**H₂ Internal Combustion Engine Research**

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*This presentation does not contain any proprietary or confidential information*
Purpose of work

- Develop a combustion concept that
  - Offers excellent fuel conversion efficiencies
  - Produces virtually zero emissions
  - Achieves power density levels of modern gasoline engines
  - Reduces the dependence on foreign oil
  - Decreases greenhouse gas emissions
Purpose of work

- Evaluate potential of hydrogen internal combustion engines
  - Investigate hydrogen combustion concepts for additional efficiency and emissions improvements
    - Analyze influence of injector location
    - Evaluate impact of injector nozzle design
  - Apply/develop diagnostic tools that allow deeper understanding of hydrogen combustion engines
    - Develop correlation of chemiluminescence measurement with engine-out NO\textsubscript{x} emissions
  - Feed information forward to multi-cylinder hydrogen engine and vehicle level application
Relevant DOE goals and objectives

- 45% Brake Thermal Efficiency
- 0.07 g/mile NO_x
- Power density similar to gasoline
- $45/kW by 2010 and $30/kW in 2015
Previous Review Comments and Actions Taken

- ‘...would like to see more analysis of the in-cylinder measurements to understand more details of the combustion.’
  - Detailed analysis of in-cylinder pressure measurements
  - Correlation between OH* chemiluminescence and engine-out NO\textsubscript{x} emissions derived

- ‘...the project should include modeling.’
  - Meetings with project partners; Simulation at Ford/Sandia
  - Post-doc candidate with hydrogen engine modeling experience identified

- ‘NO\textsubscript{x} levels seem very high...what the plan for NO\textsubscript{x} control was.’
  - In-cylinder measures
    - Multiple injection data presented at last review
    - Optimized injector location and nozzle design
    - Additional measures (EGR, water injection...)
  - Lean NO\textsubscript{x} aftertreatment (Ford, ORNL)
Barriers

- Operation with hydrogen port injection
  - Combustion anomalies (knock, pre-ignition) prevent extension of high efficiency regimes towards higher engine loads
  - Low power density

- Operation with hydrogen direct injection
  - Trade-off between NO\textsubscript{x} emissions and power density
  - Trade-off between NO\textsubscript{x} emissions and engine efficiency at low engine loads
Approach (Overview)

- Ford Hardware
- ANL
  - Metal engine
  - Endoscope
- ORNL
  - Aftertreatment
- DOE Targets
  - Efficiency/emissions
- SNL
  - Simulation
  - Optical engine
Approach (Project)

DOE/Partners

Targets
Efficiency/ emissions

H₂ engine optimization

Partners

Tools
- Emissions instrumentation
- Combustion analysis
- Endoscopic imaging

Concepts
- Combustion strategy
- Additional measures

Ford
Progress
Hardware upgrade

- New cylinder head installed with
  - Central and side injector location for Direct Injection
  - Endoscope access

- Spark Plug
- Central Location
- Side Location
- Pressure Transducer
- Endoscope
Progress
Novel nozzle designs

- Symmetric 6 hole nozzle for central injection
- Asymmetric 5 hole nozzle for side injection
- 4 configurations tested:
  - Symmetric 6 hole central
  - Symmetric 6 hole side
  - Asymmetric 5 hole side jets up
  - Asymmetric 5 hole side jets down
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

10 deg CA ATDC

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

12 deg CA ATDC

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

14 deg CA ATDC

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

16 deg CA ATDC

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

18 deg CA ATDC

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central SOI=80
6-hole side SOI=80
5-hole side up SOI=80
5-hole side down SOI=80

20 deg CA ATDC

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

22 deg CA ATDC

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

24 deg CA ATDC

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

26 deg CA ATDC

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

28 deg CA ATDC

0 | 500

OH* Intensity [a.u.]
Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central
SOI=80

6-hole side
SOI=80

5-hole side up
SOI=80

5-hole side down
SOI=80

30 deg CA ATDC

OH* Intensity [a.u.]
Technical accomplishments
Correlation between NO\textsubscript{x} and endoscopic images

- Average Peak OH\textsuperscript{*} Intensity explanation
- Good correlation

![Graph showing correlation between NO\textsubscript{x} and endoscopic images](image)
Progress

- Emissions levels comparable to port injection
- High loads – NO\textsubscript{x} optimization potential

**2000 RPM Efficiency Optimized SOI MBT Spark Timing**

**H\textsubscript{2} Port Injection**

**NO\textsubscript{x} Emissions [ppm]**
Progress

- Improvement compared to port injection
- Low loads – efficiency optimization potential

2000 RPM
Efficiency optimized SOI
MBT Spark Timing

Indicated Thermal Efficiency [%]

H₂ Port Injection

6 hole central
6 hole side
5 hole side up
5 hole side down

IMEP [Bar]
Technology Transfer

- Multi-cylinder hydrogen direct-injection engine proposal
- Vehicle level application
  - Mobile Advanced Technology Testbed (MATT) concept studies
  - ETEC Silverado durability testing (NETL)
  - Development of test procedures with BMW Hydrogen 7 vehicles
Activities for Next Fiscal Year

- Evaluate custom designed injector nozzles
- Investigate in-cylinder NO\textsubscript{x} reduction measures
  - Water injection
  - Cylinder charge motion (swirl)
- Expand operating regime to higher engine speeds
- Verify H\textsubscript{2}-DI findings in a multi-cylinder DI engine
  (separate proposal for FY08)
Publications

Recently published


Upcoming events


Summary

- Hydrogen direct injection engine research seeks to develop a combustion concept with high engine efficiency and virtually zero emissions while maintaining the power density of current gasoline engines.
- Main barriers are combustion anomalies with hydrogen port injection as well as trade-offs between NOx emissions and power density and engine efficiency.
- Several nozzle designs for hydrogen direct injection with central and side injector location have been tested.
- 2% increase in engine efficiency with hydrogen direct injection compared to port injection without NOx emissions penalty.
- Further work will include evaluation of additional NOx reductions measures (water injection, swirl etc.), expansion of operating regime and testing of advanced injection concepts with optimized custom nozzles.
H$_2$ Internal Combustion Engine Research

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