Low-Temperature Diesel Combustion Cross-Cut Research

Project ID: ace_05_pickett

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Sandia National Laboratories

FY 2009 DOE Vehicle Technologies Program Annual Merit Review
ACE05, Salon E&F, 11:00 – 11:30 AM, Tuesday, May 19, 2009

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

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:
  FY08 - $580K
  FY09 - $570K

Barriers

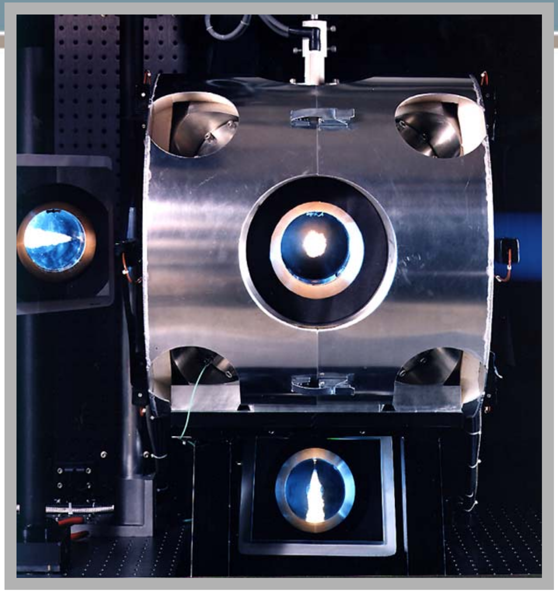
- Engine efficiency and emissions
  - Sources of unburned hydrocarbons and CO for LTC combustion
- Low-load limitations for LTC
- CFD model improvement for engine design/optimization

Partners

- 15 Industry partners in the Advanced Engine Combustion MOU
- Participants in the Engine Combustion Network
  - Experimental and modeling
- Project lead: Sandia
  - Lyle Pickett (PI)

Overall Approach

- 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



Experiments in CV
- Well-defined boundary conditions
- Quantitative diagnostics at engine conditions
- Improved physical understanding

Computer models
- Sum of many sub-models
- Adds knowledge about things that are not “measurable”
- Parametric design optimization
- Saves time and cost over “hardware” iteration

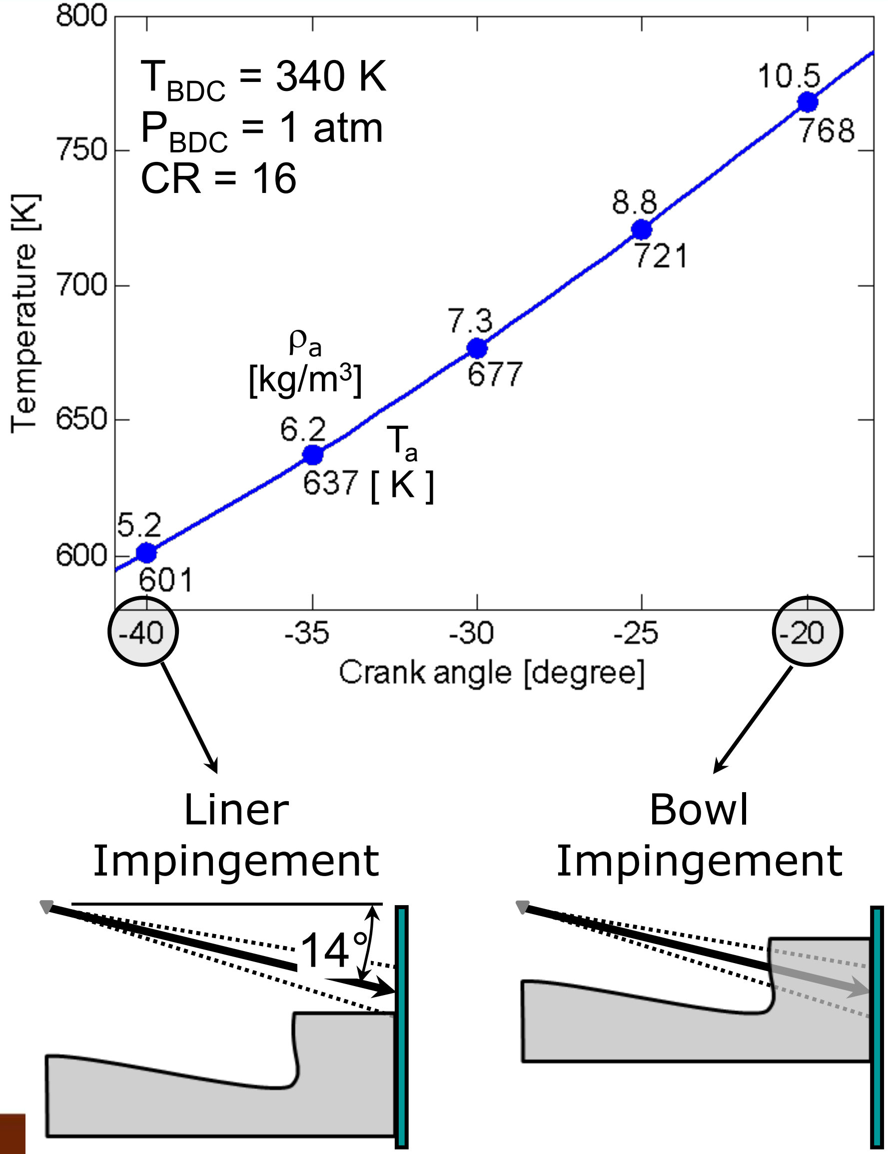
High-Efficiency, Low-Emissions Engine

Objectives/Milestones

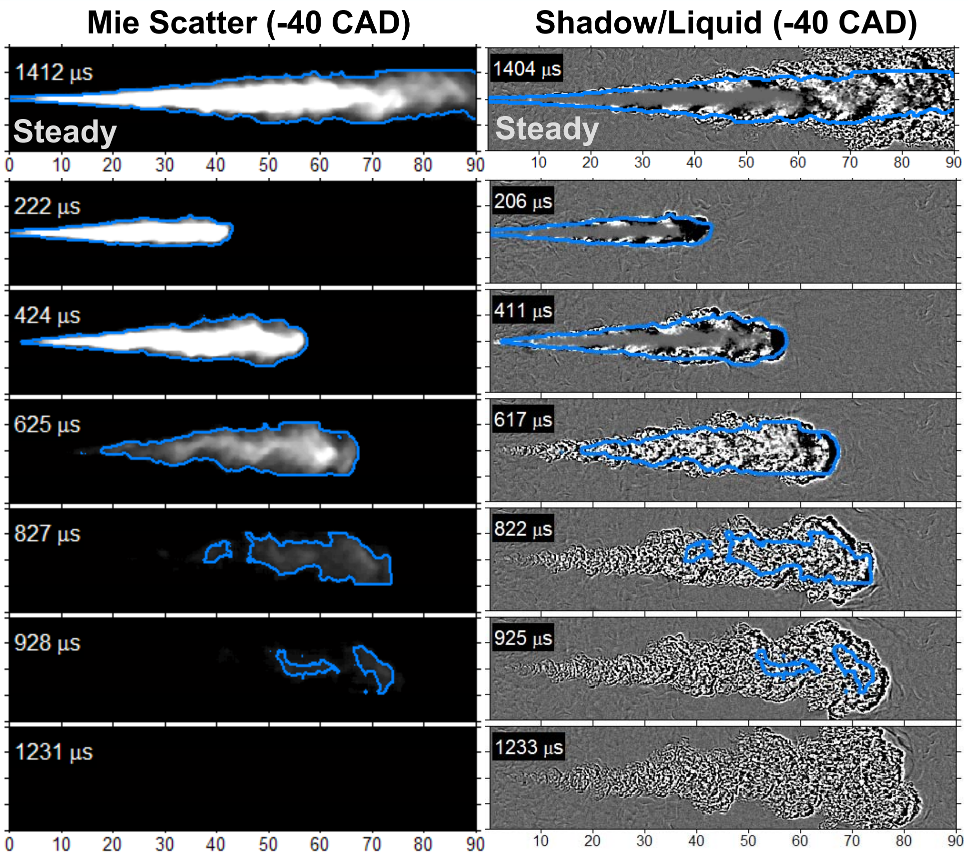
- Determine the factors that cause liquid wall impingement at early-injection LTC conditions (FY07-FY09).
  - Addresses an important source of UHC, oil dilution, inefficiency.
  - FY09 (1): Root causes and limitations for early-injection liquid penetration explained and modeled.
- Characterize liquid vaporization and flame/ignition propagation after the end of injection (FY08-FY09).
  - UHC may remain near the injector when using LTC combustion.
  - FY09 (2): Investigate the controlling parameters that extinguish or permit combustion near the injector after the end of injection.
- Aid the development of computational models for engine design and optimization (ongoing).
  - Experimental and modeling collaboration through the Engine Combustion Network: http://www.ca.sandia.gov/ECN
  - FY09 (3): Develop a baseline high-temperature, high-pressure condition, attain injector set for experimentation by multiple laboratories.

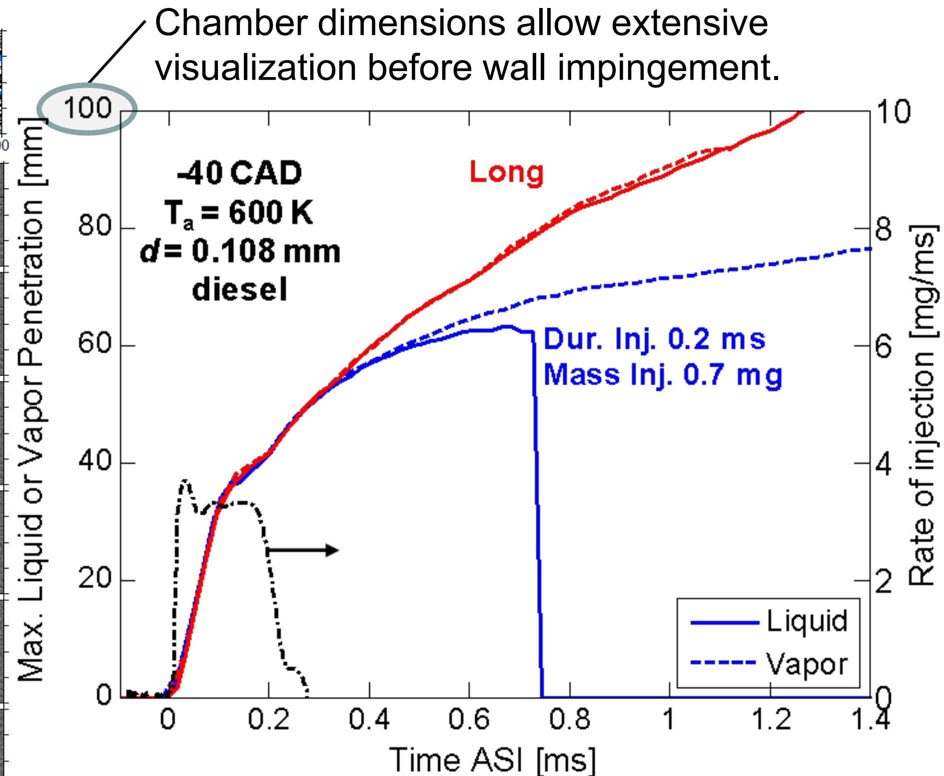
(1) Characterize liquid wall impingement at early-injection LTC conditions.

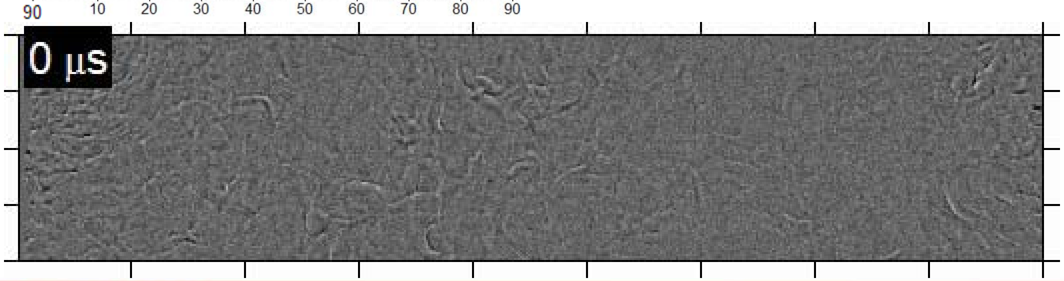
- Provide quantitative measurement of liquid penetration using optical techniques.
- Assess the effects of
  - temperature
  - boost (density)
  - fuel
  - nozzle size
  - injection pressure
- Prevention by using short and multiple injections.
- Liquid penetration modeled using mixing-limited vaporization (Siebers 1999).



(1) High-speed imaging of liquid and vapor boundaries of penetrating spray







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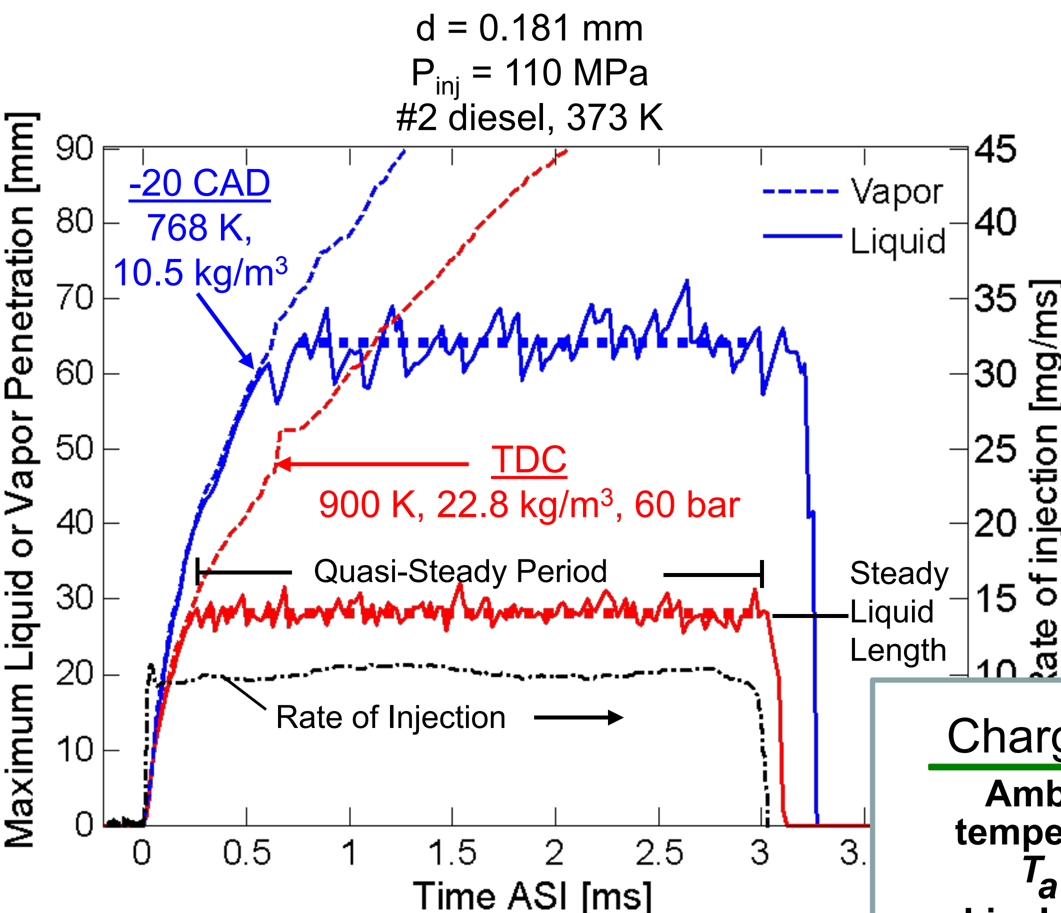
Past research focused on TDC, steady conditions, rather than transient, early-injection.



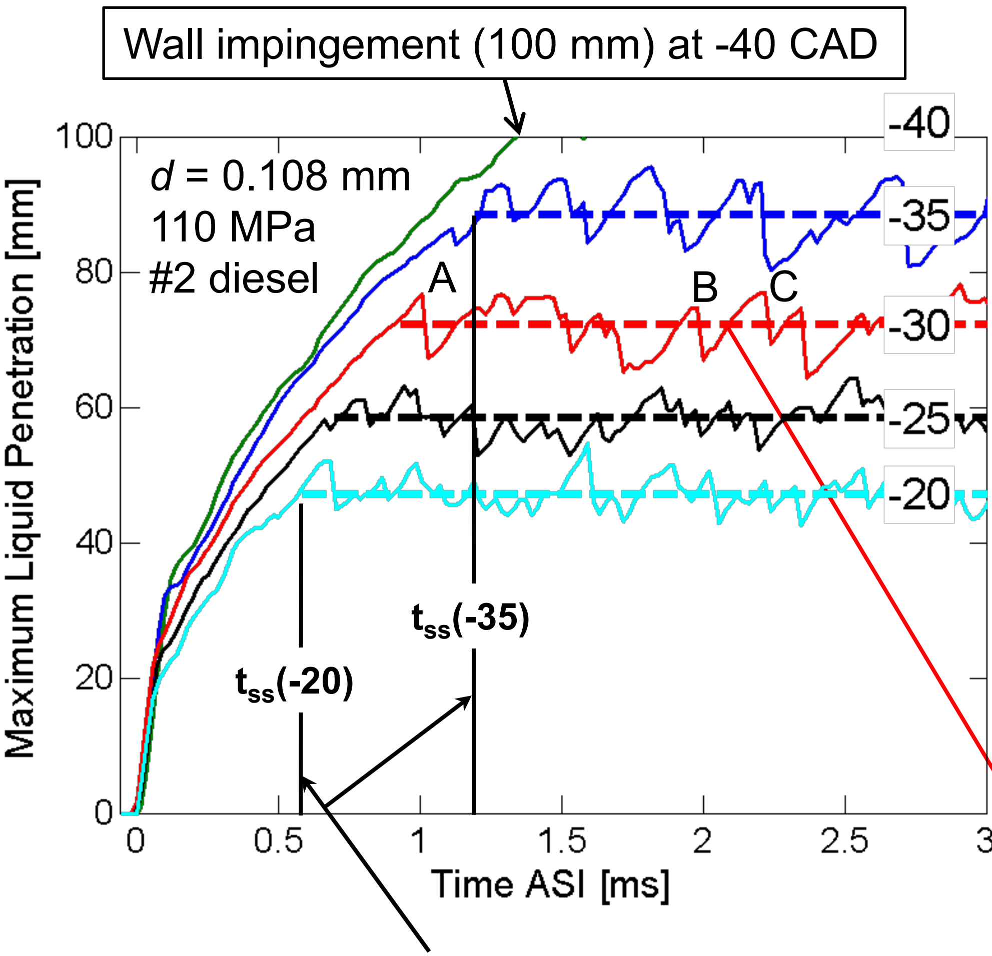
- Liquid penetration follows vapor until some critical distance (max. liquid length).
- Steady liquid length identified at early-injection conditions.
  - Much longer than TDC liquid length.
  - Liquid wall impingement likely.

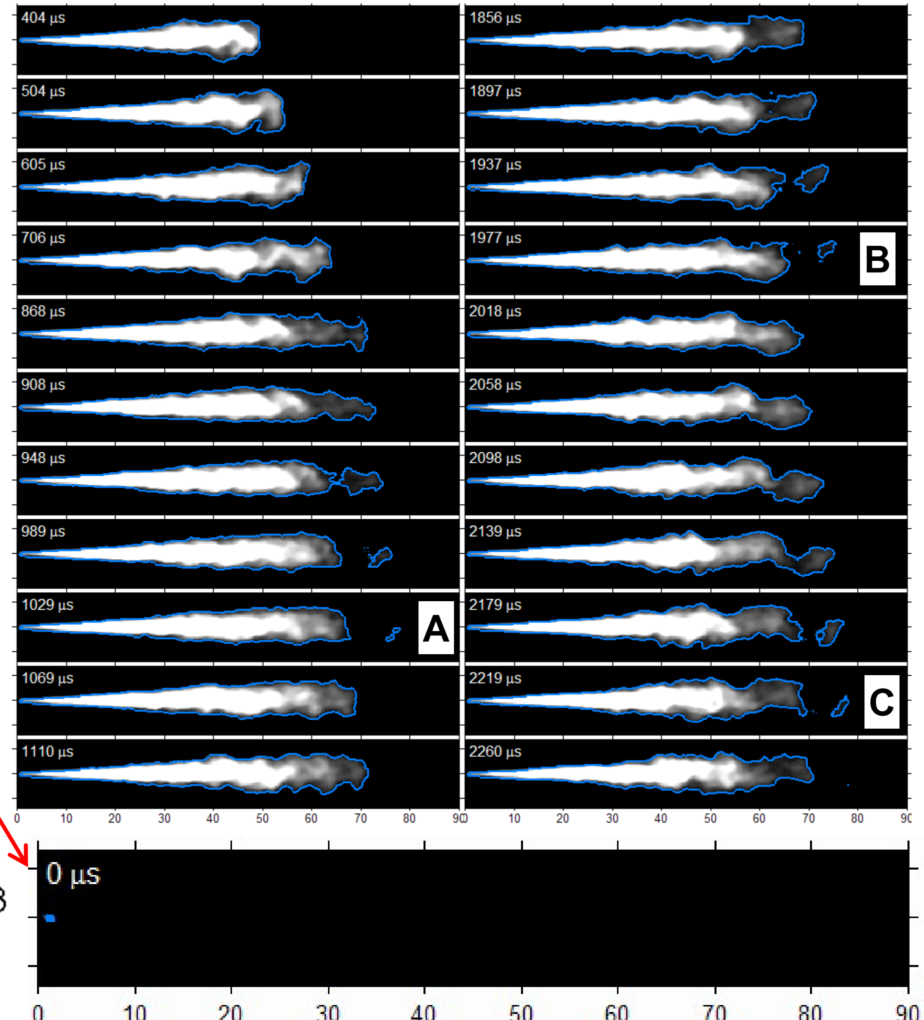
Siebers 1999

Charge gas/injector effects on liquid length

	Ambient temperature T_a ↑	Ambient density ρ_a ↑	Orifice diameter d ↑	Injection pressure P_{inj}↑	Fuel 90% boiling pt. T_{90}↑
Liq. length:	↓	↓	↑	none	↑

Advanced injection timing increases liquid penetration.





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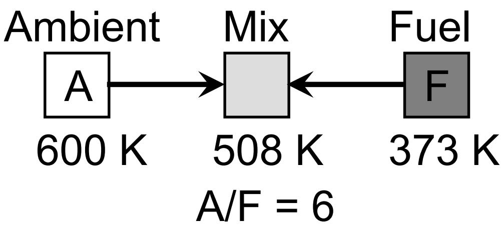
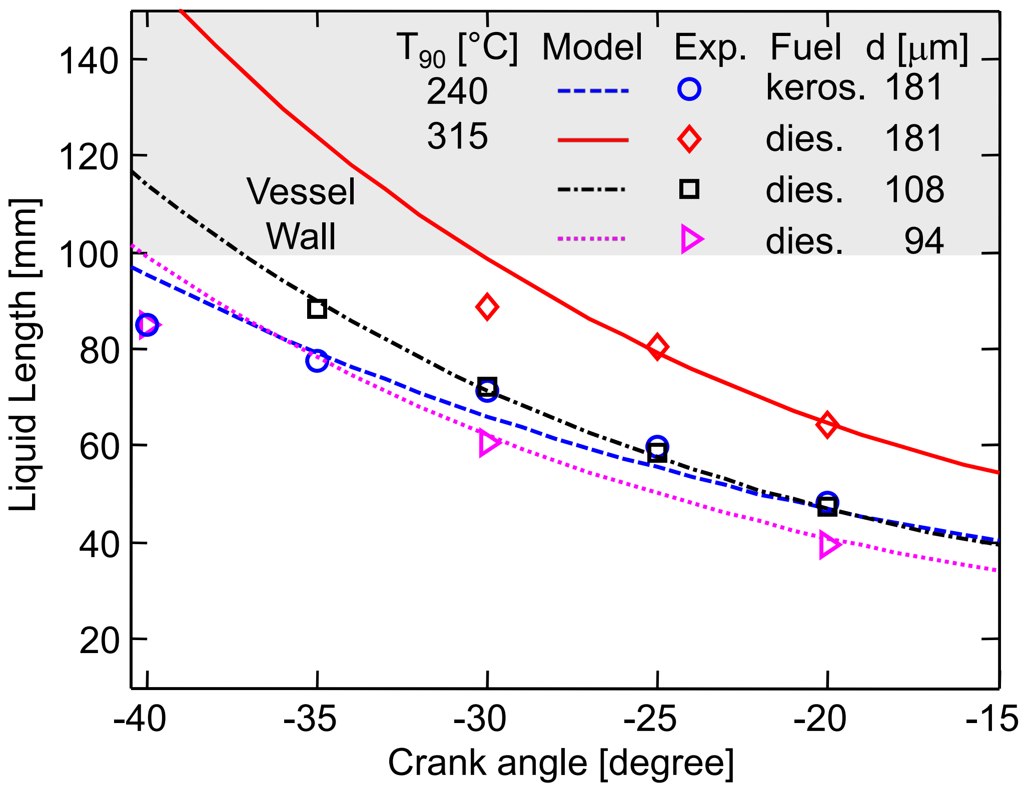
- Time ASI to attain steady liquid length, t_{ss}, increases.

Liquid length model shows ability to capture trends wrt to ambient conditions, fuel, nozzle.



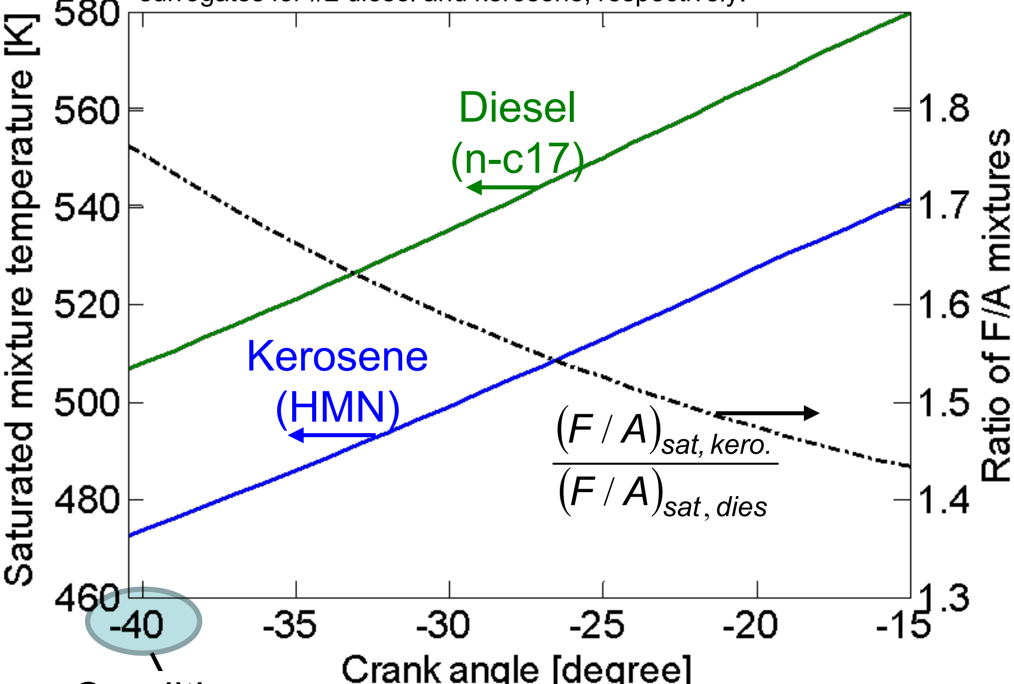
Mixing fuel and ambient to saturated mixture state. Spray spreading angle, fuel/ambient thermodynamic properties used as inputs (Siebers 1999).



- Use of low-boiling-point fuel can significantly lower liquid penetration.
  - T_{90} is 75 °C less for kerosene than diesel.
- Reducing nozzle orifice size will reduce liquid penetration.
- Low-boiling-point fuel more effective at reducing liquid penetration than use of a small nozzle orifice.
  - Liquid length does not increase as sharply for kerosene compared to diesel when advancing injection.
  - Confirmed by both experiments and modeling results.
- Model overpredicts liquid length at earlier CAD.

Why does injection advancement cause less liquid length increase for kerosene over diesel?

heptadecane (n-c17) and heptamethylnonane (HMN) used as surrogates for #2 diesel and kerosene, respectively.

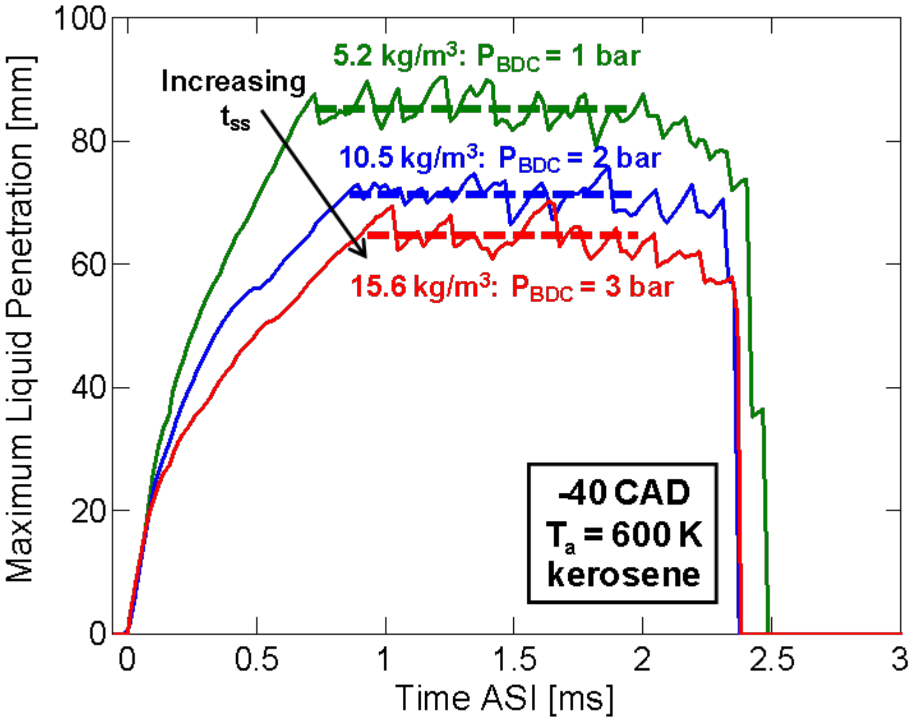


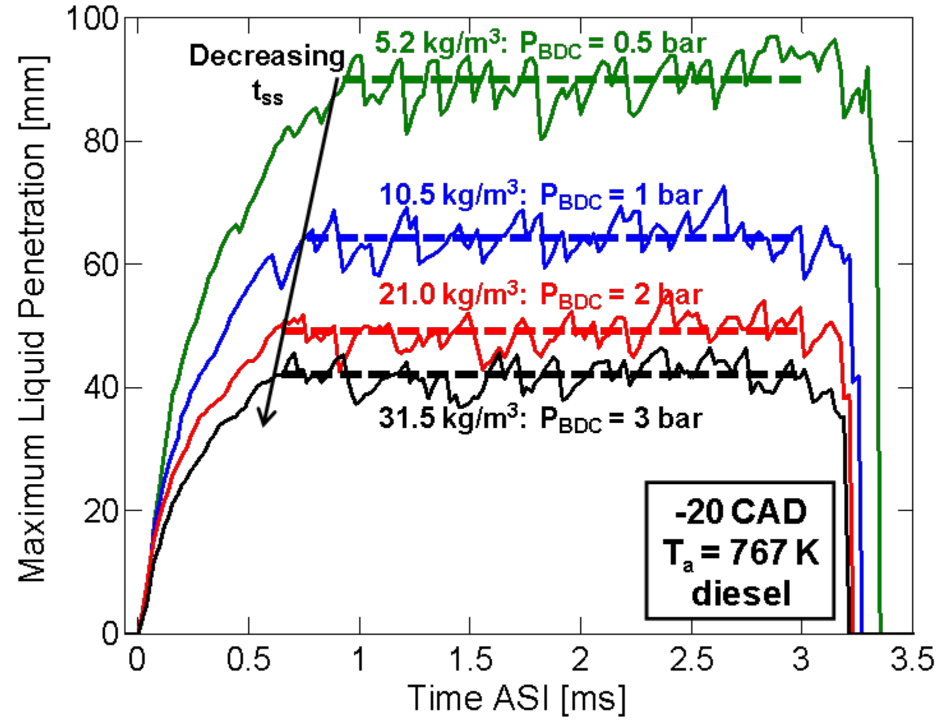
Conditions

Ambient	Fuel	Diesel	Kerosene
600 K	373 K	T_{sat} = 508 K	T_{sat} = 474 K
5.2 kg/m^3		$(F/A)_{sat}$ = 0.17	$(F/A)_{sat}$ = 0.29

- Mixture thermodynamics show:
  - Lower saturated temperature T_{sat} for kerosene.
  - Higher $(F/A)_{sat}$ for kerosene.
- With earlier CAD, $\frac{(F/A)_{sat,\,kero.}}{(F/A)_{sat,\,dies}}$ progressively increases.
  - Higher saturated F/A ratio → shorter liquid length
- Kerosene more resistant to wall-wetting with early injection, even compared to diesel and small nozzle orifice diameter.

Boost significantly lowers liquid penetration.





- Boost helps to reduce wall impingement when using early injection.
  - Spray penetration speed also reduced.
- Time to reach steady state t_{ss} depends upon conditions.
  - At early CAD, boost increases t_{ss}.
  - At later CAD, boost decreases t_{ss}.

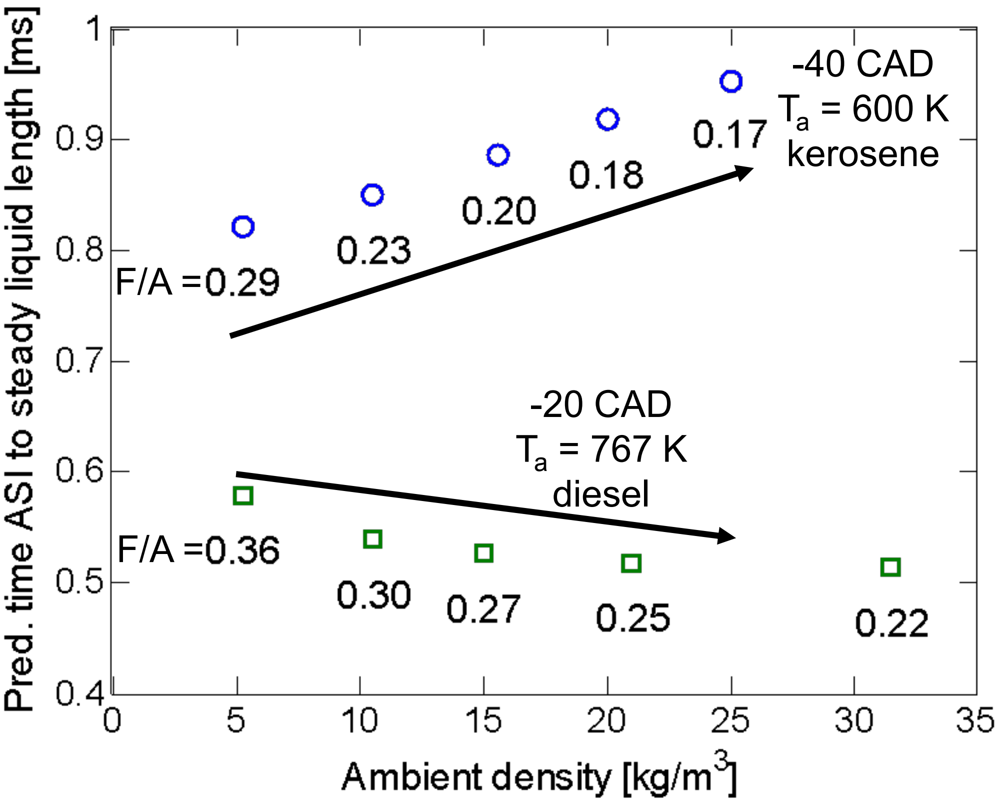
Why does t_{ss} increase or decrease with boost at various injection timings?

Use model jet penetration (Naber and Siebers 1996) and liquid length prediction (Siebers 1999).

- Liquid length *L* depends upon density and $(F/A)_{sat}$. (1)
- *L* decreases with increasing density.

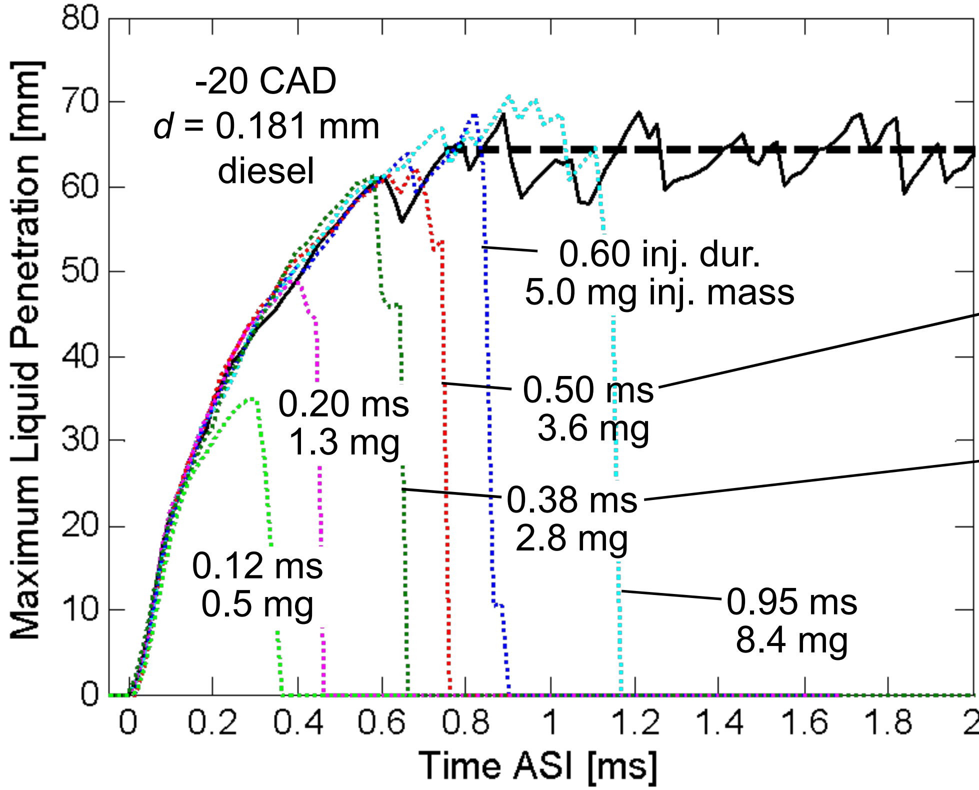
$$t_{ss} \propto \frac{L}{U_f} \cdot \frac{1}{(F/A)_{sat}}$$

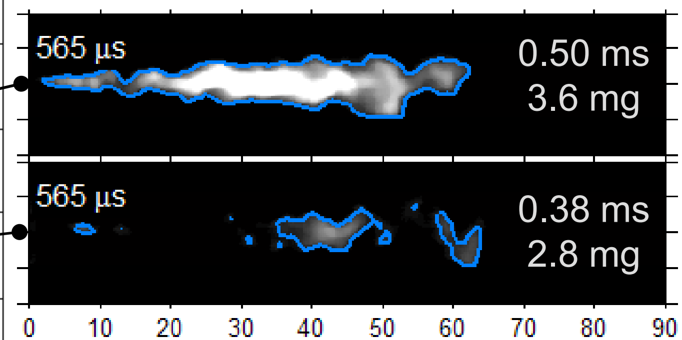
- $(F/A)_{sat}$ depends only on mixture thermodynamic properties. (2)
- $(F/A)_{sat}$ decreases with increasing pressure (boiling point T increases).



- The tradeoff between (1) and (2) determines whether the time to attain a steady liquid length will increase or decrease.

Reducing injection duration/mass produces injections with shorter liquid penetration.

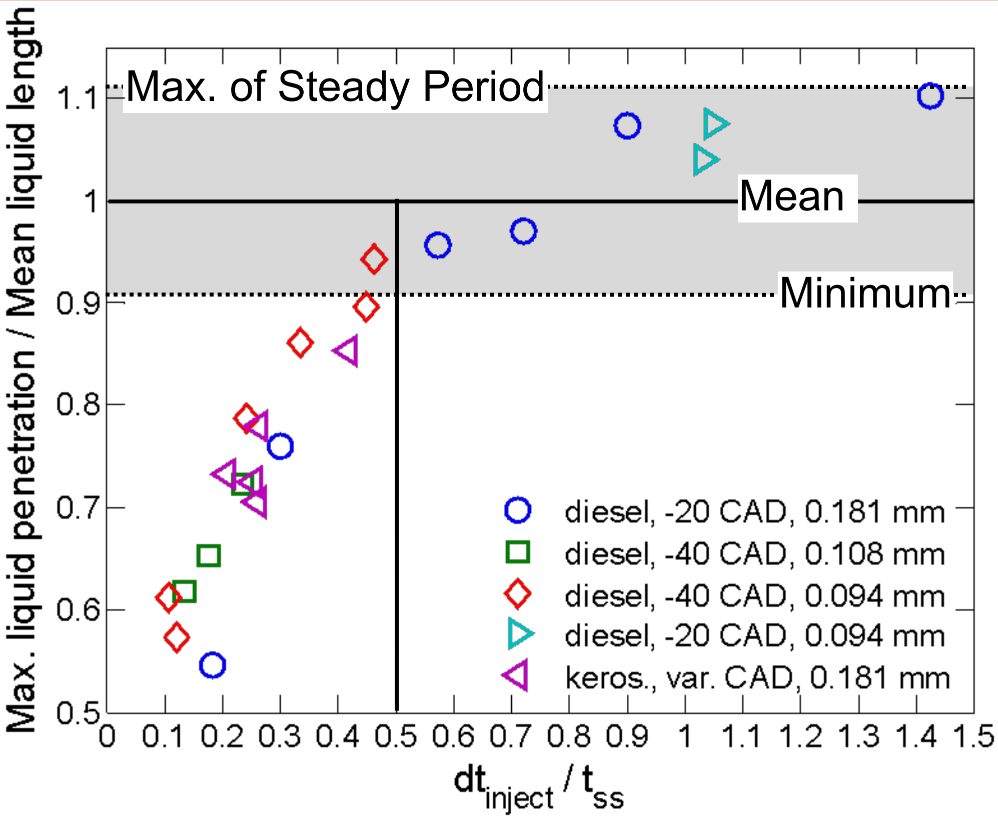


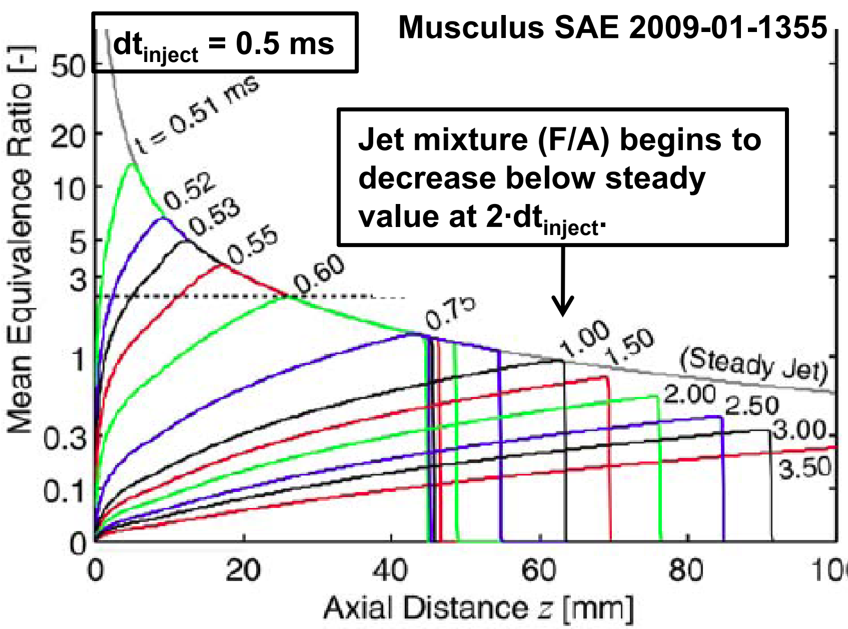


Even when reaching the steady liquid length, short-injection sprays are not as dense.

- The injection duration must be shorter than t_{ss} to have maximum liquid penetration less than the quasi-steady liquid length.

Injection duration must be less than ½ of t_{ss} to reduce the maximum liquid penetration.





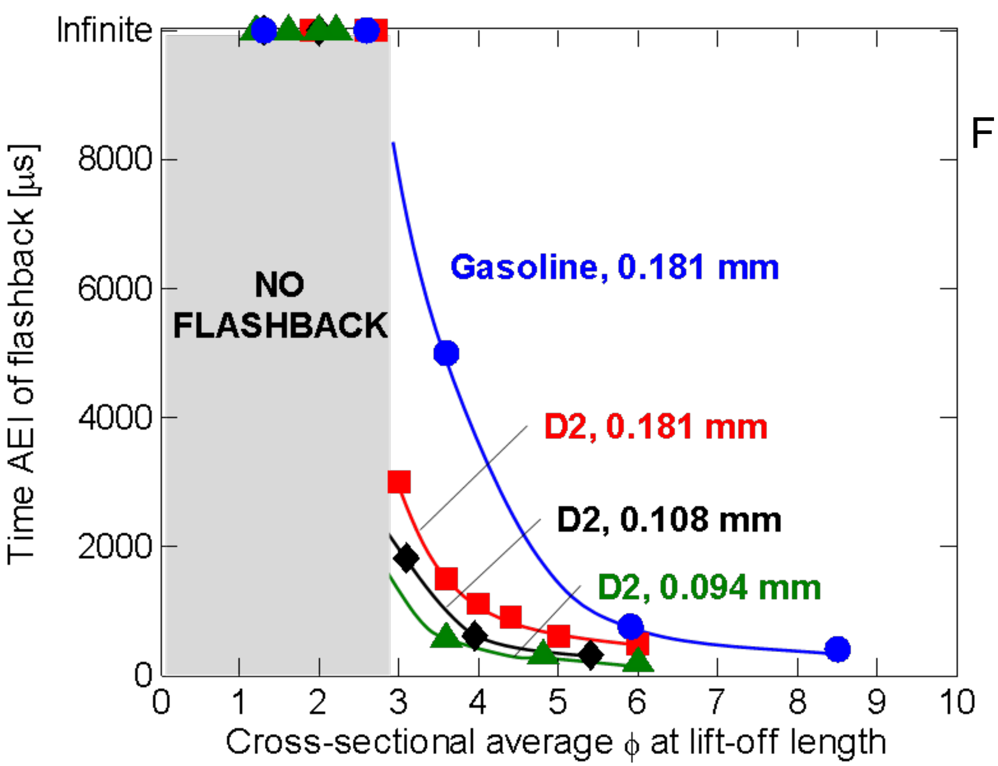
- Increased ambient entrainment must propagate downstream to the jet head to reduce F/A and vaporize liquid fuel.
- Musculus' jet model shows that the entrainment wave reaches the jet head at 2 times the injection duration.

Relevance of early-injection liquid penetration research to LTC.

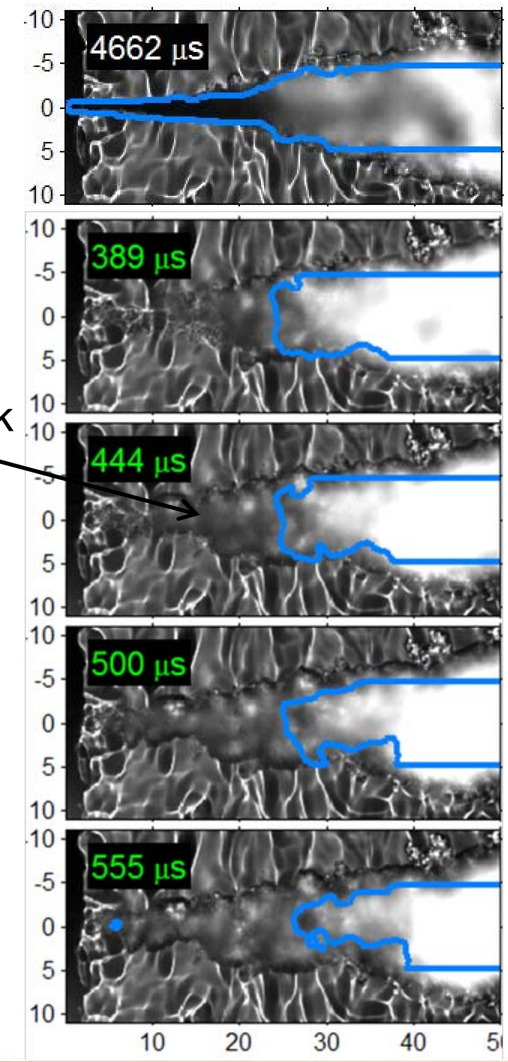
- Experiments provide data on the steady liquid length and time of penetration that is critical for spray model validation.
- Knowledge about the critical injection duration to limit liquid penetration (½ of t_{ss}) allows injection rate control optimization.
  - Multiple injections limit the liquid penetration and increase the injected mass.
  - Provides a pathway to increase engine load for LTC.
- New understanding about low-boiling-point fuels and their resistance to wall-wetting (superior to diesel+small nozzles) allows further optimization of LTC using alternative fuels.
- Well-controlled environment (pressure and temperature) reveals the fundamental causes of liquid penetration.
  - Needed to understand spray events in an unsteady engine environment.
- Findings provide comprehensive understanding needed to minimize liquid wall impingement and UHC in LTC engines.

(2) Accomplishment: Flame extinction after EOI affected by fuel/ambient mixture.

- Dataset shows lack of flashback for lower equivalence ratio conditions when ϕ(H) < 3.
- Flashback determines whether or not near nozzle region produces UHC.



Flashback



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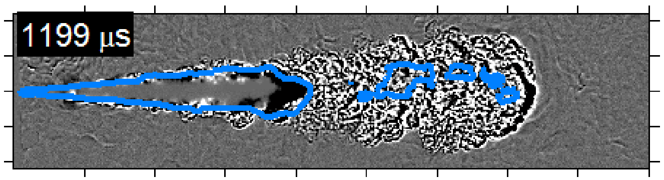
(3) Accomplishment: Development of ECN is accelerating model development.

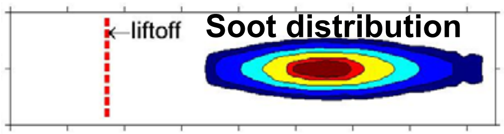
Engine Combustion Network
http://www.ca.sandia.gov/ECN



Experimental Data

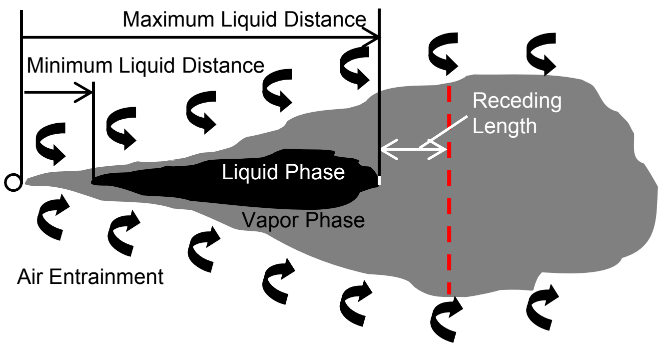
Liquid penetration
Vapor penetration
Lift-off length
EGR effects
Multi-Injection
Nozzle size

Soot volume fraction
Mixture fraction
Rate of injection



Ignition Delay
Heat-release
Fuel effects
Temperature
Pressure
Inject. Pressure

Better physical understanding of LTC.



Improved, predictive models

SAE 2008-01-1331 Vishwanathan, Reitz
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

(Multiple modeling groups using our spray data!)

Successful LTC Engines

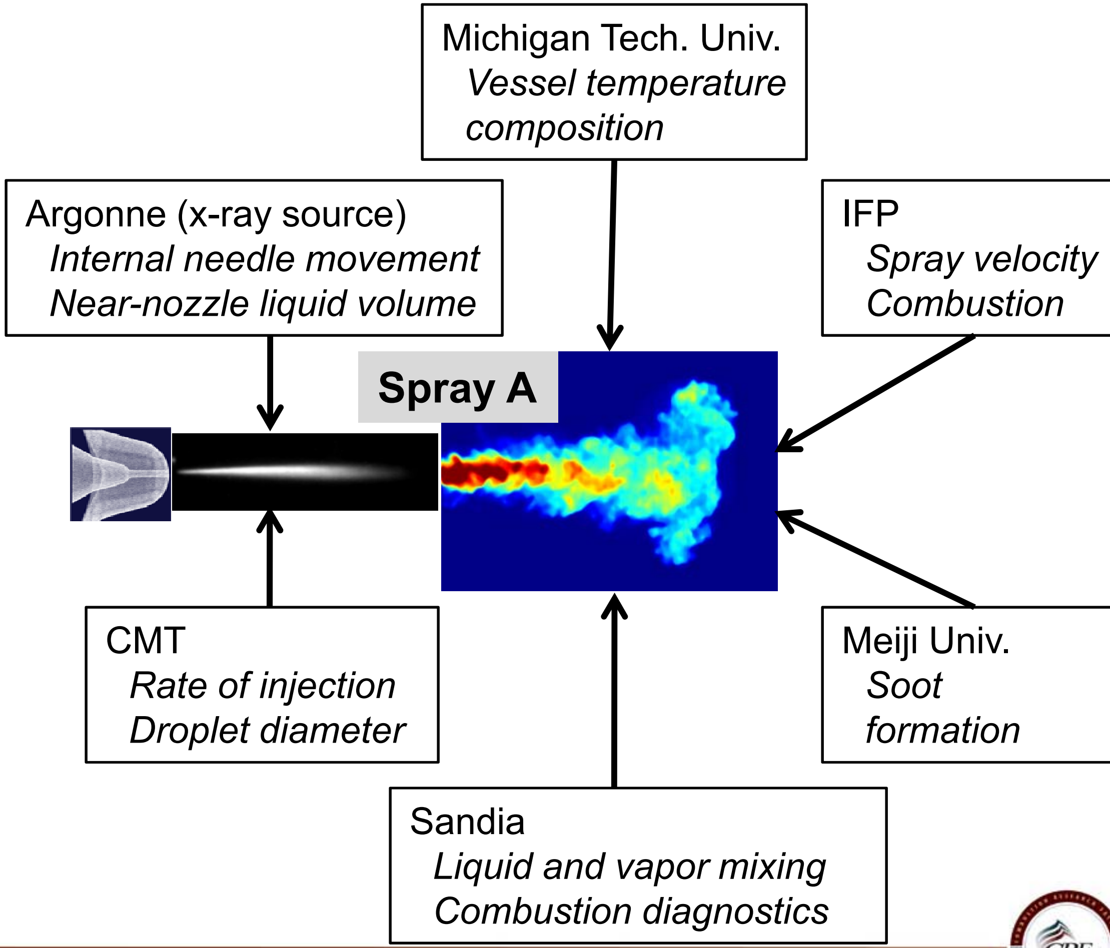
Future work:
Experimental collaboration in the ECN

- Multiple groups to work on the same baseline experimental condition: "Spray A"
  - Repeat experiments at multiple facilities.
  - Accurate models require accurate measurements/b.c.
- Bosch to donate "identical" injectors/nozzles to Sandia.
  - Sandia will distribute to other groups for voluntary experimentation at this condition.
- Acceleration of LTC model development.

Spray A

Ambient: 900 K, 60 bar (22.8 kg/m³)

Injector: 1500 bar, 0.090 mm nozzle, KS1.5/0.86



Future work (continued)

- Fundamental study of liquid wall impingement at DPF regeneration conditions (post injection).
  - Oil dilution and increased fuel consumption are problematic!
  - Combustion vessel ideal to investigate high-temperature, low-density conditions typical of post- injection.
- Lift-off (UHC and soot) effects with jet-jet interaction.
  - Addresses the gap in understanding between single-spray combustion and that using a multi-hole, practical fuel injector.
- Mixing measurements of Spray A condition.
  - Past mixing dataset with older injector has proven invaluable for spray and CFD model validation.
  - Mixing measurements also performed as a function of ambient gas density. Needed to quantify "spreading angle" in vaporizing spray environment.
- Velocity measurements of combustion vessel
  - Improved boundary condition information needed for CFD model development.

Presentation Summary

- 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.
- FY09 approach addresses critical LTC needs.
  - Measurements and new understanding for spray liquid-phase transients for early-injection LTC where wall-wetting is problematic.
  - Factors that influence liquid vaporization and flame flashback after the end of injection.
- 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.
  - "Spray A" characterization for the ECN.