

Sandia Hydrogen Combustion Research

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Sponsor:

DoE / OVT



Program Manager:

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Bethesda, MD

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This presentation does not contain any proprietary or confidential information.



The purpose of this work is to understand hydrogen engine combustion.

- Hydrogen energy chain includes production, transportation, storage, conversion.
- For transportation use, hydrogen engines are an option building on existing, mass-produced, cost-effective technology.
- This program aims to develop the science base needed by engine companies to optimize the design of advanced hydrogen engines.
- All existing vehicles have port injection, but advanced hydrogen engine concepts are based on direct injection.



Barrier: Lack of fundamental knowledge about in-cylinder processes in hydrogen DI engines.

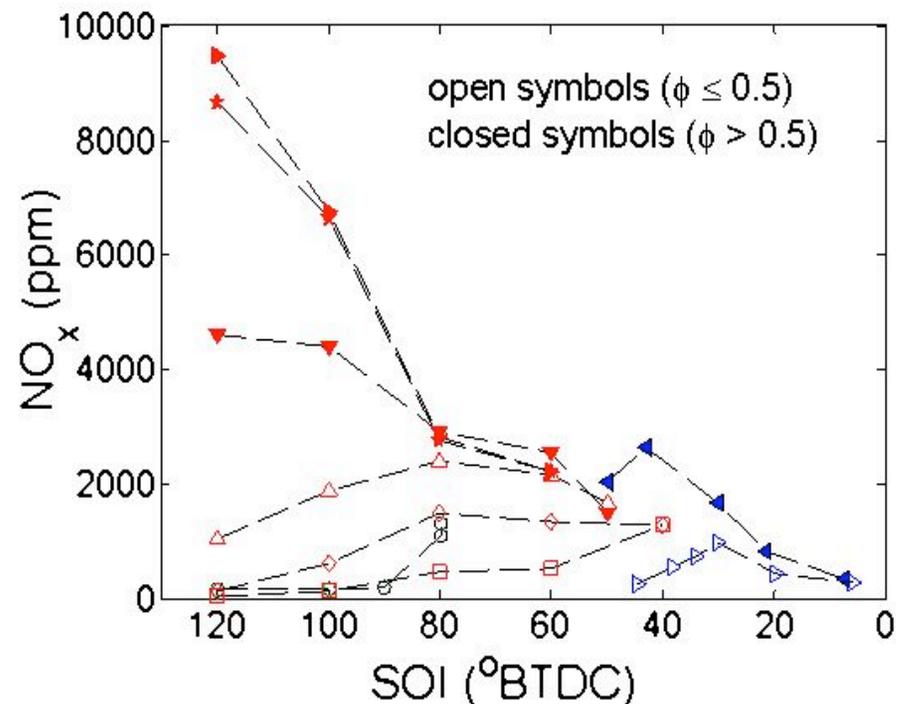
Strategy: In-cylinder injection after intake valve closure (DI H₂ICE)

Benefits:

- Higher power density
- Less preignition, no backflash
- Partial recovery of tank energy
- With optimal mixture preparation:
 - increased efficiency (> diesel)
 - reduced NO_x

Technical challenges:

- DI operation relies on control of fuel-air mixing and combustion regimes.
- short available mixing times (1-20 ms)
- Complex flow and fuel distribution dynamics
- H₂ injector (durability issues)



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



- Spatially resolved measurements of in-cylinder processes
 - Fuel distribution
 - Flow field
 - Combustion

} Mixture formation
- Provide data for validation of high-fidelity calculations (and learn from those)
- Investigate operating strategies of interest to Ford and Argonne
- Experimental facility similar to those of other SNL presenters

There were no specific reviewer comments last year.

Sandia's experimental H₂ICE work was presented at the poster session.

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Sandia Hydrogen Combustion Research
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Program Goals and FY2007 Objectives

Goal: Develop the science base needed by engine companies to optimize the design of advanced hydrogen engines. These engines will serve as an enabling power plant technology for building a hydrogen economy (see Fig. 1).

2007 Objectives:

- peak brake thermal efficiency (BTE) > 40%.
- Fuel/brand emissions or brake (NO_x, CO, HC) > 10%.
- power densities greater than present-day gasoline engines.

Objectives:

- focus on the decarbonization (CO) hydrogen engine.
- provide experimental data to support modeling efforts at SNL using the Large Eddy Simulation (LES) technique.
- identify operational conditions that are of value to Ford, component manufacturers at ANL, and academia in engine engines.

Technical Barriers

Strategy: In-cylinder injection after intake valve closure (ICI) H₂ICE, see Fig. 2.

Barriers:

- greater density requirement (the displacement of air by H₂)
- mitigate engine-out and emissions degradation.

Technical challenge in mixture preparation (see Fig. 3 and Fig. 4):

- with poor mixture preparation
 - reduced NO_x emissions (good symbol, Fig. 3)
 - increased efficiency (data not shown)
- with poor mixture preparation
 - increased NO_x emissions (good symbol, Fig. 3)
 - decreased efficiency (data not shown)

Approach

A combined study using laser-based experimental techniques in an optically-transparent engine and high-speed numerical simulations is employed to obtain a physical understanding of the in-cylinder transport processes (concentration and temperature) in a CI H₂ICE. (Note: numerical work by J. Oakton (SNL) reviewed separately.)

Experimental approach:

- experimental development of experimental techniques to provide a spatially-resolved quantitative measure of in-cylinder hydrogen concentration: Planar Laser Induced Fluorescence (PLIF) → H_2 concentration
- Particle Image Velocimetry (PIV) → in-cylinder velocity field
- provide experimental data to validate numerical schemes, grid resolution, and models implemented in the Large Eddy Simulation.
- focus on operational conditions that are of value to Ford, component manufacturers at ANL, and academia in engine engines.

Guidance from FY2006 Review

Recommended major actions for FY2007:

- Investigate in-cylinder hydrogen-air mixing using planar laser induced fluorescence (PLIF)
 - Assisted PLIF studies have been performed and continue to be refined.
 - A laser injection angle of 45 degrees needs to be investigated to measure exhaust gas emissions.
 - In the process of building an engine base to measure exhaust gas NO_x, H_2 and CO.
- Investigate additional specified points
 - Identify two additional speed load points of value.
 - (1) the: investigate charge stratification to reduce the need to throttle.
 - (2) high-injection speed: study the potential for multiple injections for improved efficiency, reduced NO_x formation rates, and to control the rate of pressure rise.

Collaborations/Interactions

- Industrial partner: Ford Motor Company
 - Under the Combustion Memorandum of Understanding (MOU).
- Academic: hydrogen engine working group that meets quarterly:
 - Participants: Argonne National Laboratory (ANL), Ford, Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL).
- Participated in the European Commission's HyICE Program
 - Sandia is a contributor to HyICE as a base science and non-industrial partner.
- Sandia is a participant in the DOE supported International Energy Agency (IEA) Collaborative Task on hydrogen-fueled engines:
 - 10 participants from 7 countries.

Publications

White, C.M., Kaiser, S.A., "Experimental and Numerical Investigation of Hydrogen Combustion in a Spark-Ignited Engine," *Proceedings of the 2007 ASME Internal Combustion Engine Research Symposium*, 2007, pp. 1-10.

White, C.M., Kaiser, S.A., "Experimental and Numerical Investigation of Hydrogen Combustion in a Spark-Ignited Engine," *Proceedings of the 2007 ASME Internal Combustion Engine Research Symposium*, 2007, pp. 1-10.

White, C.M., Kaiser, S.A., "Experimental and Numerical Investigation of Hydrogen Combustion in a Spark-Ignited Engine," *Proceedings of the 2007 ASME Internal Combustion Engine Research Symposium*, 2007, pp. 1-10.

Invited Presentations

White, C.M., Kaiser, S.A., "Experimental and Numerical Investigation of Hydrogen Combustion in a Spark-Ignited Engine," *Proceedings of the 2007 ASME Internal Combustion Engine Research Symposium*, 2007, pp. 1-10.

White, C.M., Kaiser, S.A., "Experimental and Numerical Investigation of Hydrogen Combustion in a Spark-Ignited Engine," *Proceedings of the 2007 ASME Internal Combustion Engine Research Symposium*, 2007, pp. 1-10.

White, C.M., Kaiser, S.A., "Experimental and Numerical Investigation of Hydrogen Combustion in a Spark-Ignited Engine," *Proceedings of the 2007 ASME Internal Combustion Engine Research Symposium*, 2007, pp. 1-10.

Sandia Hydrogen Combustion Research

Sandia optical H₂ engine facility

Optical test engine

- 2000 rpm engine speed
- 4 valves, central spark plug
- 1000 cc displacement
- CR: 13.5:1 (at piston)

Optical access:

- interchangeable quartz viewports for in-cylinder optical access
- view through 30° angle (displacement)
- view through 90° angle (displacement)

Fuel-tracer PLIF measurements

Description: Acetone Planar Laser Induced Fluorescence (PLIF) is used to provide a spatially-resolved quantitative measure of the fuel concentration in the cylinder.

Experimental details: (see corresponding figures below and to the right)

- laser at mixture of 50% H_2 and 50% acetone (based by volume)
- 200 mm laser sheet used for acetone excitation
- transmittance used to check the acetone concentration as it went through the piston window.

Quantitative acetone PLIF: technical accomplishment

Procedure: Basic experimental details (1) to (5) are provided in the table below. The mapping function is determined from calibration experiments.

Figure 1: Acetone PLIF images showing the spatial distribution of acetone in the cylinder. The images show the acetone concentration in the cylinder at different crank angles. The images are color-coded to show the acetone concentration.

Figure 2: Acetone PLIF images showing the spatial distribution of acetone in the cylinder. The images show the acetone concentration in the cylinder at different crank angles. The images are color-coded to show the acetone concentration.

Figure 3: Acetone PLIF images showing the spatial distribution of acetone in the cylinder. The images show the acetone concentration in the cylinder at different crank angles. The images are color-coded to show the acetone concentration.

Figure 4: Acetone PLIF images showing the spatial distribution of acetone in the cylinder. The images show the acetone concentration in the cylinder at different crank angles. The images are color-coded to show the acetone concentration.

PLIF images compared to OH* chemiluminescence images: performance measure

Figure 5: Comparison of PLIF and OH* chemiluminescence images. The images show the acetone concentration in the cylinder at different crank angles. The images are color-coded to show the acetone concentration.

Figure 6: Comparison of PLIF and OH* chemiluminescence images. The images show the acetone concentration in the cylinder at different crank angles. The images are color-coded to show the acetone concentration.

Figure 7: Comparison of PLIF and OH* chemiluminescence images. The images show the acetone concentration in the cylinder at different crank angles. The images are color-coded to show the acetone concentration.

Figure 8: Comparison of PLIF and OH* chemiluminescence images. The images show the acetone concentration in the cylinder at different crank angles. The images are color-coded to show the acetone concentration.

Future Work FY2008

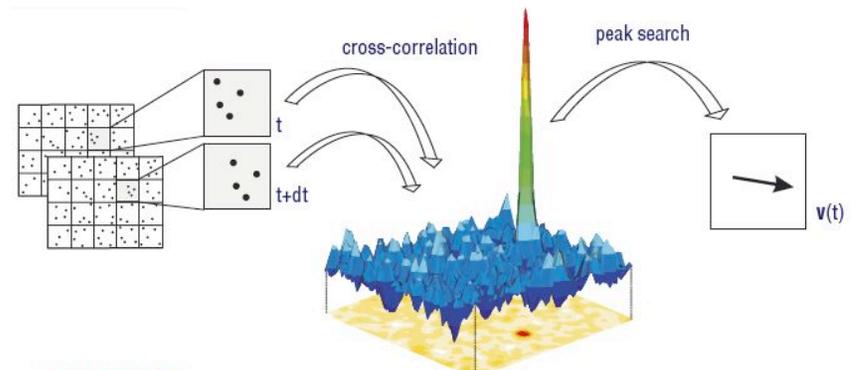
- Improve fuel tracer PLIF precision and resolution
 - a hybrid acetone tracer is being used to achieve the necessary levels of seed required for well-resolved PLIF images.
- Perform in-cylinder velocity measurements using the PIV technique
 - consider wall-to-wall (i.e., PLIF measurements) provides "complete" information on in-cylinder H_2 or mixing (includes flow-enhancing strategies (port, etc.)).
- Compare data at key operating points to LES
 - use velocity and fuel maps to assess accuracy of numerical models.
- Evaluate engine load from GM for Ford
 - facilitates close coordination with H_2 ICE work at Ford and ANL, all three will use the identical flow geometry.
- Install and calibrate emissions sensors
 - improve NO_x, H_2 , CO, component output diagnostics.

Summary

- Acetone PLIF is used to measure in-cylinder equivalence ratio in a CI H₂ICE
 - investigate the effect of ICI on mixture preparation
 - For SOI coincident with WC, a "near-homogeneous" mixture distribution is observed.
- For moderate retard of SOI from IVC, a higher injection pressure improves in-cylinder hydrogen-air mixing (good symbol)
 - With late injection (independent of injection pressure), hydrogen is concentrated in small volumes located near the cylinder wall.
 - increased result that requires further investigation.
- Injector tip geometry or injector location used in the present study is not ideal for late injection strategies due to an expected high loss to the cylinder walls
 - the Ford head possesses both large and deep injector locations

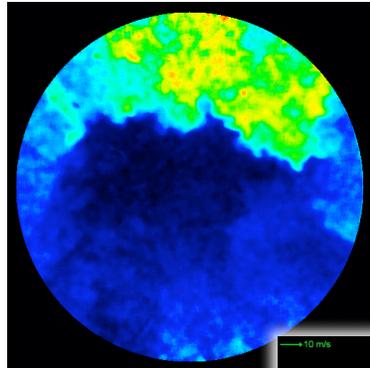
This year's major accomplishment was the investigation of in-cylinder flow.

- Quantitative imaging of fuel distribution for representative post-IVC injection timings (March 2007).
- Established high-quality 2D velocity measurements by PIV (July 2007).



- Extensively mapped flow field throughout intake and compression stroke, with and without injection (August 2007 - current).
- Comparison to Large Eddy Simulation is in progress.
- New engine head (Ford) is at Sandia. Install when current measurement series is complete.

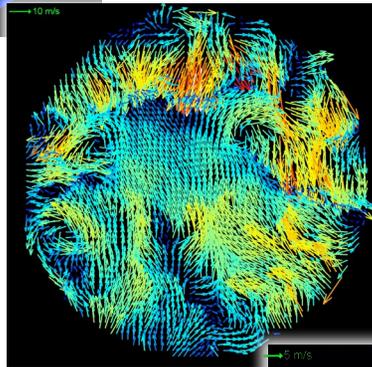
Here, we focus on the influence of injection-induced flow on the fuel distribution.



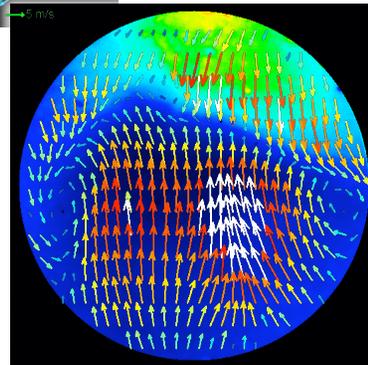
Fuel-tracer PLIF → Equivalence ratio



Separate measurements



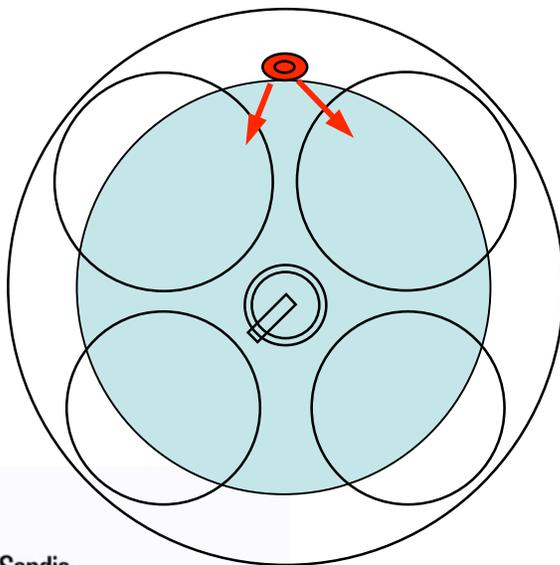
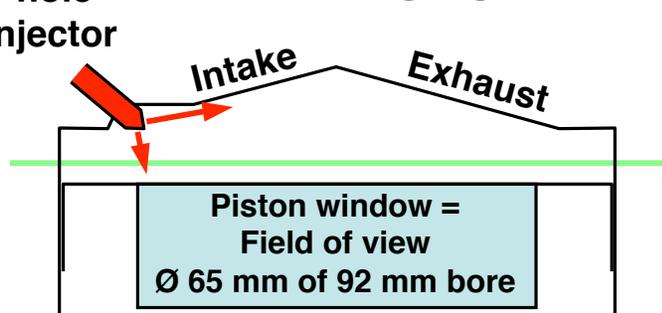
PIV → Velocity

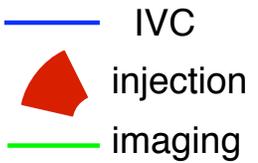
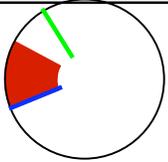
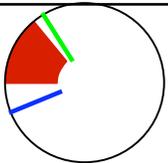
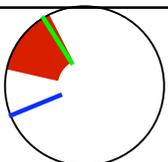


Injection-induced flow

Three different post-IVC injection timings were used: Early, intermediate, late.

6-hole injector Imaging at -32° CA



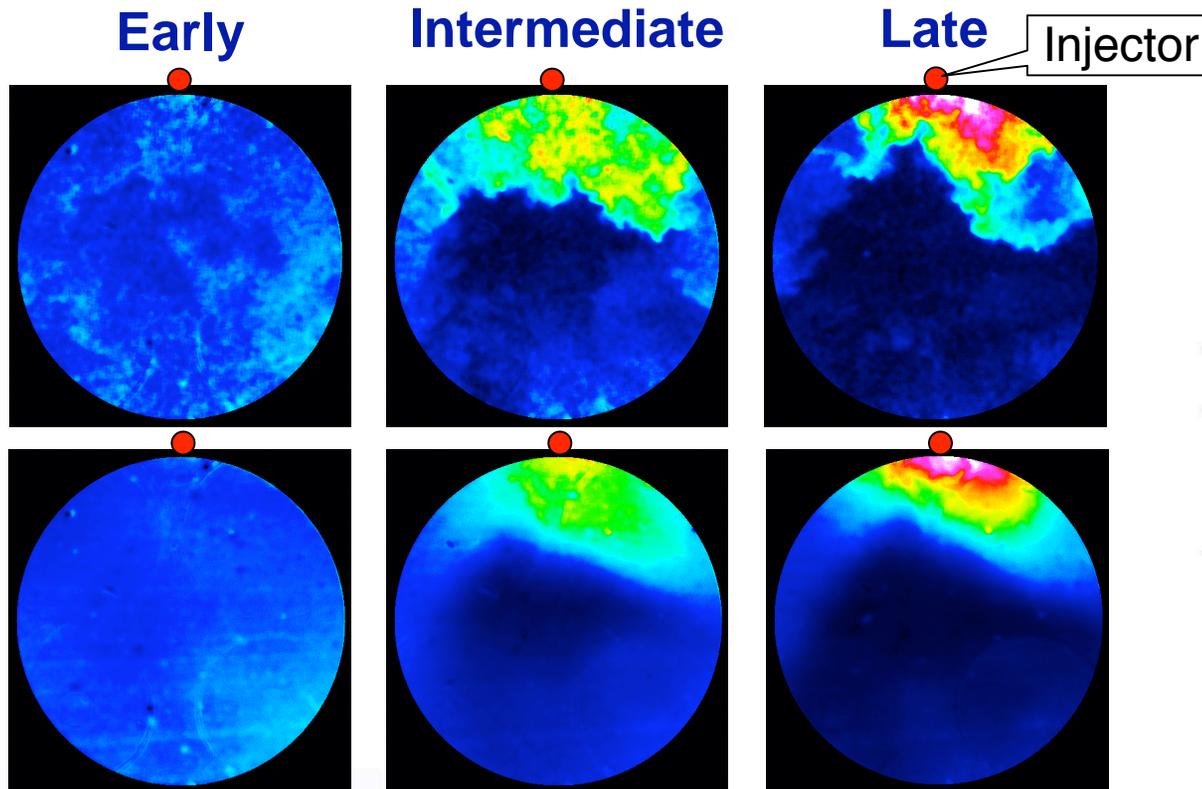
Timing	SOI [CAD]	EOI [CAD]	
early	-112	-62	
intermediate	-90	-40	
late	-77.5	-27.5	

1200 rpm, $\phi = 0.55$

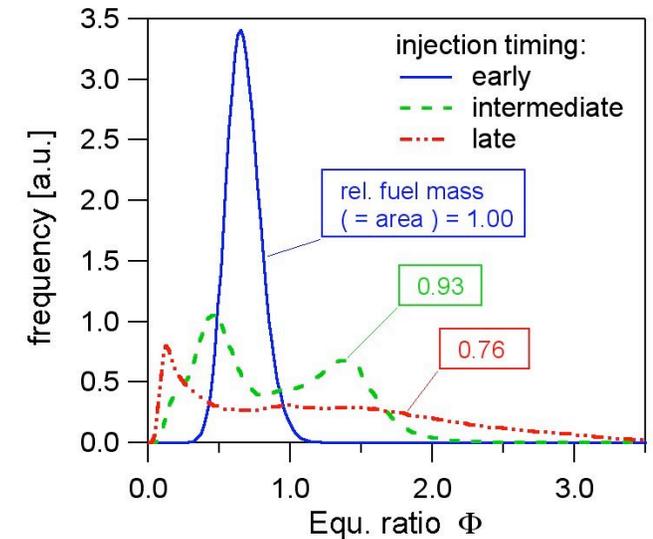
$p_{in} = 0.5$ bar, $p_{H_2} = 25$ bar.

Early injection leads to near-homogenous mixture, intermediate and late timing to stratification.

Equivalence ratio fields for different injection timings

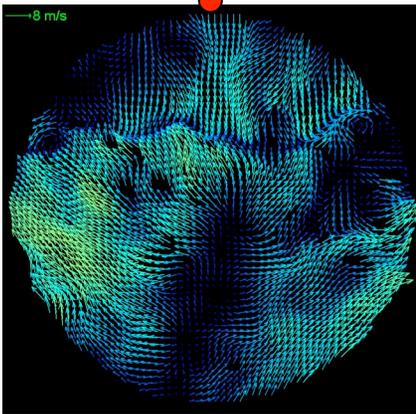


Mass-weighted histogram

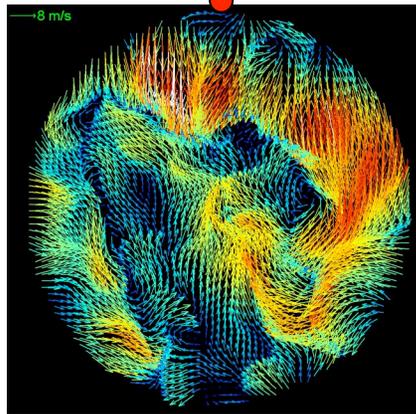


In the multi-cycle mean, fuel distribution and velocity correlate very well.

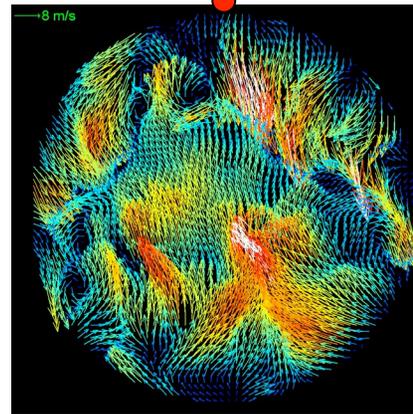
No injection



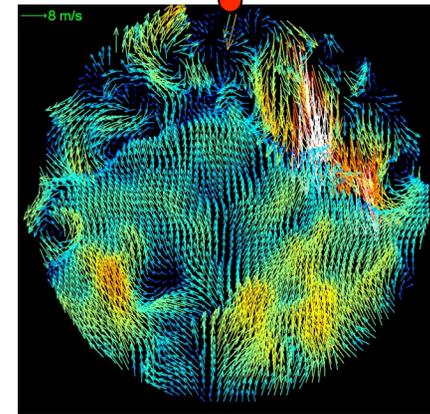
Early



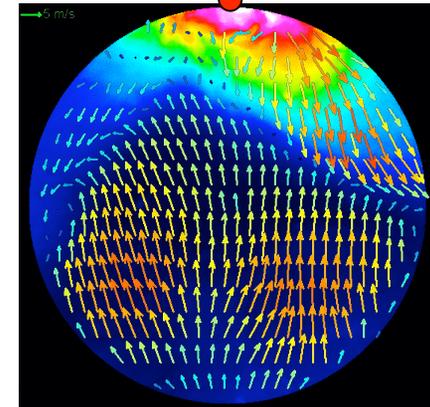
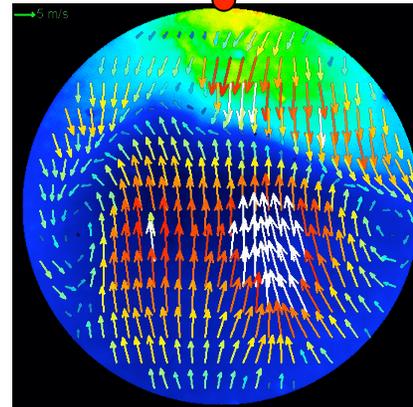
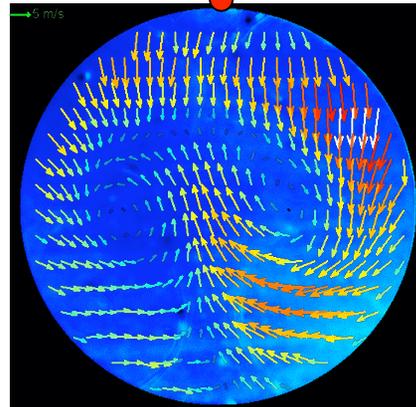
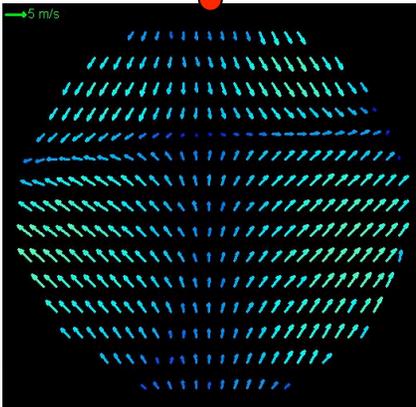
Intermediate



Late

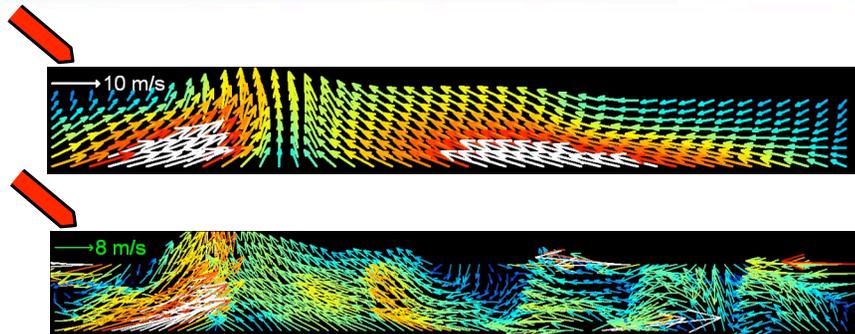


Single shot v



Mean ϕ and v

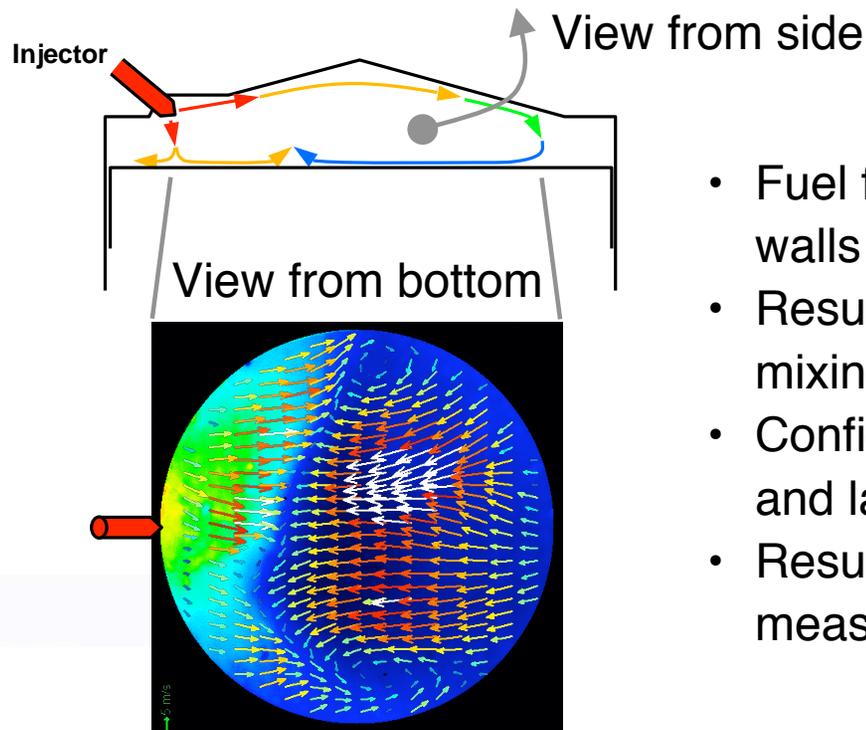
For intermediate and late timing, injection-induced flow prevents effective mixing.



Mean

Single shot

Intermediate injection timing



- Fuel from the top jets is re-directed by the walls and piston
- Resulting counter-flow is stable and prevents mixing
- Configuration is not suitable for intermediate and late injection
- Result confirmed by drop-off in efficiency measured at ANL for SOI later than -100° CA

Technology transfer is an integral part of our approach.

- Industrial partner Ford Motor Company under the Combustion Memorandum of Understanding.
- Advanced Hydrogen Engine Working Group that meets semi-yearly:
Argonne National Laboratory (ANL), Ford, Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL)
- Lead Organizer of International Energy Agency's Collaborative Task on Hydrogen-fueled Engines; participated in the European Commission's HylCE Program
- New collaborations with University of New Hampshire, University of Orléans



Activities for next year include measurements coordinated with Ford and ANL.

- Further optical characterization of fuel distribution and flow at key operating points as identified by Ford in metal-engine tests.
- Optical measurements with multiple injection
 - Multi-DI strategies have shown great promise at Ford.
 - Why they work? Fuel distribution? Combustion regime?
 - Imaging will provide understanding for optimization.
- New engine head from Ford is at Sandia
Ford, ANL, and Sandia will have identical geometry (Summer 08)
- Validation of companion Large Eddy Simulation (J. Oefelein, SNL):
Motored cycles - in progress
Injected cycles - September 08

In summary, DI-H₂ICE development profits from measurements in the optical engine.

- H₂ICE will be a highly efficient transportation power plant in the hydrogen energy chain. Petroleum displacement is dependent on overall energy system.
- Direct injection is an enabling technology for power density and emissions.
 - Control of fuel-air mixing and combustion regimes is critical.
 - Experiments in optical engine provide physical understanding.
 - Quantitative measurements for simulation validation.
- Accomplishments:
 - Fuel distributions imaged for representative injection timings.
 - In-cylinder flow field mapped extensively.
 - High-quality velocity measurements now routine.
- Technology transfer through collaboration with Ford, ANL, other national labs, IEA.
- Next: Advanced injection strategies, homogenization of experimental platform (Ford head), simulation validation.

Publications and presentations

S.A. Kaiser, C.M. White, *PIV and PLIF to Evaluate Mixture Formation in a Direct-Injection Hydrogen-Fuelled Engine*, paper 08PFL-743, SAE World Congress, April 14-17, 2008, Detroit, MI.

C.M. White, *A Qualitative Evaluation of Mixture Formation in a Direct-Injection, Hydrogen-Fuelled Engine*, SAE Paper 2007-01-1467, 2007.

C.M. White, *OH* chemiluminescence measurements in a direct injection hydrogen-fuelled internal combustion engine*, Int. J. Engine Res. 8:185-204, 2007.

C.M. White, *Advanced Hydrogen-Fueled Engines: Potential and Challenges*, presented at the ERC Symposium on Fuels for Future Internal Combustion Engines, University of Wisconsin, Madison, WI, June 6, 2007.

S.A. Kaiser, C.M. White, *Sandia Optical H₂ICE*, presented at the Ford/National Labs H₂ICE Meeting, Combustion Research Facility at SNL, Livermore, CA, February, 2008.

S.A. Kaiser, C.M. White, J.C. Oefelein, D.L. Siebers, *Sandia Hydrogen Combustion Research: Simulation and Experiment*, presented at the International Energy Agency Task Leaders Meeting, Gembloux, Belgium, September 2007.