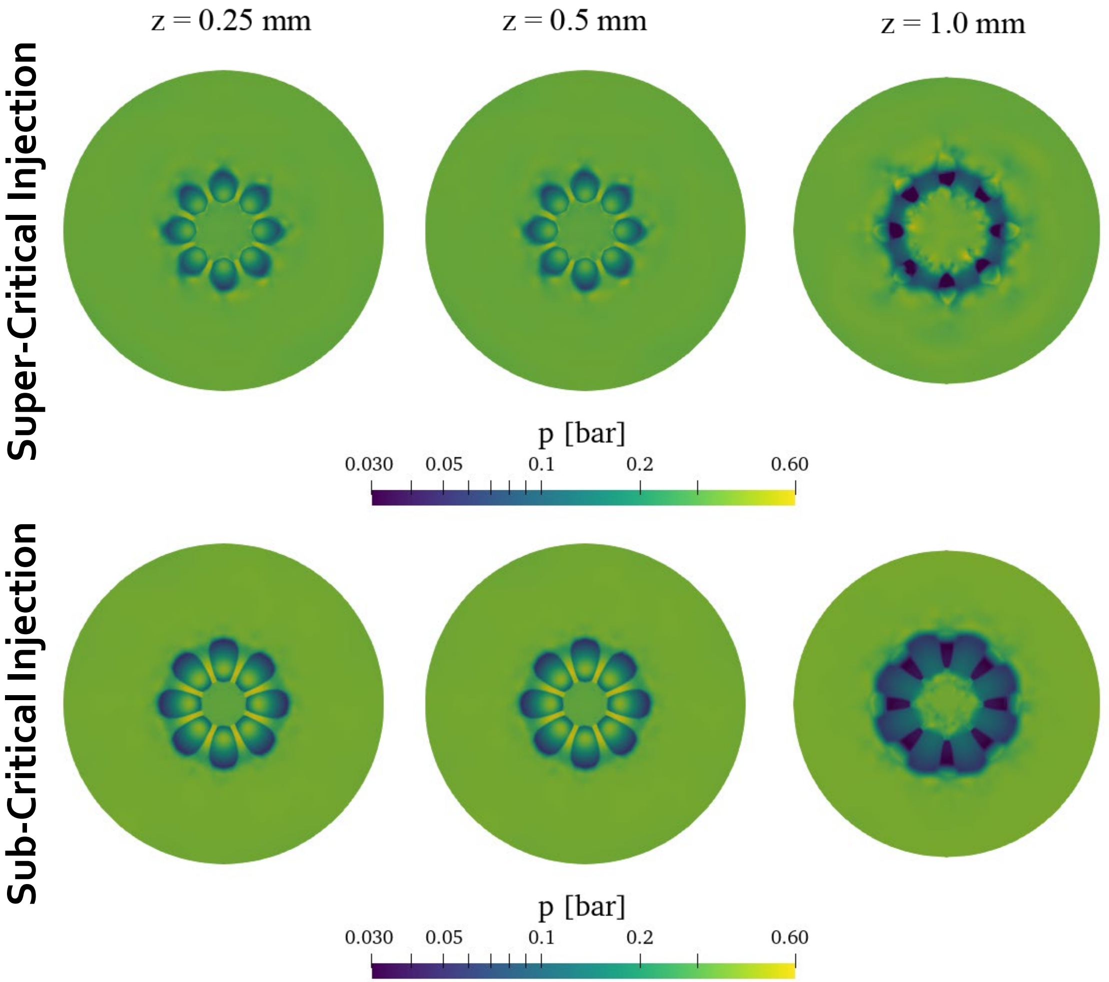
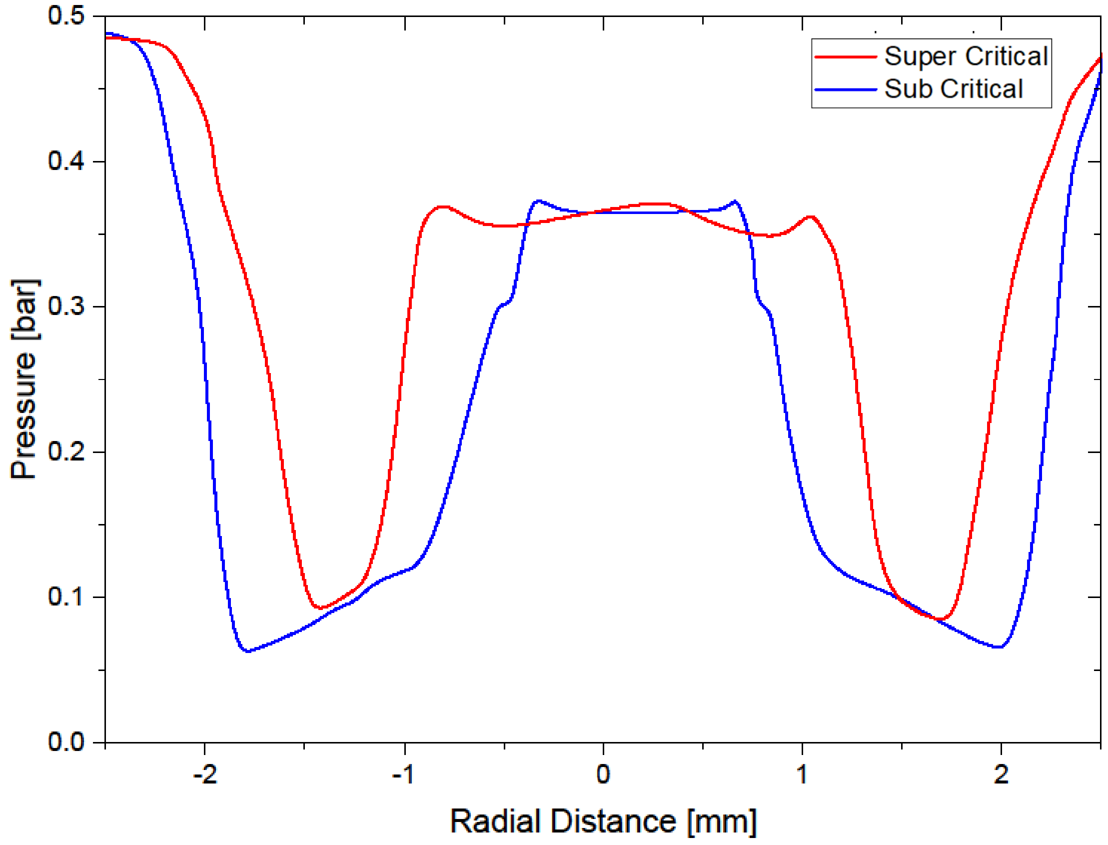
Pressure Field: Axial Cross Sections





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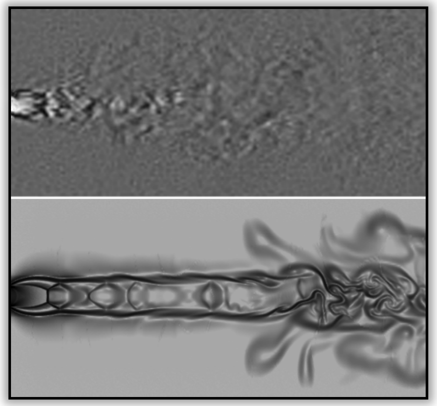
Challenges on Injection Processes CFD Simulation

Near Nozzle: Eulerian Approach



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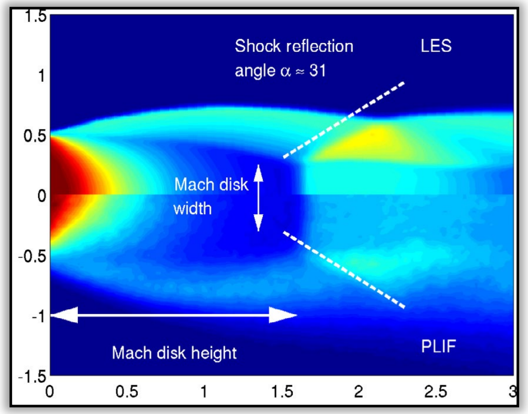

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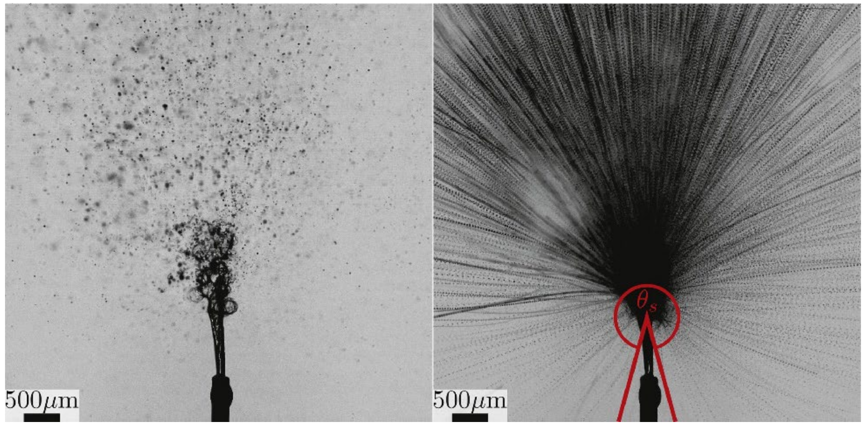
Whole Spray: Eulerian-Lagrangian Approach

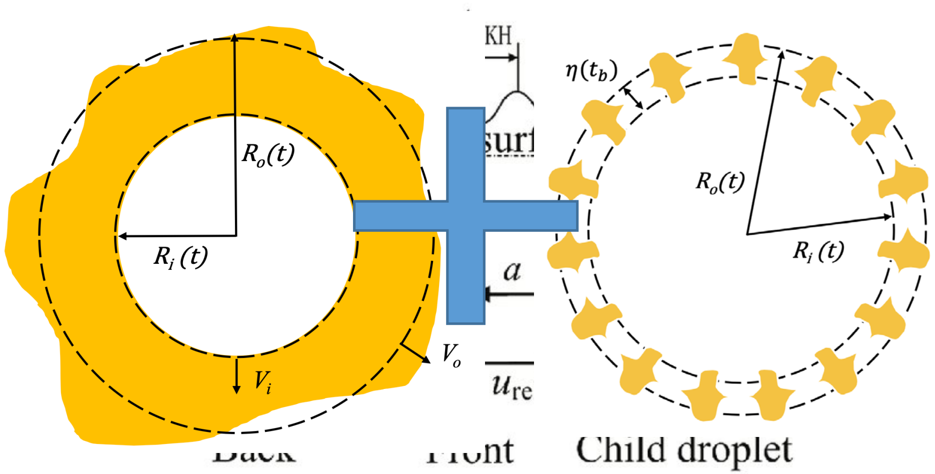


Key Models:

- ✓Phase change: Adachi/Price
- ✓Breakup: …

  Rayleigh-Plesset Equation !?

fbBreakup model: Flash Boiling Breakup



Aerodynamic breakup mechanisms are:

- driven by aero-dynamic instabilities on droplet surface
- mainly function of liquid-gas relative velocity

Flash boiling induced breakup is:

- driven by bubbles $R_i(t)$ growing within the droplets $R_o(t)$
- influenced by the liquid thermodynamic properties (<u>especially saturation pressure!</u>)
- Breakup occurs when the instability amplitude $\eta(t)$ grows larger than a «characteristic length» of the spray

fbBreakup model: Parameters

Breakup criterion:

$$\eta_0 e^{\int_0^t \omega dt} > k_b\left(R_o(t) - R_i(t)\right)$$

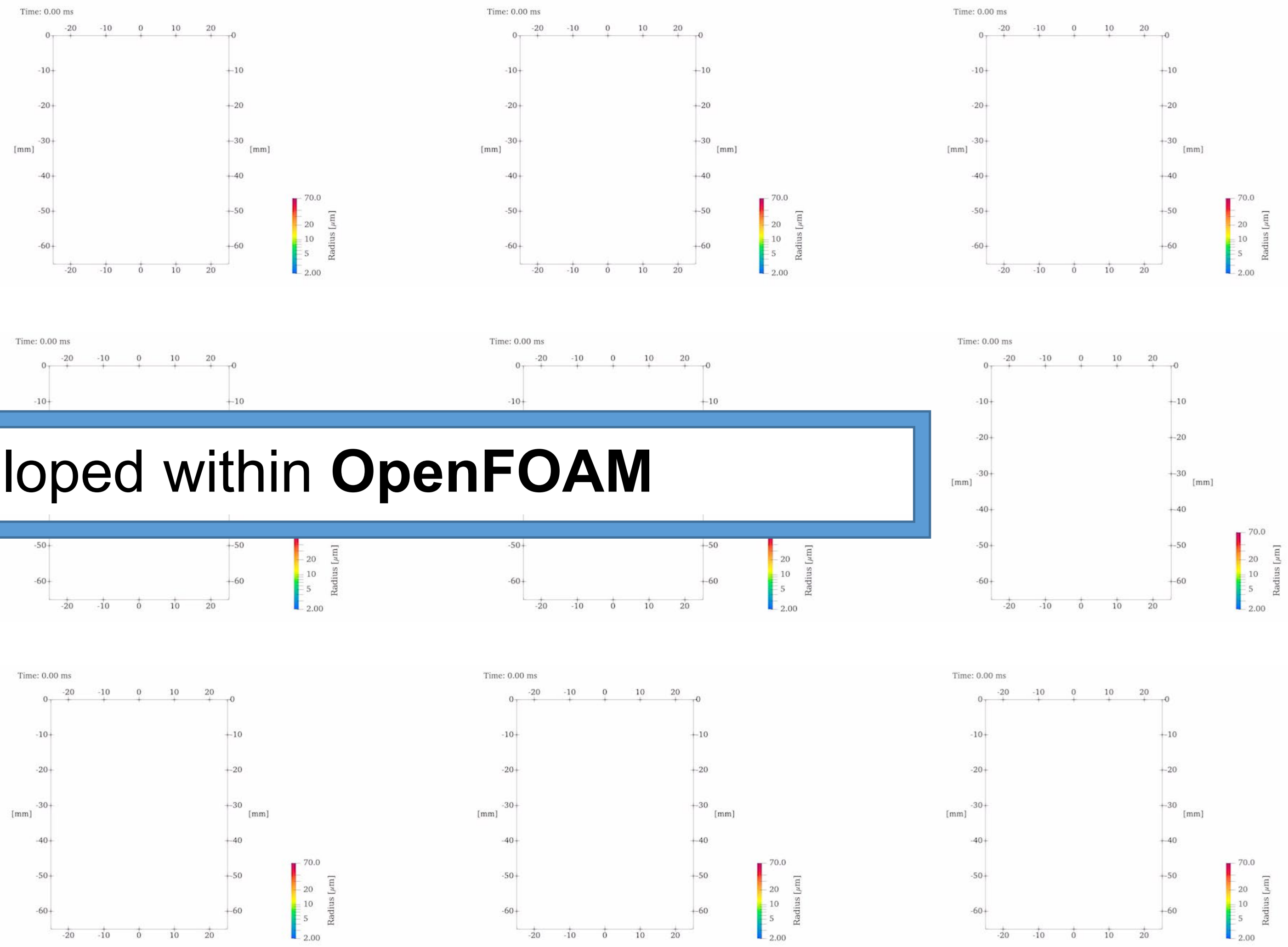
$R_o(t), R_i(t)$ growth rate is p_{sat} dependent:

fbBreakup was developed within OpenFOAM

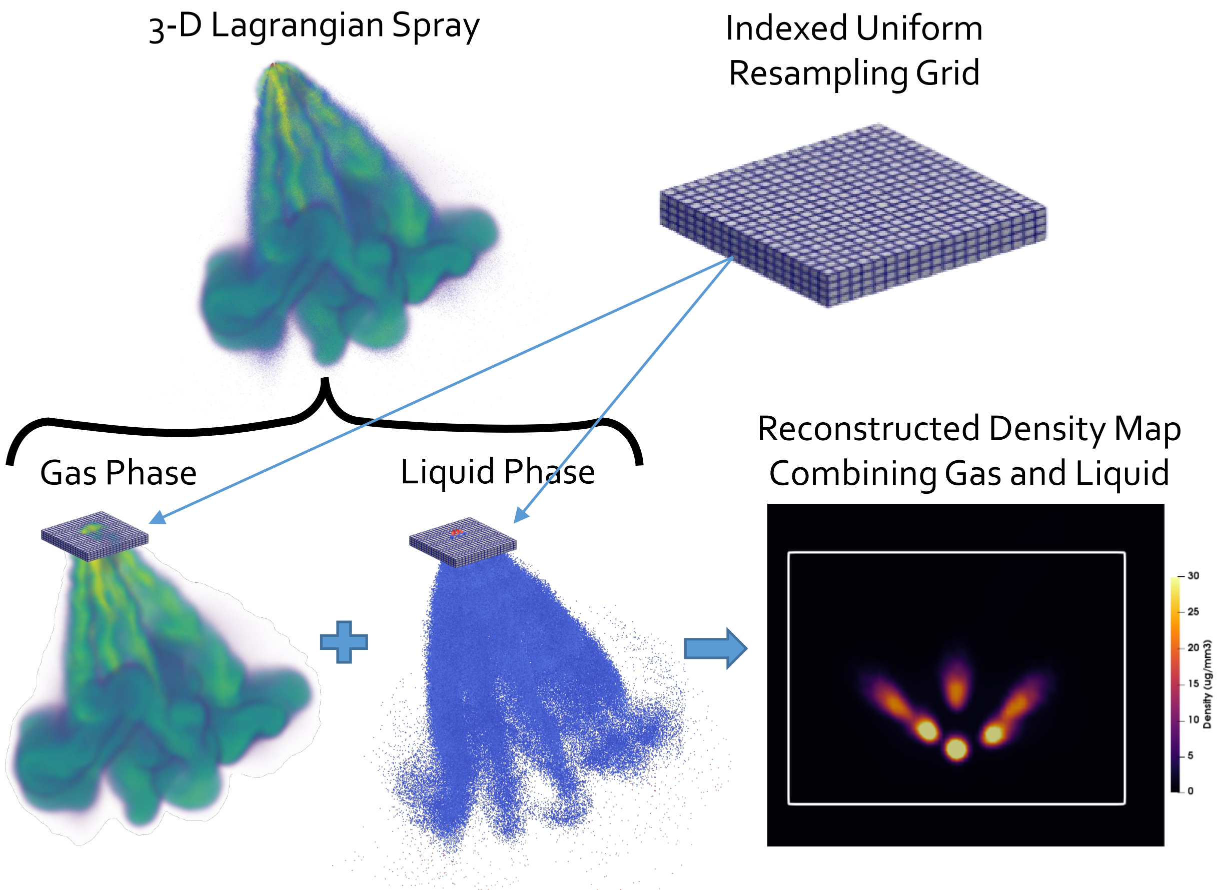
After breakup added a radial component:

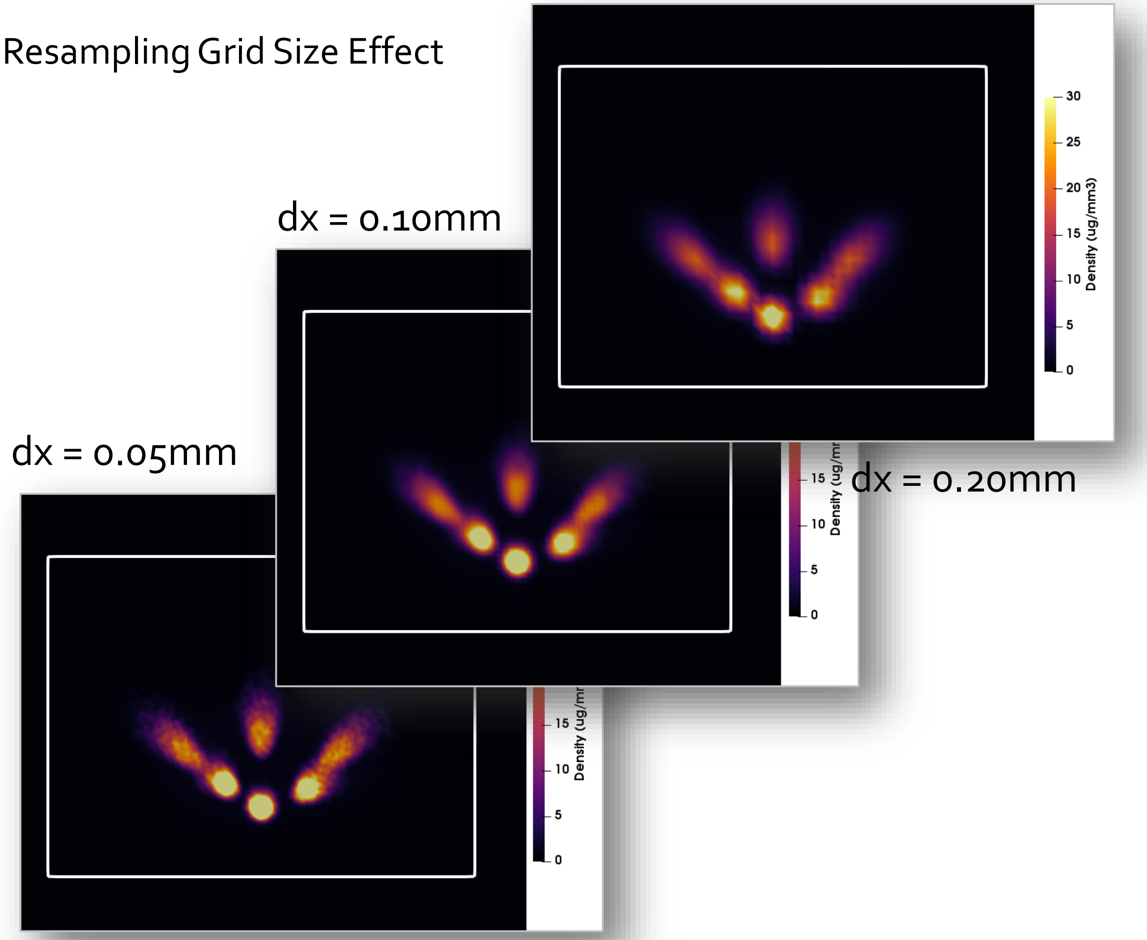
$$U_r = k_v \frac{3R_i^2 V_i(R_o - R_i)}{R_o^3 - R_i^3}$$

Assessment of Lagrangian Spray Simulation Procedure using Realistic GDI Injector and Fuel under Flash-Boiling Condition - *Francesco Duronio, Anqi Zhang, Le Zhao and Angelo De Vita*



Post-processing approach

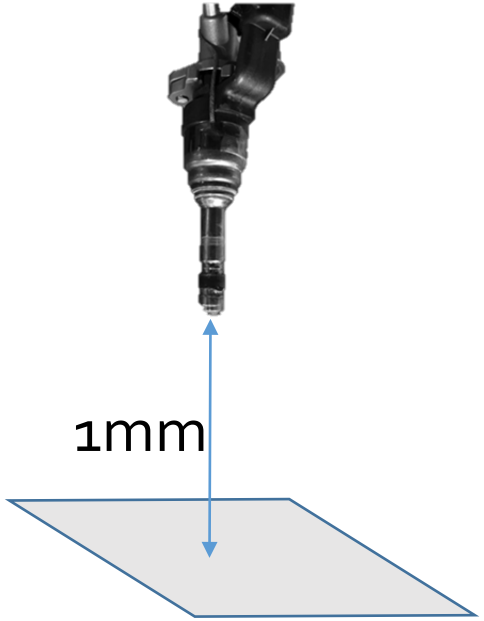




Robust post-processing developed to enable subsequent model performance evaluation

Near Nozzle Validation: Exp. Campaign

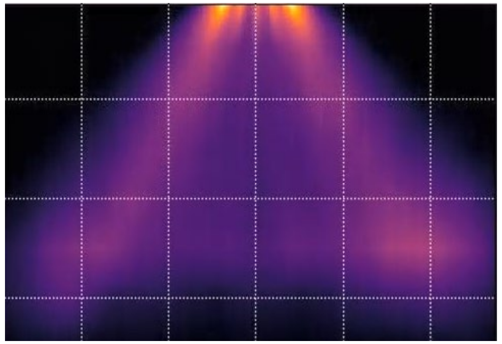
- Bosch GDI injector
- 6-hole side-mounted



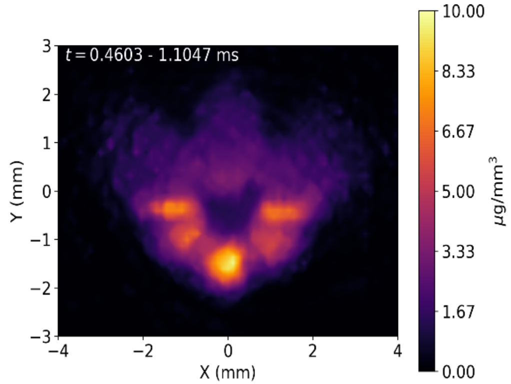
- EU5 : real gasoline surrogate properties developed @ aramco

Fuel Temp. [K]	Amb. Temp. [K]	Amb. Press. [bar]	Injection Press. [bar]
363.15	298.15	0.4	50

Near-Nozzle Fuel Density



Spray Tomography

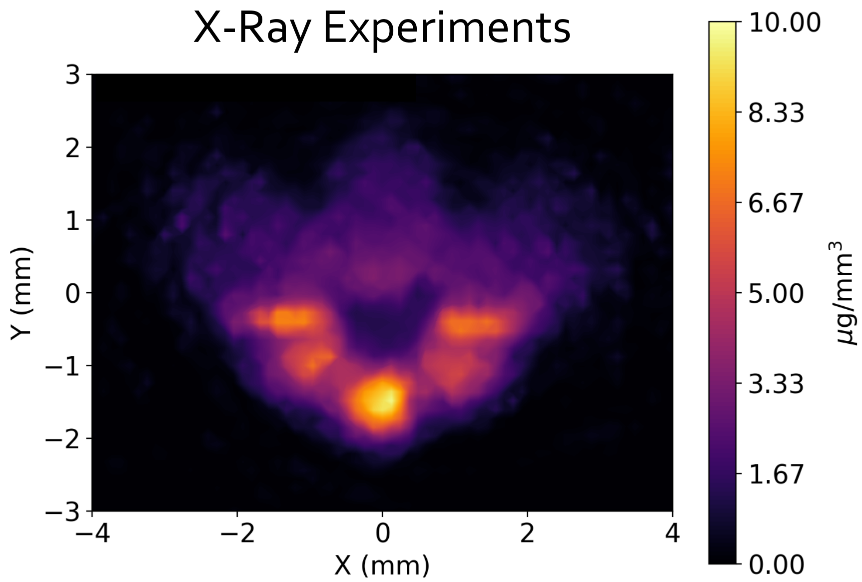


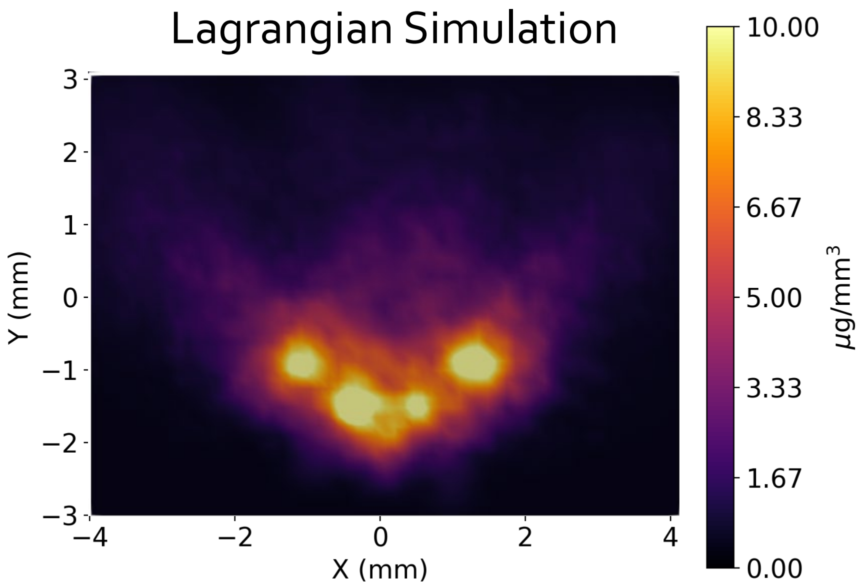
Near Nozzle Validation: CFD Model

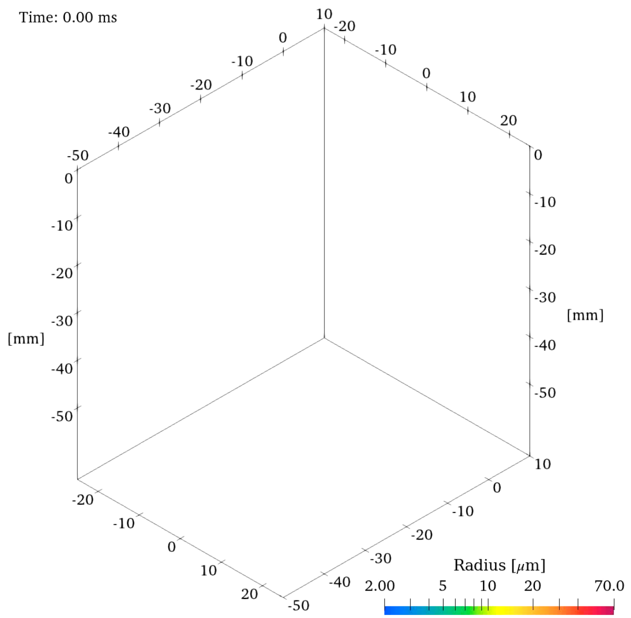
EULERIAN FRAMEWORK	
Integration domain	Cylindrical, 100 x 85 mm
Base Grid	1 x 1 x 1 mm
Near Nozzle Grid	0.125 mm
Turbulence	RANS RNG *k-ε*

Plume cone angle and plume direction set equal to the nominal value obtained from the manufacturer

LAGRANGIAN FRAMEWORK	
Injection method	Uniform
Effervescent Breakup	fbBreakup $k_v = 2.5$ $k_b = 2$ and $k_{Vb} = 3$
Aereodynamic Breakup	Reitz Diwakar
Vaporization	Adachi + Price (flash-boiling vaporization)

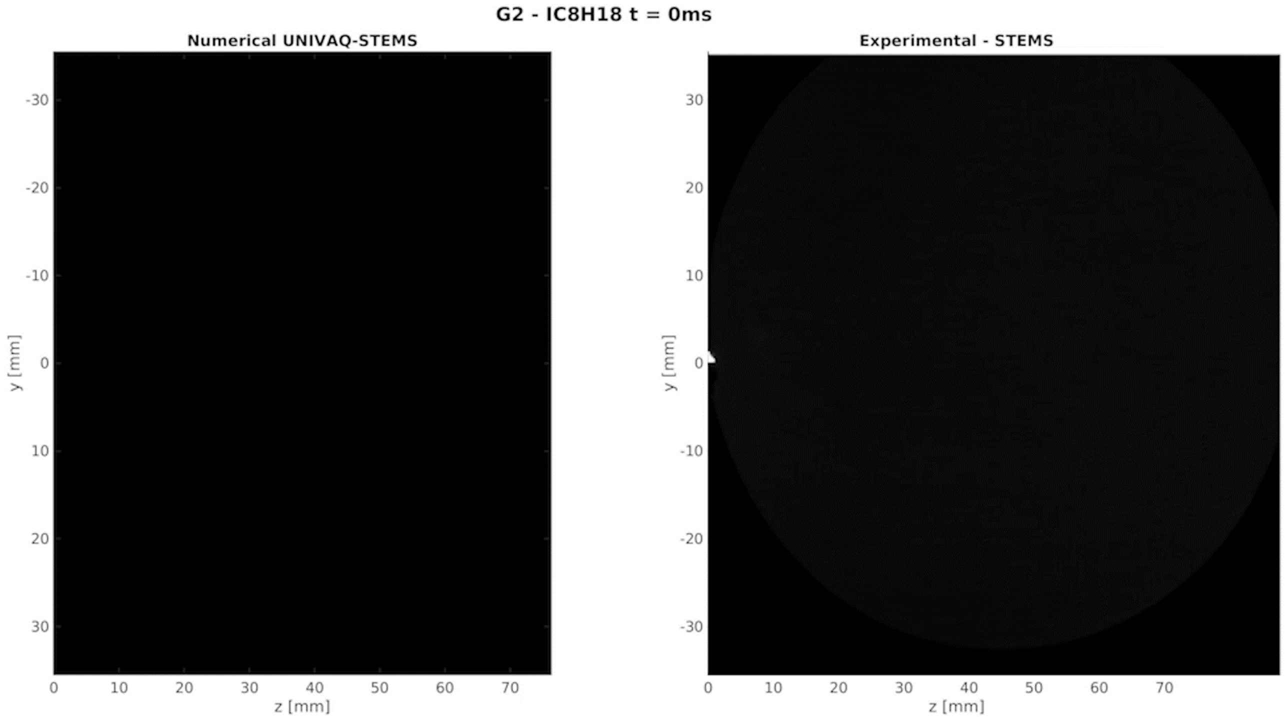




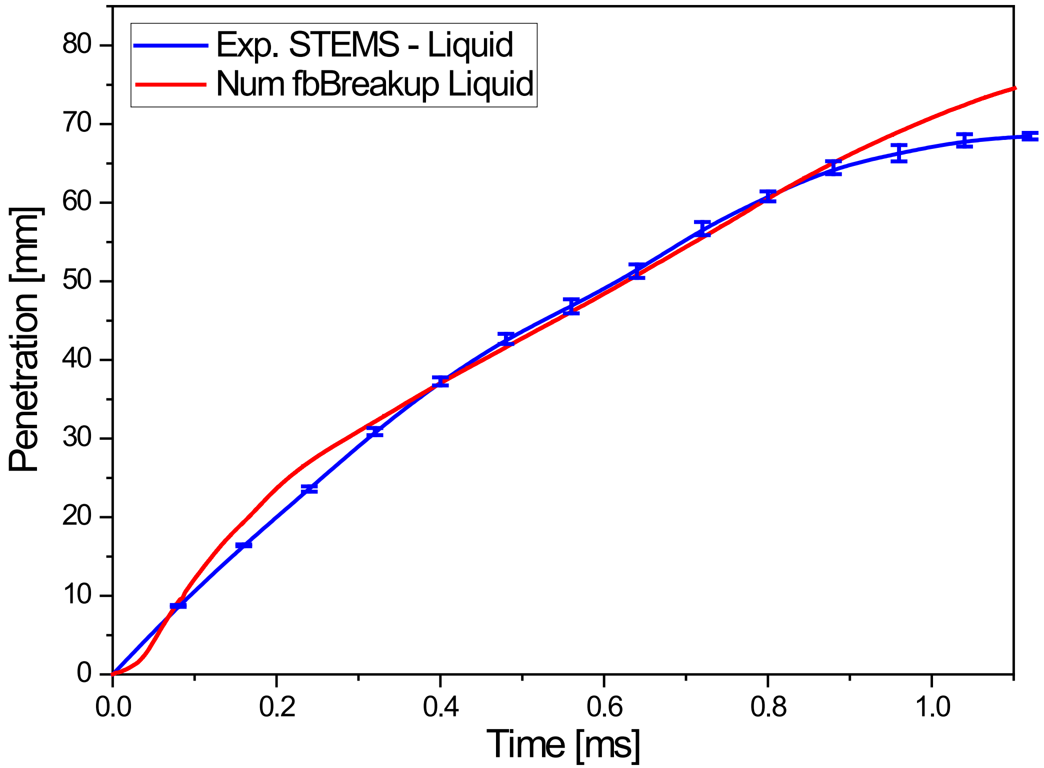


Spray G Validation: $G2_{SFB}$

$G2_{SFB}$: G2 with lower ambient pressure 0.2 bar



Mie Scattering

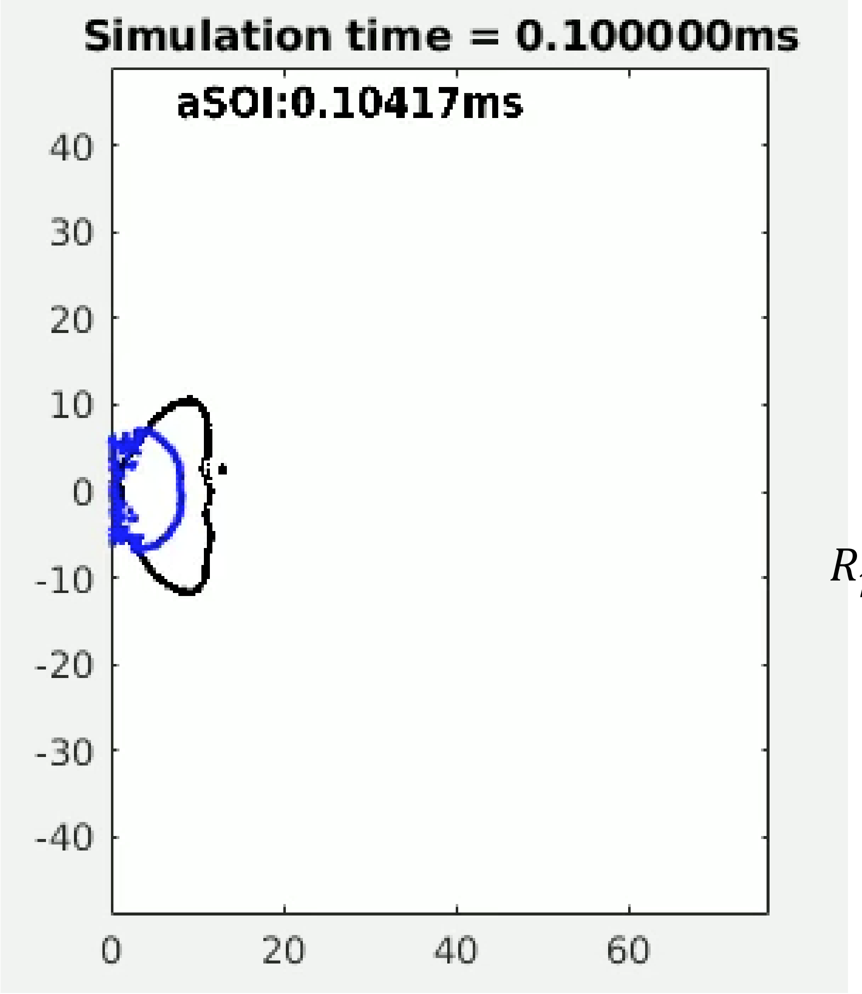


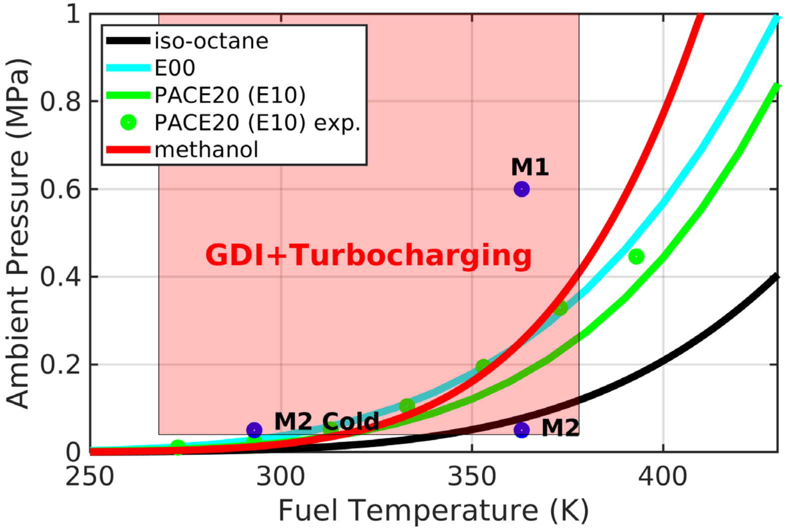
- ✓ Aereodynamic Breaup: Reitz Diwakar
- ✓ $k_b = 2.5\ k_{vb} = 2.5\ k_v = 3.5$
- ✓ Plume Cone Angle: 27°
- ✓ Plume direction: 35°

Duronio, F., Ranieri, S., Montanaro, A., Allocca, L. and De Vita, A., 2021. ECN Spray G injector: Numerical modelling of flash-boiling breakup and spray collapse. International Journal of Multiphase Flow, 145, p.103817.

ECN 9 – Spray M - MeOH & PACE20

M2 - Methanol





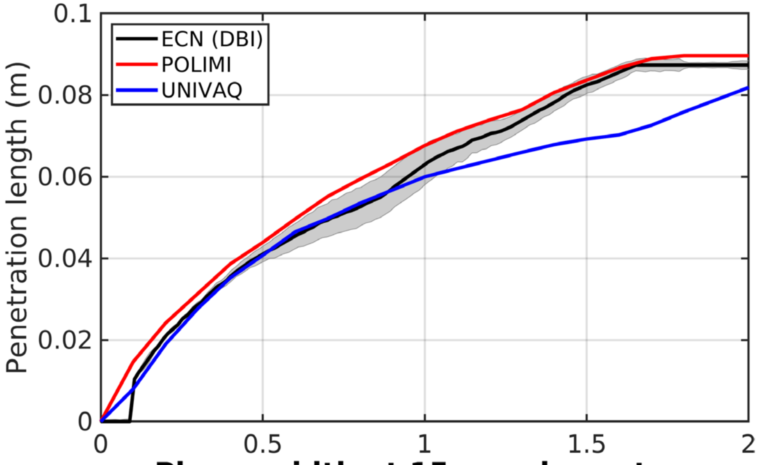
$$R_p = \frac{p_{amb}}{p_{sat}(T_0)} \begin{cases} R_p < 0.3 & \text{Flash boiling} \\ 0.3 < R_p < 1 & \text{Transition regime} \\ R_p > 1 & \text{Non-flash boiling} \end{cases}$$

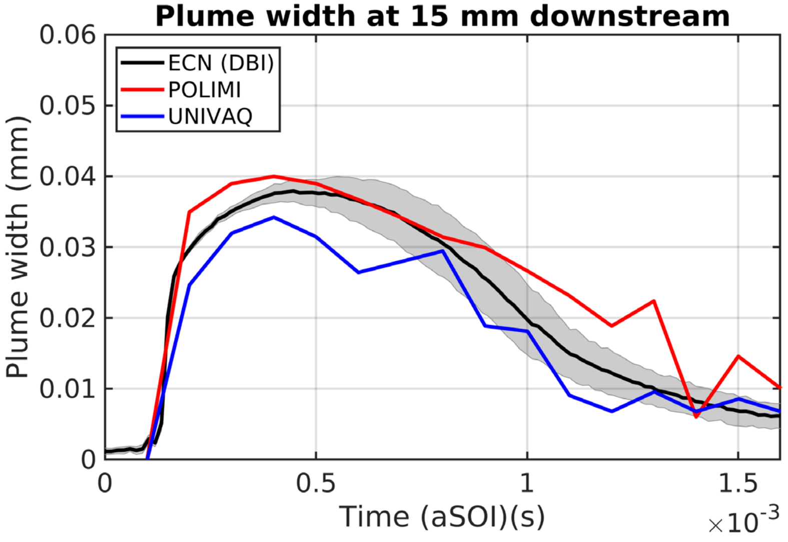
C_8H_{18}: $R_p = 0.69$

PACE 20: $R_p = 0.21$

MeOH: $R_p = 0.197$

M2 – PACE 20





Conclusions

Near Nozzle: Eulerian Approach

✓ Development of a low dissipative code for simulating multiphase flows with:

- Flux-splitting schemes for compressible flows
- Real fluid properties
- HRM phase change model

→ **realCentralHRMFoam**

✓ Validation with Spray G2 data and C_3H_8 injections: promising performances reproducing multiphase under-expanded jets

Whole Spray: Eulerian-Lagrangian Approach

✓ Effervescent breakup model allow to predict quite well fb spray morphology both in the near nozzle zone and in the far field

✓ fbBreakup model is **capable to reproduce spray collapse without changing spray angles**

✓ fbBreakup model is sensible to the fuel properties

Contact Info

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Thank you !

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Company: **University of L'Aquila**

Job: **Research Fellow**

Email: **francesco.duronio@univaq.it**