Optimizing Low Temperature Diesel Combustion

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Office of FreedomCAR and Vehicle Technologies Program

Merit Review meeting, Bethesda, Maryland

February 25-28, 2008

Acknowledgements

DOE LTC Consortium project DE-FC26-06NT42628

DOE Sandia Laboratories

Industry Partners

British Petroleum, Caterpillar

Diesel Emission Reduction Consortium (DERC)

GM-ERC Collaborative Research Laboratory (CRL)

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Optimizing Low Temperature Diesel Combustion

US EPA mandates require emissions of PM and NOx from heavy-duty diesel engine exhaust to be reduced by 90% between 1998 and 2010
– meet emissions targets without compromising fuel efficiency

Goals: Develop methods to further optimize and control LTC engines in-cylinder, with emphasis on diesel-fueled engines

Barriers: Control of fuel/air mixing and wall-wetting is difficult due to low volatility of diesel fuel. Combustion phasing determined by chemical kinetics

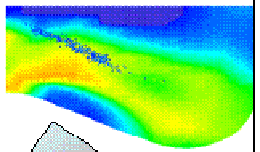
Approach: Use high fidelity computing and high-resolution engine experiments synergistically to create and apply advanced tools needed for low emissions engine combustion design

Engine technologies to be considered include operation on LTC-D with transition to advanced Compression Ignition Direct Injection (CIDI) combustion at higher loads and starting conditions (“mixed-mode” operation)

Outcomes: Efficient, low-emissions combustion concepts proposed, evaluated and understood

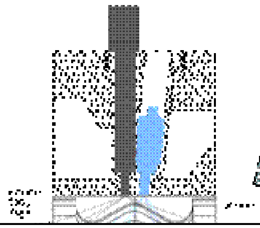
Approach – 5 Tasks

Task 1: Fundamental understanding of LTC-D and advanced model development

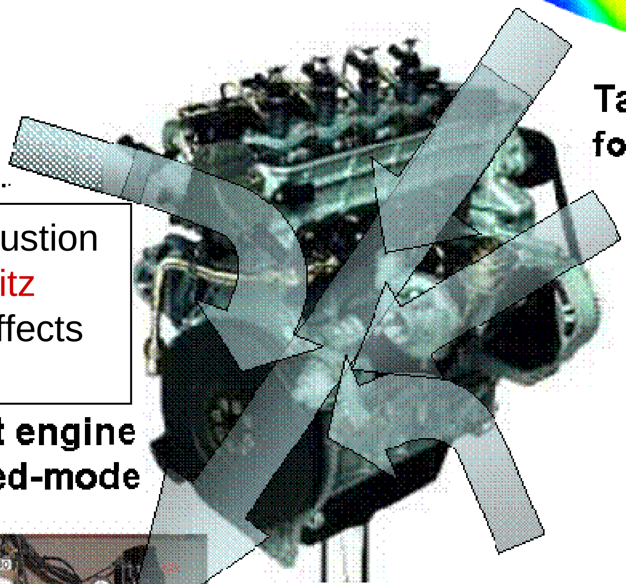


1.1a Develop combustion models - Reitz
1.1b Optical engine measurement - Sanders
1.2a LES turbulence Models - Rutland
1.2b Mixing Measurements - Ghandhi

Task 2: Experimental investigation of combustion control concepts

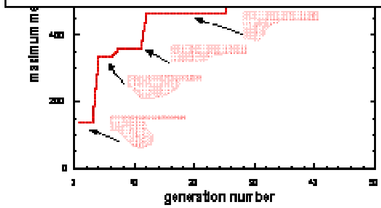


2.1 VVT/VGS for combustion control HD engine - Reitz
2.2 Injection and fuel effects LD engine - Foster

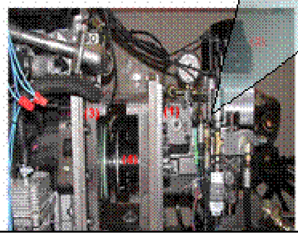


Task 3: Application of models for Optimization of combustion & emissions

3.1 GA Optimized piston geometry - Reitz
3.2 Optimized spray characteristics - Reitz
3.3 Improving mixing using LES - Rutland

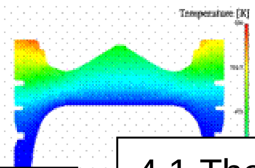


Task 5: Transient engine control with mixed-mode combustion



5.1 Multi-cylinder LD engine control with mixed-mode combustion – Foster/Farrell
5.2 Engine system analysis with mixed-mode regime transitions - Rutland

Task 4: Impact of heat transfer and spray impingement on LTC-D combustion

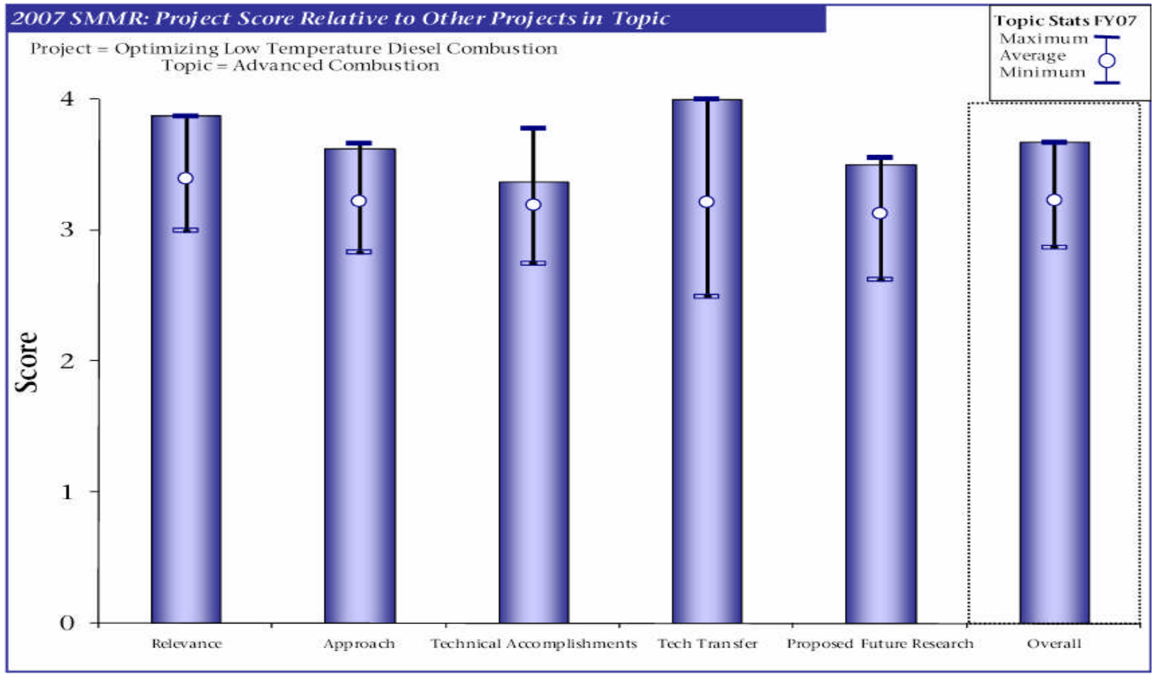


4.1 Thermal analysis with CFD + metal heat conduction - Reitz
4.2 Temperature & heat flux measurements - Ghandhi

Response to Reviewer Comments - SMMR 6/07

Question 1: Relevance to DOE - Strong tie to emissions, link to efficiency?
Response: Use of diesel gives improved efficiency (plus alternative fuels).

Question 2: Approach - i.) PLIF less resolved than LES?
Response: PLIF resolution exceeds LES: provides accurate model input.
ii.) Hardware needed for mixed-mode operation plus after-treatment costly.
Response: Optimized in-cylinder combustion minimizes after-treatment needs & offers improved fuel efficiency and after-treatment system durability.
iii.) GA matches injector to piston geometry? Response: Yes



Response to Reviewer Comments - SMMR 6/07

Question 3: Technical Accomplishments/Progress to DOE goals

Two injector system is costly – can incorporate into one injector?

Response: Demonstrate efficacy of VIP/VGS (e.g., multiple injections)

Question 5: Approach/relevance of proposed future research

i.) Reduced chemical kinetics validation ? Response: Project 1.1b's data

ii.) Account for combustion noise? Response: Optimized multiple injections

iii.) Use of merit functions in optimization? Response: Use MOGA methodology

Strengths/Recommendations:

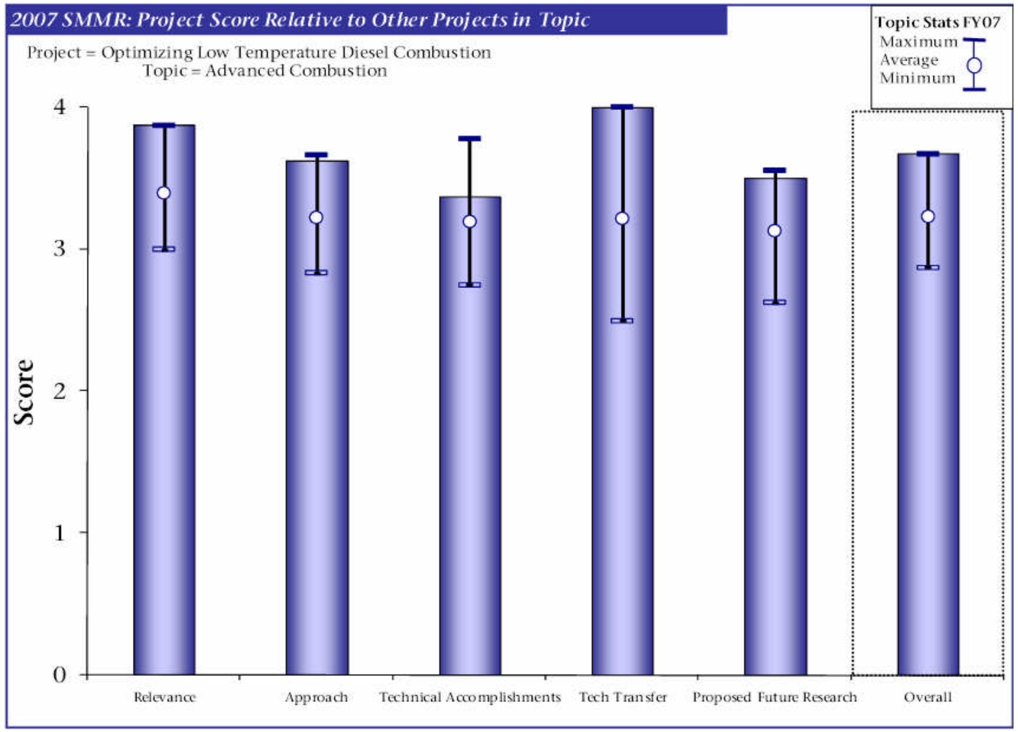
Identify DERC role.

Response: 20% match fund

Weaknesses: Clarify technologies to be used with after-treatment.

Response:

- focus on minimized need for after-treatment
- increase LTC load range.



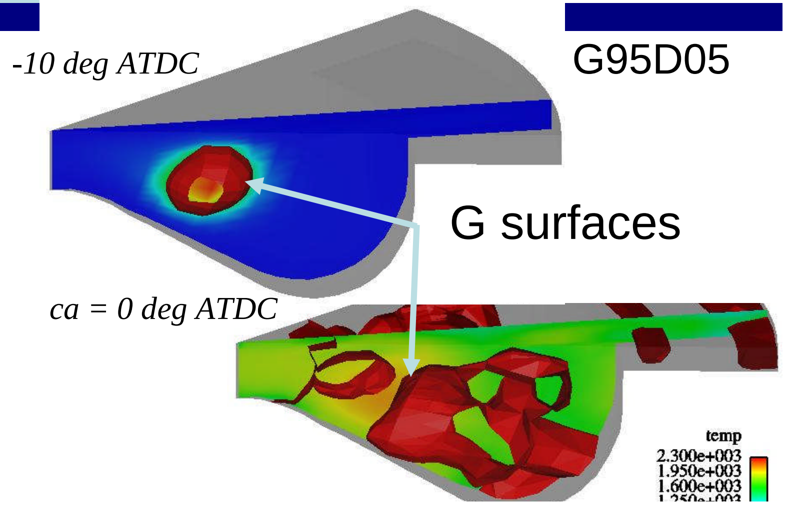
Task 1: Fundamental understanding of LTC-D and advanced model development: 1.1a Combustion models

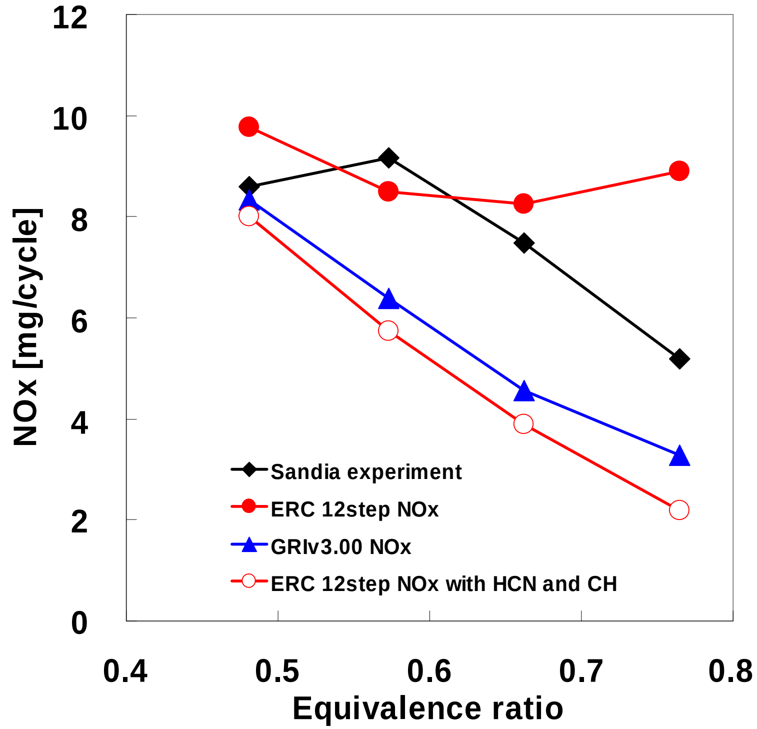
HCCI/LTC attractive due to low NOx and soot emissions. However, ignition and combustion is controlled by complex chemical kinetics and turbulence interactions

Approach: Develop accurate reduced chemistry mechanisms for auto-ignition. Combine chemistry with advanced combustion CFD model (KIVA-CHEMKIN-G)

Accomplishments: PRF-Bio mechanism developed (< 55 species) and validated with engine data. Volumetric and flame propagation combustion models integrated using Damköhler number time scale switch criterion. Improved NOx model with HCN

Plans for Next Year: Validate reduced mechanisms with engine data, with in-cylinder species measurements from Task 1.1b.





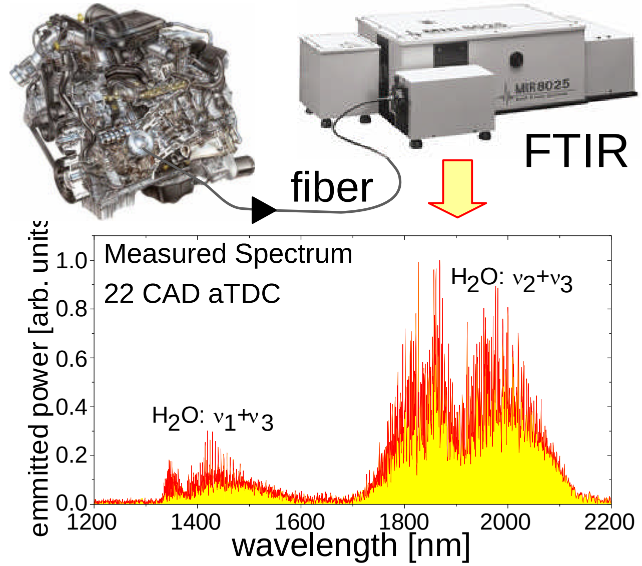
Task 1: Fundamental understanding of LTC-D and advanced model development: 1.1b Experimental validation

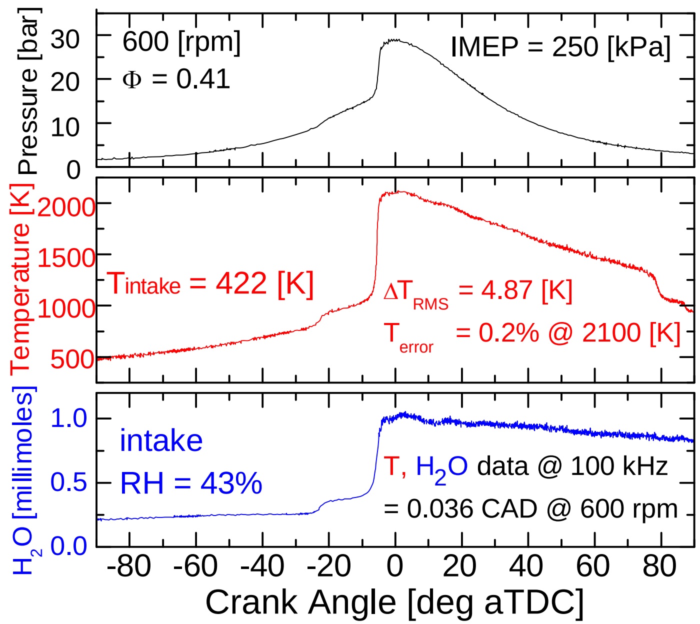
Comparison of measured and simulated in-cylinder species composition histories will help optimize low-temperature combustion processes.

Approach: Using advanced laser sensors and novel applications of traditional optical instruments, catalog in-cylinder gas properties under varied engine operating conditions.

Accomplishments: H_2O vapor sensing near 1350 nm has been developed. Temperature precision is < 5 K at 100 kHz (better at lower data rates). In-cylinder FTIR demonstrated, many species including H_2O, CO_2, CO, NO, C_2H_2, and CH_2O are now accessible.

Plans for Next Year: Interact with Task 1.1a by collecting in-cylinder species data to compare with simulation results





Task 1.2 Formulation of turbulence and mixing models for LTC-D: 1.2a,b Computational LES/ Experimental Investigations

High-efficiency low-emission combustion requires precise control of mixing

Approach: Develop high fidelity, computationally efficient models of mixing through integrated comparison with high resolution in-cylinder experiments

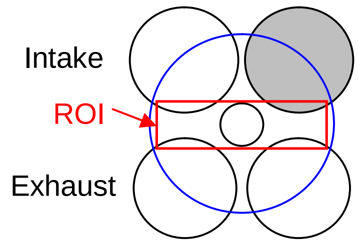
Modeling Accomplishments: LES scalar dissipation model integrated in flamelet model with detailed chemistry. Dissipation used to differentiate flamelet burning and homogeneous combustion modes.

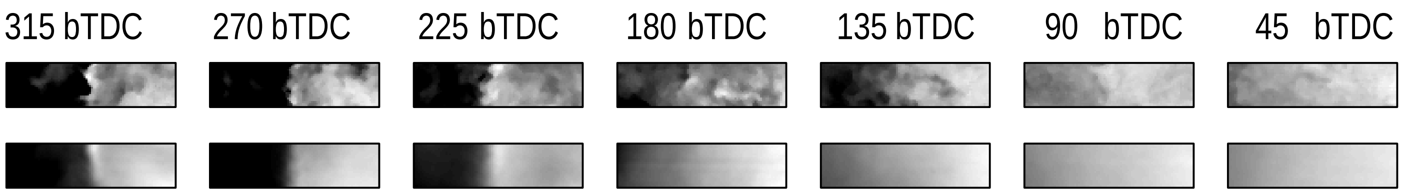
Technical Barriers: Limited LES grid resolution → accurate models.

Plans for Next Year: Detailed comparison of dissipation model results with experimental data

Experimental Accomplishments: Fluorescence saturation measurements performed with 3-pentanone. Mixing measurements during the intake and compression stroke performed.

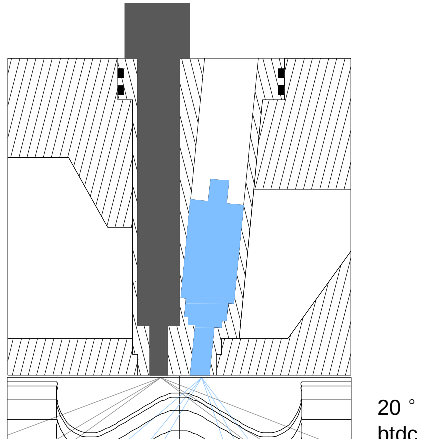
Plans for Next Year: Complete characterization of intake flows, develop database of diesel and gas jets. Investigate dissipation spectra to resolve differences in experimental and modeled resolution levels.





Task 2: Experimental investigation of LTC-D combustion control concepts: 2.1 VVT-VGS in HD engine

Caterpillar 3401 SCOTE



Early injection provides sufficient time for fuel/air mixing for HCCI, but can have excessive wall wetting and too early ignition with diesel fuel

Approach: Use late IVC VVA to control Comp. Ratio, plus variable geometry/injection pressure sprays. Assess Adaptive Injection Strategy - 2 Stage Combustion (TSC) with low/high injection pressures.

Accomplishments: 2010 emissions levels demonstrated with TSC at 11 Bar IMEP. 2-injector system has low emissions HCCI, with soot/BSFC controlled by late injection.

Plans for Next Year:
Assess IVC timing/EGR/Boost effects with TSC

D=Diesel, H=n-heptane, G=Gasoline

(g/kW-h)	D/D 70/30	D/H 50/50	D/H 50/50	D/H 50/50	G/G 70/30
SOLI	7.5	5	10	15	12.5
NOx	0.60	0.46	0.37	0.33	0.26
PM	0.94	0.29	0.11	0.03	0.01
CO	11.8	11.7	12.8	14.2	11.9
HC	0.22	0.39	0.45	0.54	0.91
BSFC	253	253	275	310	270

Model Results - GA Optimum 1757rpm, 57% Load

IVC (° CA)	SOLI (° CA)	EGR (%)	1st Fraction
-95	17	28	0.7

BSFC 214 g/kW-h	NOx	Soot	CO	HC
Optimum	0.181	0.033	12.88	2.04

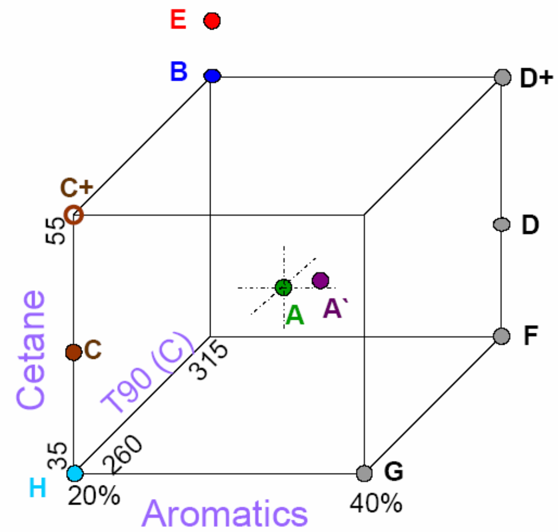
Task 2: Experimental investigation of LTC-D combustion control concepts: 2.2 injection and fuel effects on mixing

Investigate potential of achieving LTC-D operation with different nozzle geometries and with a range of fuels

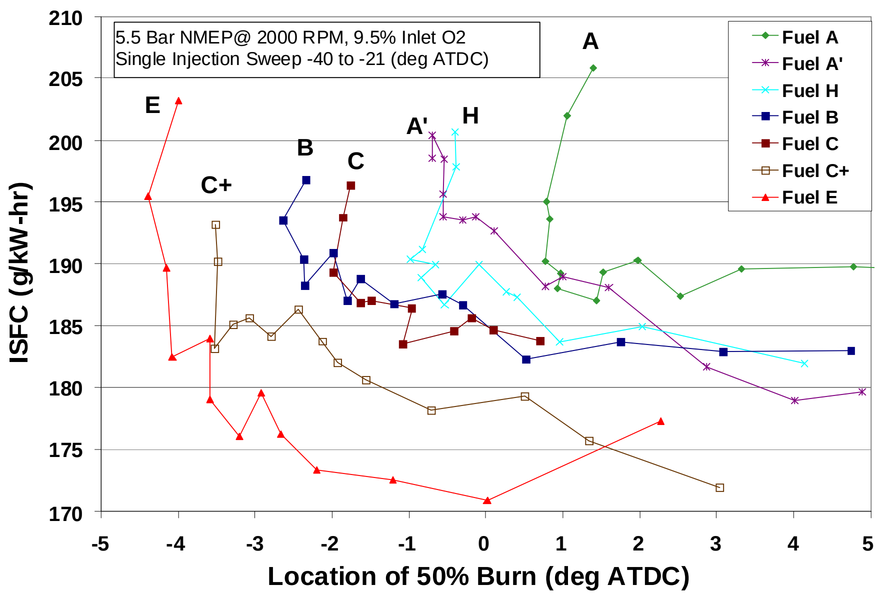
Approach: Use advanced injection systems with different nozzle configurations, on research GM 1.9L diesel engine with fuel property variations from FACE matrix (from BP)

Accomplishments: Chose an optimal nozzle. Tested fuels ECD-1, US-ULSD 1 & 2, and Blends E, H, C, and C+. At this load (5.5 bar) significant improvement of CO, HC, and ISFC from increasing cetane number and volatility,

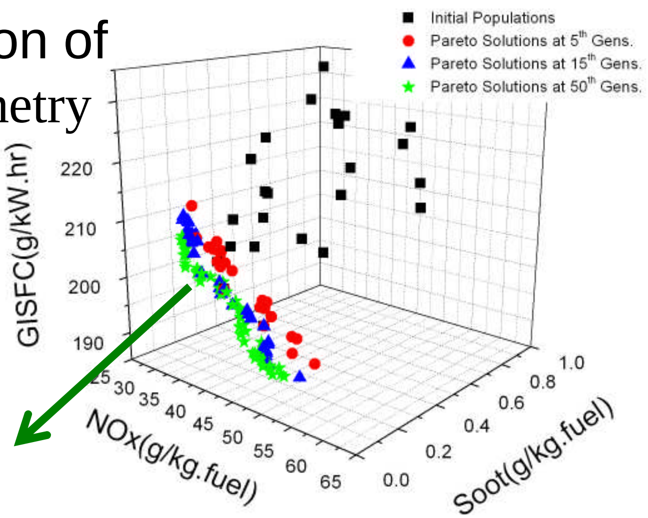
Plans for Next Year: Complete tests on remainder of fuels, evaluate impact of specific FACE matrix parameters.



FACE Fuel Matrix

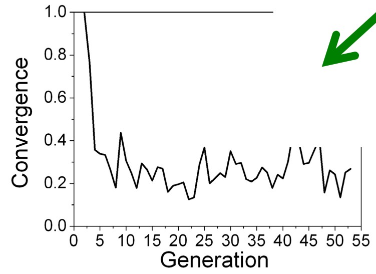


Task 3: Application of detailed models for Optimization of LTC-D: 3.1 Optimization of HD engine piston bowl geometry

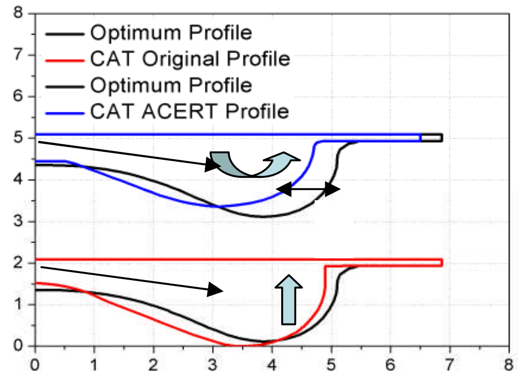


Simultaneously optimize piston shape and spray for low emissions and fuel economy

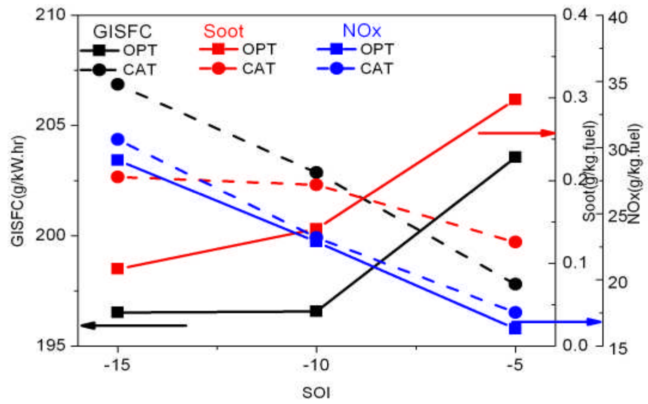
Approach: Apply multi-objective optimization genetic algorithm (MOGA) with KIVA-CTC code. Validate results with KIVA-Chemkin.



Accomplishments: Highly efficient MOGA (NSGA II) formulated – SAE 2008-01-0949
Real-time method for determining convergence.
Optimum piston design and spray parameters found for both high- and low-load operation.

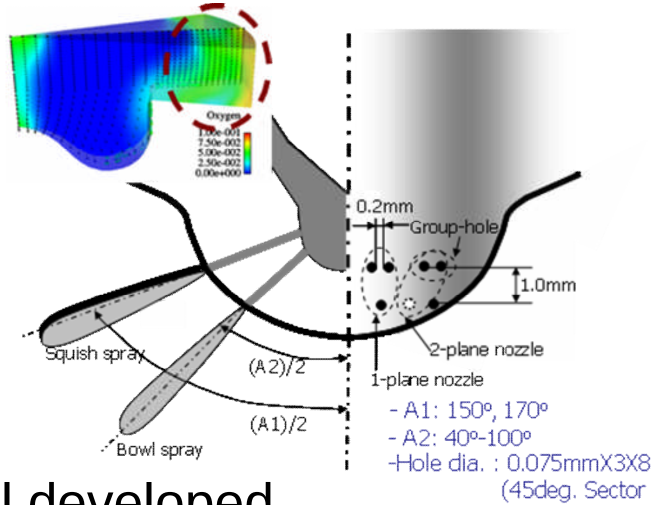


Plans for next year: Validate optimized piston experimentally on Caterpillar 3401 HD engine.
- Implement data mining methods to reduce computational resource requirements.
- Further improve MOGA, and reduce CPU time of KIVA-Chemkin simulation to directly couple MOGA with detailed chemistry.



Task 3: Application of detailed models for Optimization of LTC-D: 3.2 optimal spray characteristics

Develop optimal injection and combustion methodologies for low emissions operation

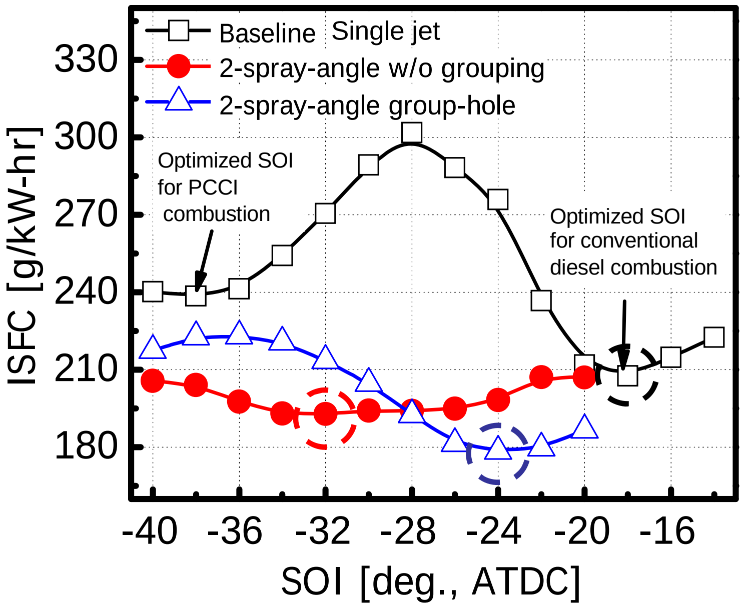


Approach: 2-Spray angle, group-hole nozzle explored - Combine bowl spray with squish spray for improved mixing for near-homogeneous HCCI-like combustion/improved access to oxygen

Accomplishments: Grid-independent spray model developed for standard and group-hole nozzles – SAE 2008-01-0970

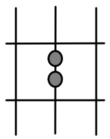
2-Spray angle gives improved fuel preparation

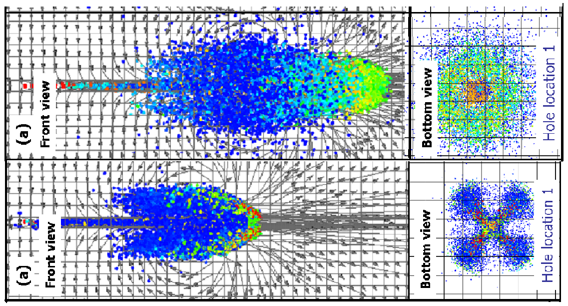
Plans for next year: Use Genetic Algorithm to optimize spray parameters over range of speed/loads.



Group-hole nozzle sprays

Improved spray model





Standard KIVA

Task 3: Application of detailed models for Optimization of LTC-D: 3.3 LES Studies of Early Injection and VVA

Improve understanding of early injection and variable valve actuation on LTC efficiency and emissions

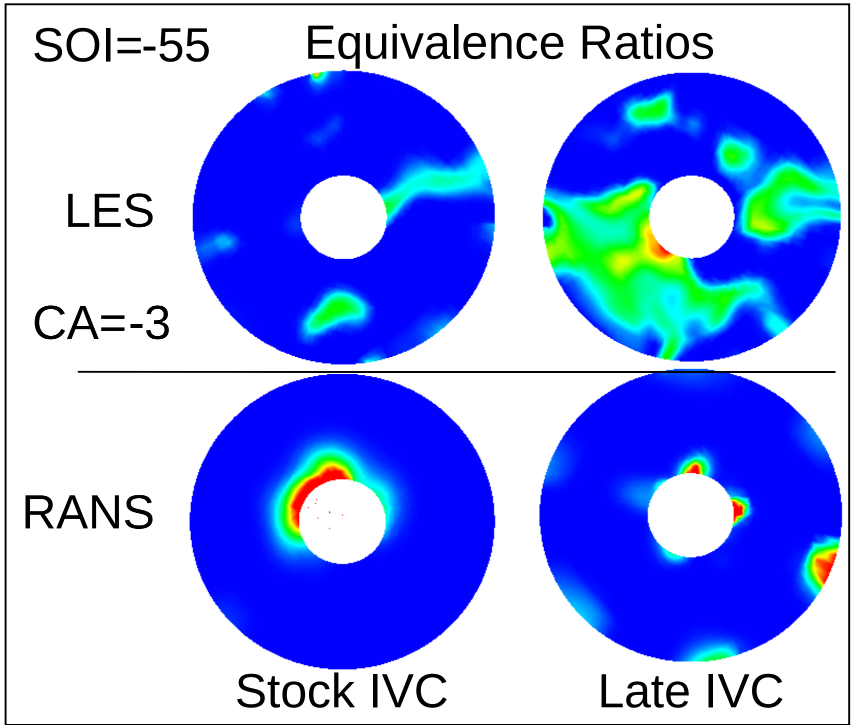
Approach: Develop and use advanced LES turbulence, mixing, and combustion models in validated engine CFD

Accomplishments:
- Grid resolution studies of sprays
- Implemented and tested LES flamelet combustion model
- Successfully simulated changes in emissions due to IVC changes

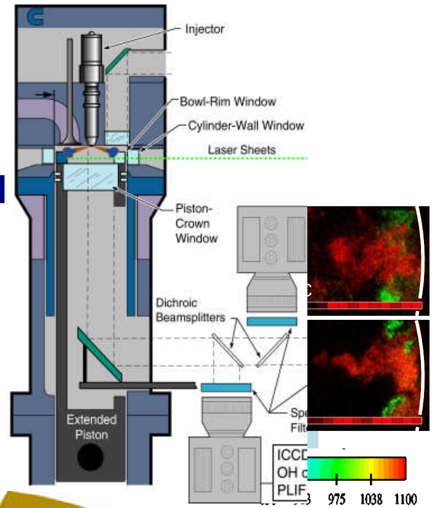
Plans for Next Year: Continue validation with experimental data and extend studies to higher load conditions and advanced injection

	NOx ratio	SOOT ratio
Exp.	0.4	2.0
LES	0.9	1.8
RANS	2.1	1.1

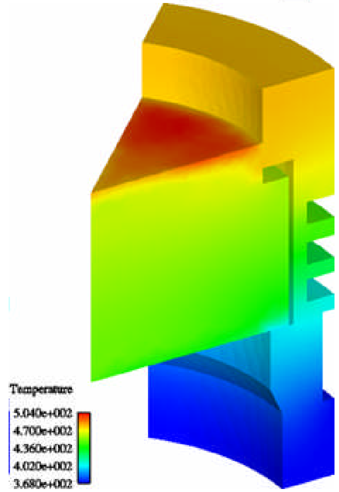
Emission: ratios of late IVC (275 CA) to stock IVC (217 CA)

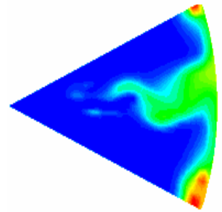


Task 4: Impact of heat transfer and spray impingement on LTC-D: 4.1 & 4.2 Thermal Analysis Modeling & Experiments



Thermal management critical for LTC control, especially for transient operation.
Project explores heat transfer effects on ignition timing, emissions, and heat release

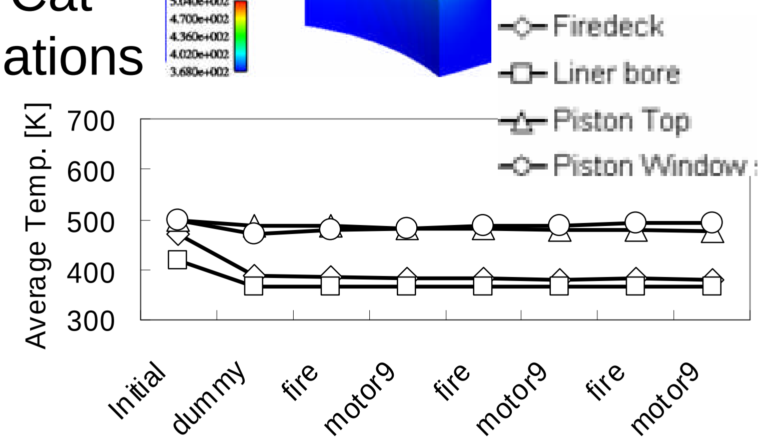




Approach: 1.) Use Sandia HD engine for model development 2.) Design and implement mechanical linkage or telemetry system for Caterpillar HD diesel engine to measure (piston) heat flux and temperature

Accomplishments: Sandia engine temperature field characterized. Position of heat flux sensors on Cat piston and head selected with KIVA-HCC simulations Mechanical linkage system under test.

Plans for Next Year: Engine tests with instrumented piston. Investigate heat transfer mechanisms. Compare data with simulations. Modify operating conditions to isolate heat-transfer effects.



Average surface temperature history for Late injection w/ radiation

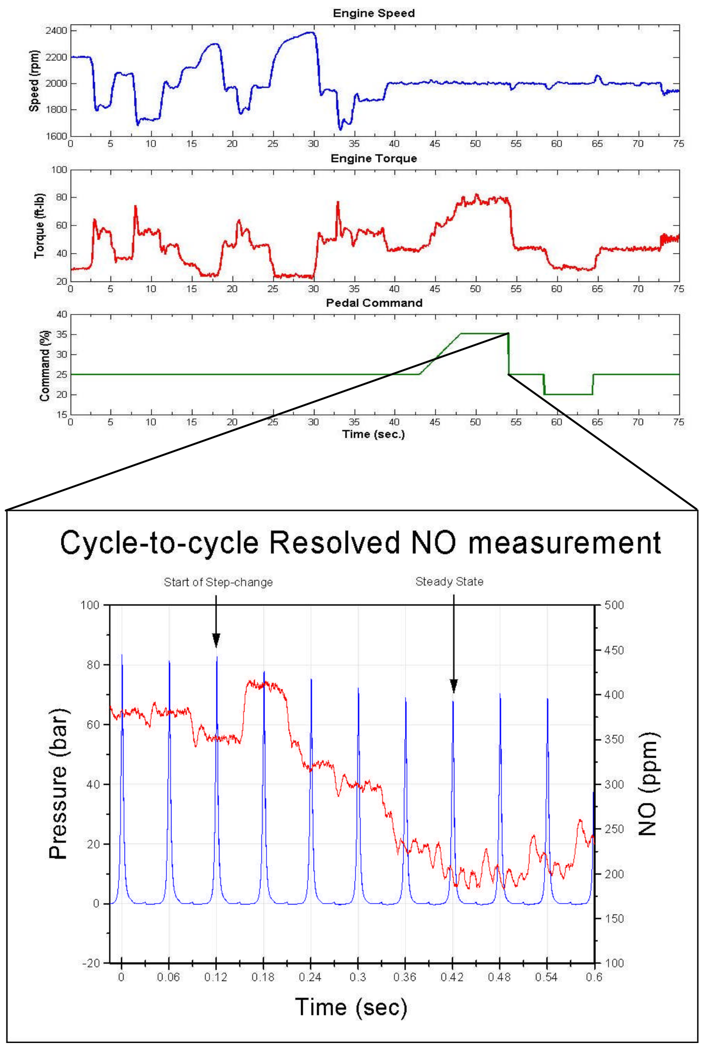
Task 5: Transient engine control with mixed-mode combustion: 5.1 & 5.2 Experiments and Modeling

Evaluate steady state and transient LTC operation to understand requirements for combustion phasing control

Approach: Use coordinated engine experiments and system simulations to study LTC load and mode transients

Accomplishments: Initiated testing program on transient multi-cylinder engine. Implemented and tested multi-cylinder system simulation with advanced combustion models; simulated potential operating conditions for DPF regeneration experiments; explored EGR and combustion phasing interactions.

Plans for Next Year: Use system model to study combustion control for near stoichiometric operation and high EGR. Investigate transient LTC-D and emissions



High Speed NO Measurement, 5 bar to 2.5 bar, 2000 RPM

5 Tasks integrated to develop methods to optimize and control LTC-D for fuel efficiency and low emissions

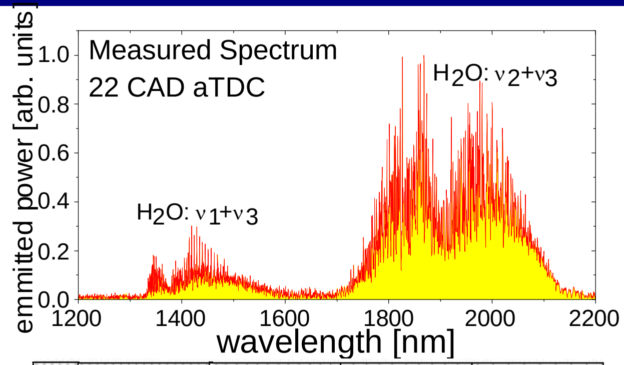
Approach: Use novel diagnostics, fuel-types, injection concepts, optimized piston geometry with advanced CFD models and coordinated engine experiments

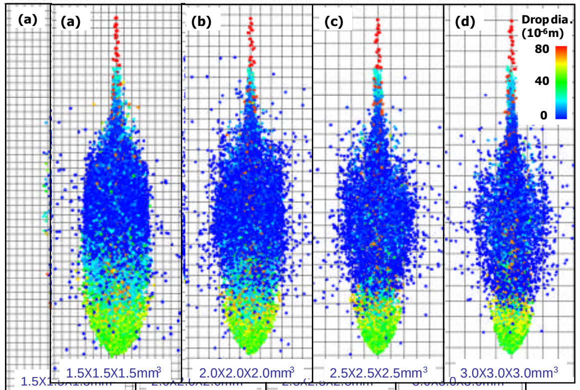
Accomplishments:

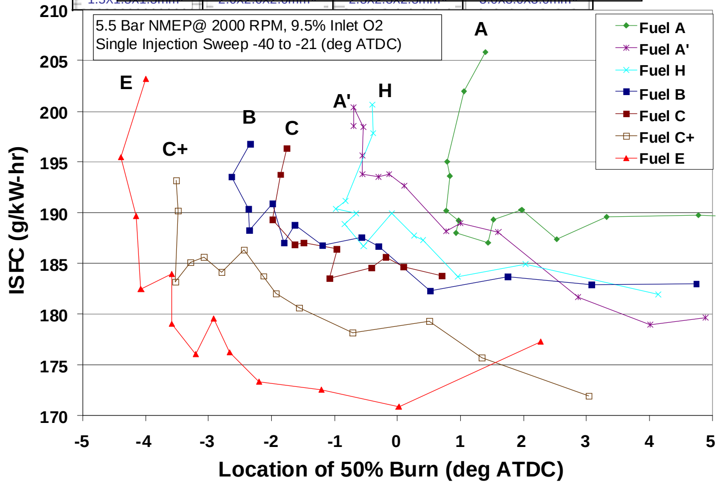
- In-cylinder FTIR species diagnostic developed
- Grid-independent spray model developed
- LES applied to identify low emissions operation
- Low emissions demonstrated with IVC control and Adaptive Injection System
- Improvement of CO, HC, and ISFC with increased cetane number and volatility in PCCI
- System model and transient dyno operational for load change/ mode transition exploration

Plans for Next Year: Explore methods to reduce emissions and increase fuel efficiency

- Further demonstrate LTC on HD and LD engines
- Optimize injection strategies, matched with piston
- Demonstrate and test transient control strategies







Tech. Transfer & Collaborations/Interactions

DOE LTC Consortium project DE-FC26-06NT42628

British Petroleum
General Motors CRL
DOE Sandia Labs
Caterpillar Inc.

Diesel Emissions Reduction Consortium (DERC) 24 member companies

Caterpillar Inc.;
CDadapco;
Chevron;
Corning Incorporated;
Cummins, Inc. Fleetguard Inc.;
DaimlerChrysler AG;
Delphi Corporation;
Detroit Diesel Corporation;
FEV Engine Technology;
Ford Motor Company;
GE Global Research;
GM R&D and Planning and Powertrain;
Hyundai Motor Company;
International Truck & Engine Corp.;
John Deere Company;
MotoTron;
Nippon Soken Inc.;
Nissan Motor Co.;
Oak Ridge National Laboratory;
PACCAR;
Renault;
Thomas Magnete USA, LLC.;
Toyota Technical Center USA;
Volvo Powertrain

Publications, Presentations, Patents

Patents

- Sun, Y., and Reitz, R.D., “Adaptive Injection Strategy (AIS) for Diesel Engines,” UW WARF Patent Application P07342US, May, 2007
- Sanders, S. T.,“Multiplexed-wavelength lasers based on dispersion mode-locking,” UW WARF Patent Application P07171, 5/15/2007.

Selected Publications

- Brakora, J.L., Ra, Y., Reitz, R.D., McFarlane, J., and Daw, S., "Development and Validation of a reduced Reaction Mechanism for Biodiesel-Fueled Engine Simulations," SAE 2008-01-1378, 2008.
- Shi, Y., and Reitz, R.D., "Assessment of Optimization Methodologies to Study the Effects of Bowl Geometry, Spray Targeting and Swirl Ratio for a Heavy-Duty Diesel Engine Operated at High Load," SAE 2008-01-0949, 2008.
- Shi, Y and Reitz, R. D., “Study of Engine Size-Scaling Relationships based on Turbulent and Chemistry Scales”, SAE 2008-01-0955, 2008
- Sun, Y., and Reitz, R.D., "Adaptive Injection Strategies (AIS) for Ultra-Low Emissions Diesel Engines," SAE 2008-01-0058, 2008.
- Tamagna, D., Gentili, R., Ra, Y., and Reitz, R.D., "Multidimensional Simulation of the Influence of Fuel Mixture Composition and Injection Timing in Gasoline-Diesel Dual-Fuel Applications," SAE 2008-01-0031, 2008.
- Abani, N., Kokjohn, L. S., S. W. Park, Bergin, M., Munnannur, A., Ning, W., Sun. Y., and Reitz, R.D., “An improved Spray Model for Reducing Numerical Parameters Dependencies in Diesel Engine CFD Simulations”, SAE 2008-01-0970, 2008.
- Ra, Y., Reitz, R.D., McFarlane, J., and Daw, S. "Effects of Fuel Physical Properties on Diesel Engine Combustion using Diesel and Bio-diesel Fuels," SAE 2008-01-1379, 2008.

Publications, Presentations, Patents

Publications (Cont.)

- “Investigation of Mixing and Temperature Effects on UHC/CO Emissions for Highly Dilute Low Temperature Combustion in a Light-Duty Diesel Engine”, Richard Opat, Youngchul Ra, Manuel Gonzalez, Roger Krieger, Rolf Reitz, David Foster – UW Madison, Russell Durrett and Robert Siewert – GM R&D Center, SAE 2007-01-0193
- Hu, Bing, Rahul Jhavar, Satbir Singh, Rolf D. Reitz, and C.J. Rutland, 2007, “LES Modeling of Diesel Combustion under Partially Premixed and Non-premixed Conditions,” SAE Paper 2007-01-0163, SAE International Congress, Detroit, MI April 2007.
- England, S.B., C.J. Rutland, and D.E. Foster, Yongsheng He, 2007, “Using an Integrated Diesel Engine, Emissions, and Exhaust Aftertreatment System Level Model to Simulate Diesel Particulate Filter Regenerations,” SAE Paper 2007-01-3970, SAE Fall Powertrain and Fluids Systems Conference, Chicago, IL, Oct. 2007.
- “Comprehensive Characterization of Particulate Emissions from Advanced Diesel Combustion” Dave Foster, CLEERS Workshop, May 2007, Dearborn, MI
- “Simulating Integrated Engine-Emissions-DOC-DPF Performance,” Chris Rutland, CLEERS Workshop, Invited presentation, May 1, 2007, Dearborn, MI
- “LES for IC Engine Simulations,” Chris Rutland, Mechanical Engineering Dept., University of Michigan, Invited presentation, Oct. 26, 2007, Ann Arbor, MI
- Petersen, B.R., Ghandhi, J.B. and Koch, J.D., "Fluorescence Saturation Measurements of 3-Pentanone," submitted to Applied Physics B.