Fuel Effects on Mixing-Controlled Combustion Strategies for High-Efficiency Clean-Combustion Engines

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Project ID#: FT004

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Overview

Timeline

- Project provides fundamental research to support DOE/ industry fuels-technologies projects
- Project directions and continuation are evaluated annually

Budget

- Project funded by DOE/VT:
  FY12 – $800K
  FY13 – $750K

Barriers *(from DOE/VT MYPP 2011-2015)*

- Inadequate data and predictive tools for understanding fuel-property effects on
  - Combustion
  - Engine efficiency optimization
  - Emissions

Partners

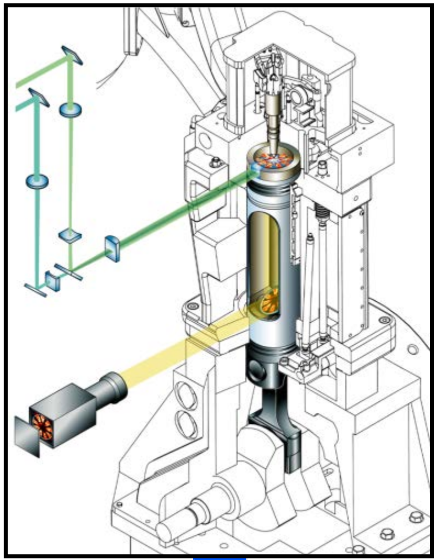
- Project lead: Sandia (C.J. Mueller, PI)
- 15 industry, 6 univ., and 6 nat'l lab partners in Advanced Engine Combustion MOU
- Coordinating Research Council (CRC)
- Ford Motor Company
- Caterpillar Inc.

Relevance – Objectives

Develop the science base to enable high-efficiency, clean-combustion (HECC) engines using fuels that improve US energy security

- **Specific objectives of work since FY12 Annual Merit Review**
  - Apply a robust, engine-based evaluation methodology for quantifying fuel effects on mixing-controlled combustion
    - Parametric study of five chemically well-characterized diesel ref. fuels
  - Assess the feasibility of using raw liquids from the fast pyrolysis of woody biomass as fuels for compression-ignition (CI) engines
    - Conduct a thorough literature review and deliver conclusive analysis
  - Develop a fuel-flexible high-pressure common-rail fuel-supply system (HCFS) capable of outlet pressures to 3000 bar

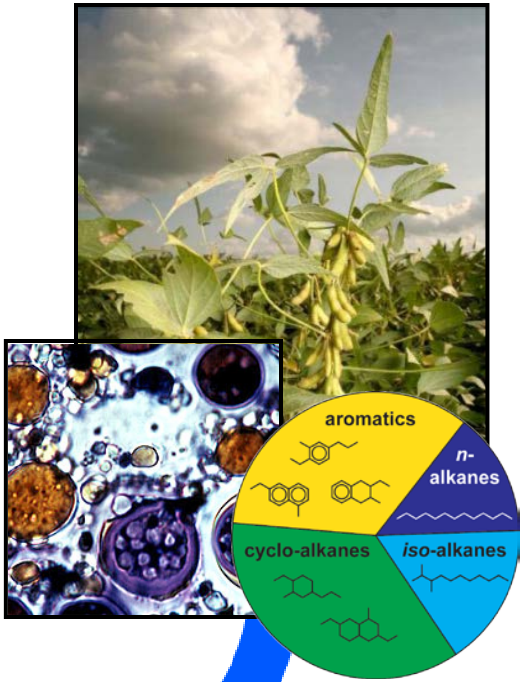
Approach



Unique and comprehensive diagnostic capabilities

Ford
GM
CHRYSLER
CATERPILLAR
Cummins
INTERNATIONAL
DETROIT DIESEL
GE
JOHN DEERE
CRC
VOLVO
ARGONNE NATIONAL LABORATORY
Lawrence Livermore National Laboratory
Los Alamos NATIONAL LABORATORY
NREL National Renewable Energy Laboratory
Innovation for Our Energy Future
OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY
PHILLIPS 66
bp
Chevron
ExxonMobil
CanmetENERGY
Shell Global Solutions

Collaboration with key stakeholders



16 years of fuel-effects research

HECC engines using fuels that improve US energy security

Approach – Milestones

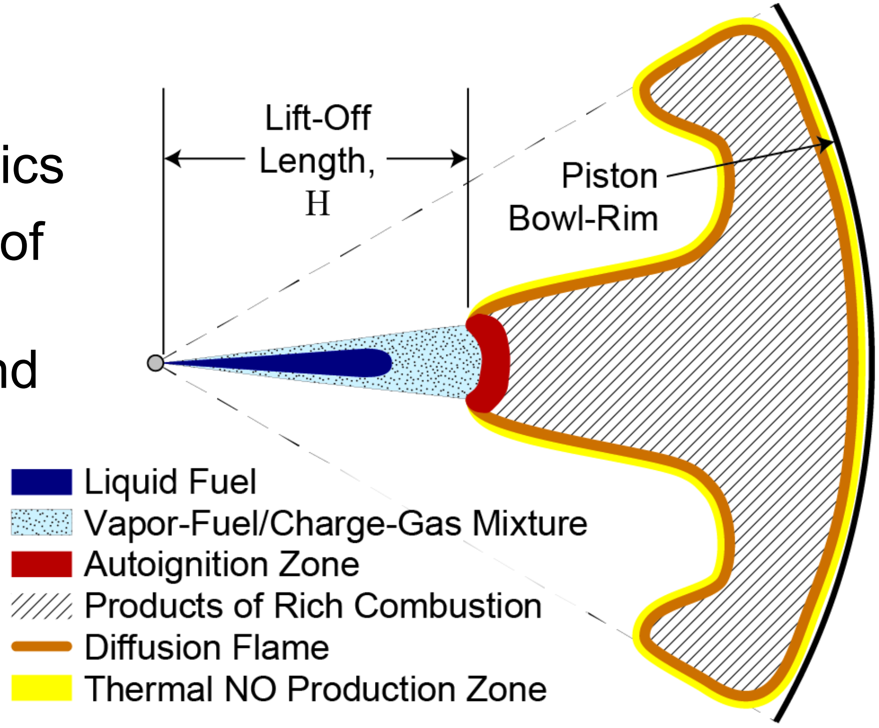
- ✓ **September 2012**
  Complete mixing-controlled combustion evaluation experiments on subset of Fuels for Advanced Combustion Engines (FACE) diesel fuels
- ✓ **January 2013**
  Complete paper assessing the feasibility of using raw liquids from fast pyrolysis of woody biomass as fuels for CI engines
- **July 2013**
  Complete leaner lifted-flame combustion (diesel combustion that does not form soot) experiments with an oxygenated renewable fuel
- **September 2013**
  Complete publication from parametric study of effects of diesel reference fuels on engine combustion, efficiency, and emissions
- **December 2013**
  Complete mixing-controlled combustion evaluation experiments on one or more target/surrogate fuel pairs

Technical Accomplishments Summary

1. **Conducted a parametric study of fuel effects on mixing-controlled combustion using a new, engine-based evaluation methodology**
   - Approach employs a wide range of conventional and optical diagnostics applied over a range of dilutions & injection pressures
   - Significant fuel effects observed (data analysis is in progress)
2. **Showed that raw liquids from the fast pyrolysis of woody biomass are not suitable as fuels for modern CI engines**
   - Barriers include instability, corrosivity, poor ignition quality, high viscosity, and undesirable water/solids/energy contents
3. **Created a fuel-flexible 3000-bar common-rail fuel-supply system for studying advanced combustion modes with emerging fuels**
   - Demonstrated 2750 bar injection pressure with methyl decanoate (a biodiesel fatty-acid methyl ester)

TA#1: Quantifying Fuel Effects on Mixing-Controlled Combustion (1 of 3)

- **Problem: No robust, general, engine-based methodology has been available to determine fuel effects on mixing-controlled combustion**
  - We have developed and are refining such an approach
- **Overview of methodology**
  - Employs a comprehensive set of conventional and optical diagnostics
  - 2-hole injector tip lessens impact of engine-configuration-dependent effects (e.g., jet-jet interactions and premixed-burn magnitude)
  - Enables study of a range of mixing-controlled strategies
    - Current approaches thru Leaner Lifted-Flame Combustion (LLFC)
      - LLFC = mixing-controlled combustion that does not form soot



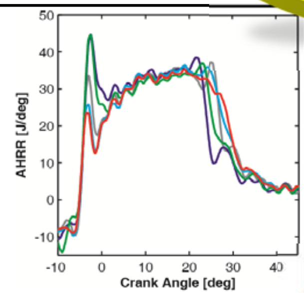
TA#1: Quantifying Fuel Effects on Mixing-Controlled Combustion (2 of 3)

New Fundamental Understanding

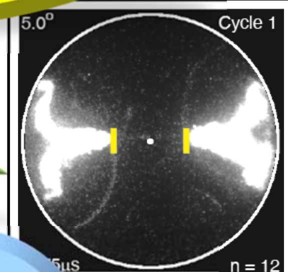
Detailed Analysis

— 5 fuels —
4 CRC FACE diesel fuels
& 1 emissions cert. fuel
— 2 inj. pressures —
800 & 1800 bar
— 3 dilutions —
21, 18, & 16 mol% O_2

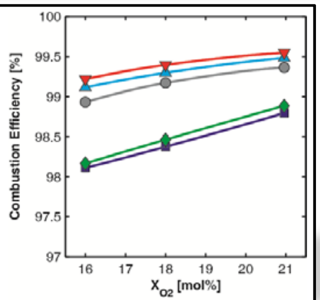
Cylinder pressure → heat release, temperatures



Chemiluminescence → lift-off length (H), equivalence ratio at H

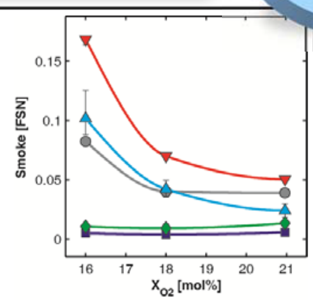


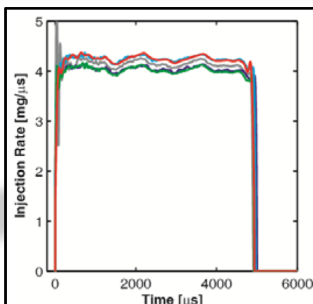
Efficiency → combustion & thermal



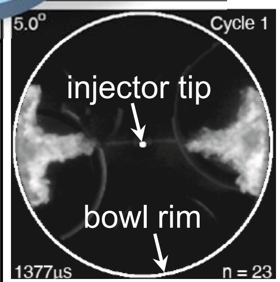
Elastic scattering → liquid fuel penetration

Emissions → smoke, NO_x, HC, CO, O_2, CO_2, & exhaust LII





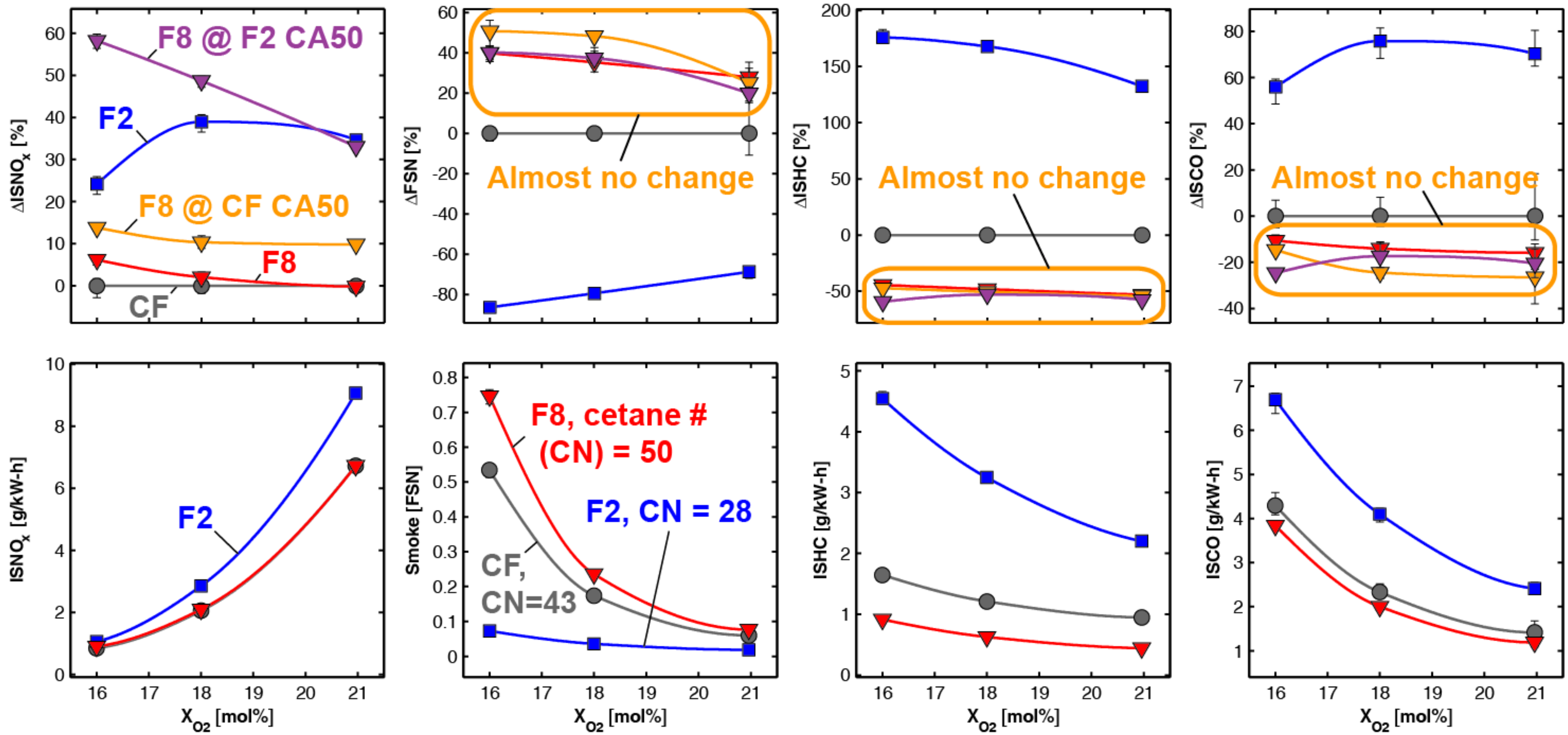
Injection rate and quantity



Natural luminosity → spatial distribution of hot soot

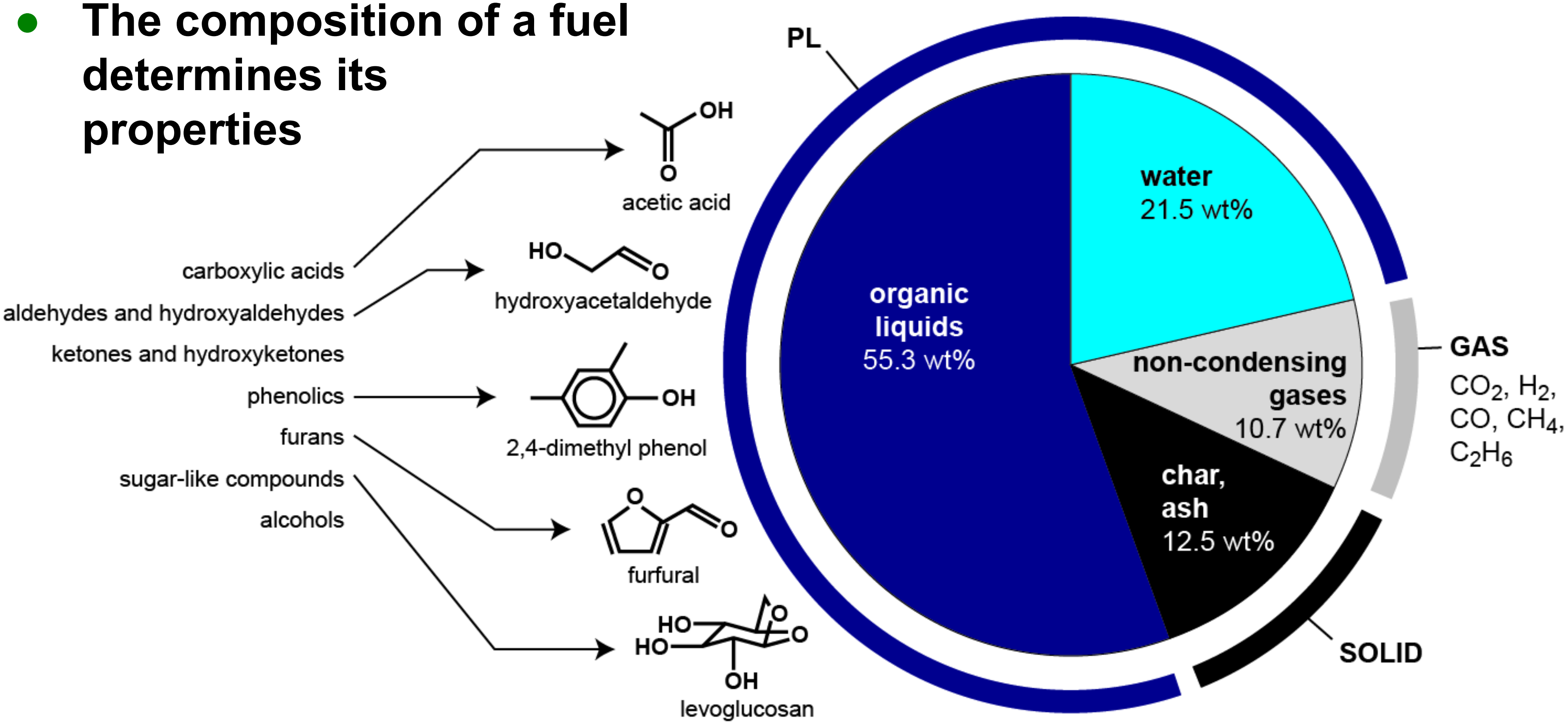
TA#1: Quantifying Fuel Effects on Mixing-Controlled Combustion (3 of 3)

- **Example results:**
  - Fuel-property changes can significantly affect emissions
  - Many differences cannot be offset by changing combustion phasing



TA#2: Assessed Feasibility of Raw Pyrolysis Liquids as CI-Engine Fuels (1 of 2)

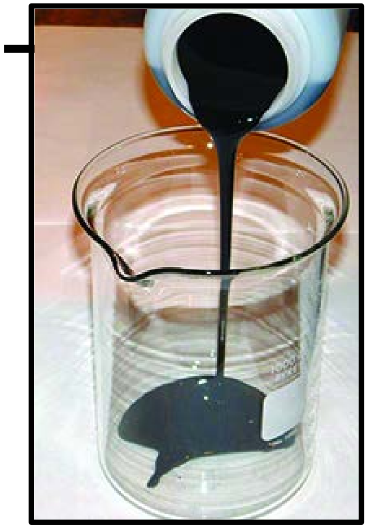
- **Question: Are raw liquids from the fast pyrolysis of woody biomass suitable as fuels for modern CI engines?**
  - Pyrolysis liquids (PLs) are renewable, can be produced domestically
- **The composition of a fuel determines its properties**



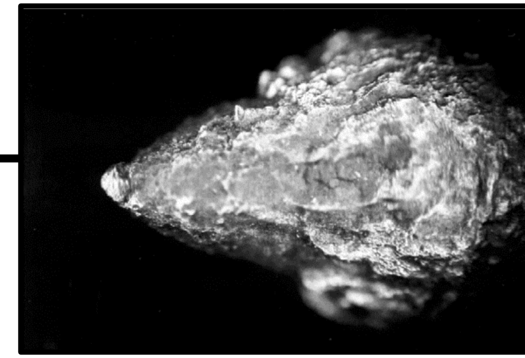
TA#2: Assessed Feasibility of Raw Pyrolysis Liquids as CI-Engine Fuels (2 of 2)

- **Literature review shows many challenges associated with PL use in CI engines**
  - Corrosion/erosion of injector components
  - Deposit formation
  - High viscosity, solids content
  - Phase separation
  - Poor ignition quality
  - High water content, low energy per unit mass and volume

Figure above reprinted from *Bioresource Technology*, Vol. 100, Bennett N.M., et al., "Extraction and hydrolysis of levoglucosan from pyrolysis oil," Pp. 6059-63, Copyright 2009, with permission from Elsevier. http://www.journals.elsevier.com/bioresource-technology



Brown, R.C., http://www.cset.iastate.edu/research/current-research/pyrolysis-process-development-unit/, used with permission of the author.

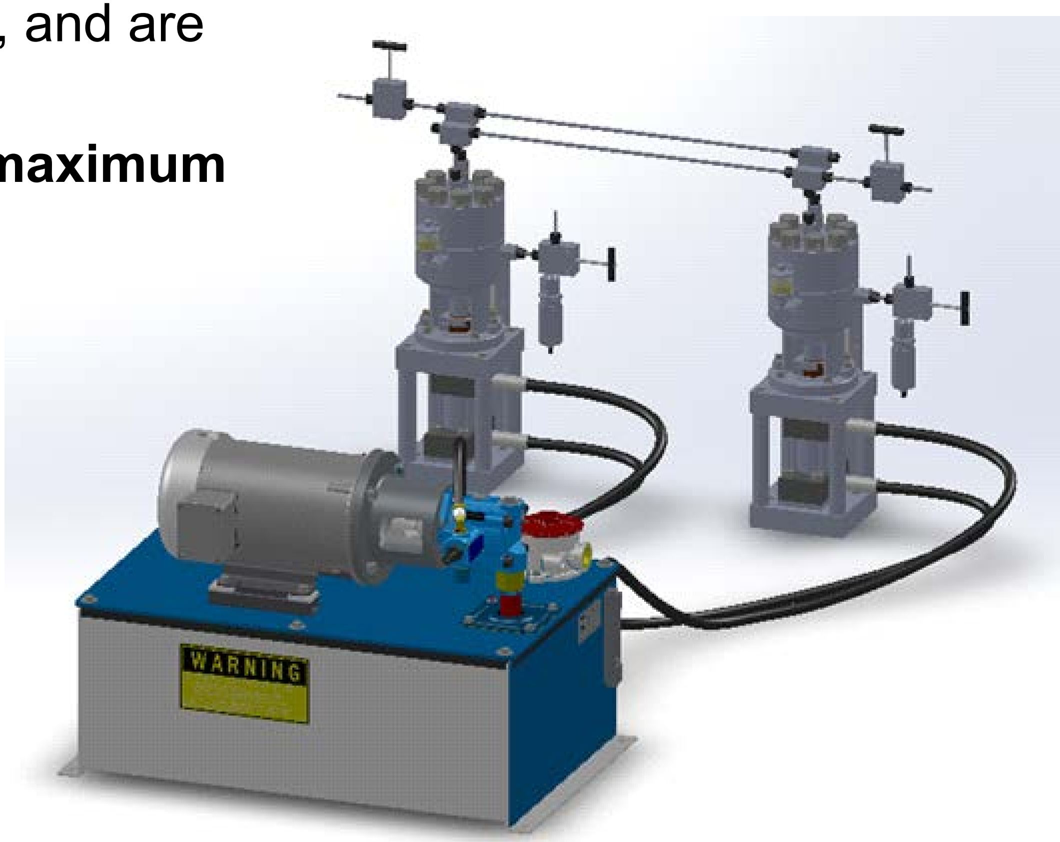


Figures above reprinted from *Biomass and Bioenergy*, Vol. 25, Chiaramonti, D., et al., "Development of emulsions from biomass pyrolysis liquid and diesel and their use in engines - Part 2: Tests in diesel engines," Pp. 101-111, Copyright 2003, with permission from Elsevier. http://www.journals.elsevier.com/biomass-and-bioenergy

- **Conclusion: Raw PLs from woody biomass are not suitable fuels for modern CI engines**

TA#3: Fuel-Flexible High-Pressure Common-Rail Fuel-Supply System (HCFS)

- **Problem: It is impossible to study the effects of unconventional fuels in advanced CI engines without a system capable of supplying these fuels at high injection pressures**
  - We have developed, built, and are refining such a system
- **All fuel-wetted parts have maximum chemical compatibility**
  - Stainless steel, Teflon, and Kalrez only; no fuel-wetted dynamic seals
- **Hydraulic drive makes system compact, powerful**
  - 3000-bar peak pressure
- **Can be used with gaseous as well as liquid fuels**



Collaboration and Coordination with Other Institutions

- **Combustion research conducted with guidance from Advanced Engine Combustion (AEC) working group**
  - 10 engine OEMs, 5 energy companies, 6 national labs, 6 univ's
  - Semi-annual meetings and presentations
- **Co-leading surrogate diesel fuel research conducted under auspices of CRC; participants from**
  - 4 energy companies, 1 Canadian + 6 US national labs, 1 auto OEM
  - Tri-weekly teleconferences, tri-annual presentations
- **DOE/VT FOA 239 contract to study fuel effects on LLFC**
  - Partnership with Ford Motor Co.
  - Tri-weekly teleconferences, semi-annual reporting
- **Work-for-others contract**
  - Funds-in agreement with Caterpillar Inc.
  - Tri-weekly teleconferences, semi-annual meetings

Proposed Future Work (through FY14)

- **Continue to apply the robust, engine-based evaluation methodology for quantifying fuel effects on mixing-controlled combustion**
  - Focus on overcoming barriers to LLFC by using oxygenated fuels
    - Biodiesel esters and/or heavy ethers
    - Utilize new fuel-flexible 3000-bar common-rail fuel-supply system
  - Engine testing of diesel surrogate/target-fuel pairs
    - To determine if adequate surrogate/target matching has been achieved
    - To provide well-characterized, comprehensive experimental data for comparisons to computational modeling results
  - Focus on soot processes
    - To better understand in-cylinder soot formation, distribution, and oxidation
- **Continue development of diesel surrogate fuels under auspices of Coordinating Research Council Project AVFL-18a**
  - Explore effects of new palette compounds & formulation strategies

Summary

- **Goal of this research is to provide an improved understanding of fuel effects on advanced, mixing-controlled combustion strategies**
  - Focused on overcoming DOE MYPP barriers by providing high-quality data and analyses on fuel effects
    - To achieve HECC with fuels that enhance energy security and environmental quality
  - Includes close collaboration and guidance from engine mfrs., energy companies, national labs, and academia
- **Significant technical progress has been made**
  - Conducted a parametric study of fuel effects on mixing-controlled combustion using a robust, engine-based evaluation methodology coupled with insightful analysis
  - Conclusively showed that raw liquids from the fast pyrolysis of woody biomass are not suitable as fuels for modern CI engines
  - Created a high-pressure fuel-supply system to facilitate the study of emerging/unconventional fuels in advanced combustion modes