Low-Temperature Diesel Combustion Cross-Cut Research

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FY 2008 DOE Vehicle Technologies Program Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
2:50 – 3:10 PM, Monday, February 25, 2008, White Flint Amphitheater

Sponsor: **DOE/OVT**
Program Manager: **Gurpreet Singh**

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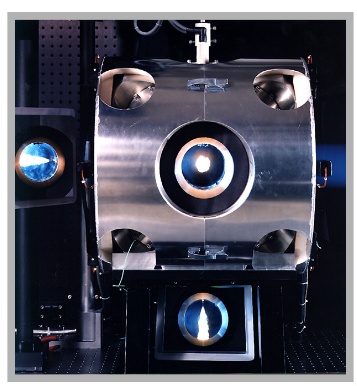
Overall Motivation of DCSF Research

- Overcome barriers to development of highly efficient, low-emission engines.
  - 30% efficiency gain: ≈50 billion gallons of fuel saved per year!
- Facility dedicated to fundamental combustion research for both heavy-duty and light-duty engines (cross-cut research).
  - Well-defined charge-gas conditions
    - Pressure, temperature, EGR level
  - Well-defined injector parameters
    - Injection pressure, fuel, multi-injections
- Aid the development of computational models for engine design and optimization:
  - Physical insight for improving submodels
  - Well-characterized data over a wide range of conditions



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Project changes based on 2007 review

- Recommendation: "Accompanying modeling should be applied to experimental results to address physics and help understanding."
  - Deepened collaboration with UW-ERC.
  - Simplified control-volume jet model (developed by Musculus) applied.
  - Archival website for experimental data, Engine Combustion Network, has been expanded.
    - http://www.ca.sandia.gov/ECN/
- Recommendation: "More interaction with industry."
  - Specific project plans reflect suggestions/approval by MOU partners.
- Recommendation: "Research on multiple injections is far more complex than single injections. Experiments must be posed well."
  - Rate-of-injection meter developed for in-place measurements at injector temperature and pressure.

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Addressing barriers to LTC implementation

Barrier to LTC	Recent research in our facility	
Premixed combustion by early injection causes wall wetting	-Methods for prevention of liquid wall impingement at typical early-injection LTC conditions.	**FY07**
High unburned hydrocarbons	-Determine the location of UHC production. -Investigate spray mixing at EOI.	**FY07** **FY08**
Use of EGR (needed to reduce NOx) can increase exhaust PM	-Quantify soot levels formed within reacting sprays for high EGR conditions. -Find injection strategies/charge gas combinations that eliminate soot formation.	**FY06** **FY07** **FY08**
Noise and ignition control Low-load limitation	-Interaction between multiple injections and impact on soot and UHC production.	**FY08**

- Observations in controlled environment.

  ->Improved understanding and models.

  ->Application in complicated engine environment.

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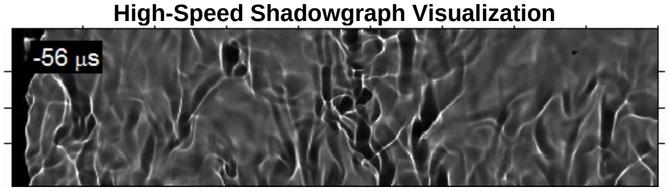
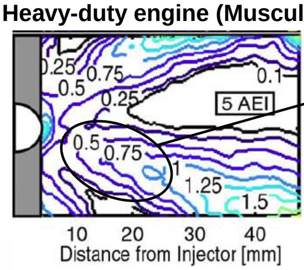
Significant fuel remains unburned near the nozzle for short-injection, LTC conditions.

- What creates fuel-lean mixtures near the injector?
- What prevents high-temperature reaction in these regions?

High-Speed Shadowgraph Visualization



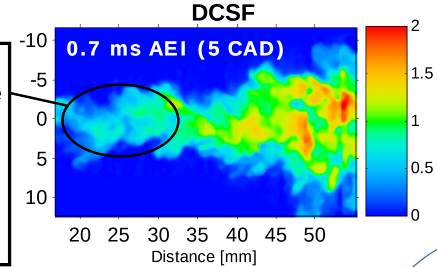
Heavy-duty engine (Musculus)



-Existence of fuel-lean zones persisting near the nozzle confirmed using two facilities/injectors (SAE 2007-01-0907)

-Other diagnostics confirm source of UHC.

DCSF



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Approach since last review (June 2007)

- Determine spray liquid-phase location and vaporization fate during end-of-injection transients.
  - Use high-speed imaging to identify liquid and vapor regions.
  - Vary ambient temperature, density, nozzle size, and injection pressure.
  - Apply Musculus control-volume jet model to understand trends.
- Determine how multiple injections affect UHC and soot.
  - Vary injection duration and dwell.
- Investigate fundamental causes for lift-off stabilization, impacting both UHC generation and soot formation at LTC conditions.
  - Combustion models rely on flame-propagation or ignition-based models. Which is correct/needed?
  - Artificially change lift-off location by laser-igniting spray. Monitor response of the reacting jet.

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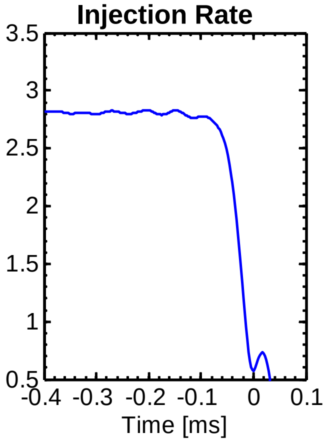
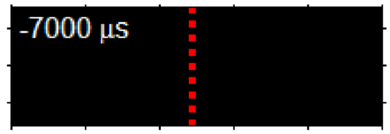
Liquid region and jet spreading angle visualized using high-speed imaging.

Injection Rate



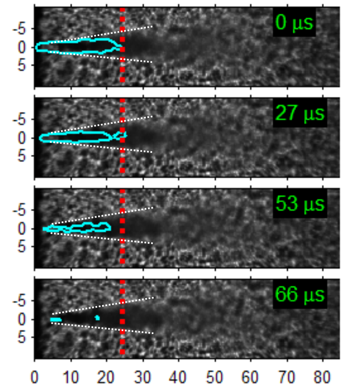
High-speed liquid droplet Mie scatter



<u>Ambient</u>
14.8 kg/m^3
850 K

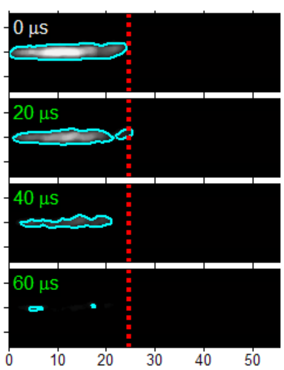
<u>Fuel</u>
1500 bar
0.090 mm nozzle
#2 diesel

Shadowgraph

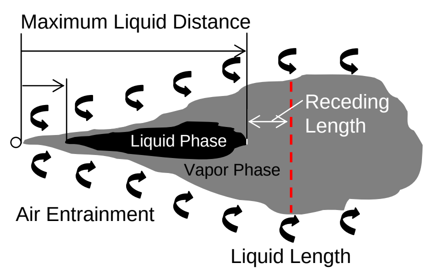


- Liquid reaches a quasi-steady maximum distance.
- Common-rail injector ramp down is less than 0.1 ms.
- Vaporized jet spray angle is nearly constant during end of injection.

Liquid droplets recede towards injector during EOI and do not reach quasi-steady liquid length.



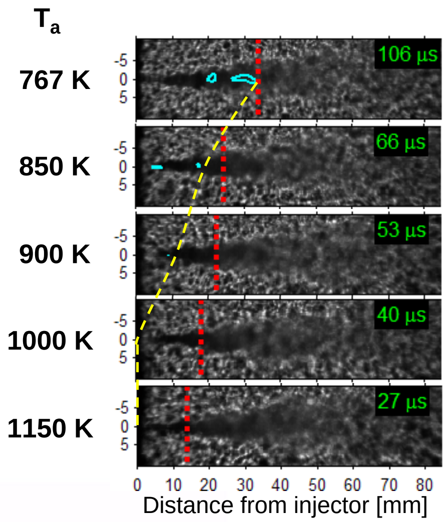
Spray Liquid and Vapor at EOI

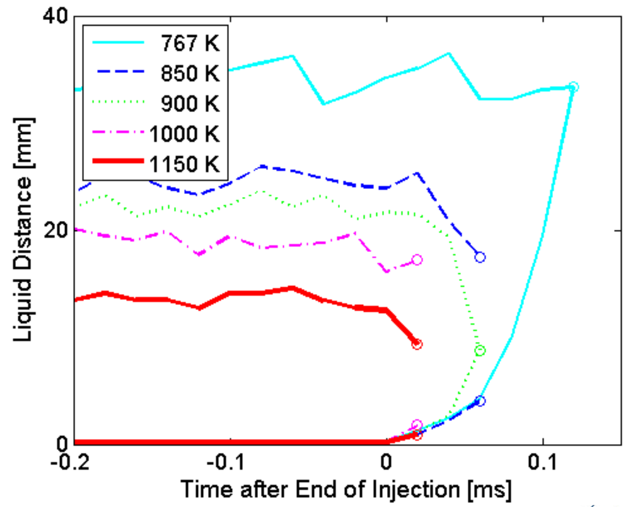


- Liquid shrinks to center of jet at end of injection.
- Liquid RECEDES towards injector for this condition, rather than continuing to vaporize at the quasi-steady liquid length.
- Receding length defined as the distance from the quasi-steady liquid penetration length to last droplets at EOI.

Liquid spray changes from “recede” to “detach” classification with decreasing temperature.

– Last liquid to vaporize penetrates all the way to quasi-steady length at lower ambient temperatures.

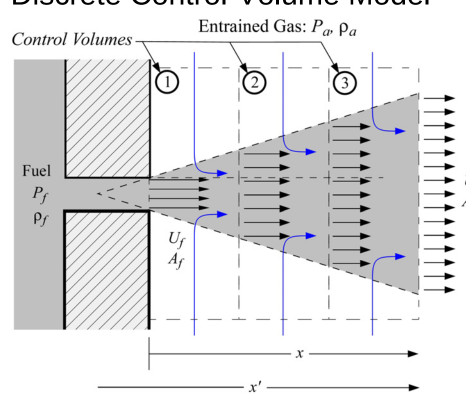




Simplified model applied to understand end-of-injection mixing processes.

- Musculus et al. have developed a new model for analysis of variable rate-of-injection mixing.
  - Includes short-, multiple-, and end-injection mixing and jet penetration.
  - Naber and Siebers (1996) used single control volume analysis to reach analytical solution for jet mixing and penetration.
  - Discrete control-volume analysis required.
- Assumptions
  - Jet spreading angle is constant, even after end of injection.
  - Velocity and mixing have assumed “real profiles, rather than uniform.
- Liquid boundary obtained by assuming mixing-limited vaporization.
  - Siebers (1999) accurately predicted STEADY liquid penetration lengths over a very wide range of conditions.

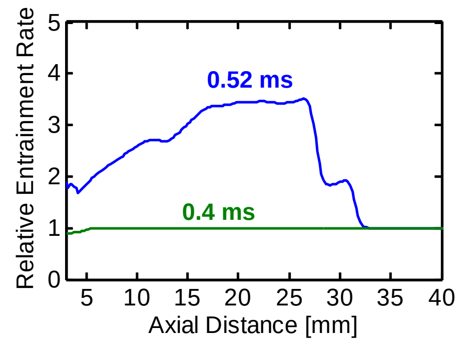
Discrete Control-Volume Model

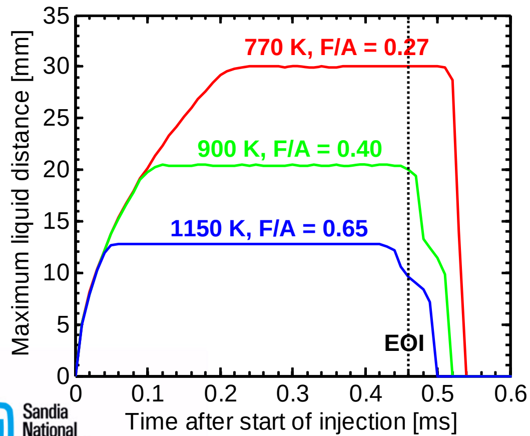


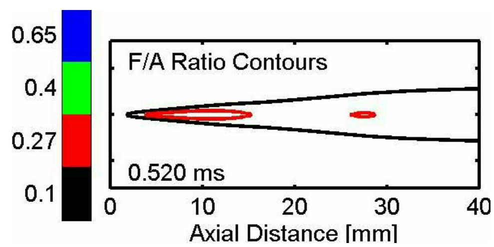
T_a	F/A	T_{mix}
770 K	0.27	576 K
900 K	0.40	600 K
1150 K	0.65	635 K

Entrainment "wave" at EOI causes fuel-lean mixtures to form near the nozzle.

- If downstream of entrainment wave, liquid stays at quasi-steady value.
- If upstream, liquid recedes back to injector.







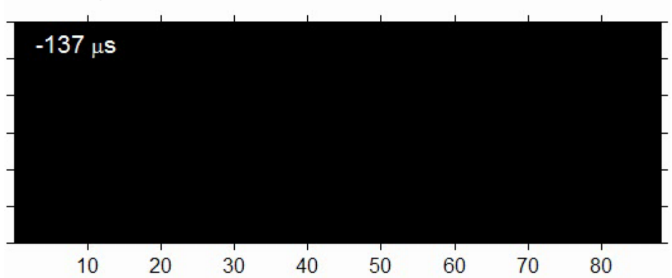
Summary of technical accomplishments (1)

- Liquid phase history depends strongly on end-of-injection rate shape coupled to the local ambient entrainment of the spray.
  - Liquid may detach and move away from the injector…
  - or recede toward the injector depending upon conditions.
- Behavior is predicted with control-volume jet model and the assumption of mixing-limited vaporization.
- New understanding of sprays at end of injection provides needed information for the development of proper spray models.
- Guides optimization of injector hardware for reduction of unburned hydrocarbons.

Summary of technical accomplishments (2)

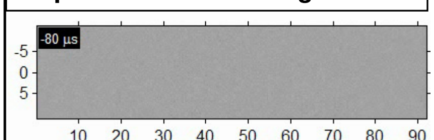
- Short-dwell, multiple injections do not cause combustion of near-nozzle UHC. However, soot formation is decreased or avoided.
- Perturbation of flame lift-off (laser ignition) causes reaction to stabilize upstream for a substantial time period (>4 ms).
  - Shows that ignition sites can start a chain of events that effectively controls lift-off length.
  - Natural ignition sites also visualized upstream.
  - Has significant implications for combustion model development for LTC engines.

High-Temperature Chemiluminescence



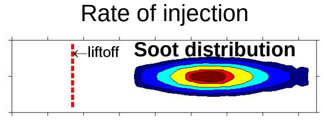
Transfer of technology hastened with expansion of the Engine Combustion Network

Engine Combustion Network
http://www.ca.sandia.gov/ECN

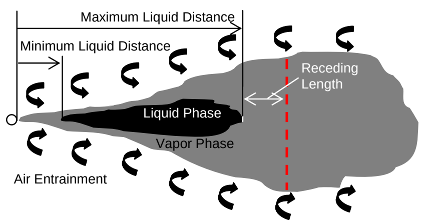


Experimental Data

Liquid penetration	Soot volume fraction	Ignition Delay
Vapor penetration	Mixture fraction	Heat-release
Lift-off length	Rate of injection	Fuel effects
EGR effects		Temperature
Multi-Injection		Pressure
Nozzle size		Inject. Pressure



Better physical understanding of LTC.



Improved, predictive models

SAE 2008-01-1331	Vishwanathan, Reit *University of Wisconsin*
SAE 2008-01-0968	Campbell, Hardy, Gosman *Imperial College*
SAE 2008-01-0961	Karrholm, Tao, Nordin *Chalmers University*
SAE 2008-01-0954	D'Errico, Ettorre, Lucchini *Politecnico di Milano*

Successful LTC Engines

Plans for FY08-FY09

- Address methods for mitigation of UHC.
  - Multiple injections and injector ramp-down effects coupled to specific LTC conditions with various lift-off lengths.
  - Quantitative measurement of reacting mixture at EOI at LTC conditions.
- Mixing measurements for direct comparison with CFD and calibration of model jet scaling laws.
- Post-injection liquid wall impingement.
  - Oil dilution is problematic for DPF regeneration conditions.
  - Fuel effects (biodiesel).
- Lift-off (UHC and soot) effects with jet-jet interaction.
  - Vary nozzle spacing and angle.

FY08 Summary

- DCSF work focused on relevant barriers to high-efficiency, low-emission engines.
  - Observations of combustion in controlled environment lead to improved understanding/models for engine development.
- FY08 approach addresses serious LTC needs.
  - Spray liquid-phase transients at end-of-injection ramp down.
  - Multiple injection effects on UHC and soot formation.
  - Parametric variation (nozzle, temperature, density) leads to improved fundamental understanding.
  - Lift-off stabilization mechanisms, affecting both soot and UHC, discovered by laser-igniting spray.
- Collaboration expanded to provide greatest impact (MOU, Engine Combustion Network)
- Future plans will continue effort
  - Post-injection liquid wall impingement.
  - Lift-off (UHC and soot) with jet-jet interaction.

Acknowledgements

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Kyle Kattke	*Sandia National Laboratories*
Ryan Gehmlich	*University of California-Davis*
Helena Persson	*Lund University*
Oivind Andersson	*Lund University*

Additional Resources

Kook, S., Pickett, L.M. Musculus, M.P.B., Gehmlich, R. “Liquid-Phase Diesel Spray Penetration During the End of Injection,” COMODIA 2008.

Pickett, L.M., Hoogterp, L.. “Fundamental Spray and Combustion Measurements of JP-8 at Diesel Conditions ,” SAE paper 2008-01-1083.

Musculus, M.P.B, Lachaux, T., Pickett, L.M., and Idicheria, C.A. “End-of-Injection Over-Mixing and Unburned Hydrocarbon Emissions in Low-Temperature-Combustion Diesel Engines,” SAE paper 2007-01-0907.

Idicheria, C.A. and Pickett, L.M. “Quantitative Mixing Measurements in a Vaporizing Diesel Spray by Rayleigh Imaging,” SAE paper 2007-01-0647.

Idicheria, C.A. and Pickett, L.M. “Formaldehyde Visualization Near Lift-Off Location in a Diesel Jet,” SAE paper 2006-01-3434. Winner of SAE Springer Award.

Pickett, L.M., and Idicheria, C.A. “Effects of Ambient Temperature and Density on Soot Formation under High-EGR Conditions ,” THIESEL, 2006.

Pickett, L.M., and Idicheria, C.A. “Effects of Ambient Density and Temperature on Soot Formation under High-EGR Conditions ,” DEER, 2006.

Idicheria, C.A., and Pickett, L.M., “Effect of EGR on Diesel Premixed-Burn Equivalence Ratio,” Proc. Combust. Inst., 31:2931-2938, 2006.