Next-Generation Ultra Lean Burn Powertrain

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MAHLE Powertrain, LLC

5/16/2013

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

Technology Enabler

Test engine platform

WERC

CFD analysis

DELPHI

Custom injector design and development

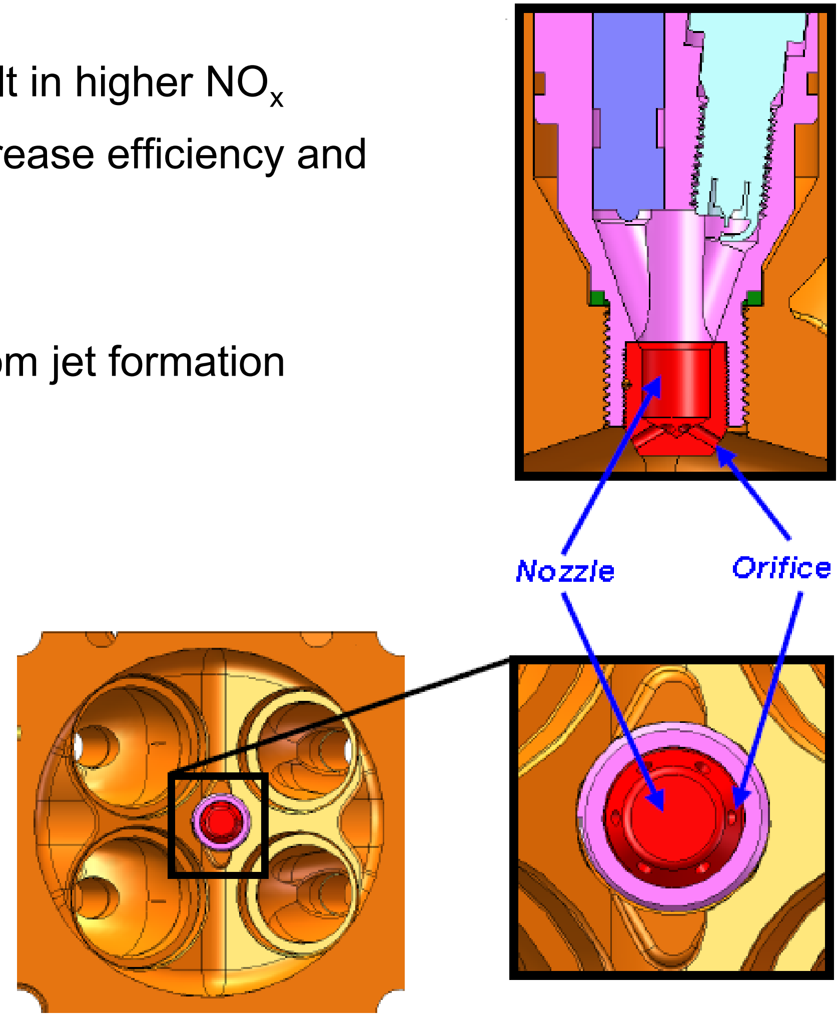
Relevance

Background

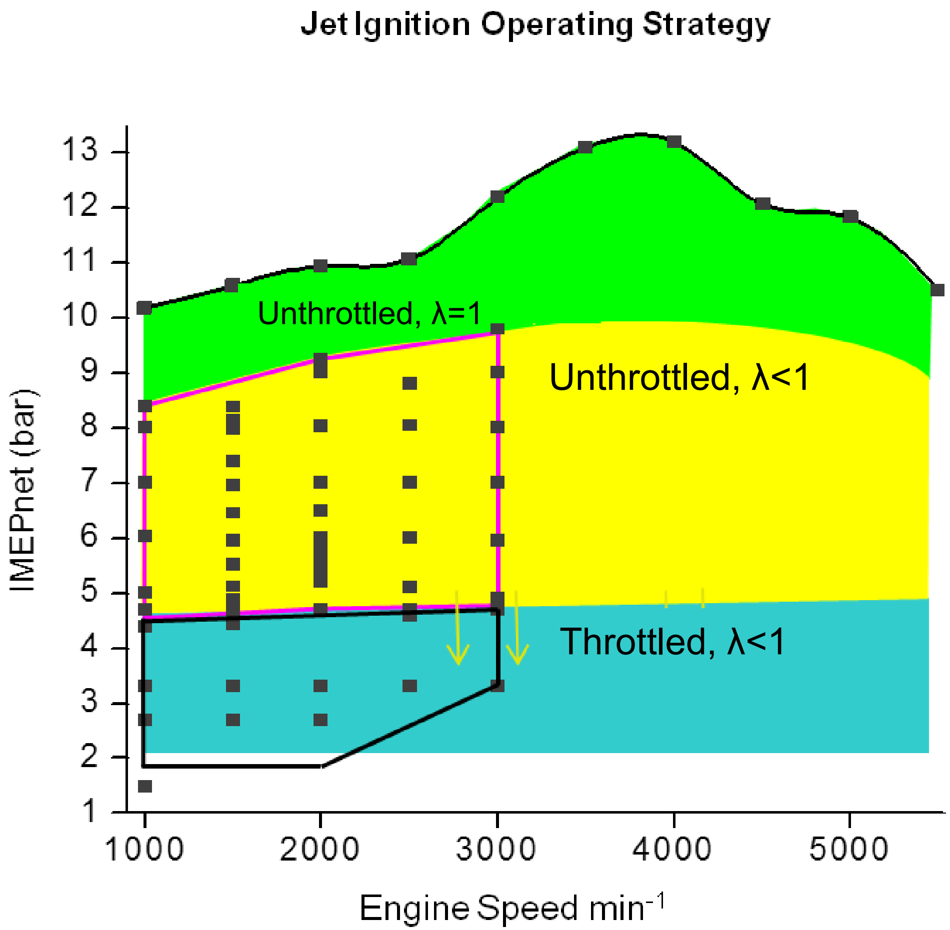
- Demand for highly efficient and clean engines
  - Lean operation increases efficiency but may result in higher NO_x
  - Ultra lean operation ($\lambda>2$) has been shown to increase efficiency and reduce NO_x due to low cylinder temperatures

- Turbulent Jet Ignition (TJI) offers distributed ignition from jet formation enabling ultra lean operation
  - Low NO_x at part loads
  - Increased knock resistance at high loads
  - Minimal modifications to existing hardware

- Enabling Technologies
  - TJI + Boosting



TJI Intent

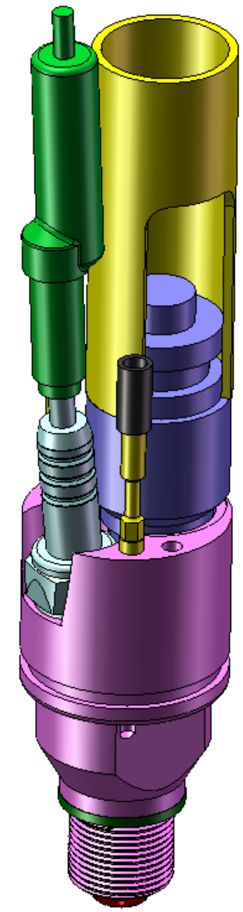


From Attard et al., SAE Int. J. Engines, Vol. 5, Issue 2 (May 2012)

- Knock resistance allows TJI to operate in the WOT high load area of the map (λ=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 λ=1

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

Milestones

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Milestones	Completion Date
BP1	
Milestone 1 – Phase 1 Design Work Complete	07/25/12
Milestone 2 – Component Procurement Complete	10/30/12
BP2	
Milestone 3 – Single-cylinder Engine Testing Complete	04/04/13
Milestone 4 – Phase 1 Research Completion	04/10/13
Milestone 5 – Boosted Single Cylinder Engine Shakedown Complete	05/16/13
Milestone 6 – Boosted Single Cylinder Engine Optimization and Vehicle Fuel Economy Prediction Complete	02/13/14
Milestone 7 – Phase 2 Complete	02/21/14
BP3	
Milestone 8 – Boosted Multi-Cylinder Engine Build and Shakedown Complete	05/08/14
Milestone 9 – Boosted Engine Optimization and Vehicle Fuel Economy Prediction Complete	09/05/14
Milestone 10 – Project Complete	11/13/14

Phase 1 Approach

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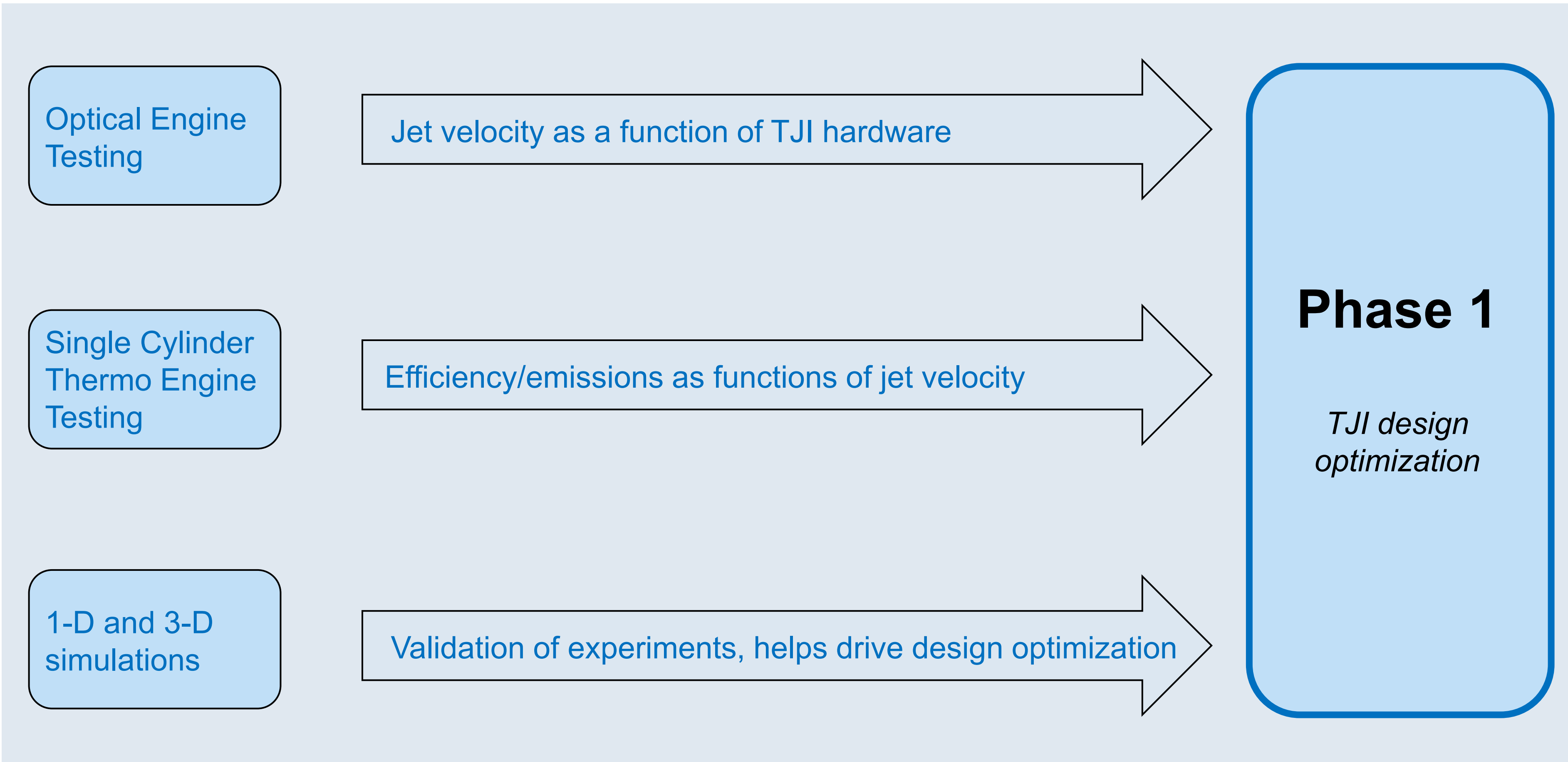

Phases 2 and 3 Approaches

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Input	Activity	Outcome
Boosted Single Cylinder Thermo Engine Testing	Fuel injection timing/quantity and spark timing sweeps	**Phase 2** *TJI design validation, operating parameterization*
1-D and 3-D simulations	Validation of experiments	
Boosted Multi-Cylinder Thermo Engine Testing	Mini-map generation provides input to 1-D simulation	**Phase 3** *Map generation and drive cycle simulation*
1-D simulations	Predict TJI vehicle drive cycle fuel economy improvement	

Design and Build of a Single-Cylinder Optical Engine

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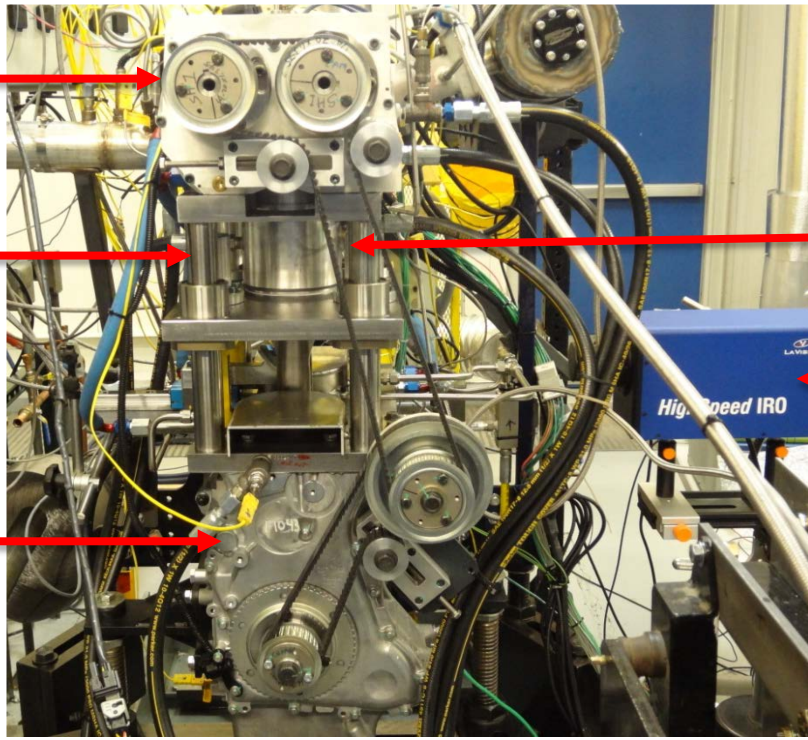
- Single-cylinder optical engine successfully designed and assembled
- Purpose: determine pre-chamber design effects on jet velocity, jet penetration and jet variability

Custom cylinder head with TJI

Hydraulic assembly

Bottom end assembled using Ford 4-cylinder components

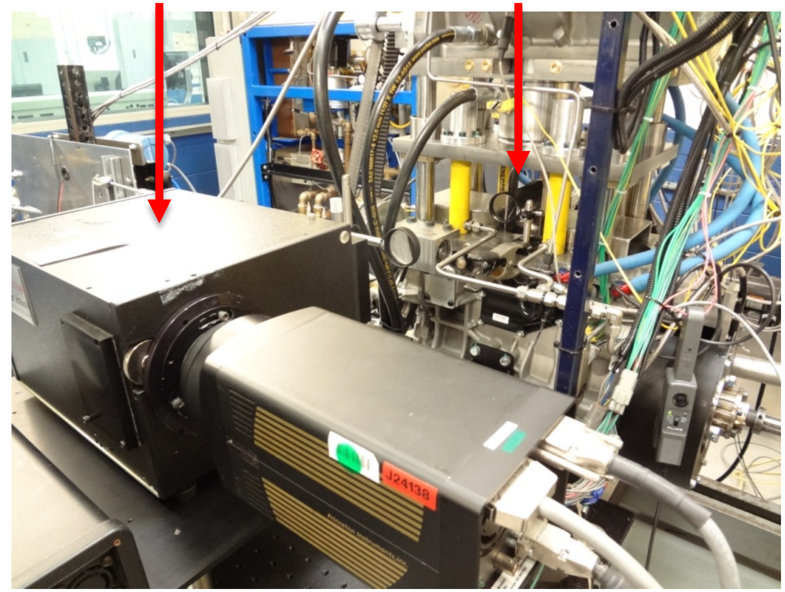


Optical combustion chamber

High speed camera

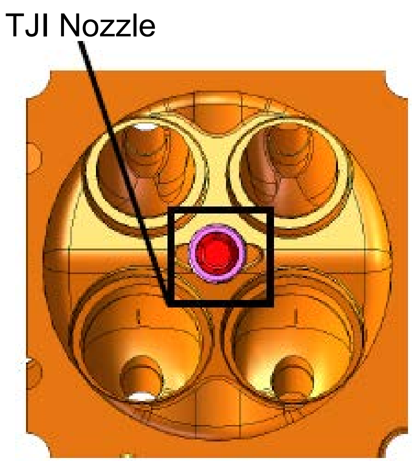
High speed spectrometer

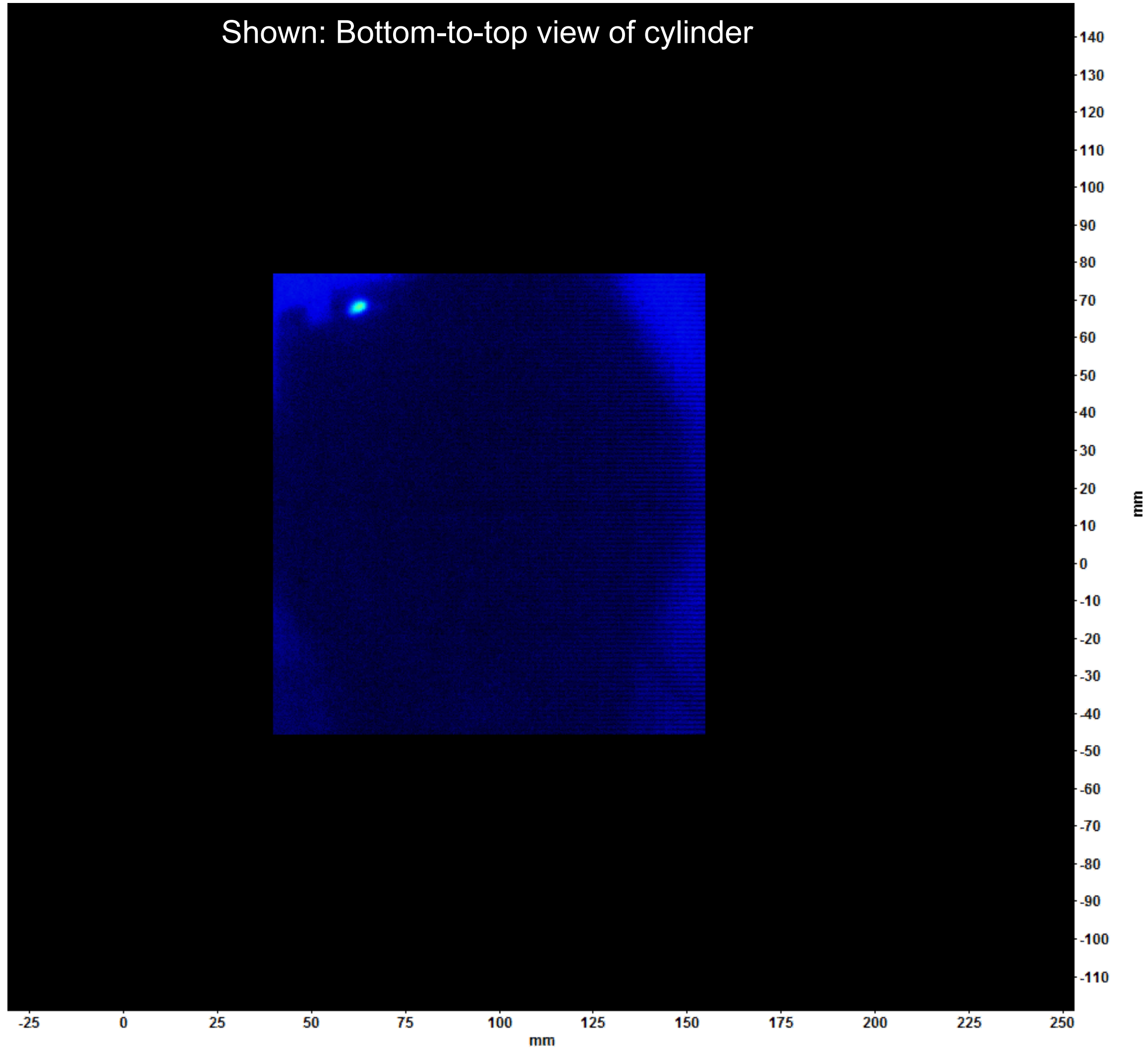
Mirror at 45 degrees



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: ~65 m/s





Optical Engine Data Analysis and Findings

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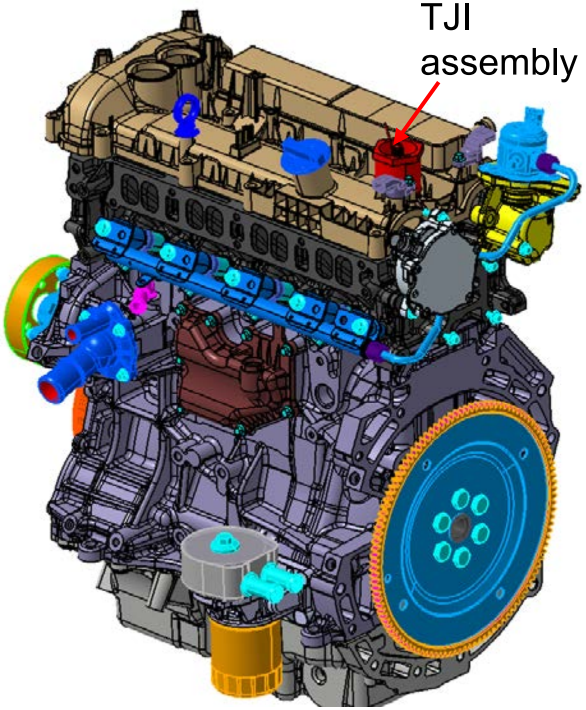
- Findings:
  - Use of two hole fuel-injector aids jet velocity and reduces cyclic variability
  - Reducing pre-chamber volume increases jet velocity
  - Optimum nozzle hole number appears to be 6
  - Optimum hole diameters appears to be 1-1.2 mm
    - Smaller orifices inhibit gas exchange to the main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

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

CFD – Insight into Flame Propagation and Jet Formation

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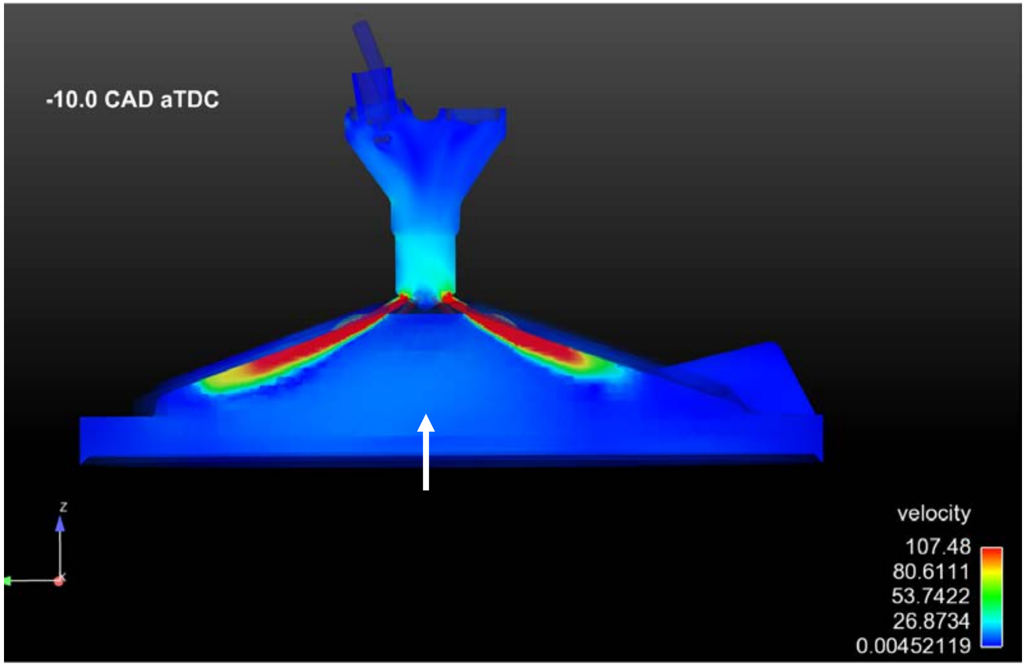
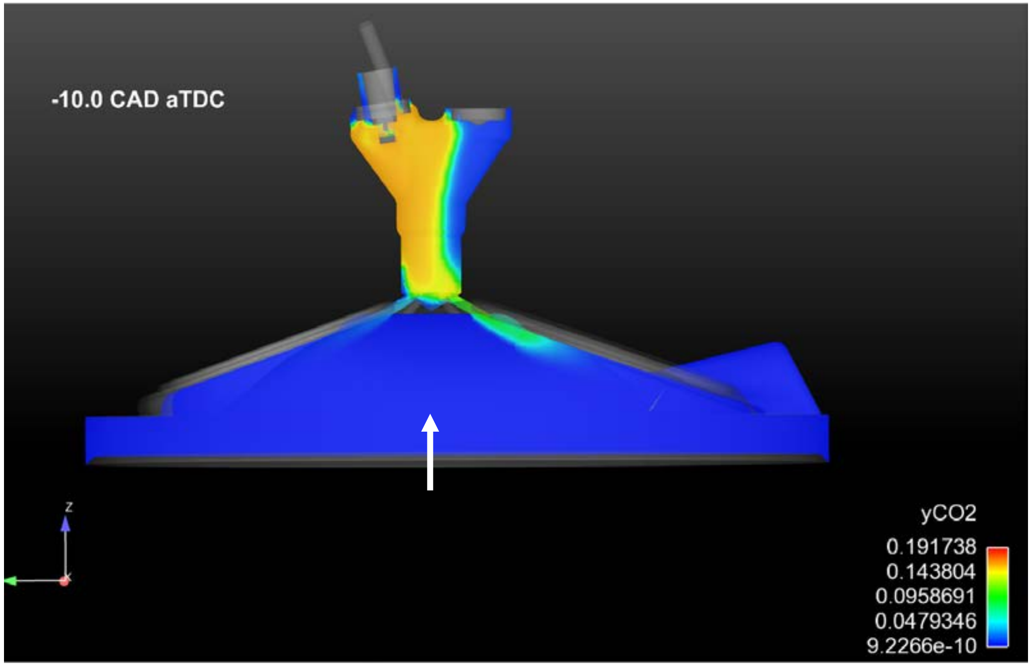
Fluid velocity (m/s)



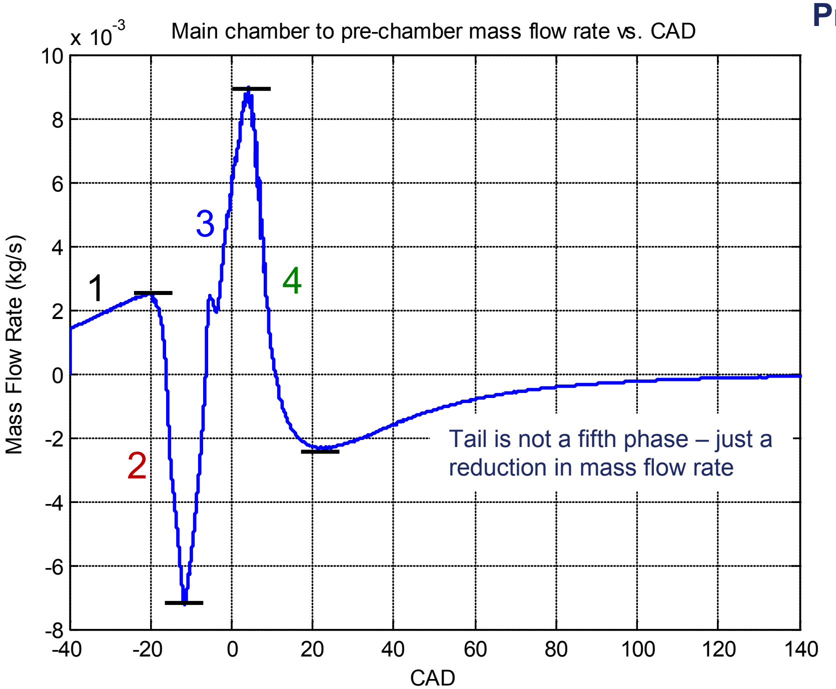
CO_2 mass fraction (-)

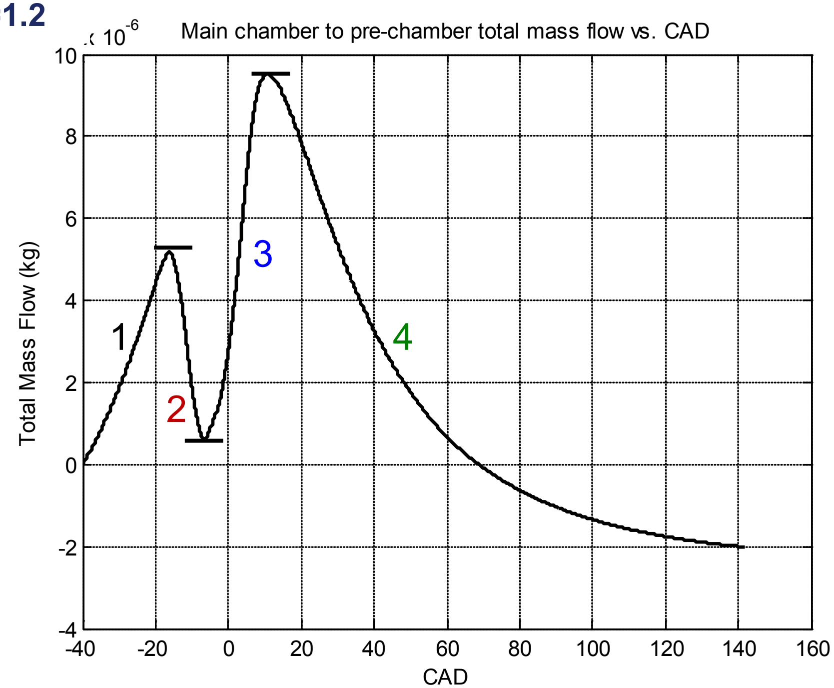


- Spark timing: 20 CAD bTDC
- Burning pre-chamber charge pushes gases into the main chamber
- Piston motion is still upward but expanding gases overwhelm compression action
- Flame front forming in the main chamber before entire pre-chamber charge has been consumed
- Jet variability directly linked to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

CFD – Main Chamber to Pre-chamber Flow Phases

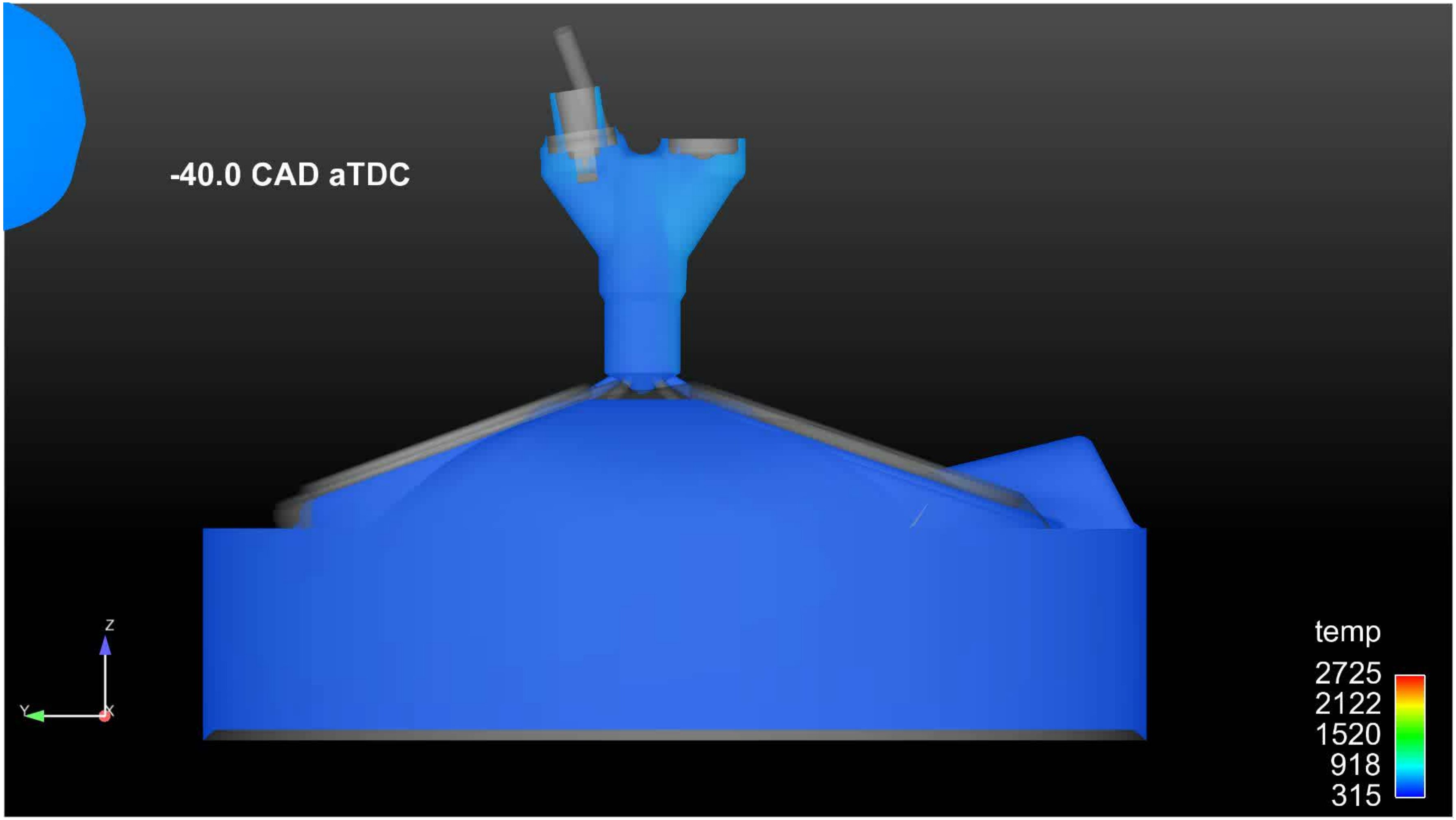
Premixed, λ=1.2





- 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

CFD – Temperature Field Visualization



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

Collaborations

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- **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

Project Timeline

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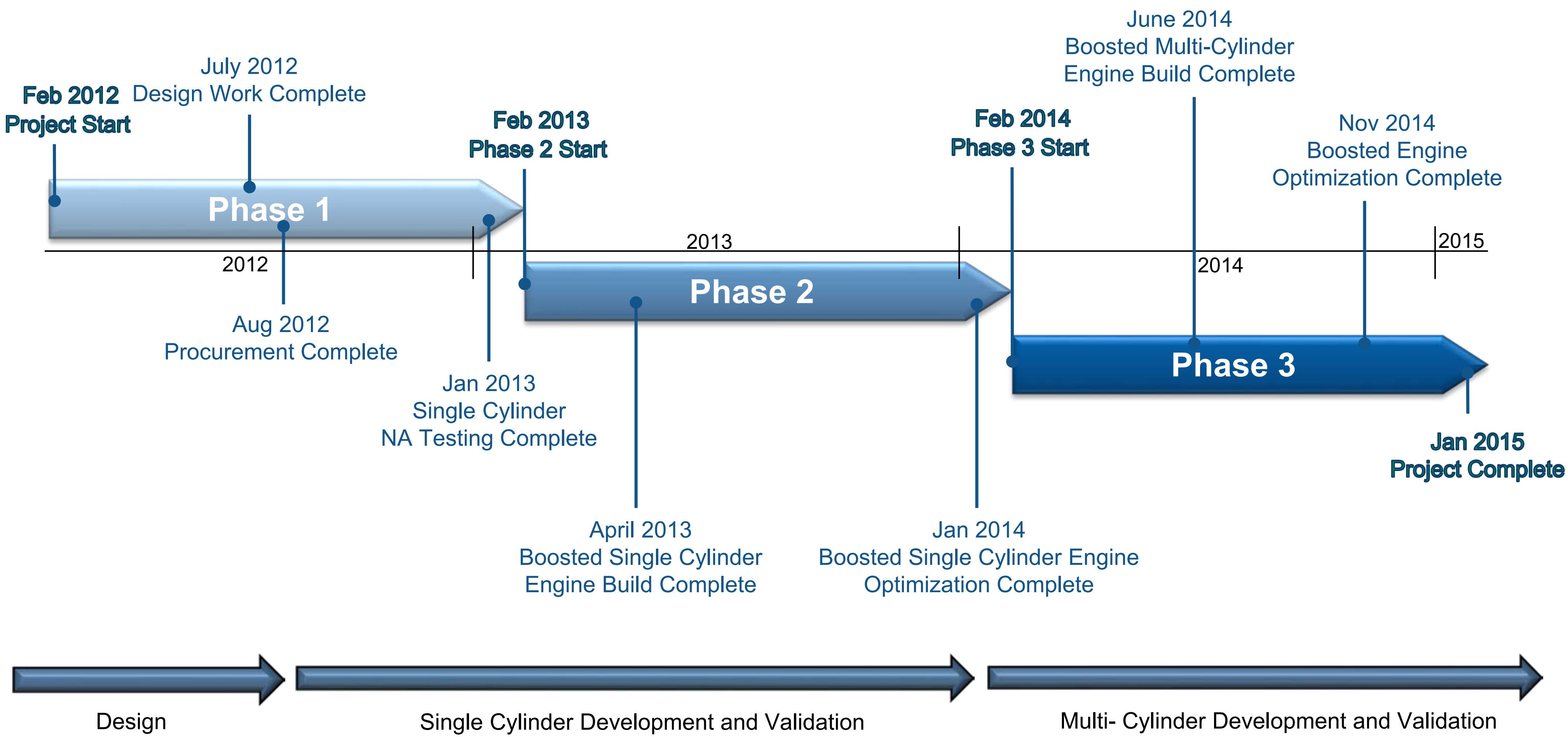


Upcoming Project Work

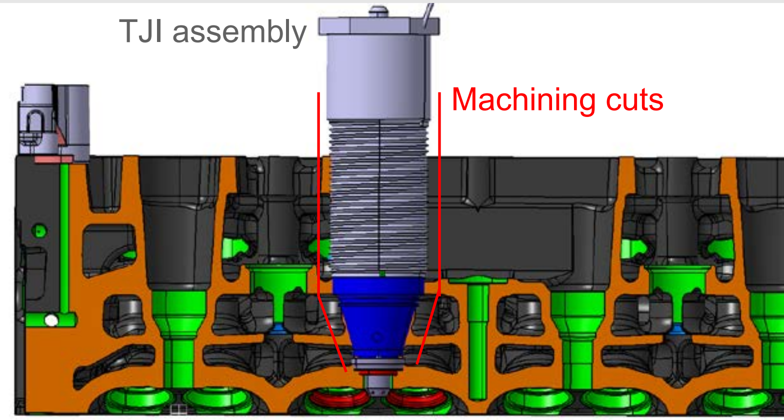
- **Phase I**: Concept Design/Analysis and Single Cylinder Engine Testing
  - Complete metal engine testing and analysis
  - Refine and expand CFD simulations

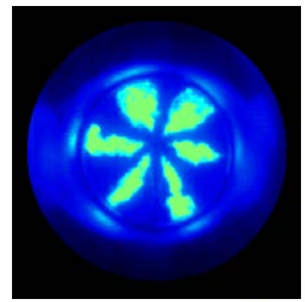
- **Phase II**: Boosted Single Cylinder Engine Testing
  - Identify and build optimal TJI design based on data consolidation
  - Validate optimal TJI design on the metal engine
  - Perform additional experiments that may be required
  - Utilize CFD to further analyze experimental results

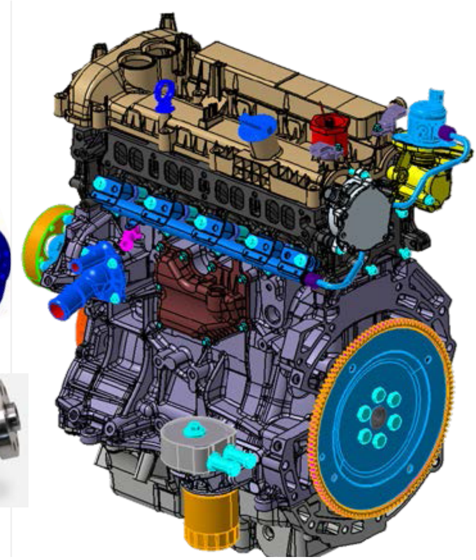
- **Phase III**: Boosted Multi-Cylinder Engine Testing
  - Create a mini-map using boosted multi-cylinder engine with TJI as input to 1-D model
  - Use 1-D analysis to predict TJI vehicle drive cycle fuel economy improvement

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





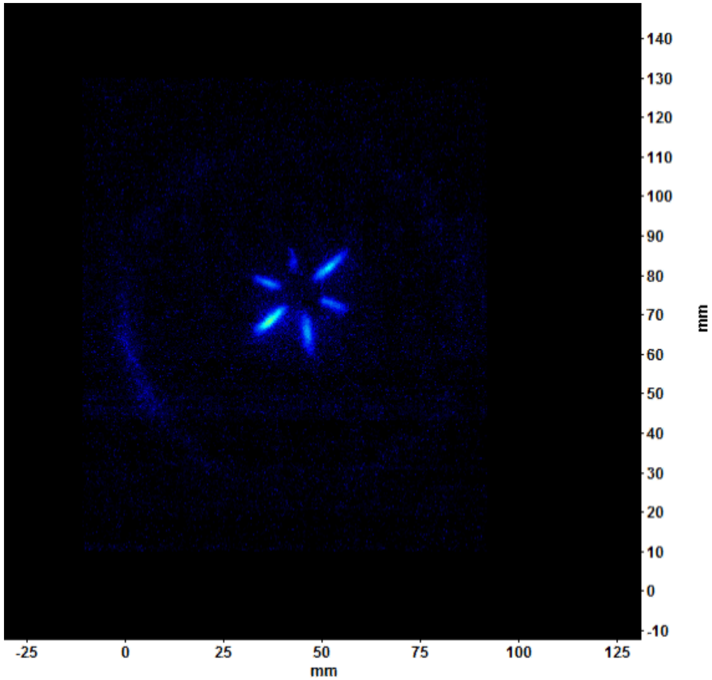


MPT would like to acknowledge DOE Office of Vehicle Technologies for funding this work.

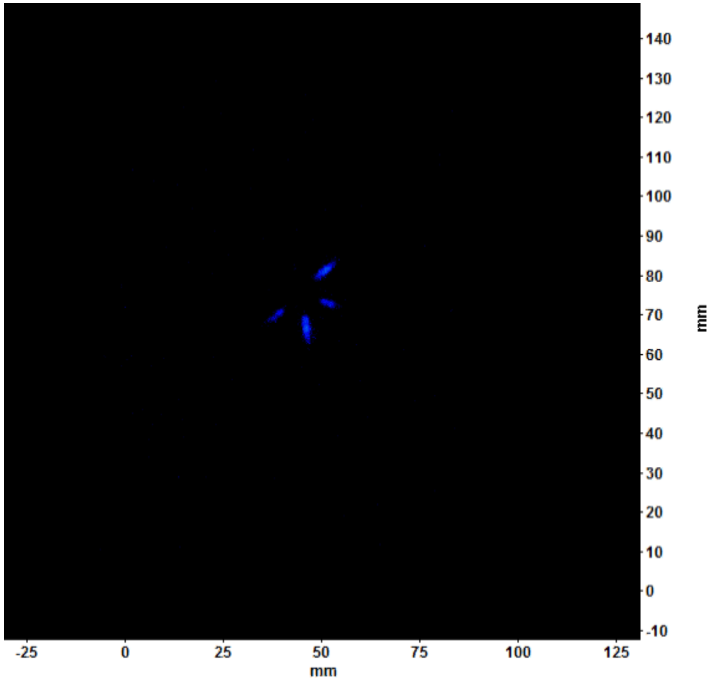
Technical Back-Up Slides

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