FPC2024

Future propulsion Conference

National Motorcycle Museum, Solihul
28th & 29th February 2024

Combustion System Development for Zero-carbon Fuels

Mike Bassett and Jonathan Hall
MAHLE Powertrain Limited

28th February 2024

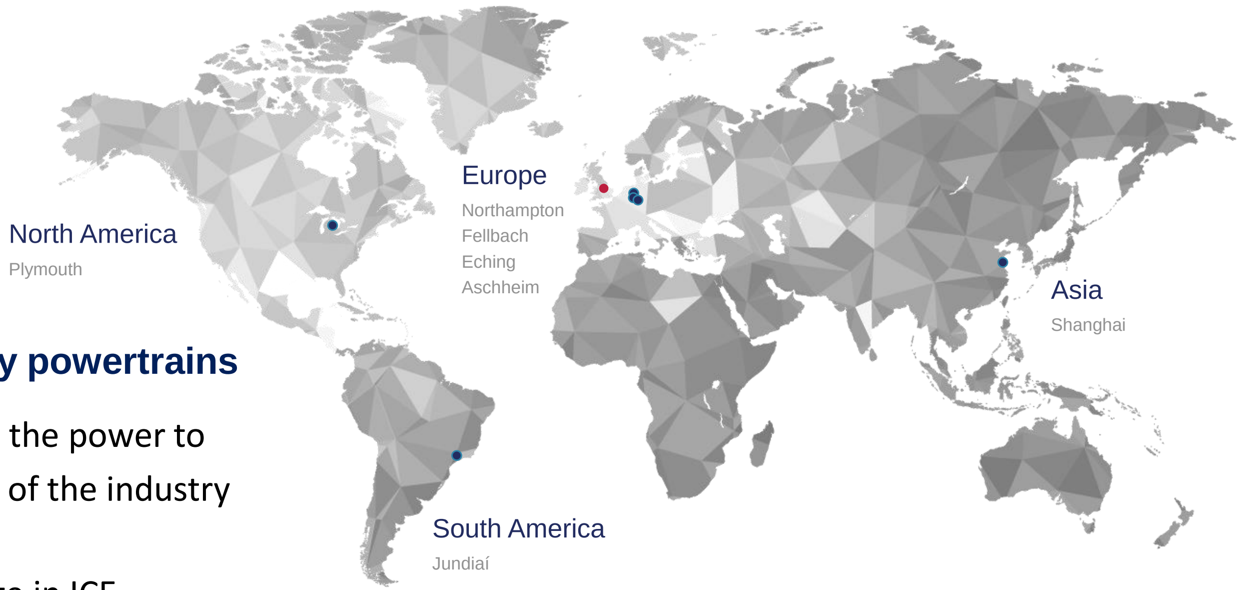
MAHLE Powertrain

Combustion System Development for Zero-carbon Fuels

MAHLE Powertrain Overview

01

MAHLE Powertrain

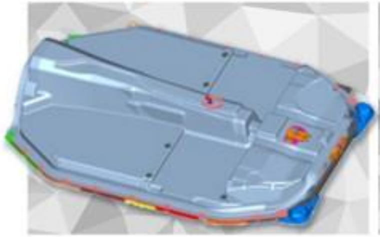


Who We Are

A global **Engineering Services** provider specialising in **high efficiency powertrains**

- For over 60 years, MAHLE Powertrain has provided automotive OEMs with the power to solve complex engineering challenges and adapt to the changing demands of the industry
- Expertise in electrification and thermal management built on a rich heritage in ICE
  - Support customers with expertise across entire powertrain
  - Strength lies in the knowledge and experience of our exceptional people
  - Agile and flexible approach, geared around the true needs of the customer

Core Capabilities



Battery Systems

Advanced Engines & Hybrids

Transmissions & E-Axles

Electric Machines

Bespoke Controls & Software

Development & Validation

Vehicle Integration

Potential Zero Carbon Fuels

02

MAHLE Powertrain

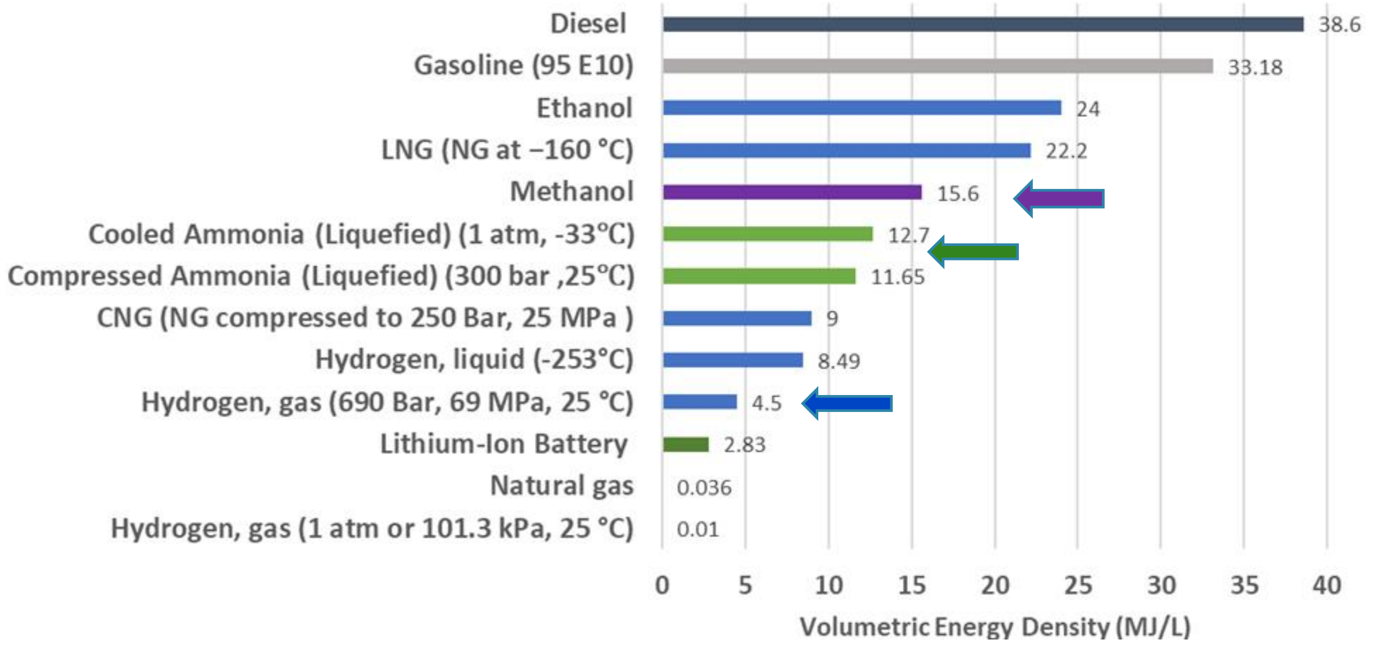
Alternative Fuel Properties Comparison

+Approximate chemical formula for gasoline
*Applicable for large marine and captive off-highway applications only

	Gasoline	Methanol	Hydrogen	Ammonia*
Chemical formula+	$C_{7.2}H_{12.6}$	CH_3OH	H_2	NH_3
Lower heating value (MJ/kg)	42.9	19.9	12	18.8
Laminar burning velocity @λ=1 (m/s)	0.35	0.36	3.51	0.07
Auto-ignition temperature (K)	530	712	773 - 850	930
Research octane number	92-98	119	>100	130
FL in air (vol. %)	1.4-7.6	6.7-36.5	4.7-75	15-28
Quench distance (mm)	0.1-2.0	2.7	0.9	22.1
Absolute minimum ignition energy (mJ)	0.1-0.8	0.14	0.01-0.02	8.00

Alternative Fuels

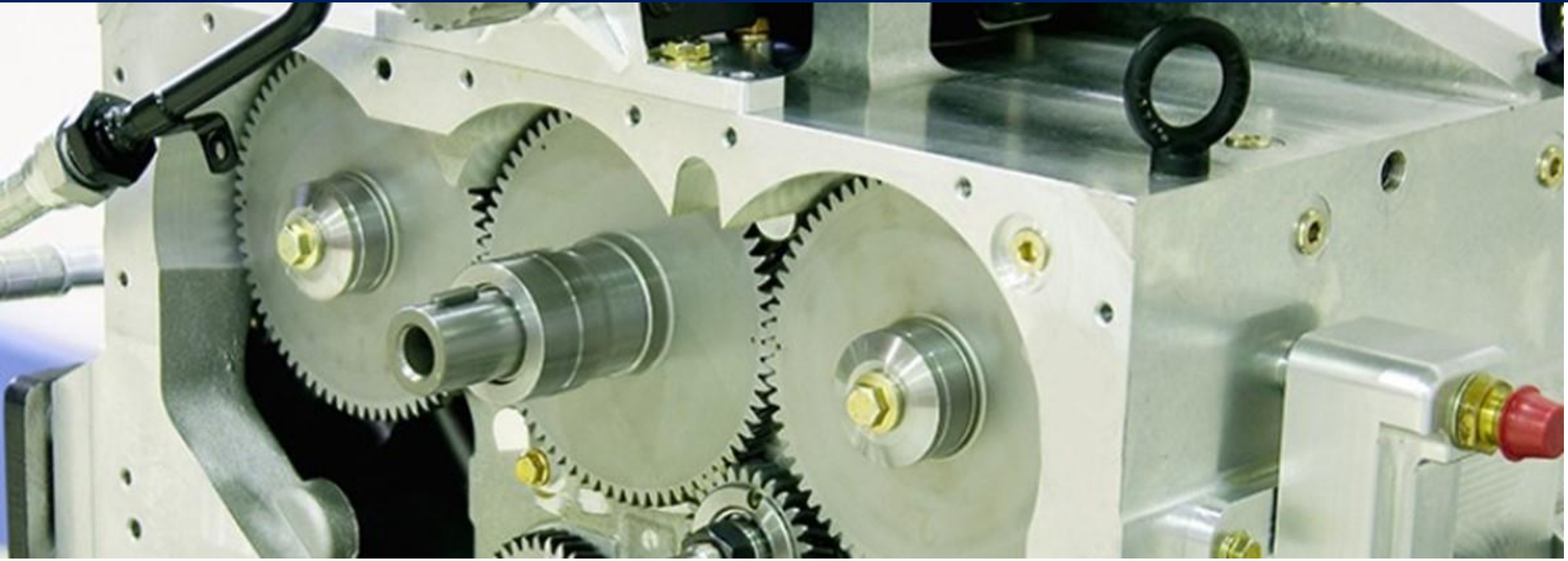
- Methanol
  - Liquid fuel
  - Higher RON -> High CR
- Hydrogen
  - Gas -> hard to store/transport
  - Very fast burning
  - Combusts over a wide AFR range
- Ammonia
  - Liquid fuel
  - Hard to combust
    - High ignition energy and auto-ignition temperature
    - Large quenching distances
    - Slow burning velocity



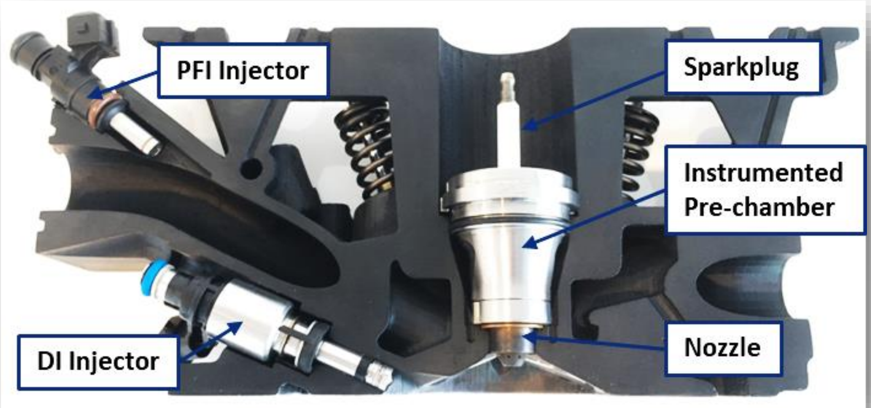
MAHLE Powertrain

Single Cylinder Research Engines

03

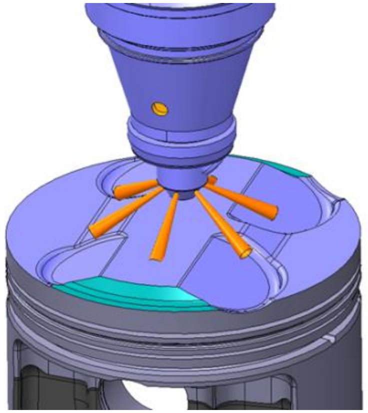


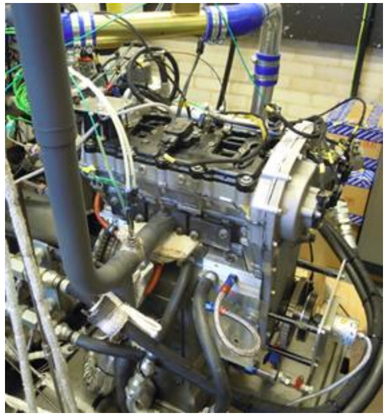
Di3 Derived Single Cylinder Engines (Di1)



Aims

- Based on MAHLE advanced 3-cylinder downsizing demonstrator engine architecture
- Zero-carbon fuel focussed research
- Single-cylinder research engines equipped with spark ignition & pre-chamber combustion based around MAHLE DI3 combustion architecture at:
  - **Nottingham University**
    - Fuels Available: **NH_3**, H2, MeOH, E100, Gasoline
  - **Brunel University**
    - Fuels Available: **H_2**, MeOH, E100, Gasoline





MAHLE Powertrain

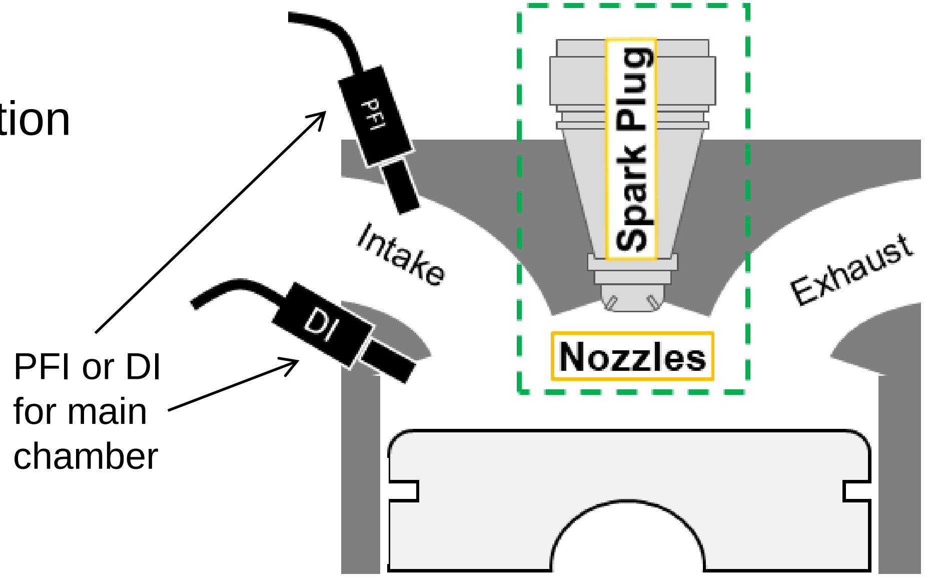
MAHLE Jet Ignition (MJI)

04

MAHLE Jet Ignition (MJI) - Pre-chamber Based Combustion System
Passive Pre-chamber System

- Pre-chamber ignition systems are not new
  - Recent renewed interest for high efficiency
  - Key challenges
    - Whole map operation
    - Cold start

- Pre-chamber concepts
  - Active
  - Passive

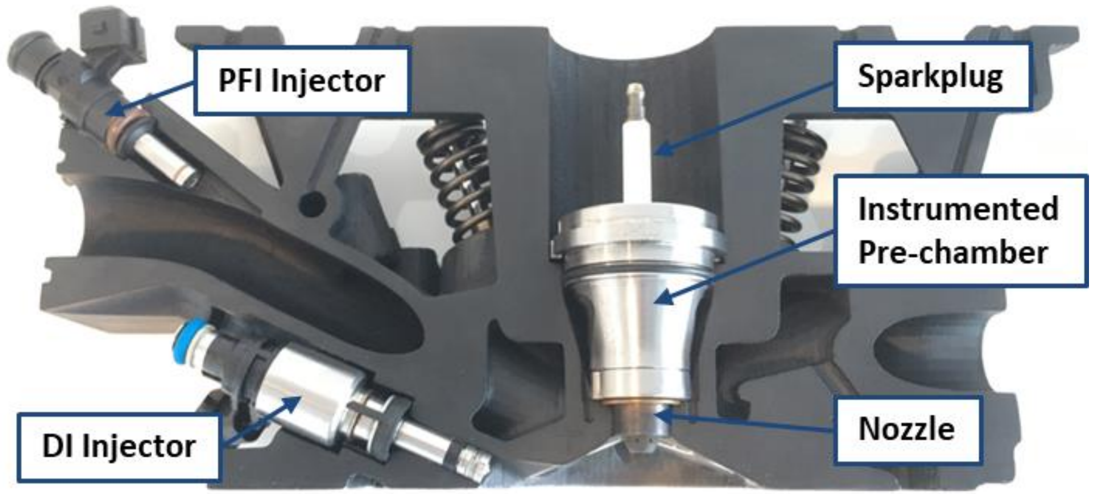


Passive Layout:
- 1 Injector
- λ=1
- EGR Dilution
- Conventional After-treatment

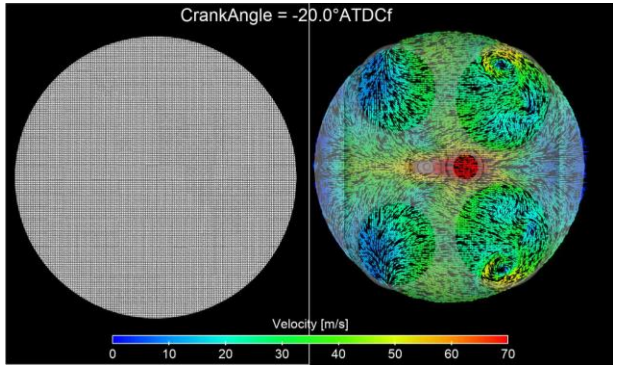
Key Benefits:
- Knock Reduction
- Faster more Stable Combustion

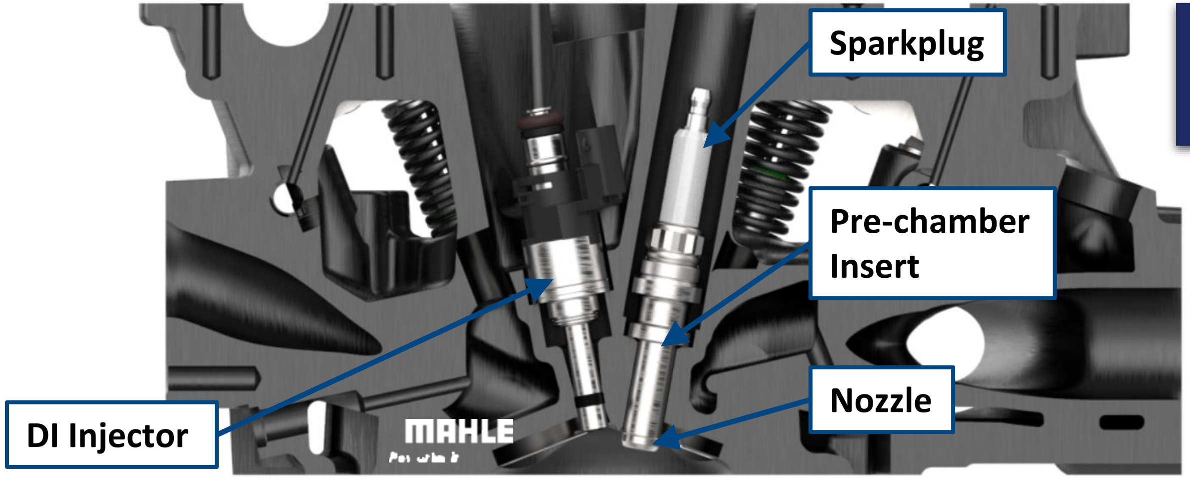
MAHLE Powertrain

Passive MJI Insert Installation Examples



Research Installation

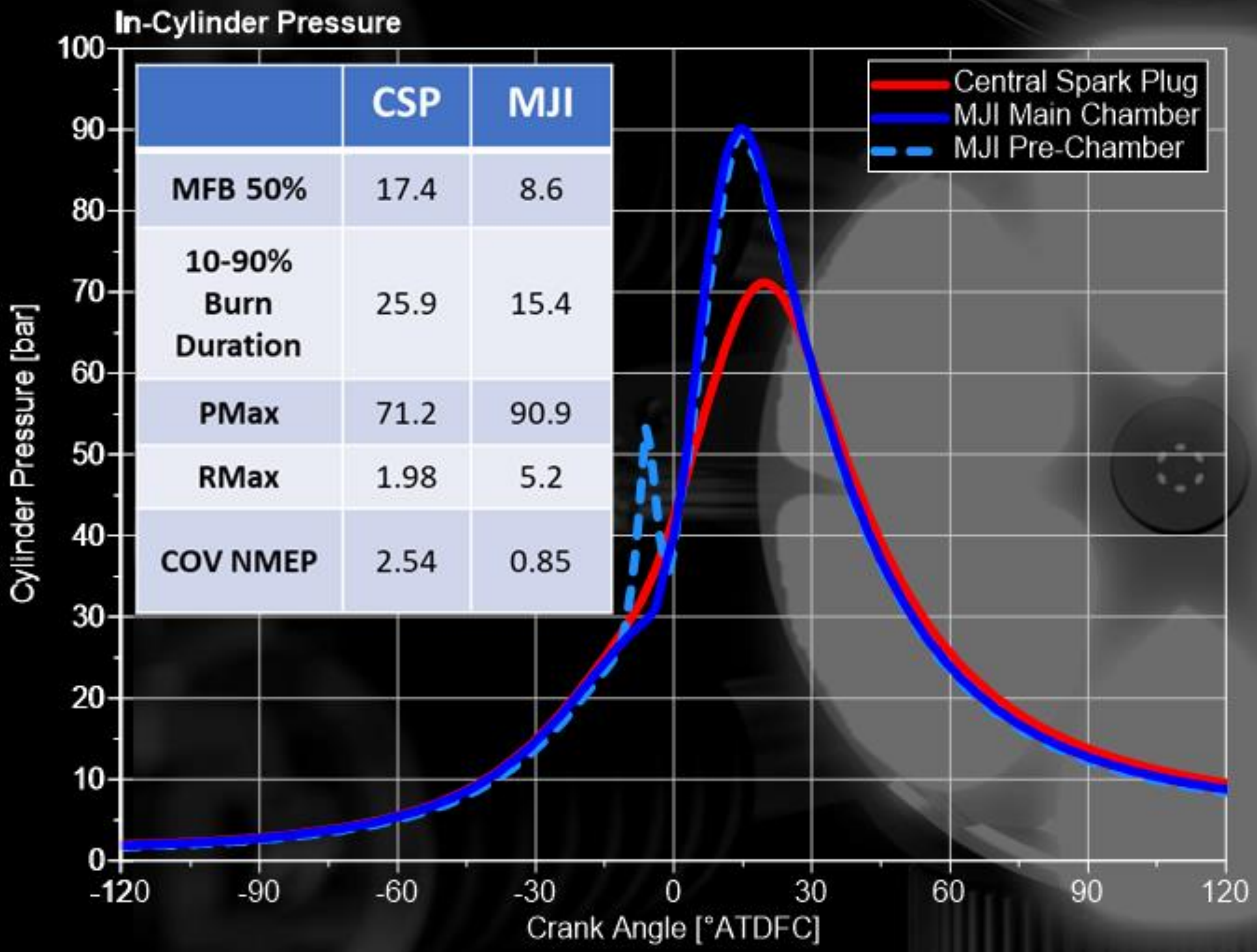




Production Installation

MAHLE Powertrain

Introduction



	CSP	MJI
MFB 50%	17.4	8.6
10-90% Burn Duration	25.9	15.4
PMax	71.2	90.9
RMax	1.98	5.2
COV NMEP	2.54	0.85

Standard Spark Plug

Passive MAHLE Jet Ignition

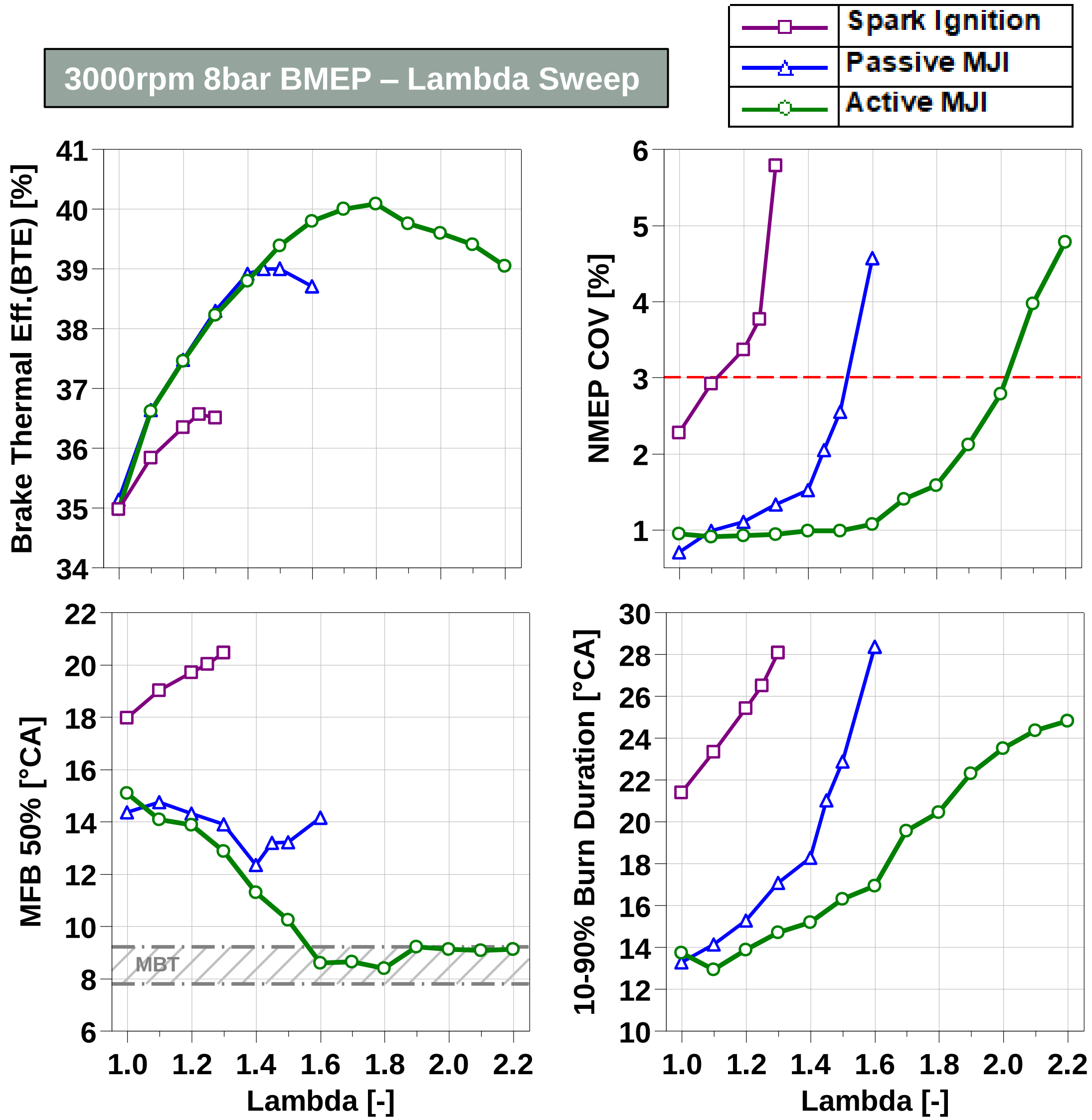
Effects:

- Faster Combustion
- Knock Mitigation
- Improved Stability
- Higher Maximum Pressure
- Higher Pressure Rise Rate

MJI – Lean Limit Extension

Gasoline Combustion

- **Spark Ignition**
  - Heavily limited by knock (High CR16)
  - Low tolerance to dilution
  - Slow burn & low BTE
- **Passive MJI**
  - Faster burn duration & adv phasing
  - BTE increases by 3.2% (39%)
- **Active MJI**
  - High tolerance to dilution (Maximum at λ2.0)
  - Improved jet penetration leads to faster burn
  - BTE improvement from Passive MJI to 40.1%

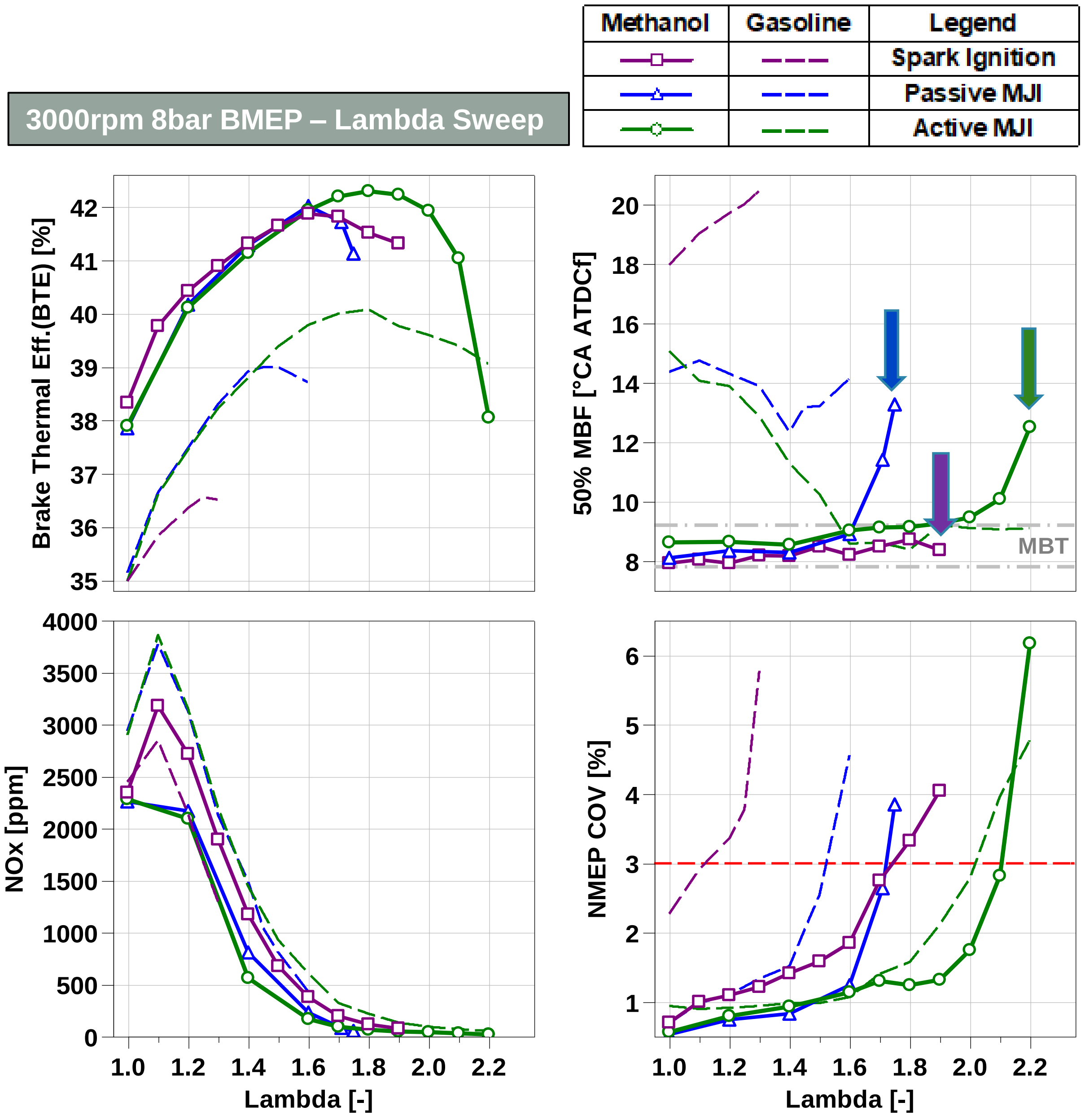


Methanol

05

Powertrain

Methanol Tests with MJI



Methanol Combustion – Lean Sweep

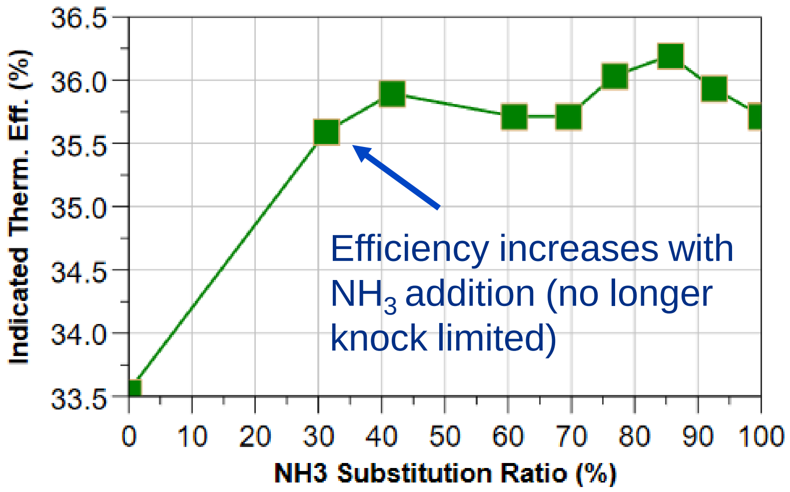
- **Spark Ignition**
  - shows largest BTE improvement on Methanol
    - Increase in max enleanment = λ1.1 to λ1.7
    - High RON allows for MBT spark timing throughout λ range
- **Passive MJI**
  - Shows a modest improvement
    - Increase in max enleanment = λ1.5 to λ1.7
    - Moderate reduction in NOx = 810ppm to 229ppm
- **Active MJI**
  - Maximum enleanment only increases by a small amount but:
    - BTE increase = 40% to 42.3%
    - Increase in max enleanment = λ2 to λ2.1
    - NOx = 97ppm to 41ppm

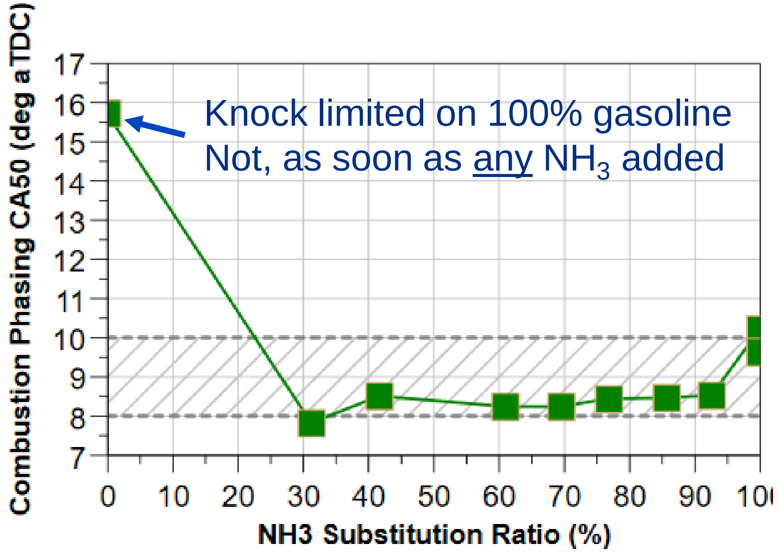
Ammonia

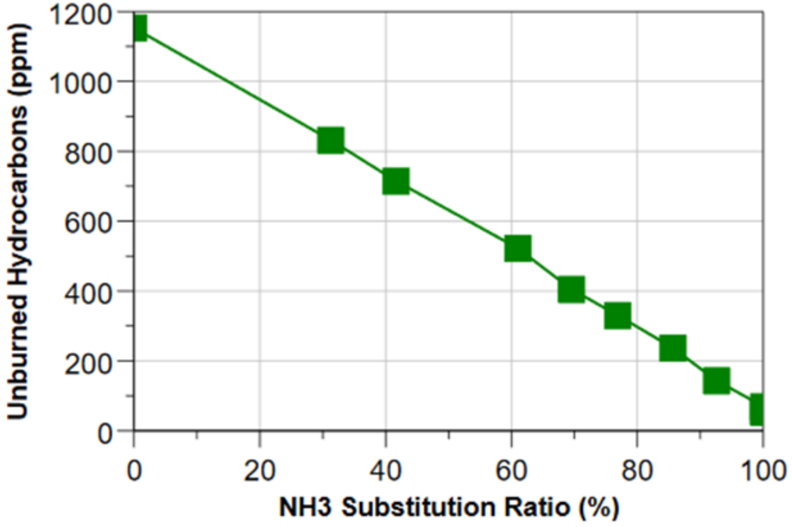
06

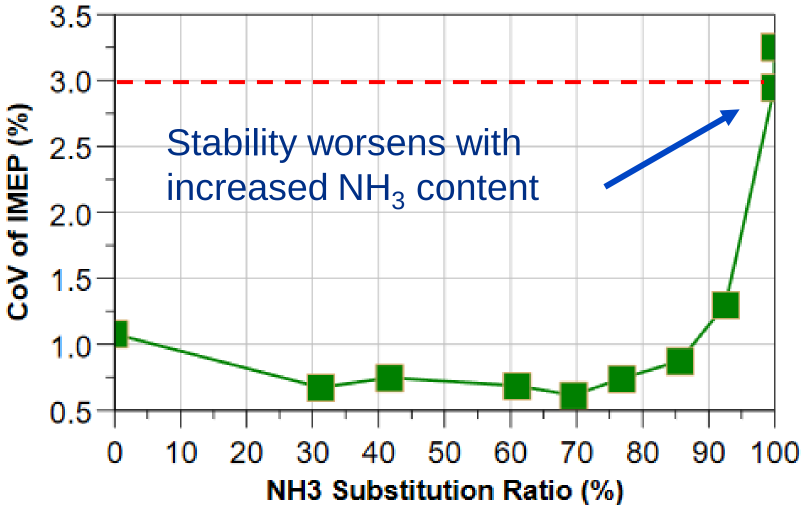
Ammonia Combustion Tests: Spark Ignition

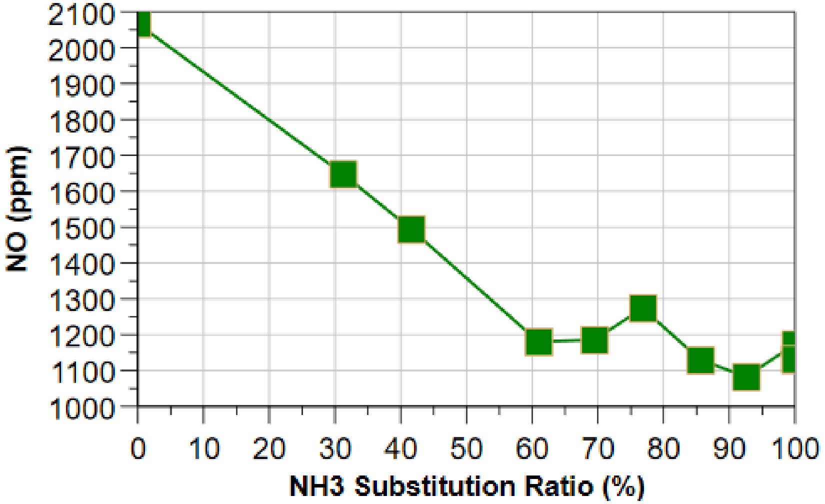
Data set from initial gasoline/ammonia substitution investigation (1800 rpm, 12 bar IMEP)

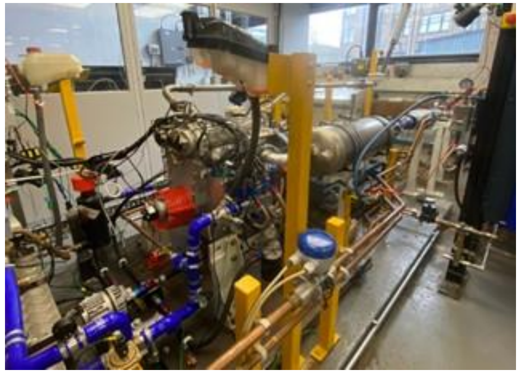






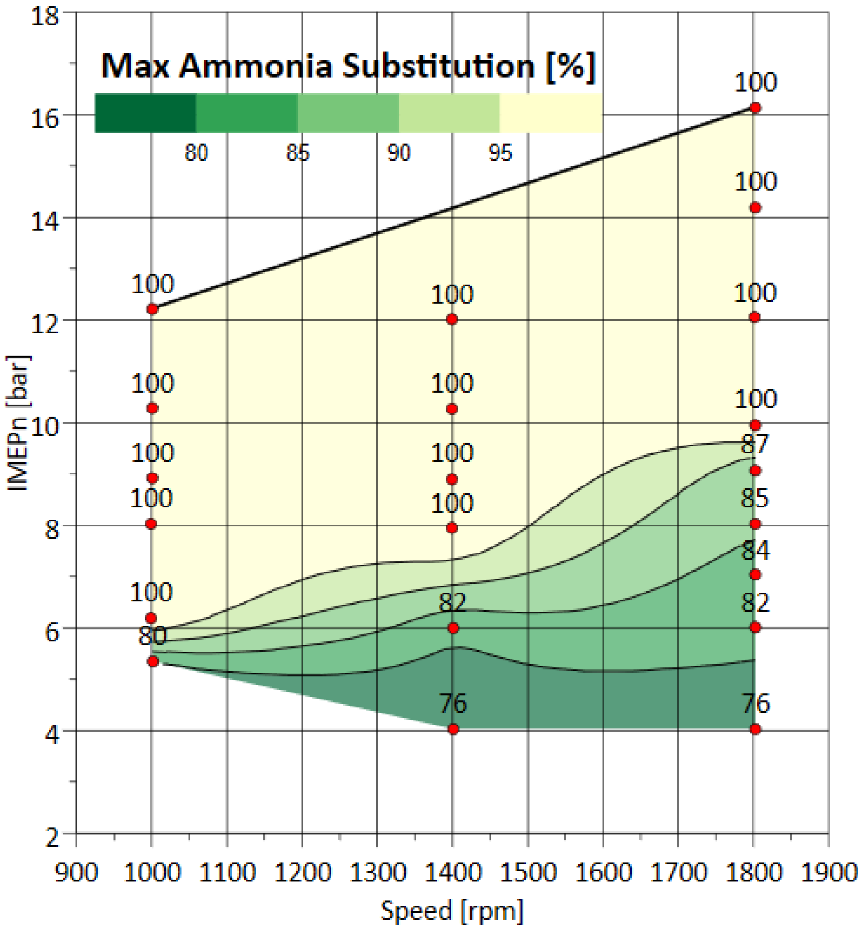


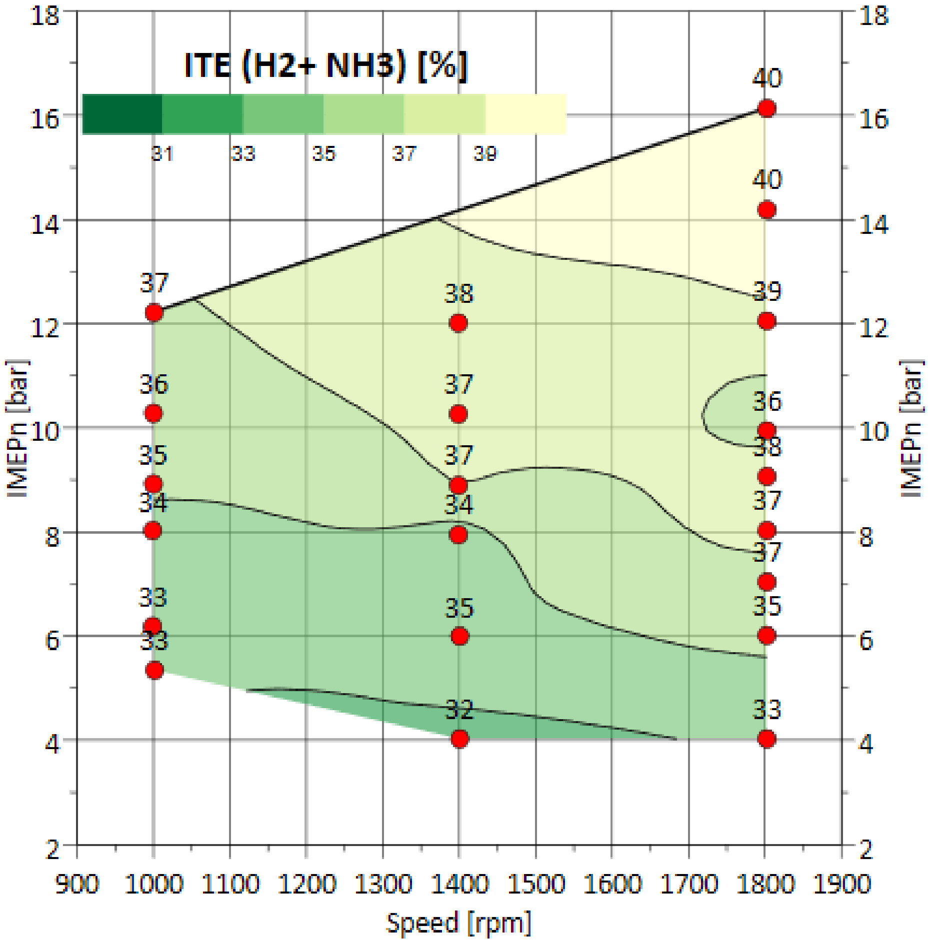




Ammonia Combustion Tests

Maximum Ammonia Substitution and Efficiency





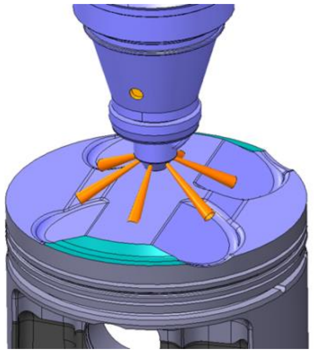
MAH

Ammonia Combustion Tests: Jet Ignition

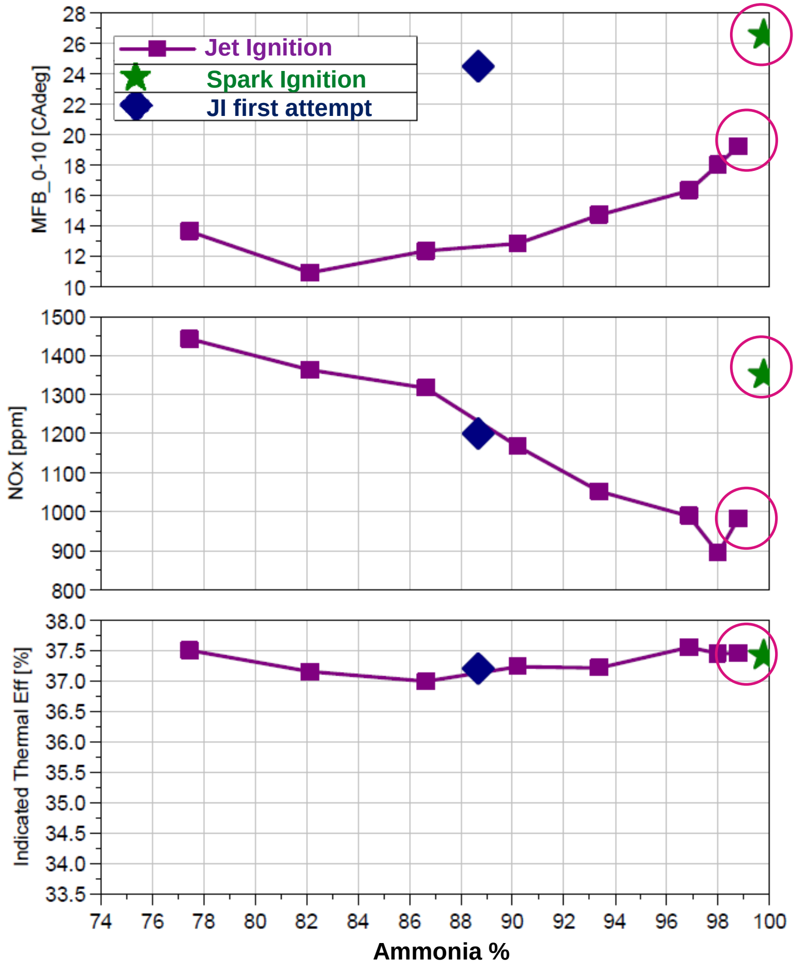
Speed/load?

Ammonia MJI (Stoichiometric)

- MAHLE Jet Ignition minimises the need for supplementary hydrogen
  - As little as 1% H_2 can give a clear benefit
  - MAHLE Jet ignition speeds up the flame development period (faster early burn)
  - ~30% reduction in engine-out NOx
  - in NH_3 slip



	Spark Ignition	Jet Ignition
H_2	0	1%
NOx	1350ppm	990ppm
0-10% MFB	27°ca	19°ca



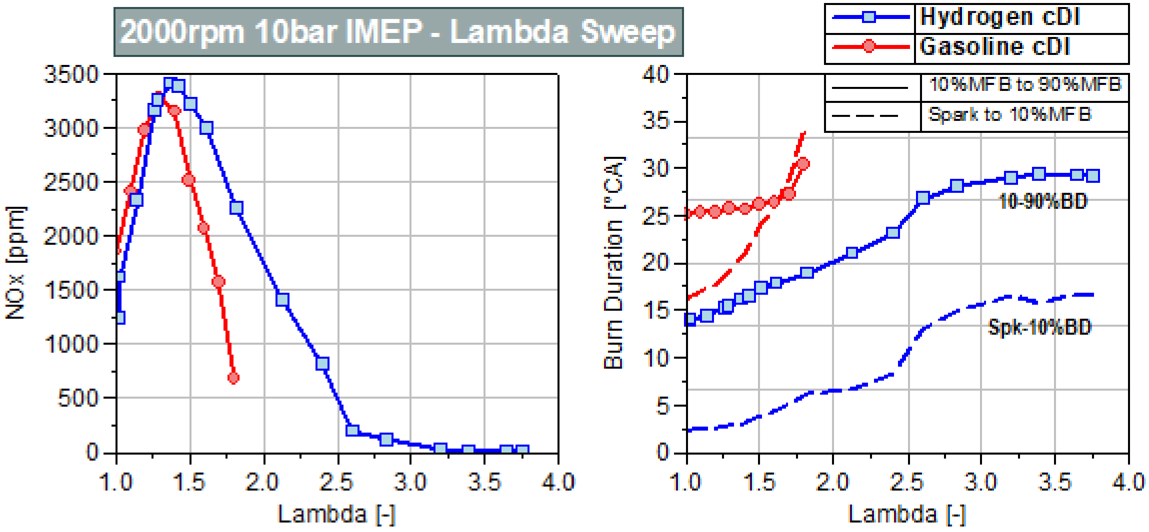
Hydrogen

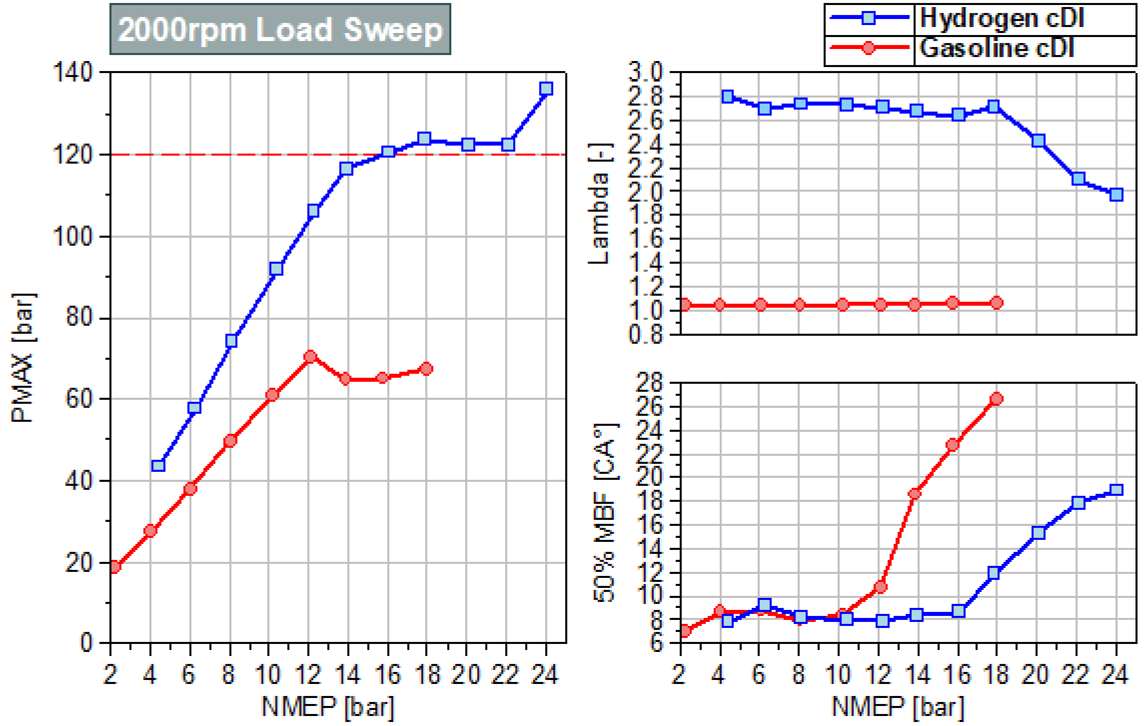
07

Hydrogen Combustion

Hydrogen Combustion Charateristics

- Hydrogen burns very quickly
- Easy to ignite
- Wide flammability limits
- High Pressures, temperatures and rate of pressure rise
  - Can lead to high NOx emissions at high load
- High stability
  - Combustion is easy to start
  - All hydrogen burns
  - Very (very) late burning possible
    - High exhaust gas temperatures
- Gasoline style (pent roof / high tumble) combustion system
  - Highly robust engine architecture required
    - High Pmax
    - High Rmax

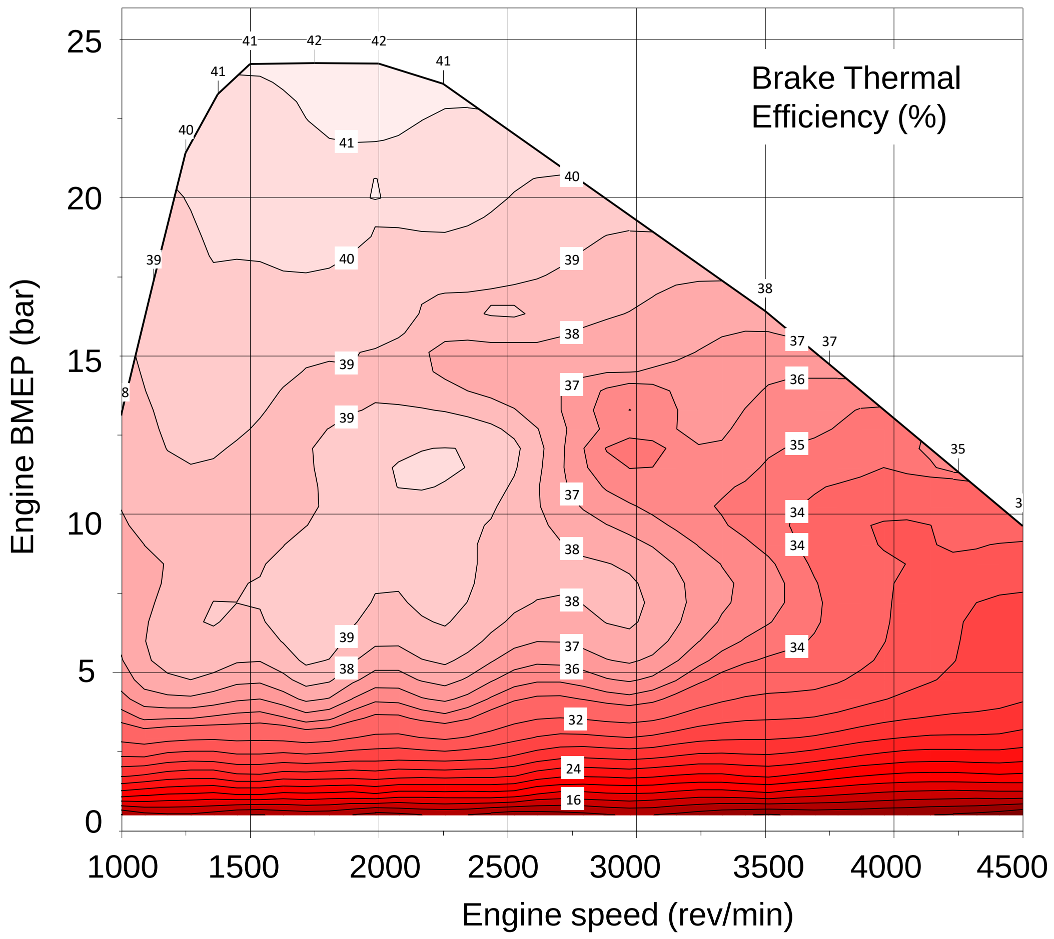


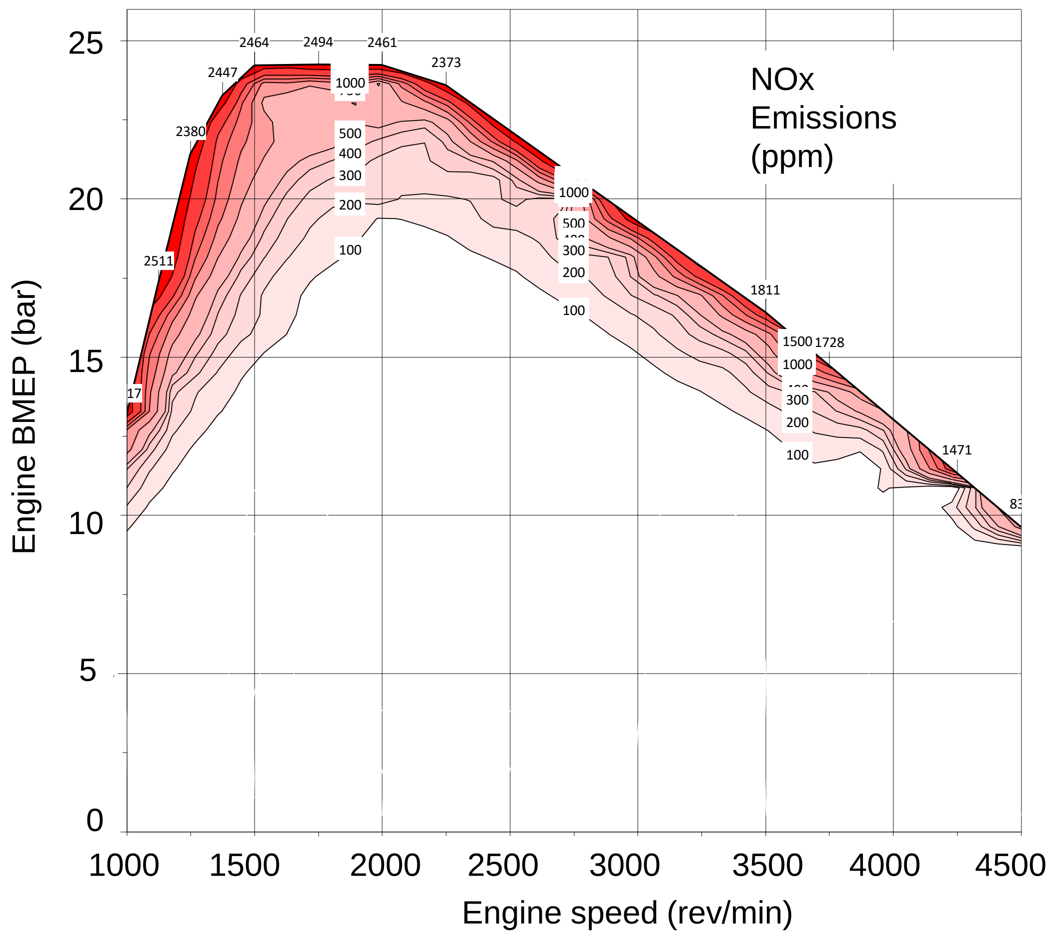


Brunel University London

MAHLE Powertrain

Hydrogen Operating Map





- 24 bar BMEP
- High efficiency across majority of operating map

- Negligible engine out NOx across majority of map (lambda >2.5)
- Higher load NOx readily treated with lean aftertreatment system

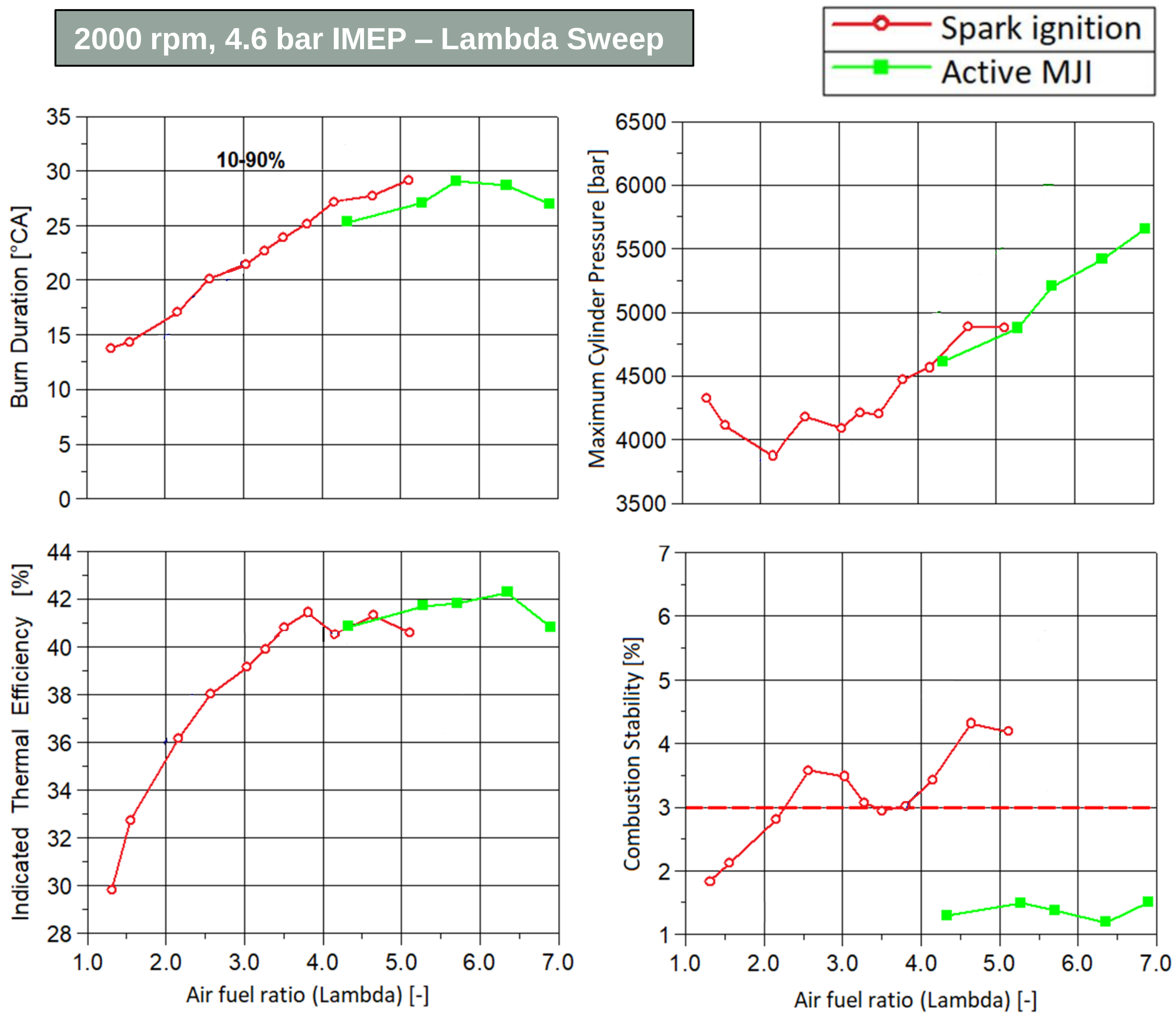
MAHLE Powertrain

Hydrogen with MAHLE Jet Ignition

MAHLE Jet Ignition

- Ultra-lean operation
  - Lambda = 6 – 7 possible with Active MJI
  - Still retains excellent combustion stability
- Engine out NOx negligible (<10 ppm)
- Slower combustion
  - Reduced knock
- Boosting system requirement is high
  - High boost levels to get good power density

2000 rpm, 4.6 bar IMEP – Lambda Sweep

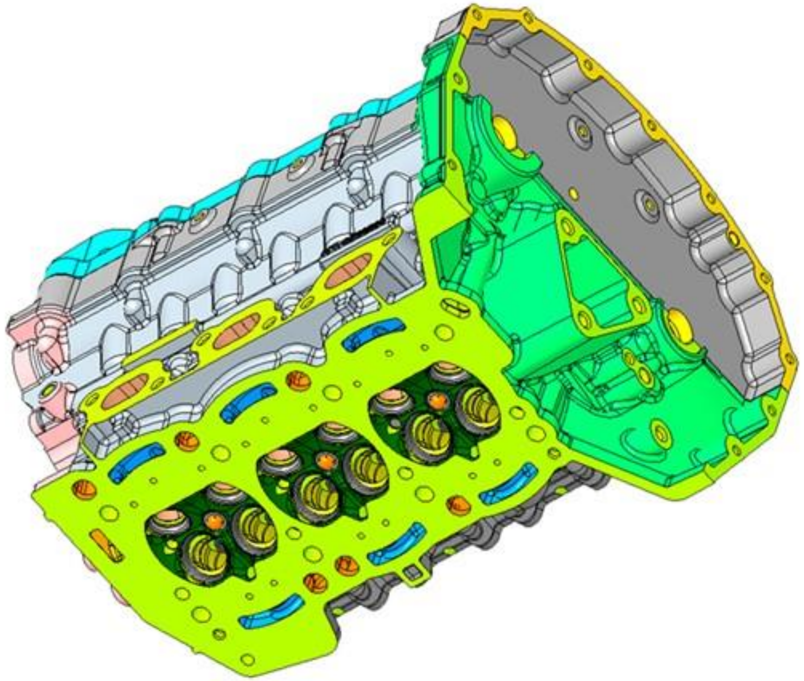


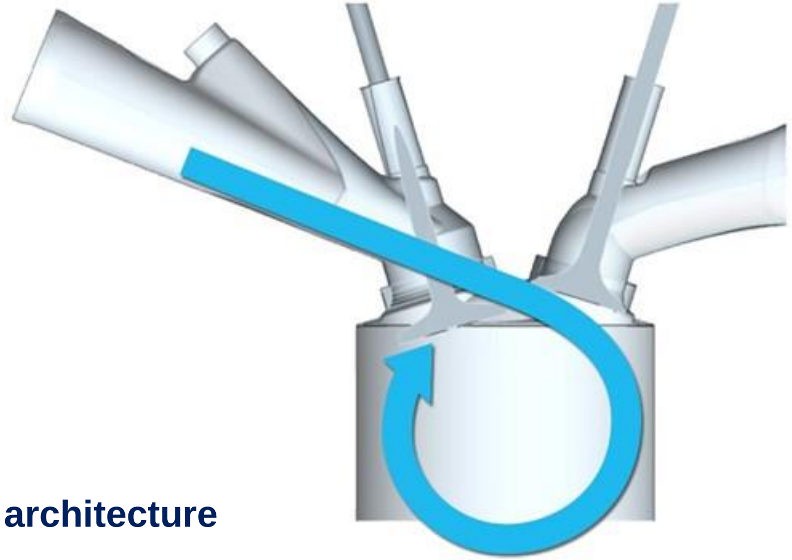
Conclusions

08

MAHLE Powertrain

Conclusions





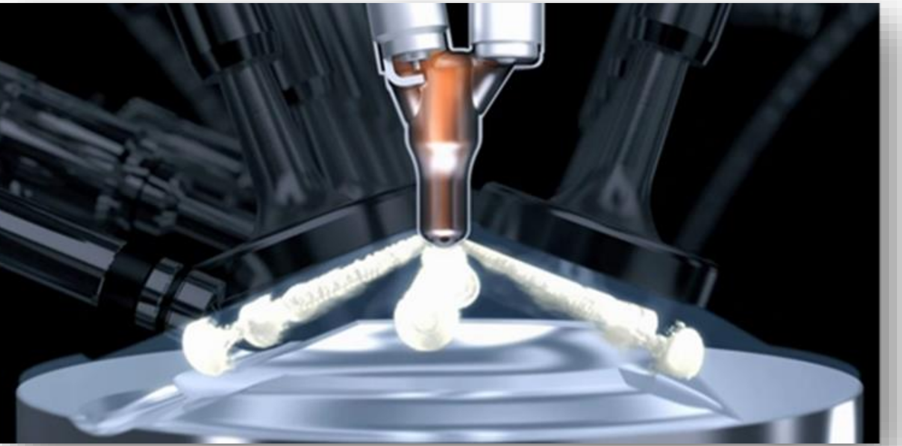
Key Takeaways

- Methanol
  - Liquid fuel -> good energy density
  - Combustion similar to gasoline combustion, with higher knock resistance
    - High CR required for best efficiency

- Ammonia (Large marine vessels and captive off-highway fleet applications)
  - Liquid fuel
  - Difficult to ignite
    - A modest amount of hydrogen (~1%) with active pre-chamber system gives excellent results

- Hydrogen
  - Low energy density
  - Fast combustion
  - Ultra-lean operation (λ>2.5) is key for ultra-low engine out NOx
    - Active MJI is useful to enable stable combustion at very lean conditions

- **All of these fuels work well with a conventional spark-ignition gasoline combustion system architecture**



Thank you

For further information please contact:
powertrain@mahle.com
www.mahle-powertrain.com

MAHLE Powertrain