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May 11th, 2010

DOE Project DE-EE0000203

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Overview

• TIMELINE
  – Start - Oct 2009
  – Finish – Dec 2012
  – 50% completed

• BARRIERS ADDRESSED
  – Improved fuel economy in light duty gasoline engines
  – Fundamental knowledge of advanced engine combustion

• BUDGET
  – Total project funding - $3,000k
  – Rec’d FY10 - $1,000k
  – Rec’d FY11 - $500k

• PARTNERS
  – Universities – UCB, MIT
  – Collaborations – SNL, LLNL, ORNL, ANL
  – Industrial – GM, Conoco-Phillips, BP, Ford
Objectives and Relevance

DOE VTP Technical Target:
- Demonstrate path to achieve 45% peak engine efficiency with 25 - 40% potential vehicle fuel economy (FE) gain

Project Objectives:
- Explore advanced dilute, high pressure combustion modes and fuel properties as enablers to achieve FE targets
  - Develop analytical link between engine combustion results and potential in-vehicle FE gains
  - Investigate benefits of stratification
  - Explore multi-mode combustion: Spark Assisted Compression Ignition (SACI), and Microwave Assisted Spark Plug (MWASP)
  - Determine potential of novel fuel properties for improved FE

* GT=Power simulation includes: heat transfer, friction, CR = 12, and constant B10-90 = 25 °, CA50 = 10 °ATC
Approach

• Task 1: System and FE analysis tools
  – Establish link between advanced combustion modes and potential vehicle FE gains with GT-power and Matlab simulations (UM)

• Task 2: Stratification as a means to control combustion
  – Carry out experiments in RCM and gasoline fueled boosted diesel (MIT)
  – Apply numerical modeling to study turbulent autoignition modes (UM)

• Task 3: Multi-mode combustion
  – Conduct engine experiments on SACI in FFVA DI engine (UM)
  – Use CFR engine to test combustion limits with MWASP (UCB)
  – RCM and Optical Engine experiments on SACI (UM)
  – Use 1-D modeling of laminar flames in high preheat, high dilution mixtures to develop correlations for multi-dimensional models
  – Develop CFD model of SACI with KIVA (UM)

• Task 4: Fuel properties for optimum FE
  – Explore low octane and other gasoline based fuels in FFVA engine (UM)
  – Gather fundamental ignition and kinetic data for alternate fuels in RCF (UM)
Consortium Experimental Facilities

UM optical engine (SACI and fuels)

UM diesel engine (fuels)

UM camless FFVA engine (multi-mode combustion)

MIT rapid compression machine (fuel ignition)

UCB CFR engine (MWASP)

MIT boosted Diesel (stratification)

UM RCF (ign. chemistry)
Technical Accomplishments (highlights)

• Task 1: System and FE analysis tools
  – Thermodynamic analysis shows engine efficiency benefits of HPLB (UM)
  – Vehicle FE framework shows potential vehicle-level gains with HPLB strategy (UM)

• Task 2: Stratification as a means to control combustion
  – Stratification moderates heat release rate for gasoline HCCI (MIT)
  – Identified combustion modes with thermal stratification using DNS tools (UM)

• Task 3: Multi-mode combustion
  – SACI extends high load limit in fully flexible valve actuation (FFVA) engine (UM)
  – Microwave-Assisted Spark Plug (MWASP) extends lean limit (UCB)
  – Developed laminar flame speed (SL) correlations for SACI conditions (UM)
  – Developed CFD model of SACI using new laminar flame speed correlations (UM)

• Task 4: Fuel properties for optimum FE
  – Low octane fuel extends HCCI high load limit in FFVA engine (UM)
  – New RCF data obtained on the ignition characteristics of n-butanol (UM)
Task 1: Thermodynamic Analysis Shows Engine Efficiency Benefits of HPLB (UM)

- **Objective:** Determine thermodynamic conditions for best FE
- **Approach:** Use GT-Power model with ideal T/C and fixed burn duration
- **Results:**
  - Optimal boosting strategy increases fuel-to-charge equiv. ratio ($\Phi'$) as boost is increased
  - Best overall engine efficiency occurs under highly dilute, high pressure conditions, i.e. advanced combustion
  - Peak brake engine efficiency ~ 42%
  - BSNOx < 0.26 g/kWh up to 18 bar BMEP
- **Future Work:**
  - Refine analysis with realistic combustion and T/C constraints; apply simple aftertreatment constraints ($T_{EX}$) for HC, CO emissions
  - Link FE projections to experimental data in Tasks 2, 3, and 4.
Task 1: Low NOx Emissions Are Achievable with Optimum Boosting Strategy

• Optimum boosting strategy and T/C efficiency of 50% result in BSNOx < 0.26 g/kWh
  – Up to 18 bar BMEP (Air dilution)
  – Up to 25 bar BMEP (EGR dilution)
  – Peak $\eta_{\text{brake}} \sim 42\%$
Task 1: Vehicle FE Framework Shows Vehicle Level Gains with HPLB Strategy (UM)

- **Objective:** Provide projection of vehicle FE gains achievable with advanced combustion
- **Approach:** combine GT-Power generated BSFC maps of 3 ideal engine strategies (previous slide) with Matlab drive cycle simulation
- **Results:**
  - 1→2 dilution (N. A.) ~ 25% gain (assumes optimum combustion at all points, and 100% comb. Efficiency)
  - 2→3 dilution + boosting + downsize ~ 50% gain (assumes T/C eff = 50%)
- **Future Work:**
  - Include more realistic combustion characteristics and constraints

* Circled numbers refer to engine combustion strategies on earlier slide
Task 2: Stratification Moderates Heat Release Rate for Gasoline HCCI (MIT)

- **Objective:** investigate benefits of interaction between gasoline fuel properties and stratification

- **Approach:**
  - Obtain fuel ignition data in RCM
  - Vary injection characteristics in boosted diesel engine to vary stratification

- **Results:**
  - Correlation developed for $\tau_{\text{IGN}}$ in RCM
  - In engine, late injection ($90^\circ$ ABDC) is effective in setting up stratification by moderating heat release rate

- **Future work:**
  - Connect RCM results with engine data
  - Vary fuel properties

![Graph showing correlation between temperature and knock index](image)

- Later injection
- Incr. Stratification

![Additional graph showing effect of dilution on knock index](image)
Task 2: Identified Combustion Modes with Thermal Stratification Using DNS Tools (UM)

- **Objective**: characterize ignition regimes in thermally stratified HCCI combustion
- **Approach**: Use Computational Singular Perturbation (CSP) analysis of timescales in a reacting flow field to determine Importance Index
  \[ I^T = \left| I^T_{(T-\text{Diffusion})_{\text{slow}}} \right| + \left| I^T_{(T-\text{Convection})_{\text{slow}}} \right| \]
  (Shows relative importance of deflagration / flame vs. autoignition)
- **Results**: Turbulent stratified combustion invokes multiple reaction modes
- **Future work**: Application of method to higher hydrocarbon fuels, Compositional stratification

In Collaboration With Mauro Valorani, University of Rome, La Sapienza

\[ M = 1 \] contour in black [denotes active reaction zone]

\[ H: \text{Homogeneous kernel}, F: \text{Front} \]
\[ S: \text{Spontaneous Ignition}, D: \text{Deflagration} \]
**Objective:** demonstrate load extension with spark assist

**Approach:**
- Increase load by adding fuel and reducing trapped residual gas (NVO) with $\Phi = 1$ (increase fuel-to-charge $\Phi'$)
- Control phasing with spark timing

**Results:**
- Heat release rate moderated by SACI
- Maximum load increased to 7.3 bar
- Encountered SI knock at highest loads

**Future Work:**
- Explore variations in proportion of flame vs. autoignition heat release.
- Extend work to higher pressures (cell upgrade in progress to provide boost)

Task 3: Microwave-Assisted Spark Plug (MWASP) Extends Lean Limit (UCB)

- **Objective:** Evaluate the potential benefits of MWASP for advanced combustion modes
- **Approach:**
  - Use CFR engine (CR = 7, 9) to test ignition under lean limit conditions
  - Model ignition with simplified methane kinetics and electron gas dynamics
- **Results:**
  - Lean limit extension observed
  - Modeling suggests benefit may decrease at higher pressures
- **Future Work:**
  - Extend experiments into SACI range (higher CR, leaner, and more preheat)

Task 3: Developed Laminar Flame Speed \( (S_L) \) Correlations for SACI Conditions (UM)

- **Objective**: Understand fundamental flame behavior and properties for highly preheated, highly dilute mixtures

- **Approach**:
  - Use transient flame code HCT to build dataset of flame properties in SACI regime where experimental data is limited
  - Build mathematical correlations for use in turbulent combustion models

- **Results**:
  - Viable flames predicted in regions where SACI observed
  - Correlations made for AIR and EGR dilute flames

- **Future Work**:
  - Validate vs. images from optical engine and in RCF

\[
S_L = \left(1 - D_2 Y_{EGR} \Phi \right) \frac{P_1}{T^m} F Y_{f,u} \exp \left(-G/T^0 \right) \left( \frac{T_u}{T^0} \right) \left( \frac{T_b - T^0}{T_b - T_u} \right)^n
\]

Form of correlation shows Air and EGR dependence

Task 3: Developed CFD Model of SACI Using New Laminar Flame Speed Correlations (UM)

- **Objective**: develop CFD model of SACI and use to explore possible benefits
- **Approach**: combine laminar flame speed correlations with models of coherent flamelet and multizone autoignition (CFMZ model)
- **Results**:
  - Model compares well with images obtained in UM optical engine
  - Good qualitative agreement with heat release curves in metal engine
- **Future work**:
  - Perform parametric studies on variables affecting heat release partition between flame and autoignition and sensitivity to spark timing
  - Validate limits vs. metal engine data

Task 4: Low Octane Fuel Extends HCCI High Load Limit in FFVA Engine (UM)

**Objective:** Explore ways to use fuel properties to increase HCCI load limit

**Approach:**
- Use NVO in FFVA engine to provide control over combustion phasing
- Inlet temperature = 45°C
- Initially compare gasoline vs. a low octane surrogate NH40 (40% n-heptane in gasoline)

**Results:**
- NH40 had higher load limit possibly because it had faster 10-90 burn duration and could be retarded more without instability

**Future Work:**
- Expand range of test fuels
- Explore benefit of spark assist
Task 4: New RCF Data Obtained on the Ignition Characteristics of n-butanol (UM)

- **Objective:** Investigate ignition of alternative fuels such as n-butanol as a possible infrastructure compatible fuel and blending component for bio-fuels

- **Approach:**
  - RCF provides ignition delay data
  - Sampling system gives intermediate species data
  - Both data are necessary to quantify the impact on fuel reactivity and exhaust emissions

- **Results:**
  - Measured ignition delays are in excellent agreement with Black et al. model
  - RCF speciation data identify weaknesses in reaction pathways important for predicting and mitigating emissions

- **Future work:**
  - Study fuel blends using RCF and optical engine
Future Work FY11-12

• Task 1: System and FE analysis tools
  – Refine analysis of optimum combustion strategy with realistic combustion constraints and turbocharger characteristics. Apply simple $T_{ex}$ constraint for CO, HC aftertreatment. Explore tradeoff between CR and T/C efficiency.
  – Link FE projections to experimental data from Tasks 2, 3, and 4.

• Task 2: Stratification as a means to control combustion
  – Connect RCM ignition results with engine timing data; vary fuel properties
  – Apply Computational Singular Perturbation (CSP) method to higher hydrocarbon fuels and compositional stratification

• Task 3: Multi-mode combustion
  – Explore variations in partition of flame vs. autoignition heat release in SACI in FFVA engine
  – Extend FFVA SACI work to higher pressures (cell upgrade in progress to provide boost)
  – Extend MWASP experiments into SACI range (higher CR, leaner, and more preheat)
  – Compare flame front model results vs. experimental images in optical engine and RCF
  – Use CFMZ model of SACI to investigate variables affecting details of heat release; sensitivity to spark timing; and nature of limits by comparison to metal engine data.

• Task 4: Fuel properties for optimum FE
  – Expand range of test fuels, and include spark assist in testing
  – Carry out RCF studies of ignition properties of fuel blends
Collaborations and Coordination

- Working on boosted single cylinder HCCI studies with GM
- Working with Microwave Enhanced Ignition device supplied by Yuji Ikeda, Imagineering, Inc., Japan
- Collaborating on SACI and combustion stability with Robert Wagner (ORNL)
- Supplied engine maps for HCCI to Argonne National Labs
- Currently working with Ford on the next steps towards changing our optical engine to direct injection.
- Working with Chevron on enhancing the effectiveness of stratification on controlling LTC heat release with fuel (MIT)
- Studying sensitivity of spark-assisted HCCI engines to range of market fuels; with BP and Ford (MIT)
- Working with Jacqueline Chen (Sandia National Laboratories), Ramanan Sankaran (ORNL), Mauro Valorani (University of Rome, La Sapienza), Chris Rutland (UWisc) on mixing effects on HCCI combustion.
- Collaborated with C. K. Westbrook and Bill Pitz (LLNL) on validating reaction mechanisms for long chain alkanes, small esters – now working on alcohols
- Working with Marco Mehl (LLNL) to apply new surrogate fuel kinetics to engine models
Summary

**Task 1: System and FE analysis tools**
- Thermodynamic analysis confirms HPLB strategy; BTE of 42% with BSNOx < 0.26 g/kWh
- System framework developed for vehicle FE assessment: demonstrated potential vehicle level impact of boosted dilute strategies

**Task 2: Stratification as a means to control combustion**
- Initial experiments carried out with stratified gasoline fueled diesel engine show stratification moderates heat release rate
- DNS simulation showed multiple combustion/ignition modes in thermally stratified mixture ranging from spontaneous ignition to deflagration front

**Task 3: Multi-mode combustion**
- SACI extends high load limit in naturally aspirated FFVA engine
- MWASP ignition extends lean limit under NA conditions with potential gains for LTC combustion
- Laminar flame correlations developed for high dilution / high preheat conditions
- CFD model of SACI developed; good qualitative agreement with optical engine images

**Task 4: Fuel properties for optimum FE**
- Studies of low octane gasoline fuel shows potential for higher load operation in FFVA (NVO enabled) HCCI operation
- Initial studies on ignition of n-butanol carried out in RCF; speciation results show need for improvements to kinetic models