Optimization of Direct-Injection H_2 Combustion Engine Performance, Efficiency, and Emissions

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Overview

Timeline

- Project start: 2005
- Project end: Ongoing project

Barriers

- Understand, characterize and optimize hydrogen engines with focus on direct injection
- Evaluate in-cylinder emissions reduction techniques
- Improve injector design

Budget

- Funding in FY09: 500k$
- Funding in FY10: 500k$
- Funding for FY11: 500k$ request

Partners

- Industrial partners: Ford, Westport
- Collaborator: Sandia and Lawrence Livermore National Laboratories
- International team members: BMW, Graz University of Technology, Ghent University

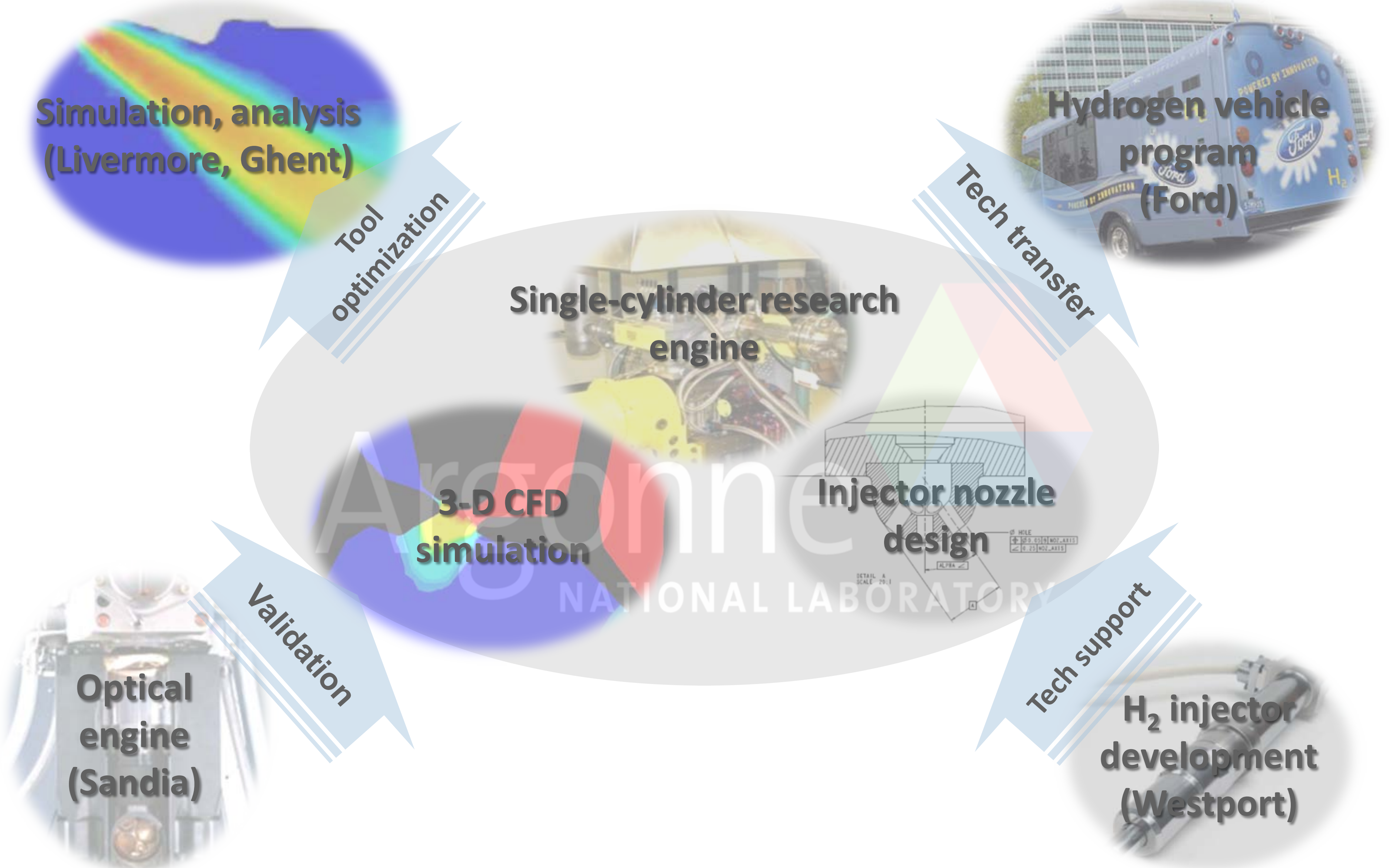
Objectives – Project relevance

- Provide a clean and efficient, readily available tool for utilization of hydrogen as an energy carrier
- Overcome the trade-off between engine efficiency and NOx emissions in hydrogen direct injection (DI) operation to reach 2010 peak brake thermal efficiency goal of 45% with minimal emissions penalty (Tier 2, Bin 5 or better)
- 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 location/orientation and develop optimized configurations
- Investigate the potential of multiple injection strategies

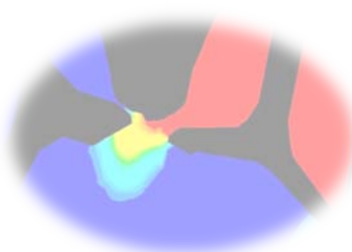
Milestones

- 3-D CFD simulation validated using optical results from Sandia National Laboratories (03/2009)
- NOx emissions reduction potential of EGR evaluated (07/2009)
- Analysis of individual optimization measures completed (09/2009)
- Upgrade to optimized engine geometry finished (12/2009)
- Piezo-actuated DI injectors implemented (01/2010)
- Baseline performance comparison of optimized engine geometry completed (03/2010)
- Efficiency mapping of optimized engine configuration with Piezo injectors started (04/2010)

Approach – Integration and Collaboration

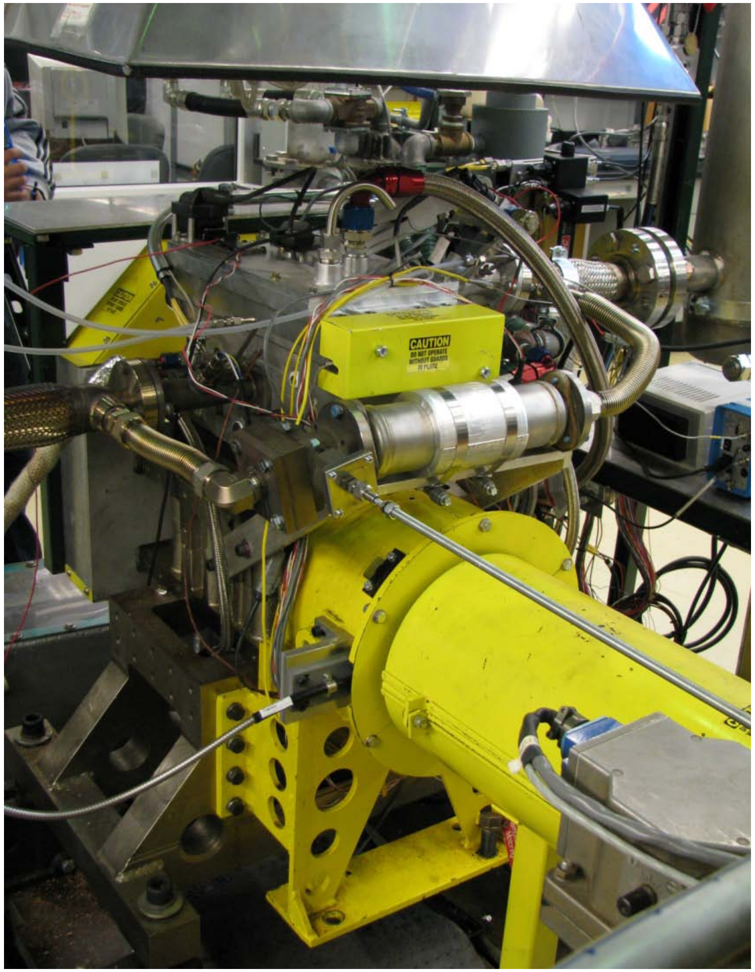


Technical accomplishments
Overview



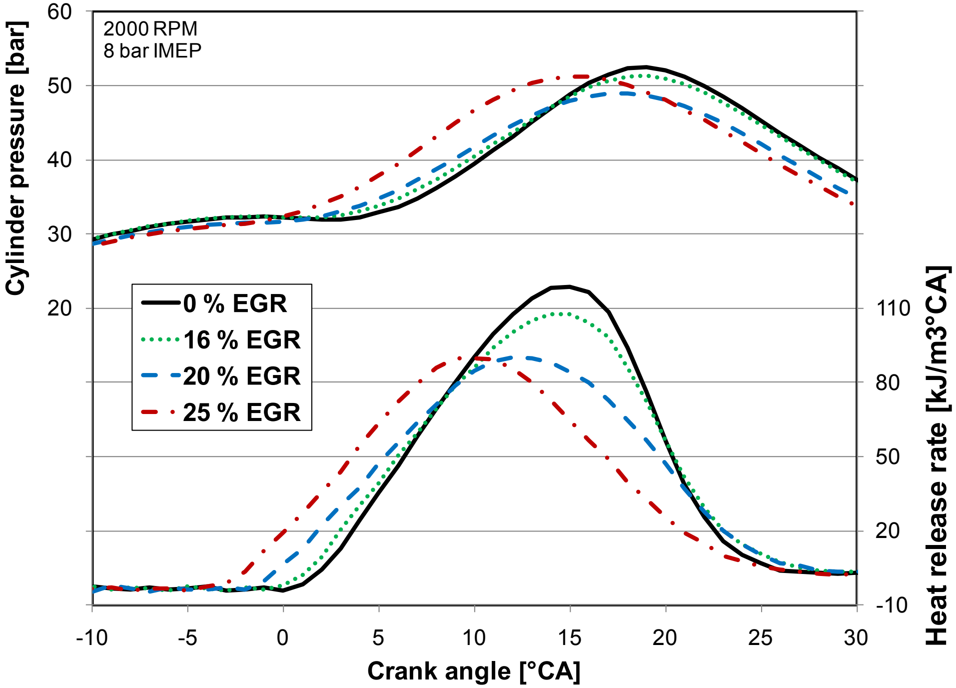
- **In-cylinder emissions reduction**
  - Efficiency/emissions trade-off with exhaust gas recirculation (EGR)
  - Assessment of EGR versus water injection
- **Optimized H_2 DI combustion engine**
  - Analysis of efficiency improvement with optimized engine geometry
  - Impact of optimization on emissions
- **Improved injector design**
  - Validated 3D-CFD simulation used to predict mixture stratification

Exhaust gas recirculation (EGR) Setup and goals

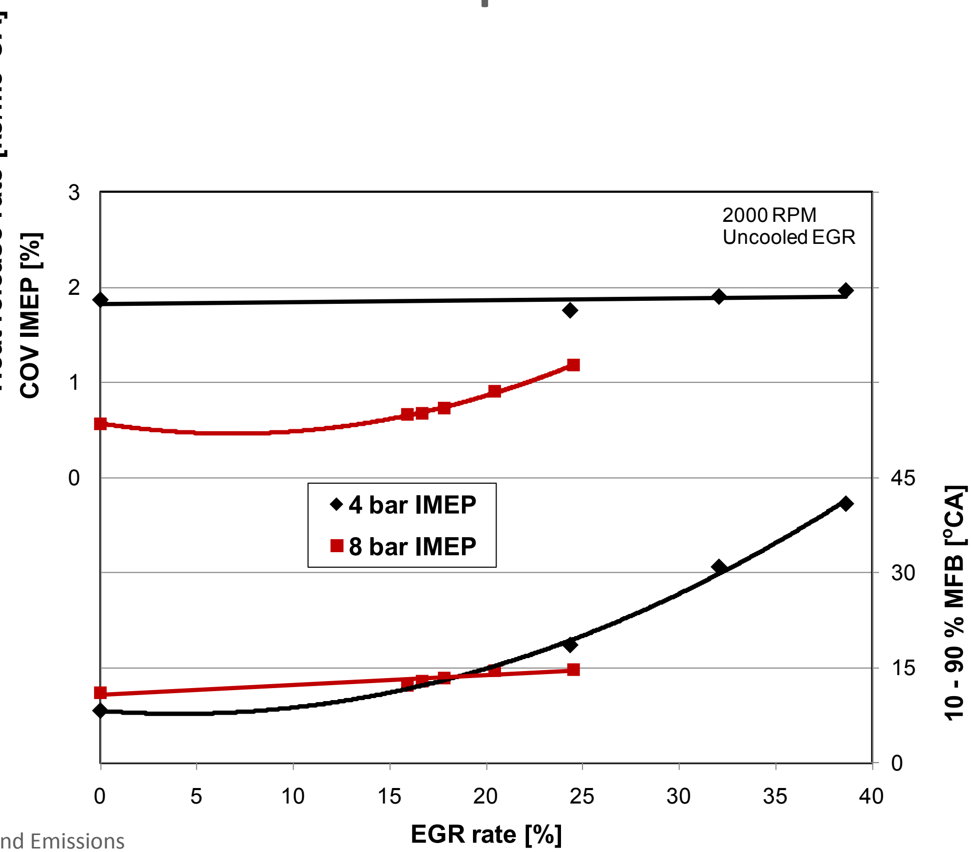


- **Exhaust gas recirculation**
  - Setup using automotive EGR valve
  - Intake and exhaust pressure individually adjustable
  - Integrated automotive EGR cooler
- **Approach**
  - Evaluate EGR rate determination strategies in hydrogen operation
  - Assessment of impact of EGR rates and temperatures on
    - NOx emissions
    - Engine efficiency
    - Combustion stability

Exhaust gas recirculation (EGR) Efficiency/emissions trade-off

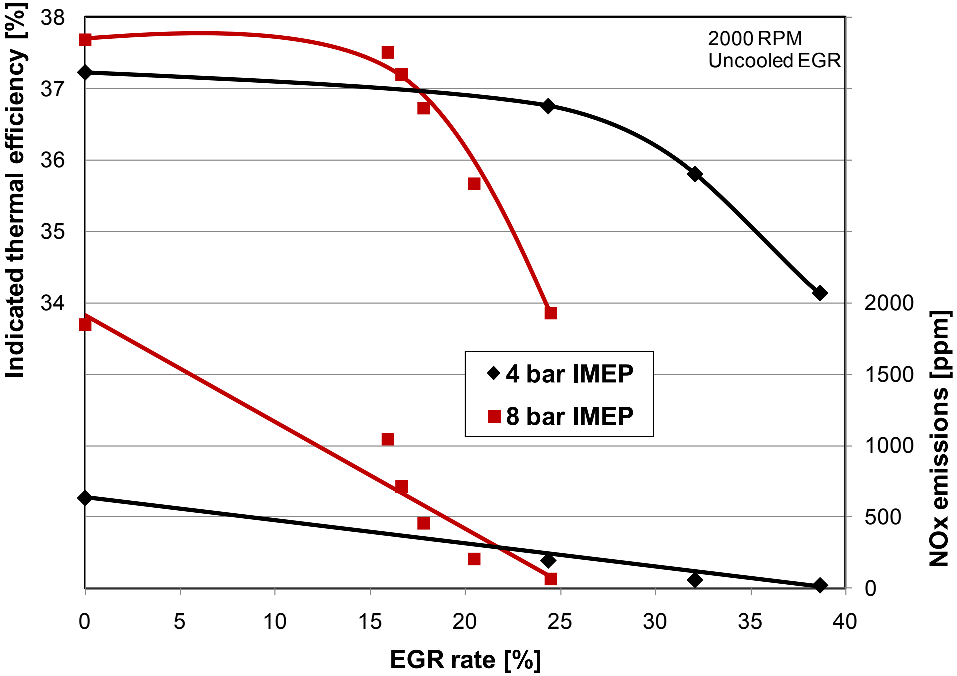


- Increasing EGR rates lower peak cylinder pressures and maximum rate of heat release ultimately reducing combustion temperatures

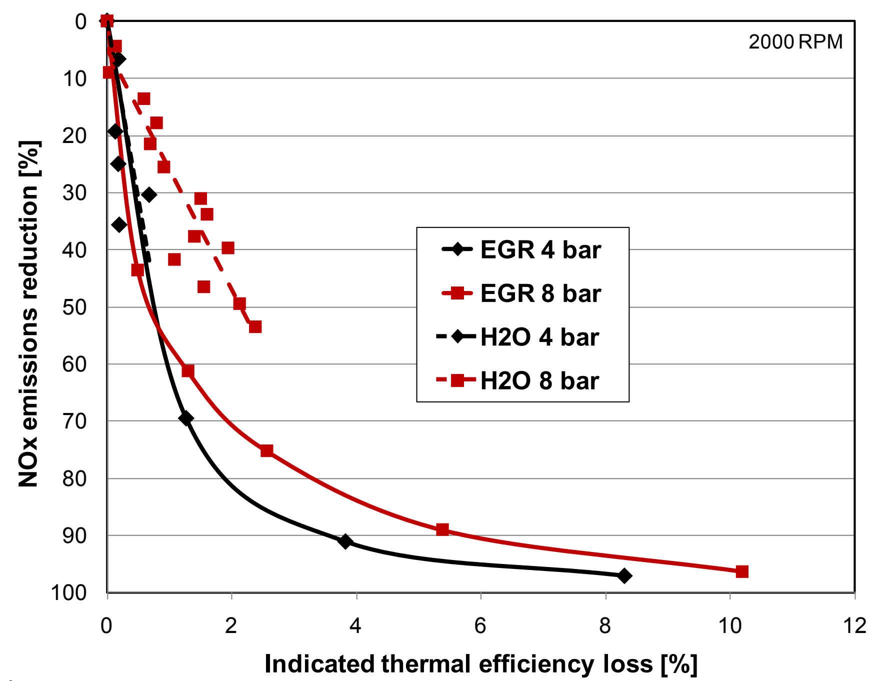


- Increasing EGR rates have negligible effect on combustion stability
- Increasing EGR rates result in increased combustion duration

Exhaust gas recirculation (EGR) Comparison to water injection

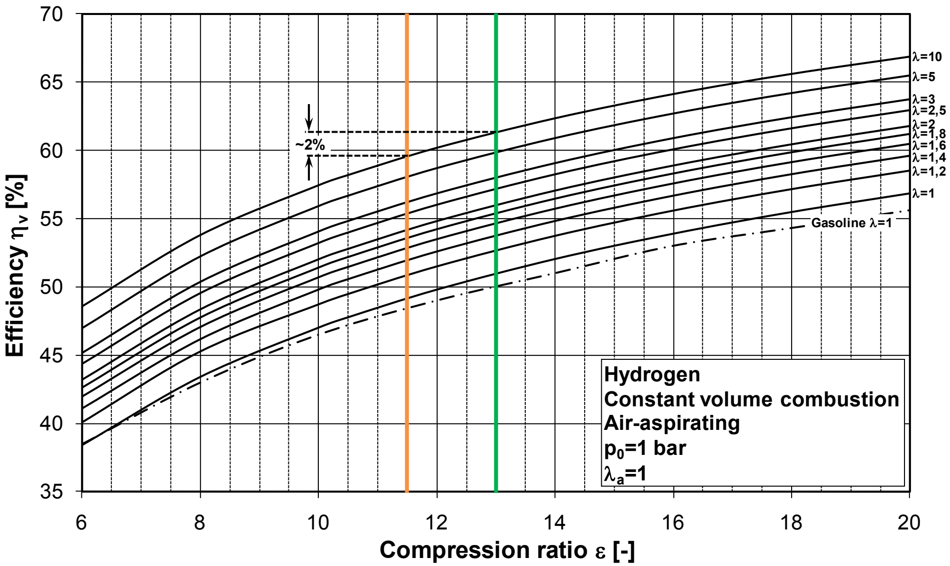


- 60 % NOx emissions reduction with EGR with respective loss in indicated thermal efficiency below 1 %
- NOx emissions in single digits achievable with efficiency penalty



- EGR equally effective for NOx emissions reduction as water injection at medium load (40% with 1% efficiency loss)
- 50% emissions reduction with water injection results in 2% efficiency loss at high engine load - EGR is superior

Optimizing engine geometry
Basics



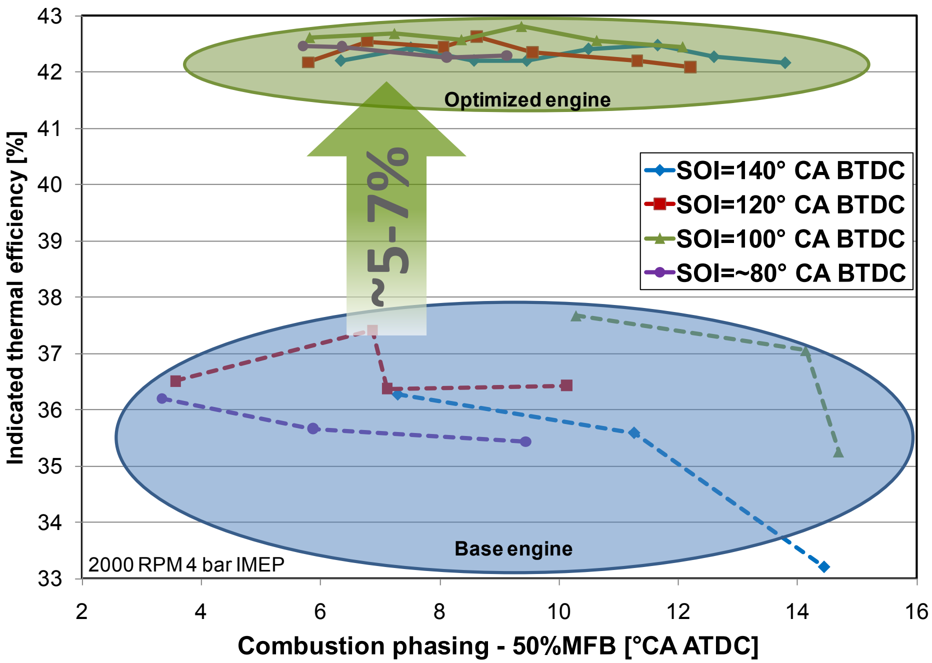
- Influence of
  - Compression ratio
  - Bore/stroke ratio
- Affecting
  - Combustion
  - Wall heat transfer

- Compression ratio increase expected to improve efficiency by ~2%
- Change in B/S ratio from 1.12 to 0.84 expected to increase efficiency by ~3%*

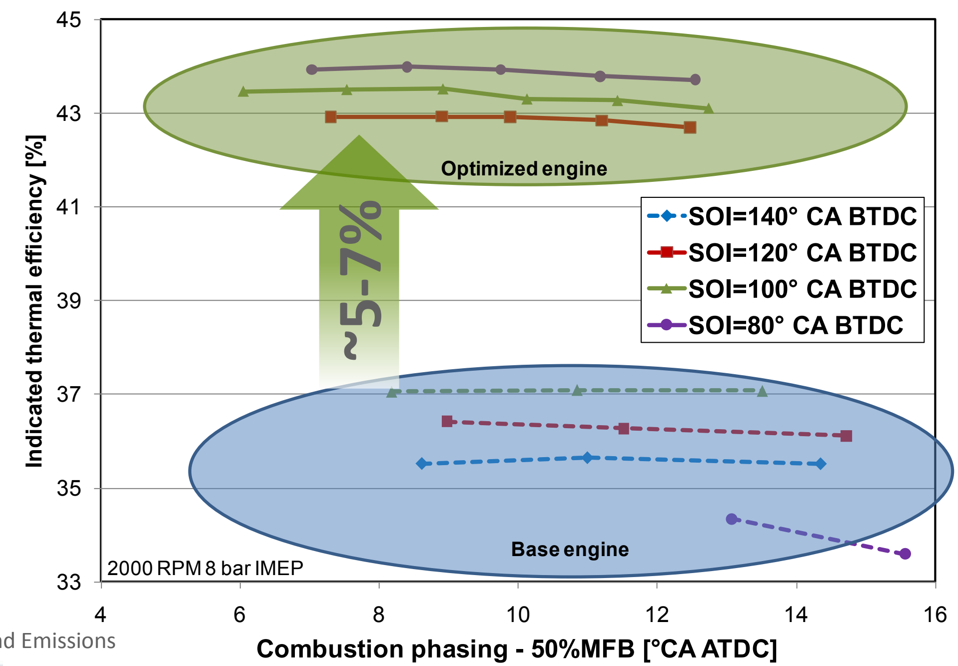
Parameter	Unit	Base engine	Optimized engine
Bore	mm	89	89
Stroke	mm	79.5	105.8
Bore/stroke ratio	-	1.12	0.84
Displacement	l	0.5	0.66
Peak cylinder pressure	bar	~120	~120-160
Compression ratio	-	11.5:1	12.9:1

* Z.S. Filipi and D.N. Assanis 'The Effect of the Stroke-to-Bore Ratio on Combustion, Heat Transfer and Efficiency of a Homogeneous Charge Spark Ignition Engine of Given Displacement ' International Journal of Engine Research, 1:2, 191-208, 2000.

Optimizing engine geometry
Efficiency results

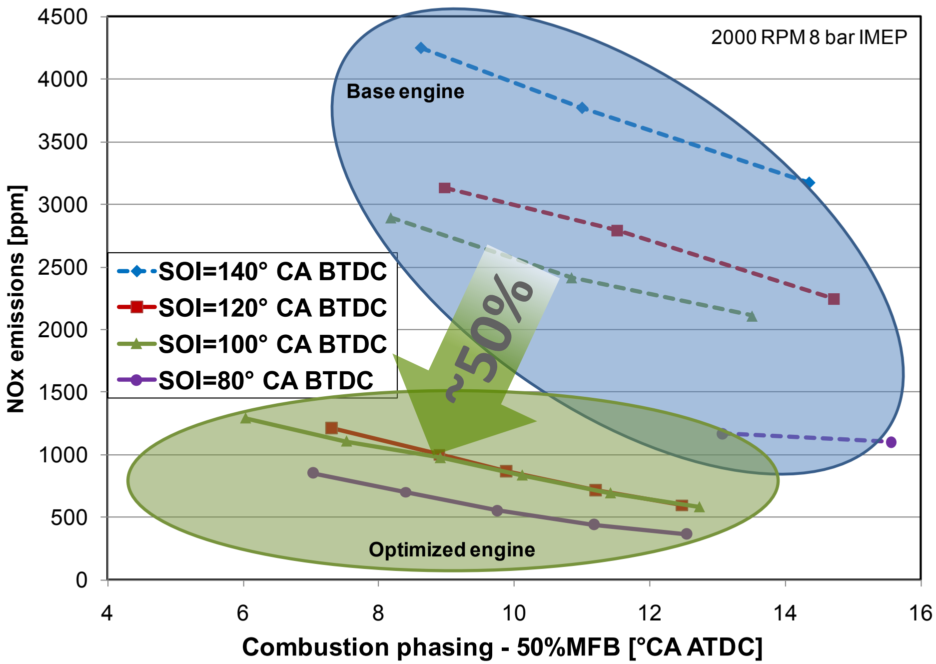


- Indicated thermal efficiency results at 2000 RPM and different loads
- Sweep of start of injection and spark timing (combustion phasing)

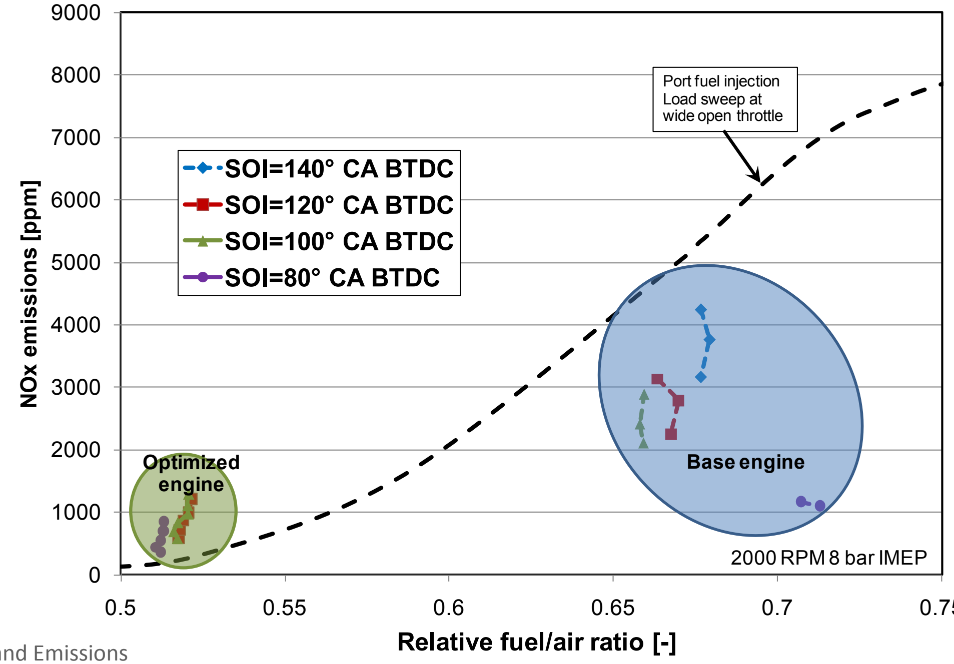


- Significant efficiency improvement (~5-7%) with optimized geometry independent of engine load
- Start of injection relevant for further optimization

Optimizing engine geometry
Emissions results

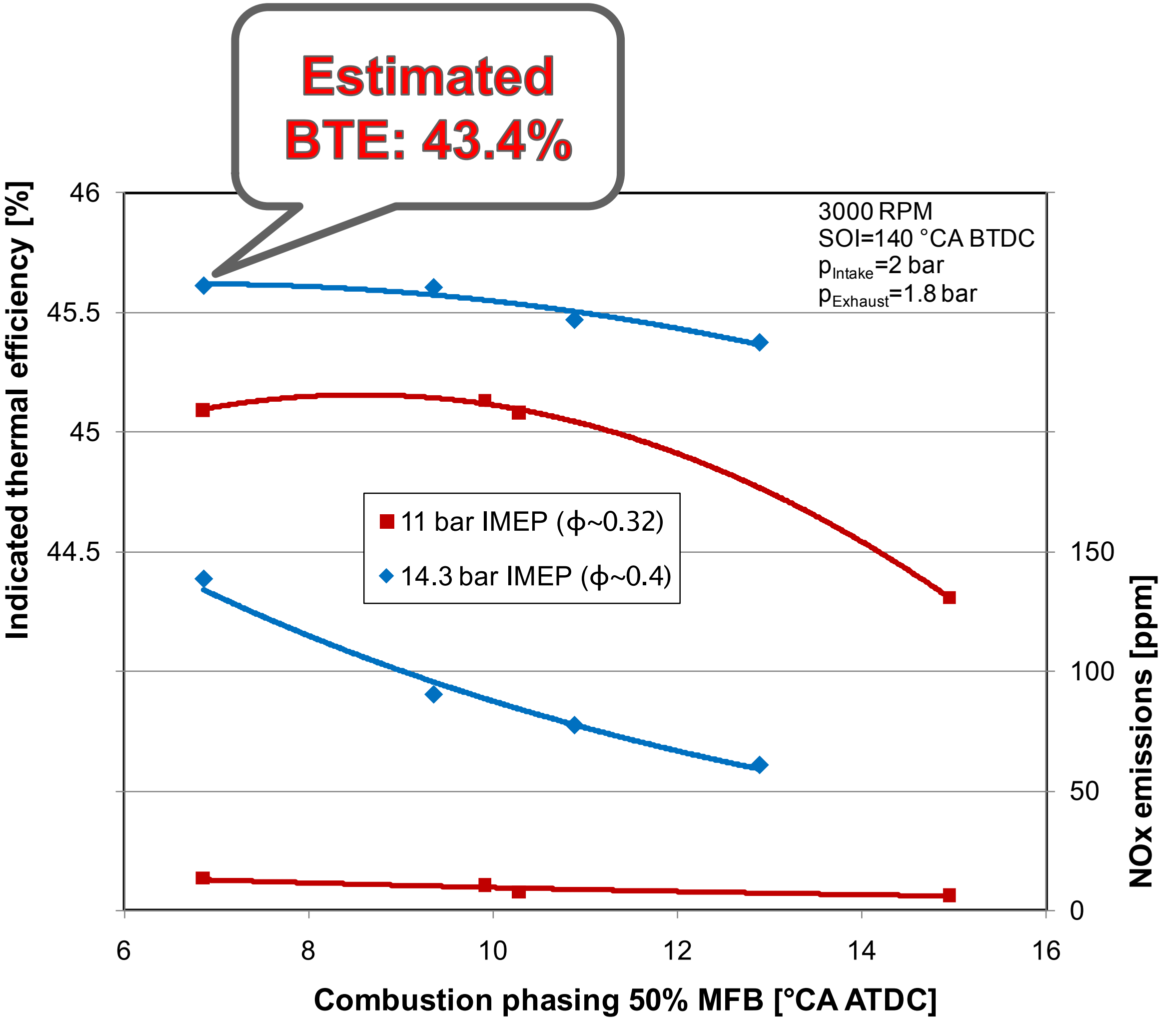


- NOx emissions only critical emissions component in hydrogen operation
- Tremendous NOx emissions reduction (~50%) with optimized geometry



- Strong correlation of NOx emissions with relative fuel/air ratio
- Start of injection critical for NOx emissions optimization

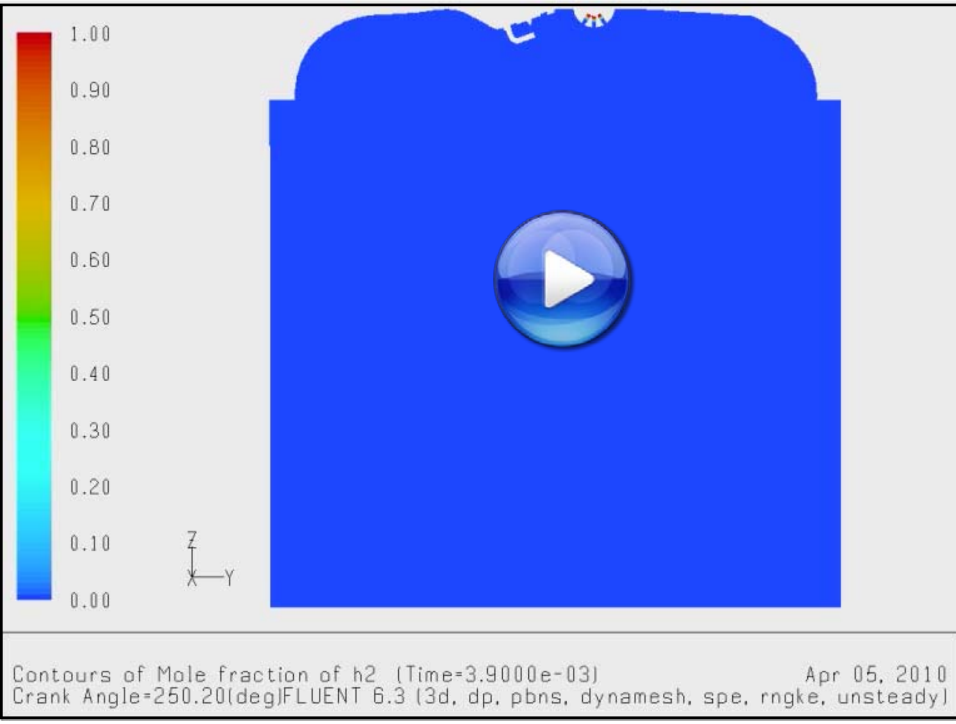
Optimizing combustion system
Current performance

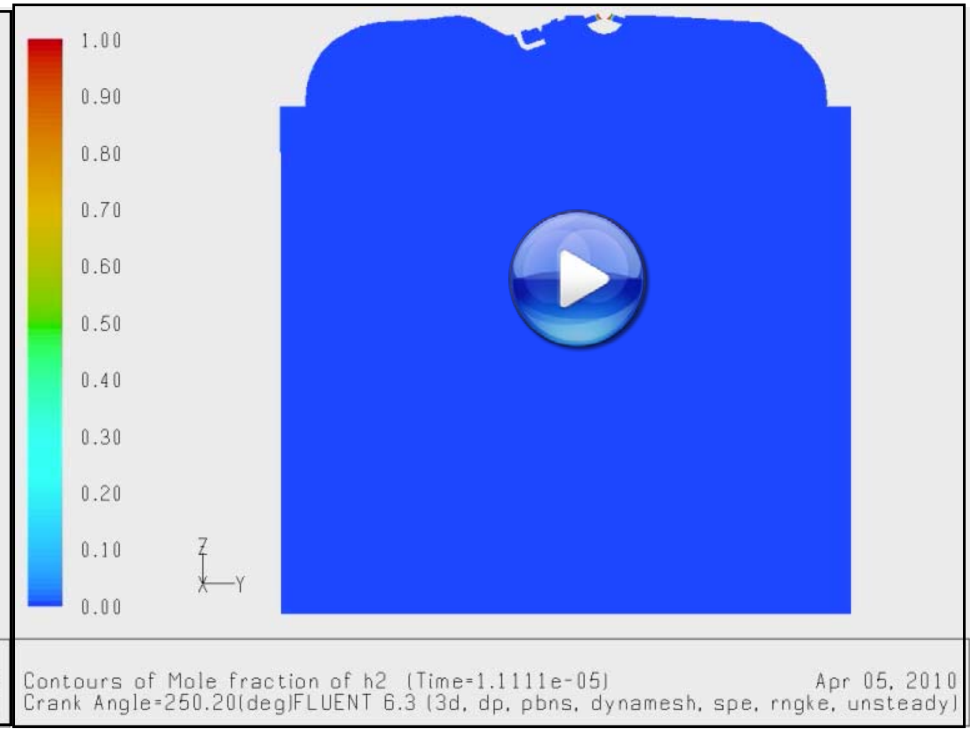


- 5-hole injector/central location
- 100 bar injection pressure
- Simulated turbocharging based on hydrogen PFI turbo results
- Operation limited due to peak cylinder pressure
- Only early DI possible (SOI=140) – later, more efficient SOIs unstable
- Brake thermal efficiency (BTE) estimated based on assumed friction of 0.70 bar (FEV data)

Optimizing combustion system
3D-CFD optimization of injector nozzle

Standard nozzle (5 hole) | **Optimized nozzle (2 hole)**

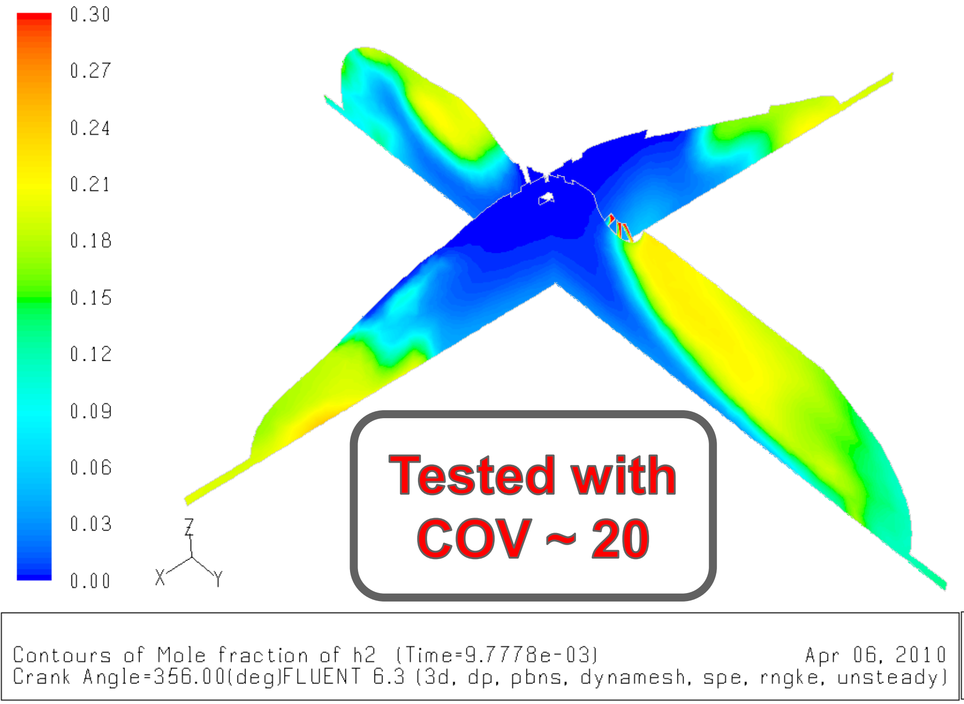




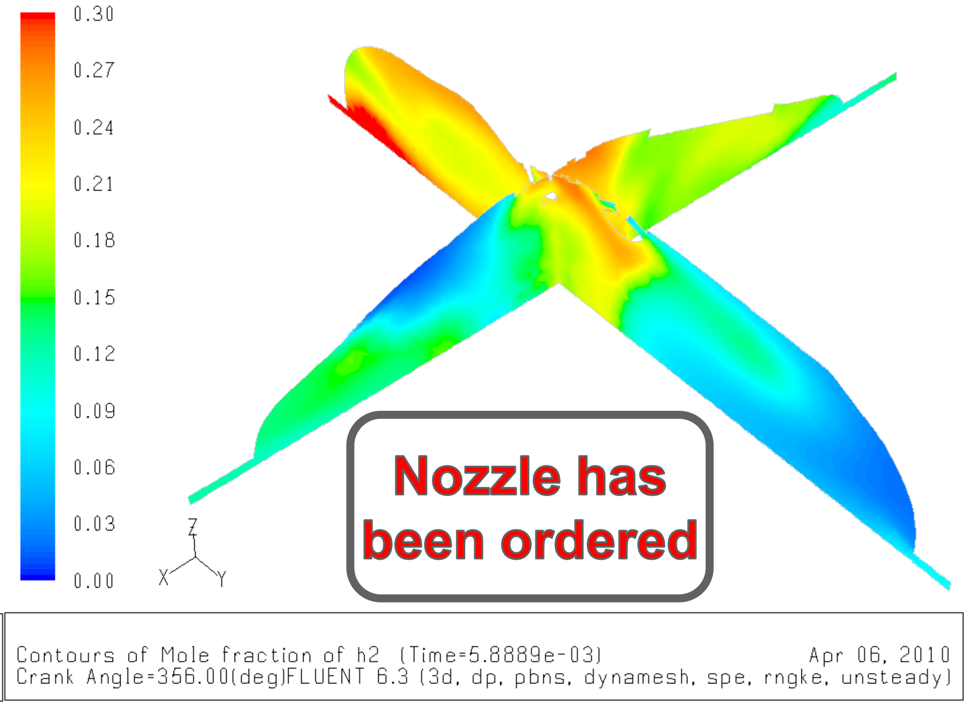
Speed	3000 RPM	Load	9 bar IMEP
Injector type	Piezo	Injection pressure	100 bar
Start of injection	110 CA BTDC	Injection duration	47 CA (2.6 ms)
Intake pressure	2 bar	Exhaust pressure	1.8 bar

Optimizing combustion system
3D-CFD optimization of injector nozzle

Standard nozzle (5 hole)



Optimized nozzle (2 hole)



CA = 4°BTDC

(Ignition Timing = 12°BTDC)

Collaboration and coordination

- Collaboration with Sebastian Kaiser’s team at Sandia National Laboratories
  - Coordination of investigated operating conditions
  - Optical results used for validation of 3D-CFD simulation
- Coordination with Dan Flower’s team at Lawrence Livermore National Laboratory
  - Currently evaluating/coordinating activities
- Contract with Westport Innovations Inc.
  - Subcontract to supply Piezo injectors, drivers and fabricate nozzles
- Guidance and support from Ford Motor Company
  - Input on test plan and activities
  - In-kind support (engine hardware)
- International collaborations
  - BMW – Mutual updates on goals, progress and research directions
  - Graz University of Technology – Pre-Doctoral appointee currently working at Argonne
  - Ghent University – Informal collaboration for data analysis

Future work

- **Mixture formation and combustion optimization**
  - Finish performance mapping of upgraded engine configuration
  - Optimize injection parameters with 3D-CFD support
  - Test 1st generation of Piezo injector nozzles
  - Assess impact of multiple injection strategies employing Piezo-actuated injectors on performance, efficiency and emissions
  - Test further generations of CFD-optimized injector nozzle designs and injection strategies
- **Hydrogen engine system optimization**
  - Combine optimized injection parameters (e.g. multiple injection) with in-cylinder emissions reduction measures (e.g. un-cooled EGR)
  - Develop injection strategies for optimized system performance

Summary

- 'Optimization of Direct-Injection H_2 Combustion Engine Performance, Efficiency, and Emissions' project is focused on
  - providing a clean and efficient, readily available tool for utilization of hydrogen as an energy carrier
  - achieving 45% brake thermal efficiency with minimal NOx emissions
- **Major accomplishments in FY2010 include**
  - demonstration of 50% NOx emissions reduction with less than 1% efficiency penalty
  - 5-7% efficiency improvement with simultaneous 50% NOx emissions reduction through optimized engine geometry and faster injectors
  - 3D-CFD simulation established as powerful tool for efficient optimization
  - 45% brake thermal efficiency achievable with turbo-charged H_2 DI engine
- **Future work includes**
  - optimization of injection parameters (nozzle geometry, injection strategy)
  - development of optimized hydrogen combustion engine system