Heavy-duty hydrogen engines for truck, marine and non-road applications

Decarbonising propulsion

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Hydrogen is recognised a critical energy carrier for the transition to a net zero economy. For the transport sector, hydrogen must be carefully targeted at applications which are not well served by direct electrification.

Applications which require high and continuous power output, such as off-highway construction equipment, long-haul heavy-duty trucks and marine propulsion, are hard to electrify. Electrical infrastructure may also by lacking in many cases. Hydrogen internal combustion engines are a promising powertrain solution for these applications. Hydrogen ICEs build on proven, robust, and cost-effective engine technologies, and are tolerant to fuel and intake-air impurities.

Ricardo has developed direct-injection hydrogen engines based on Euro VI heavy-duty diesel and natural gas engine designs. Direct injection provides more flexible injection, improves volumetric efficiency and reduces the risk of backfire compared to port fuel injection. Key specifications for the engines developed by Ricardo are shown opposite.

In many areas the baseline engine designs were retained, including the flat cylinder head and swirl port combustion system. CNG engine unit cylinder heads were modified to incorporate BorgWarner direct hydrogen injectors. The testbeds used for the single-cylinder engine and for the multi-cylinder engine are shown in Figure 1.

Engine testing covered a range of speed and load conditions representative of the operating range for heavy-duty applications. The impact of air-fuel ratio, exhaust-gas recirculation (EGR), injection timing and ignition timing were investigated.

To determine the sensitivity of the system to air-fuel ratio, swings were first carried out at a range of key-points. The lean limit was at lambda 4.5 or higher for all load conditions and combustion stability is good throughout. Across the speed range high EGR rates (>45%) can also be tolerated without misfire.

> “A well-defined process is used for developing combustion systems for conventional fuels, using in-cylinder computational fluid-dynamics (CFD)”

As expected EGR dilution slows combustion and the rate of pressure rise but leads to increased cylinder pressures due to increased trapped mass. The ability to tolerate high EGR rates provides another method to reduce pumping losses.

Figure 2 shows the characteristic relationship between NOx emissions and air-fuel ratio. Peak NOx emissions are observed at around lambda 1.4, and NOx values then drop rapidly to below 25 ppm at all conditions above lambda 3.5. Engine-out NOx emissions for the multi-cylinder engine are shown in Figure 3, for lambda 2 and 3 operation. At these NOx levels IMO Tier 3 emissions limits can be met without aftertreatment provided a suitable calibration is used.

Abnormal combustion in hydrogen engines is a complex combination of pre-ignition, end-gas knock and backfire. Hot spots, oil droplets and oil-derived particles, and ignition system characteristics, are all likely to be involved in the nucleation of these events. As a result, the mitigation of abnormal combustion requires a complete system approach to hydrogen engine design, development and calibration.

The experimental data gathered has been used to validate 1-D and 3-D simulation models of the engines, which allow different operating scenarios to be explored in parallel with engine testing. 1-D models employ a predictive Hydrogen Combustion Duration Sub-model (HCDS).

HCDS is a semi-empirical sub-model which combines laminar and turbulent flame speed calculations and empirical test data. HCDS reflects in-cylinder conditions such as lambda, pressure, and the amount of internal and external residuals. The sub-model also reacts to the change of bore, stroke and intake port design. HCDS is under continuous development to support future hydrogen combustion engines.

A well-defined process is used for developing combustion systems for conventional fuels, using in-

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Figure 1 - Engine Specifications

Country	Single-Cylinder Engine	Multi-Cylinder Engine
Bore (mm)	131	130
Stroke (mm)	158	160
Cylinders	1	6
Swept Volume (L)	2.1	12.7
Compression Ratio	12.6:1	11.9:1
Rated Power Speed (rev/min)	1800	1800
Piston and Bottom End	Diesel piston with modified bowl	CNG engine piston
Cylinder Head	Production CNG unit head modified for DI hydrogen	
Fuel Injection System	Direct injection	Direct injection Twin port injection
Fuel Pressure (bar)	35	35 (DI) 12 (PFI)

Figure 2

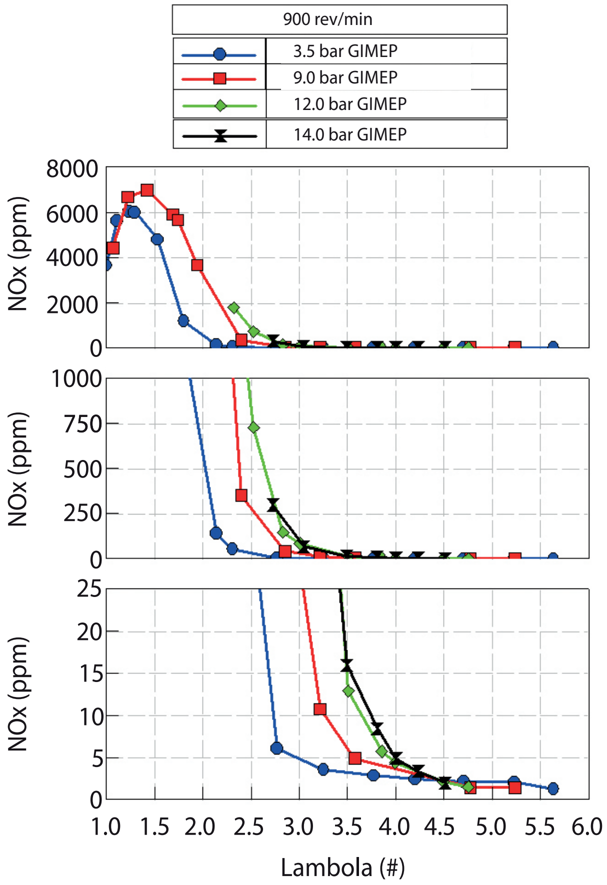


Figure 3

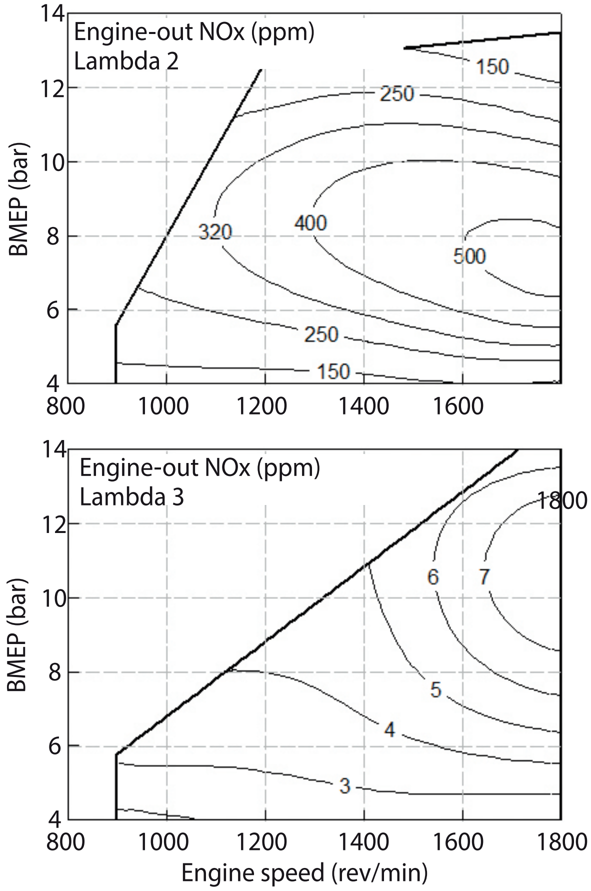
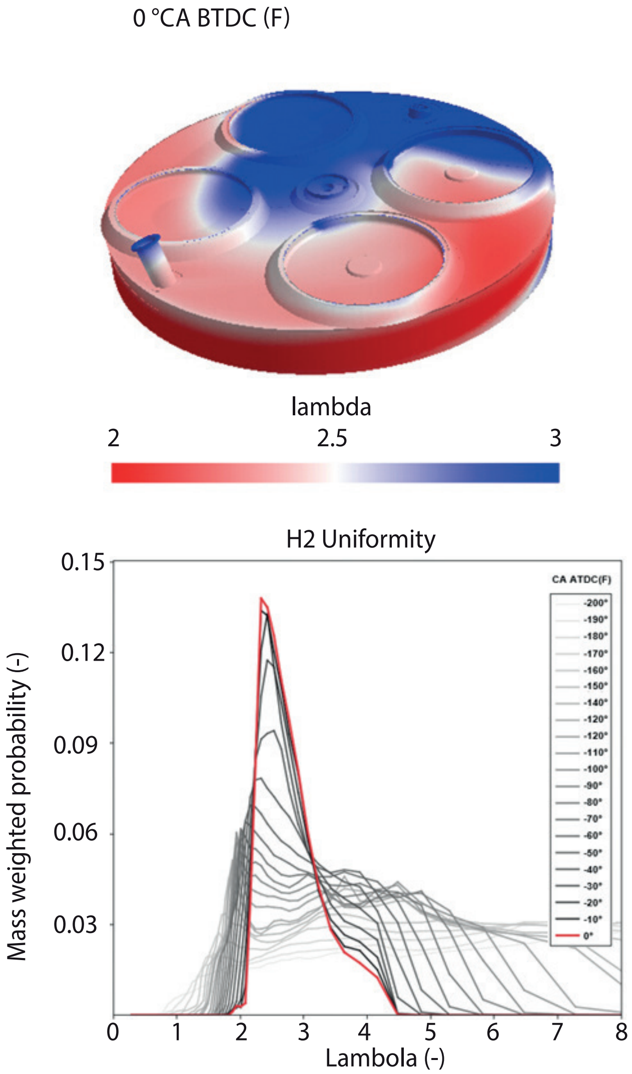
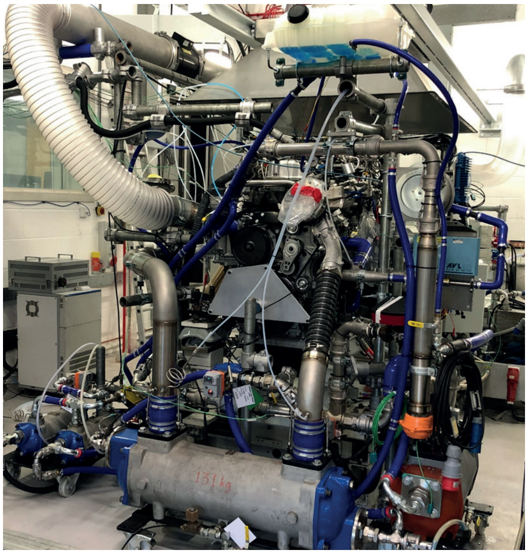


Figure 4





cylinder computational fluid-dynamics (CFD). When considering hydrogen fuel the same general approach can be employed although some modification is required.

Fuel characterisation, choice of surrogates and chemical kinetic mechanisms are simpler as hydrogen has a simple composition with known properties and a limited number of reactions. However, the flame speed behaviour of H_2 is very different to other fuels and existing flame speed models require adaptation.

Data from the experimental engines has been used to validate updated hydrogen combustion CFD models. The VECTIS code includes the thermo-diffusive instability effects and a general methodology for the prediction of hydrogen combustion. Validated spray models were incorporated into the full in-cylinder simulation allowing the interaction of the fuel spray and intake charge to be captured accurately and the evolution of mixing to be assessed. Figure 4 shows that the H_2 mixes rapidly, with the probability distribution curve rapidly becoming narrower during compression. However as shown in the accompanying image the mixture is not fully homogeneous. Ongoing work is to verify the combustion model prediction with and without EGR, and to study abnormal combustion events such as pre-ignition and knock.

> “The flame speed behaviour of H_2 is very different to other fuels”

Ricardo is developing heavy-duty hydrogen engines for a range of applications, along with the corresponding simulation tools. These engines have high tolerance to dilution, very low NOx emissions, and offer cost-effective zero carbon powertrains.