SAE International Conference on Engines and Vehicles
Capri, Italy, September 11th – 15th, 2011

SAE 2011-24-0096

Mixture Formation in Direct Injection Hydrogen Engines: CFD and Optical Analysis of Single- and Multi-Hole Nozzles

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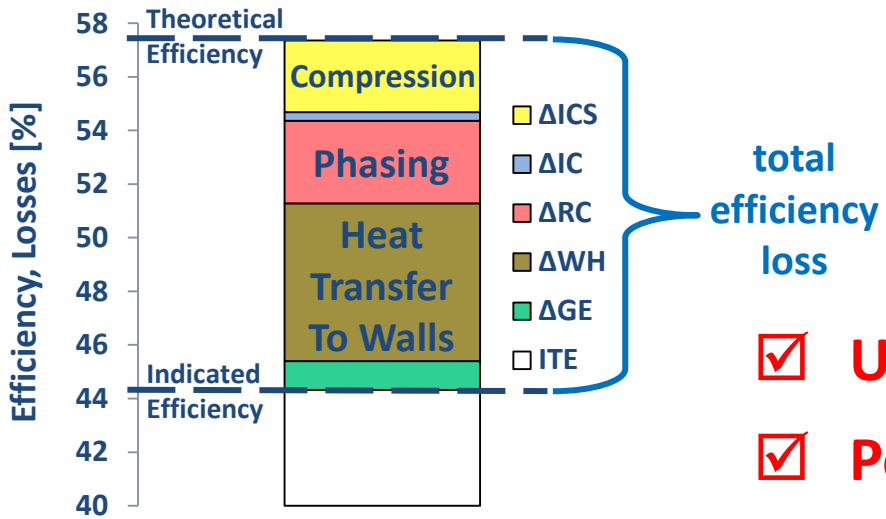
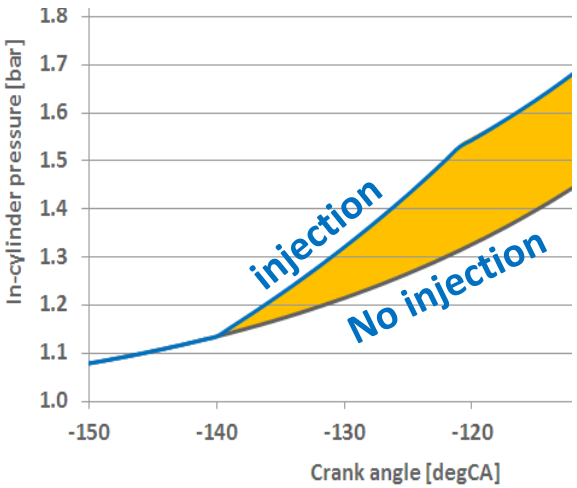
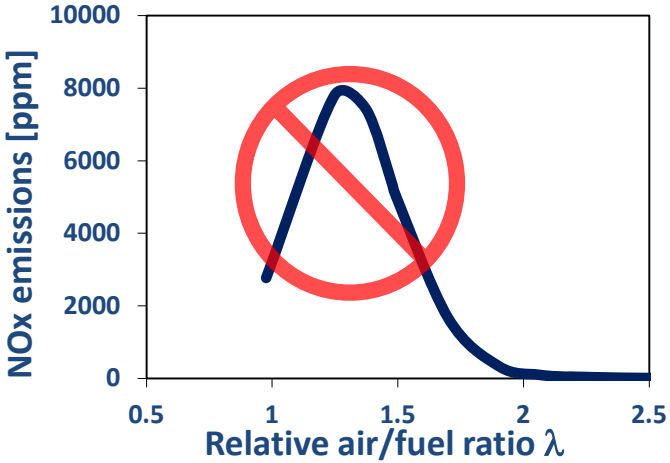
DI H_2 Engines: Objectives

1. Maximize Brake Thermal Efficiency

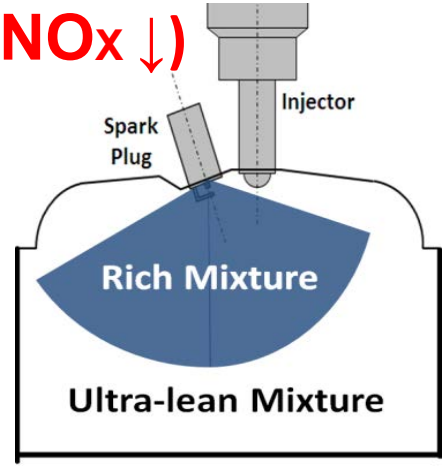




2. Minimize NOx Emissions

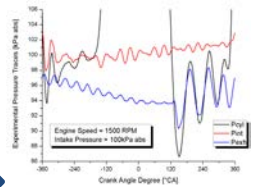


- ☑ **Ultra-Lean Burn ($\eta_{theoretical}$ ↑, NOx ↓)**
- ☑ **Perform Late Injection (ΔICS ↓)**
- ☑ **Optimize Mixture Stratification (ΔWH ↓, ΔRC ↓, NOx ↓)**



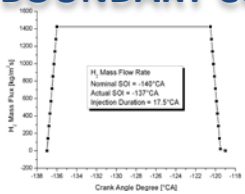
SAE 2011-24-0096 "Mixture Formation in Direct Injection Hydrogen Engines: CFD and Optical Analysis of Single- and Multi-Hole Nozzles"

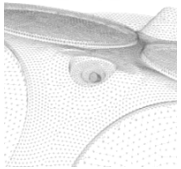
DOE Funded DI H_2 Engines Program: Approach



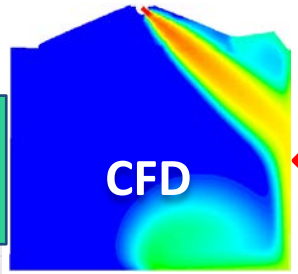
BOUNDARY CONDITIONS

ICE





45% BTE
NOx within Tier2-Bin5



CFD

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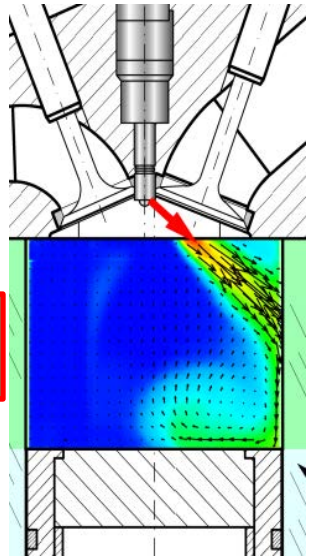
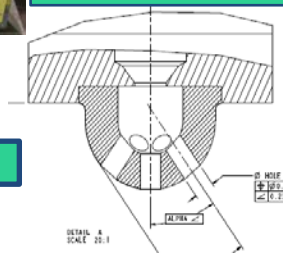
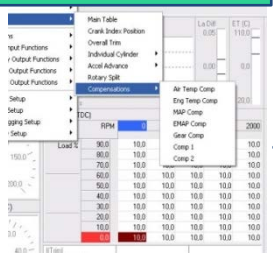
Validation

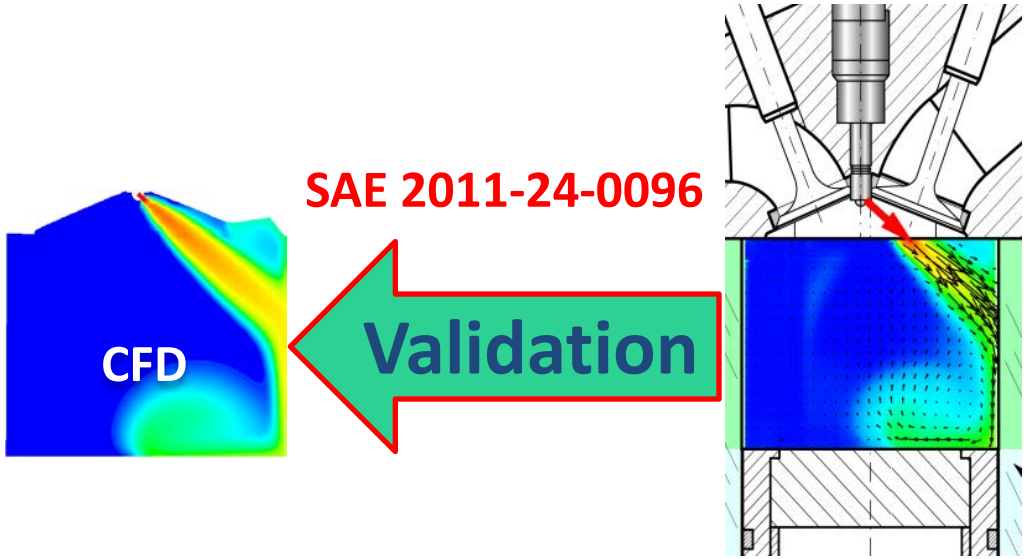






ENGINE OPTIMIZATION

DOE Funded DI H_2 Engines Program: Approach



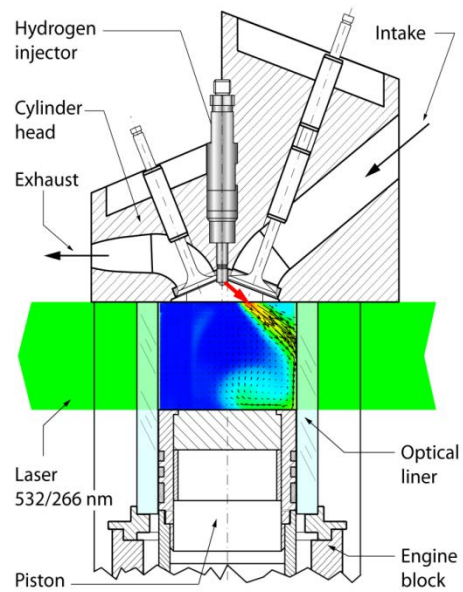
Argonne NATIONAL LABORATORY

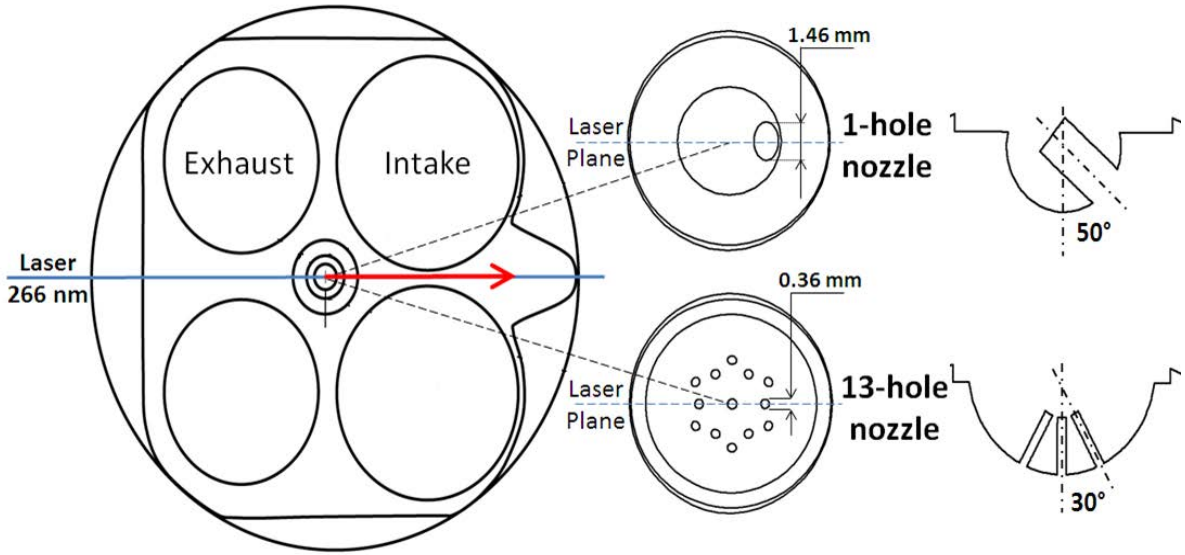
Sandia National Laboratories

Experimental Setup

Single-cylinder Optical Engine (SANDIA)

- 0.56 liters displacement (passenger car)
- Bore / stroke 92 / 85 mm
- Engine speed 1500 RPM
- Compression Ratio 11:1
- N_2 as bulk gas (to prevent ignition)
- Acetone used as a tracer (PLIF)
- *2 different nozzles (single-hole, 13-holes)*
- *Inj. Pressure 100 bar, 86 bar, 25 bar*
- *Phase-Locked Imaging (No high-speed data)*





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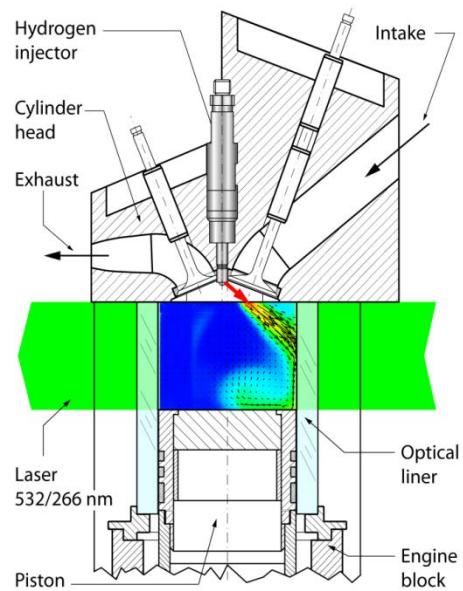
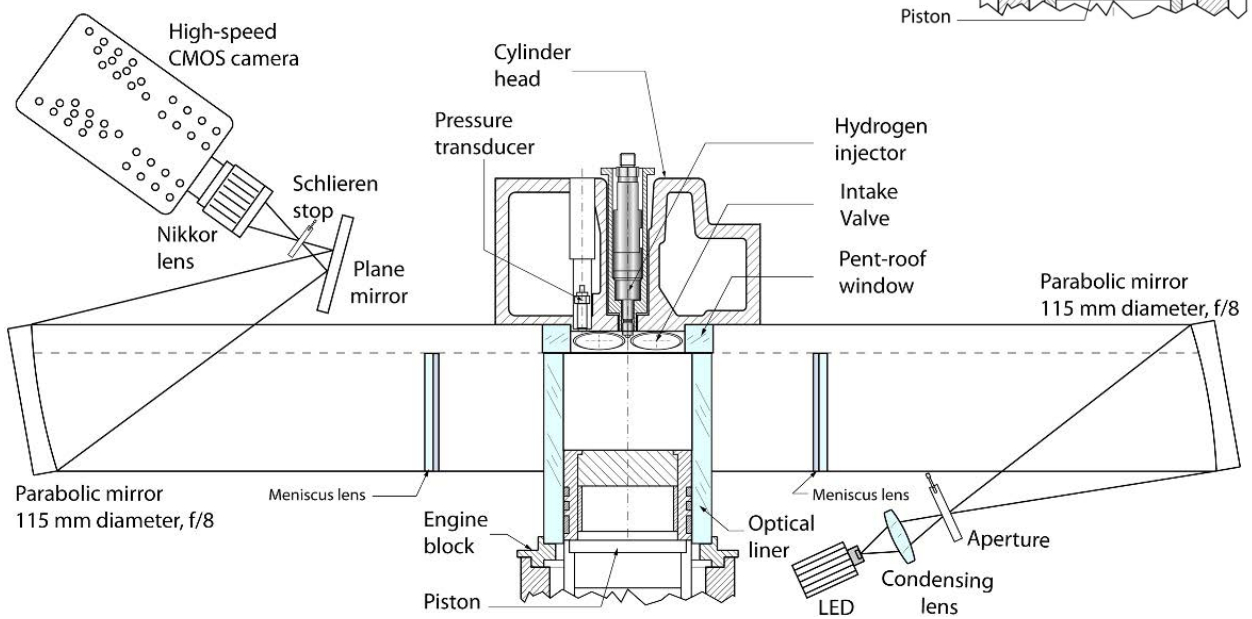
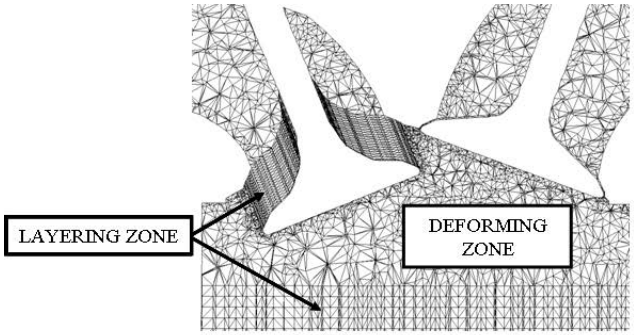
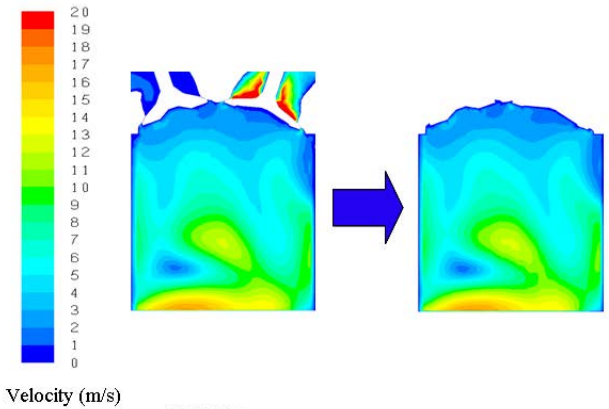
- Engine speed 1500 RPM
- Compression Ratio 11:1
- N_2 as bulk gas (to prevent ignition)
- Acetone used as a tracer (PLIF)
- *Schlieren High-Speed Imaging*
- *0.5° CA resolution*

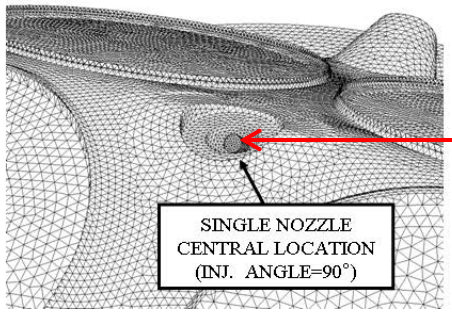




Numerical Approach







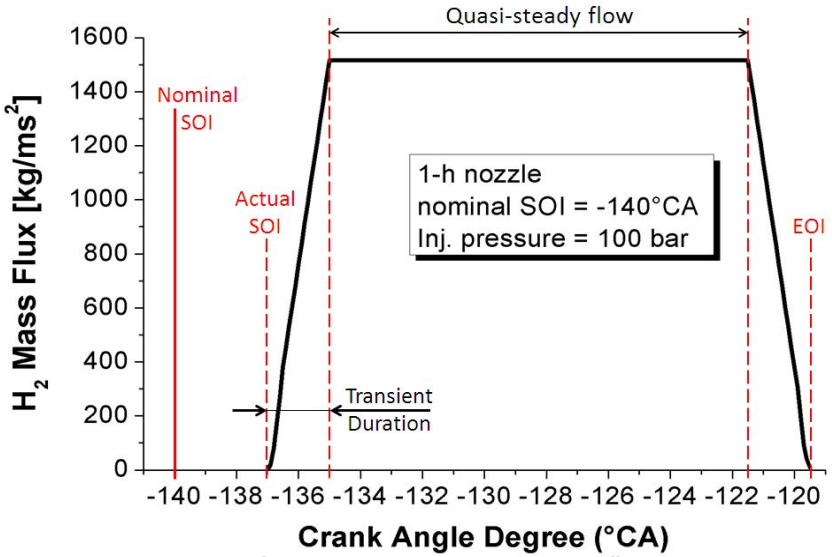
Fluent + RANS

1. Gas-exchange simulated by full-geometry grid (from EVO to IVC)
2. Information exchange between full and reduced grids at IVC
3. Mixture formation simulated by reduced grid (from IVC to TDC)

Critical Issues

- Re-Meshing algorithm (full grid) needs improvement
- No adaptive mesh refinement 1 (globally fine mesh)
- No adaptive mesh refinement 2 (jet-oriented mesh close to nozzle)
- Inlet BC needed, but injection profile is unknown → Calculated by experimental data and assumed as trapezoidal

Inlet BC



Previous Results (Single-Hole Nozzle, 100 bar) **

** R. Scarcelli, T. Wallner, N. Matthias, V.M. Salazar, S.A. Kaiser, SAE 2011-01-0675

Global Results

- Simulations correctly predict fuel injection and mixture formation
- Jet penetration is predicted better than fuel dispersion

Influence of Grid

- Results on mixture formation are grid–independent at 1,400,000 cells
- Grid resolution (near-nozzle) has strong influence on jet penetration

Influence of Turbulence Model

- The k-ε formulations (Standard, Realizable, RNG) provide similar results
- k-ε Realizable yields the best agreement
- Tuning the k-ε model improve results only quantitatively

Identified Improvements

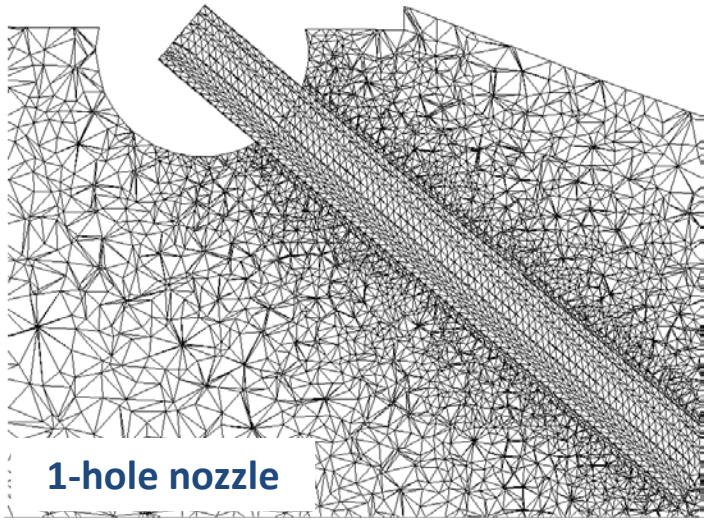
- High-speed imaging helps to validate the injection profile assumption
- Near-nozzle grid refinement provides higher detail of the under-expanded region

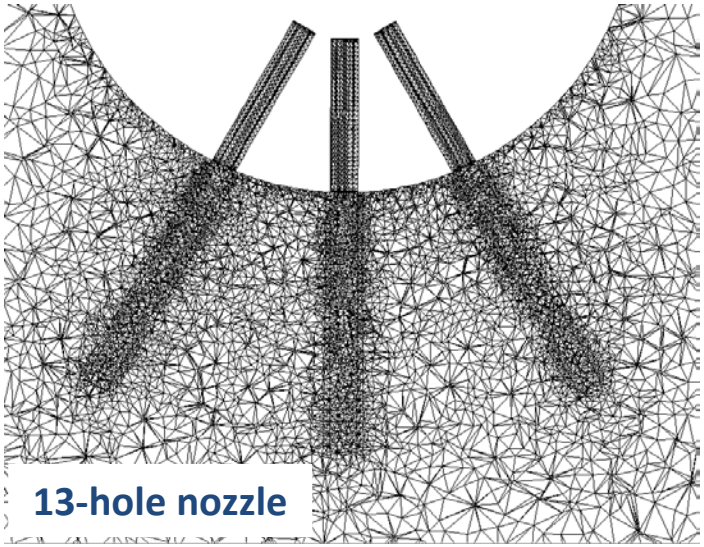
Test Cases

Engine Speed = 1500 RPM – Load = 2.5 bar IMEP

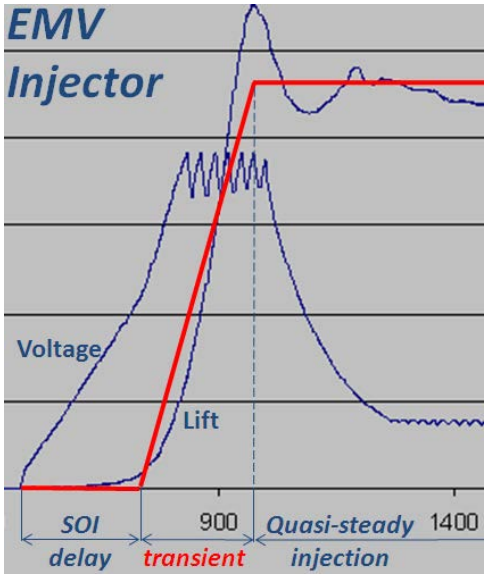
	Test Case 1	Test Case 2	Test Case 3
Nozzle	1-h	1-h	13-h
Hole Diameter	1.46 mm	1.46 mm	0.36 ÷ 0.38 mm
Tot. Inj. Surface	1.67 mm^2	1.67 mm^2	1.33 mm^2
Injection Pressure	100 bar	25 bar	86 bar
Nominal SOI	-140°CA	-137°CA	-140°CA
Actual SOI	-137°CA	-134°CA	-137°CA
Injection duration	17.5°CA	74.5°CA	21°CA

- Optimized Mesh (Refined near-nozzle, coarse overall) 850,000 cells (1 hole) – 1,200,000 cells (13 holes)
- Realizable k-ε model
- Time step corresponding to 0.1° CA during injection
- EMV Injector has a SOI delay of 3° CA @ 1500RPM
- Instantaneous mass flow rate unknown. Assumed trapezoidal profile. Transient Duration??

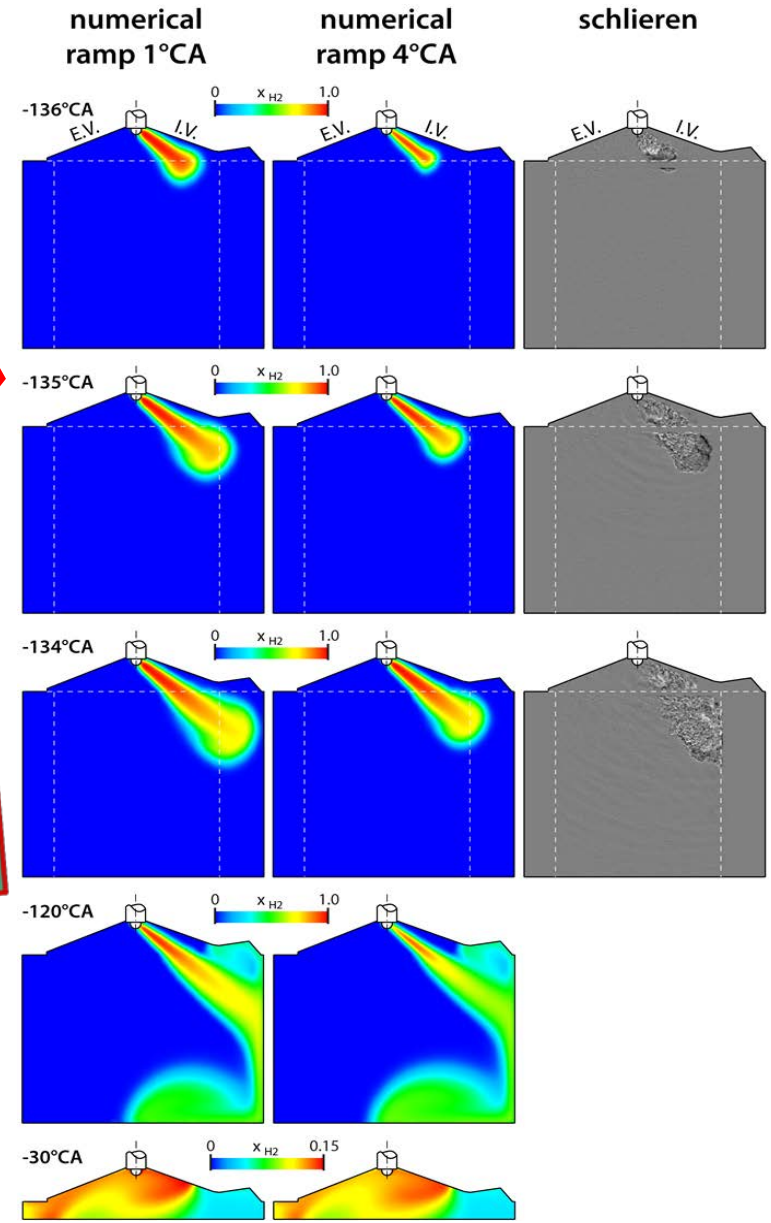




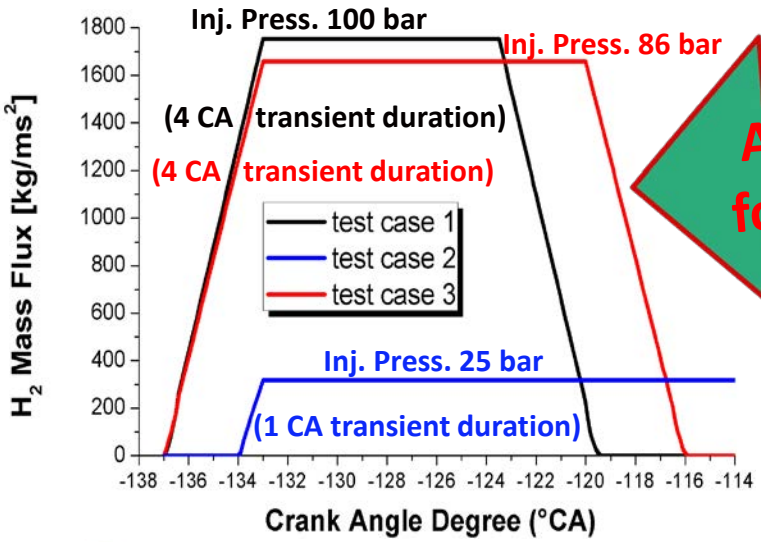
Boundary conditions and jet transient



Validation on Test case 1



Assumption for cases 2 -3

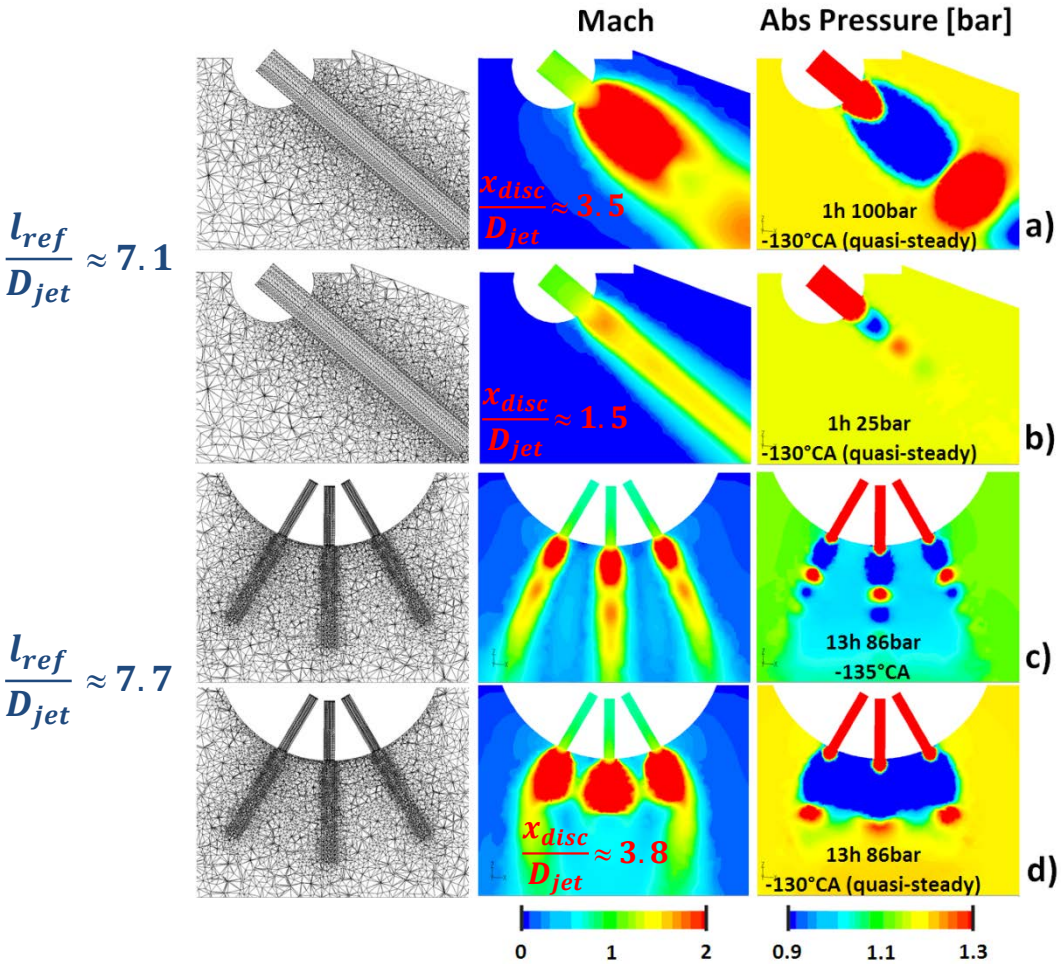


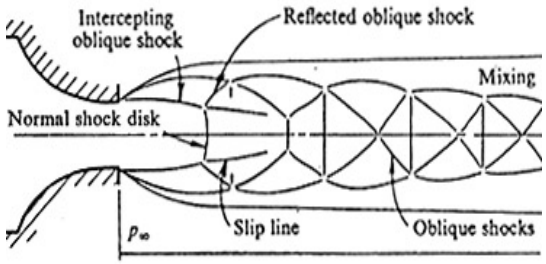
Under-expanded supersonic jets

Injection pressure = 25 ÷ 100 bar

Ambient pressure ≈ 1 bar

p2 /p1 >> 1.889 (H_2) ⟹ Supersonic Jet





(Donaldson and Snedeker, Journal of Fluid Mechanics, 1971)

$$\frac{x_{disc}}{D_{jet}} = 0.67\sqrt{\frac{p_{inj}}{p_{amb}}} \text{ ** } = \cancel{6.7} = 3.5$$

$$\frac{x_{disc}}{D_{jet}} = 0.67\sqrt{\frac{p_{inj}}{p_{amb}}} = \cancel{3.35} = 1.5$$

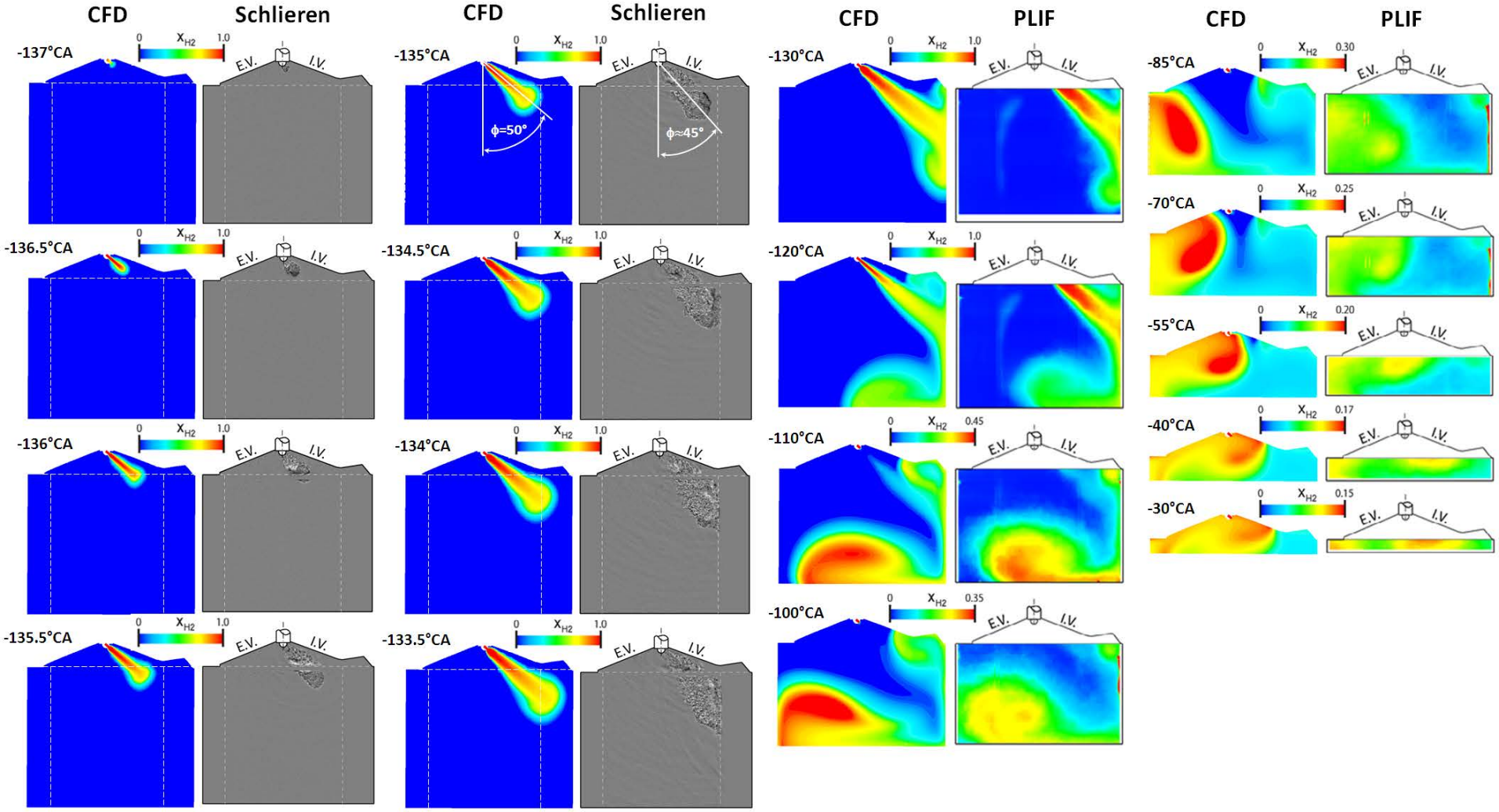
p inlet ≠ p injection

p inlet calculated by Fluent

$$\frac{x_{disc}}{D_{jet}} = 0.67\sqrt{\frac{p_{inj}}{p_{amb}}} = \cancel{6.2} = 3.8$$

** Ashkenaz and Sherman, Rarefied Gas Dynamics, 1966

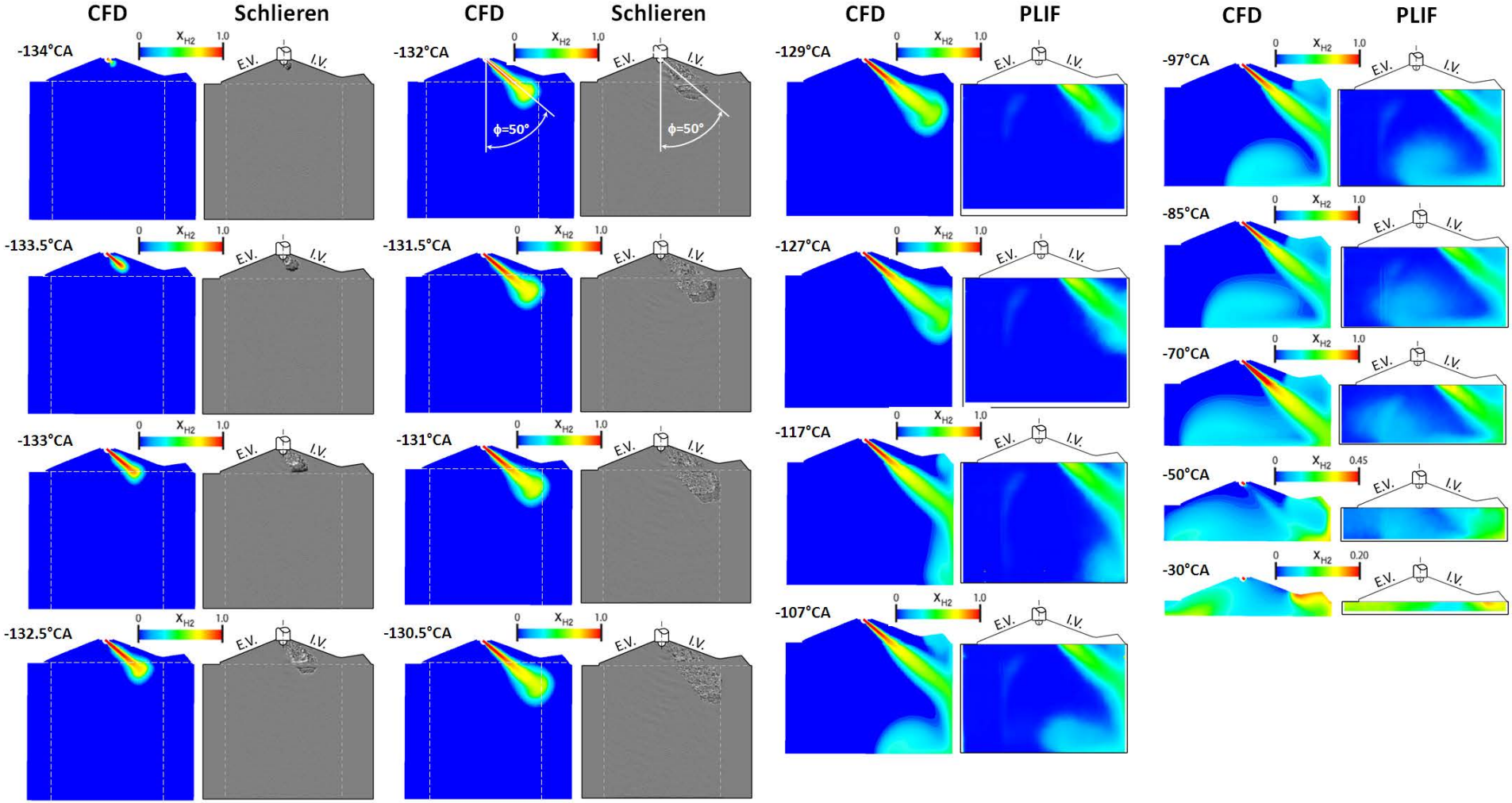
Validation (1/3): Test Case 1 (1h, 100 bar)



- Assumed transient is consistent with exp. data
- Remarkable match during entire compression
- Prediction of fuel dispersion is satisfactory

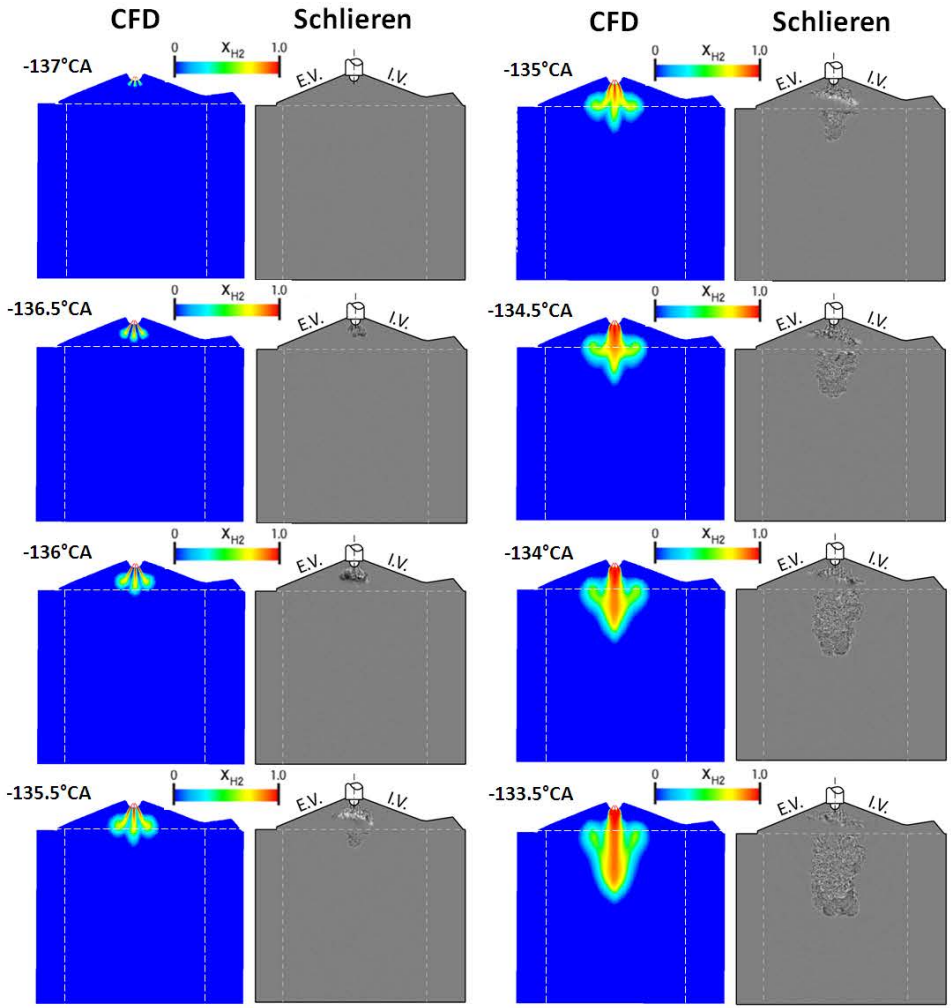
- Jet direction not perfect
- Transient is not linear
- Jet behavior along walls has to be improved

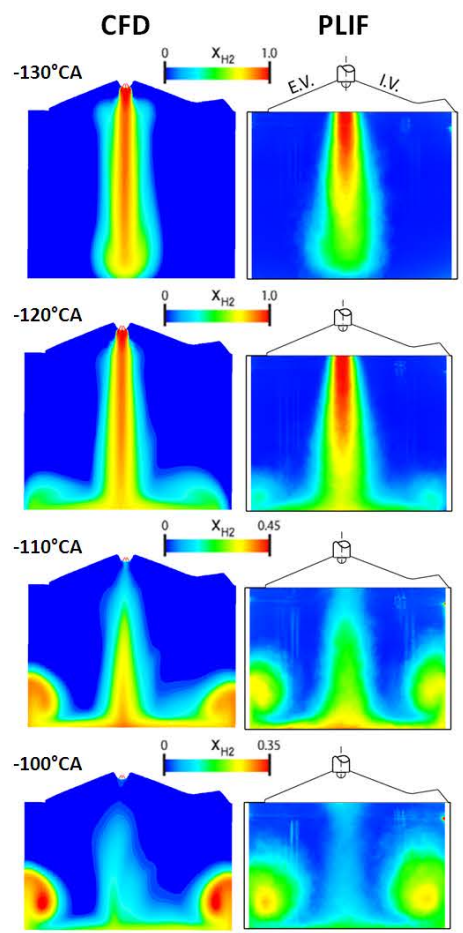
Validation (2/3): Test Case 2 (1h, 25 bar)

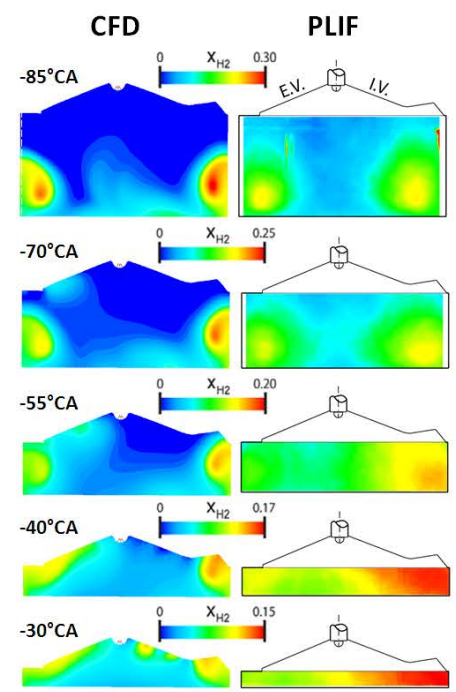


- 👍 Assumed transient is consistent with exp. data
- 👍 Prediction of fuel dispersion improves
- 👍 Jet direction matches exp. data
- 👎 Transient is not linear
- 👎 Jet behavior along walls has to be improved

Validation (3/3): Test Case 3 (13h, 86 bar)







- Assumed transient is consistent with exp. data
- Remarkable match only during injection

- Transient is not linear
- Fuel dispersion is not accurately predicted
- Jet interaction prediction is not accurate
- Jet behavior along walls has to be improved

How to improve these results?

- **Improve the description of jet impingement on the walls**
  - Increase mesh resolution at the walls
  - Use advanced wall treatment
- **Improve the prediction on fuel dispersion (interacting jets)**
  - Increase accuracy of the under-expanded region (super-fine computational grid in the near-nozzle region)
  - Switch to Large Eddies Simulations
- **Improve the description of injection profile (rate of injection)**
  - Simulate the in-nozzle flow (Nozzle geometry and lift needed)
  - Compare with high-speed data (Schlieren – X-rays)

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The Advanced Photon Source at Argonne can provide high-accuracy data on mass distribution through X-rays

Conclusions

- CFD is an effective development tool for DI H2 Engines (a new nozzle can be tested in less than 1 day through simulations)
- Mixture formation process is overall well predicted by CFD
- Non-interacting jets show remarkable results in terms of jet penetration and final mixture stratification
- Interacting jets suffer from low fuel dispersion. Penetration is correctly predicted
- Higher grid resolution (near nozzle and at cylinder walls) is a key to improve numerical prediction
- Injection profile can have a significant impact on fuel dispersion, especially for interacting jets (need to remove assumption and calculate it correctly)
- Higher accuracy will require higher-fidelity (LES) approach

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