Fuel Spray Research on Light-Duty Injection Systems

Project ID ace_10_powell

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2009 OVT Merit Review
19 May 2009
Crystal City, VA

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Overview

Timeline
- Project Start: FY2000

Budget
- Lifetime Project Funding
  - $3.13M Since FY05
- Recent Funding
  - FY2008: $500K
  - FY2009: $645K

Partners
- Bosch, ERC, Sandia
- Delphi, Caterpillar

Barriers
- “Inadequate understanding of the fundamentals of fuel injection”
- “Inadequate capability to simulate this process”
- “Inadequate understanding of fuel injector parameters (timing, spray type, orifice geometry, injection pressure, single-pulse vs. multi-pulse)”

These barriers impact:
- Low-Temperature Combustion
- Thermal Efficiency
- System Cost
Objectives

- **Entire Project:**
  - Serve industry by providing unique injector and spray diagnostics
  - Assist in development of improved spray models using unique quantitative measurements of sprays

- **FY2009:**
  - Study the effect of the number of orifices on spray structure
  - Develop new technique for measuring 3D spray density
  - Develop non-destructive needle lift diagnostic
    - Useful tool for injector manufacturers
    - Allows generation of realistic time-resolved mesh for modeling
Milestones, FY2008 and FY2009

- May 2008: Publication of study showing how spray width varies with spray chamber density
- June 2008; Completion of measurements showing how number of holes affects spray structure
- May 2009: Completion of x-ray laboratory dedicated to sprays and transportation research
Technical Approach – X-rays Reveal Fundamental Spray Structure

Visible Light Imaging

X-Ray Imaging
Studying the Effects of the Number of Spray Holes

5-hole
\( \rho_G = 21 \text{ kg/m}^3 \)

3-hole
\( \rho_G = 21 \text{ kg/m}^3 \)

5-hole
\( \rho_G = 1.4 \text{ kg/m}^3 \)

3-hole
\( \rho_G = 1.4 \text{ kg/m}^3 \)
Studying the Effects of the Number of Spray Holes

- 3-hole nozzle generates wider fuel distribution
- This agrees with predictions of Bosch CFD models
  - 3-hole nozzle has fewer “sinks” for the pressure
  - Leads to more/larger recirculation regions inside sac
  - Increase in turbulence inside the nozzle results in broader spray
3D Fuel Density Reconstruction

- Single measurement is line-of-sight projection, does not resolve 3D structure
- Density can be estimated only by making assumptions, e.g. axisymmetry
- Multiple projections allow more accurate determination of structure, density
- With only four projections, some assumptions are still required
- Can calculate true 3D density with uncertainty of ~10%
Model Reconstruction Procedure

- Obtain data across spray
- Fit data from all viewing angles with the same model
- Reconcile the fit parameters to give 2-D fuel distribution
X-Ray Measurements Highlight Flaws in Common Spray Models

- 3D fuel distribution allows you to make a visualization of the spray structure
- Assumptions:
  - The spray is composed of spherical droplets
  - The droplets are all the same size

Many spray models assume spray is composed of discrete droplets, and that drag on one droplet is not influenced by neighboring droplets. Will also affect evaporation, mixing, gas entrainment, penetration, etc. Illustrates the need for advances in computational spray modeling.
Real-Time Non-Destructive Nozzle Imaging

- High penetration of x-rays allows measurement of nozzle geometry through the steel of the nozzle
- Argonne demonstrated this capability in 2004
- High flux at the Advanced Photon Source allows this to be done with microsecond (or better) time resolution
- With multiple lines-of-sight, 3D motion of needle can be measured
- Needle lift and nozzle geometry can be used to generate accurate time-dependent mesh for computational models
- Unique diagnostic for injector manufacturers
Asymmetric Spray Results from Asymmetries in Nozzle?

Use static images to examine details of nozzle geometry.

Can see that our “axisymmetric” nozzles have notable defects: hole misalignment and differences in entrance rounding.
High-Speed Imaging of Pintle Motion: 3-Hole VCO Nozzle
Needle Axial Motion: Lift vs. Time

3-Hole Nozzle

- Variation in full lift position
- Oscillation at full lift (~6.5 kHz)
Variation In Height at Full Lift Position

- Linear increase in needle position with rail pressure, $\sim 0.72 \, \mu m/MPa$
- Compression of the needle and control rod?
  - Typical modulus for steel $E \sim 200$ GPa
  - Needle + rod length should be $\sim 150$mm
- If this is caused by compression, conventional sensors may not capture the lift correctly

\[ Y = 181.43208 + 0.06802 \, X \]

\[ Y = 193.13242 + 0.07425 \, X \]

Distance to Full Lift ($\mu m$)

Injection Pressure (bar)

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146 mm

210 mm
High-Speed Imaging of Pintle Motion: 7-Hole Mini-Sac
Measurements From Two Views Shows 3-D Pintle Motion

- Plot shows average behavior
- Time moves in direction of arrow

Transverse Motion vs. Lateral Motion

Transverse Needle Motion, μm vs. Lateral Needle Motion, μm
**Fluctuations in Spray Density Linked to Needle Eccentricity**

**Needle Eccentricity**

- Period of oscillations ~ 450 μs
  - Appears to be caused by cantilever vibration
  - Only significant in single-guided needles

**Spray Density**
Nozzle Measurements Used to Generate 4D Mesh

- Time resolved measurements of nozzle geometry and needle motion were used to generate a mesh for CFD models of in-nozzle flow.

- Accurately depicts needle lift as measured at the valve seat.

- Includes eccentricities in needle motion.

- Recently completed measurements of a nozzle being used by Sandia and UW’s Engine Research Center.

- Will contribute time-resolved images of nozzle, time-resolved needle motion, measured nozzle surface.
Previous experiments were done under a competitive proposal system
- Allowed about 6 weeks of experiments per year
- New experimental station is nearly complete
- Dedicated to transportation research, primarily fuel sprays
- >50% of the cost paid by BES

⇒ Dedicated space
⇒ Guaranteed access to x-ray beam at no cost
⇒ More time available for measurements
⇒ Enables expansion of collaborations
Future Work in FY2009

- Strengthen ties between spray experiments and engine experiments
  - Bosch has donated fuel injection equipment matching the GM 1.9L engine, including custom spray nozzles
  - Spray measurements will be performed under conditions matching engine operating conditions
  - Argonne, other labs and Universities all using this platform

- Experiments supporting Sandia’s Engine Combustion Network
  - Common injection hardware will be distributed to 10 leading spray measurement labs worldwide
  - Argonne will provide x-ray measurements of spray and needle motion
  - Data will be provided to all partners, including spray modelers

- Strengthen ties between experiments and spray modeling
  - ERC modeling student to spend 6-8 weeks at Argonne, May 2009
  - New collaboration with Gavaises and Arcoumanis studying cavitation

- Attempt to link the motion of the needle with spray structure
  - Bosch will donate injectors and nozzles with eccentric needle motion
  - Argonne will measure 3D needle motion, 3D spray structure