Sandia Optical Hydrogen-fueled Engine
Project ID: ace_03_kaiser

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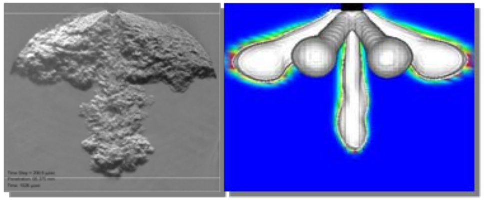
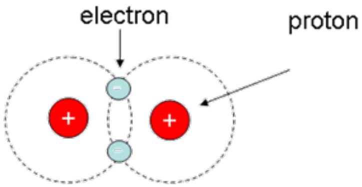


Sponsor:

DOE / OVT

Program Manager:

Gurpreet Singh



Overview: This project partners with Ford and Argonne 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 08: $500k
- FY 09: $450k

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 (new)
- Argonne Nat'l Lab (metal engine, bore-scope optical access)
- Université d'Orléans, France; U New Hampshire (Visiting scientists)

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

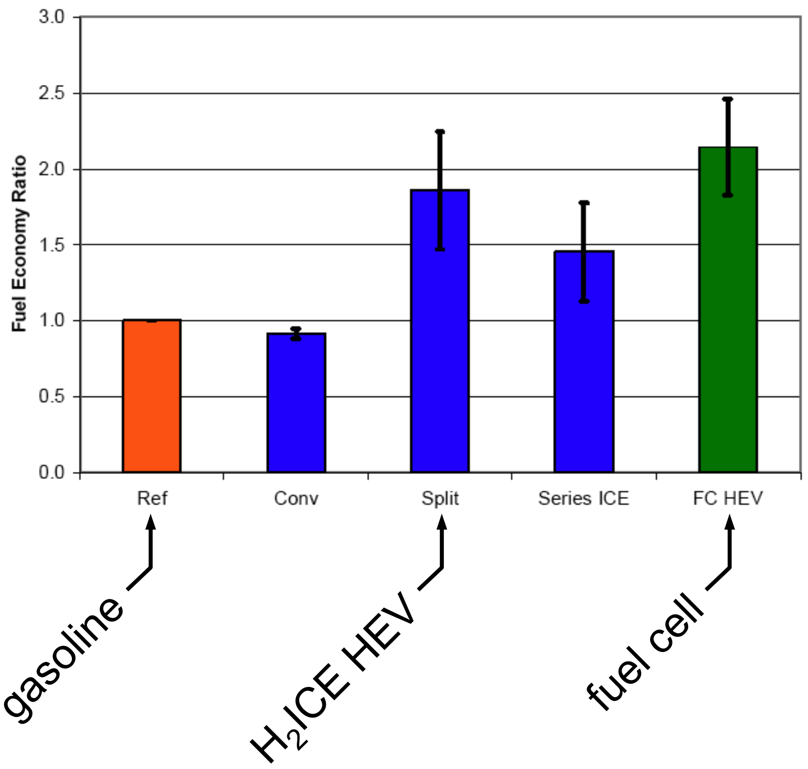
- Hydrogen engines build on existing, mass-produced, cost-effective technology.

- 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

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

Numerical Simulation Sandia (Large Eddy Simulation)	**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

  Mixture formation
- Provide data for validation of simulations (and learn from those)
- Extend experimental techniques and understanding of liquid-fueled optical engines

Objectives for this review period are to study mixture preparation, then combustion with advanced DI strategies.

- Understand influence of injector geometry and location (and other parameters) on mixture formation.
- Establish data base to support Sandia program establishing high-fidelity simulations (Large Eddy Simulation) for Engine Combustion Research.
- Integrate emissions measurements into optical experiments.
- Determine mechanisms responsible for NOx / efficiency improvement with multiple-injection DI.

The *milestones* reflect the objectives in the annual operating plan.

Milestones from Annual Operating Plans FY 08 and 09

April 2008	Investigate the effect of direct injection on fluid motion in a H_2ICE using particle image velocimetry and planar laser-induced fluorescence of a fuel-tracer.
Sept. 2008	Compare imaging results measuring pre-combustion fuel distribution and velocity fields (see above) at key operating points with Large Eddy Simulation.
Dec. 2008	Establish comprehensive parameter variation study: effect of injector location and tip geometry, engine speed, and injection pressure on mixture preparation.
Sept. 2009	Complete preliminary analysis of representative multi-DI strategies in terms of fuel distribution, flow, and flame morphology for fired conditions.

Two major *accomplishments* will be discussed: Diagnostic improvements and fuel measurements.

1) The fuel-distribution measurement was improved to provide quantitative data at any practically useful injection pressure.

2) A image database of fuel-air mixing for different injection geometries and timings was established.

3) Emissions measurements and accurate fuel metering were implemented.

4) Comparisons of optical data and large-eddy simulation were initiated.

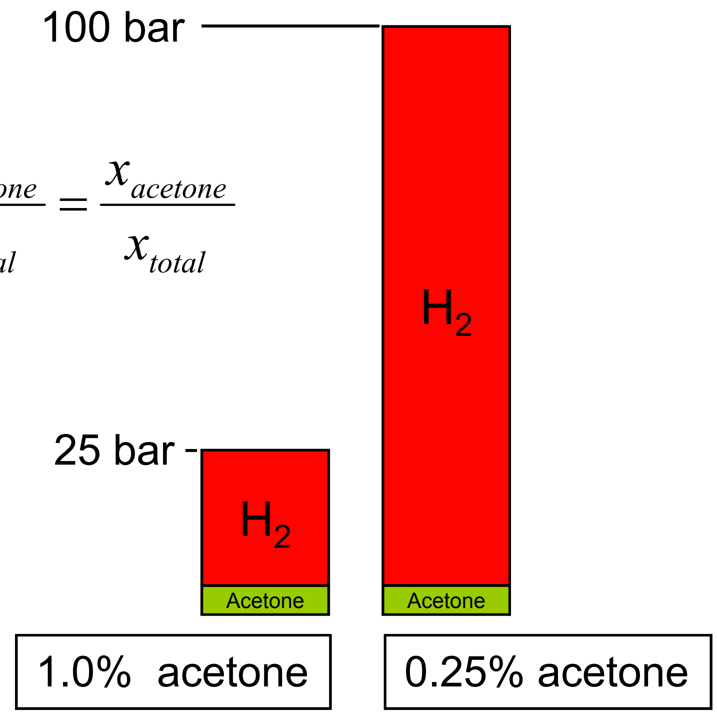
45% peak brake thermal efficiency reached in Ford research hydrogen engine.

Hydrogen work with DOE was one of 4 highlights of the ACEC for 2008.

(1) There is no "ideal" tracer for hydrogen, but acetone is a reasonable choice.

- Direct optical measurement of H_2 not practical.
- H_2 is a much smaller molecule than any organic compound.
- Vapor pressure limits amount of tracer in gas phase.

$$\frac{p_{acetone}}{p_{total}} = \frac{x_{acetone}}{x_{total}}$$

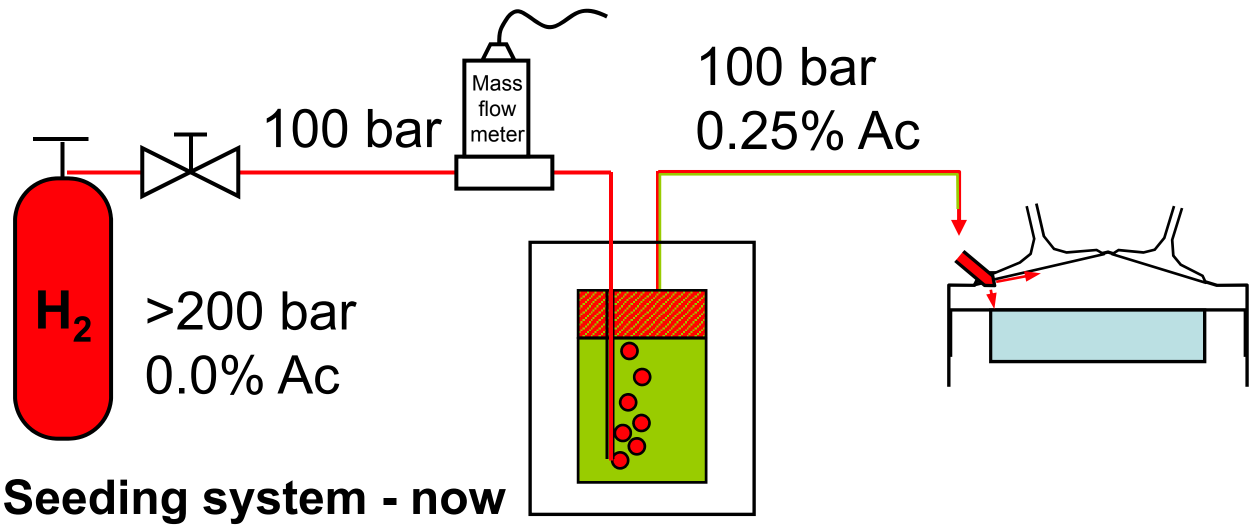


Chemical	Mol. Mass [u]	Boiling point [°C at 1 bar]
Hydrogen	2	-253
3-pentanone	86	101
Toluene	92	110
Biacetyl	86	88
Acetone	58	57

Low boiling point, non-toxic, accessible with existing lasers, known photophysics

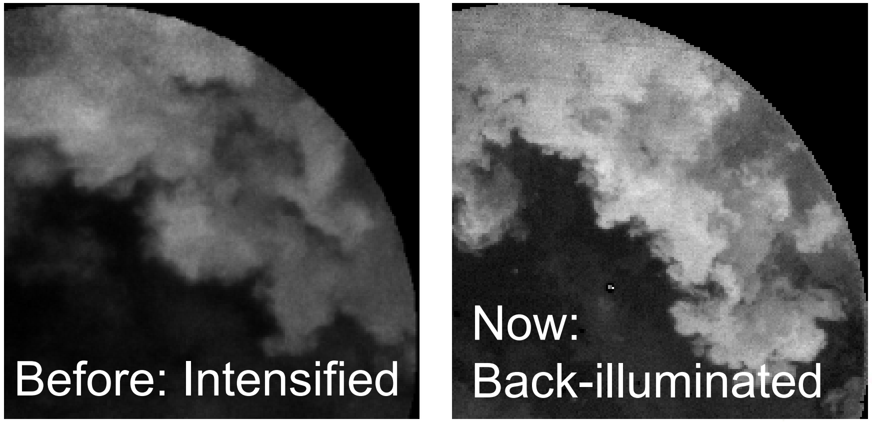
(1) The fuel diagnostic has been improved so that arbitrary injection pressures can be used.

Higher injection pressure = lower acetone saturation-concentration = lower signal



Seeding system - now

Countered by
- Diagnostic improvements
  → general and applicable to liquid fuels
- Better seeding system

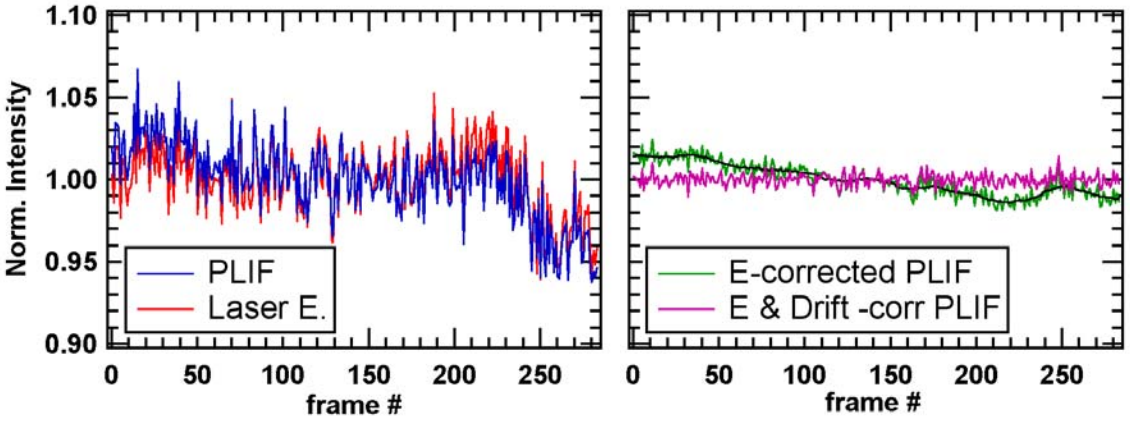


Intensified vs. back-illuminated CCD

(1) Measurement accuracy and precision are well-characterized to enable meaningful simulation validation.

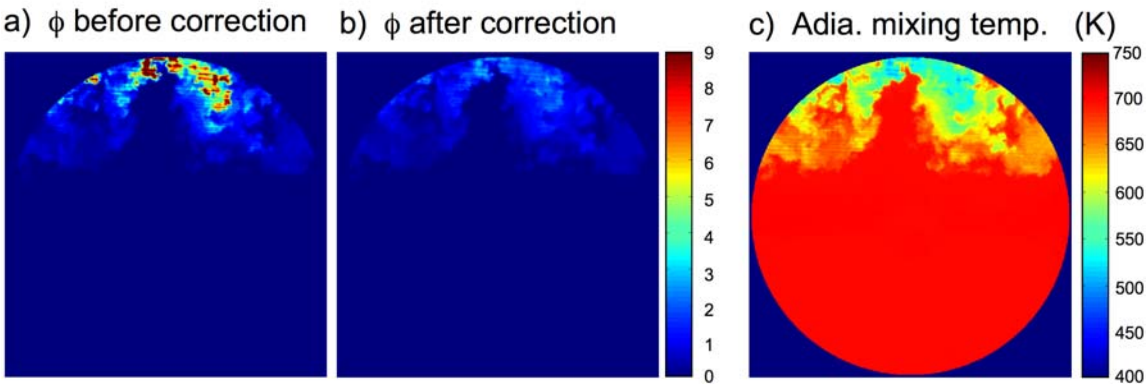
Precision

Error source	rms [%]
Gradient-induced sheet variations	6.2
Detection noise	5.0
Laser-induced sheet variations	1.45
Uncorrectable shot-to-shot fluctuations	0.4
Quadrature sum	**8.1**



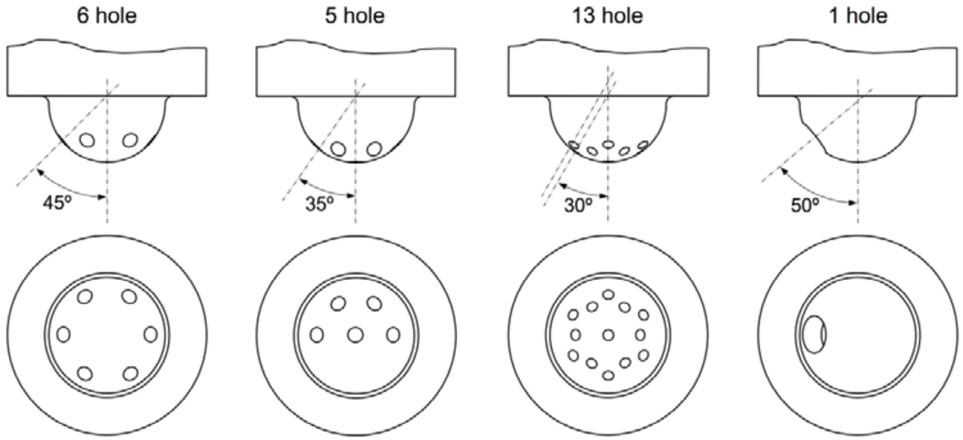
Accuracy

Error source	bias [%]
Global ϕ calibration	11
"Flatfield" (local ϕ calibration)	5.0
Background correction	16 max
Laser absorption	4.5
Local temperature correction	5
Sum	**25.5**

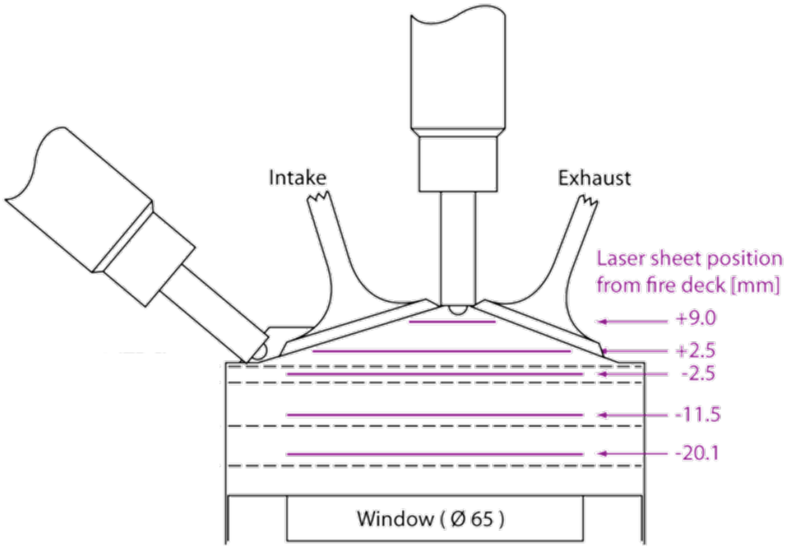


1500 rpm, p_{intake} = 1 bar, $p_{injection}$ = 82 bar, SOI / EOI = -40°/ -22°CA, ϕ_{global} = 0.25.
Imaging at -20°CA, 2.5 mm below the fire deck. 6-hole injector in side location.

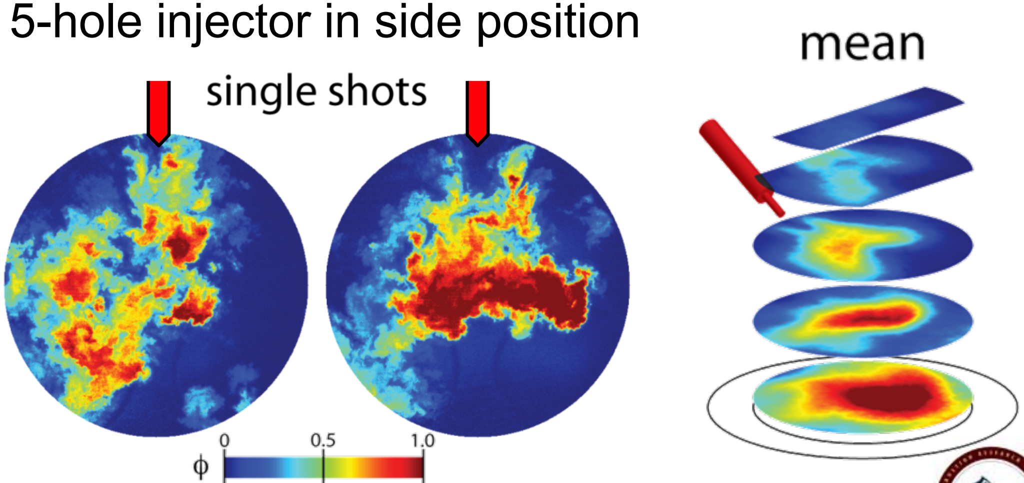
(2) A wide variety of injector configurations was studied to establish a broad data base.



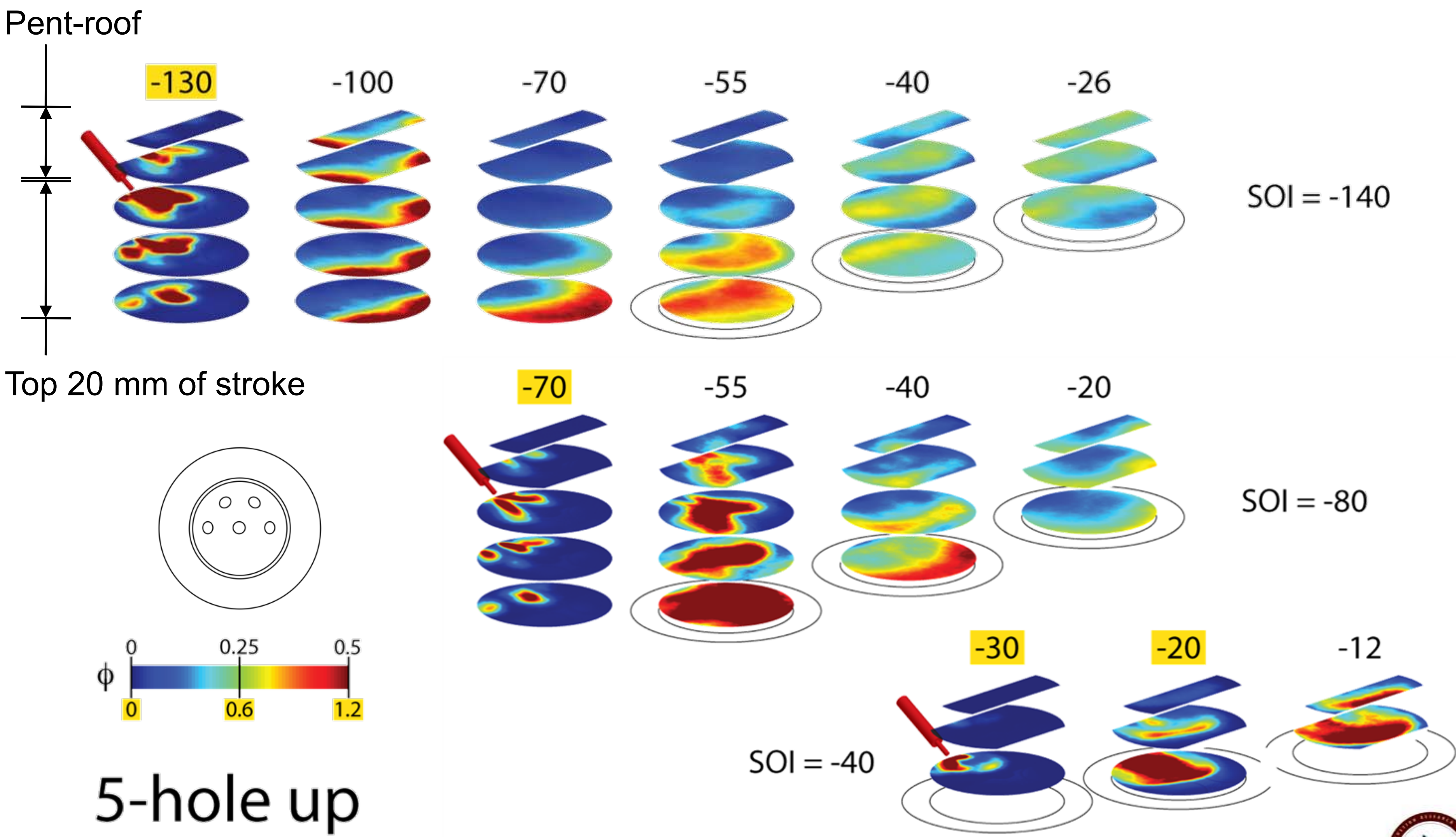
Speed	1500 rpm
Equiv. fired IMEP	2.5 bar
p_{intake}	1.0 bar
$p_{injection}$	100bar
ϕ	0.25
Injection duration	20 °CA
Start of injection	**-140, -80, -40°CA**



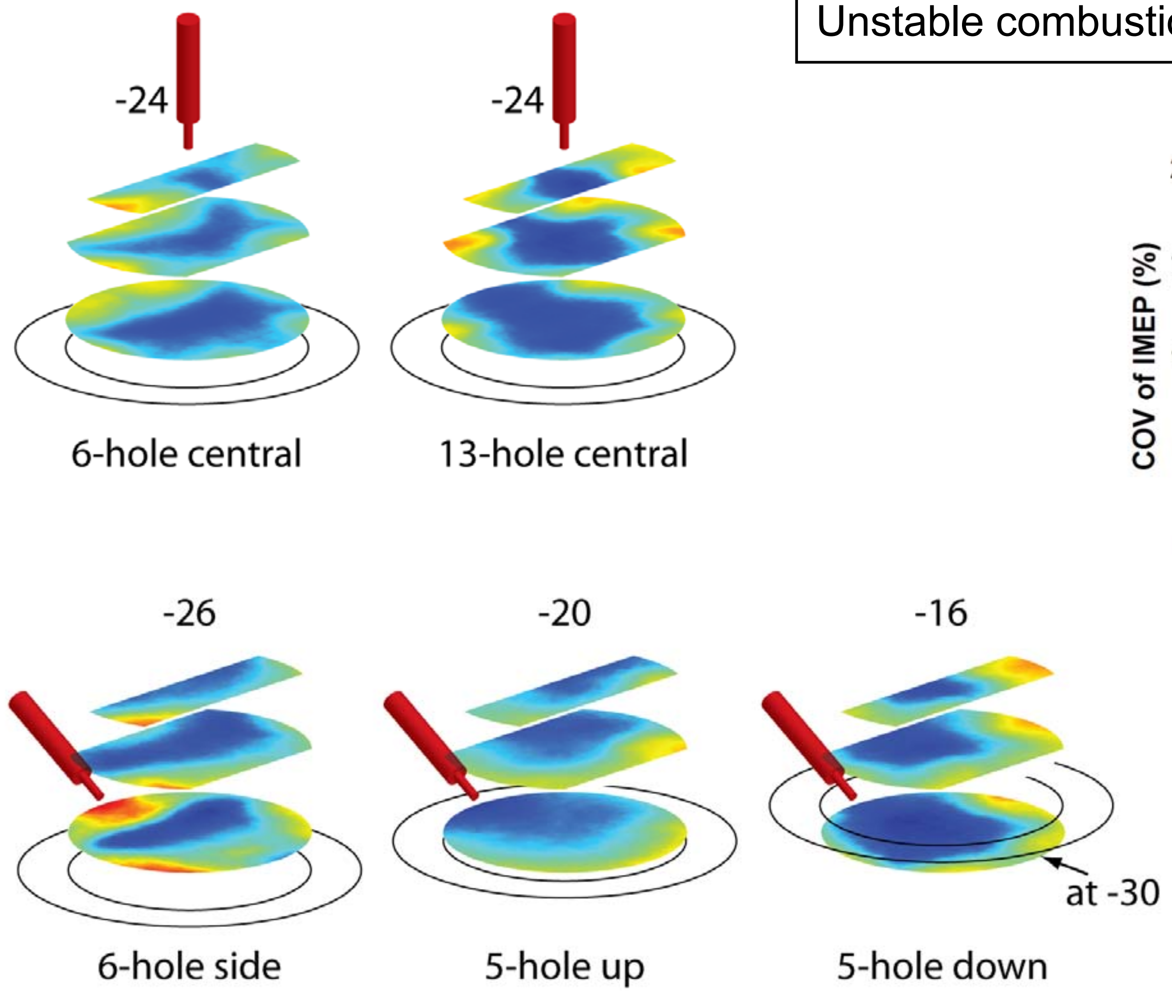
5-hole injector in side position



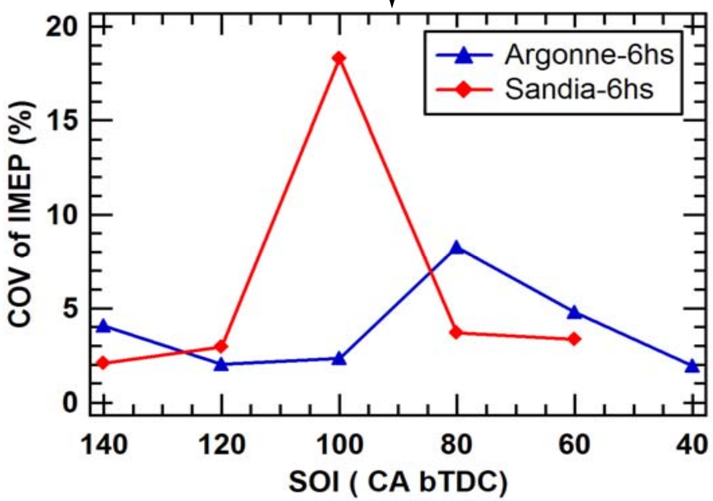
(2) The 5-hole nozzle produces an asymmetric jet pattern but may be good for late injection.



(2) For SOI = -80º, the stratification at spark is similarly bad for all injectors despite different time histories.



Intermediate injection timing:
Unstable combustion due to “hole” in fuel distribution



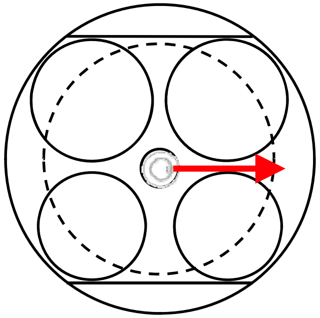
(2) The details of stratification make efficiency sensitive to the targeting of the single-hole injector.

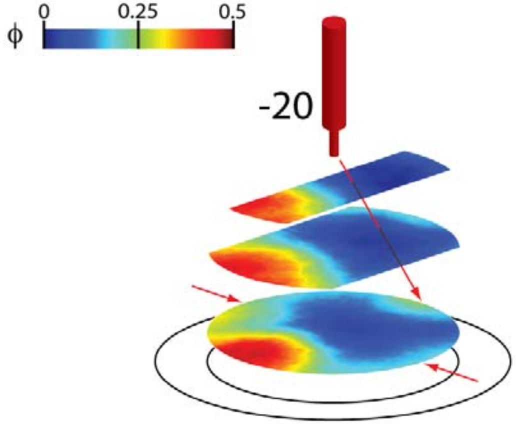
Targeting

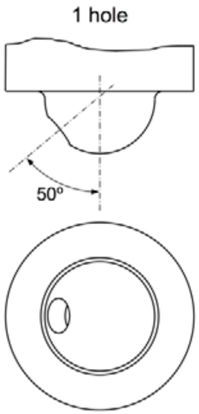
Mixture at spark for SOI = -80°CA

Performance*

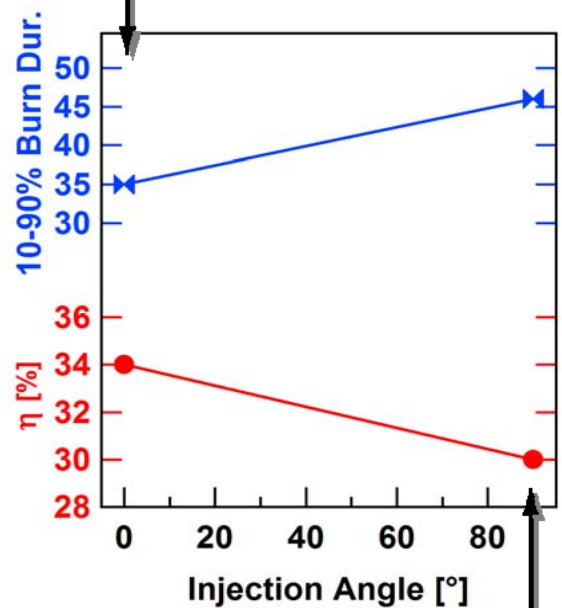
Along pent-roof





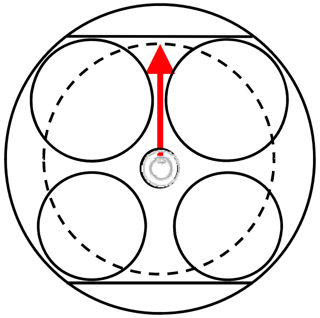


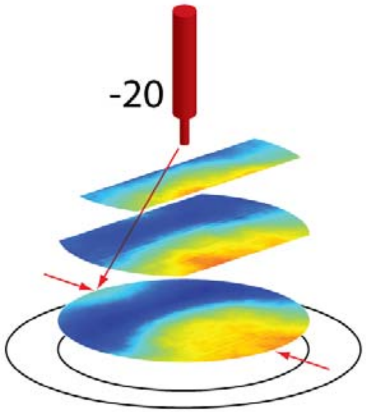
- Fuel near end of pent-roof
- More stratification - faster burn
- Higher efficiency



- Fuel in exhaust squish zone
- Wall heat losses
- Lower efficiency

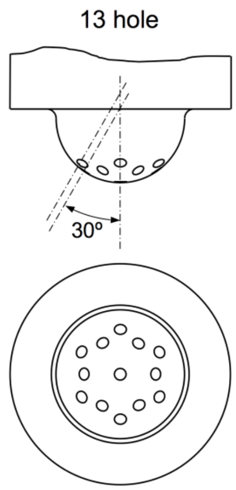
Towards intake

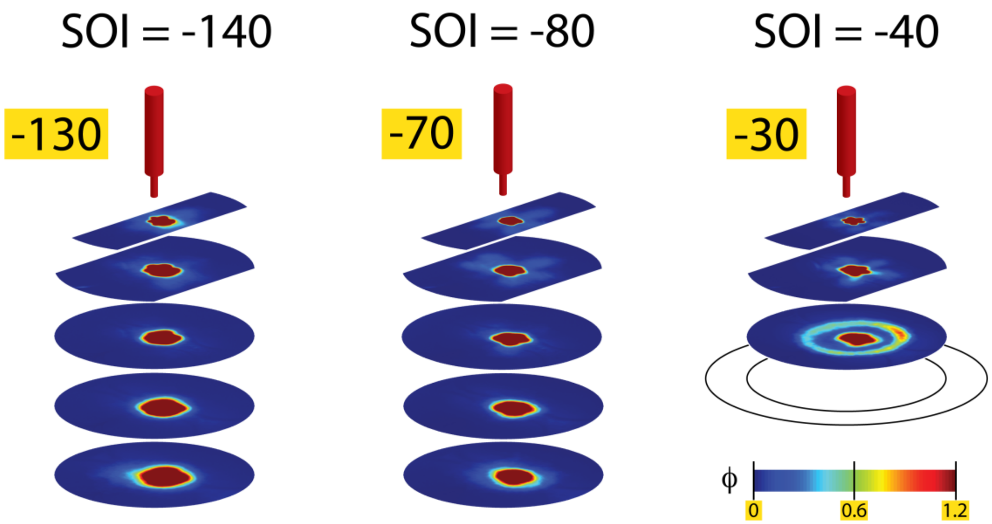




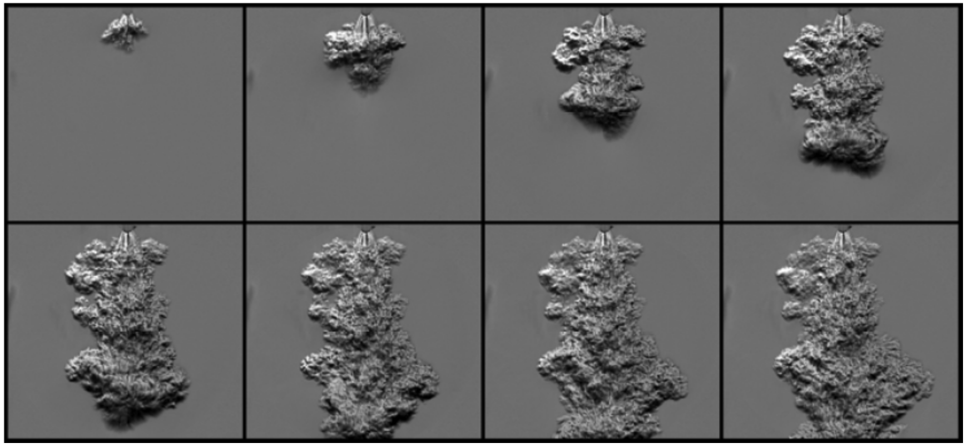
*Wallner, et al. SAE-paper 2009-01-1418

(2) The 13-hole nozzle shows complete jet collapse, consistent with Schlieren imaging by Petersen*.





From metal engine at Ford:



Despite jet collapse, this nozzle can perform well with multi-DI strategies.

*B.R. Petersen, Ph.D. Thesis, U. Wisconsin 2006

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

Blue: complete or in progress

Compile reference data set on fuel-air mixing

- Add PIV to fuel-PLIF for select conditions
- Injector geometry and location, inj. pressure, engine speed and load

Update and augment hardware

- Emissions: NO_x, O_2, H_2; accurate fuel metering
- Piezoelectric injectors and driver

Investigate multi-injection strategies

- Combustion modes and efficiency vs. NOx trade-off
- OH-PLIF, PIV, fuel-PLIF, high-speed Schlieren

Continue and improve collaborations

- Coordinate work with ANL, Ford, and other partners
- Integrate new member BMW into H_2ICE working group

Validate, learn from, and advance LES

In *summary*, understanding mixture preparation helps developing advanced DI hydrogen engines.

Two recent accomplishments were discussed in detail.

(1) PLIF of acetone as a hydrogen fuel-tracer was improved to handle any practically useful injection pressure.

(2) Imaging mixture preparation for different injection geometries and strategies yielded a database for simulation validation and general insight:

- Early injection yields homogeneous mixtures after much wall interaction. Results from late injection depend on the injector geometry.
- Intermediate injection timings with different geometries yield similar mixture stratifications, with much fuel in the squish zones and near the walls.
- The simple geometry of the single-hole injector allows for clear correlation of optical results and engine performance.