Next-Generation Ultra Lean Burn Powertrain

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Project ID: ACE087
Overview

Project Outline

Timeline
Start Date: February 1, 2012
End Date: January 31, 2015
Percent Complete: 33%

Project Goals/ACE Barriers Addressed

- 45% thermal efficiency on a light duty SI engine with emissions comparable to or below existing SI engines (A, B, C, D, F)
- 30% predicted drive cycle fuel economy improvement over comparable gasoline engine vehicle (A, C, H)
- Cost effective system requiring minimal modification to existing hardware (G)

Budget
Contract Value (80/20): $3,172,779
  - Gov’t Share: $2,499,993
  - MPT Share: $672,796
Obligated Amount: $1,620,307
Total Expensed CY2012: $515,472

Partners & Subcontractors

- Ford: Test engine platform
- DELPHI: Custom injector design and development
- WERC: CFD analysis
Relevance

Background

- Demand for highly efficient and clean engines
  - Lean operation increases efficiency but may result in higher NO\textsubscript{x}
  - Ultra lean operation (\(\lambda>2\)) has been shown to increase efficiency and reduce NO\textsubscript{x} due to low cylinder temperatures

- Turbulent Jet Ignition (TJI) offers distributed ignition from jet formation enabling ultra lean operation
  - Low NO\textsubscript{x} at part loads
  - Increased knock resistance at high loads
  - Minimal modifications to existing hardware

- Enabling Technologies
  - TJI + Boosting
Relevance

TJI Intent

- Knock resistance allows TJI to operate in the WOT high load area of the map ($\lambda=1$)
- Intent is to use TJI to increase the lean WOT part load area of the map in an effort to increase overall drive cycle fuel economy
- TJI capable of running fully premixed at $\lambda=1$

From Attard et al., SAE Int. J. Engines, Vol. 5, Issue 2 (May 2012)
Objectives/ACE Barriers

- **Objectives:**
  - Utilize TJI to achieve stated project goals
  - Increase understanding of TJI performance sensitivity to hardware and operating conditions
    - Physical testing
    - 1-D, 3-D simulation and analysis

- **Barriers Addressed:**
  - (A) Provides fundamental understanding of an advanced combustion technology
  - (B) Emissions reductions may enable reduced cost emissions controls
  - (C) Develop tools for modeling advanced combustion technology
  - (F) Produce emissions data on an advanced combustion engine
  - (G) Prioritize low cost and ease of integration
  - (H) Provide comparable levels of performance to existing SI engines
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<tr>
<th>Milestones</th>
<th>Completion Date</th>
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<td>BP1</td>
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<tr>
<td>Milestone 1 – Phase 1 Design Work Complete</td>
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<td>Milestone 2 – Component Procurement Complete</td>
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<td>Milestone 3 – Single-cylinder Engine Testing Complete</td>
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<td>Milestone 4 – Phase 1 Research Completion</td>
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<td>Milestone 5 – Boosted Single Cylinder Engine Shakedown Complete</td>
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<td>Milestone 6 – Boosted Single Cylinder Engine Optimization and Vehicle Fuel Economy Prediction Complete</td>
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<td>Milestone 7 – Phase 2 Complete</td>
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<td>Milestone 8 – Boosted Multi-Cylinder Engine Build and Shakedown Complete</td>
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<td>Milestone 9 – Boosted Engine Optimization and Vehicle Fuel Economy Prediction Complete</td>
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<td>Milestone 10 – Project Complete</td>
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Phase 1 Approach

- **Optical Engine Testing**
  - Jet velocity as a function of TJI hardware

- **Single Cylinder Thermo Engine Testing**
  - Efficiency/emissions as functions of jet velocity

- **1-D and 3-D simulations**
  - Validation of experiments, helps drive design optimization

**Phase 1**

*TJI design optimization*
Phases 2 and 3 Approaches

**Phase 2**
- **Boosted Single Cylinder Thermo Engine Testing**
  - Fuel injection timing/quantity and spark timing sweeps
- **1-D and 3-D simulations**
  - Validation of experiments

**Phase 3**
- **Boosted Multi-Cylinder Thermo Engine Testing**
  - Mini-map generation provides input to 1-D simulation
- **1-D simulations**
  - Predict TJI vehicle drive cycle fuel economy improvement

**Approach**

Phase 2 and 3 Approaches

**Phase 2**
- TJI design validation, operating parameterization

**Phase 3**
- Map generation and drive cycle simulation
Technical Accomplishments

Design and Build of a Single-Cylinder Optical Engine

- Single-cylinder optical engine successfully designed and assembled
- Purpose: determine pre-chamber design effects on jet velocity, jet penetration and jet variability

Custom cylinder head with TJI

Hydraulic assembly

Bottom end assembled using Ford 4-cylinder components

Optical combustion chamber

High speed camera

High speed spectrometer

Mirror at 45 degrees
Technical Accomplishments

Optical Engine Data

- Base TJI hardware with pre-chamber fuel injection
- Operating conditions
  - 1500 rpm, 3.5 bar IMEPg, $\lambda = 1.1$
- Color contours show light intensity and represent cylinder temperature
- Average jet velocity: $\sim 65$ m/s

Shown: Bottom-to-top view of cylinder
Technical Accomplishments

Optical Engine Data Analysis and Findings

- Findings:
  - Use of two hole fuel-injector aids jet velocity and reduces cyclic variability
  - Reducing pre-chamber volume increases jet velocity
  - Optimum nozzle hole number appears to be 6
  - Optimum hole diameters appears to be 1-1.2 mm
    - Smaller orifices inhibit gas exchange to the main chamber
    - Larger orifices lead to jet variability

- Goal: design a jet igniter that maximizes velocity and minimizes jet and cyclic variability

- Future work: identify the relationship between jet velocity/variability and engine performance parameters
Technical Accomplishments

Design and Build of a Single-Cylinder Engine

- Single-cylinder thermodynamic (metal) engine successfully designed and assembled
  - Cylinder head machined to accommodate the jet igniter assembly
  - Custom crankshaft offers balanced single cylinder operation

- Purpose:
  - Build the metal counterpart to the optical engine
  - Acquire accurate combustion, performance and emissions data
  - Identify relationship between jet characteristics and engine performance
  - Optimize pre-chamber design to achieve the efficiency target
Technical Accomplishments

CFD – Insight into Flame Propagation and Jet Formation

- Spark timing: 20 CAD bTDC
- Burning pre-chamber charge pushes gases into the main chamber
- Piston motion is still upward but expanding gases overwhelm compression action
- Flame front forming in the main chamber before entire pre-chamber charge has been consumed
- Jet variability directly linked to spark plug location in the pre-chamber
Plots show the magnitude of main chamber to pre-chamber gas exchange phases:

1 – Flow into the pre-chamber during compression
2 – Flow into the main-chamber during flame kernel development and pre-chamber burn
3 – Flow into the pre-chamber during main chamber burn
4 – Flow into the main-chamber during expansion

Premixed, \( \lambda = 1.2 \)
Technical Accomplishments

CFD – Temperature Field Visualization

Simulations performed using Converge CFD, at 1500 RPM, 2.62 bar BMEP, premixed charge, λ=1.2
Collaborations and Coordination

Collaborations

- **Ford Motor Company** – Project Partner
  - Donated engine hardware, offered operational advice on optical engine, will participate in data sharing

- **Delphi Corporation** – Project Subcontractor
  - Supplied pre-chamber fuel injectors and are conducting CFD analysis on fuel injection characteristics

- **Wisconsin Engine Research Consultants** – Project Subcontractor
  - May perform CFD-related tasks

- **Spectral Energies LLC** – Project Subcontractor
  - Acquired optical engine images, contributed to data post-processing
Future Work

Project Timeline

Phase 1
- July 2012: Design Work Complete
- Aug 2012: Procurement Complete

Phase 2
- Jan 2013: Single Cylinder NA Testing Complete
- Apr 2013: Boosted Single Cylinder Engine Build Complete

Phase 3
- Feb 2014: Phase 3 Start
- June 2014: Boosted Multi-Cylinder Engine Build Complete
- Nov 2014: Boosted Engine Optimization Complete
- Jan 2015: Project Complete

Timeline:
- 2012
- 2013
- 2014
- 2015

Design
- Single Cylinder Development and Validation
- Multi-Cylinder Development and Validation
Future Work

Upcoming Project Work

- **Phase I**: Concept Design/Analysis and Single Cylinder Engine Testing
  - Complete metal engine testing and analysis
  - Refine and expand CFD simulations

- **Phase II**: Boosted Single Cylinder Engine Testing
  - Identify and build optimal TJI design based on data consolidation
  - Validate optimal TJI design on the metal engine
  - Perform additional experiments that may be required
  - Utilize CFD to further analyze experimental results

- **Phase III**: Boosted Multi-Cylinder Engine Testing
  - Create a mini-map using boosted multi-cylinder engine with TJI as input to 1-D model
  - Use 1-D analysis to predict TJI vehicle drive cycle fuel economy improvement
Phase 1 Summary

- Phase 1 was dominated by design and build of the optical engines.

- Optical engine data provided insight into the effect of pre-chamber geometry on jet velocity and variability.

- Data from single cylinder thermo engine will be used to investigate the relationship between jet velocity and engine performance.

- By consolidating experimental and modeling results, MPT can design the TJI concept in order to approach the 45% efficiency, 30% fuel economy improvement targets.

*MPT would like to acknowledge DOE Office of Vehicle Technologies for funding this work.*
Technical Back-Up Slides
Technical Accomplishments

Optical Engine Data Analysis

- OH radical distribution from TJI into main chamber
- OH* results from combustion, exists briefly in products
- Relative emission intensity: 1.00

- CH radical distribution from TJI into main chamber
- CH* effectively describes the flame front, shorter lifespan than OH*
- Relative emission intensity: 1.17

- Several hardware configurations appear to effectively quench the flame from pre-chamber combustion