Automotive HCCI Engine Research

Principal Investigator: Richard Steeper
Sandia National Laboratories

(Stanford University Sub-Project
Principal Investigator: Ron Hanson)

Program Manager: Gurpreet Singh
DOE Office of Vehicle Technologies

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Outline

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Purpose of Work

- Apply optical and other advanced diagnostics to improve our understanding of automotive HCCI combustion.
  - Clarify the in-cylinder processes of fuel mixing, combustion, and emission formation to help remove barriers to the implementation of clean, fuel-efficient HCCI combustion.
  - Conduct research to promote the evolution of low-temperature combustion (LTC) strategies such as negative valve overlap (NVO).
  - Develop and adapt optical diagnostics as needed to address unresolved technical issues.
- Interact with industry and other researchers to facilitate technology transfer.
  - Address industry- and DOE-identified research issues.
  - Enhance similarities between optical and prototype engines to improve the relevance of our experimental results.
- Contribute to the development of models that accurately simulate HCCI combustion.
  - Provide experimental data for model validation.
  - Apply available models to help guide and interpret experiments.

Barriers

- We address barriers detailed in OVT's *Roadmap for Light-Duty Powertrains*:
  - Mixture preparation:
    - "Inadequate fundamental understanding of the effects of fuel injection, air motion, and combustion chamber geometry on fuel-air mixing, combustion, and emission formation processes for LTC."
    - "Inadequate understanding of fuel injector parameters (timing, spray type, injection pressure, etc.)."
    - "HC and CO emissions and associated combustion inefficiencies occur at low loads, especially for pure HCCI combustion."
  - Ignition control:
    - "Methods using temperature to control ignition timing need to be investigated."
  - Model development:
    - "Inadequate ability to accurately simulate all these processes."
- We also address detailed barriers identified by our industry partners:
  - Inadequate understanding of the fuel-reformation process during NVO operation.
  - Uncertain relative importance of thermal and chemical effects of NVO on phasing.
  - Inadequate details of temperature/composition non-uniformities in HCCI engines.

Previous Review Comments

- "The modeling work is welcome and needs to continue in coordination with experimental work."
  - We have continued work with 3 models of the automotive HCCI engine this year.
- "Explain why LEM is used in this program."
  - Development of LEM is part of another project (J. Oefelein); We apply LEM to answer questions about turbulence and cycle-to-cycle variability in our engine.
- "Cam timing must be carefully selected or addressed parametrically."
  - We have addressed the issue of NVO cam timing experimentally and computationally.
- "More interaction with industry."
  - We interact primarily with the automotive sector. Our interactions with GM are extensive, and we are intent on increasing interactions with Ford and Chrysler.
- "Widen the scope to include a diesel fuel focus."
  - The Office of Vehicle Technology directs our project to focus on automotive gasoline engines.

Approach

- Apply LIF diagnostics to address automotive HCCI technical barriers:
  - Characterize the mixing of fuel, air, and EGR to understand the effect of mixture preparation and dilution on HCCI combustion.
  - Measure in-cylinder temperature distributions to clarify the influence of HCCI thermal stratification on combustion phasing and duration.
- Facilitate development of diagnostic tools needed to understand HCCI:
  - Direct a joint Stanford-Sandia project developing in-cylinder temperature diagnostics.
- Expand facility capabilities to maintain relevance of research:
  - Extend our experiments from ‘pure’ HCCI to NVO operation.
  - Plan engine upgrades for enhanced optical access and extended operating range.
- Employ modeling tools to guide HCCI experiments and understand results.
  - Employ a range of models from 1-D full-engine simulations to 3-D cylinder flow and combustion codes.

Accomplishments

1. Established NVO operation in optical engine.

2. Characterized NVO performance in optical engine.

3. Implemented two-wavelength PLIF diagnostic.

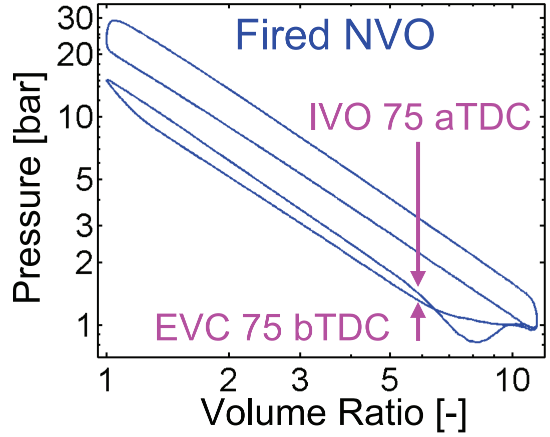
4. Applied optical engine models.

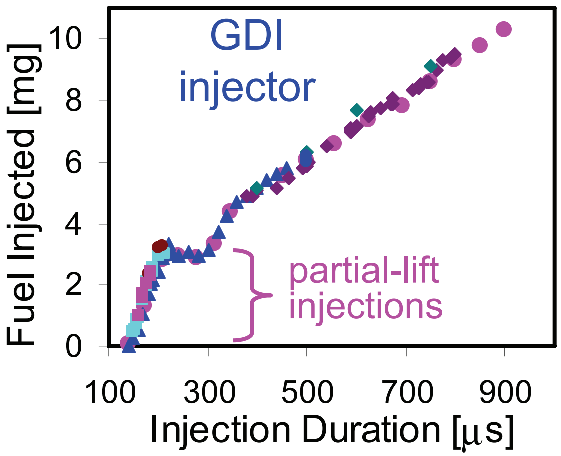
1. NVO Operation in Optical Engine

- Rigorous protocol developed for transition into NVO mode.
  - Background:
    - High residual fraction of NVO requires a transition strategy.
    - Optical engine requires fail-safe, rapid, clean preheat and transition.
    - Other approaches are not currently possible in our optical engine.
  - We developed a dual-fuel strategy using port-injected DME + direct-injected iso-octane for rapid preheat and transition to iso-octane-fueled NVO.
  - Method provides control of phasing and heat release during warm-up; It provides rapid, smooth transition to a range of target NVO operating conditions.
- Facility modified to enable safe NVO operation in optical engine.
  - We expanded our engine-control hardware to permit multiple, variable-duration injections of gaseous & liquid fuels.
  - We enhanced the safety system to monitor complex fuel-injection sequences and eliminate over-pressure events following misfires.

2. NVO Performance in Optical Engine

- Cam phasing optimized.
  - Background: valve lift and duration are fixed at industry-recommended values; valve timing is adjusted manually.
  - We determined the range of valve timings that permit NVO operation.
  - We identified an optimal timing that allows NVO operation over a wide range of loads.
- NVO performance benchmarked.
  - We conducted sweeps of several NVO parameters at the optimal valve timing: total fuel, fuel split between NVO & main injections, and fuel-injection timing.
- Fuel-injector performance characterized.
  - We mapped fuel delivery for NVO operating conditions.
  - Conventional GDI injectors are not well suited for the small, milligram-quantity injections required by NVO.





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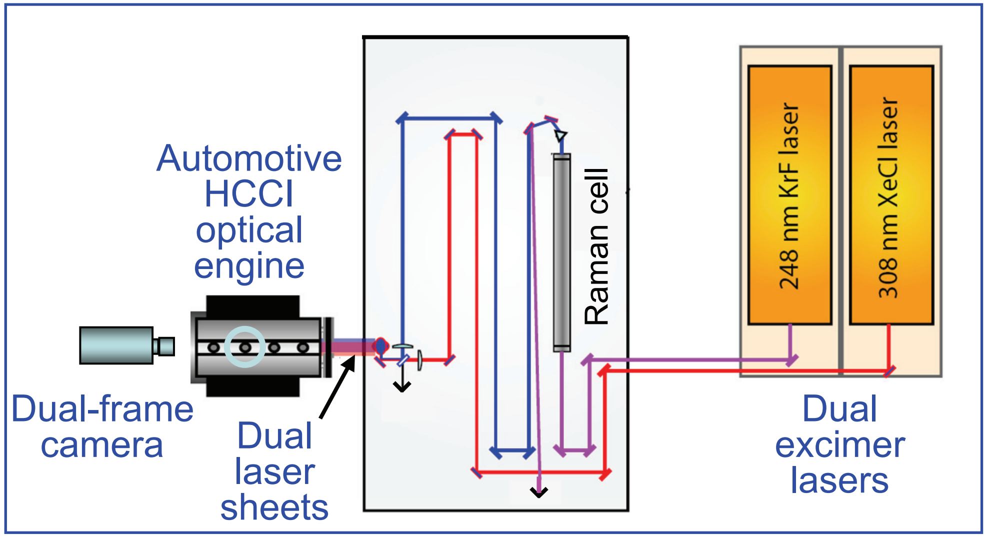
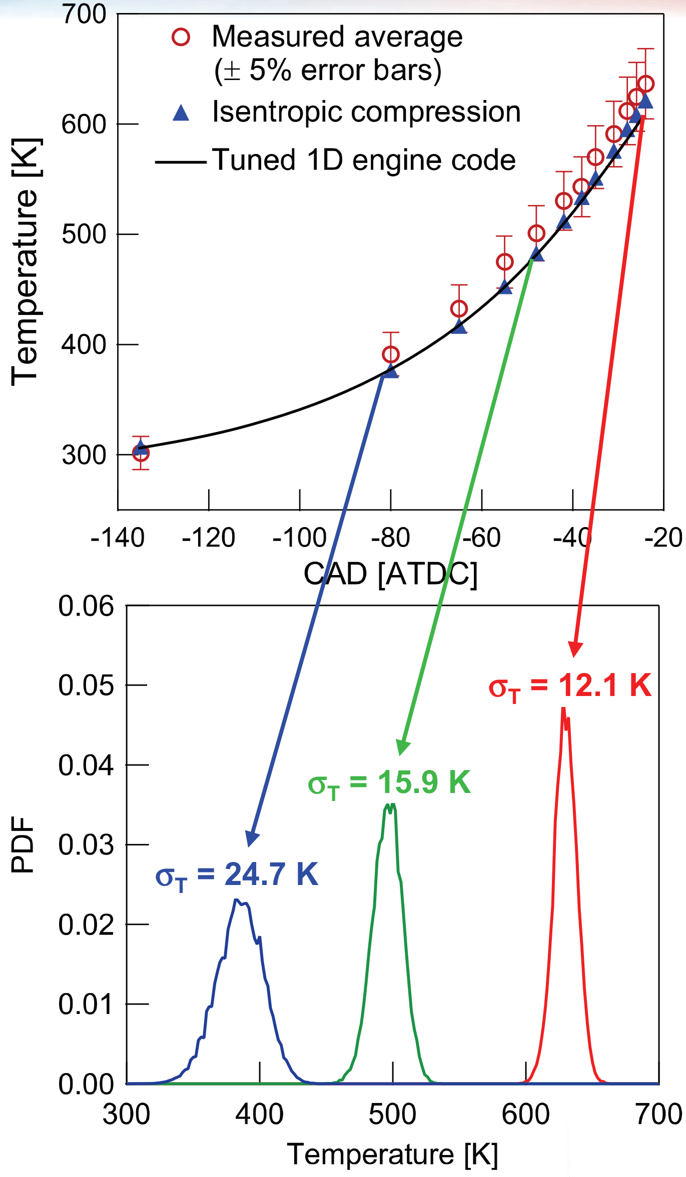
3. Two-Wavelength PLIF Diagnostic – Background

- Sub-project: Diagnostic developed at Stanford; tested and applied at Sandia.
  - Two-wavelength technique based on tracer LIF enables simultaneous, 2-D temperature and composition measurements in the engine.
  - The diagnostic provides sensitive measurements of in-cylinder mixture non-uniformities important for understanding HCCI combustion.
- Technical details and results are presented in three papers written this year.
  - The next few slides summarize our accomplishments…



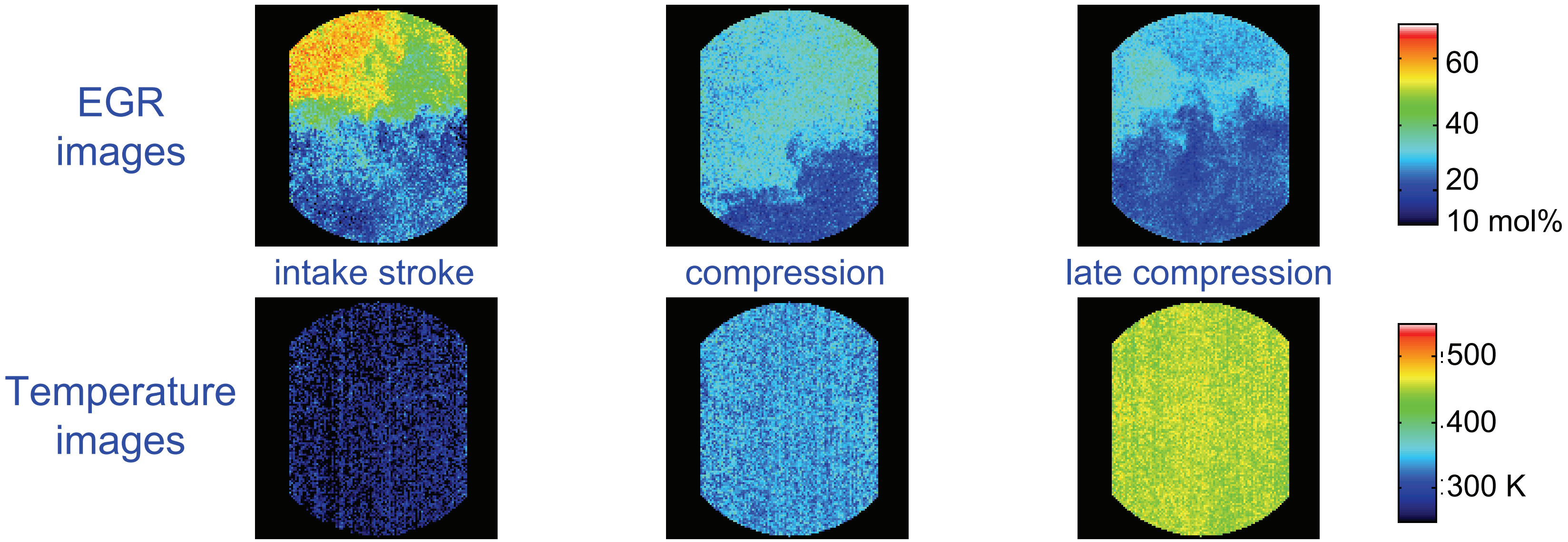
3. Two-Wavelength PLIF Diagnostic – Uncertainty

- We have characterized diagnostic uncertainty.
  - Data shown are ensemble-average values derived from images recorded during the motored compression stroke.
  - The accuracy of measured temperatures is better than 5%.
  - The estimated precision of single-shot temperatures is as low as 12 K late in the compression stroke.



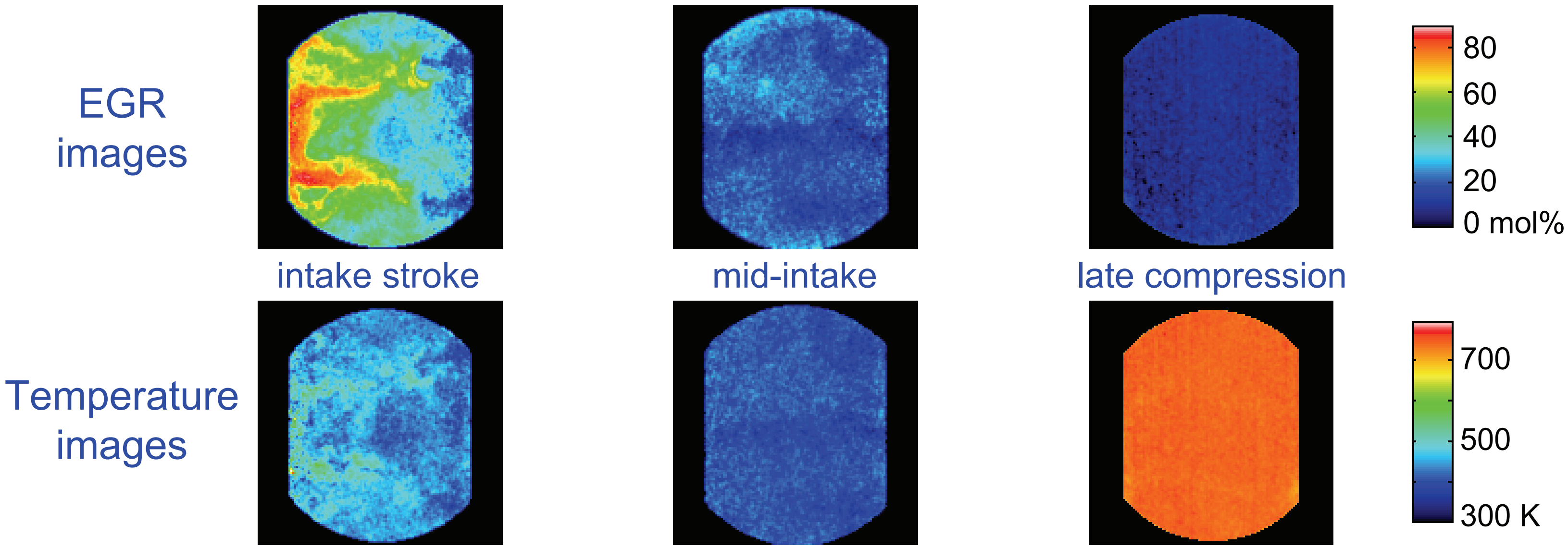
3. Two-Wavelength PLIF Diagnostic – Motored Operation

- We demonstrated simultaneous EGR/temperature measurements during motored operation.
  - EGR can be measured by seeding the air and fuel with tracer (1 – signal).
  - Simulated EGR was injected via one intake port; air at the same temperature in the other.
  - The sample image pairs illustrate the independence of the simultaneous measurements.



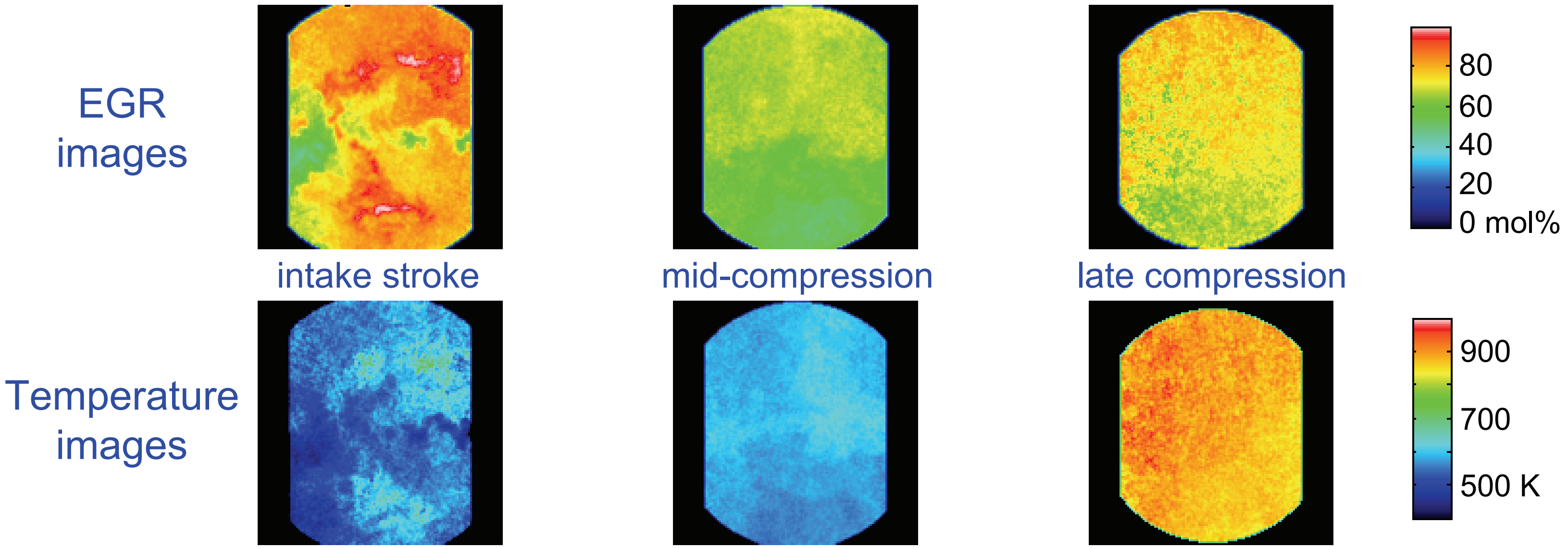
3. Two-Wavelength PLIF Diagnostic – HCCI Fired Operation

- We have performed measurements of fired HCCI operation.
  - At the start of intake, regions of high EGR are pushed to the exhaust side by incoming fresh charge. High EGR concentrations correspond to higher temperatures.
  - The experiments indicate that mixing is rapid for this low-EGR operating condition: the mixture is homogeneous by the start of combustion.



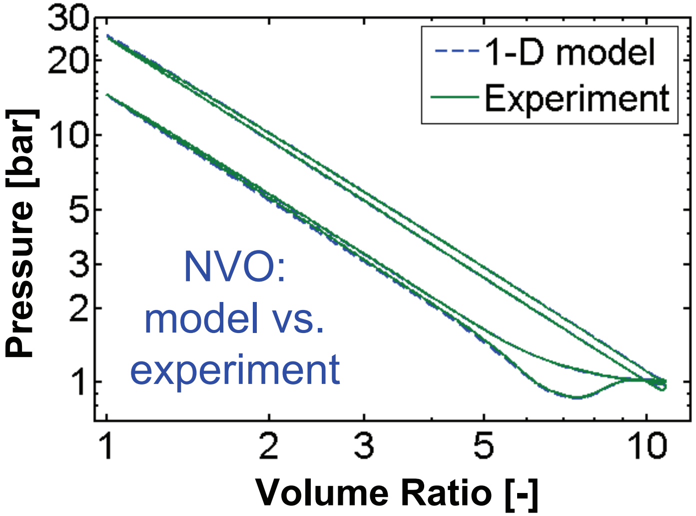
3. Two-Wavelength PLIF Diagnostic – NVO Fired Operation

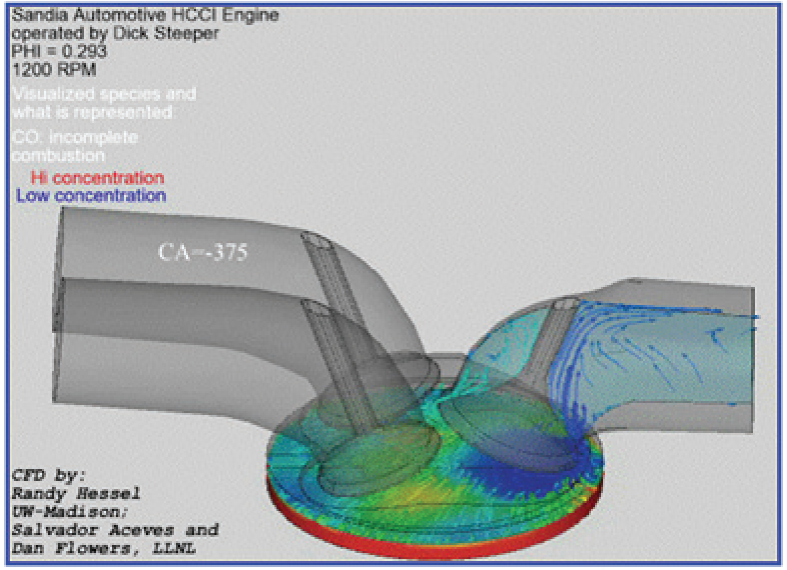
- We have begun measurements during fired NVO operation.
  - NVO operating mode is characterized by high EGR content and elevated temps.
  - Again, the images identify hot EGR regions and cold fuel-air regions.
  - The experiments indicate that fuel/air/EGR mixing is not complete by the end of compression – this may be a significant detail when analyzing NVO combustion.



4. Optical Engine Models

- We continued development and application of our 1-D engine model.
  - Useful for optimizing and characterizing our HCCI/NVO operating parameters.
  - Current work: incorporating NVO heat release.
- We continued collaboration with UW and LLNL on CFD/kinetics model of our engine.
  - Results provide insights that complement our experimental measurements.
  - A paper describing model was written this year.
- We continued internal collaboration applying LEM turbulence model in HCCI engine.
  - The model provides insights into the effect of fuel-mixture coarseness on HCCI combustion.
  - A paper was published this year describing the project.
  - Currently discussing use of the model by GM.





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Technology Transfer

- Biannual DOE Advanced Engine Combustion meetings:
  - Research reports presented to 15 vehicle- and petroleum-industry partners.
- Interaction with automotive OEMs:
  - We maintain an extensive collaboration with GM:
    - Our optical engine incorporates parts and dimensions provided by GM.
    - Bi-monthly conferences facilitate transfer of technical results and ensure that our research addresses industry needs.
  - We will explore increased interactions with Ford and Chrysler.
- Collaboration with national labs and academia:
  - Our joint project with Stanford has advanced two technologies for in-cylinder temperature measurements. The diagnostics are already adopted by some OEMs.
  - Our collaboration with UW and LLNL has resulted in a detailed 3-D model to help understand HCCI combustion.
  - Technology transfer also occurs within Sandia: we currently interact with modelers from the reacting flow department, and with a team testing fiber-laser spark ignition.

Future Activities

- NVO operation:
  - Understand the effect of NVO fuel-injection quantity and timing on overall combustion and emissions.
  - Characterize the extent and effect of non-uniformities in temperature and EGR for NVO operation.
- Modeling:
  - Apply UW/LLNL 3-D model to characterize the reformation process during NVO recompression.
  - Advance LEM engine simulation through collaboration with GM and through validation experiments.
- Hardware upgrade:
  - Plan installation of a modern optical engine head in common with new GDI Future Fuels lab at Sandia.
- Diagnostics:
  - Continue the application of Stanford diagnostics for HCCI and NVO operation.
  - Identify diagnostics for measuring the extent of reformation reactions during NVO recompression.

Summary

- Approach: Our project applies advanced diagnostics in an optical HCCI engine to address technical barriers to the implementation of fuel-efficient, clean gasoline engines.
- Accomplishments:
  - Implemented NVO operation in the optical engine.
  - Optimized and benchmarked NVO operation.
  - Measured simultaneous EGR/temperature distributions using the two-wavelength PLIF diagnostic during fired HCCI and NVO operation.
  - Collaborated with several partners to advance our automotive HCCI models.
- Tech Transfer: Our research is guided by continual feedback from the automotive industry, and our technical results are communicated to them and to our collaborative partners.
- Future Work: Next year we will focus on NVO technical issues identified by industry, applying both experimental and modeling tools. We will identify additional diagnostics required for this work, and we will plan future hardware upgrades that improve our relevancy to current prototype engines.

Publications and Presentations

- Publications:
  - R. R. Steeper, V. Sankaran, J. C. Oefelein, and R. P. Hessel, “Simulation of the Effect of Spatial Fuel Distribution Using a Linear-Eddy Model,” SAE Paper 07FFL-186, 2007.
  - D. A. Rothamer, J. Snyder, R. K. Hanson, and R. R. Steeper, “Optimized Two-Line Tracer PLIF Measurements of Temperature and Composition in an IC Engine,” Fall Meeting of the Western States Section of the Combustion Institute, Sandia, October 2007.
  - R. P. Hessel, D. E. Foster, S. M. Aceves, D. L. Flowers, W. Pitz, and R. R. Steeper, “Pathline Analysis of Full-cycle Four-stroke HCCI Engine Combustion Using CFD and Multi-zone Modeling,” SAE Paper 08PFL-853, submitted January, 2008.
  - D. A. Rothamer, J. Snyder, R. R. Steeper, and R. K. Hanson, “Two-Wavelength PLIF Diagnostic for Temperature and Composition,” SAE Paper 08PFL-726, submitted January 2008.
  - D. A. Rothamer, J. A. Snyder, R. K. Hanson, R. R. Steeper, and R. P. Fitzgerald, “Simultaneous Imaging of Exhaust Gas Residuals and Temperature During HCCI Combustion,” Proceedings of the Combustion Institute, submitted January 2008.
- Presentations
  - June 2007: DOE Office of Vehicle Technologies Peer Review Meeting, Washington, D.C.
  - October 2007: DOE Advanced Combustion Engine Working Group Meeting, USCAR, Detroit.
  - October 2007: Fall Meeting of the Western States Section of the Combustion Institute, Sandia.
  - October 2007: SAE Powertrain, Fuels, and Lubes Meeting, Chicago.