SAND2022-4649C

Exceptional service in the national interest

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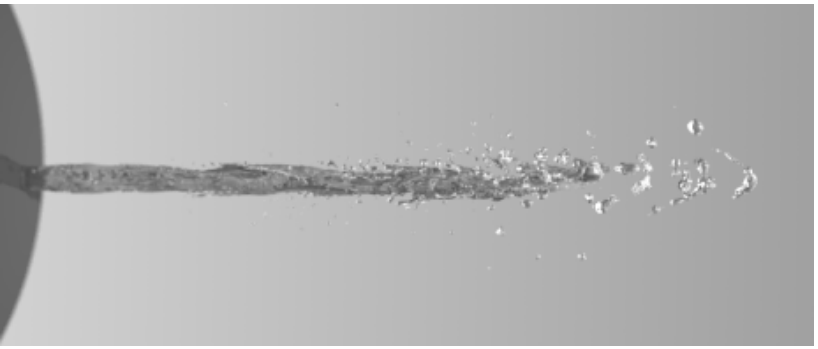

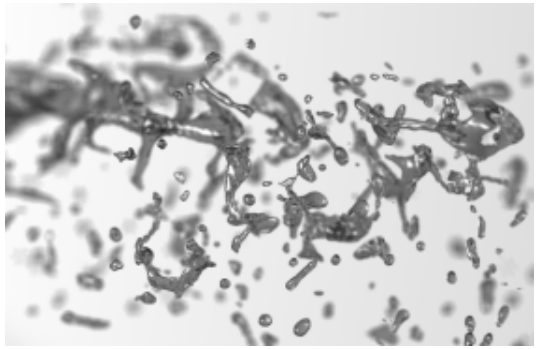

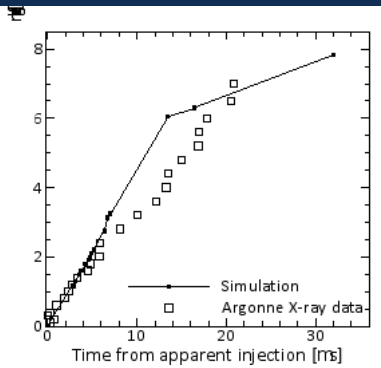

Compressibility effects in the initial transient of high-pressure Diesel injection

Marco Arienti[a] and Mark Sussman[b]

(a) Sandia National Laboratories

(b) Florida State University

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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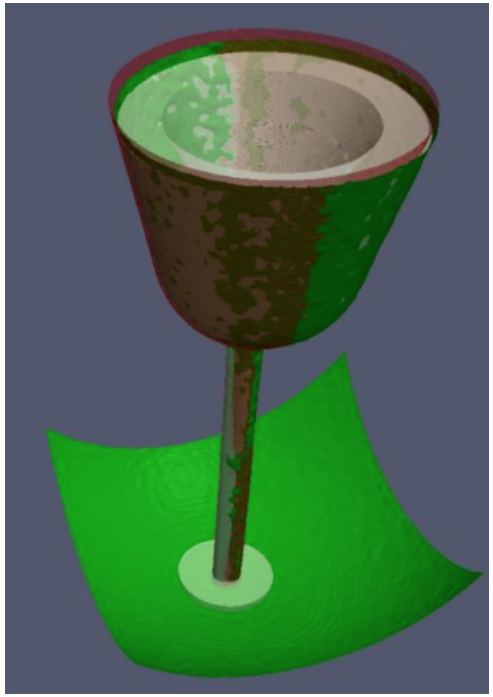
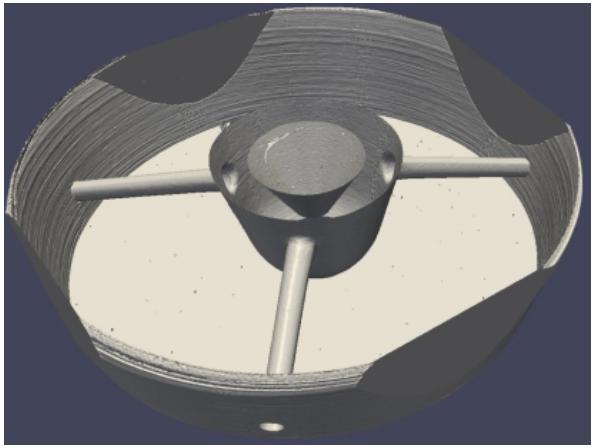
A family of fuel injectors

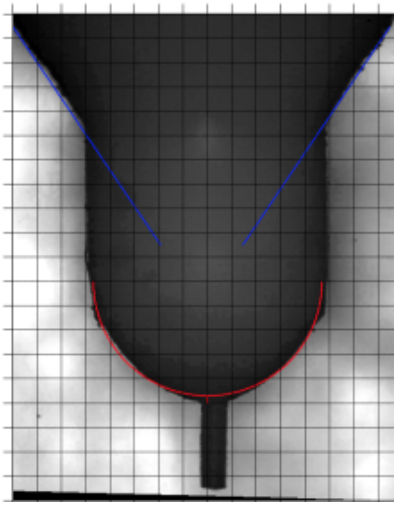
Go to the Engine Combustion Network webpage:
http://www.sandia.gov/ecn/index.php



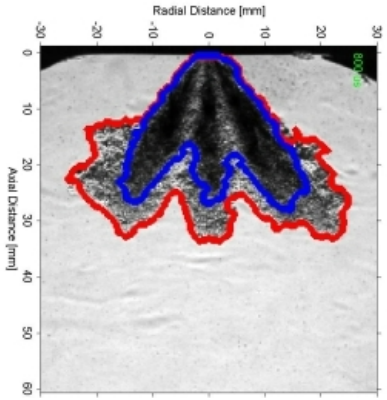
Spray A
Diesel (n-dodecane),
single hole,
mildly or not cavitating

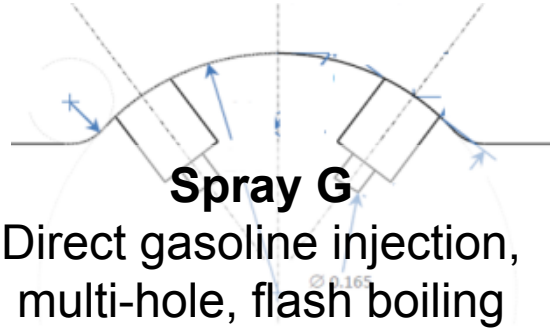


Spray B
Diesel, multi-hole



Spray H
Diesel (n-heptane), single hole,
prone to cavitation

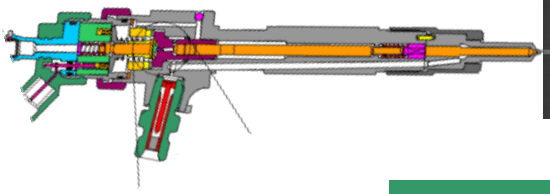




Spray G
Direct gasoline injection,
multi-hole, flash boiling

Spray A effort: a snapshot (April 2014)

30+ different measurements by 10+ different institutions
15 years of research performed in 3 years



Nozzle geometry
Sandia/CAT/Argonne/Infineum/ESRF

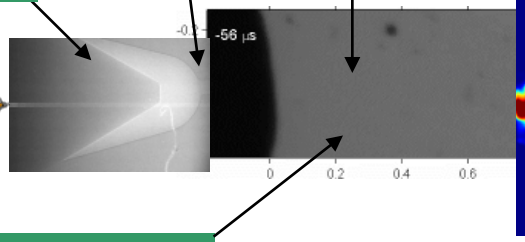
Needle lift motion
Xray, Argonne

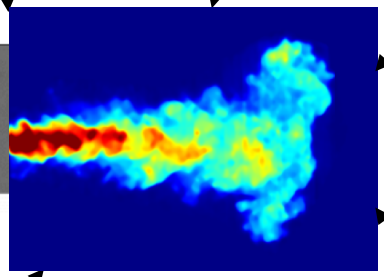
Liquid size

Combustion structure
CH_2O & OH LIF
IFPEN, TU/e, Sandia

Soot fv, size
LII, TEM
IFPEN,
Sandia, Meiji

Temperature





Liquid vol. fraction,
dense spray structure
Radiography, ballistic imaging, microscopy
Argonne/Chalmers/Sandia

Fuel concentration
Rayleigh
Sandia

Velocity
PIV, IFPEN

Other species

Standard: liq & vap penetration, lift off, AI
Mie/Shadowgraphy/Schlieren
Sandia/IFPEN/CAT/CMT/TUe

Already available on the website
Exp. done, to be published
In progress
Considered

Computational features

Starting point: the Combined Level Set Volume of Fluid (CLSVOF) method

- "A sharp interface method for incompressible two-phase flows" Sussman et al. J. Comp. Phys. (2007)

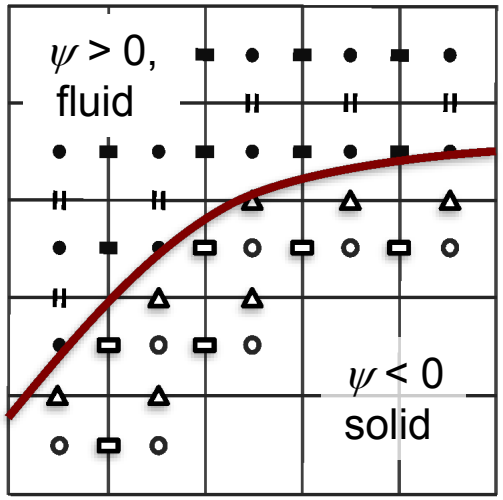
Additional / revamped features:

- An embedded boundary approach for complex geometries
- Directionally split Eulerian-Implicit Lagrangian-Explicit (EI-LE) advection
- Compressible formulation of Poisson solver step
- The Moment-of-Fluid (MOF) formulation

The embedded solid boundary

A simple level set-based staircase approach

- The solid boundary is represented as the zero level set of a signed distance function, ψ.
  A "solid face" has $\psi_{i,j,k} \cdot \psi_{i+1,j,k} < 0$
- ψ is calculated from a given triangulation (mesh) of the body surface: when N solid bodies exist, $\psi = \min(\psi^1, \psi^2, \ldots \psi^N)$
- In case of solid motion, ψ and wall node normals $\mathbf{n}_{node}$ are recalculated at every iteration

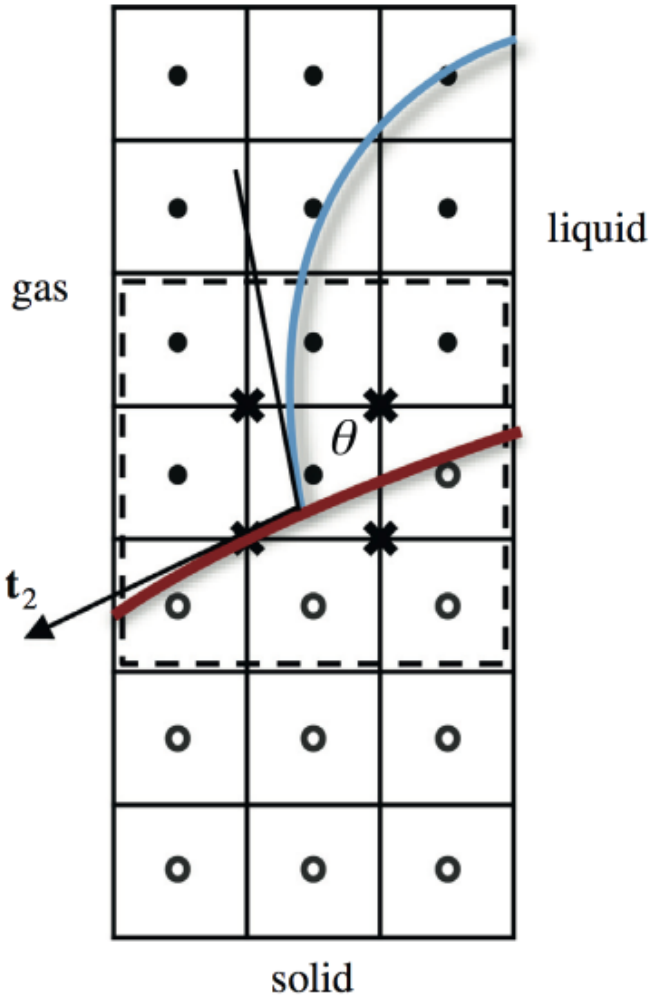


- The components of flow velocity at the wall are made consistent with the no-slip boundary condition through the Poisson equation and the projection operator:
  $\mathbf{u}^* = \mathbf{v}$ so that $\nabla p \cdot \mathbf{n}_{face} = 0$ at solid faces
- The values of $\mathbf{v}$ are extended into the ghost region by a front-advancing procedure where an unmarked cell takes its value from the neighboring cells that have already been marked

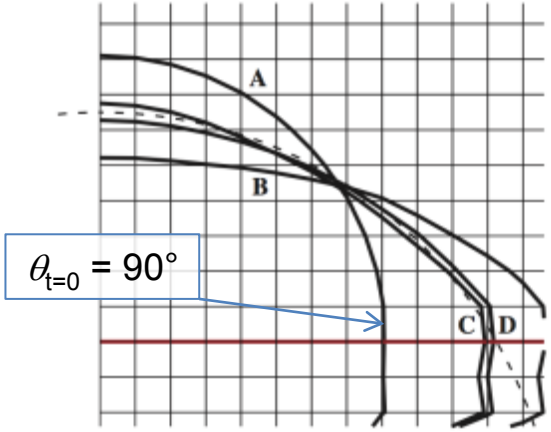
[Arienti and Sussman, IJNMF, 2014]

Contact point on solid surface

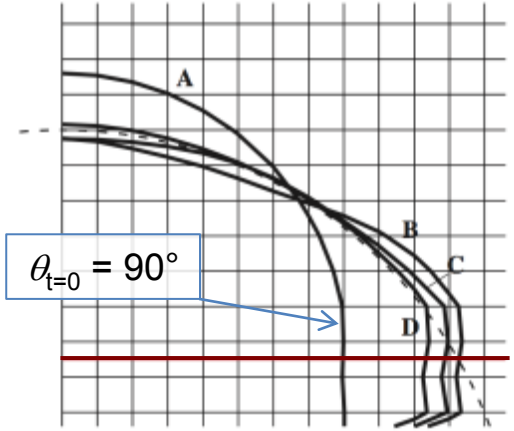
- The contact angle θ_w is prescribed
- The algorithm for curvature reverts to calculating the divergence of the interface normals near the contact point
- If the cell center falls in the solid region, $\mathbf{n}_\phi$ is replaced by $\mathbf{n}(\mathbf{n}_\psi, \theta_w)$



Effect of wall location for a drop with θ_w = 60°



Wall overlaps the cell faces



Wall passes through the cell centroids

Extension to compressible flow

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Asymptotically preserves the incompressible pressure projection in the limit of infinite sound speed

- Evaluate the "advective pressure," p^a and the "advective sound speed" $(c^2)_a$ (Kwatra, Su, Grétarsson, Fedkiw, J. Comput. Phys., 2009)
  - In a cut cell, p^a is evaluated from the equation of state for the material $m*$ that occupies **the largest volume fraction** in the cell

$$p_j^a = EOS^{m*}\left(e_{int}^{m*,\,a}, \rho^{m*,\,n+1}\right)$$

- Solve for P^{n+1}

$$P^{n+1} - \rho^{n+1}\left(c^2\right)^a \Delta t^2 \nabla \cdot \left(\frac{\nabla P^{n+1}}{\rho^{n+1}}\right) = p^a - \rho^{n+1}\left(c^2\right)^a \Delta t \nabla \cdot \mathbf{u}^a$$

using mass-weighted interpolation of the cell centered $\mathbf{u}^a$

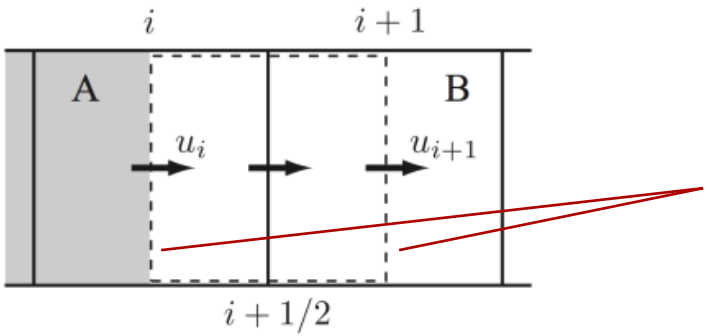
[Jemison, Sussman and Arienti, J. Comp. Physics 2013]

Consistency of mass and momentum advection (Sussman and Jamison)

- The full Navier–Stokes equations for multimaterial flow are split in (1) advection and (2) semi-implicit pressure correction for momentum and energy
- The nonlinear terms in the momentum equations are solved using the momentum-conserving approach by Raessi and Pitsch (Annual Research Brief 2008)

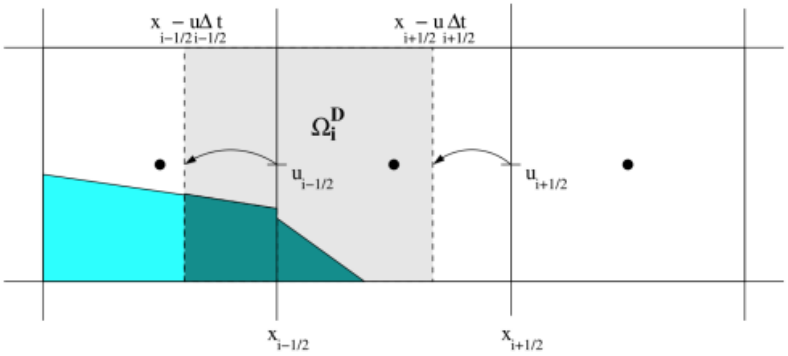
Incoming momentum $\rho_A u_i \neq u_i \dfrac{\rho_A + \rho_B}{2}$

Face density $\rho_B \neq \dfrac{3}{4}\rho_B + \dfrac{\rho_A}{4}$



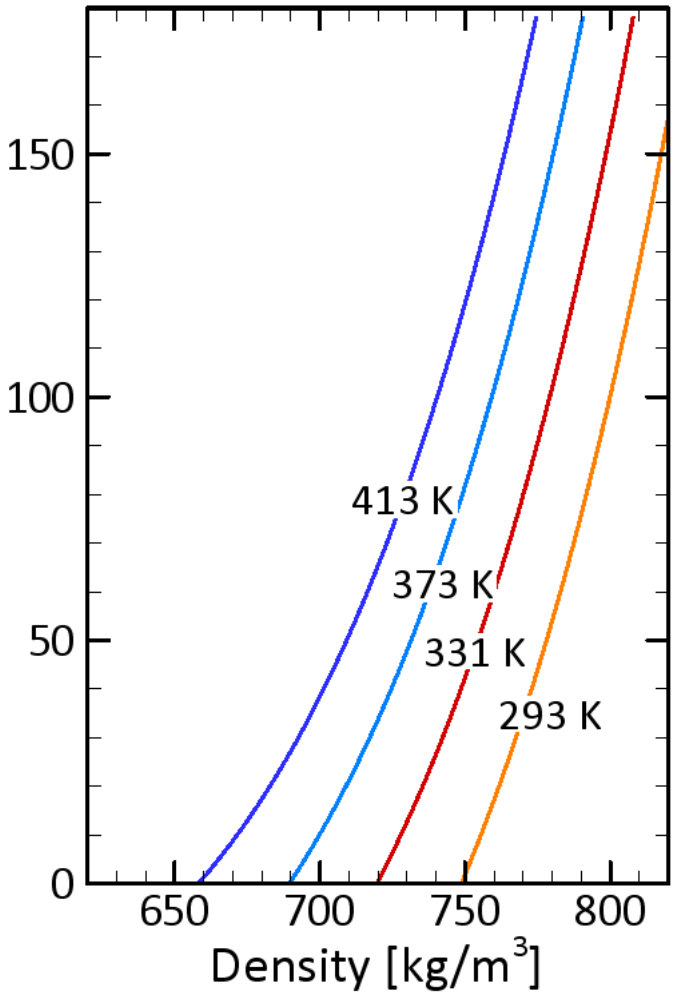
Faces of momentum control volume

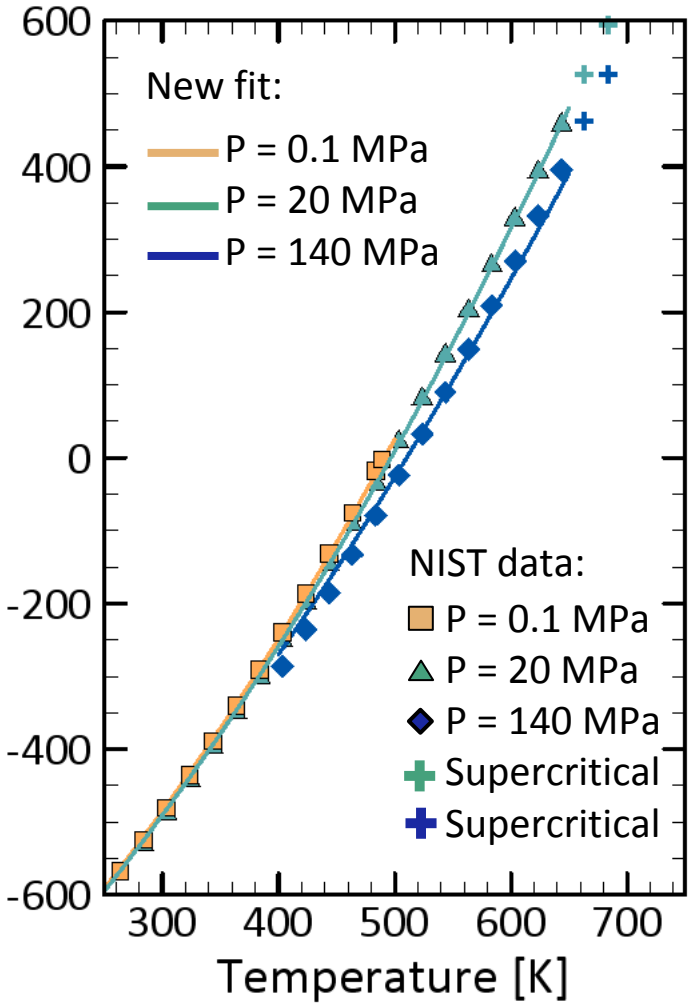
- Velocity is maintained and updated at both cell centers and face centers.
- In 1D use backward characteristic tracing



Equation of state of n-dodecane

Calibrated Tait's EOS and a new e(ρ,T) fit to data

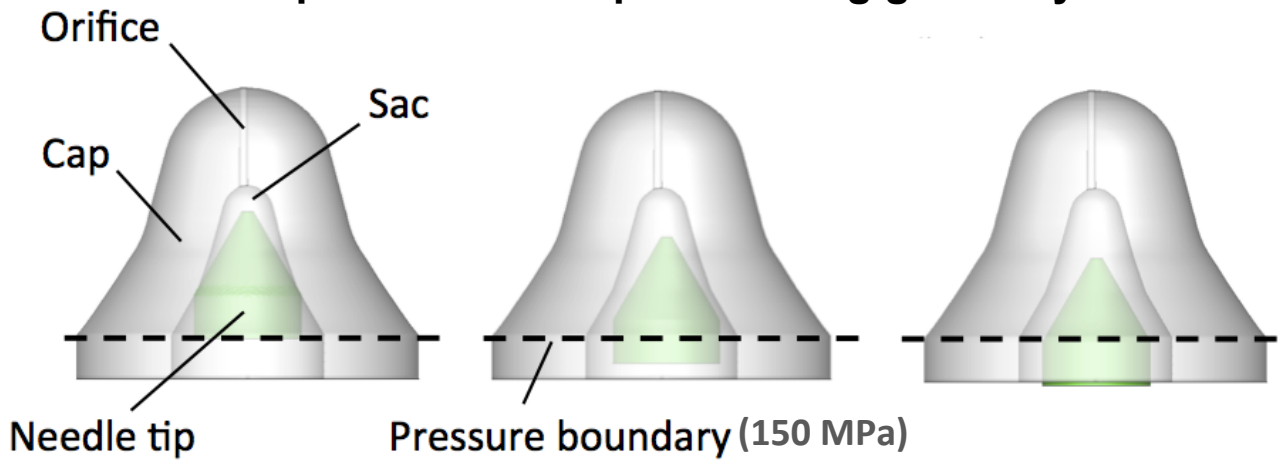


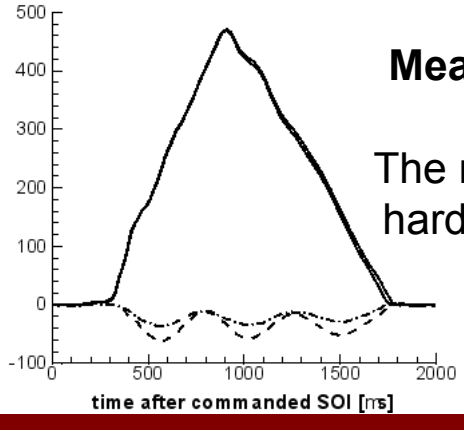


The needle's unseating

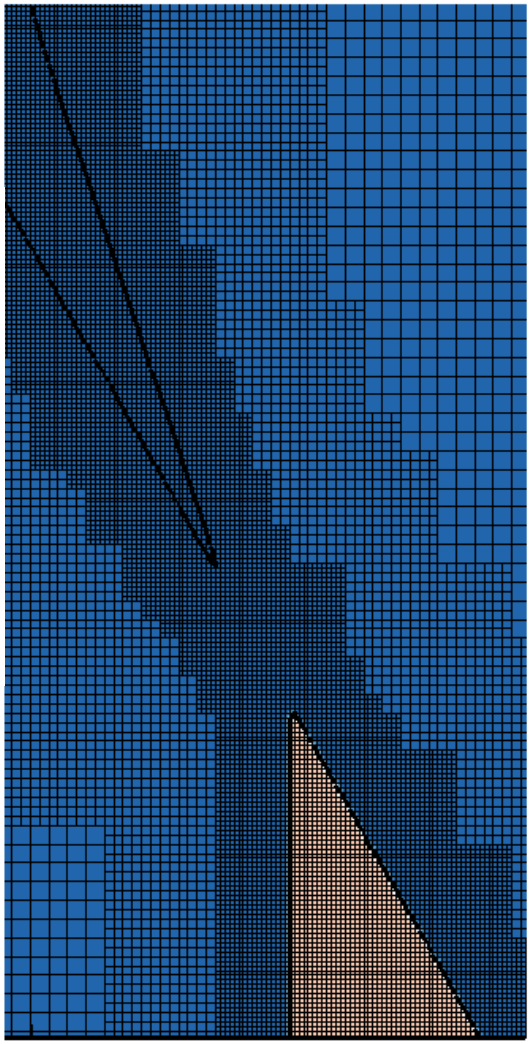
Successful pressure discharge following the needle's motion

Computational set-up for moving geometry

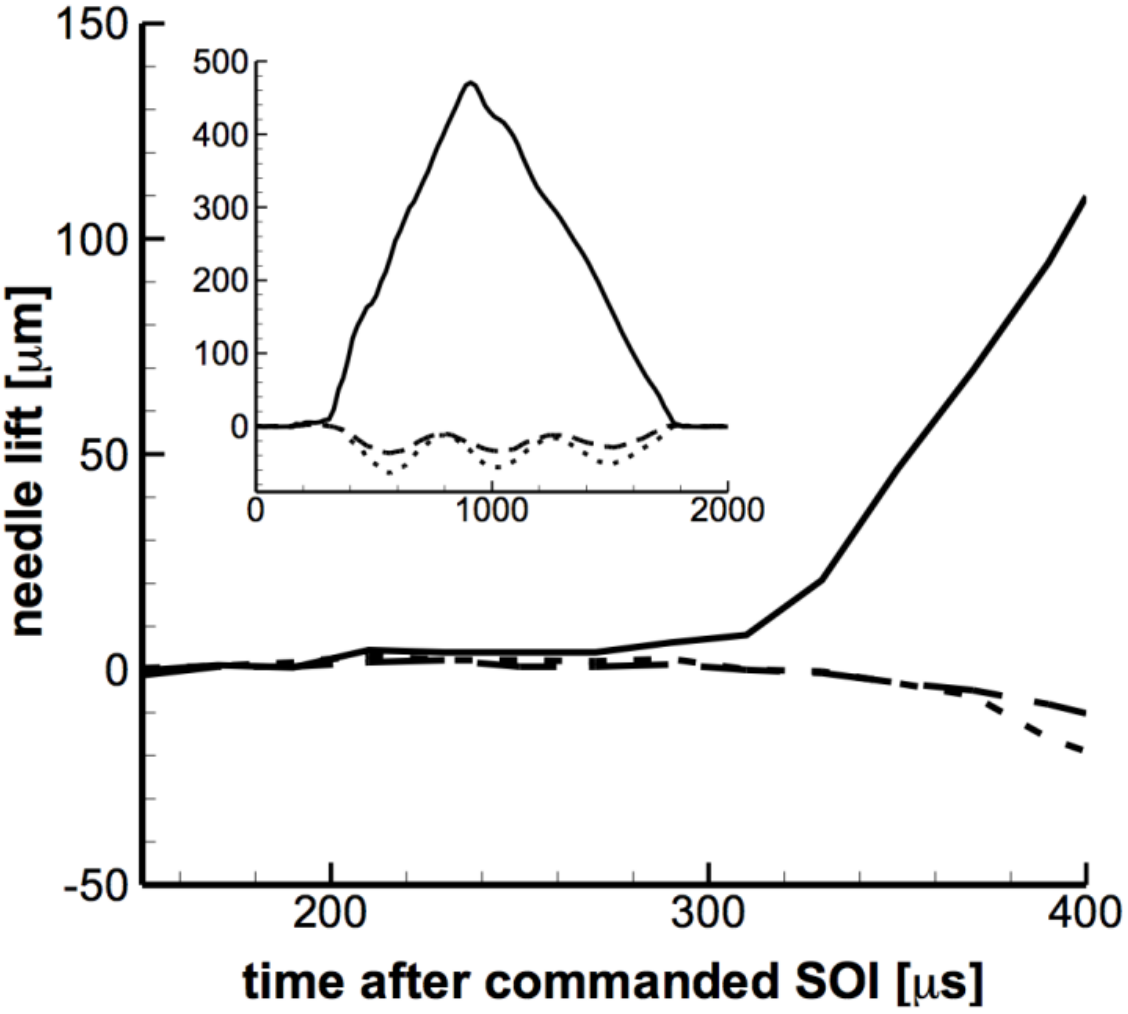




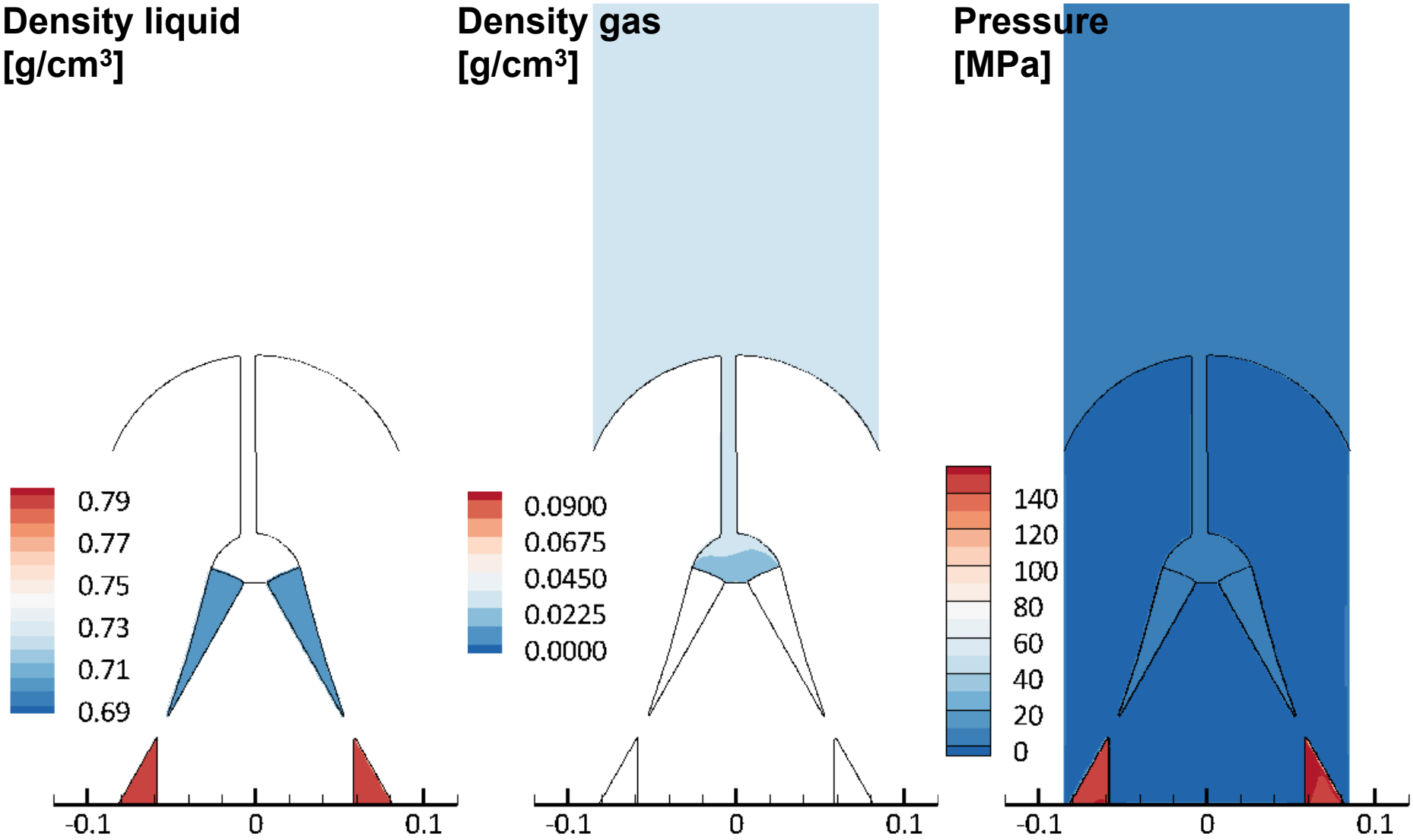
Measured needle's trajectory:
The needle' wobble is hardware-dependent



So far covered 339+35 μs from commanded start of injection (SOI)

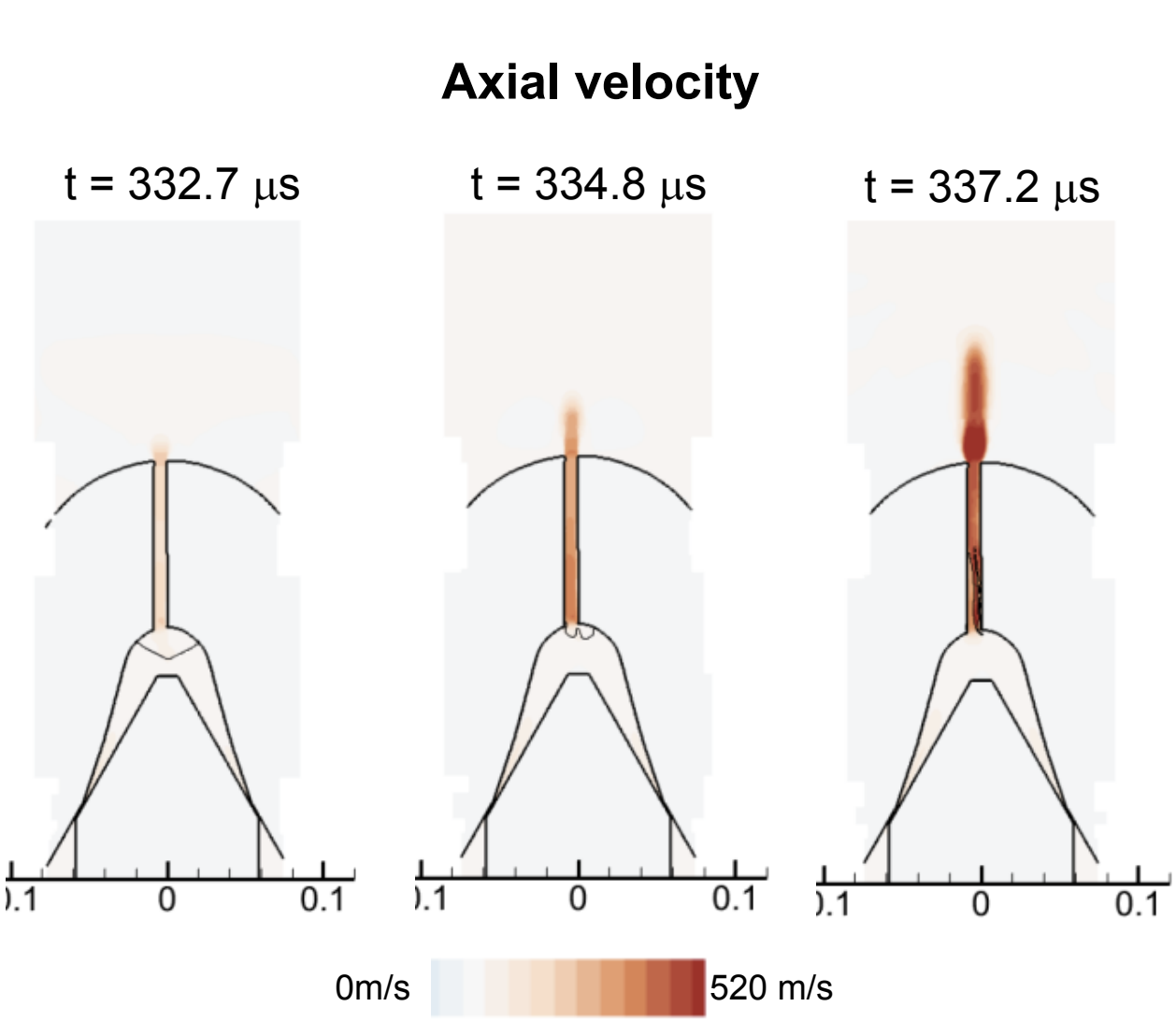


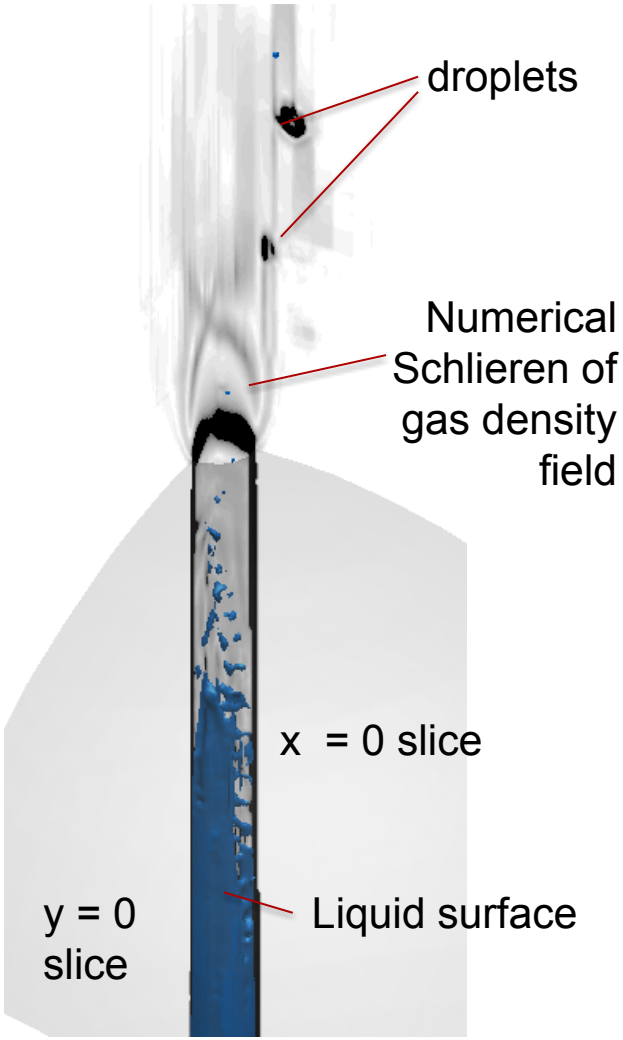
Dynamics of opening transient



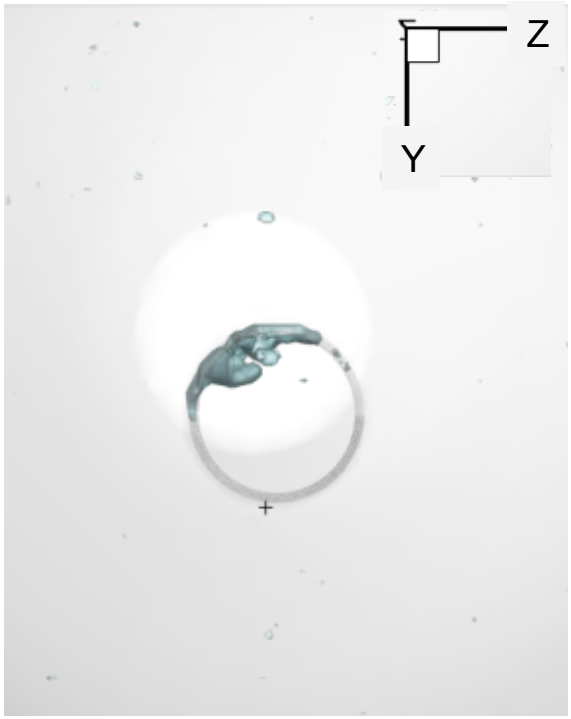
Under-expanded gas jet at the orifice

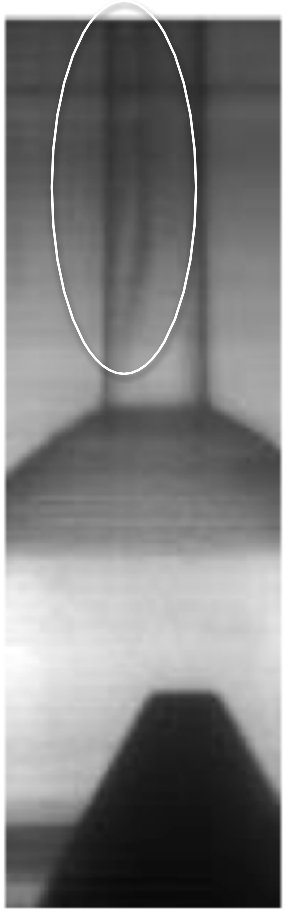
Example of multiphase supersonic flow





Evidence of trapped gas at the orifice



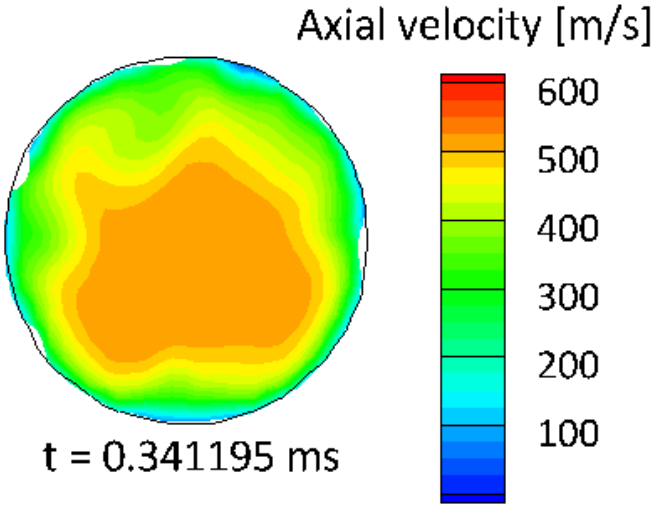


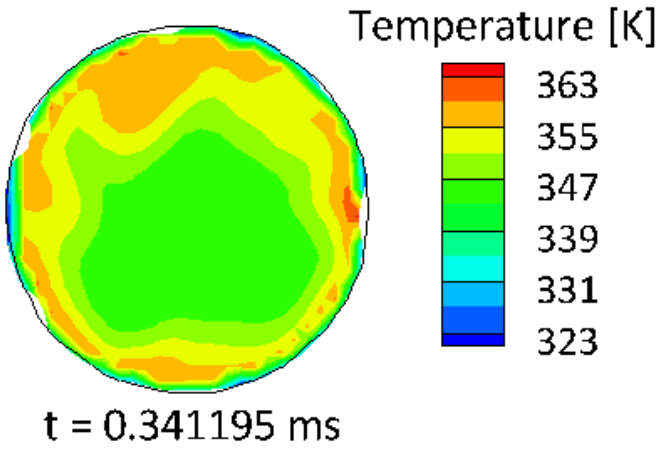
Transparent injector (courtesy of Ansgar Heilig, Hannover)

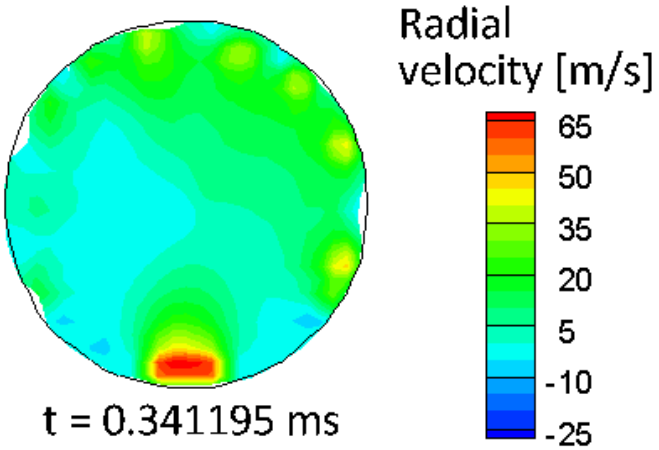
- Estimated gas volume ~3 10^{-7} cm^3 = 0.0015 V_{sac}
- The average density of the gas inside the bubble is ~0.2 g/cm^3
- The estimated residual gas mass is ~ $6 \cdot 10^{-8}$ g

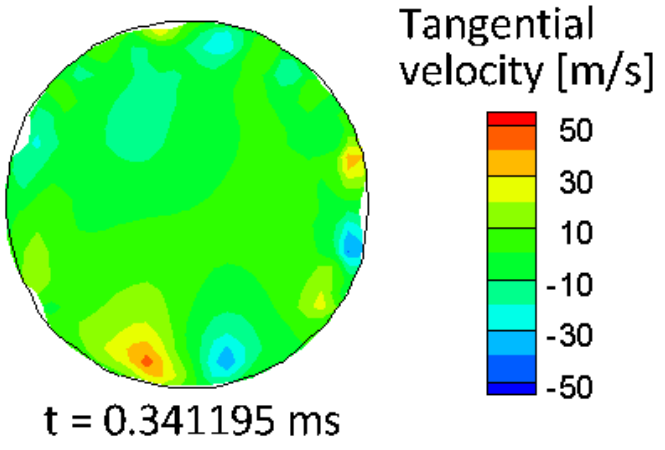
Flow cross-sections at the orifice

Turbulent and asymmetric flow, but over-estimated boundary layer



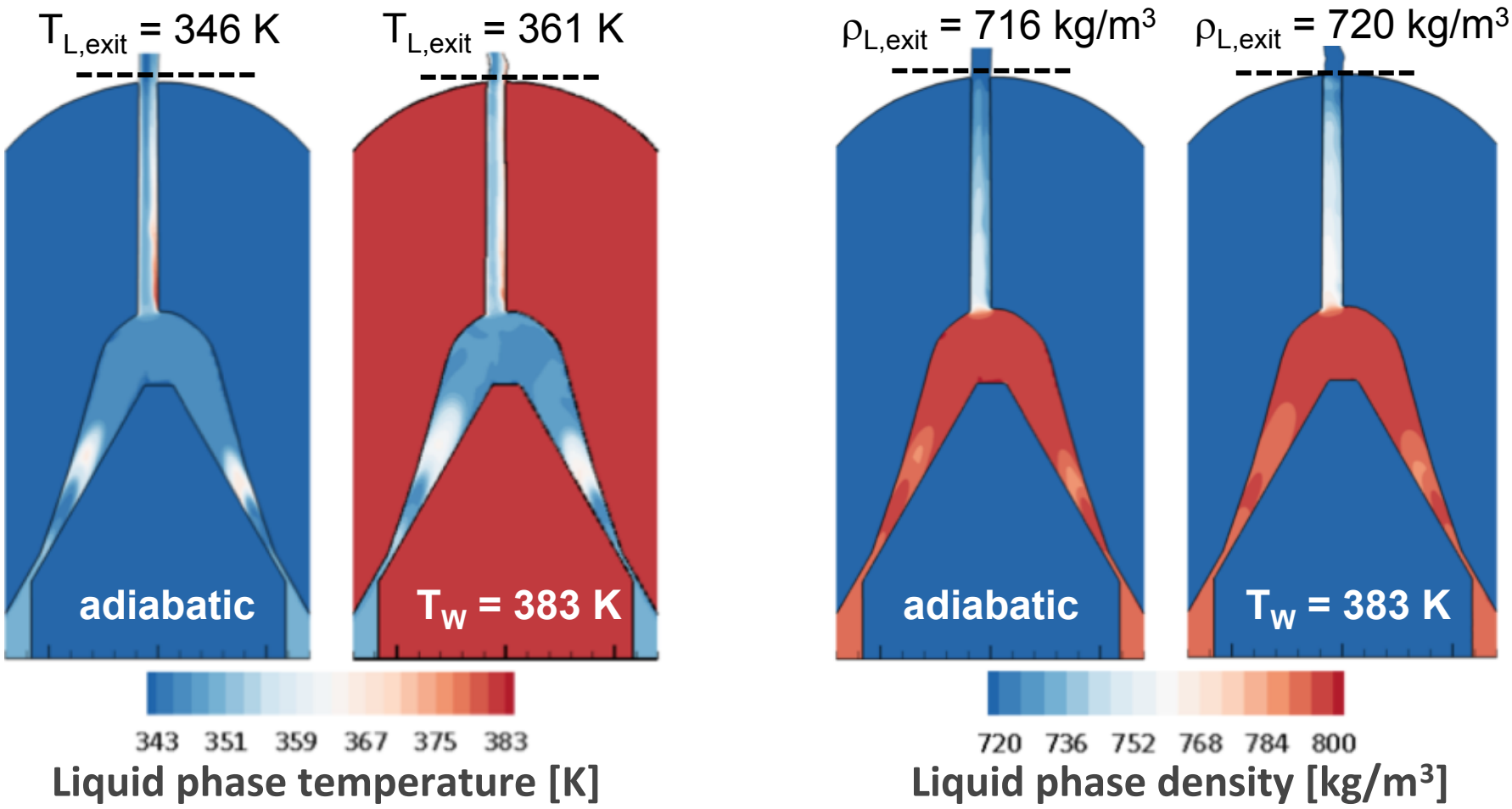






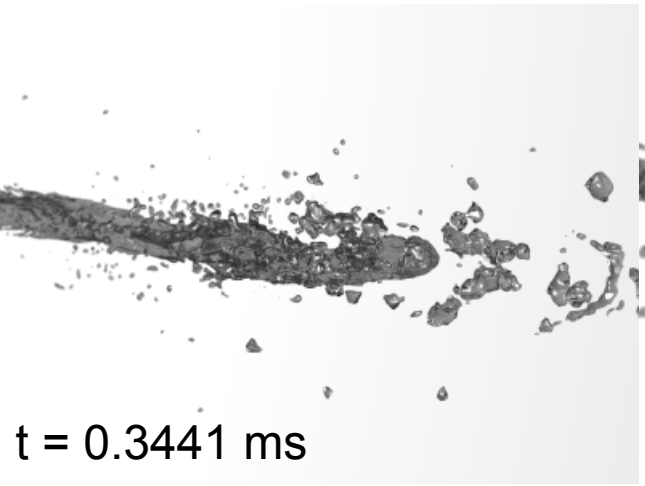
In progress: effect of wall heat transfer on fuel temperature

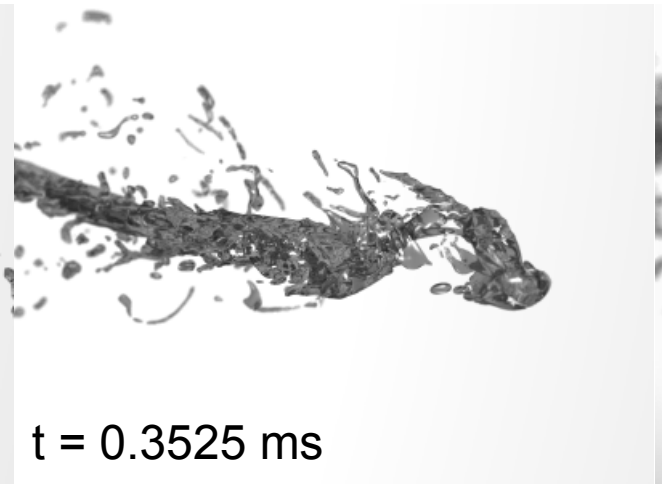
Observed limited temperature increase from $T_{L,0}$ = 343 K

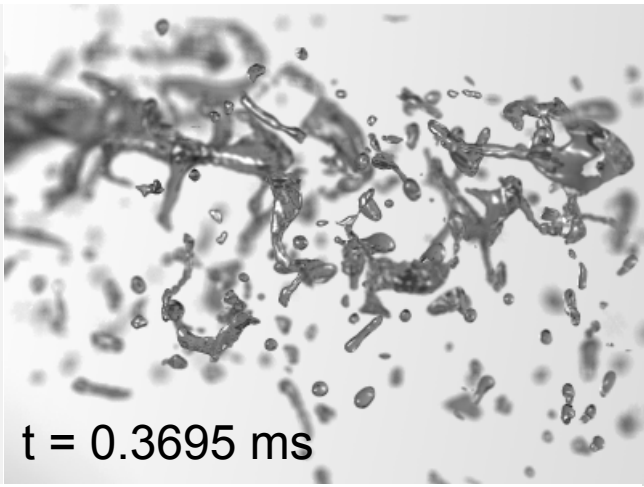


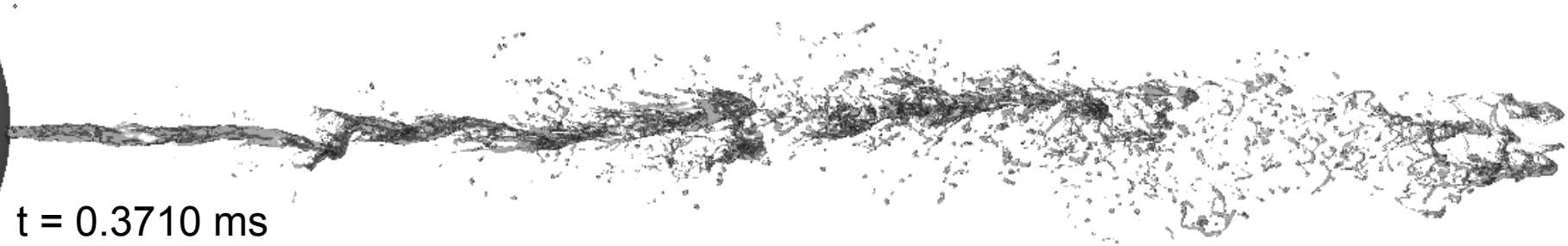
Jet tip structure

- Rapid disintegration of the jet
- No jet tip “mushroom” because of the internal flow dynamics



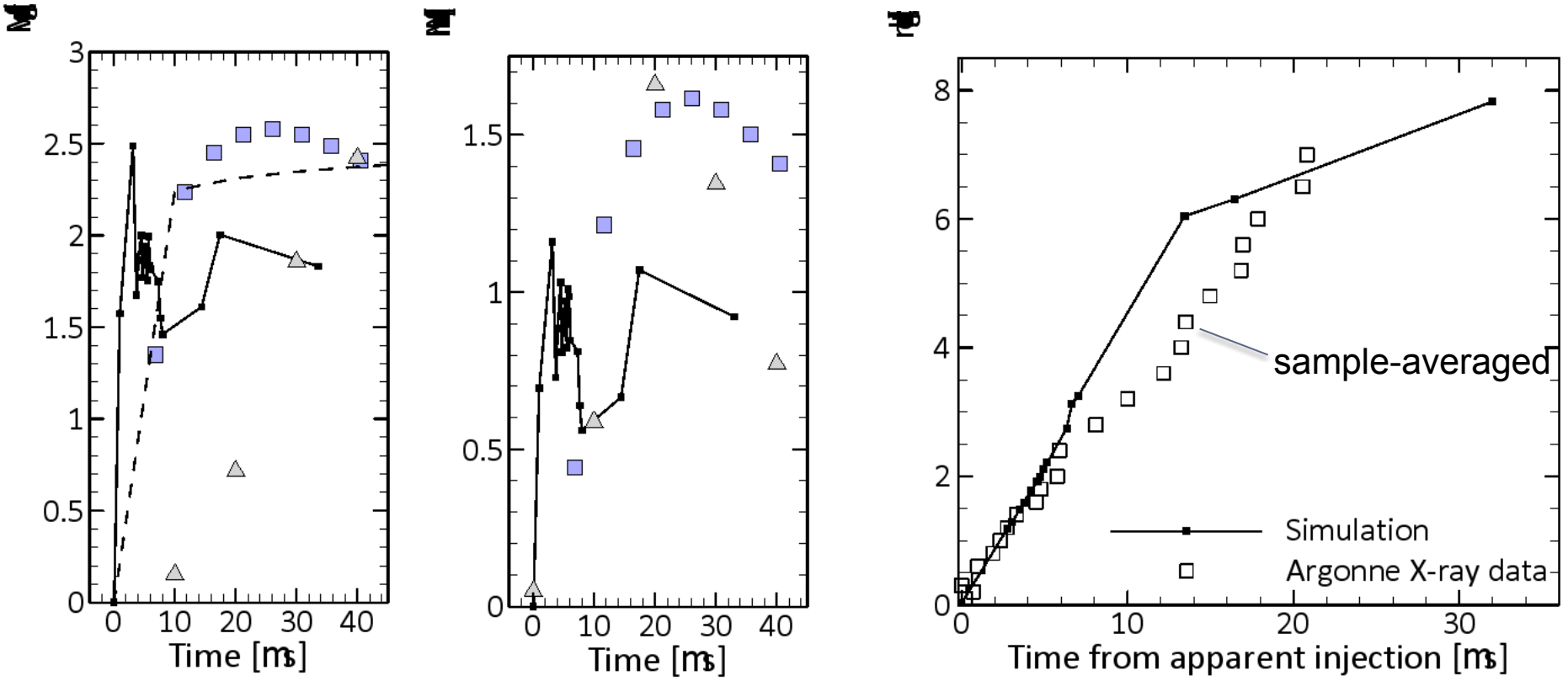






Flow rate and jet penetration

Transient flow rate and momentum flux below measured values, but reasonable agreement with penetration



- CMT measurements
- Sandia measurements
- Model from filtered data
- This simulation

Nominal mass flow rate:
3.5-3.7mg/1.5 ms = 2.3-2.5 g/s

Does simulation need to include manufacturing defects?

Sandia National Laboratories

- Needle's wobble causes pressure distribution asymmetries at the orifice exit
  - Increasingly relevant with decreasing sac volume
- Perturbed liquid jet tip at the exit
  - Different from typical initial condition assumed for Diesel injection
  - No mushroom shape
- Misaligned orifice position causes asymmetric flow
  - Residual gas bubbles trapped at the orifice entry
- Partial fuel filling in the sac before unseating affects the time to apparent injection
  - One of the causes of cycle-to-cycle variability?

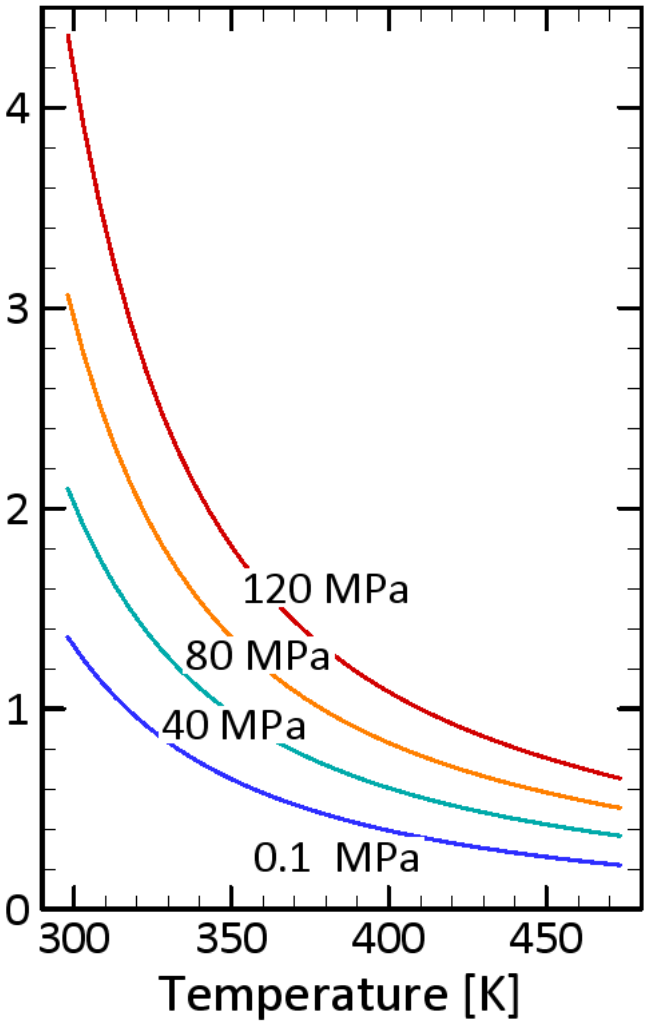
Questions?

Acknowledgements. The support by Sandia National Laboratories via the Laboratory Directed Research and Development program is gratefully acknowledged. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U. S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

BACKUP

Dependence of viscosity on pressure

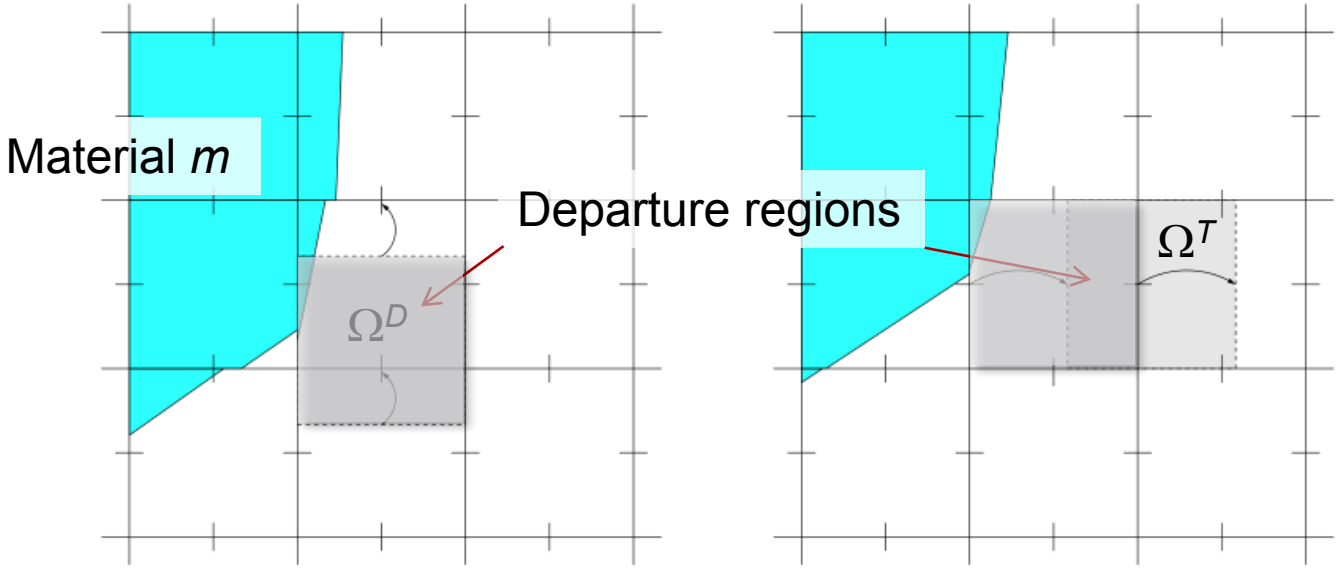


Conditions and setup

- "Argonne conditions" (cold flow): T_L = 343 K; T_G = 303 K
- Partially filled sac
- Back and ambient pressure: P_L = 150 MPa; P_G = 2 MPa
- Adiabatic walls, contact angle $\theta_w = 90^o$
- No turbulence models, no wall model
- Equation of state for n-dodecane compiled from data by Caudwell et al., Int. J. of Thermophysics, 2004; Khasanshin, et al., Int. J. of Thermophysics, 2003. Padilla-Victoria et al., Fluid Phase Equilibria 2013.
- Perfect gas EOS
- 64x64x576 coarse grid with 3 levels of refinement:
  the finest grid resolution is Δx_f = 3.32 μm (~30 grid points across orifice)
  adaptive stable time step Δt ~ 2 ns
- From 70 M to 210 M cells
- Run on Sandia's redsky (from 64 to 168 dual socket/quad core nodes)

2D/3D: directionally split advection

Eulerian-Implicit/Lagrangian-Explicit (EI-LE)



First sweep: back-tracing Eulerian Implicit

Second sweep: forward-tracing Lagrangian Explicit

(in alternate sweeps)

Interface reconstruction

$$\Omega^D_{i,j} = \left[y_{j-1/2} - \Delta t\, v_{j-1/2},\ y_{j+1/2} - \Delta t\, v_{j+1/2} \right] \qquad \Omega^T_{i,j} = \left[x_{i-1/2} + \Delta t\, u_{i-1/2},\ x_{i+1/2} + \Delta t\, u_{i+1/2} \right]$$

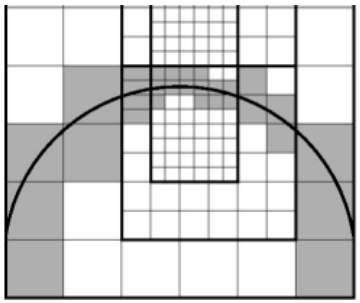
[Jemison, Sussman and Arienti, J. Comp. Physics 2013]

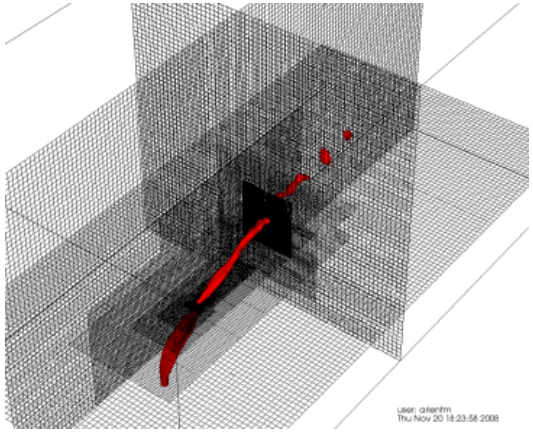
A box-structured data hierarchy

Adaptive mesh refinement and parallel structure managed by Boxlib

https://ccse.lbl.gov/BoxLib/

Proper nesting
(no more than one level change at a coarse/fine border)

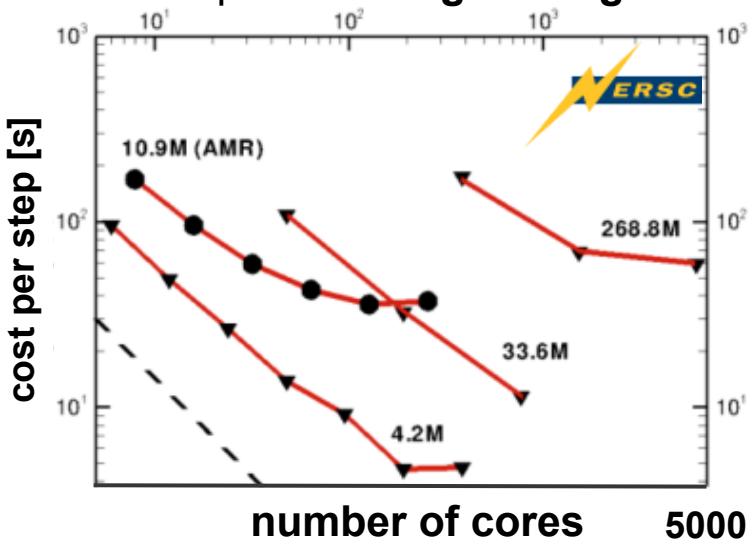




Example:
3 levels over 256x128x128 base

- AMR enables compact and efficient distribution of resources
- Data distribution and communication overhead limit scalability

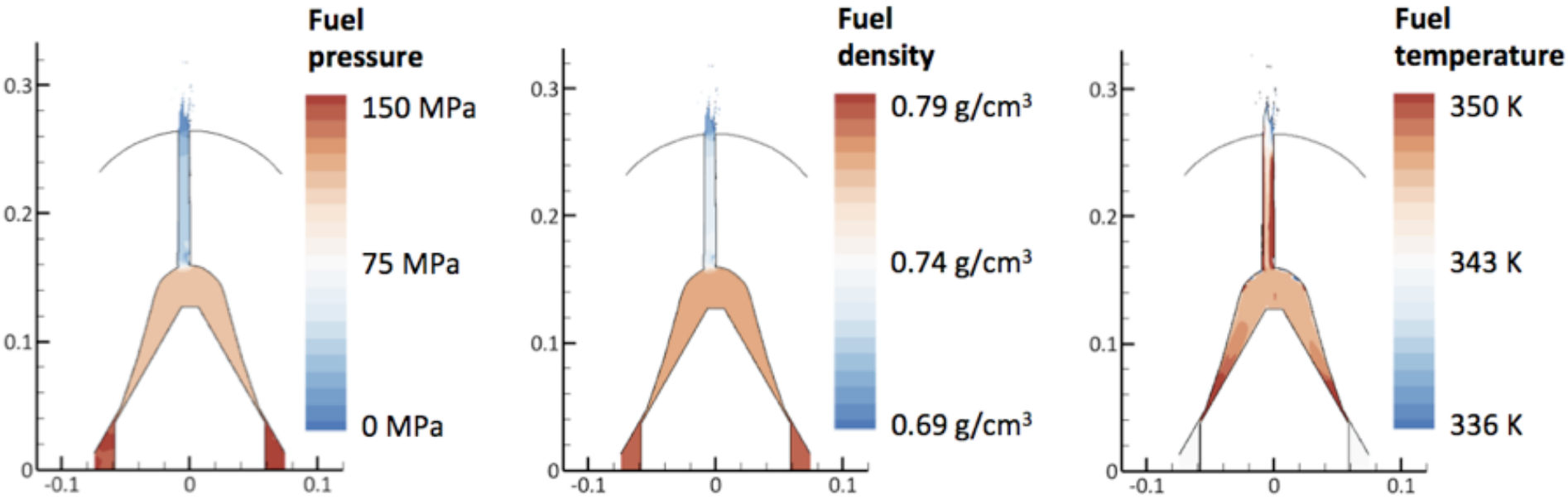
Example of **strong scaling test**



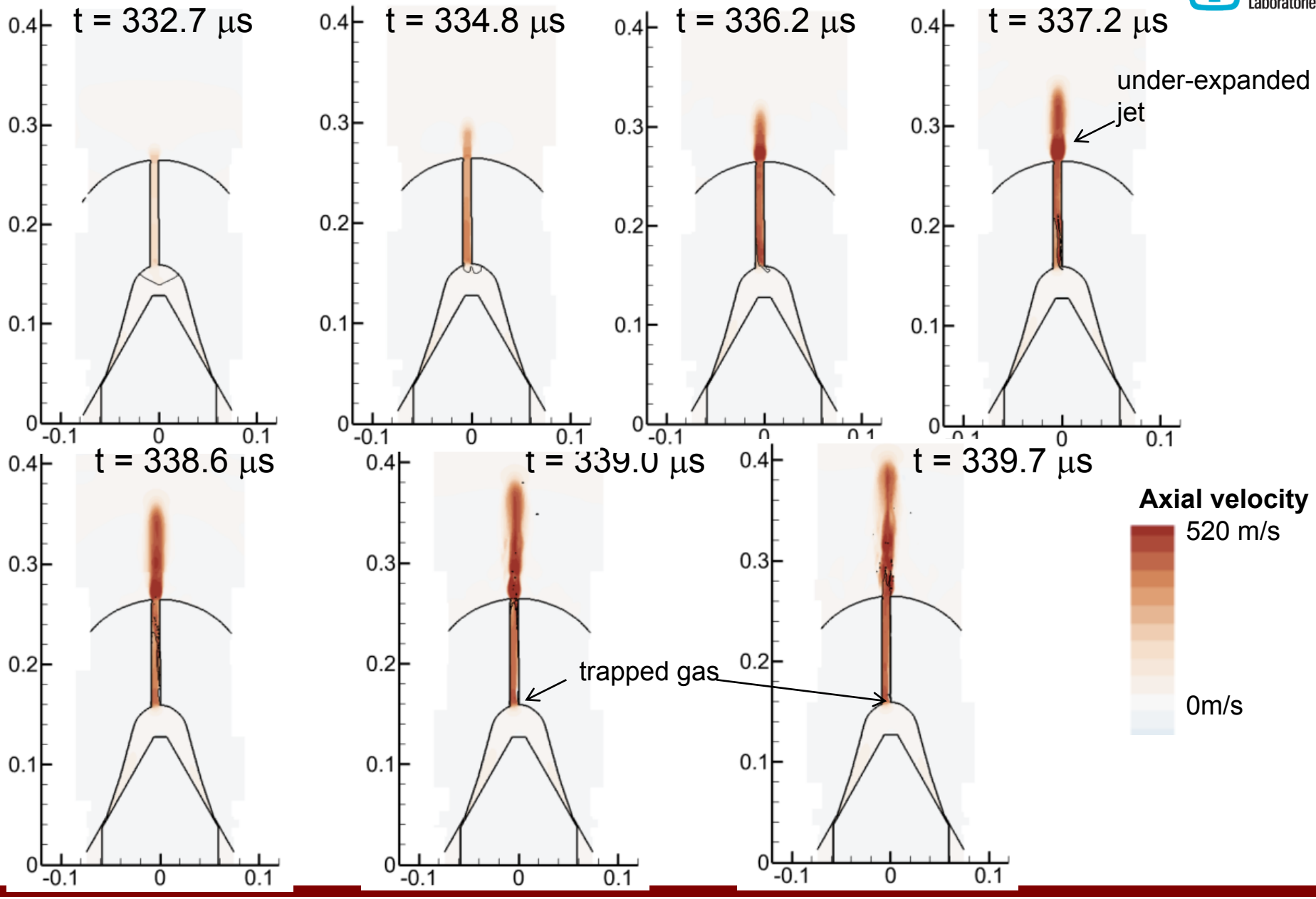
[Li and Soteriou, SciDAC 2011]

Pressure, density and temperature distribution of liquid fuel

Sandia National Laboratories

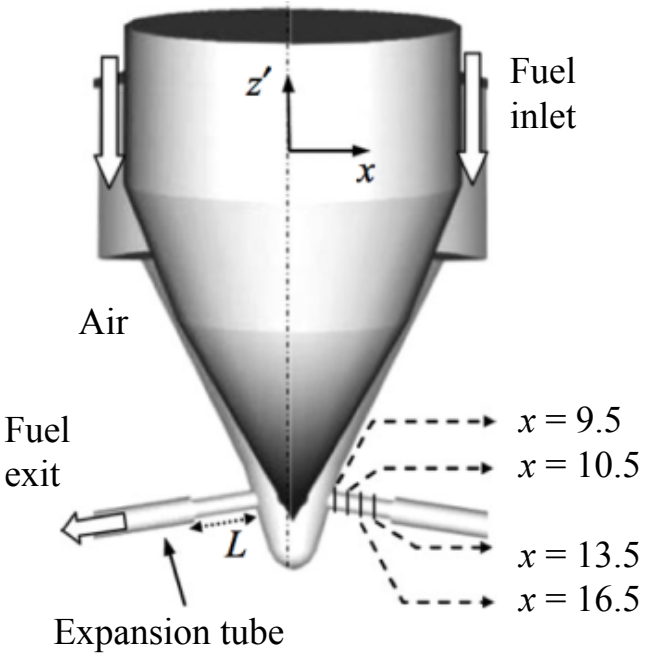


- Start of injection (SOI) from half-filled sac: t = 0.339 ms
- Adiabatic expansion of the liquid near the exit

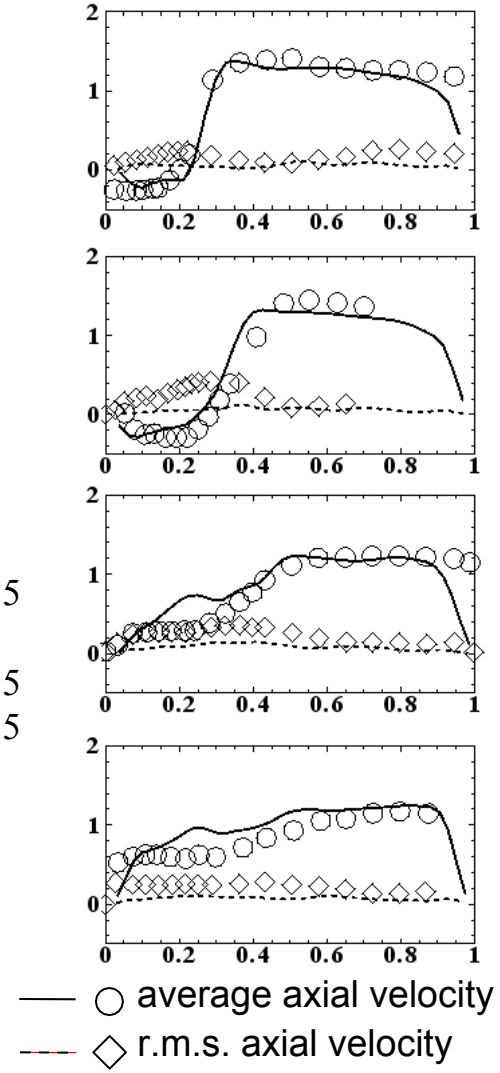

t = 332.7 μs
t = 334.8 μs
t = 336.2 μs
t = 337.2 μs
under-expanded jet
t = 338.6 μs
t = 339.0 μs
t = 339.7 μs
trapped gas
Axial velocity
520 m/s
0m/s

Validation: six-hole 20x Bosch Diesel injector

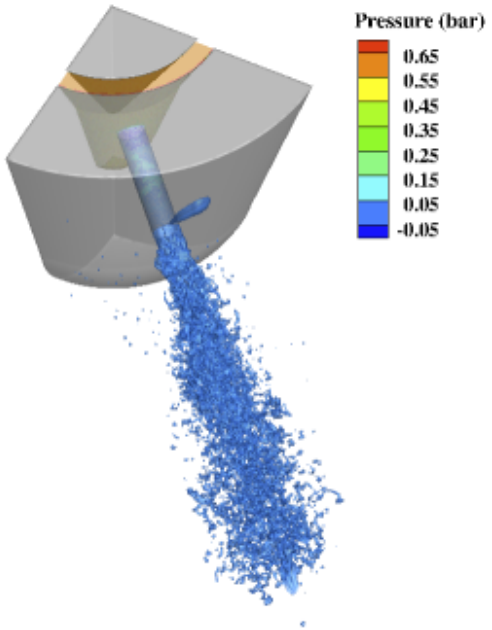
Positive match within the limits of under-resolved turbulence

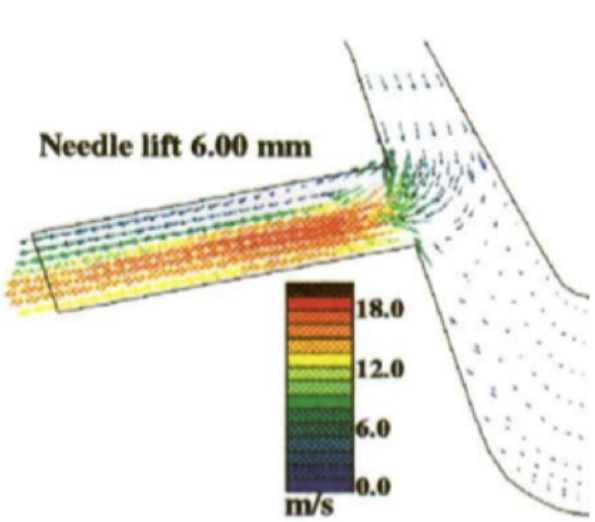


[Arcoumanis et al., *SAE Technical Series*, 980911, 1998]

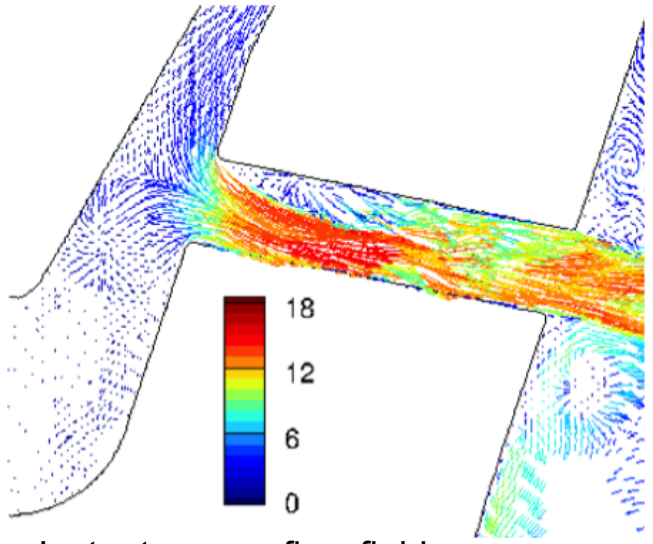


Six-hole 20x Bosch Diesel injector





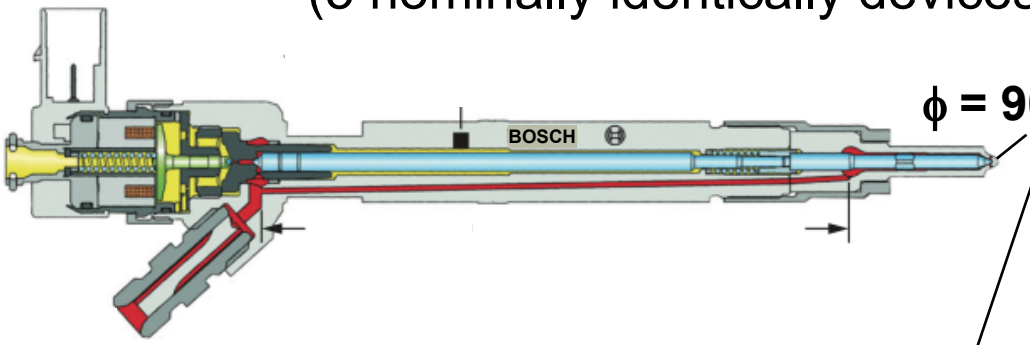
RANS velocity flow field from Arcoumanis et al. (1998)



Instantaneous flow field from current simulation

Does simulation need to include manufacturing defects?

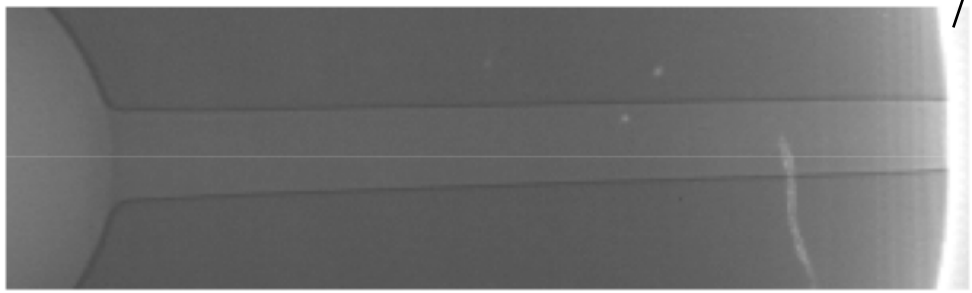
Spray A: a second-generation Bosch common-rail injector
(5 nominally identically devices donated to ECN)

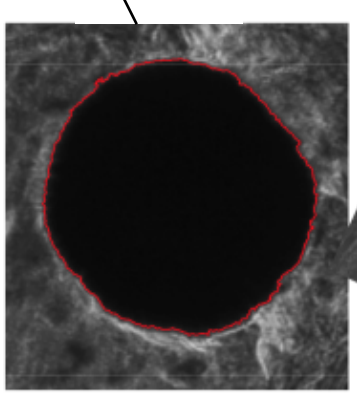


ϕ = 90 μm

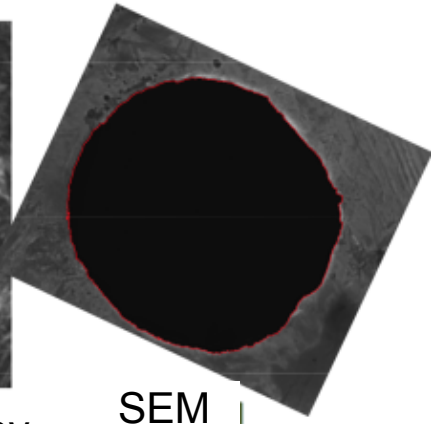
Orifice exit: holes are elliptical at the outlet, not round (2-7 μm)

Phase contrast imaging of the orifice:
the orifice is misaligned w.r.t. the injector and has irregular taper





Optical microscopy



SEM