

Combustion development of a Hydrogen ICE using Jet Ignition and alternative injection methods

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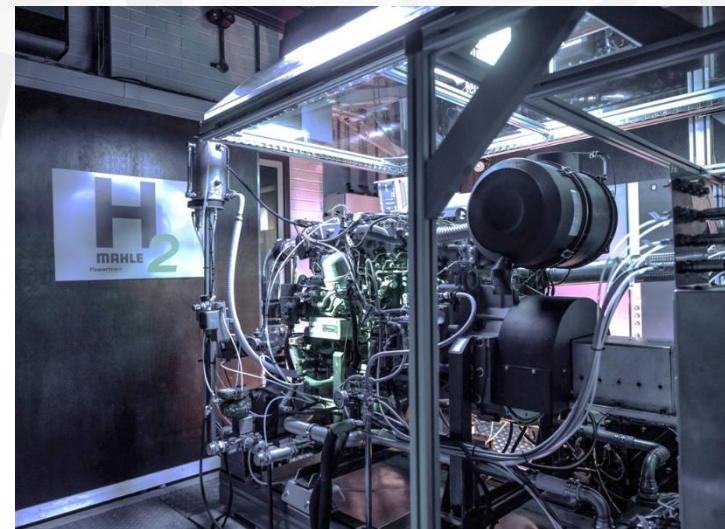
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Vehicle Integration

Hydrogen Engine Development Roadmap



Gen 1:

- Retrofit - Dual Fuel
- Diesel fallback
- Carbon Emissions
- Minimum hardware changes

Common approach for retrofit:

- Often with piggy-back ECU
- Key benefit is the Diesel fallback when H_2 unavailable
- Not zero CO_2

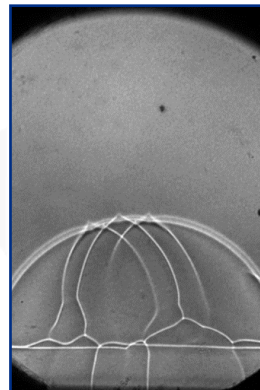


Gen 3:

- OE - Fully optimised for Hydrogen
- Bespoke combustion architecture
- Advanced Tech. (Boosting and combustion systems)

Gasoline 'pent roof' style tumble based combustion system:

- Designed for air/fuel mixing and turbulent energy (TKe) near spark plug at ignition



Gen 2:

- Retrofit & OE - Spark ignition
- Full decarbonisation
- Good efficiency
- Clean Tailpipe Emissions

Diesel type (swirl or quiescent) combustion system retained:

- Diesel injector swapped with a sparkplug
- Port fuel injection commonly adopted

Hydrogen ICE Emissions Focus

Global Warming Potential (GWP):

- Need to consider Global Warming Potential (GWP)

Useful GWP numbers:	GWP ₂₀	GWP ₁₀₀
– Carbon Dioxide (CO ₂)*	1	1
– Hydrogen (H ₂)**	35	12
– Nitrous oxide (N ₂ O)*	273	273

- Need to minimise hydrogen slip (unburned fuel)

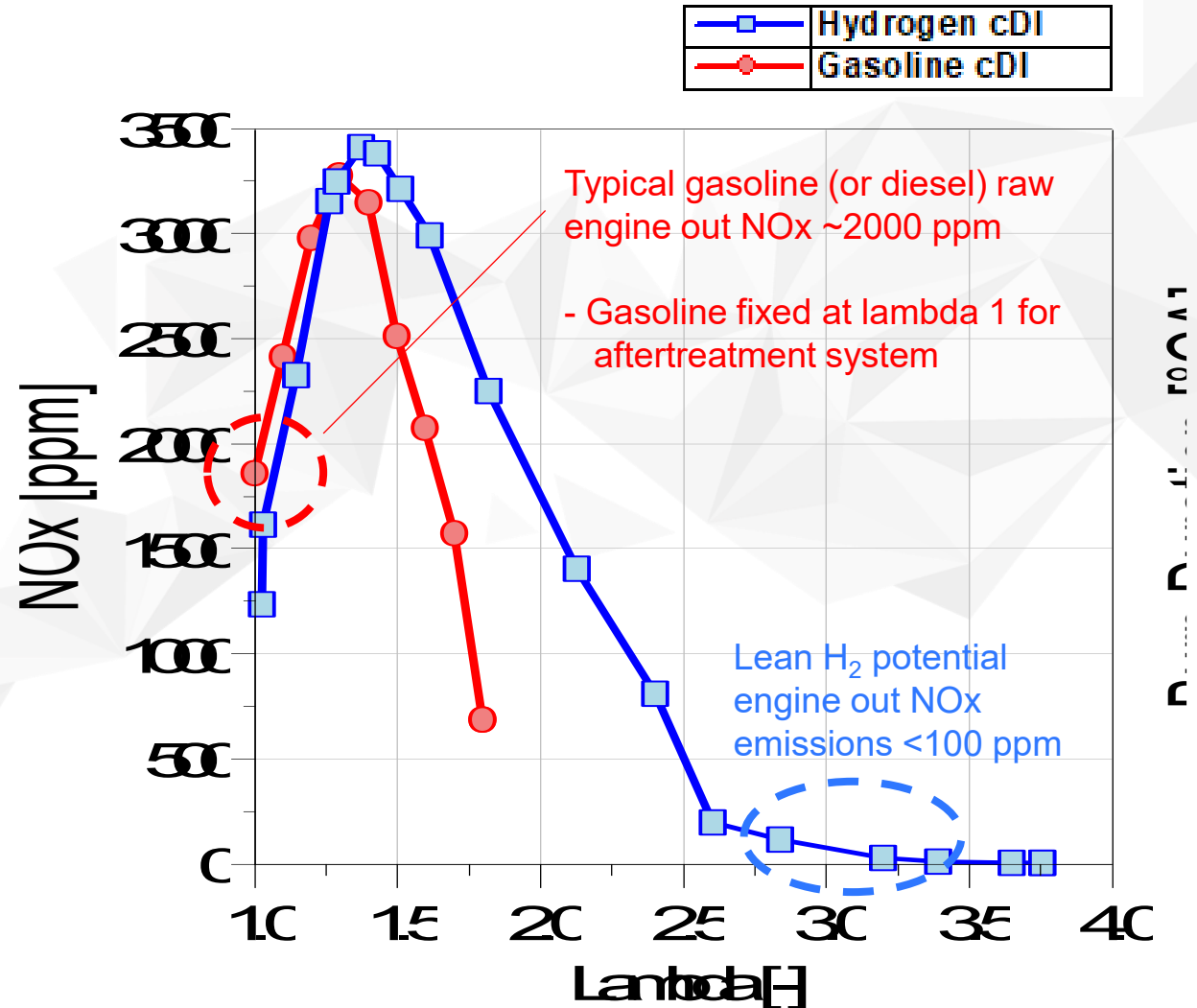
- Need to minimise NOx emissions

- Lean operation is key to clean hydrogen combustion**

* IPCC Global Warming Potential Values 6th Assessment Report (AR6)

** Sand et al, 2023 doi.org/10.1038/s43247-023-00857-8

*** Ammonium Nitrate decomposition to N₂O as reference for worst case

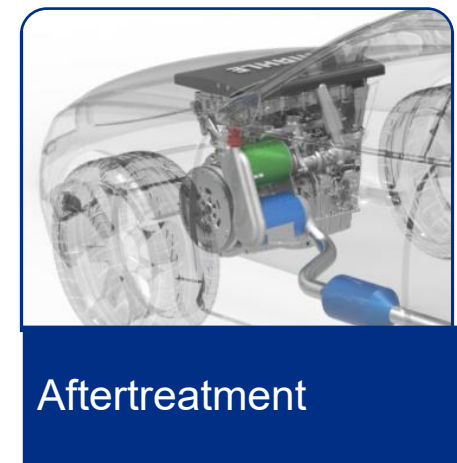
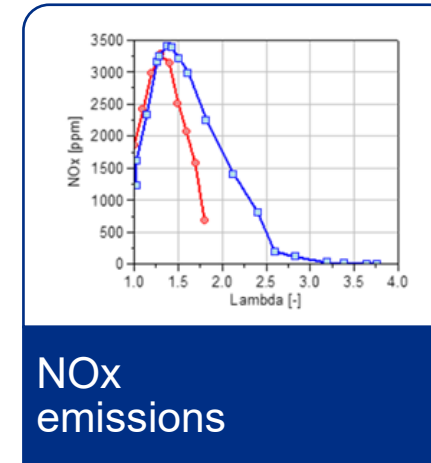
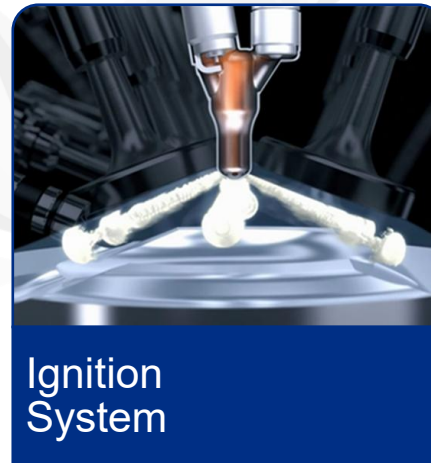
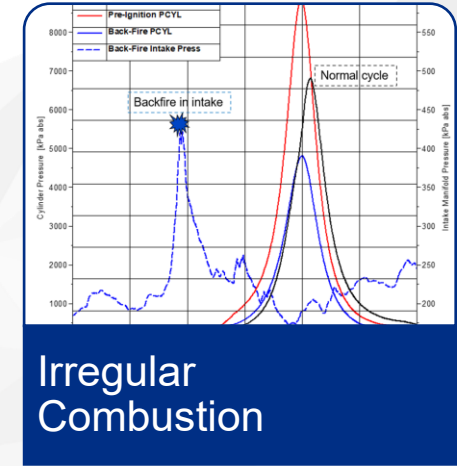
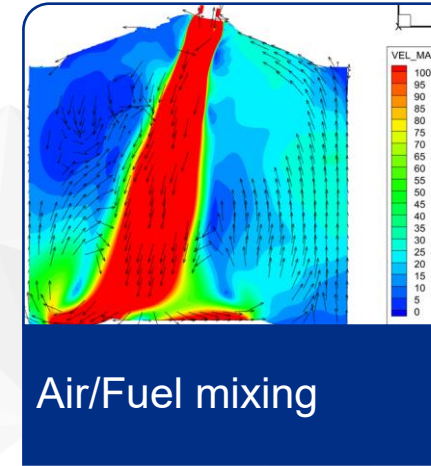
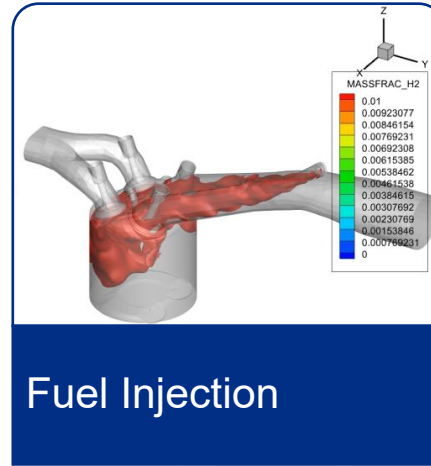


Measured 2000 rev/min 10 bar BMEP Lambda sweep

Challenges with Hydrogen Combustion

For H₂ ICE development it is key to:

- Minimise NOx emission
- Maximise efficiency
- Minimise or eliminate irregular combustion
- Provide robust ignition of air/fuel mixture
- Enable lean air/fuel mixtures



Direct vs Port Fuel Injection

Good mixture preparation is key:

Predictable / stable combustion:

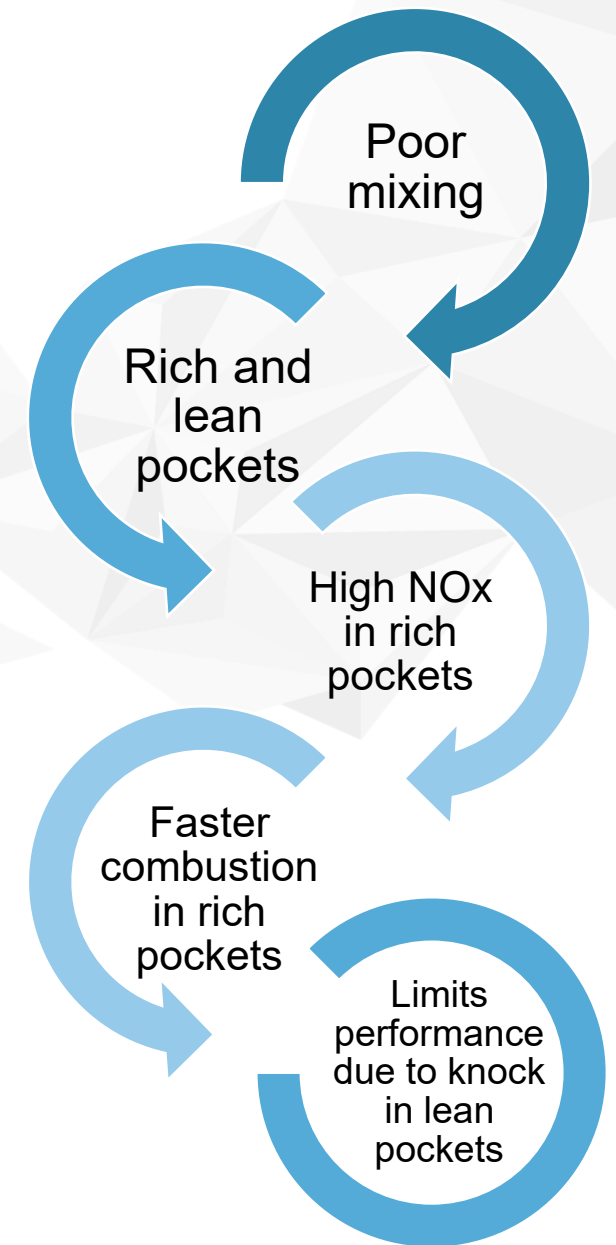
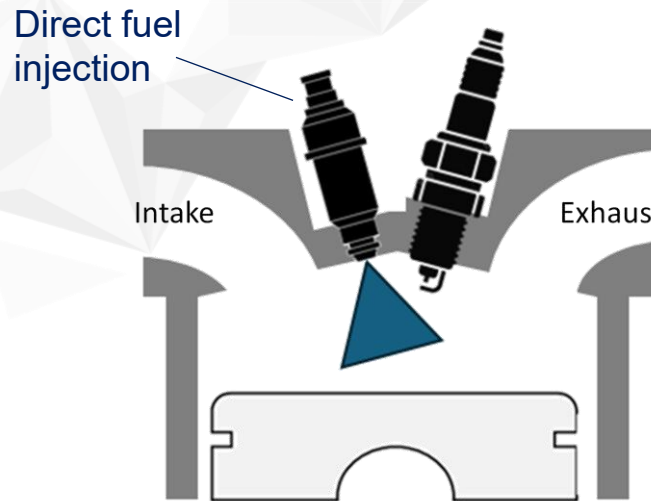
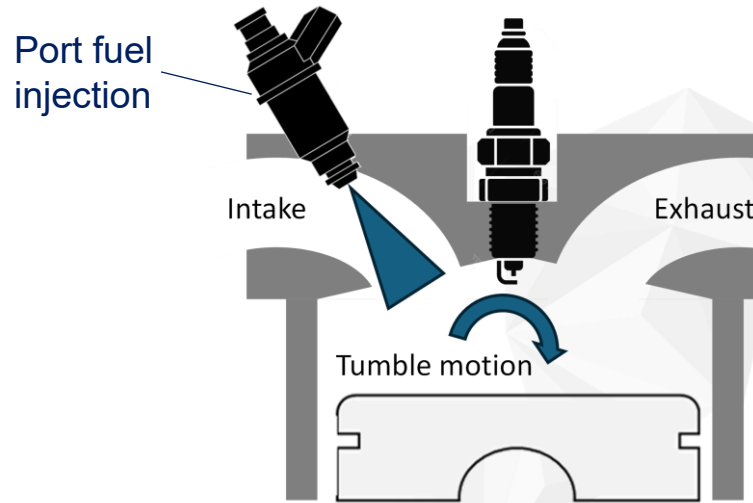
- Uniform burn
- Low emissions
- High efficiency
- Minimal irregular combustion

Port fuel injection:

- Good mixing
- High boost pressures
- Intake manifold backflash risk

Direct injection:

- Challenges with mixing
- Lower boost pressures
- Lower irregular combustion risk



Direct vs Port Fuel Injection

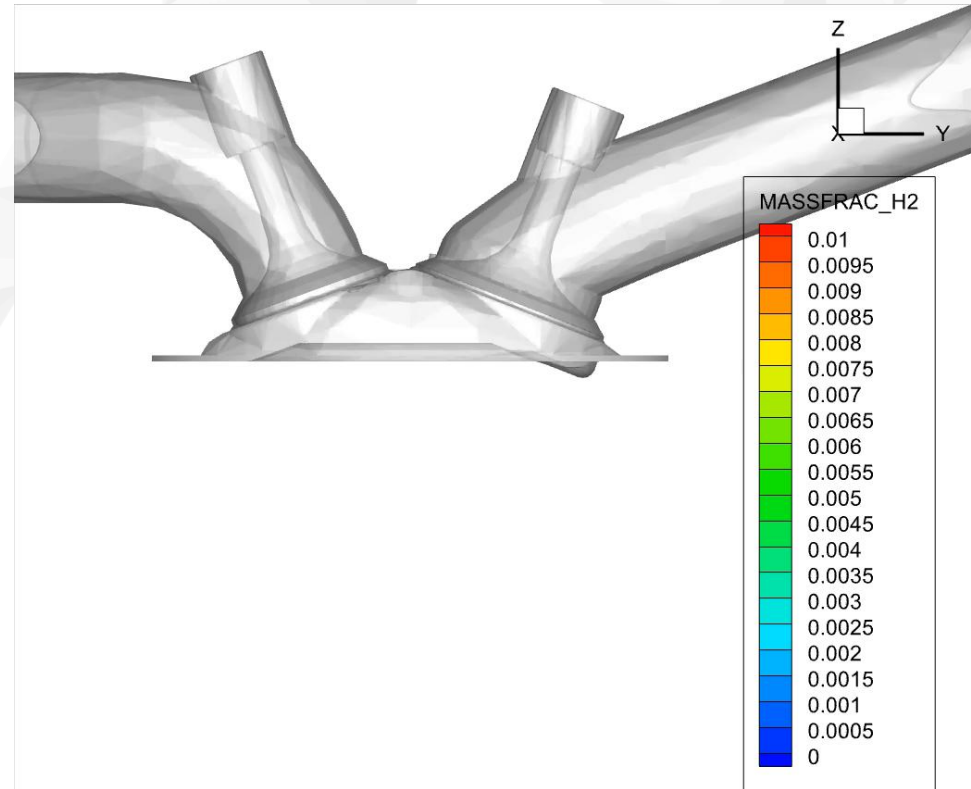
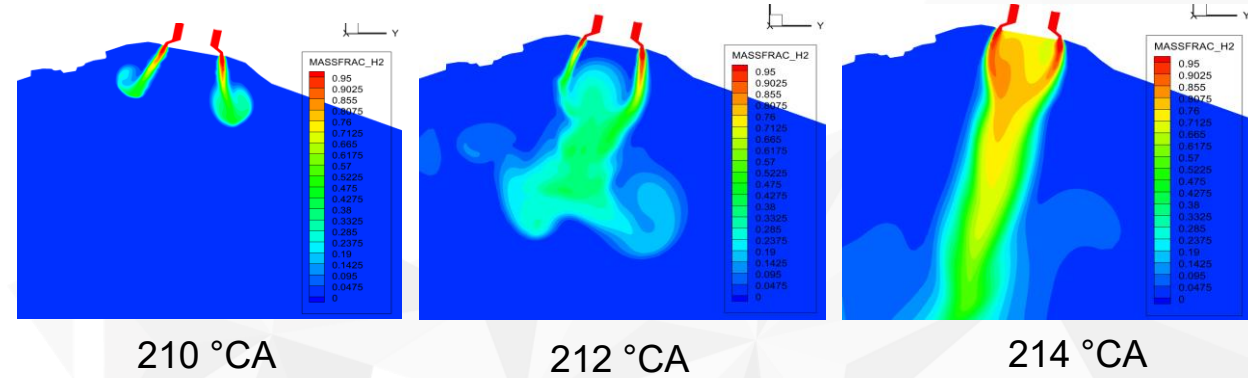
Development tools at MAHLE Powertrain

Combustion CFD:

- 1D modelling for boundary conditions
- Moving mesh 3D model
- Injection modelling
- Advanced techniques for H₂ combustion

Design optimisation:

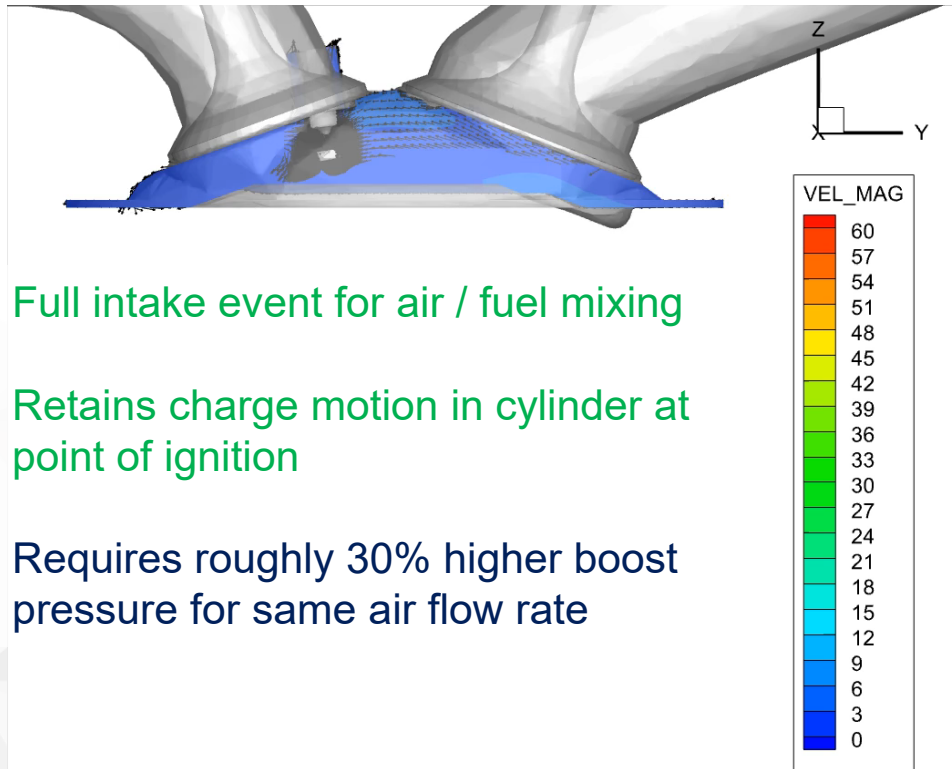
- Injection pressures & timing
- Combustion chamber design
- Intake port geometry
- Injector nozzle optimisation



Direct vs Port Fuel Injection

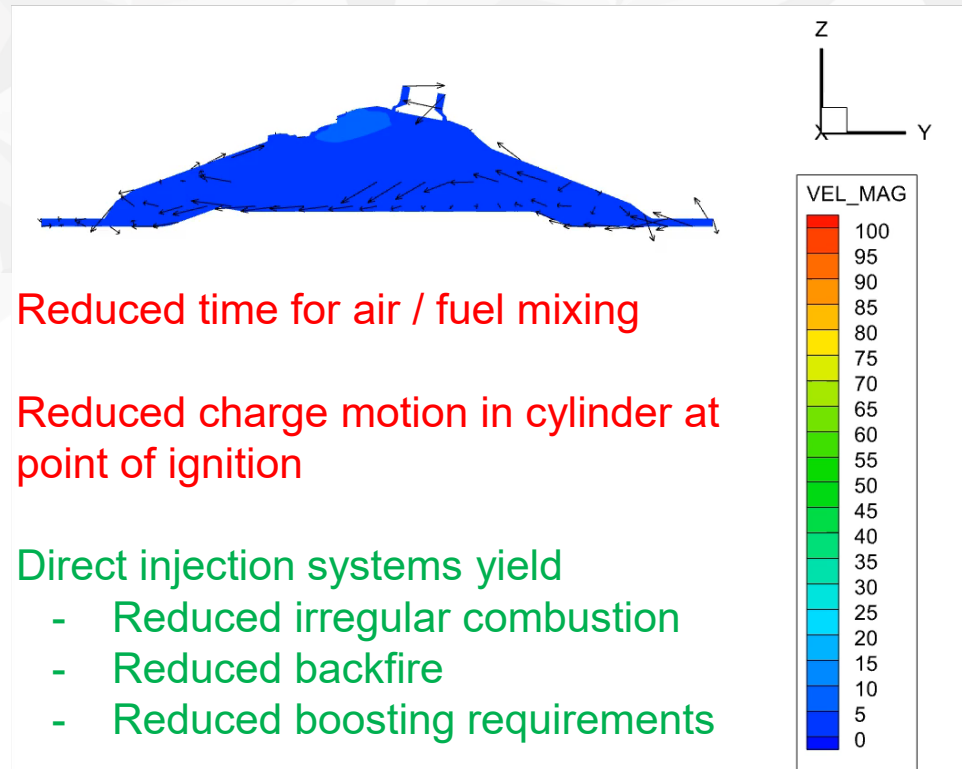
CFD optimisation

Port Fuel Injection – In-cylinder Velocities



- Full intake event for air / fuel mixing
- Retains charge motion in cylinder at point of ignition
- Requires roughly 30% higher boost pressure for same air flow rate

Direct Injection – In-cylinder Velocities



- Reduced time for air / fuel mixing
- Reduced charge motion in cylinder at point of ignition
- Direct injection systems yield
 - Reduced irregular combustion
 - Reduced backfire
 - Reduced boosting requirements
- Requires careful optimisation

MAHLE Jet Ignition

MJI Overview

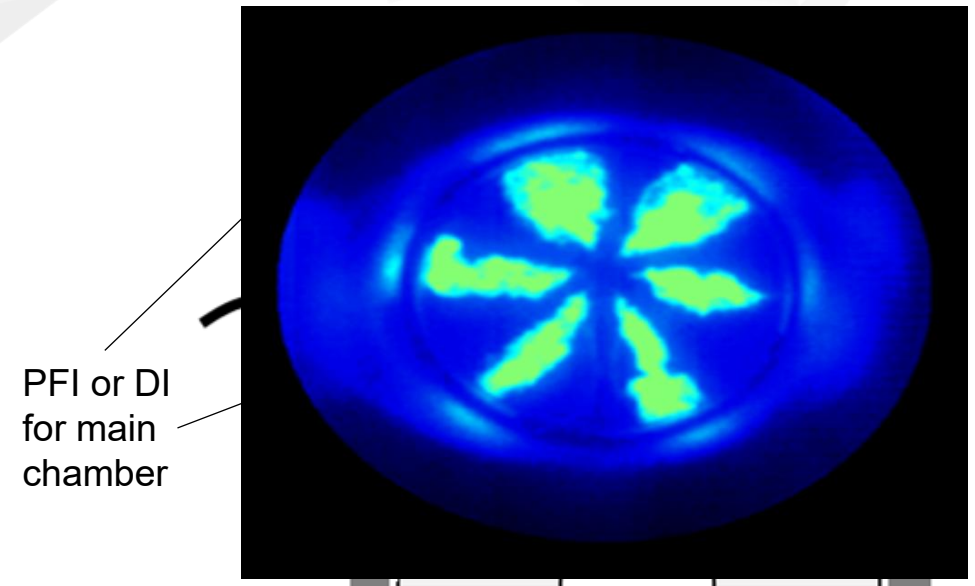
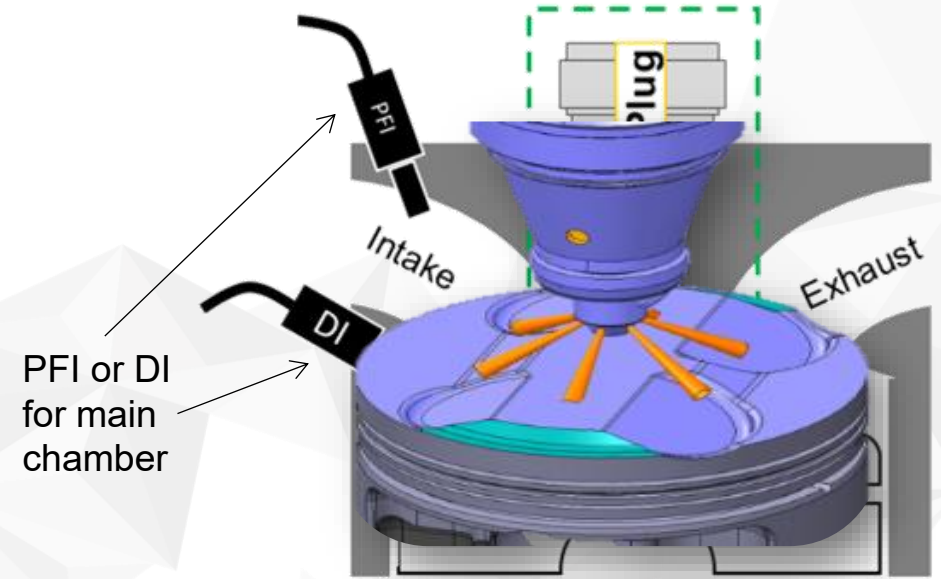
- Original system developed for F1, now in road engines
- Enables higher compression ratio, efficiency and performance on Gasoline, Natural Gas and Biofuels

Passive Layout

- Only 1 fuel injector (for main chamber)
- Common air-fuel ratio in main and pre-chambers
- Multiple ignition sites in main chamber
- Fast and stable combustion event with reduced knock

Active Layout

- Dedicated pre-chamber injector
- Decoupling of air-fuel ratio in main and pre-chambers
- Typically used for ultra-lean operation

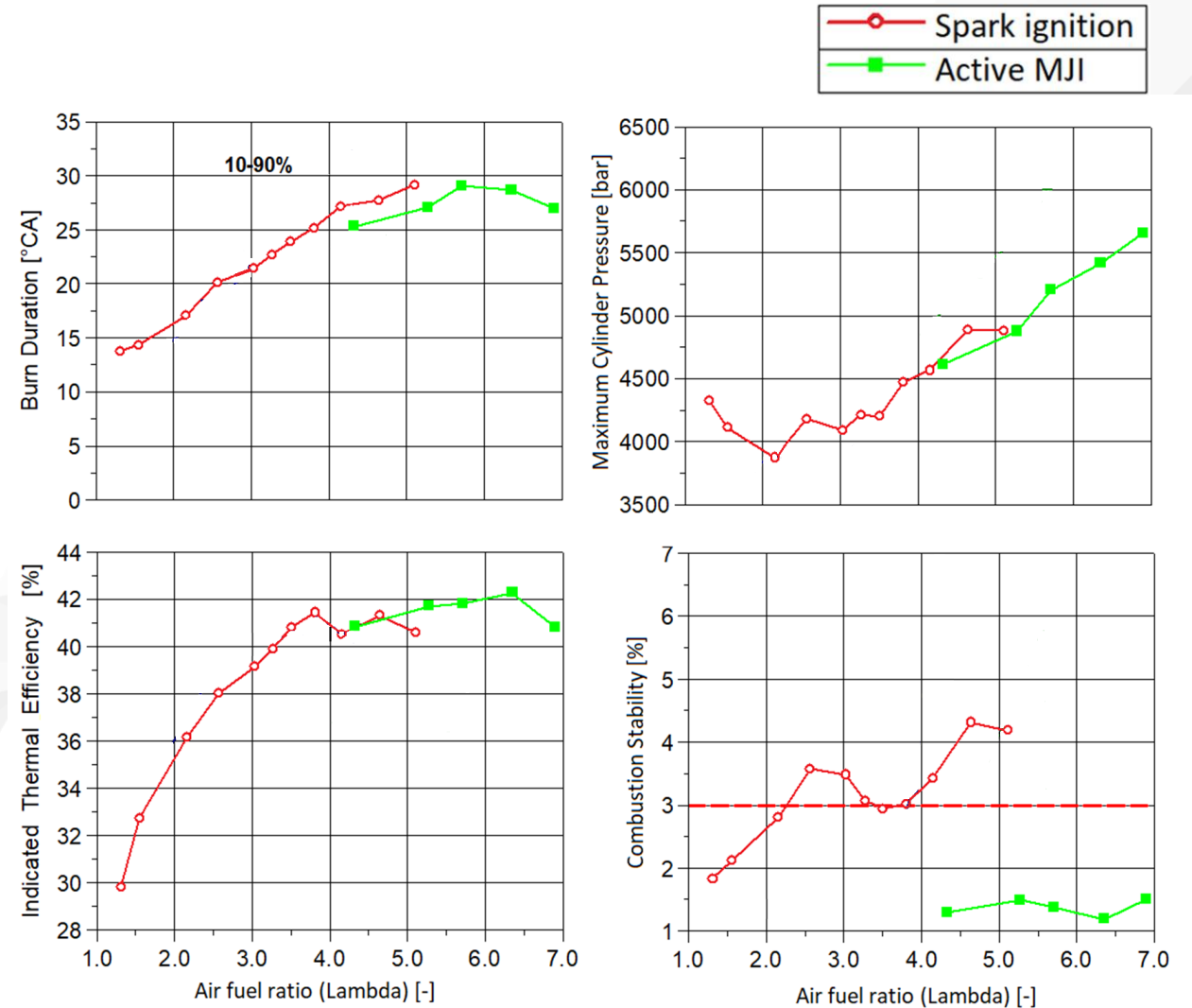


MAHLE Jet Ignition

H2 ICE benefits

Ultra-Lean mixtures

- MJJ enables ultra-lean combustion
- $\Lambda = 7$ achieved in testing
- High efficiency
- Ultra-low (effective zero) engine-out NOx
- Aftertreatment-free potential



Measured 2000 rev/min 4.6 bar IMEP Lambda sweep

Conclusions

Optimising Combustion for Hydrogen

- **Combustion system optimisation** – Fundamental for efficient and reliable Hydrogen Internal Combustion Engines
- **Combustion CFD** – Essential tool for optimisation of fuel injection, fuel mixing and overall combustion optimisation
- **Direct or Port Fuel Injection** – select the correct fuel injection system for the application and optimise
- **MAHLE Jet Ignition** – Enables ultra-lean combustion with improved ignition, emissions and efficiency
- **Hydrogen ICE: Clean, Efficient and Zero Carbon**

