Sandia Optical Hydrogen-fueled Engine
Project ID: ACE 003

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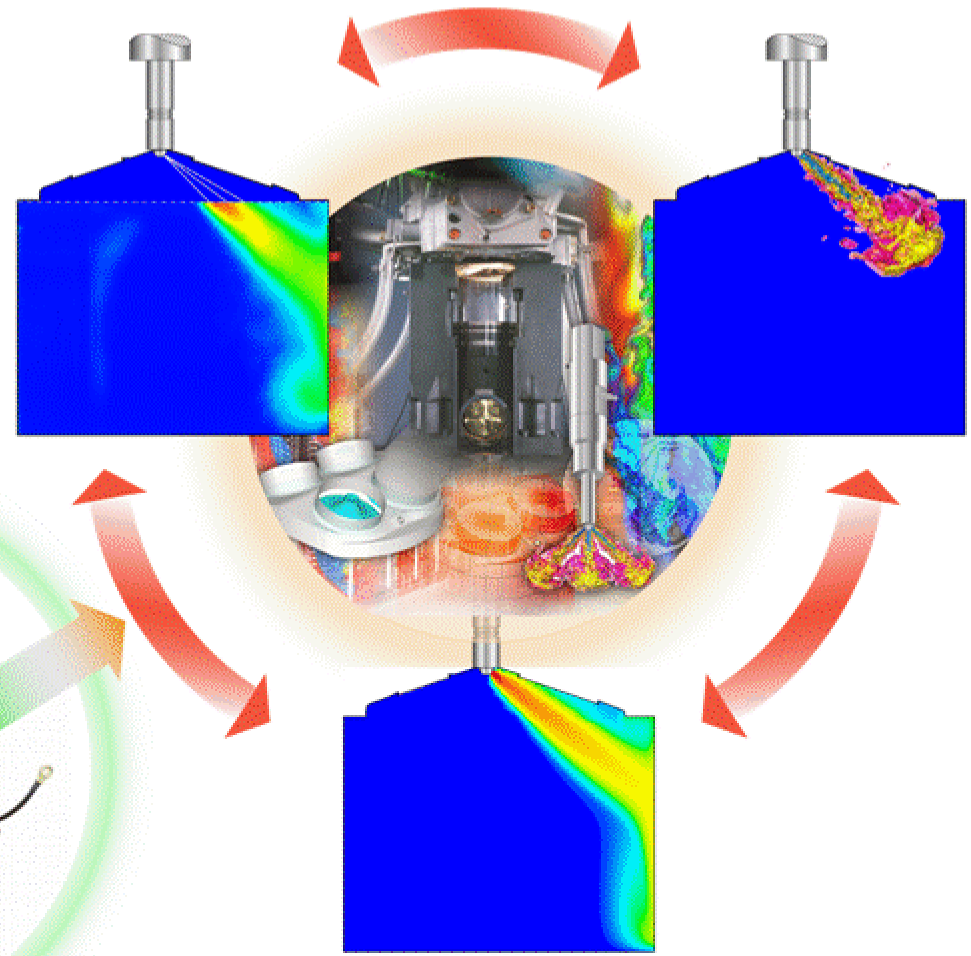
Sandia National Laboratories



Sponsor:

DOE / OVT

Program Manager:

Gurpreet Singh

Overview: This project partners with Ford, ANL, and LLNL to address the barriers of DI H_2ICEs.

Timeline:
- Project provides fundamental research that supports DOE / industry hydrogen-engine development projects
- Reviewed annually by DOE and industry

Budget:
- Fully funded by DOE / VT on a year-by-year basis
- FY 09: $450k
- FY 10: $620k

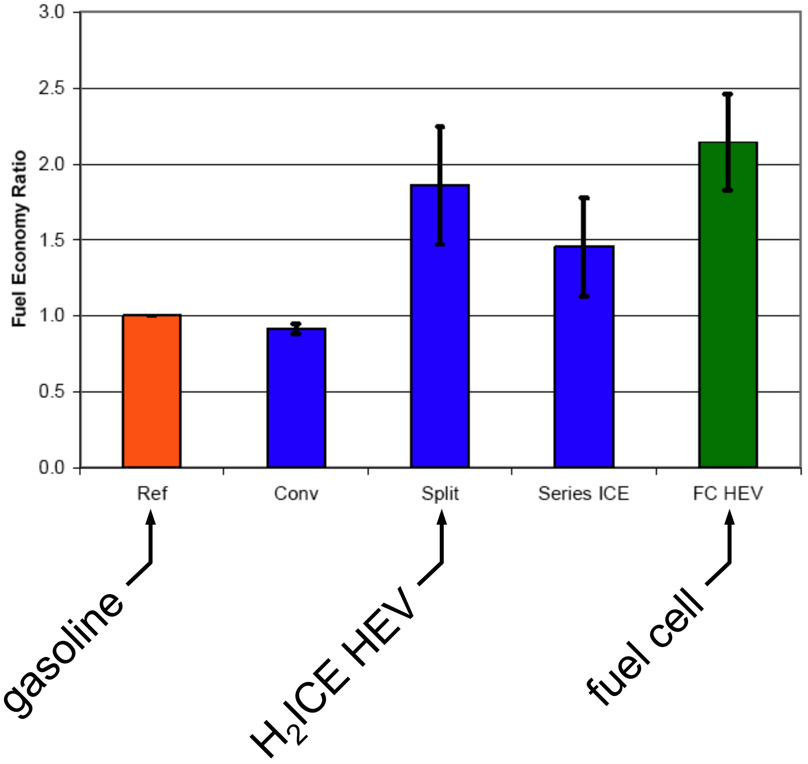
Barriers addressed:
- Lack of fundamental knowledge about in-cylinder processes in hydrogen DI engines.
- Unique, sparsely-studied combustion regimes

Partners:
- Ford Motor Company (metal engine w/ turbo), BMW
- Argonne Nat'l Lab (metal engine, industry-type CFD)
- Lawrence Livermore Nat'l Lab (CFD, sub-model development)

Vehicles with advanced hydrogen-fueled engines are competitive with systems based on fuel cells.

- Hydrogen engines build on existing, mass-produced, cost-effective technology.
- Advanced high-efficiency hydrogen engines are based on direct injection (DI).
- Higher power density, better efficiency, lower NOx are possible with DI.
- Relies on control over fuel-air mixing despite complex flow and short time scales

Vehicle-system modeling by ANL*



Insight into in-cylinder processes needed → Optical engine, Simulation

*Rousseau et al., SAE-paper 2008-01-2378

Approach: Data from optical engine provide physical understanding and simulation validation.

Numerical Simulation
ANL, LLNL, Sandia

Optical Measurements
Sandia

Metal Engine
Argonne
Ford (not DOE funded)

- Automotive-sized optical engine
- Spatially resolved measurements of in-cylinder processes
  - Fuel distribution
  - Flow field
  - Combustion

Fuel distribution, Flow field: Mixture formation

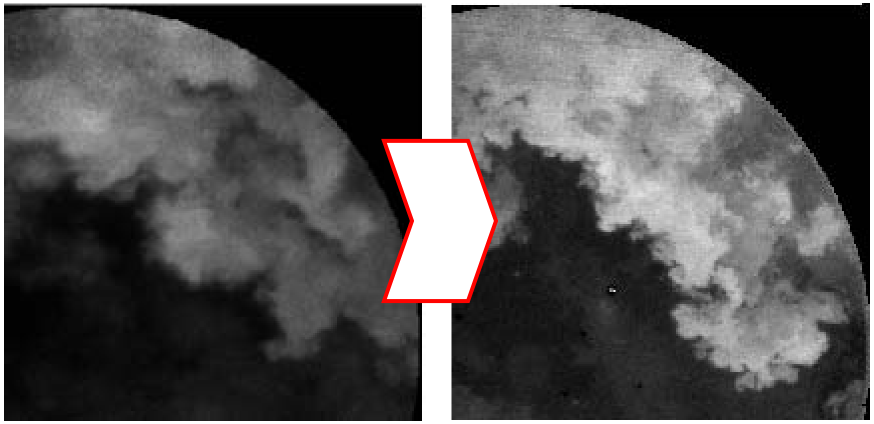
Goals:

Fundamental understanding of in-cylinder processes in H2ICEs

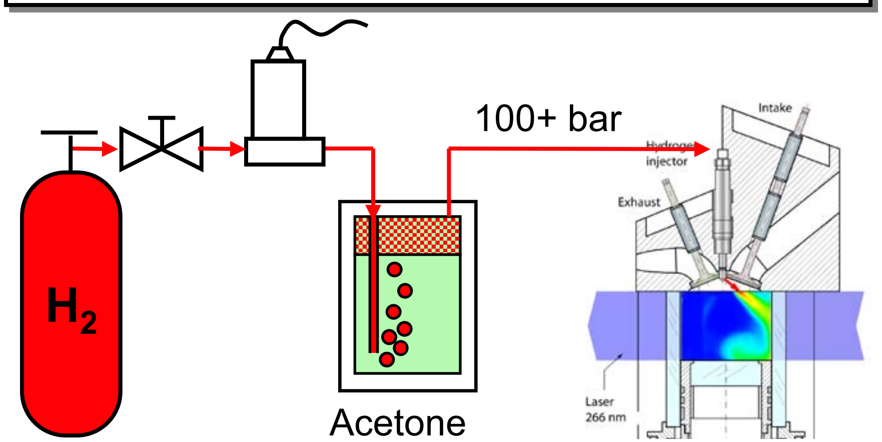
Predictive design capabilities through validated simulations

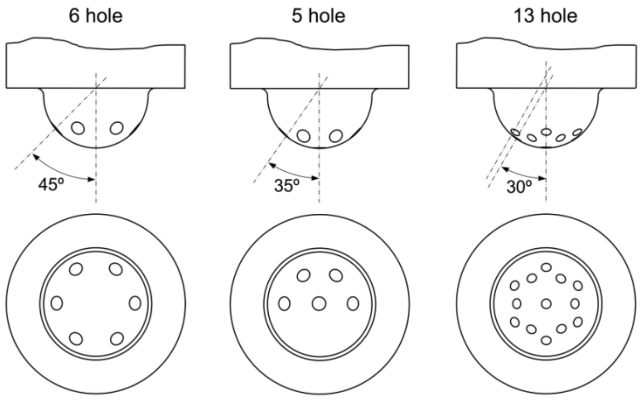
Expand science base for both gas and liquid-fueled engine development

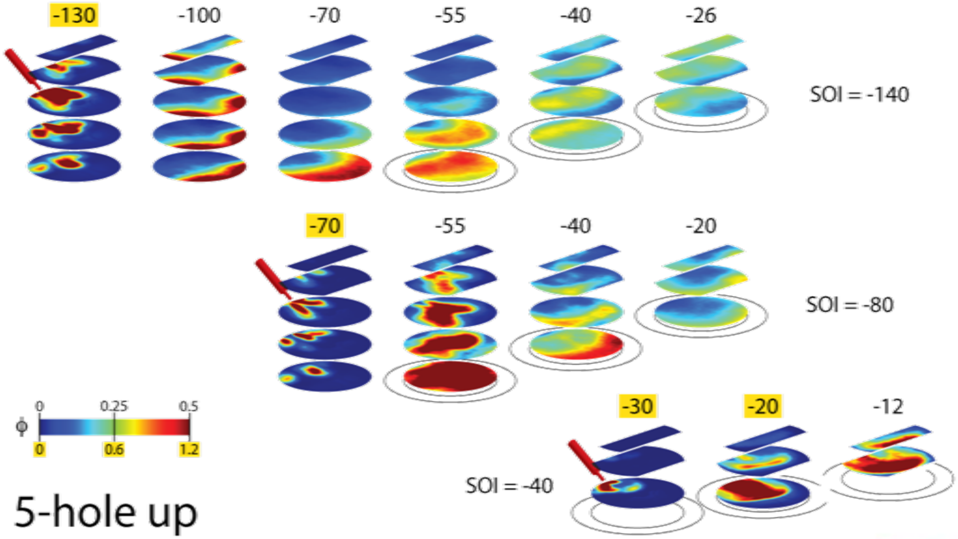
Last year, accurate fuel imaging was developed and used to study multi-hole injectors.



Improved diagnostics and tracer seeding enable accurate fuel imaging at any injection pressure.







This year, we focused on collaborative simulation validation using a simple injector geometry.

Previous reviews suggested more emphasis on developing **predictive tools for design optimization**.

Working with Argonne and Lawrence Livermore to **validate industry-type 3-D CFD** for DI-H2ICE.

The project needs to be more integrated with simulation before the results can be used for engine design.

2008 reviewer

…would like to see much more simulation.

2009 reviewer

The optical-engine flow-field study is good, but time consuming. If the study were combined with 3D modeling the effects would be better.

2009 reviewer

Sandia Objectives:

- Support and coordinate simulation initiation and validation
- Provide optical data to examine areas of concern for simulations:
  - Walls
  - Base flow field
  - Flow / injection interaction

Detailed study of mixture preparation in **simple, yet instructive configuration**

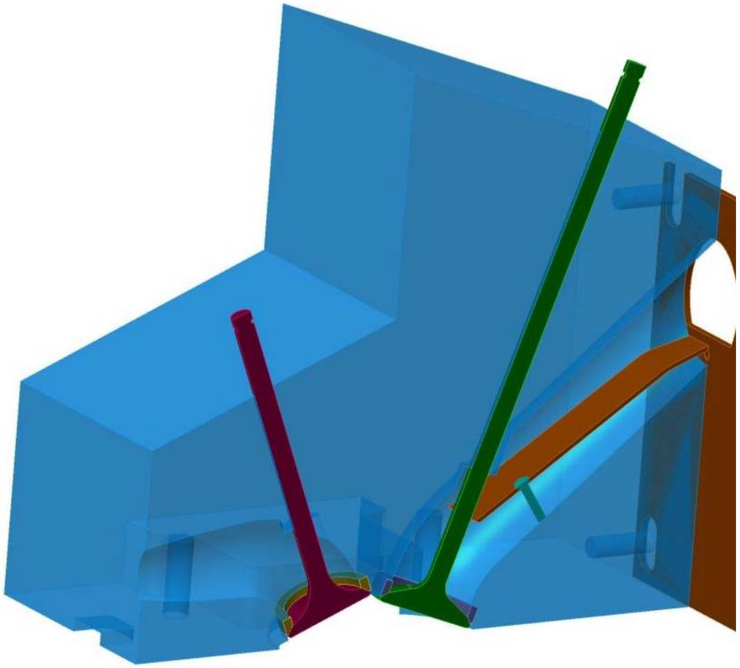
Three accomplishments will be discussed.

1) A data package for simulation initiation, including an accurate solid model of the engine head, was assembled.

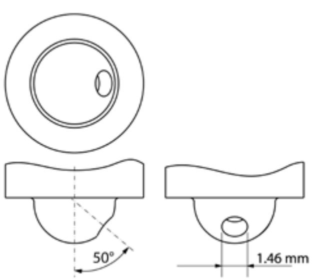
2) The interaction of intake-induced flow and injection was assessed by quantitative, wide-field imaging of fuel concentration and flow field.

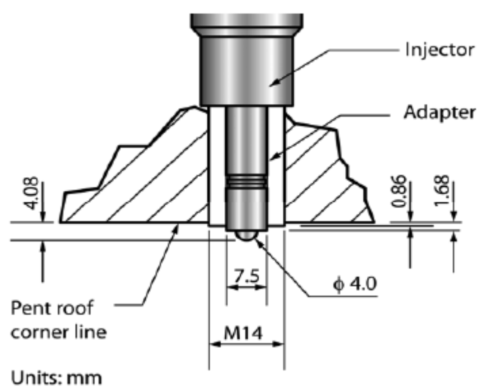
3) Cross-comparison of two simulations, performed independently by collaborators, with experimental data was coordinated to advance predictive capabilities.

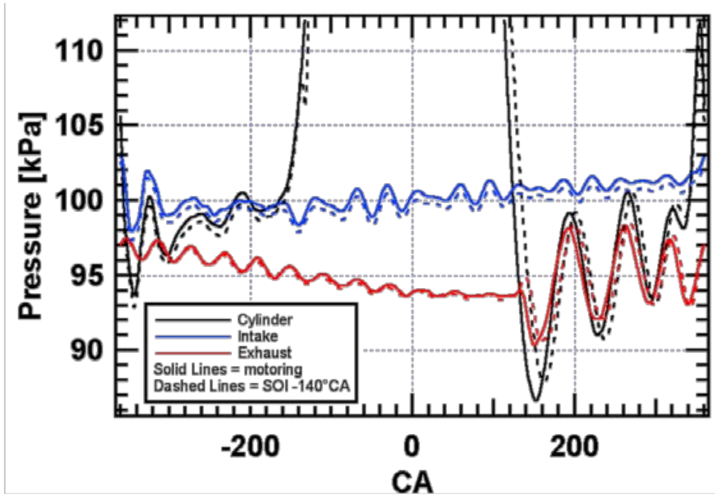
(1) An engine data package, including a detailed solid model of the head, was assembled.



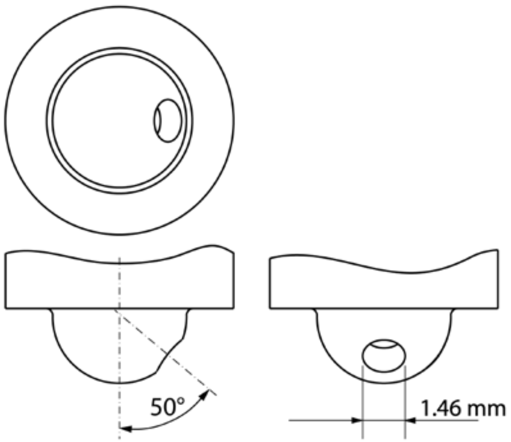
Engine head solid model
+
Other geometry
Flow rates
Valve and injector timings
Pressure traces
Temperatures

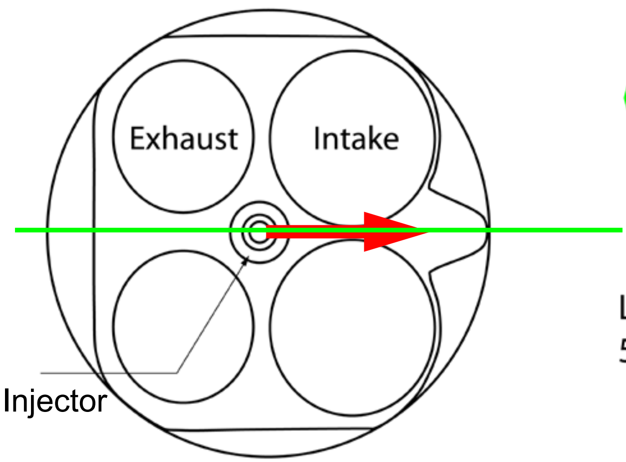




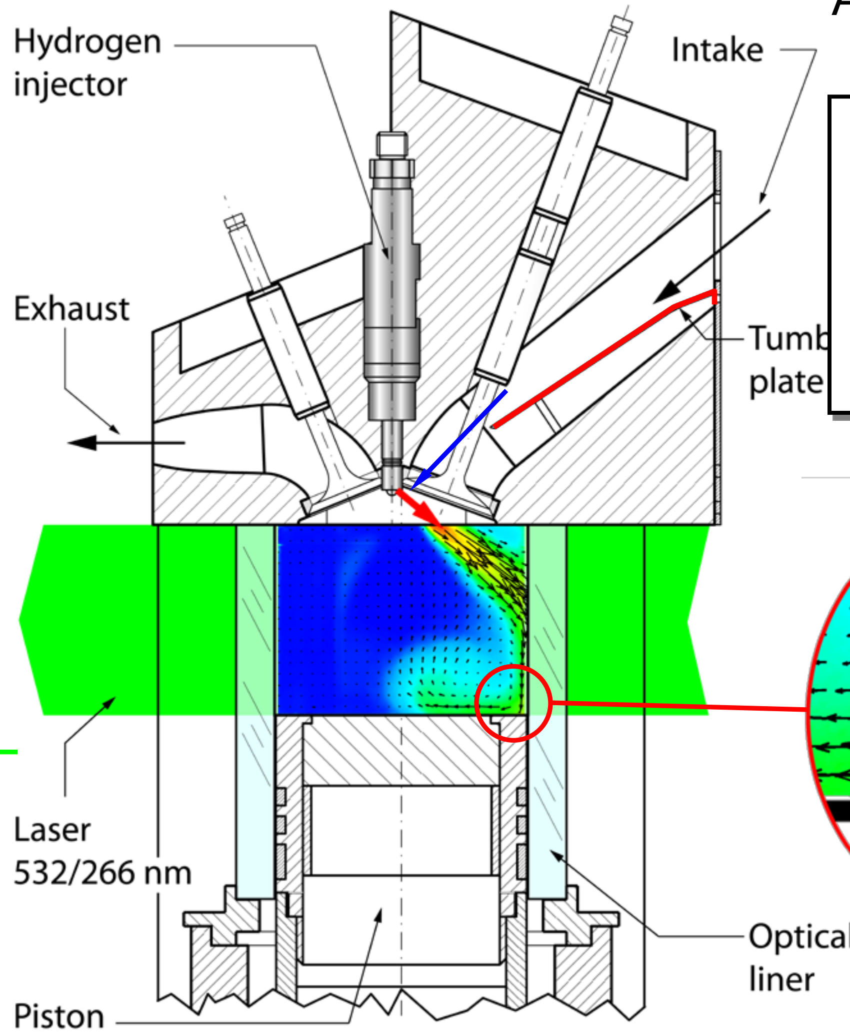


(2) A single-hole injector avoids jet-jet interaction. Measurements ideally suited for simulation validation.



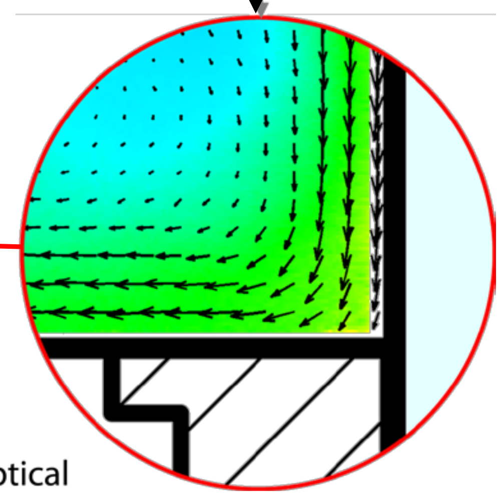


Acetone PLIF + PIV

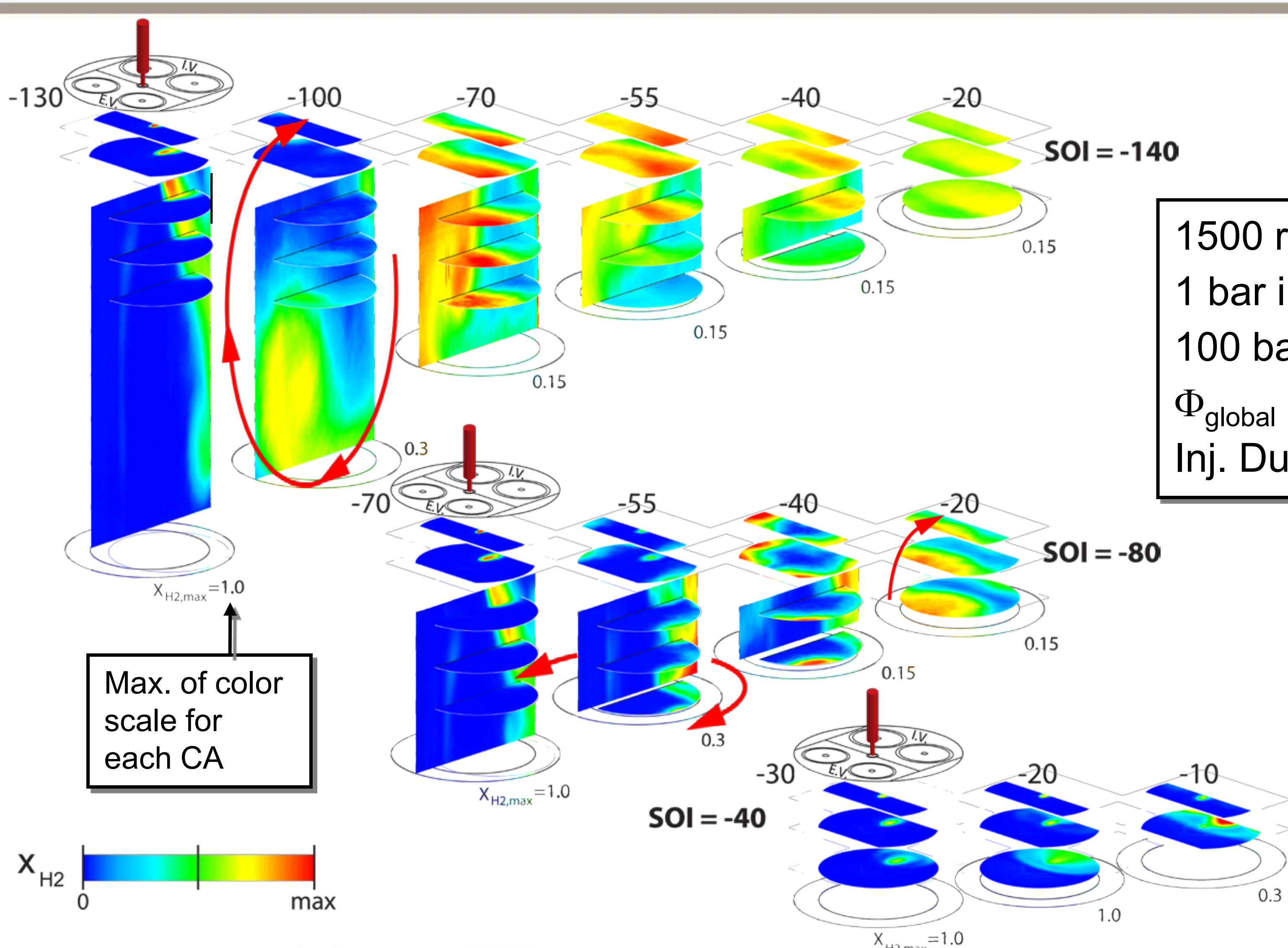


Unique measurements

- full bore & stroke
- almost to walls
- quantitative



(2) Cross-plane imaging of the fuel concentration gives an overview of large-scale convection.



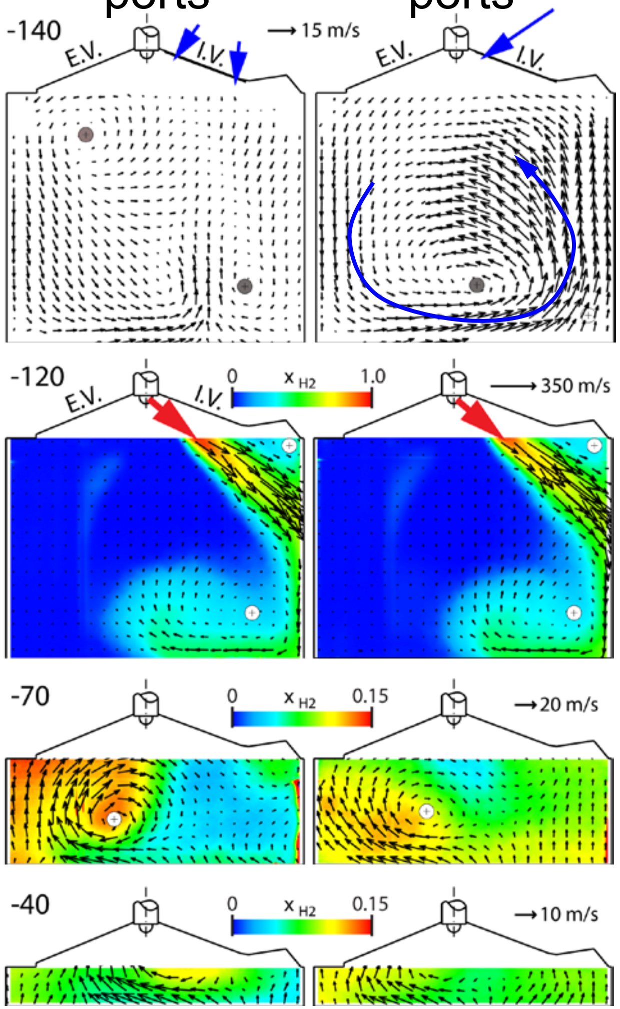
1500 rpm
1 bar intake pressure
100 bar injection p.
Φ_{global} = 0.25
Inj. Duration 17.5ºCA

(2) Enhanced tumble significantly changes bulk convection and mixing.

Just before injection

At the end of injection

During com-pression



SOI = 140ºCA, p_{inj} = 100 bar

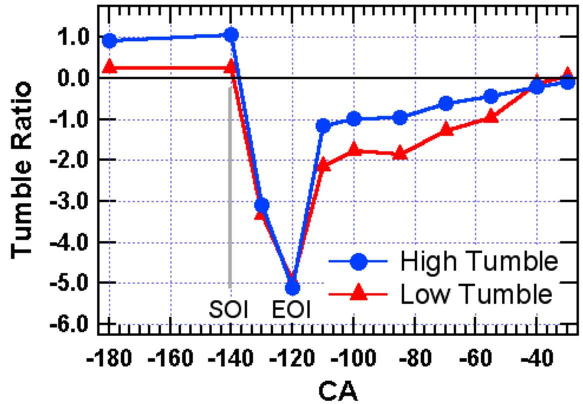
Mean velocity and hydrogen mole-fraction

Intake modification increases tumble by 4x.

Injection and tumble are in counter-flow.

High tumble retards fuel convection and increases mixing.

Injection disrupts flow, but momentum difference high vs. low tumble is preserved.



(2) The wall jet retains the patterns of free jets. This could be important for sub-model extension.

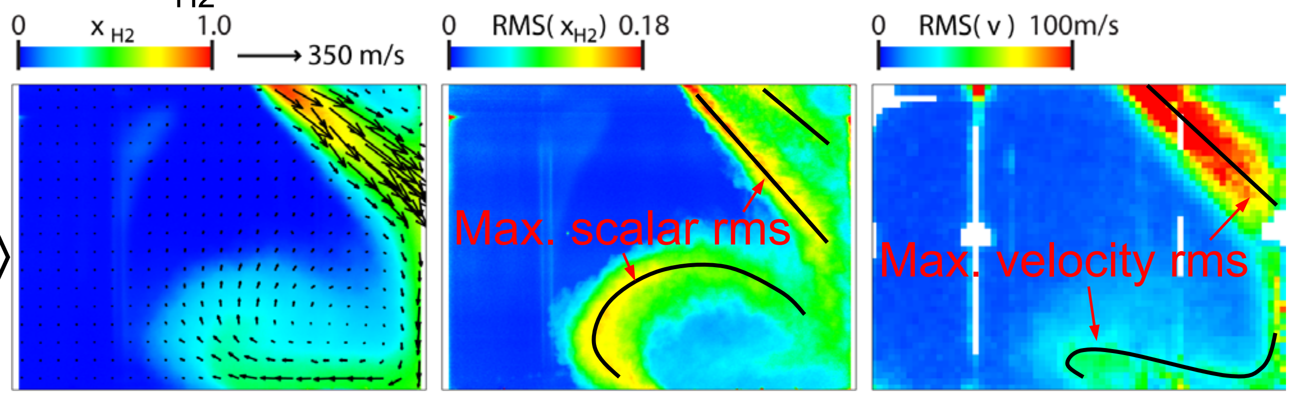
Structural similarities between free jet and transient wall jet

-120°CA
At the end of injection

mean v
mean x_{H2}

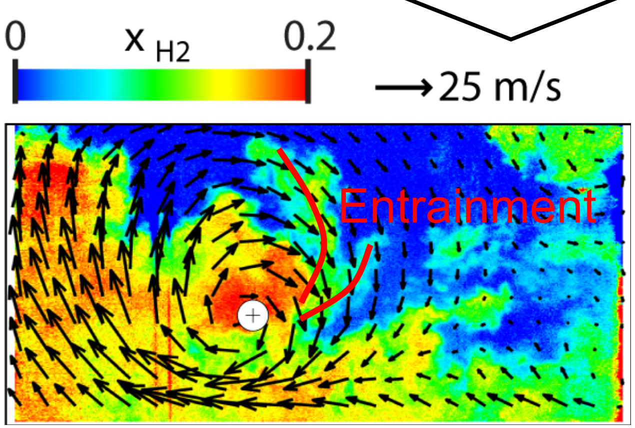
RMS (x_{H2})

RMS (v)



single-shot x_{H2}
mean v

-85°CA



Peak in scalar fluctuations in wall jet is "outside" of peak velocity fluctuation
→ Similar to free jet

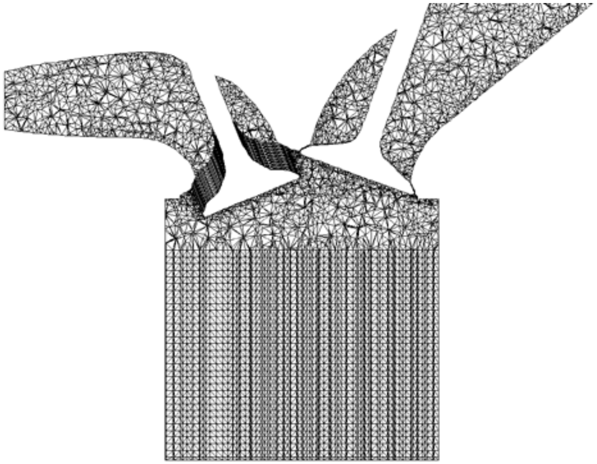
Intermittent fuel-rich structures are at ~45° with respect to mean velocity
→ Similar to free jet

→ **Jet model extension?**

(3) Comparing different CFD approaches promises unique insight into their strengths and weaknesses.

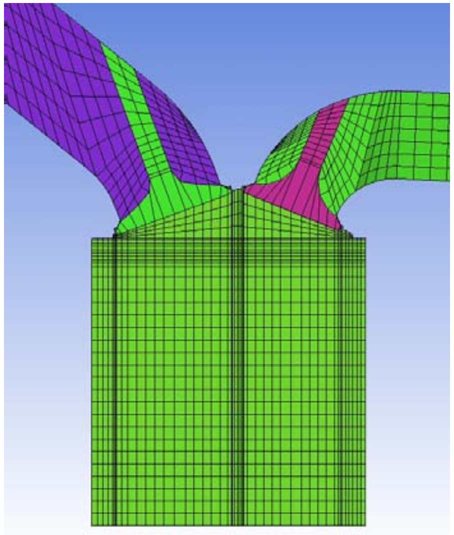
Initiated last review period

FLUENT simulation at Argonne NL.
- Commercial code
- No jet sub-model
- 1.2M gridpoints, parallel on 8 cores
- Partially unstructured mesh
- ICEM-CFD mesh generator



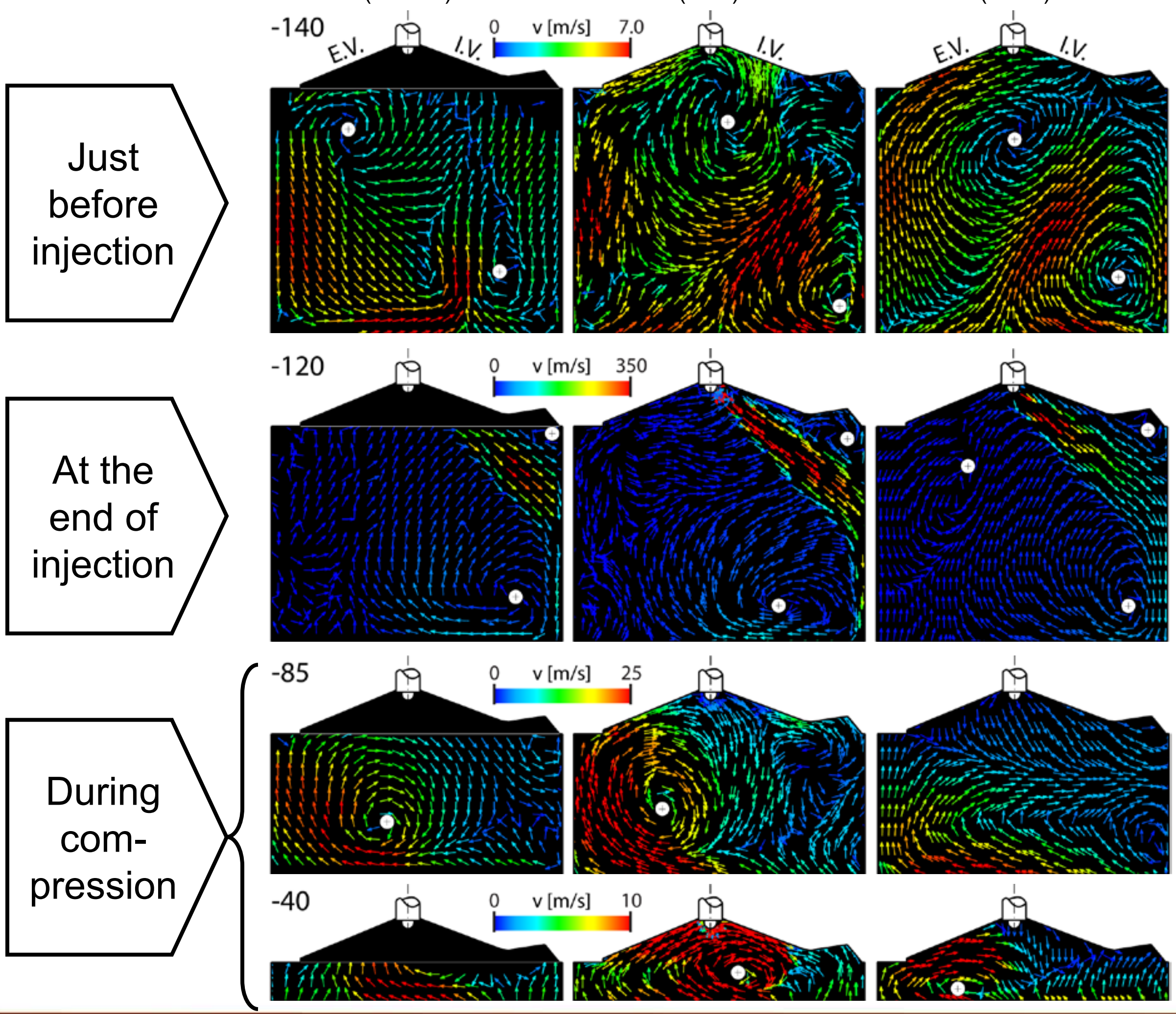
Just started

KIVA 3V simulation at LLNL.
- “Open source” code
- Sub-model for H_2 jet
- 80k gridpoints, single core
- Block-structured mesh
- GAMBIT mesh generator



First target:
Mixture formation with single-hole nozzle,
SOI = -140 ºCA

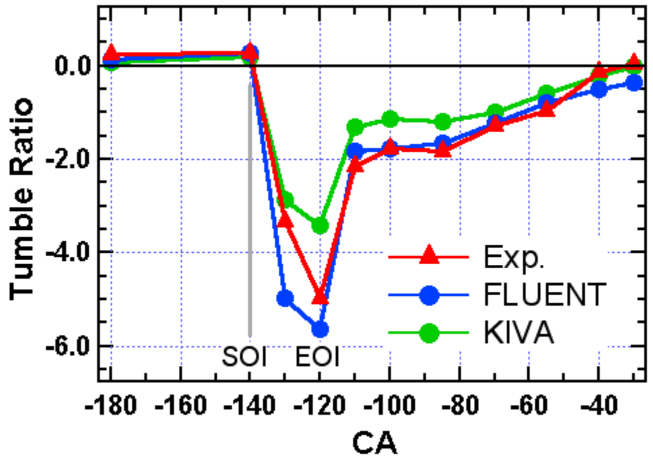
(3) The simulations are able to predict the mean flow field reasonably well.



SOI = 140ºCA, low tumble

Mean velocity

Both simulations predict pre-injection flow accurately.



FLUENT captures convection accurately.

KIVA captures main features OK.

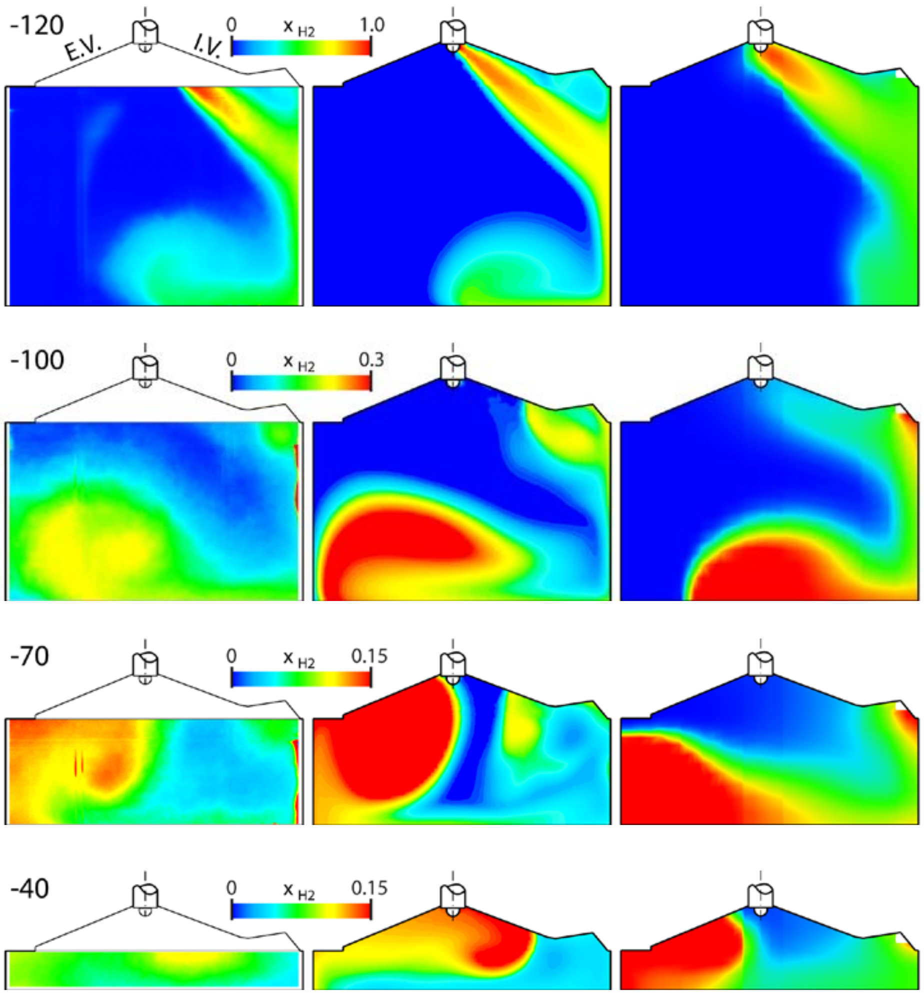
(3) Fuel convection is predicted well by FLUENT. Mixing is under-predicted by both simulations.

Mean hydrogen mole fraction

Experiment (Sandia)	FLUENT (ANL)	KIVA (LLNL)

At the end of injection

During com-pression



LLNL's jet model in KIVA predicts turbulent diffusion in free jet well, but not jet penetration.

FLUENT accurately captures fuel convection, but under-predicts dispersion.

→ Could result in problems for combustion part of simulation

Currently, KIVA sim. is inaccurate in convection and dispersion.

→ May need mesh refinement (only 80k cells now)

Future work will continue to target fundamental issues of H_2ICE combustion in collaborative work.

Support validation of mixture-preparation phase in simulations

- Complete velocity measurements (pent-roof region, horizontal plane)
- Assess refined simulations

Understand stratified hydrogen combustion and pollutant formation

- High-speed imaging of flame front propagation
- Develop diagnostics to examine pollutant formation (NOx, Temperature)

Investigate advanced operating strategies

- EGR, Multiple injections, …
- Gaseous fuels other than H_2 ?

Continue and improve collaborations

- Coordinate work with Ford, ANL, LLNL, and other partners
- Integrate imaging data into Engine Combustion Network

Validate, learn from, and advance simulations

In *summary*, a focus on simulation validation is driving towards predictive tools for H2ICE optimization .

(1) Collaborations with Argonne and Lawrence-Livermore Labs were initiated to advance industry-type 3D CFD as a predictive tool for H2ICE optimization.

- Assembled data package, including detailed engine geometry.
- Coordinated simulation initiation and validation of results by telecommunication and regular H2ICE working-group meetings.

(2) Quantitative imaging of fuel mole-fraction and flow field with a single-hole injector showed interaction of injection and intake-induced flow.

- Enhanced intake-induced tumble significantly alters convection and mixing.
- Both pre-injection flow and small differences in geometry influence mixture formation when changing nozzle pointing *(not discussed in this presentation).*

(3) Unique data set allowed for detailed assessment of the simulations' accuracy in predicting DI mixture formation.

- FLUENT (at ANL) is accurate in fuel convection, underpredicts dispersion.
- KIVA (at LLNL) needs more resolution; convection and dispersion less accurate.