Investigation of Bio-Diesel Fueled Engines under Low-Temperature Combustion Strategies

Principal Investigator: Chia-Fon F. Lee*

Co-PI: Alan C. Hansen**

Mechanical Science and Engineering Department

*****Agricultural and Biological Engineering Department***

University of Illinois at Urbana-Champaign

2009 Annual Merit Review and Peer Evaluation Meeting

May 19, 2009

Project ID# ftp_01_lee

This presentation does not contain any proprietary, confidential or otherwise restricted information

Overview

Timeline

- Start: October 2005
- Finish: May 2010
- 60% Complete

Budget

- Total Project Funding
  - DOE: $468,000
  - UIUC:$117,000
- Funding received
  - FY08/09:$140,172

Barriers

Educational and research challenges

- Optimizing combustion of biodiesel LTC engines needs a detailed understanding of fuel properties, fuel/air mixing, combustion and emissions
- Biodiesel properties relevant to automotive combustion remain an almost uncharted area
- Biodiesel utilization is limited by its higher NOx emissions under conventional engine operation
- Non-conventional injection strategies and new injector required for LTC in practical diesel engines

Partners

Local and International

- Ford
- Caterpillar
- Quantlogic
- Energy Biosciences Institute
- Gamma Technologies
- Cummins
- Deere & Company
- BP
- Incobrasa Industries

Objectives

- Estimate properties of pure bio-diesel and bio-diesel/diesel blends for LTC combustion modeling
- Investigate effect of bio-diesel fuel properties on combustion and emissions in LTC engines using experiments, laser diagnostics, and multi-dimensional computations
- Increase understanding of emissions formation from bio-diesel in LTC engines
- Identify effect of engine operating parameters
- Develop strategies for reducing emissions and increasing efficiency from bio-diesel combustion

Milestones

Phase II: (20 months) June 2008 – January 2010 Computational Modeling of Cylinder Processes, Metal and Optical Engine Data Acquisition

Month/Year	Milestone
January 2010	**Task 2.1 - Computational Modeling of Cylinder Processes** *The developed models will be used to compute the air-fuel mixing process, combustion process, NOx and particulate matter formation processes. Computational data will be compared with experimental results. Sub-models will be modified and recalibrated to explain and predict the experimental data.*
January 2010	**Task 2.2 – Metal Engine Experiments** *Complete the operating map for the metal engine. Performance mapping will be completed by varying engine speed and load, injection strategy, intake air temperature and pressure, and EGR ratio for selected biodiesel blends.*
January 2010	**Task 2.3 - Optical Engine Experiments** *Measure the air-fuel mixing, combustion, and emissions formation processes in the optical engine using laser diagnostics and high-speed imagining. Fuel liquid and vapor distribution will be measured. Early non-luminous flames, and luminous flame from an entire combustion cycle will be visualized. Soot and NOx emissions within the combustion chamber will be measured.*

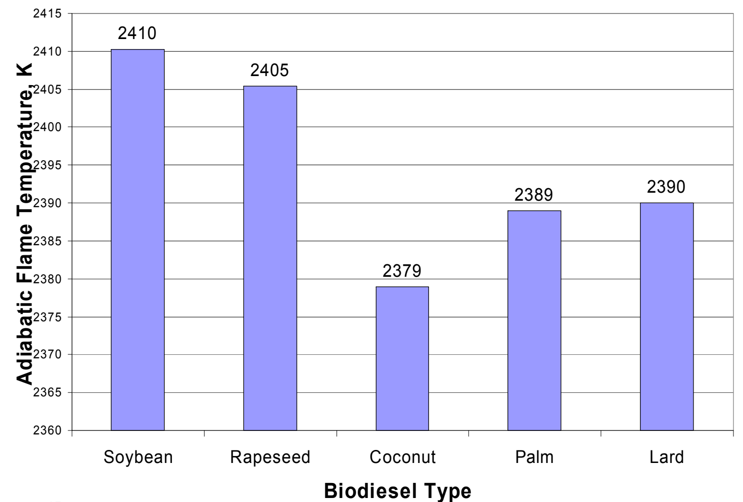
Technical Approach

- Fuel properties of various biodiesel fuels will be measured and modeled. The experiments will be conducted on a production diesel engine (metal engine), on a single-cylinder research engine modified for optical access (optical engine), and on a combustion chamber. The latest laser diagnostic and multi-dimensional modeling techniques will be used to conduct the investigation.
- The computational model will provide information on flow field, quantitative fuel liquid and vapor distributions, and temperature distribution. Performance mapping will be completed for the metal engine by varying engine speed and load, injection strategy, intake air temperature and pressure, and EGR ratio. The optical engine and the combustion chamber will be utilized to provide a clear picture of the air-fuel mixing process, low temperature ignition and combustion characteristics, NO and soot formations of biodiesel LTC engines. Experimental results will be compared with the computational model.
- With combined experimental and modeling efforts, the measurements and modeling accuracy can be improved and will provide useful physical insight and detailed quantitative information needed to optimize biodiesel LTC engine performance and minimize emissions.

Biodiesel Property Measurement and Computation

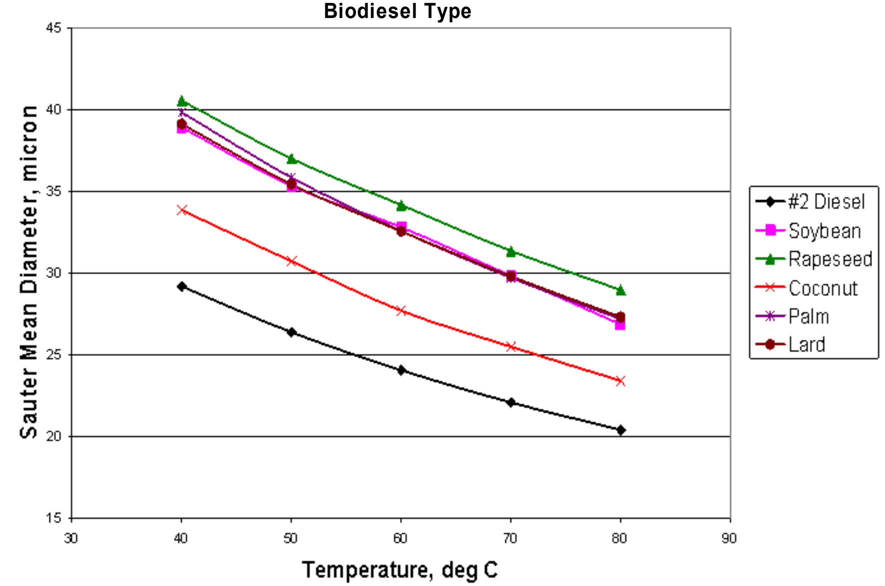
Goal

To measure properties of biodiesel produced from selected source materials and develop predictive methods based on fatty acid methyl ester composition for use in combustion modeling



Major Results

- Soybean and rapeseed biodiesel fuels contain high quantities of long chain, unsaturated methyl esters that raise the adiabatic flame temperature and may lead to increases in NOx emissions
- Coconut, palm and lard biodiesel fuels contain shorter chain, saturated methyl esters that lower adiabatic flame temperature and can lower NOx emissions
- Atomization processes are strongly influenced by the viscosity and surface tension of the fuel
- Sauter Mean Diameter of fuel droplets based on viscosity, surface tension, and density was higher for biodiesel than #2 diesel fuel



Optically Accessible Biodiesel Engine Experiment

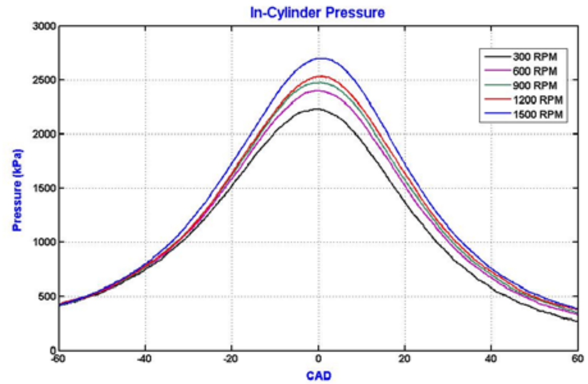
Goal

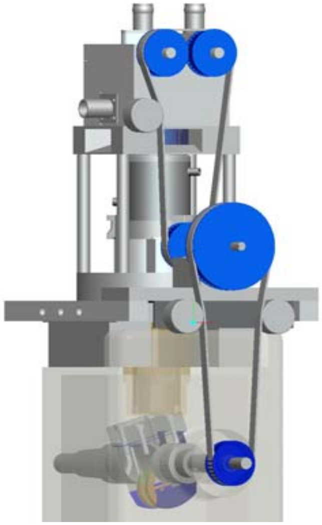
Ground-up construction of a new optically accessible engine for biodiesel studies

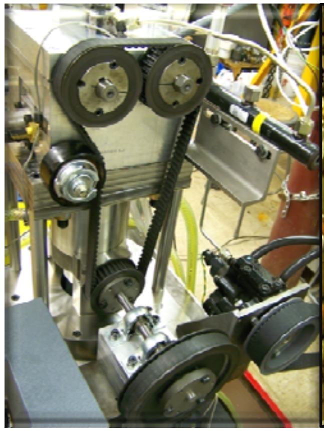
- 81mm bore & 88mm stroke
- Geometry based on Ford Lion V6 engine

Progress

- The optical engine was fully assembled and is currently running with metal piston.
- Fuel injection system was commissioned; injection spray tests were completed.
- Engine control was finalized; Labview was developed for data acquisition and engine management.
- Motoring tests were completed at up to 1500 rpm. The engine is well-balanced at 1500 rpm. In-cylinder pressure data were acquired and analyzed.







Multiple-Cylinder Biodiesel Engine Experiment

Progress

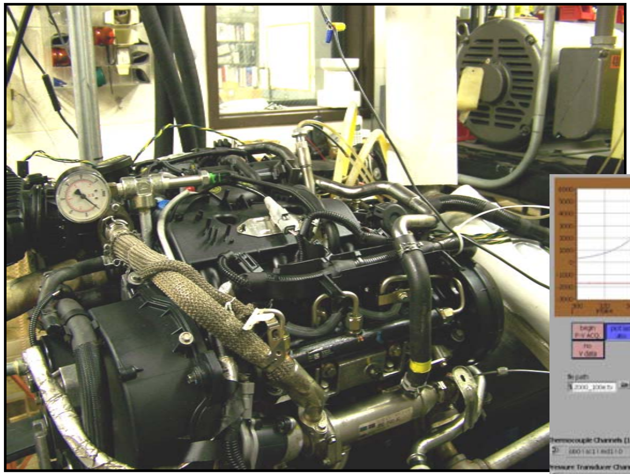
- Engine was completely set up and is currently running.
- Fuel Engine control was complete using the onboard ECU through ETAS INCA.
- Data acquisition system was finalized using Labview programs.
- Diesel and bio-diesel fuels tested.
- Combustion tests were done at various engine speeds up to 2000 rpm. In-cylinder pressure data and emissions were acquired.

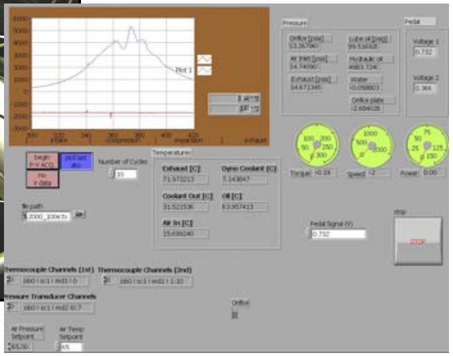
Specifications

- 2.7-liter V6 Ford Lion diesel engine
  - Compression ratio = 17.3
  - Turbocharged
  - Dual-water-cooled EGR pumps
  - Common-rail piezo-electric injection system

Facilities

- Midwest eddy-current dynamometer with Dyne Systems controller
- AVL in-cylinder pressure transducer
- Horiba MEXA 720 and MEXA 554JU exhaust analyzers
- Bosch smoke meter
- Independent intake pressure and temperature control system





ECU Calibration Effects on the Biodiesel Engine

Goal

To study how original ECU calibrations affect biodiesel combustion and emissions

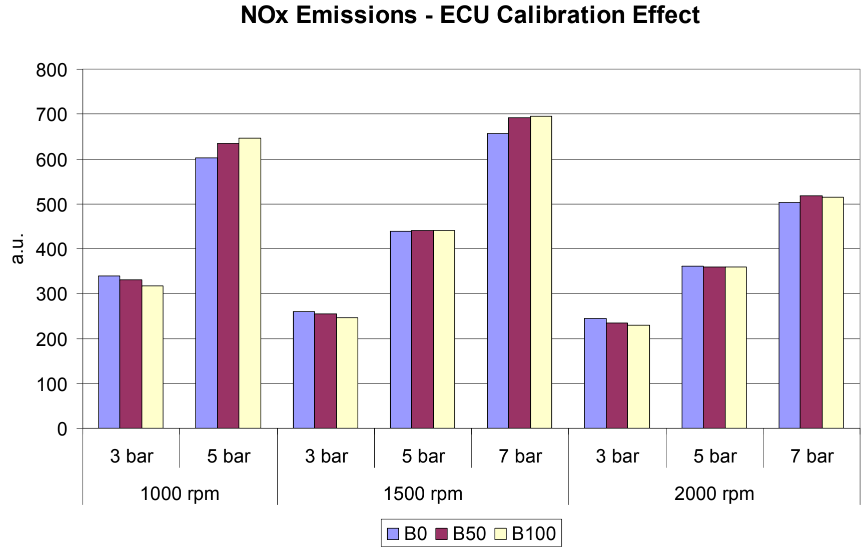
- Determine how engine parameters change with different fuels
- Determine if ECU is optimized for biodiesel combustion

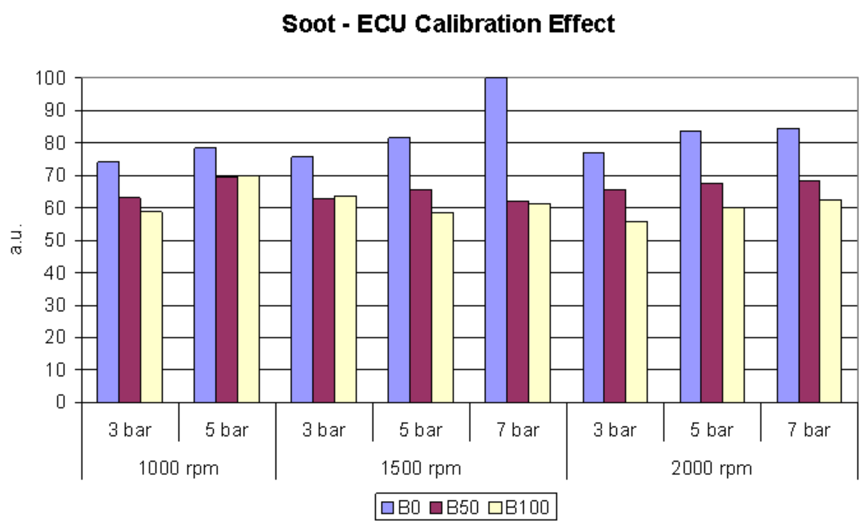
Test Conditions

- Speed = 1000, 1500 & 2000 rpm
- BMEP = 3, 5 & 7 bar
- ECU calibrations = default, EGR = 0
- Fuel = B0, B50 & B100

Results

- Injection timing change –
  - Main SOI is advanced
  - Pilot SOI is slightly retarded
- NOx emissions decrease at low load but increase at higher load with increasing biodiesel content





Fuel Effects on the Biodiesel Engine

Goal

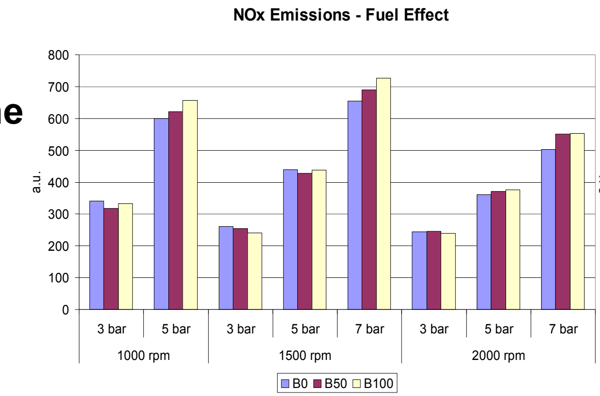
To study how different fuels affect combustion and emissions without the effects of ECU calibrations

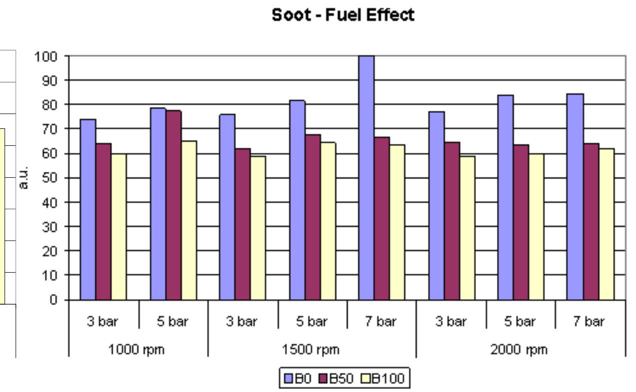
Test Conditions

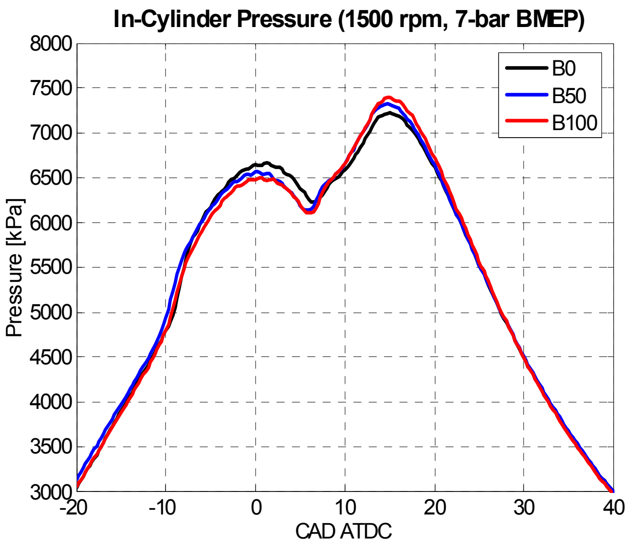
- Speed = 1000, 1500 & 2000 rpm
- BMEP = 3, 5 & 7 bar
- ECU calibrations = reconfigured to match injection timings and intake pressure
- Fuel = B0, B50 & B100, EGR = 0

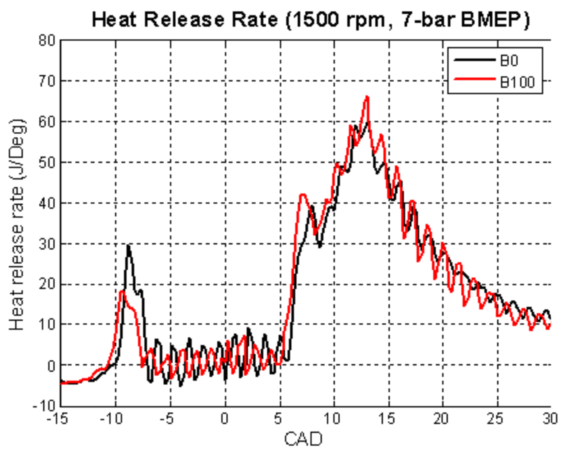
Results

- Ignition delay for biodiesel was shorter
- NOx emissions increased by 10% at higher loads
- Smoke emissions were reduced by about 20% at all loads and speeds









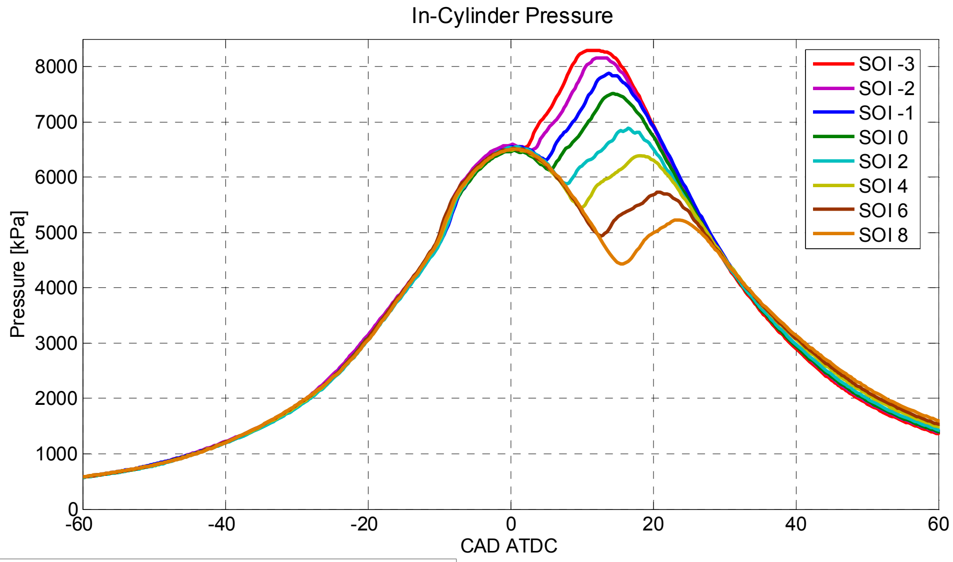
Optimization of the Biodiesel Engine

Goal

To optimize biodiesel combustion and emissions through varying main injection timings

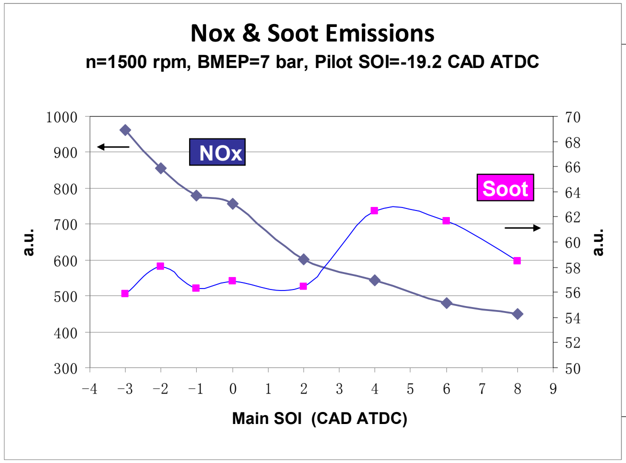
Test Conditions

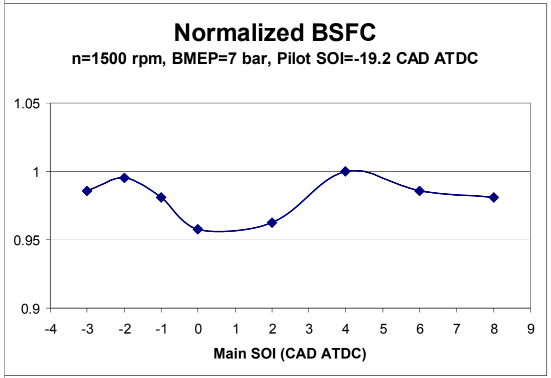
- Speed = 1500 rpm, BMEP = 7 bar
- ECU calibrations = reconfigured to vary only main SOI from -3 to 8 CAD ATDC
- Pilot SOI = -19.2 CAD ATDC, EGR = 0



Results

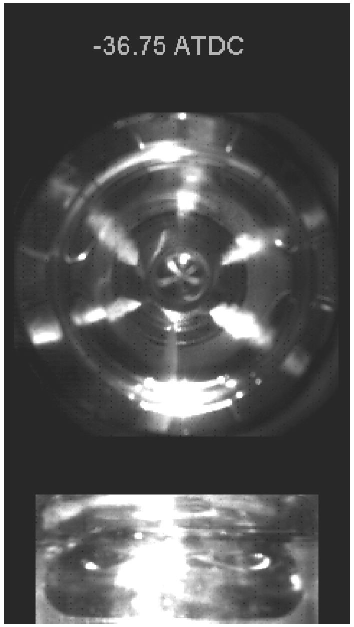
- NOx emissions decreased as main SOI was retarded. More than 50% reduction as SOI varied from -3 to 8 CAD ATDC.
- Soot emissions increased when main SOI was further retarded.
- Optimized SOI = 2 CAD ATDC for best trade-off in NOx and soot emissions and BSFC.



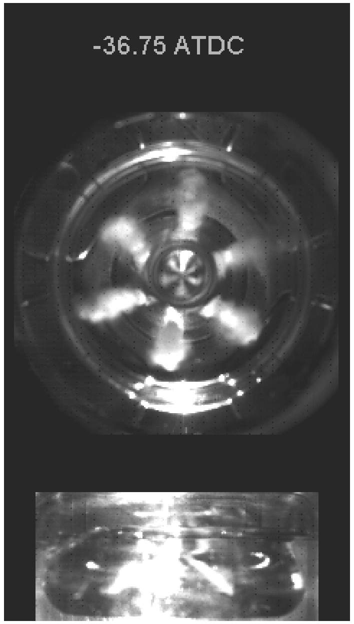


Narrow Angle Injectors in an Optical Engine

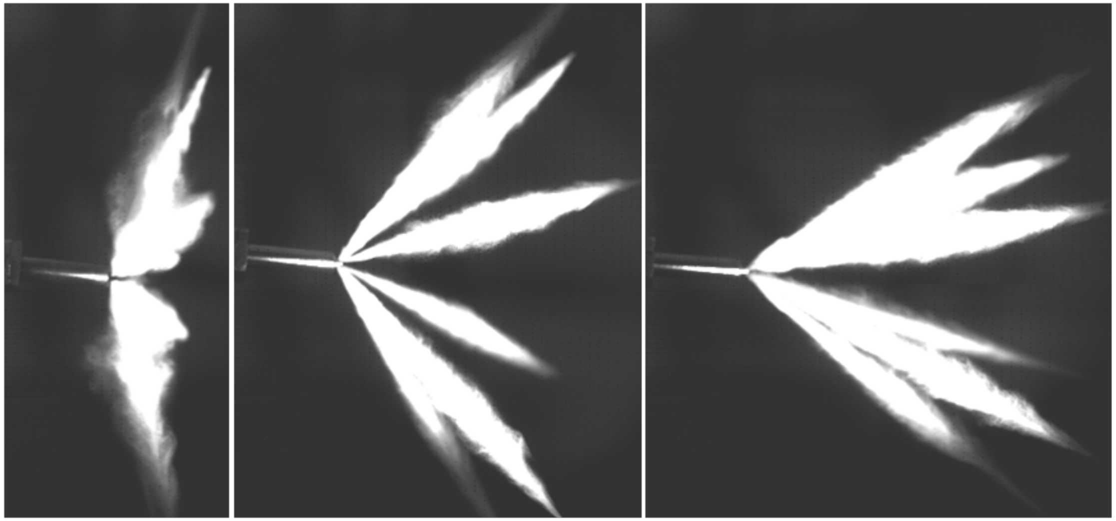
- Spray goes into the squish region for earlier timing with larger injection angles
- Narrower injection angles provide more crank angle span with spray confined in the bowl region



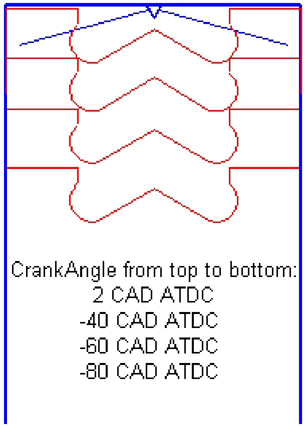
150 Deg Tip



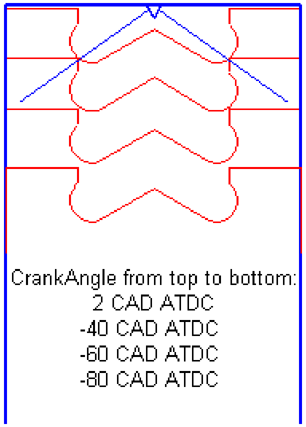
70 Deg Tip



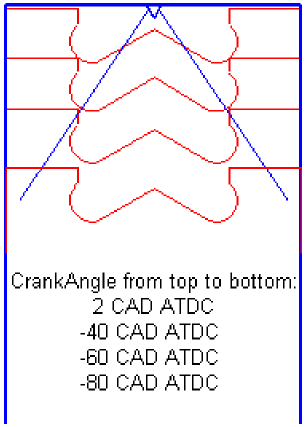
150 Deg Tip 110 Deg Tip 70 Deg Tip



Cone Angle :150.00 Deg



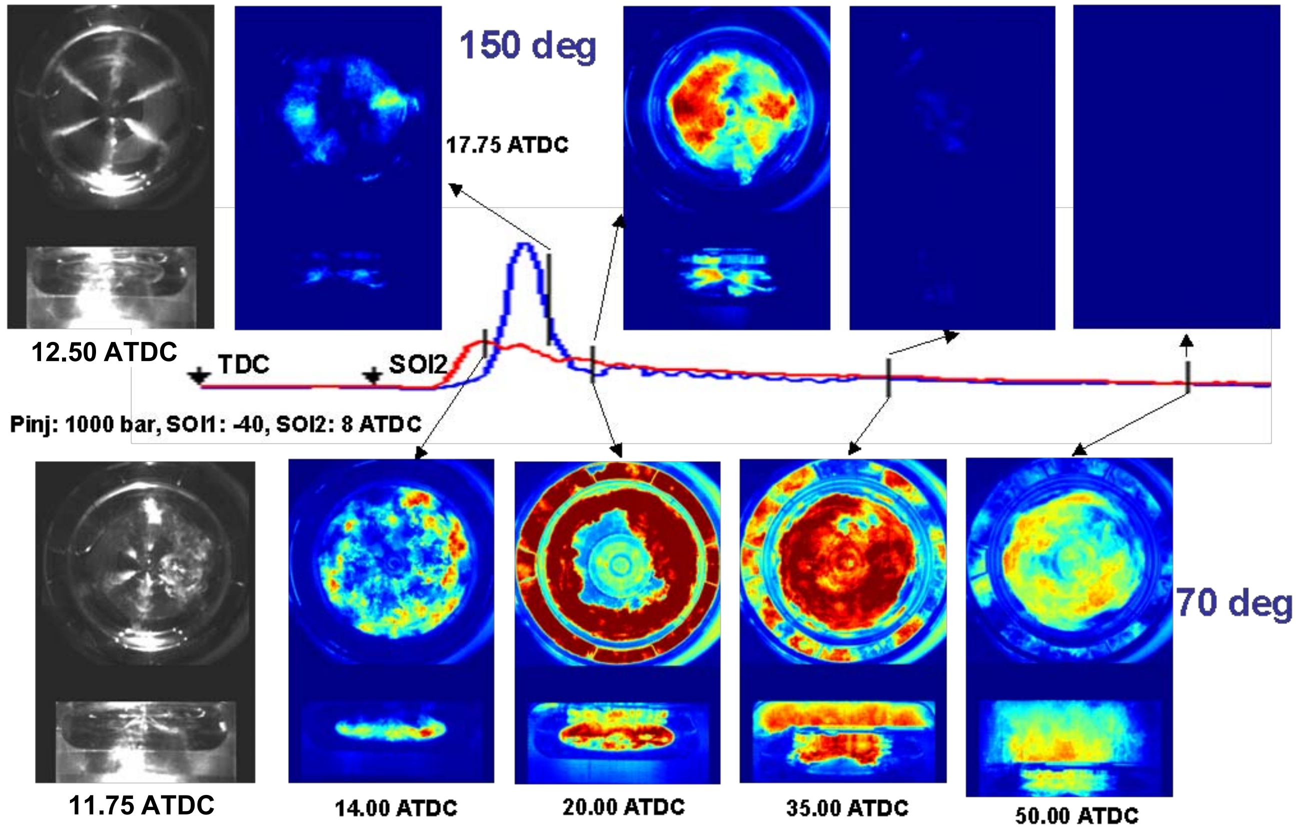
Cone Angle :110.00 Deg

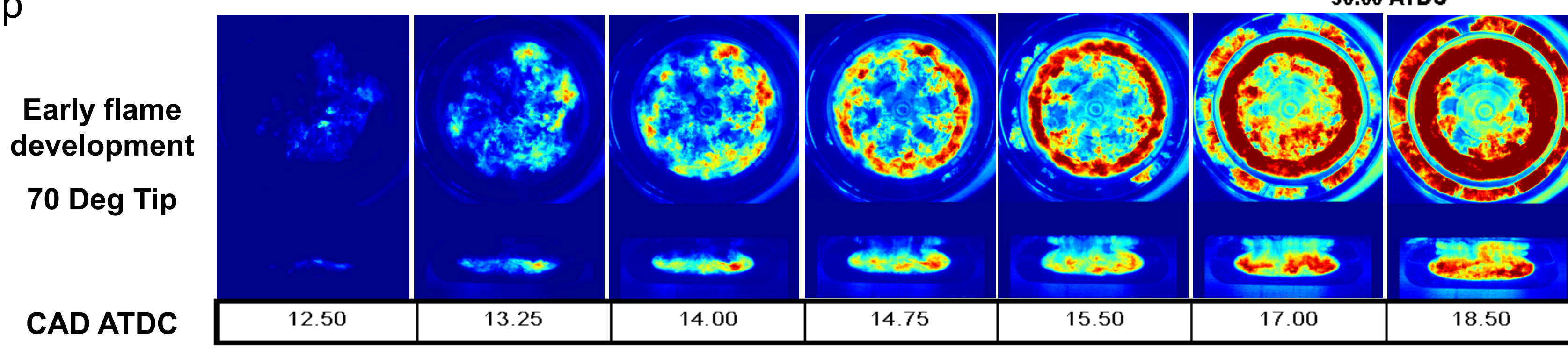


Cone Angle :70.00 Deg

Effects of Spray Angles on LTC

- The 150 deg tip leads to a premixed clean combustion mode
- The 70 deg injection angle results in a typical diffusion flame combustion with more soot formation
- Different from that of the 150 deg tip, combustion flame is observed on the bowl wall and filling in the squish region for the 70 deg tip





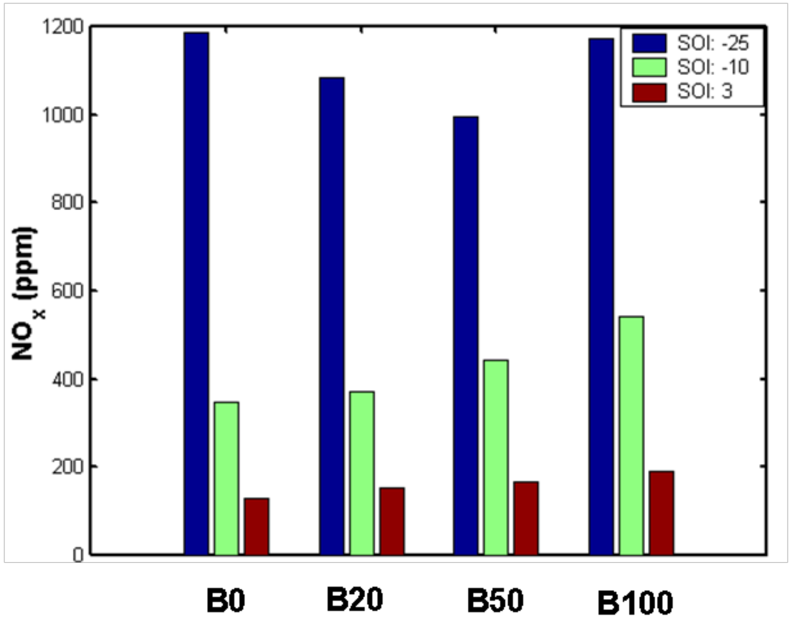
Combustion of Biodiesel/Diesel blends in an Optical Engine

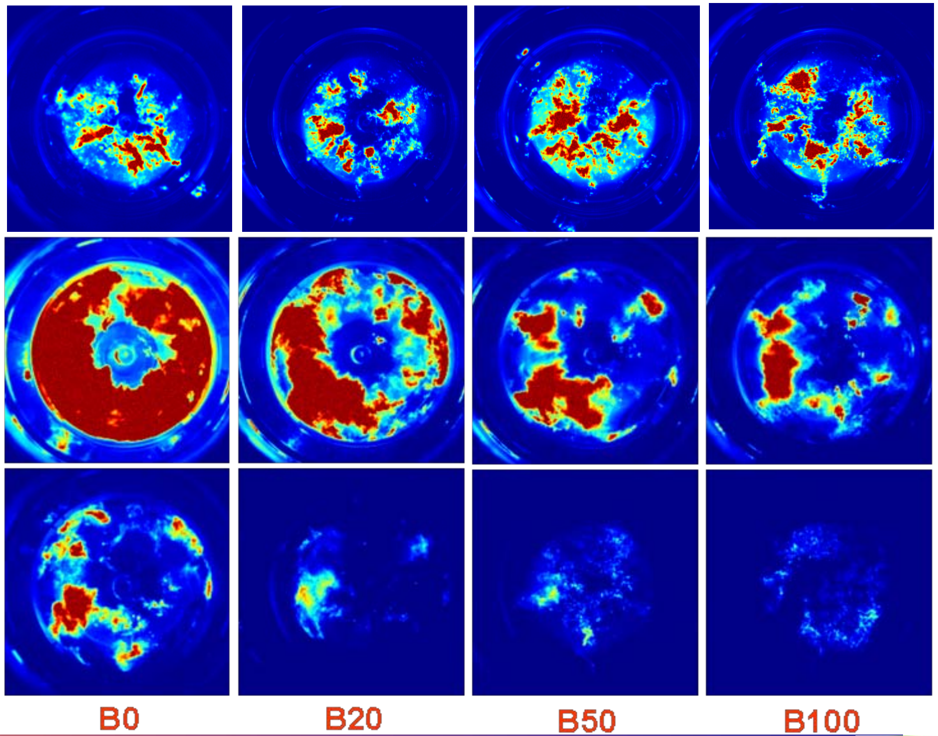
- Bio-diesel fuel reduces soot formation with increased NOx emissions
- Low temperature biodiesel combustion simultaneously reduces soot and NOx emissions

B0
European Low Sulfur Diesel

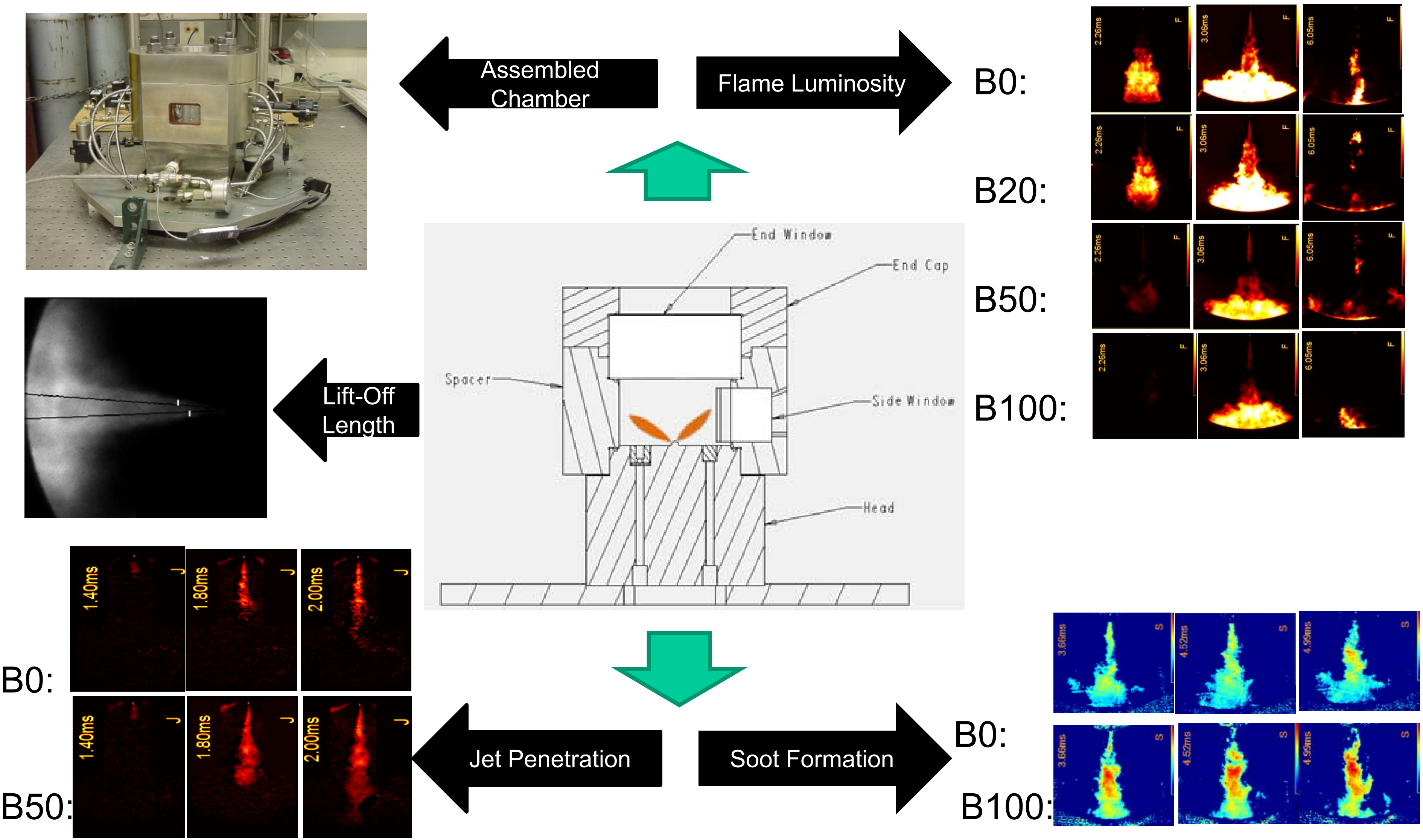
B50
50% Soybean Biodiesel

B100
100% Soybean Biodiesel





Constant-Volume Combustion Chamber Experiment



Fuel and Temperature Effects on Penetration and Lift-Off Length

Goal

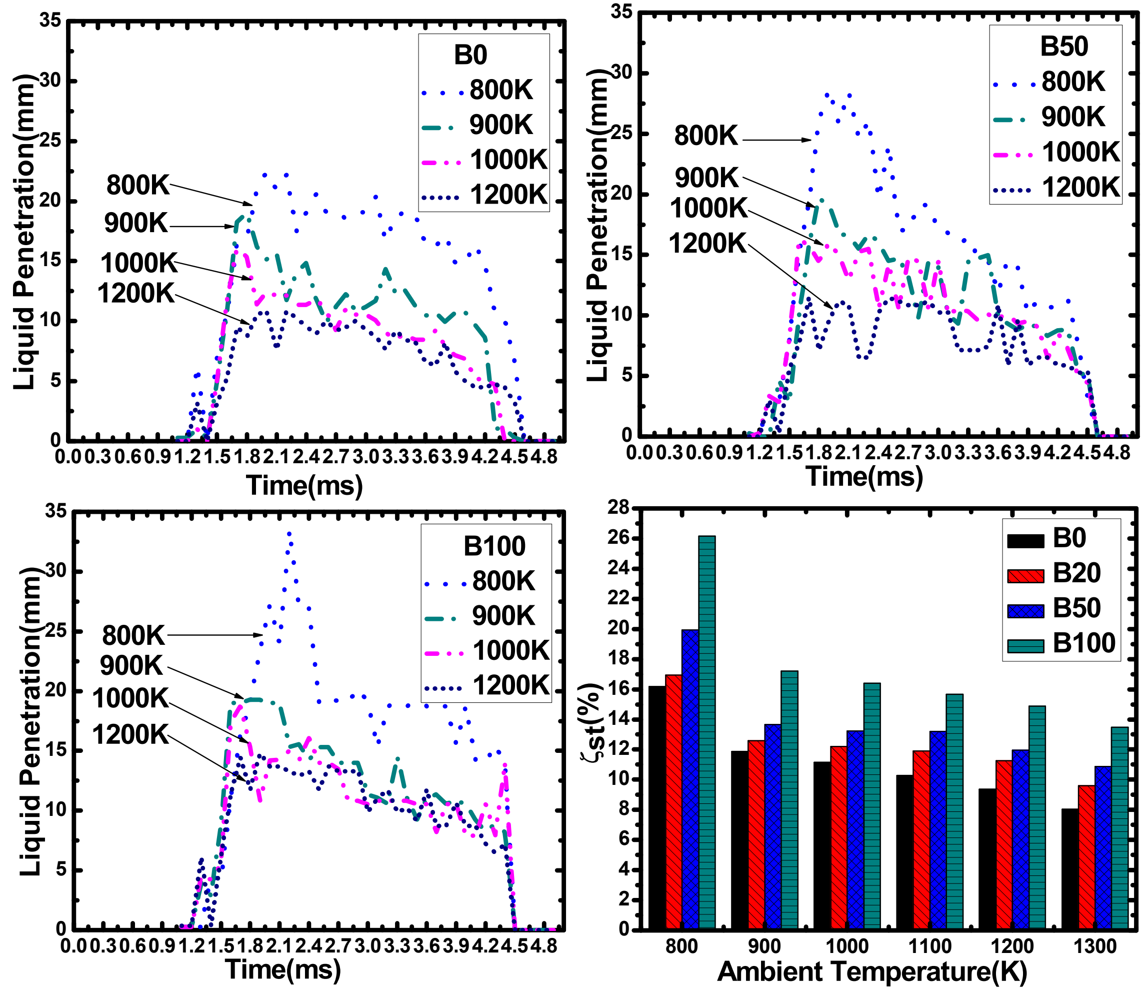
To study how different fuels and ambient temperatures affect liquid jet penetration and lift-off length

Test Conditions

- Injection pressure: 134 MPa
- Injection duration: 3.5 ms
- Injection fuel amount: 120 mm^3
- Ambient density: 15 Kg/m^3
- Ambient temp.: 800 to 1300K
- Ambient O_2 concentration: 21%
- Fuel: B0, B20, B50 & B100

Major Results

- Liquid jet penetration increased as the ambient temperature decreased and the biodiesel content in the fuel increased
- The lift-off length results showed trends similar to liquid jet penetration



Fuel and Temperature Effects on Luminosity and Soot Formation

Goal

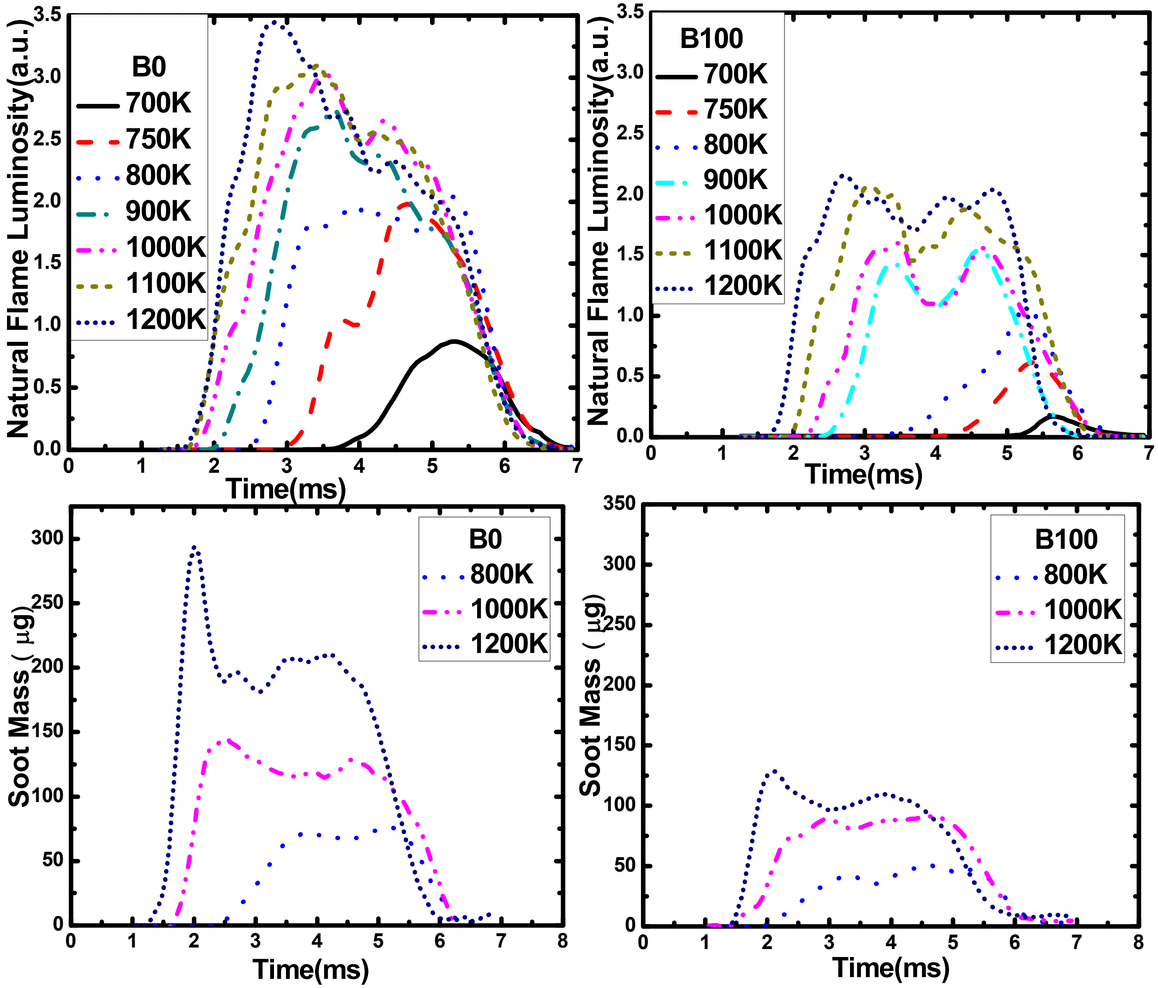
To study how different fuels and ambient temperatures affect natural flame luminosity and soot formation

Test Conditions

- Injection pressure: 134 MPa
- Injection duration: 3.5 ms
- Injection fuel amount: 120 mm^3
- Ambient density: 15 Kg/m^3
- Ambient temperature: 700 to 1200K
- Ambient O_2 concentration: 21%
- Fuel: B0 and B100

Major Results

- Natural flame luminosity increased as the ambient temperature increased for both fuels; B0 had relatively higher luminosity than B100 at same ambient temperature
- Soot decreased with B100, especially at 1200K.



LTC with Biodiesel using Dual Injections in HSDI Engine

Goal

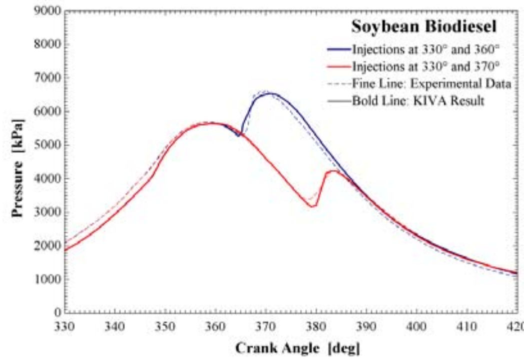
To study the effect of biodiesel combustion on engine emissions

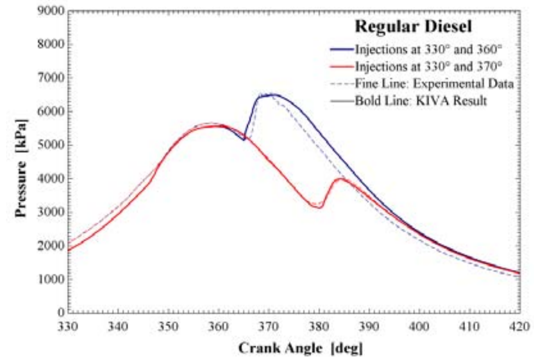
Test Conditions

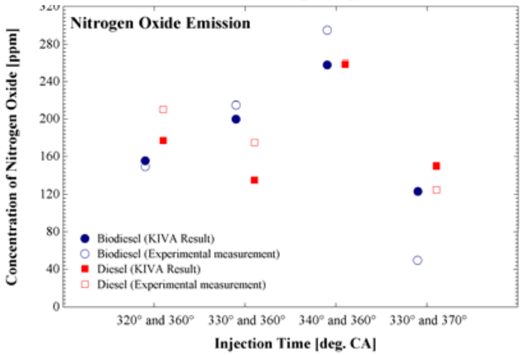
- Speed = 1500 rpm
- Engine output = 400 kPa IMEP
- Initial injection: 320, 330 or 340°
- Main injection: 360 or 370°
- Fuel = B0, B20, B50 & B100
- No EGR

Improvements in Modelling

- Expanded fuel library to include thermo-physical properties for biodiesel
- Properties were generated using BDProp
- Multi-component model for fuel blends was included







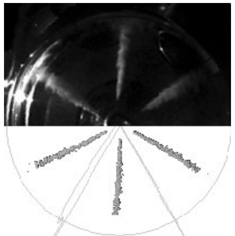
Verifications

- Numerical predictions of spray penetrations, combustion characteristics and emission matches well with experimental measurements


B0


B20

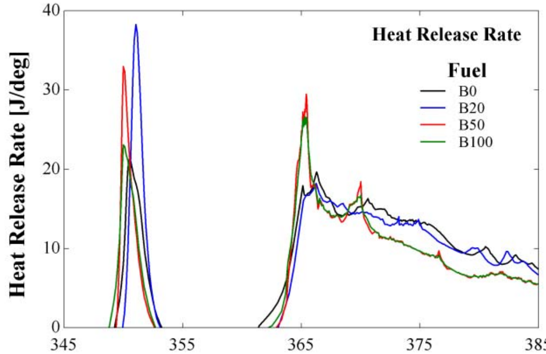

B50

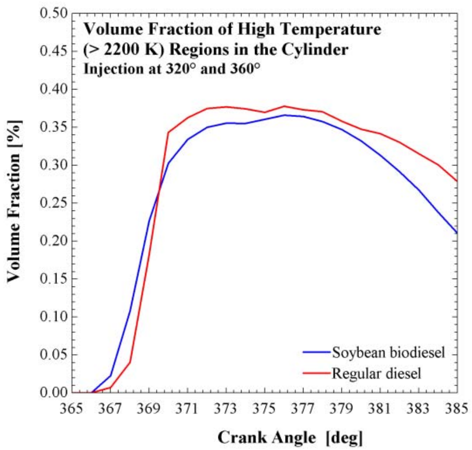

B100

LTC with Biodiesel using Dual Injections in HSDI Engine

Heat Release Comparisons

- Pure biodiesel has longer ignition delay for initial injection
- Shorter duration of combustion for pure biodiesel
- Blends with higher biodiesel content have longer ignition delay
- Strength and duration of combustion is inconclusive for fuel blends

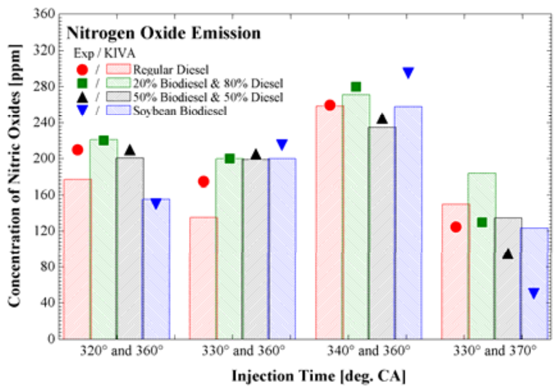




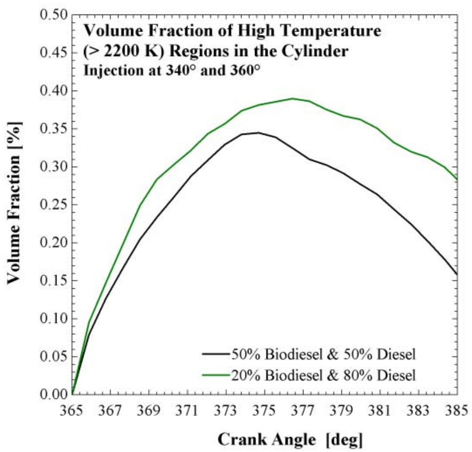
Lower engine cylinder temperature after biodiesel and B50 combustion

NO_x Emission

- Retarding main injection effectively reduces the emission
- Biodiesel may or may not increase NOx emission
- High temperatures promote formation of NOx
- Lower NO_x was observed in fuels with more biodiesel in some cases



- A larger proportion of the cylinder remains at high temperature for diesel combustion
- Lower cylinder temperature after biodiesel/B50 combustion



Effects of Spray Angle on Diesel/Biodiesel LTC Engine

Goal

To study the effect of spray angle in engine emissions and its performance

Test Conditions

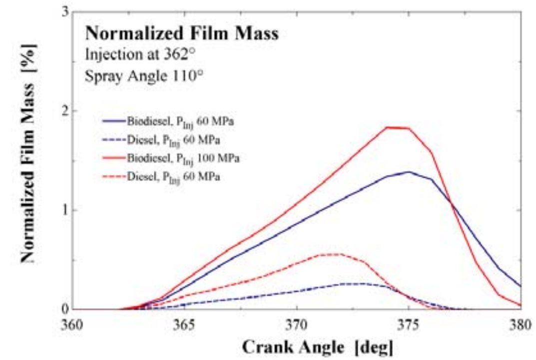
- Speed = 1500 rpm
- Engine output = 500 kPa IMEP
- Injection: 362°
- Fuel = Diesel, Biodiesel
- Spray Angle = 150°, 110°, 70°
- No EGR

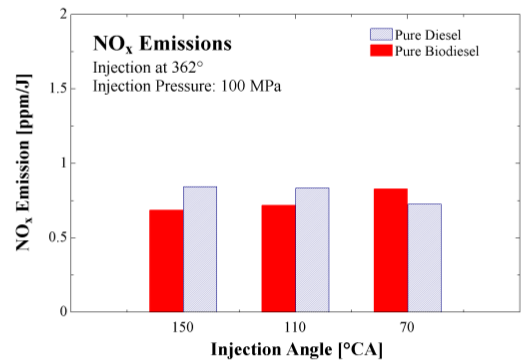
Spray Impingements

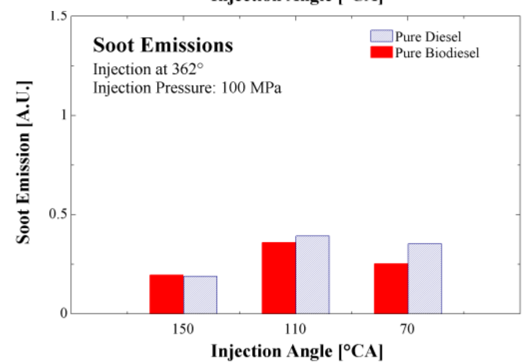
- Smaller spray angles also increase spray impingement
- Stronger impingement is observed in biodiesel spray
- Wall film can increase soot emission due to the rich air/fuel mixture close to wall surface

Emissions

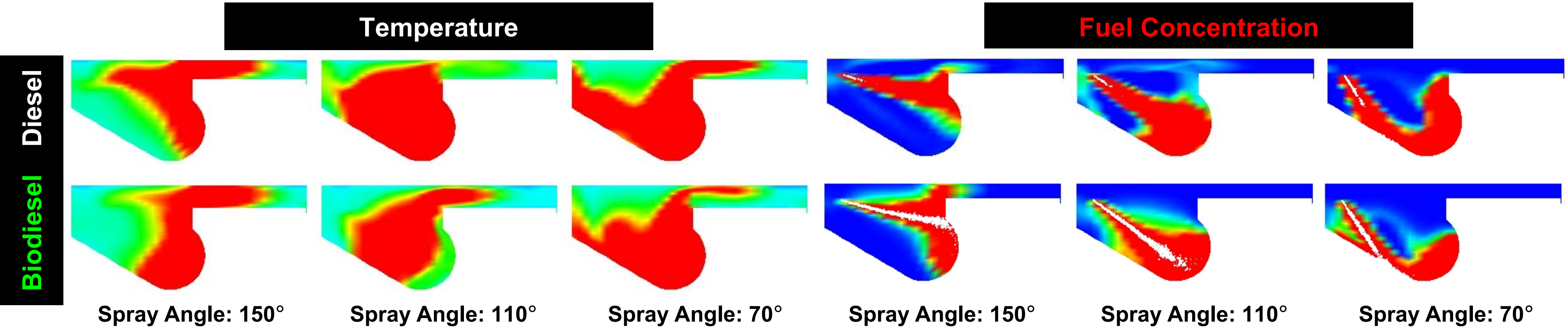
- Smaller spray angle leads to higher NOx for biodiesel
- Smaller spray angle tends to reduce emissions for diesel
- Higher injection pressure increases emissions
- Trend for emission same for both diesel and biodiesel
- Lowest soot emission for biodiesel observed with spray angle of 70°
- Higher injection pressure may increase or decrease emissions from biodiesel





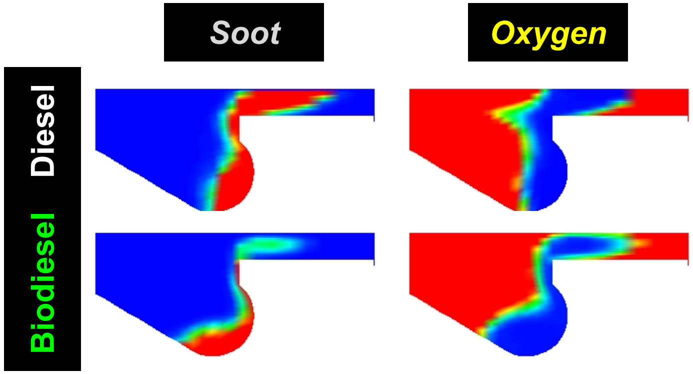


Effects of Spray Angle on Diesel/Biodiesel LTC Engine



Effects on Combustion

- Combustion first confined in the piston bowl for narrow angle spray
- Stronger impingement with narrow angle spray
- For small spray angle, combustion confined deep in the piston bowl, may lead to local high temperature spot, causing higher NO_x emission



Effects on Soot Emission

- Fuel flows along the bowl wall and overflows into the squish region
- Abundance of oxygen in the squish region
- Soot in the squish region readily oxidized
- Soot located within the piston bowl is oxidized at a much slower rate due to deficiency of oxygen after combustion
- Any strategy that pushes soot out of piston bowl can improve the oxidization process, thus, reducing soot emission

Application of Varying Spray Angle Injector in LTC Engine

Goal

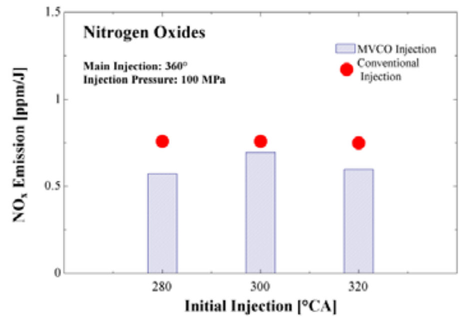
To study the applicability of a varying spray angle injector (the MVCO injector) in the same engine, its effects on the performance and emissions

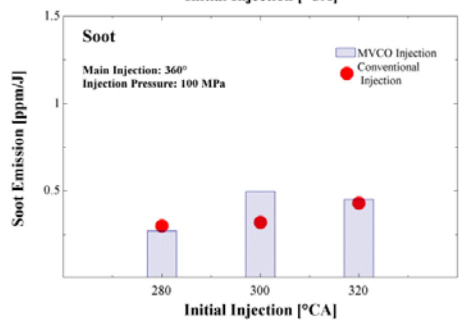
Test Conditions

- Speed = 1500 rpm
- Engine output = 500 kPa IMEP
- Initial injection: 280, 300 or 320°
- Main injection: 360 or 370°
- Fuel = B0, B20, B50 & B100
- Injector = Conventional, MVCO

Fuel Economy

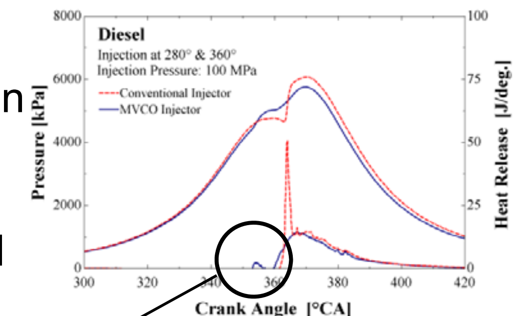
- MVCO injection causes better fuel consumption
- Initial injection burns more completely under MVCO injection
- No ignition for initial injection with conventional injector for early cycle pilot injection
- Higher thermal efficiency observed with biodiesel and blends and MVCO injection



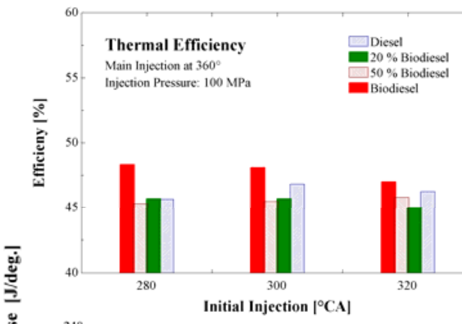


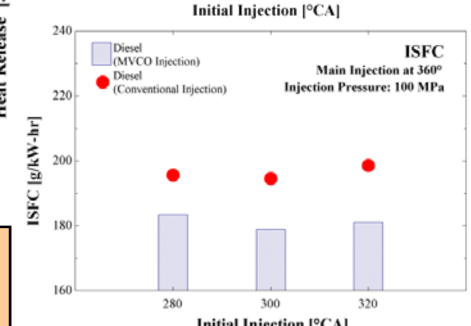
Emissions

- MVCO injection lowers NO_x emission
- With MVCO injection, soot emission is at least as good as conventional injection
- Further reductions in emission are possible with MVCO injections through optimizing the engine operation conditions



Combustion for 1st injection occurs before TDC





Summary

- Both ECU calibration and fuel effects influence the performance and emissions of the biodiesel engine. Optimized calibration for various biodiesel fuels and their diesel blends will be needed.
- Numerical predictions of spray penetrations, combustion characteristics and emission match well with experimental measurements. Sub-models have been successfully modified to predict the experimental data. The mechanism of NOx emissions in biodiesel and diesel engines was carefully investigated.
- Narrow angle direct injections provide more flexibility in injection strategy optimization for low temperature combustion. The effects of spray angles were investigated through measurements in an optical engine and computations.
- Studies of varying spray angle injector in the same engine show promising potential of the new injector on the performance and emissions of biodiesel LTC engines.
- Laser diagnostics of biodiesel low-temperature combustion in the chamber provide excellent data for model improvement and fundamental understanding.

Future Work

- Continue characterization of the effects of ECU calibration and fuels on the biodiesel metal engine. Injection and operating parameters will be varied to study LTC to provide information needed for the optimization calibration in Phase III.
- Laser diagnostics of selected conditions based on the metal engine results to study air-fuel mixing, combustion, and emissions formation processes in the optical engine.
- Modeling computations and comparison with the new engine results will be performed to provide deeper insight of the biodiesel LTC processes.
- Further computational investigation of spray angle effects and varying spray angle injector will be conducted to explore the potential of the new injection strategy for the optimization of biodiesel LTC engines.
- Continue laser diagnostics of biodiesel LTC in the chamber, and comparison of the computed and measured results will be made to further improve the sub-models and provide fundamental understanding.