H₂ Internal Combustion Engine Research
Towards 45% efficiency and Tier2-Bin5 emissions*

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Overview

Timeline
- Project start: 2005
- Project end: Ongoing project

Budget
- Funding in FY08: 400k$
- Funding in FY09: 500k$
- Funding for FY10: 840k$ request

Barriers
- Understand and optimize hydrogen direct injection engine operation
- Evaluate in-cylinder emissions reduction techniques
- Improve injector design

Partners
- Collaborators: Ford, Sandia
- Potential partner: BMW
- Injector supplier: Westport
Objectives

- Overcome the trade-off between engine efficiency and NOx emissions in hydrogen direct injection (DI) operation
- Evaluate the NOx emissions reduction potential of in-cylinder measures (e.g. water injection, EGR) in hydrogen DI operation
- Assess the impact of injector nozzle geometry and injector orientation and design optimized configurations
- Investigate the potential of multiple injection strategies
Milestones

- Correlation between OH* intensities from endoscopic measurement and NOx emissions established (02/2008)
- Comparative study of central versus side injector location completed (05/2008)
- Influence of injector jet direction analyzed for single and multiple injection cases (07/2008)
- Water injection demonstrated as an effective technique for NOx emissions reduction (09/2008)
- 3-D CFD simulation useable for optimization (03/2009)
- Evaluation of NOx emissions reduction potential of exhaust gas recirculation (expected 05/2009)
- Implementation of piezo-actuated hydrogen DI injectors (expected 07/2009)
Technical Approach… Collaboration

- Single-cylinder research engine
- 3-D CFD simulation
- Injector nozzle design
- Validation
- Optical engine (Sandia)
- Tech transfer
- H₂ injector development (Westport)
- Tech support

Hydrogen vehicle program (Ford)
Technical accomplishments/progress/results

Overview

- **Improve injector design**
  - Single-hole nozzle injector tested to evaluate injection direction for single and multi-pulse injection

- **Understand and optimize H₂ DI**
  - 3-D CFD simulation integrated to support data analysis and development of advanced configurations

- **In-cylinder emissions reduction**
  - Water injection study to establish basis for exhaust gas recirculation (EGR) tests completed
  - EGR system for uncooled and cooled testing integrated
Single-hole nozzle design
Simple configuration with great flexibility

- Motivation to test single hole nozzle
  - Easy to machine
  - No jet-to-jet interaction
  - Useable in central and side injector location
  - Basic understanding of jet penetration

- Tests performed (central injection)
  - Single injection with variation of Start of Injection (SOI) Injection Angle
  - Multiple injection with variation of Injection Angle Fuel split between injections
Multiple injection strategies
Overview of injection strategies

- **PFI used as early baseline**
- **Early DI** – low emissions at low load
- **Late DI** – reduced emissions at high load
- **Multiple injection** – reduced emissions and peak pressure at high load
Single injection at high engine load
4% efficiency change with angle – Late SOI reduces NOx

Indicated thermal efficiency [%] vs NOx emissions [ppm]

2000 RPM
8 bar IMEP
MBT Spark

SOI [°CA BTDC] vs Injection angle [°]

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Single injection at low engine load
5% efficiency change with angle – SOI dominant for NOx
Merge experiment with simulation
3-D CFD results using a commercial code

- Motivation to 3-D CFD simulation
  - Further insight into the mixture formation process
  - Straightforward validation of 3D-CFD simulation using data from Sandia National Laboratory
  - Support development and optimization of advanced mixture formation concepts

- Approach
  - Use detailed grid and experimental data to correctly simulate gas exchange (once for each load point)
  - Switch to reduced grid for compression and injection process
  - Use reduced grid for variation calculations
How does simulation help?
No ignitable mixture at spark plug
Multiple injection operation
Angle impacts efficiency – Ratio reduces NOx up to 95%

Indicated thermal efficiency [%]

NOx emissions [ppm]

1000 RPM
6 bar IMEP
MBT Spark
Multiple injection operation
Hypothesis for NOx emissions reduction

- **Primary injection**
  - Very low NOx emissions if air/fuel ratio of primary pulse is lower than 0.5

- **Secondary injection**
  - Occurs during combustion
  - Hydrogen burns at stoichiometric air/fuel ratio avoiding NOx critical regime (0.5<Φ<1)
Water injection
Setup and strategy

- Use production gasoline injector to accurately control water injection into the intake manifold
- Coriolis meter used to measure water flow
- Water injection tested as benchmark for effectiveness of exhaust gas recirculation
Water injection at medium engine load
Comparison of effectiveness with spark retard

- **Spark retard**
  - 25% NOx emissions reduction with 1.3% efficiency loss

- **Water injection**
  - 40% NOx emissions reduction with 0.4% efficiency loss

**Graphs:**
- Upper graph: Comparison of NOx emissions reduction with spark retard at different spark timings.
- Lower graph: Effect of water flow on NOx emissions and indicated thermal efficiency.
**Water injection at high engine load**

**Emissions reduction potential and impact on combustion**

### Water injection
- 55% NOx emissions reduction with 0.8% efficiency loss

### Combustion with water injection
- Water injection reduces peak heat release rate, therefore temperatures and NOx emissions
Exhaust gas recirculation
Setup complete and tests in progress

- Exhaust gas recirculation
  - Setup using automotive EGR valve
  - Intake and exhaust pressure individually adjustable
  - Integrated automotive EGR cooler

- Approach
  - Evaluate EGR rate determination strategies in hydrogen operation
  - Assessment of impact of EGR rates and temperatures on
    - NOx emissions
    - Engine efficiency
    - Combustion stability
Future work

- Complete assessment of exhaust gas recirculation for NOx emissions reduction
- Implement and test piezo-driven hydrogen DI injectors at elevated engine speeds (single and multiple injection)
- Upgrade research engine to optimized bore/stroke ratio
- Expand hydrogen combustion strategy development to a ‘Diesel-style’ combustion chamber with flat cylinder head and piston bowl
Summary

- Engine efficiency and NOx emissions is very sensitive to mixture formation strategy, in particular injector design, location, as well as injection strategy.
- 3-D CFD simulation and optical engine work are ideally suited to provide further understanding of hydrogen mixture formation processes.
- Multiple injection as well as water injection can significantly reduce NOx emissions at high efficiency levels.
- Future work will focus on exhaust gas recirculation, integration of higher flow, piezo activated injectors and assessment of Diesel-style combustion chamber design.