Spray Combustion Cross-Cut Engine Research

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Sponsor: DOE Office of Vehicle Technologies
Program Manager: Gurpreet Singh

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Overview

Timeline
- Project provides fundamental research that supports DOE/industry advanced engine development projects.
- Project directions and continuation are evaluated annually.

Budget
- Project funded by DOE/VT:
  - FY10- $660K
  - FY11 - $730K

Barriers
- Engine efficiency and emissions
- Load limitations for LTC
- CFD model improvement for engine design/optimization

Partners
- 15 Industry partners in the Advanced Engine Combustion MOU
- >20 participants in Engine Combustion Network
  - Experimental and modeling
- Project lead: Sandia
  - Lyle Pickett (PI)
The role of spray combustion research for high-efficiency engines.

- Future high-efficiency engines use direct injection.
  - Diesel, gasoline direct injection, partially-premixed compression ignition.
- Complex interactions between sprays, mixing, and chemistry.
  - Multiple injections
  - Mixing driven by spray
  - Two-phase system
  - Complicated internal flows within injectors
- Optimum engine designs discovered only when spray modeling becomes predictive.
Studies of spray combustion in constant-volume chamber.

- Well-defined ambient conditions:
  - 300 to 1300 K
  - up to 350 bar
  - 0-21% $O_2$ (EGR)

- Injector
  - single or multi-hole injectors
  - diesel or gasoline (cross-cut)

- Full optical access
  - 100 mm on a side

- Boundary condition control needed for CFD model development and validation.
  - Better control than an engine.
  - Easier to grid.
A combined experimental/modeling pathway towards clean, high-efficiency engines.

**High-Efficiency Engines**

- Predictive
- Design optimization
- New hardware identified

Engine CFD Modeling

- Well-controlled B.C.s
- Engine conditions
- Quantitative

**Increasing Sophistication**

- In-situ species
- Mixing, velocity, turbulence
- Spray liquid shape/volume fraction
- Injector int. geometry

**Current**

- Flame luminosity
- Pressure-based AHRR
- Engine-out emissions
- Spray model tuning
- Grid-dependent solutions
- Surrogate fuel properties

**Improved Engines**

- High-performance computing
- Detailed chemical kinetics
- Large-eddy simulation

**Increasing Sophistication**
Objectives/Milestones

• Aid the development of computational models for engine design and optimization (ongoing).
  – FY10-FY11(2): Develop “Spray A” diesel dataset at high-temperature, high-pressure condition.

• Identify combustion regime for gasoline direct injection, spark and autoignition (new project for FY11).
  – Direct injection of gasoline shows promise for LTC with lower heat-release rate.
  – FY11 (3): Use laser ignition, and autoignition, to identify if combustion is by flame propagation or self ignition.
(1) Measured “global” properties of spray need further understanding in comparison to CFD.

- Spreading angle derived from vapor boundary (green), at ½ jet penetration distance (Naber, 1996).
- Measured spreading angle depends somewhat on schlieren optical setup.

Experimental Conditions
“Spray A”
900 K gas temperature
22.8 kg/m³ gas density
0% O₂-inert
1500 bar injection pressure
0.090 mm nozzle orifice
n-dodecane
Quantitative mixing diagnostic in harsh high-temperature, high-pressure environment.

- Use Rayleigh scattering in vapor portion of fuel jet.
  - Overcomes significant temperature/composition uncertainties compared to laser-induced fluorescence.
- Measure both $I_{R,a}$, $I_{R,j}$
  - Allows in-situ calibration for $I_{R,a}$ variation in laser sheet intensity.
  - Beam-steering or divergence addressed by using $I_{R,a}$ on bottom and top of jet.

$$
\frac{I_{R,j}}{I_{R,a}} = \left( \frac{\sigma_f/\sigma_a + N_a/N_f}{1 + N_a/N_f} \right) \frac{T_a}{T_{mix}}
$$

$$
T_{mix} = f(N_a/N_f)
$$

- Measurement provides
  - Fuel mixture fraction (mass fraction)
  - Mixture temperature
When modeled* penetration matches experiment, modeled mixing is also accurate.

*Variable radial profile (Musculus and Kattke 2009)

Spreading-angle adjusted to match experimental (schlieren) penetration rate.

Model predictions of mixture fraction (same spreading angle) agree with experimental Rayleigh measurements. (see SAE 2011-01-0686)
Mixing results confirmed at other injector and ambient operating conditions.

- Mixture distribution shows self-similar, $1/x$ decay
  - Such behavior is typical of gas jets.
  - Documented now for the first time in diesel sprays at engine conditions.

Experimental Conditions
- 1000 K gas temperature
- 14.8 kg/m$^3$ gas density
- 0% O$_2$-inert
- 1540 bar injection pressure
- 0.100 mm nozzle orifice
- n-heptane

![Centerline mixture fraction vs Axial distance](image1)

![Mixtures fraction vs Radial distance](image2)
Bosch Donates 10 “identical” common-rail injectors

- Operation at the same injector and ambient conditions.
- Voluntary participation
- Led by Sandia.

(2) Industrial and academic collaboration in the Engine Combustion Network for “Spray A”
## Experimental participation at Spray A

<table>
<thead>
<tr>
<th>Institution</th>
<th>Facilities</th>
<th>Personnel</th>
</tr>
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<tbody>
<tr>
<td>Sandia</td>
<td>Preburn CV</td>
<td>Lyle Pickett</td>
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<tr>
<td>IFPEN</td>
<td>Preburn CV</td>
<td>Gilles Bruneaux, Louis-Marie Malbec</td>
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<tr>
<td>CMT</td>
<td>Cold CV, Flow PV</td>
<td>Julien Manin, Raul Payri</td>
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<td>Chalmers</td>
<td>Flow PV</td>
<td>Mark Linne</td>
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<tr>
<td>GM</td>
<td>Flow PV</td>
<td>Scott Parrish</td>
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<tr>
<td>Argonne</td>
<td>Cold V, X-ray Sync.</td>
<td>Chris Powell, Alan Kastengren</td>
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<tr>
<td>Caterpillar</td>
<td>Flow PV</td>
<td>Tim Bazyn, Glen Martin</td>
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<td>Aachen</td>
<td>Flow PV</td>
<td>Heinz Pitsch, Joachim Beeckmann</td>
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<td>Meiji U.</td>
<td>Preburn CV</td>
<td>Tetsuya Aizawa</td>
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<td>Seoul Nat. U.</td>
<td>Preburn CV</td>
<td>Kyoungdoug Min</td>
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<tr>
<td>Eindhoven U.</td>
<td>Preburn CV</td>
<td>Maarten Meijor, Bart Somers</td>
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**BLUE: In progress**  **Red: Commencing in next 3 months.**
Spray A vapor penetration shows reasonable agreement at 4 different institutions.

- Despite the significant challenge to control high-T, high-P boundary conditions.
- Ongoing work to understand the sources of discrepancy, including post-processing.
- Leveraging experimental work is possible!

Vapor boundary derived from schlieren imaging (0% O₂)

- Maximum Penetration [mm]
- Time ASI [µs]

- Sandia
- IFPEN
- Caterpillar
- CMT
ECN research accelerates detailed (quantitative) understanding of engine sprays.

- Other activities during FY11:
  - Comparison of rate of injection and rate of momentum at different institutions.
  - Preburn vs. heated flow chambers.
  - Internal injector tip temperature.
  - Internal shape of nozzle by x-ray tomography and silicone molds.
  - Consistent measurement/quantification of liquid length and volume fraction.
  - Measurement of cool flame, ignition site, and lift-off length.
  - …many others now available on web. Download data at www.sandia.gov/ECN

- ECN workshop held to coordinate experimental/modeling activities.
  - May 13-14, Ventura, CA, before ILASS.
  - 60 participants; >50% attendees use ECN data for CFD model development.
(3) Breakthroughs in engine efficiency require better understanding, modeling, and control.

- Strategies navigate combustion regimes that tend to have high heat-release rate (noise) and high UHC and CO emissions
  - Can we slow down combustion, maintain control, and still retain high efficiency?
  - Can we model these processes accurately, including crossover from one regime to the other?
- Approach: Characterize transition combustion regime from flame propagation to autoignition in gasoline sprays.
2-hole gasoline injector experimental setup

Constant-volume chamber

Engine Params.
- CR = 12
- P_BDC = 1 bar
- T_BDC = 340 K

-30 CAD Conditions
- T_a = 700 K
- \( \rho_a = 6.5 \text{ kg/m}^3 \)
- P = 13 bar
- 21% oxygen (air)

Schlieren imaging (vapor)
(Side view)

Mie-scatter imaging (liquid)
(Bottom view)

<table>
<thead>
<tr>
<th>GDI fuel injector (Bosch):</th>
<th>2-hole</th>
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<tbody>
<tr>
<td>Nominal flow rate at 100 bar</td>
<td>3.75 cc/s</td>
</tr>
<tr>
<td>Inner hole diameter</td>
<td>0.125 mm</td>
</tr>
<tr>
<td>Nominal spray included angle</td>
<td>60°</td>
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<tr>
<td>Fuel injection pressure</td>
<td>100 bar</td>
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</table>
Laser ignition AEI produces flame that propagates into downstream richer mixture.

Laser Ignition Conditions

\[ T_a = 700 \text{ K} \]
\[ \rho_a = 6.5 \text{ kg/m}^3 \]
\[ \text{AEI}_{\text{laser}} = 350 \text{ } \mu\text{s} \]
Raising ambient temperature produces a connected reaction zone AFTER autoignition.

Auto Ignition Conditions
\[ T_a = 1100 \text{ K (ambient)} \]
\[ \rho_a = 6.5 \text{ kg/m}^3 \]
\[ P = 20.5 \text{ bar} \]

Ignition Time/Location
\[ 2100 \text{ \mu s ASI} \]
\[ 900 \text{ \mu s AEI} \]
\[ 20 \text{ mm downstream} \]

Schlieren imaging (vapor and flame) (+ higher sensitivity)

Mie scatter + Chemiluminescence (bottom view)

• OPPOSITE the order of spark-assist CI.
• Flame catches up with most/all of charge.
• SMOOTH heat release; also no soot.
Mixture equivalence ratio, residence time, and temperature ALL affect ignition.

- Flame propagation is possible after self-ignition because of the highly stratified (cool, high $\phi$) charge surrounding the ignition location.
**Future work**

- **Outlook for the Engine Combustion Network**
  - Measurements (not a complete list, Sandia in blue):
    - Nozzle shape
    - Internal needle movement
    - Discharge and area contraction coefficients
    - Rate of injection
    - Near-nozzle liquid volume fraction
    - Droplet size, velocity, shape
    - Maximum liquid penetration
    - Vapor penetration rate
    - Velocity and turbulence within spray
    - Mixture fraction (non-reacting and reacting)
    - Ignition delay
    - Cool flame position and timing
    - Heat-release rate
    - Quantitative soot, soot precursor distribution
    - Lift-off length
  - Side-hole spray compared to axial hole
  - Liquid volume fraction near the liquid length
  - Parametric variation in ambient temperature and injection pressure
  - ECN Workshop will coordinate modeling efforts and establish future direction

- **Gasoline direct-injection sprays**
  - Develop an ECN-type research effort to quantify mixing, liquid distribution at various target conditions.
  - Identify regimes with both autoignition and flame propagation (relevant to knock).
  - Use high-pressure diesel and low-pressure SIDI-type injectors.
• Project is relevant to the development of high-efficiency, low-emission engines.
  – Observations of combustion in controlled environment lead to improved understanding/models for engine development.

• FY11 approach addresses high-efficiency diesel and gasoline concepts.
  – Quantitative mixture fraction data permit model calibration, and relate global penetration rate to mixture distribution.
  – Massive Spray A dataset is being generated, which will be a key component for future model improvement.
  – Flame propagation AFTER autoignition observed in gasoline sprays at high ambient temperature.
  – Utilizing flame propagation after autoignition may be important for slowing heat release and controlling LTC.

• Collaboration expanded to accelerate research and provide greatest impact (MOU, leading Engine Combustion Network).
• Future plans will continue ECN-type diesel and gasoline research.
Optical diagnostics experimental setup

- **Schlieren**
  - High-Speed (61538 fps)
  - CMOS Camera
  - Nikkor Lens f=50 mm + Filters
  - Parabolic Mirror 115 mm diameter, f/8

- **Mie-Scatter**
  - High Speed (50000 fps)
  - CMOS-Camera
  - Nikkor Lens f=50 mm
  - f/1.2 Nikkor Condensing Lens

- **Xe Arc Lamp**
  - 1 mm Aperture

- **High-Pressure Combustion Vessel**

- **Close-up view of diesel spray**
  - Volume illumination of spray with Nd:YAG laser
  - central combustion chamber
  - knife edge

- **CW Nd:YAG Laser**
  - 2 W
  - 532 nm

- **Parabolic Mirror**
  - 115 mm diameter, f/8
Internal injector temperature distribution

Steady state $T^\circ$ decreases with distance to nozzle tip.

$T^\circ$ is affected by preburn. Distance to nozzle acts as a filter.
Liquid length increases slightly with increasing time after start of injection.

- Suggests that fuel cools the injector tip with increasing time ASI.
- 0.5 mm → approx. 20° C.
Analysis shows that the typical ignition site is near 20 mm. Why?

- Mixing near injector after the end of injection affects $\phi$ and $T$.
- Equivalence ratios near unity.
- High mixture temperatures, near 1000 K.
- Long residence time.
  - Some of “first-injected” fuel appears to be shed in large-scale structures to the side of the jet.
  - “First-injected” fuel has 1200 $\mu$s (the inj. dur.) longer residence time than “last-injected”.
  - Last-injected fuel goes to head of jet.