Mixture Formation and Combustion in a Hydrogen-Fueled Internal Combustion Engine

Christopher White
Sandia National Laboratories

Sponsor: DOE Office of FreedomCAR and Vehicles Technologies Program
Program Managers: Gurpreet Singh and Kevin Stork

IEA Collaborative Task Leaders Meeting
Heidelberg, Germany
August 13-15, 2006.

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H_2ICEs: A bridge to the hydrogen economy

- **Technology is available today and economically viable in the near-term.**
- **Number of test/demo vehicles: Ford, BMW among others (see below).**
  - demonstrated efficiencies in excess of today's gasoline engines.
  - operate cleanly (NO_x is the only emission pollutant)
- **Fewer constraints concerning H_2 storage compared to fuel cells.**
  - relative ease of a dual-fuel option (H_2/gasoline).
  - impurities are a non-issue

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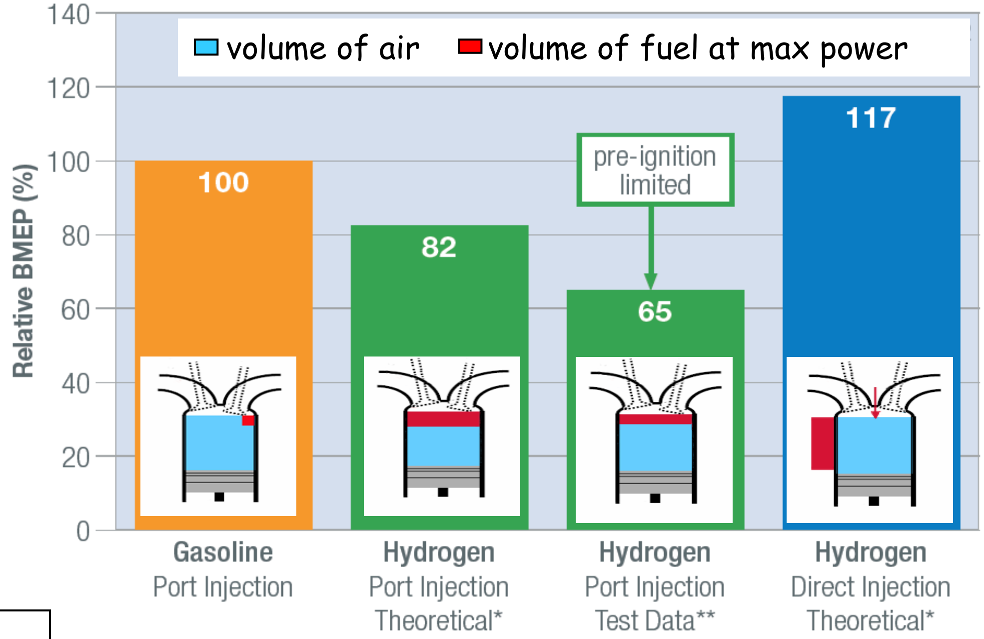
U.S. DOE's interest in the H_2ICE

- **H_2ICEs are part of DOE's transitional strategy towards a hydrogen economy.**
  - www.hydrogen.energy.gov/pdfs/hydrogen_posture_plan.pdf
- **DOE's near-term goals for the H_2ICE (same as for fuel cell vehicle):**
  - peak brake thermal efficiency (BTE) ≥ 45%.
  - Tier2/bin5 emissions or better (NO_x ≤ 0.07g/mile).
  - power densities greater than present-day gasoline engines.
- **Research is required to resolve technical barriers to meet these goals.**
  - fundamental research of in-cylinder combustion and transport processes.
  - NO_x emissions and control.
  - advanced H_2ICE concepts and related technical issues:
    - pressure boosting (preignition, CR effects, heat transfer, etc)
    - direct-injection (in-cylinder mixing, injector durability, etc) **MOST PROMISING**

Direct-injection (DI) H_2ICEs

Benefits:

- power density improvement
  - → no displacement of air by H_2
- mitigate preignition
  - → optimize injection timing
- multiple degrees of freedom
  - → improved efficiency
  - → reduced emissions



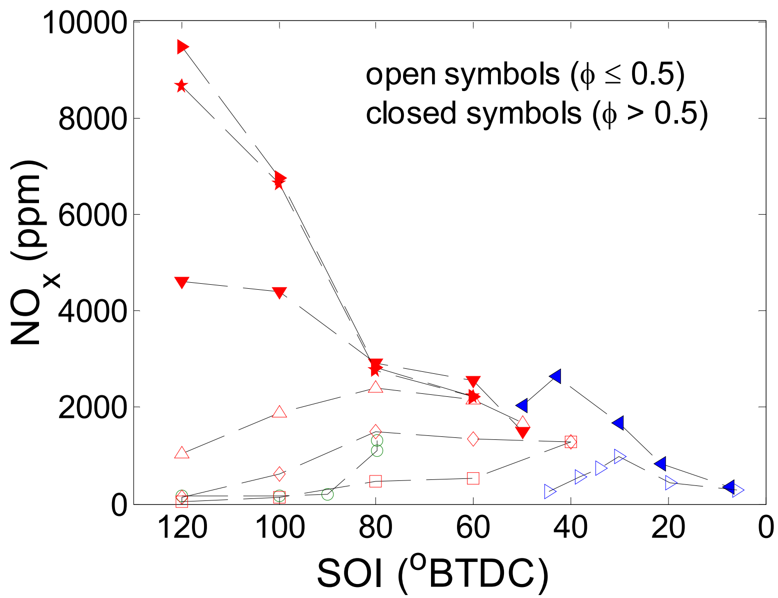
Technical challenges:

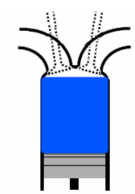
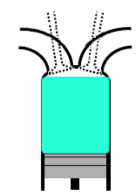
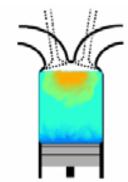
- high-pressure, high-flow rate injector
  - → durability issues
- short available mixing times
  - → **1–20 ms** depending on engine speed and injection timing.

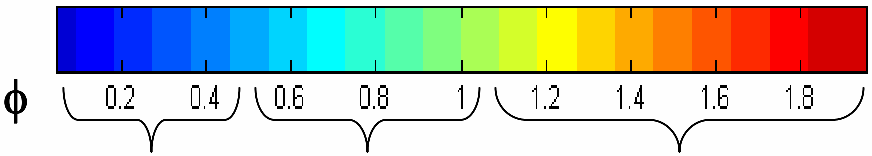
Mixture distribution at onset of combustion is critical to engine performance and emissions.

Mixture stratification in a DI-H_2ICE

Effect of start-of-injection on NOx emissions



Mixture formation	ϕ = 0.3	ϕ = 0.8
well-mixed		
stratified	 ↑ NOx	 NOx ↓



low NOx high NOx low NOx

Conjecture:
Mixture inhomogeneities

Sandia H_2 research engine facility

Optical test engine

GM single-cylinder head

- 4 valves, central spark plug
- 560 cm^3 displacement
- CR: 9.1 (flat piston)

Optical access

- interchangeable quartz liner
- interchangeable quartz piston

Hydrogen fueling

- side direct injection (Westport Innov.)

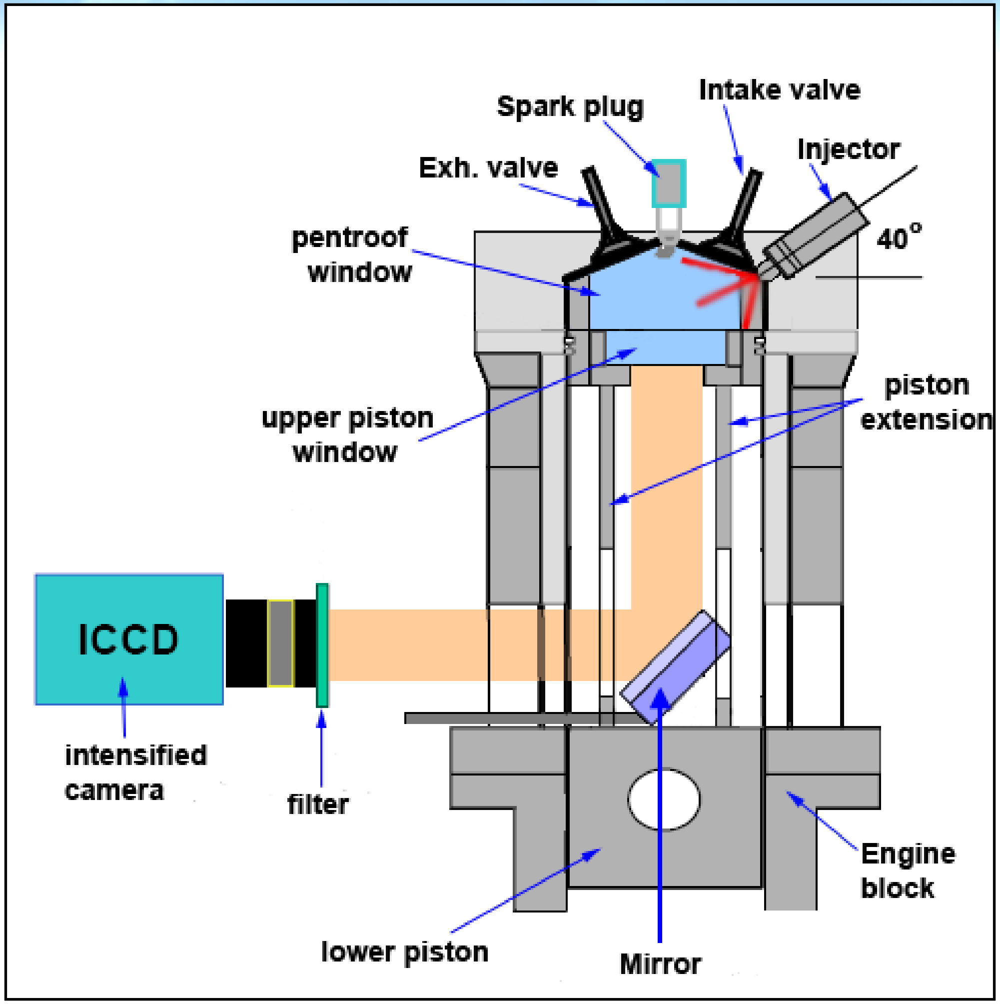
Approach

- focus on evaluation of in-cylinder mixing processes in a DI-H_2ICE
- systematic experiments
  - OH chemiluminescence imaging
  - planar laser induced fluorescence (PLIF)
  - particle image velocimetry (PIV)

OH chemiluminescence experiment

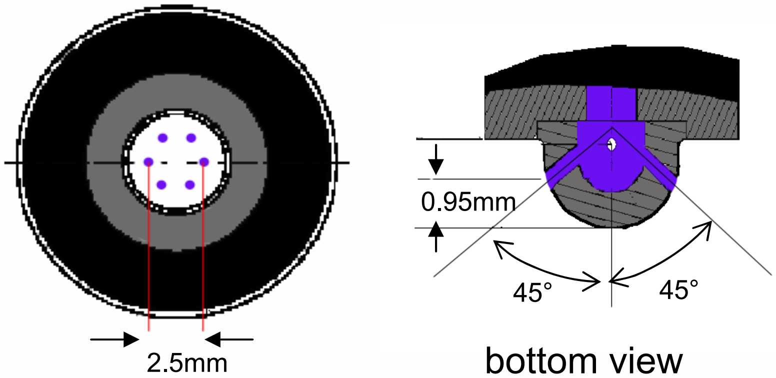
- **Relatively simple experimental technique.**
  - Natural flame luminosity due to chemical reaction that creates excited state OH.
  - OH* has a unique emission spectra with a peak about 308 nm.
- **Characterize flame front propagation characteristics**
  - OH* is a combustion intermediary that tracks heat-release (i.e. flame front)
- **Evaluate mixture formation for DI operation using premixed operation as a baseline.**
  - use OH chemiluminescence intensity as a metric for equivalence ratio.
    - ⇒ intensity increases exponentially with equivalence ratio
  - use OH chemiluminescence distribution as a metric for mixture homogeneity.
- **Limitations**
  - line-of-sight measurement
  - qualitative (at best semi-quantitative)
  - time integrated (weak signal ≈ 1 CAD at 1200 rpm)

OH chemiluminescence experimental set-up



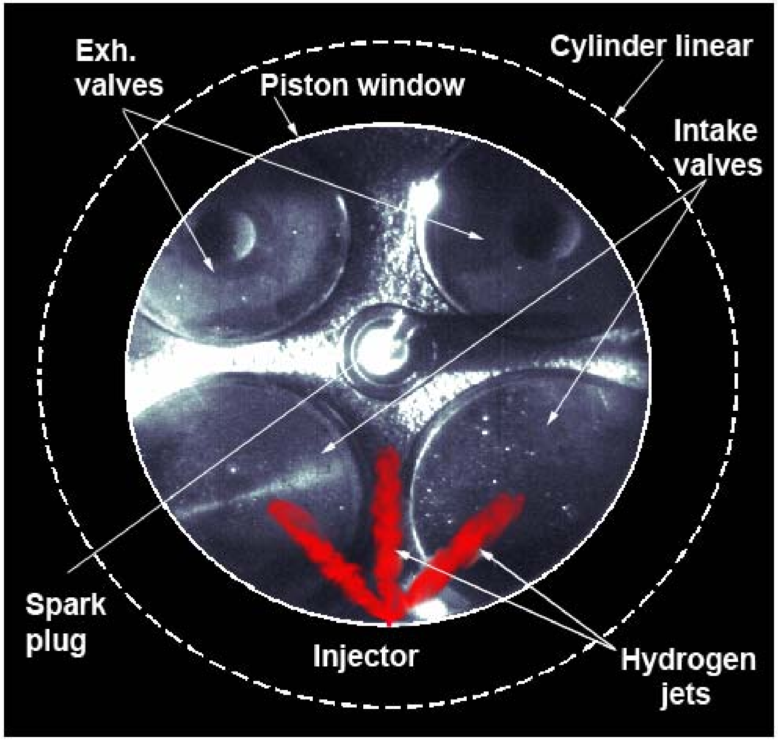
H2 DI Injector (Westport Innov.)

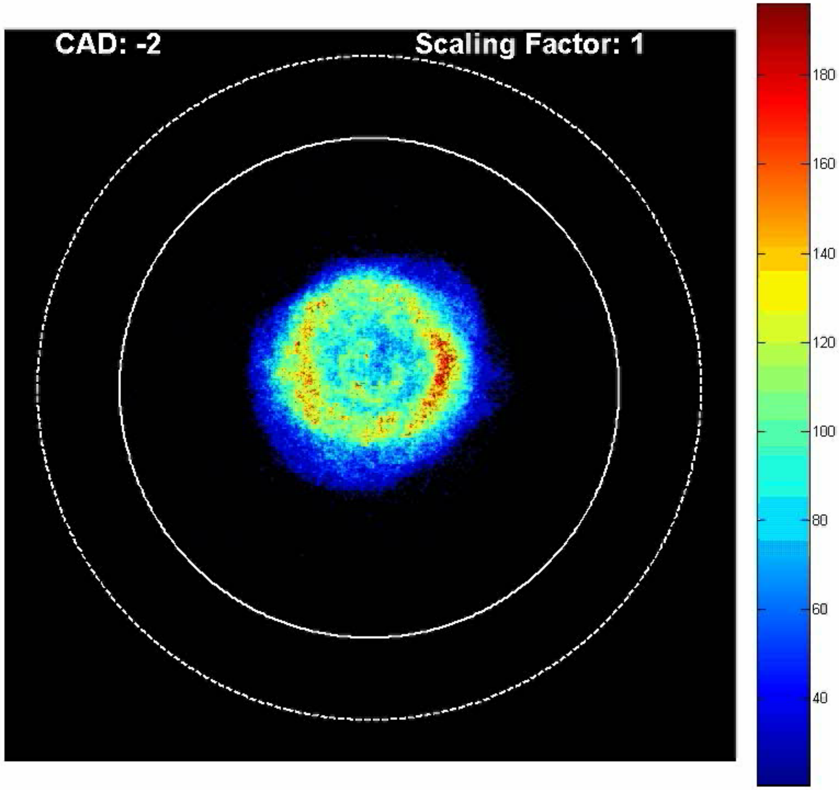
- Solenoid type injector
- six hole, D = 0.56mm
- jet angles 45° wrt to injector axis



Engine Speed	1200 rpm
Intake air pressure (BDC)	50 kPa
"Premixed" fueling (SOI/EOI)	-270/-240 CAD
Direct injection fueling (SOI)	Later than -112 CAD

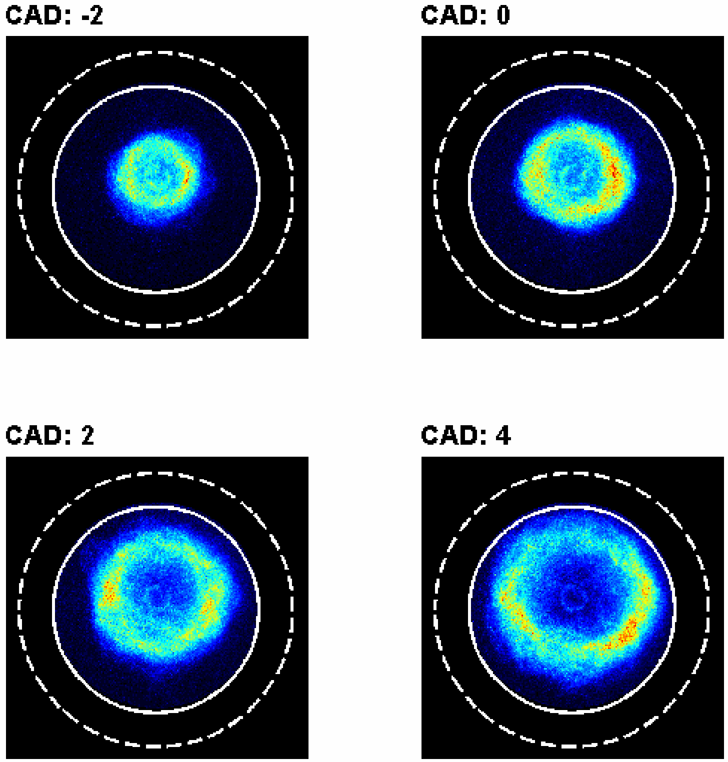
Ensemble-averaged OH* image movie: ϕ = 0.51 (premixed); spark = -11CAD;

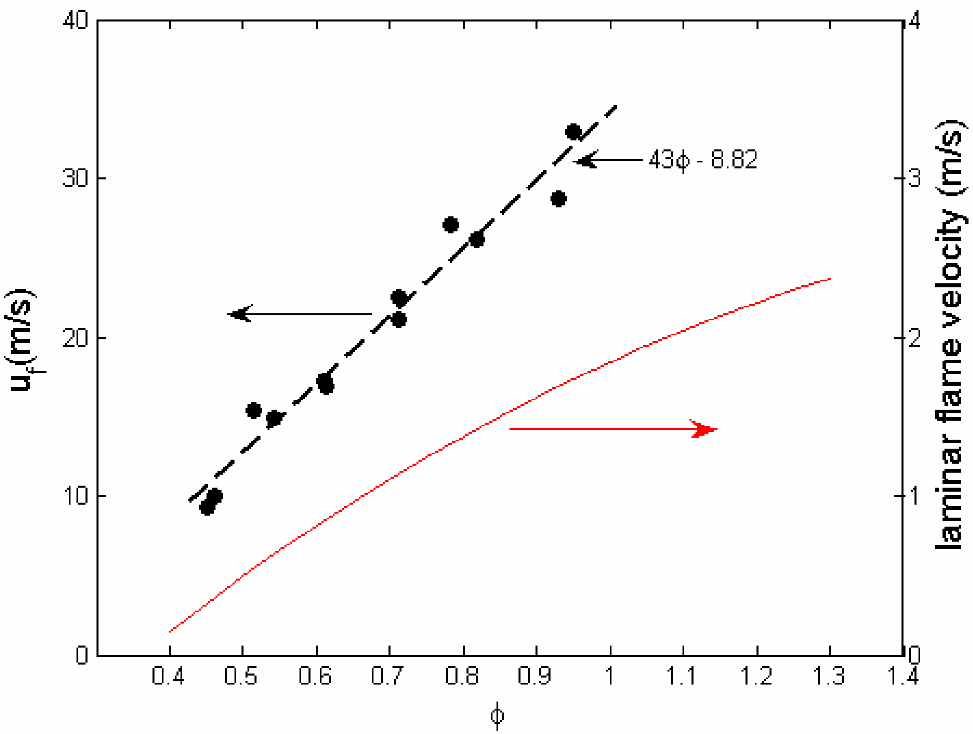




Color bar corresponds to OH chemiluminescence intensity

Flame front expansion speed ("premixed")





$$u_f = \frac{dr_f}{dCAD} \cdot \frac{dCAD}{dt}$$, where r_f is the flame radius and t is time.

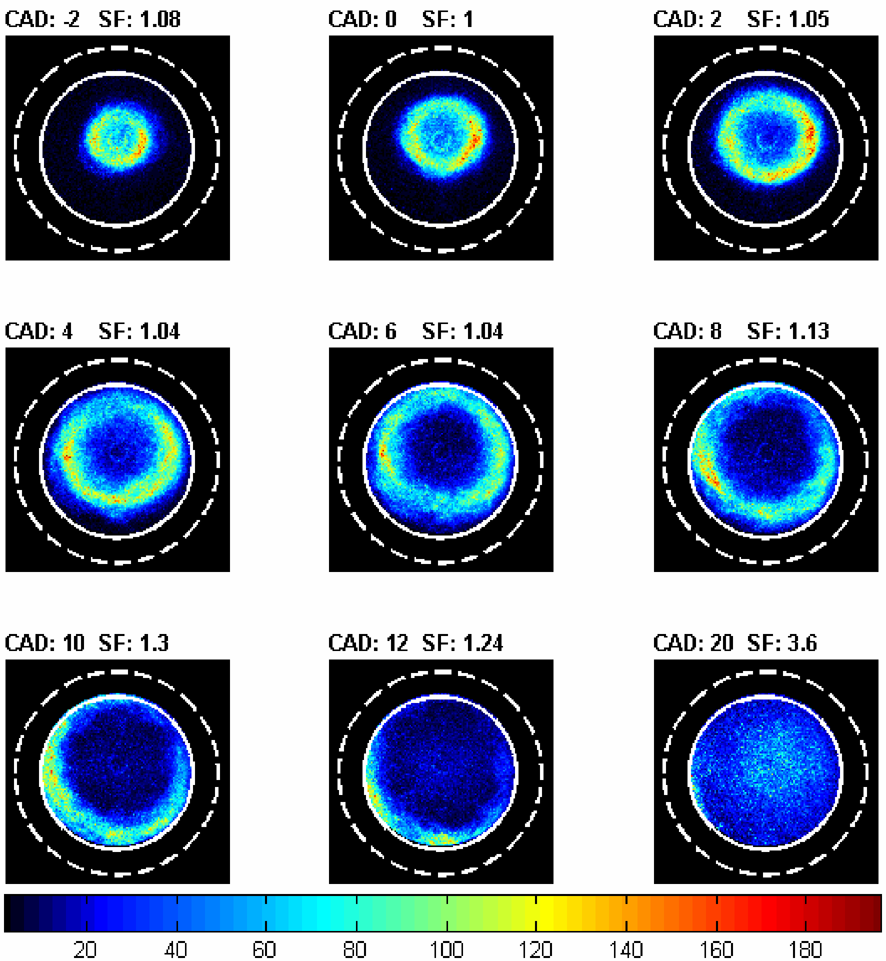
Note: u_f approximates the burned gas expansion speed

Experimental conditions for DI operation

Case	H_2 Inj. Press (MPa)	MBT Spark (CAD)	Images at CAD	SOI (CAD)	EOI (CAD)	global ϕ
i	2.5	-8	0, 1, 2, 3, 4, 5, 6, 7, 11	-112	-62	0.56
ii	2.5	-11	-3, -2, -1, 0, 1, 2, 4, 8, 12	-90	-40	0.56
iii	2.5	-11	-3, -2, -1, 0, 1, 3, 4, 8, 12	-77.5	-27.5	0.58
iv	10	-8	0, 1, 2, 3, 4, 5, 6, 7, 16	-112	-99.5	0.53
v	10	-8	0, 1, 2, 3, 4, 5, 6, 11, 16	-90	-77.5	0.53
vi	10	-5	0, 1, 2, 3, 4, 5, 6, 11, 16,	-70	-57.5	0.54
vii	10	-11	-3, -1, 1, 3, 8, 12, 16, 20, 28	-50	-37.5	0.53
viii	10	-11	-3, -1, 1, 3, 8, 12, 16, 20, 28	-40	-27.5	0.53

- Global equivalence ratio ≈ 0.55 (near the knee in NO_x curve).
- Two injection pressures:
  - P_{inj} = 25 bar and Δ_{inj} = 50 CAD
  - P_{inj} = 100 bar and Δ_{inj} = 12.5 CAD
- SOI sweep (IVC is at -112 CAD).

Baseline ensemble-averaged images: ϕ = 0.51 (premixed); spark = -11CAD;



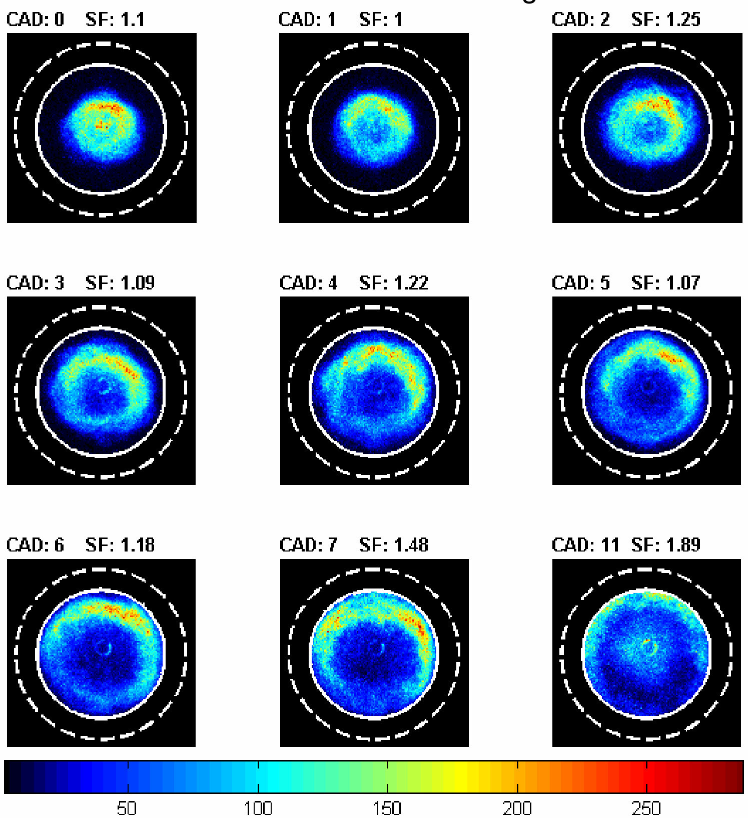
Color bar corresponds to OH chemiluminescence intensity

- Radial "flame" development
- "Flame" front is beyond field-of-view after 8 CAD.
- Peak intensities 190 counts.
  - fairly low signal!
- SF is a multiplicative scaling factor based on maximum intensity (utilize the same color bar)

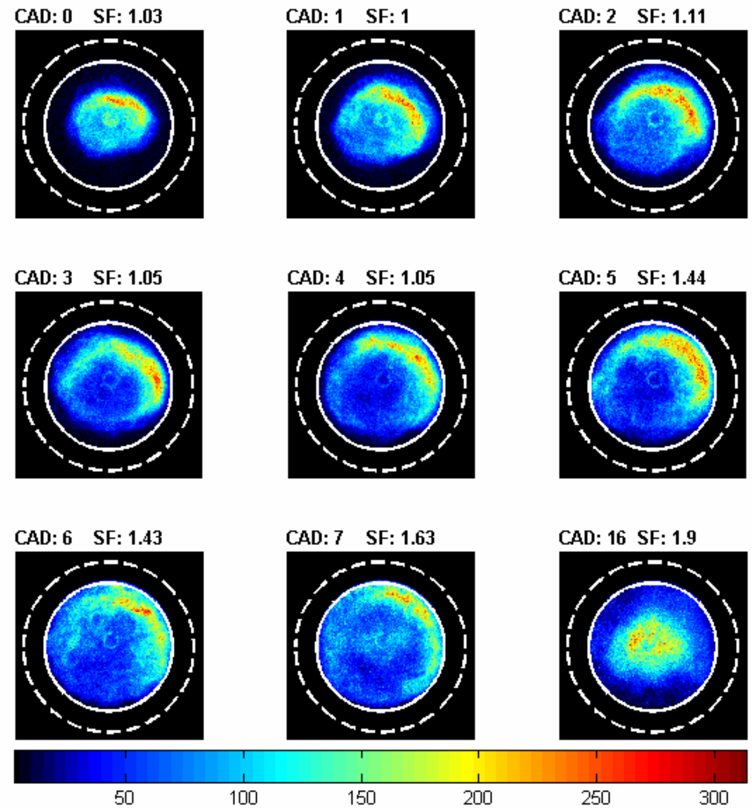
<u>Next few slides:</u>
Evaluate mixture formation for DI compared to premixed operation.
(1) use OH chemiluminescence intensity as a metric for equivalence ratio.
(2) use OH chemiluminescence distribution as a metric for mixture homogeneity.

Early Injection: SOI at IVC, spark = -8CAD

P_{inj} = 25 bar,
SOI(-112)/EOI(-62), ϕ_{global} = 0.56



P_{inj} = 100 bar,
SOI(-112)/EOI(-99.5), ϕ_{global} = 0.53



Main observations

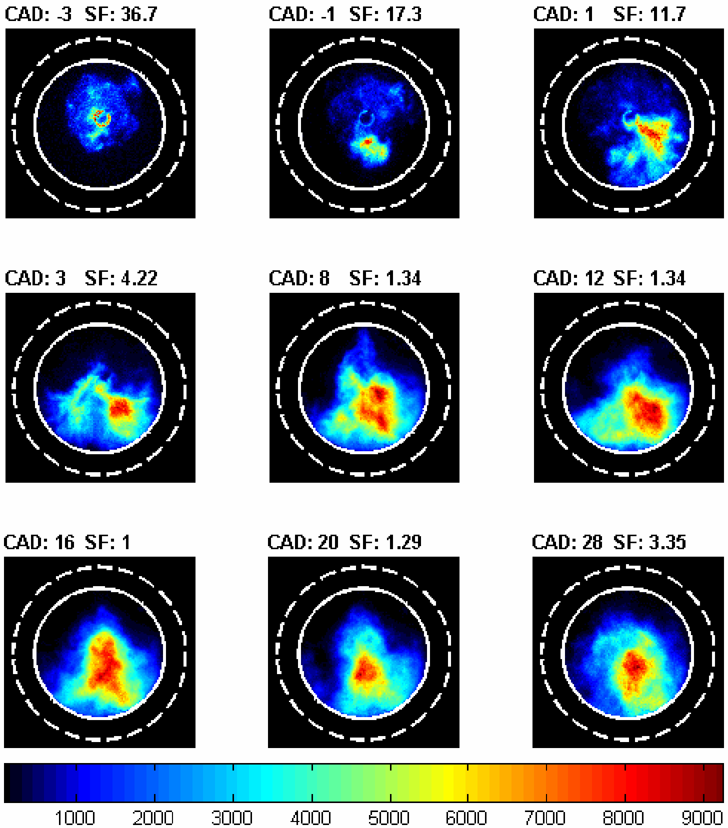
- Intensity scale similar to premixed case.
  $\rightarrow \phi_{local} \approx \phi_{global}$
- Radial "flame" development.
- High intensities opposite injector.

Summary:

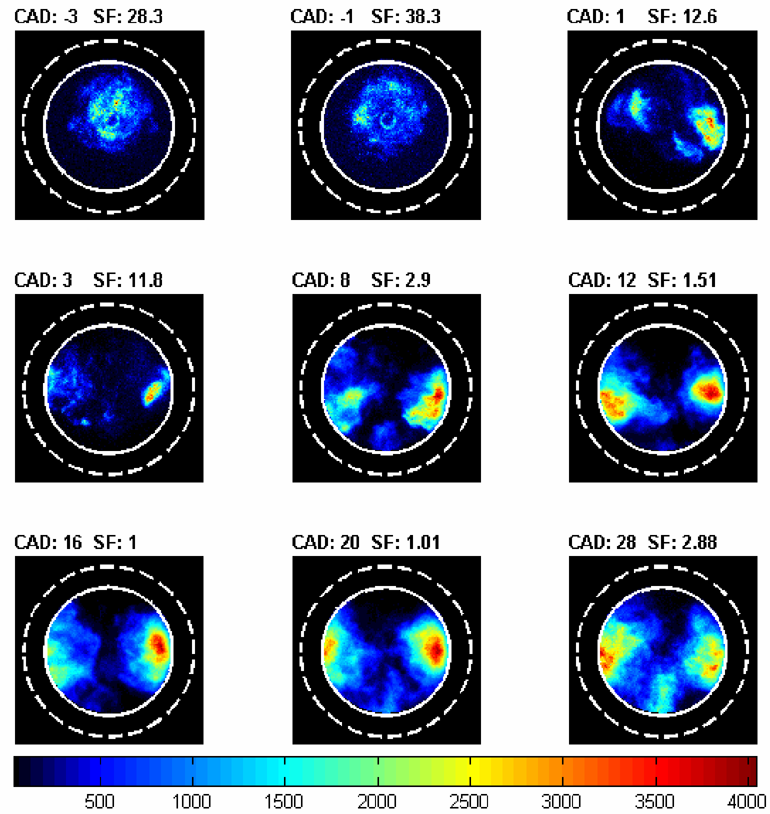
- Near-homogeneous mixture
- Similar characteristics as premixed case
- Little difference with injection pressure

Late Injection: EOI at -27.5CAD, spark = -11CAD

P_{inj} = 25 bar,
SOI(-77.5)/EOI(-27.5), ϕ_{global} = 0.57



P_{inj} = 100 bar,
SOI(-40)/EOI(-27.5), ϕ_{global} = 0.53



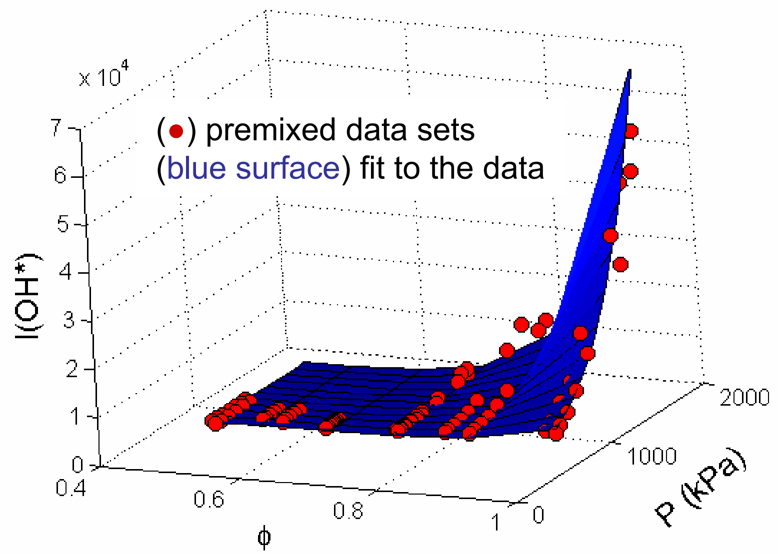
Main observations

- Intensity scale greater than premixed case.
  - $\phi_{local} > \phi_{global}$
- No clear flame front.
- High intensity local regions.

Summary:

- Strongly heterogeneous mixture
- Significant difference with injection pressure
  - intensity scale
  - spatial distribution

Empirical relationship



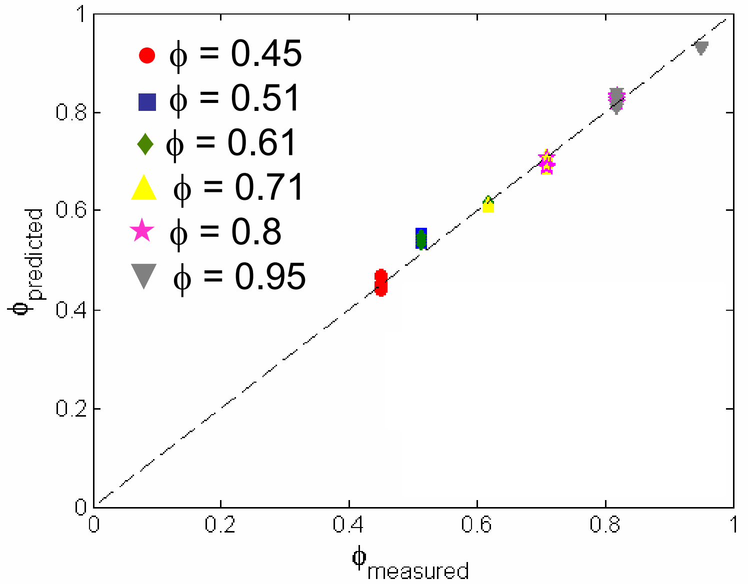
Four parameter fit:

$$I = AP^{B}\exp(CP^{D}\phi)$$

$$\phi_{predicted} = \frac{\ln(I / AP^{B})}{CP^{D}}$$

Evaluate ϕ_{local} during combustion from measurement of I and P.

Premixed data sets

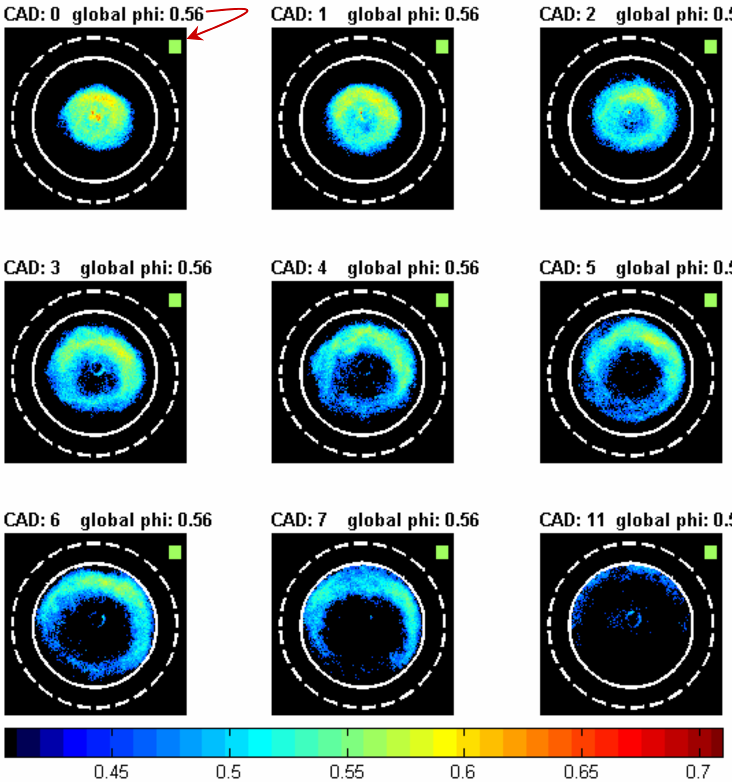


- measure of how well the empirical relationship fits the data.
- % difference is within ± 8%

% difference ≡ $(1 - \phi_{predicted}/\phi_{meaured}) \times 100$

Evaluation of ϕ from I(OH*) for DI data-sets

P_{inj} = 25 bar,
SOI(-112)/EOI(62), ϕ_{global} = 0.56

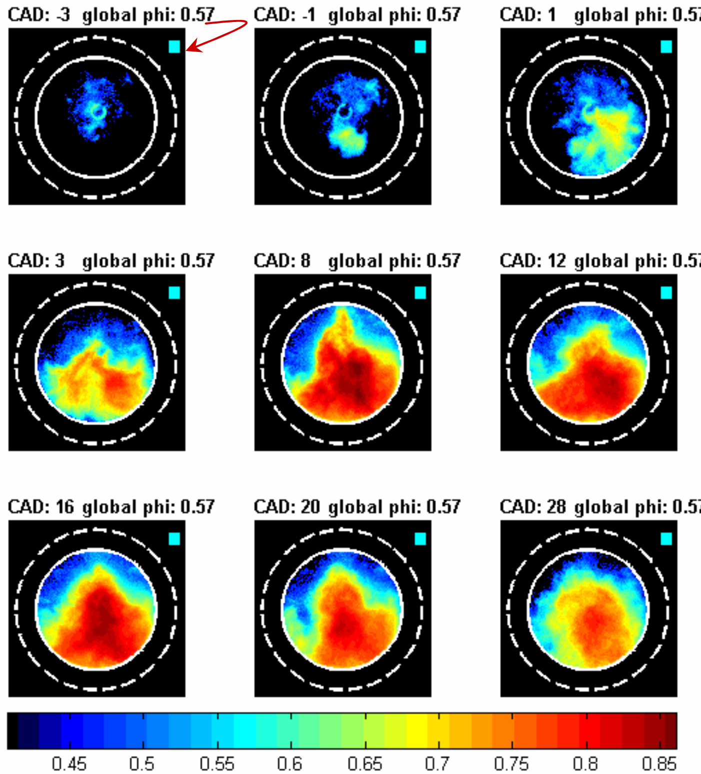


Color bar corresponds to equivalence ratio

Main observations

- Method is valid only for max ϕ on flame front.
  - inherent limitation of the method.
- equivalence ratio on flame front similar to global equivalence ratio (credence to method)

P_{inj} = 25 bar,
SOI(-77.5)/EOI(-27.5), ϕ_{global} = 0.57

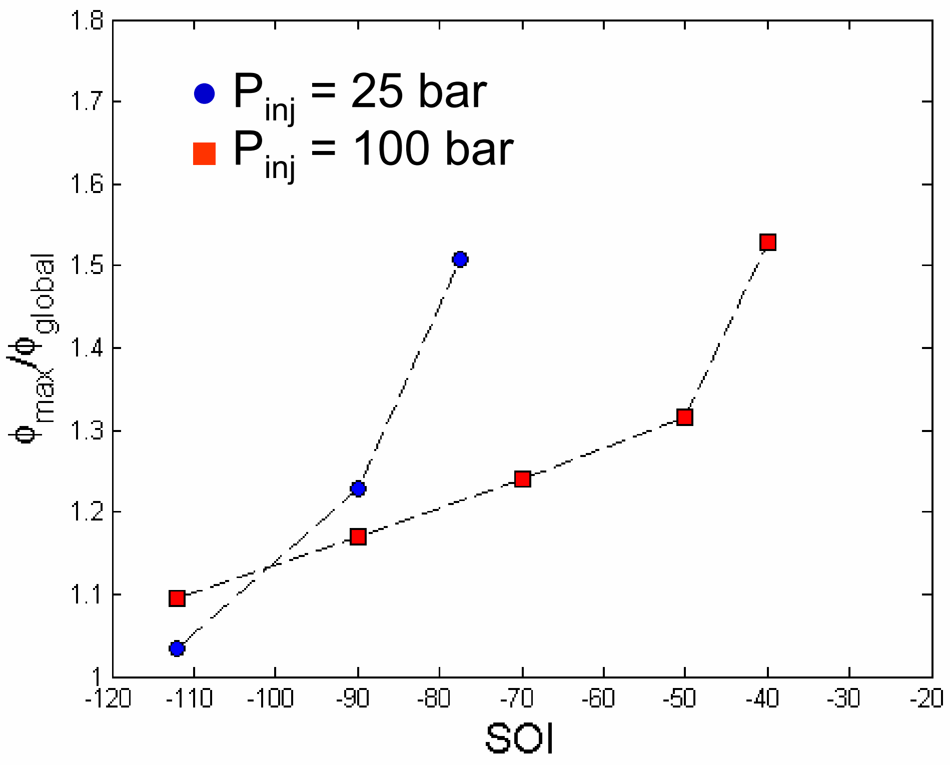


Color bar corresponds to equivalence ratio

Main observations

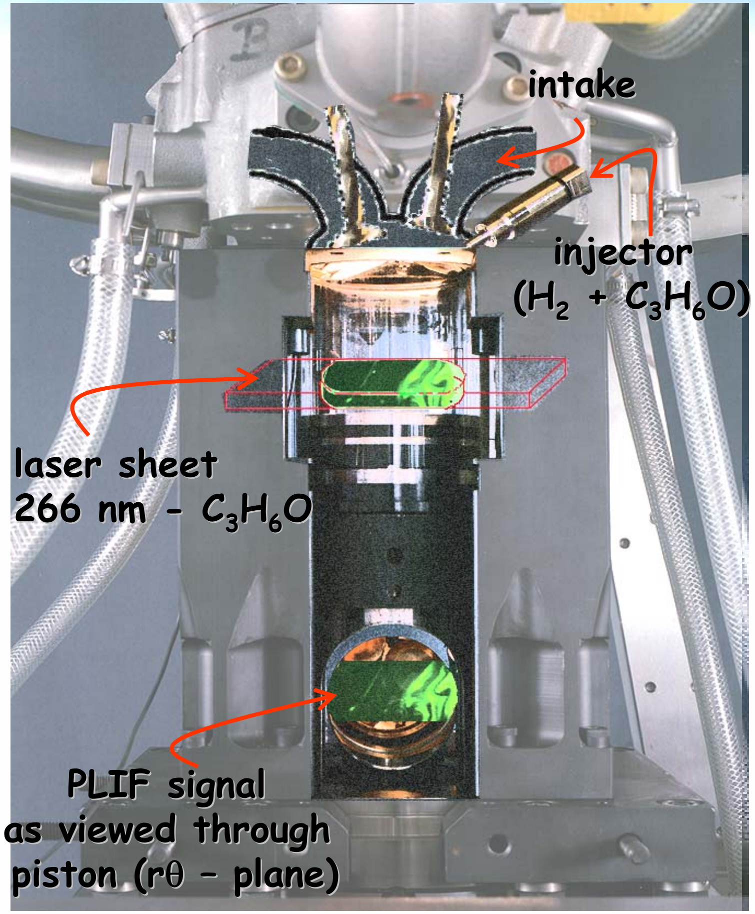
- No clear flame front (interpretation difficult)
- Limited to looking at max ϕ during cycle

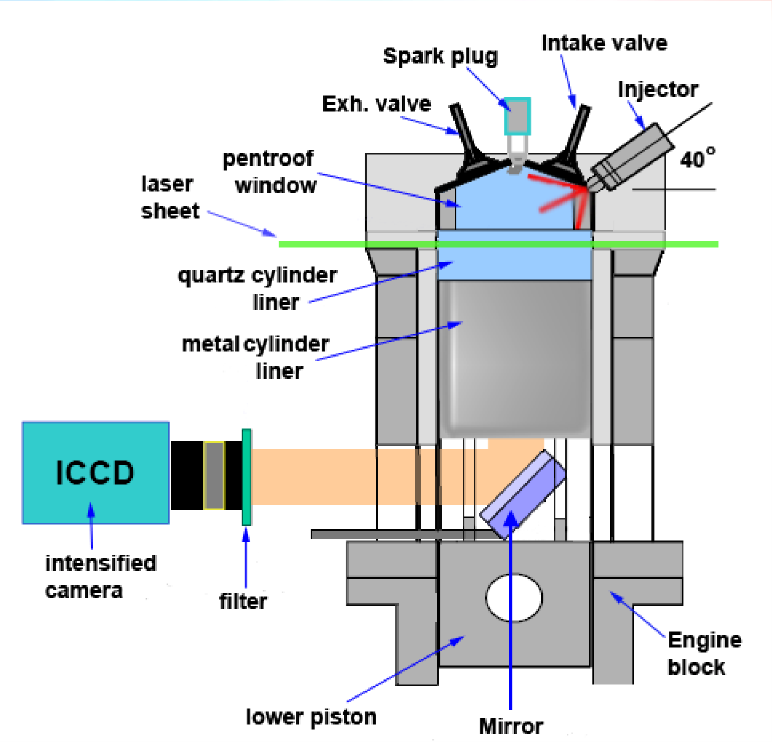
Maximum equivalence ratio verses SOI



- Maximum local equivalence ratio increases monotonically with retard of SOI for both injection pressures.
- Results agree with trends of NO_x emission with retard of SOI (in the literature).
- Excellent “starting point” for advanced laser-based diagnostics.

PLIF experimental set-up

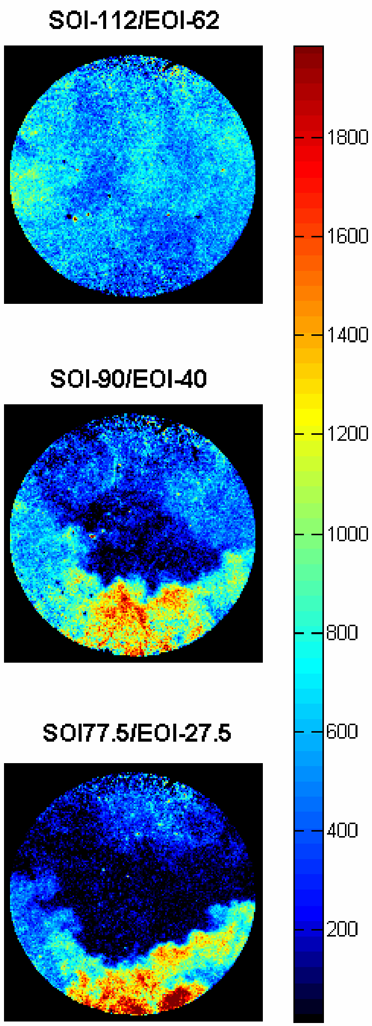




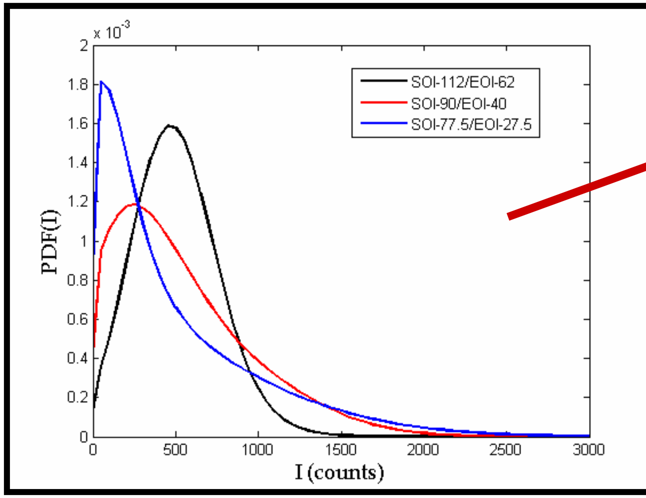
Engine Speed	1200 rpm
Intake air pressure (BDC)	50 kPa
Pinj	25 bar
global_phi	0.55
Acetone mole fraction	5×10^{-3}

PLIF Results

Representative Images
(100 images per SOI)

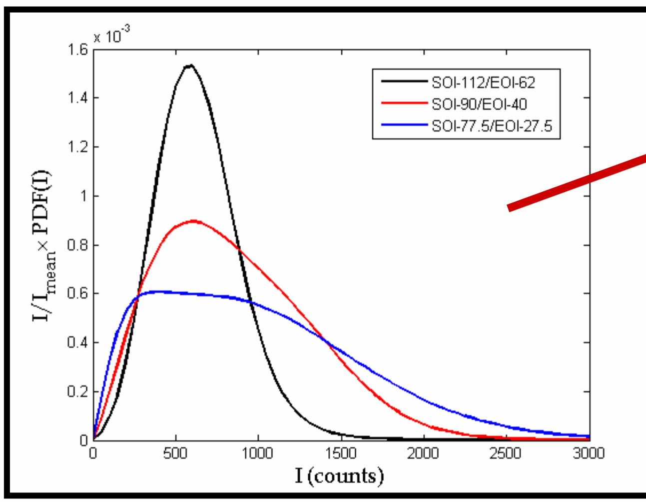


PDF of Intensity



Retard of SOI produces increasing regions of low and high intensity

Weighted PDF of Intensity



Proportional to fuel mass distribution:
With retard of SOI fuel mass is increasingly concentrated in small volumes that are locally "rich".

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Summary and Conclusions

- Measured flame front propagation speeds for "premixed" hydrogen-air mixtures for various equivalence ratios.

- DI operation with SOI at IVC produces similar results as premixed operation.
  - little difference between low and high injection pressures.

- Developed a method to evaluate ϕ_{local} from OH chemiluminescence images.

- Showed that the maximum ϕ_{local} increases monotonically with retard of SOI from IVC for both injection pressures.
  - however temporal and spatial distribution differs significantly.

- PLIF images are consistent with results/conclusions from the OH* chemiluminescence images.