ENABLING EFFICIENT, AFFORDABLE AND ROBUST USE OF RENEWABLE HYDROGEN IN TRANSPORT AND POWER GENERATION

Final Knowledge Sharing Report

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Disclaimer

1. Project summary and scope

This project aimed to demonstrate the performance and value of highly efficient, reciprocating engines operating on renewable hydrogen. This includes the use of novel spark and compression ignition engine systems coupled with other advanced technologies. These engines were developed through first and second-generation prototypes informed by more fundamental experiments and numerical modelling.

The key activities of this project were as follows.

(a) the Pressurised Flow Reactor (PFR) Programme aimed to develop chemical kinetic models of hydrogen autoignition to be used in the High-Performance Computation (HPC) programme;

(b) the Constant Volume Combustion Chamber (CVCC) Programme aimed to obtain comprehensive optical measurements of the fuel jet and the flame, thereby forming a validation database for the HPC programme;

(c) the Cooperative Fuel Research (CFR) Engine Programme aimed to show definitively how hydrogen's autoignition and combustion properties limit how aggressively engines can be designed for high efficiency;

(d) the HPC Programme employed advanced, computational fluid dynamic (CFD) simulations to provide fundamental understanding of hydrogen injection, ignition, and combustion;

(e) the Spark-ignition (SI) Engine Programme aimed to demonstrate SI engine efficiency of at least 45%;

(f) the Compression-ignition (CI) Engine Programme aimed to demonstrate CI engine efficiency of at least 45%;

(g) the Techno-economics Programme employed state-of-the-art techno-economic modelling to demonstrate the value of highly efficient, reciprocating engines in different systems that either generate, transport or use renewable hydrogen.

This report presents an update on the activities undertaken at the second half of this project. This includes our progress in programmes (c), (d), (e), (f) and (g) above.

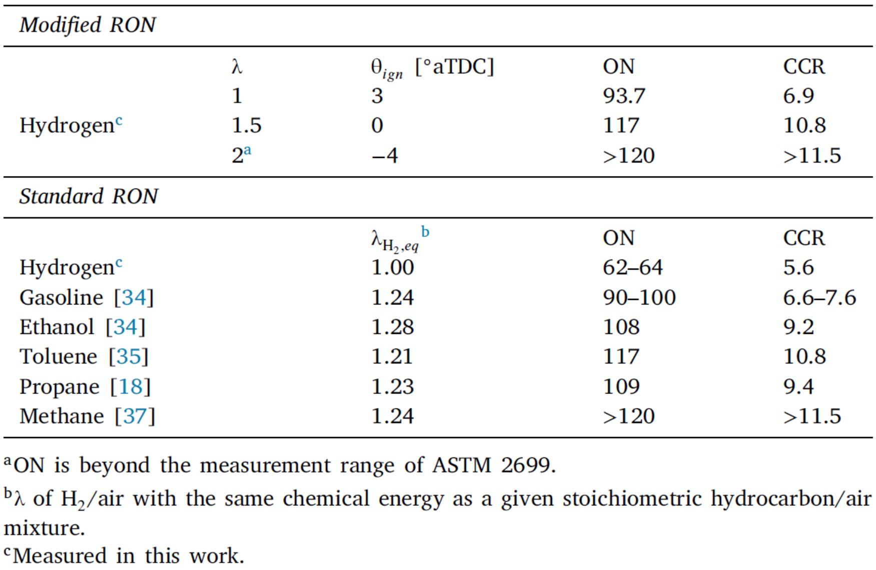
2. Progress update

2.1 The CFR Engine Programme

In this programme, an experimental and numerical study of hydrogen's combustion, autoignition and octane rating was undertaken. The experiments were conducted in a standard engine that is compliant for rating liquid fuels to the ASTM's Research Octane Number (RON) method, with minor modifications to enable hydrogen fuelling. The numerical analysis was undertaken using a combination of calibrated, two-zone combustion and kinetic modelling of the end-gas. Application of the standard RON method first showed that hydrogen has a RON of 62 – 64, which is significantly lower than that of standard gasolines. However, this standard RON method requires conditions that are irrelevant to practical, hydrogen-fuelled engines and, indeed, do not appear to feature autoignition and knock. A set of modified RON tests were therefore undertaken at more practical conditions. These indicated that hydrogen at standard knock intensity and non-dimensional air-to-fuel ratio of $\lambda = 1$, 1.5 and 2 has a modified RON of 93.7, 117 and greater than 120 respectively, spanning the range of λ that match the energy delivered by common SI engine fuels.

Together, the results of this work showed that hydrogen is significantly more knock-resistant than standard gasolines when providing similar energy to the premixture (see Table 1). Indeed, it should have comparable knock resistance

Table 1 The modified RON and critical compression ratio (CCR) of hydrogen compared to the standard RON and CCR of common SI engine fuels [5].



Modified RON				
	λ	θ_{ign} [°aTDC]	ON	CCR
Hydrogen[c]	1	3	93.7	6.9
	1.5	0	117	10.8
	2[a]	−4	>120	>11.5
Standard RON				
		$\lambda_{H_2,eq}$[b]	ON	CCR
Hydrogen[c]		1.00	62–64	5.6
Gasoline [34]		1.24	90–100	6.6–7.6
Ethanol [34]		1.28	108	9.2
Toluene [35]		1.21	117	10.8
Propane [18]		1.23	109	9.4
Methane [37]		1.24	>120	>11.5

[a] ON is beyond the measurement range of ASTM 2699.

[b] λ of H_2/air with the same chemical energy as a given stoichiometric hydrocarbon/air mixture.

[c] Measured in this work.

to some high-octane fuels. We, however, demonstrated that care must be taken when examining hydrogen's autoignition, knock and abnormal combustion more generally. Hydrogen's high flame speeds near stoichiometric conditions can produce high rates of pressure rise at lower compression ratios that can be mistakenly identified as autoignition, even with contemporary in-cylinder pressure measurement, while higher compression ratios near stoichiometric conditions can cause detonation. The identification and avoidance of conventional knock and other forms of abnormal combustion was therefore found particularly important for hydrogen fuelled engines. The findings of this work also have implications for the development of standard test methods for determining the octane and methane numbers of hydrogen-rich fuel blends.

2.2 The HPC Programme – part I

2.2.1 HPC modelling of the UoM's CFR engine:

In this programme, we conducted a numerical study of normal and knocking combustion of hydrogen in UoM's cooperative fuel research (CFR) engine. Using the Reynolds Averaged Navier Stokes (RANS) framework, a single compression ratio and four different spark timings were considered to investigate the transition from normal to knocking combustion. The results were thoroughly validated against the experimental pressure trace data for both normal and knocking combustion.

It was shown that for knocking cases an initial autoignition hotspot appears near the exhaust valve, where the unburnt temperature is higher than the rest of the domain (see Figure 1). A pressure wave then propagates, forming a secondary autoignition spot and autoignitive flame that eventually merges to the first flame front. The propagation speed of the autoignitive flame front was found to be 6 - 10 times higher than that of the premixed flame. Furthermore, zero-D homogeneous reactors were found to be suitable for capturing the autoignition timing, while 3-D RANS results showed a more comprehensive picture about how temperature stratification impacts the location of AI events.

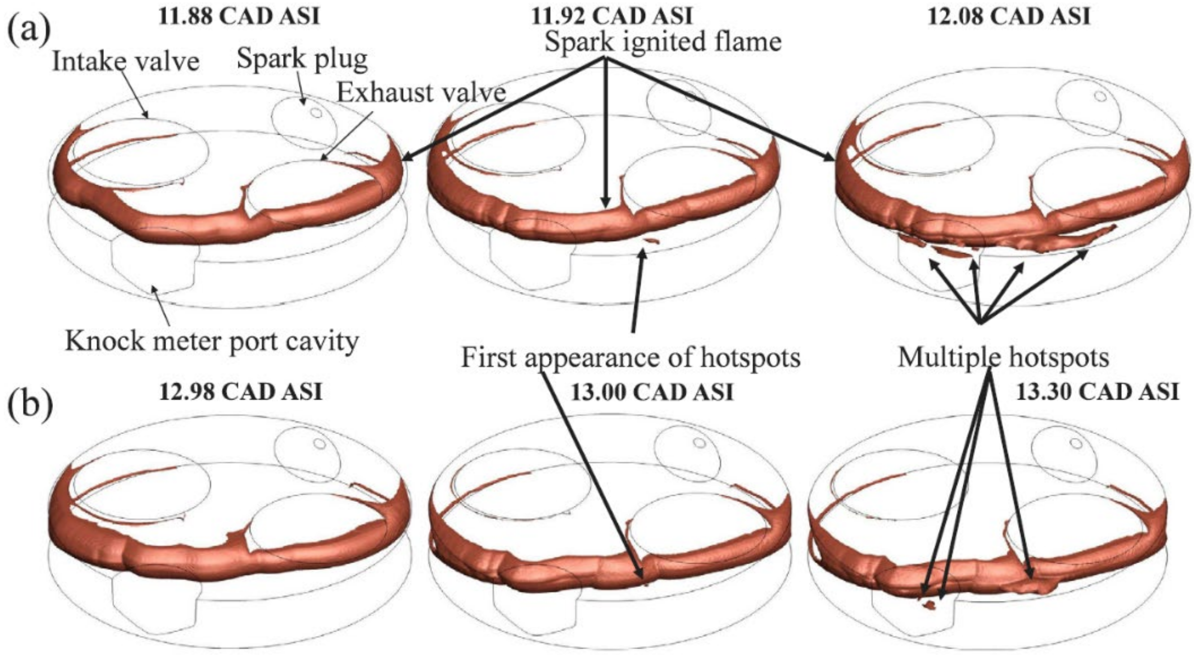


Figure 1 Flame development and hot spot location in the end gas region for a spark timing of (a) 13 and (b) 10 bTDCf [7].

2.2.2 HPC modelling of UNSW's 1st generation CI engine:

In this work, RANS simulations were conducted for UNSW's first-generation engine using the commercial software Converge. The aims were to validate the modelling and to explore the in-cylinder phenomena with a view to understanding trade-offs between performance and emissions of the engines. In a first series of simulations, hydrogen energy fraction was held fixed at 50%, while the hydrogen injection timing was varied. Pressure traces were compared between model and experiment and good agreement for the timing of combustion was obtained. Analysis of the model results showed a more inhomogeneous hydrogen distribution was obtained with later injection timings, as was expected. The most important finding was that the highest efficiency occurred for intermediate injection times; however, this condition also produced the most oxides of nitrogen (NOx). A second series of simulations was carried out with a fixed injection timing and varying hydrogen substitutions, up to a 90% level, which had not yet been achieved in the laboratory. A thorough analysis examined the causes of efficiency penalties, notably heat loss to the cylinder walls, and performance-NOx emissions trade-offs. Notably, the analysis indicated that a premixed type of combustion results in lower in cylinder temperatures, reduced NOx and reduced wall heat loss. Wall heat loss was driven by combustion phasing, the near-wall equivalence ratio, and turbulence (Figure 2). The results in both studies show the strong impact of the hydrogen injection parameters on engine performance, which was borne out in engine tests. The moreover show the critical need to tailor the in-cylinder hydrogen distribution when operating in dual-fuel compression ignition mode. Advanced fuel distribution tailoring strategies were later applied in the laboratory.

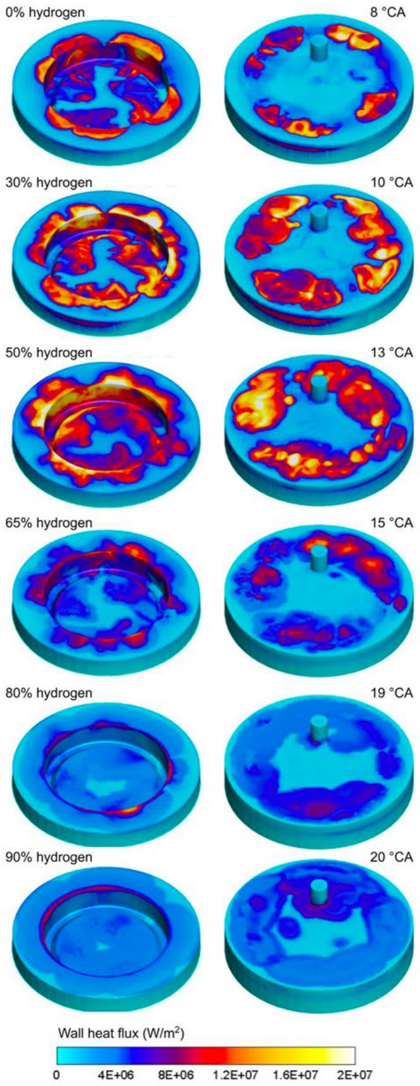


Figure 2 Wall heat fluxes on the upper and lower surfaces of the engine cylinder for different hydrogen fractions by energy share

2.3 The HPC Programme – part II

2.3.1 HPC modelling of the UoM's 2nd generation DISI hydrogen-fuelled engine:

In this part of the HPC programme, Reynolds Averaged Navier Stokes (RANS) simulations of the 2nd generation, hydrogen-fuelled direct injection spark ignition engine were done at different spark and start of injection (SOI) timings. Six cases were simulated, including three with various spark timings at a low boost level and three with advanced to late injection timings at a higher boost level. The numerical simulations were validated with experimental data for four out of six cases, while the other two cases were considered to be blind computational fluid dynamics (CFD) simulations.

It was shown that the autoignition occurs with advanced spark timing due to a high in-cylinder pressure and unburnt temperature (see Figure 3). For different SOIs, it was demonstrated that flame propagation involved a spark-initiated flame combined with an autoignition-generated flame. Intermediate injection resulted in the maximum thermal efficiency since retarding the injection timing further led to poor mixing, the presence of lean mixtures near the spark plug and thus a slower combustion. In all cases, both mixture and temperature stratification were found to be present.

Simulations of zero-dimensional chemical reactors demonstrated that this stratification must be correctly captured for accurate prediction of autoignition timing.

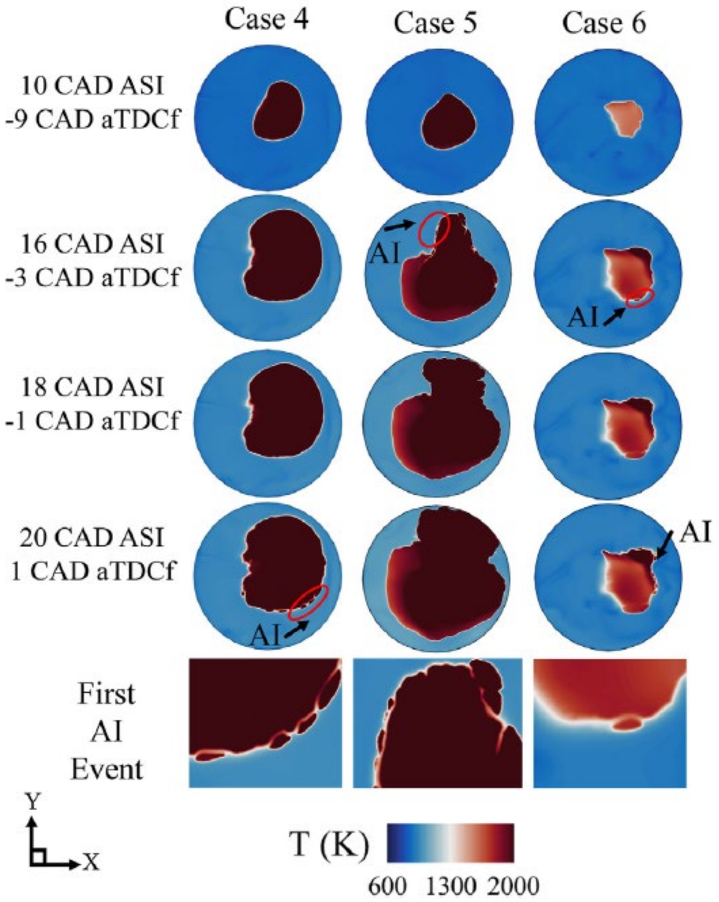


Figure 3 Snapshots of the flame propagation using temperature field for Cases 4 to 6, representing the hydrogen injection timing of 350 to 190 CAD bTDCf [6].

2.3.2 HPC modelling of relevant to UNSW's 2nd generation dual-fuel, CI engine:

In this work, detailed, first-principles direct numerical simulations (DNS) were carried out to investigate the ignition of stratified mixtures in mixing-layer configurations under conditions relevant to the second-generation CI engine, where an n-dodecane fuel-rich region is surrounded by an ultra-lean hydrogen-air mixture (dual-fuel/DF cases) or air (single fuel/SF cases). Results showed that the ignition of DF cases is delayed compared to the SF cases because hydrogen consumes OH species (a highly reactive chemical intermediate) during the low-temperature oxidation of n-dodecane. In the simulations, two-stage and multi-mode ignition processes with low- and high-temperature ignition kernels, cool flames, and different modes of edge-flame structures are observed in both DF and SF cases. However, different characteristics of these kernels and flames were detected between SF and DF cases (Figure 4). The concurrent existence of these different combustion modes presents a significant challenge in the design of predictive engineering models for hydrogen-DF CI engines.

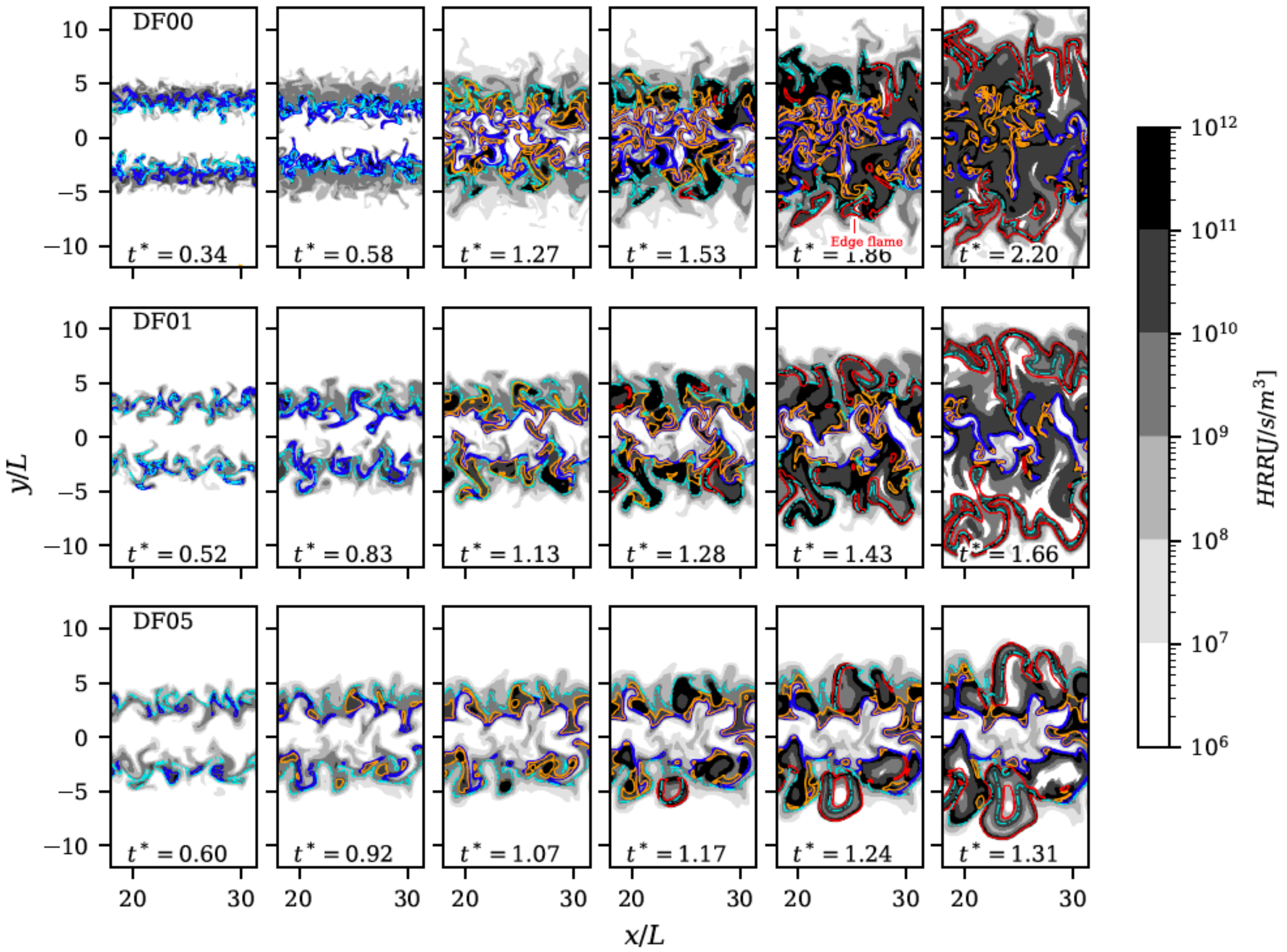


Figure 4 Detailed numerical simulations of combustion in stratified mixing layers between a lean hydrogen-air mixture and n-dodecane (a diesel surrogate fuel). Images show local heat release on a grey scale. The stoichiometric surface is denoted by light blue dashed contours. Dark blue contours define regions of low-temperature chemistry activation, orange contours bound the low-to high temperature induction period; and in the regions encircled by red contours are those in which high-temperature chemistry is active.

2.4 The Engine Programme

2.4.1 Analysing the performance of the UoM's 2nd generation DISI hydrogen-fuelled engine:

In this work, an experimental and numerical study of the second-generation DISI hydrogen-fuelled engine was undertaken under boosted conditions. Figure 5 shows the second-generation hydrogen-fuelled engine developed at the University of Melbourne. Consistent with prior works, engine operation with compression ratios of 12:1 and 14:1 was found to be knock-limited at richer conditions, more advanced spark timings, and particularly at the higher compression ratio. Retarding the injection timing from early and homogeneous injection also demonstrated trade-offs between efficiency, power, and NO emissions, and were again consistent with prior studies. Water injection into the intake manifold was then implemented to suppress autoignition and knock, and thus enable diesel-like power via richer operation at more optimal operating conditions (see Figure 6).

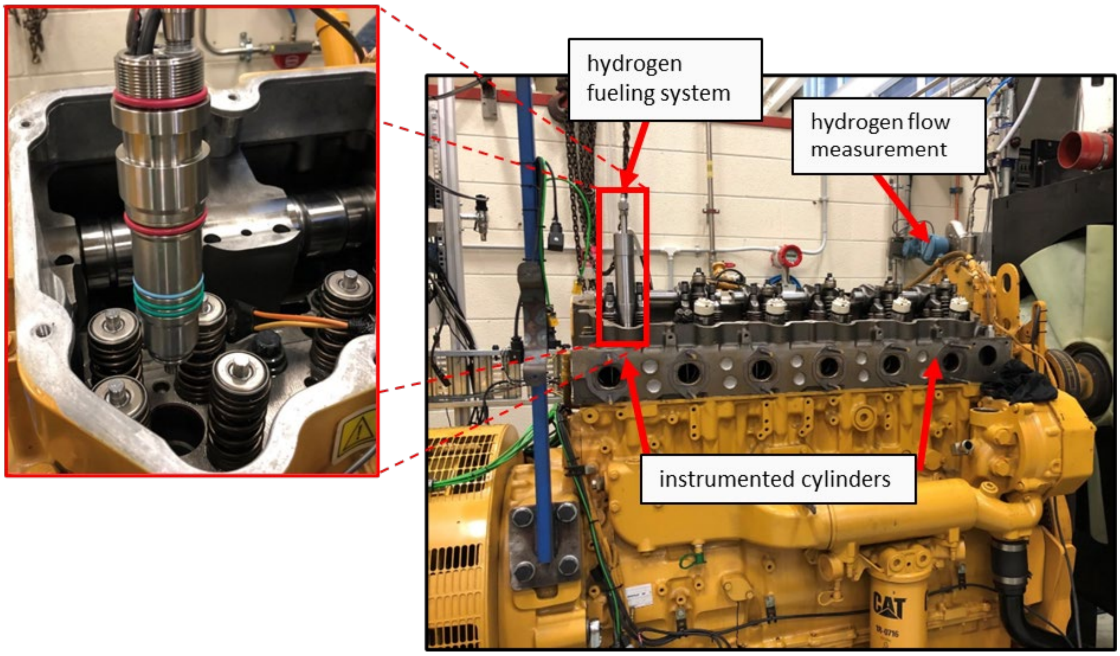


Figure 5 Converted diesel engine to run on hydrogen fuel in cylinder 6. The detailed section shows the integrated injection and ignition system as a drop-in solution developed for this conversion.

The dependence of these observed trends in engine efficiency, power and emissions on key physical processes occurring in the engine was then examined numerically. This included considering water injection to potentially impact autoignition via three potential routes - a charge cooling effect, a thermophysical effect and a kinetic effect. The impact of charge cooling was found to be dominant, with the thermophysical effect also significant but the kinetic effect weak.

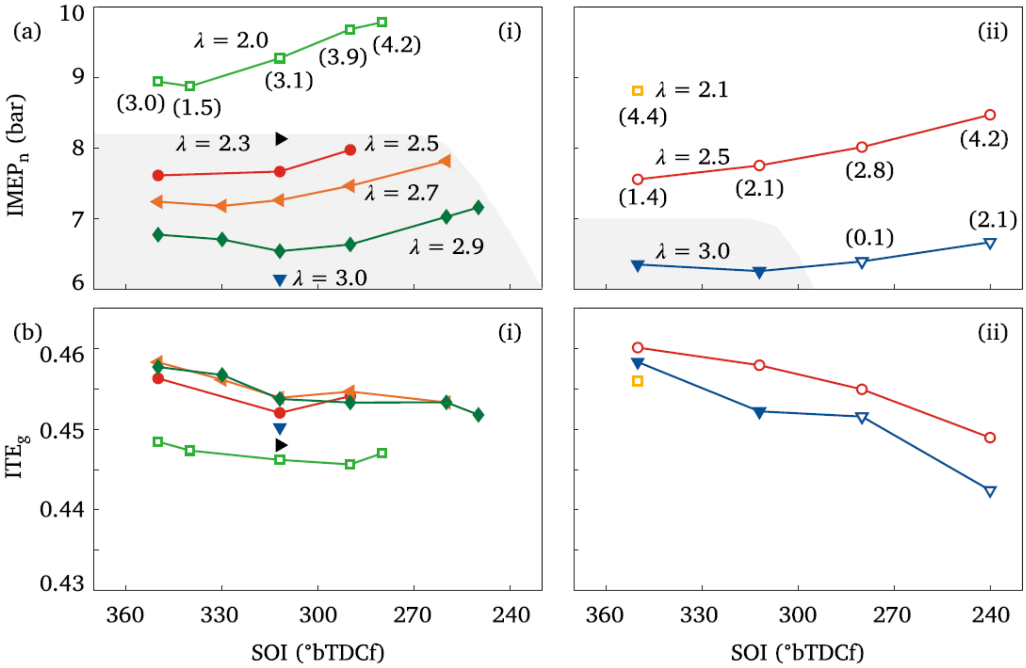


Figure 6 Variation of (a) IMEPn and (b) ITEg with SOI, CA50 = 5 ± 1°aTDCf and boost of 0.4 bar: (i) CR = 12:1, (ii) CR = 14:1. Open markers represent the use of the minimum quantity of water injection to suppress autoignition. The shaded areas in the top two figures are the approximate regions of controlled combustion (i.e. not autoigniting or misfiring) when water injection is not used. Values in parentheses are injected water-to-hydrogen mass ratios [4].

2.4.2 Analysing the performance of the UNSW’s 2nd generation CI hydrogen-fuelled engine:

In this part of the programme, a hydrogen-diesel dual direct injection engine was successfully operated, where over 90% energy supplied from hydrogen. A commercial diesel engine head was modified to install an additional hydrogen direct injector, which was also modified from a conventional direct injector with a single-hole cap welded on the original nozzle.

The engine was operated at a maximum torque speed of 2000 rpm and fixed combustion phasing of -10 crank angle degrees before top dead centre (°CA bTDC) while evaluating the power output, efficiency, combustion and engine-out emissions. A parametric study was conducted for varied hydrogen energy fractions and injection timings ranging 180-0 °CA bTDC with no knocking or preignition. The optimised injection timing was found, which showed 57.2% thermal efficiency and 85.9% CO2 reduction compared to the diesel baseline.

The hydrogen injection timing was found to directly control the mixture condition and combustion mode. Early hydrogen injection timings exhibited premixed combustion behaviour while late injection timings produced mixing-controlled combustion, with an intermediate point reached at 40 °CA bTDC hydrogen injection timing. An important efficiency-NOx trade-off characteristics was found. The earlier injection timing led to higher efficiency, but the NO_x increase was inevitable due to enhanced premixed combustion. To keep the NO_x increase minimal and achieve the same combustion phasing of a diesel baseline, intermediate hydrogen injection timing of 40 °CA bTDC was found to be optimal.

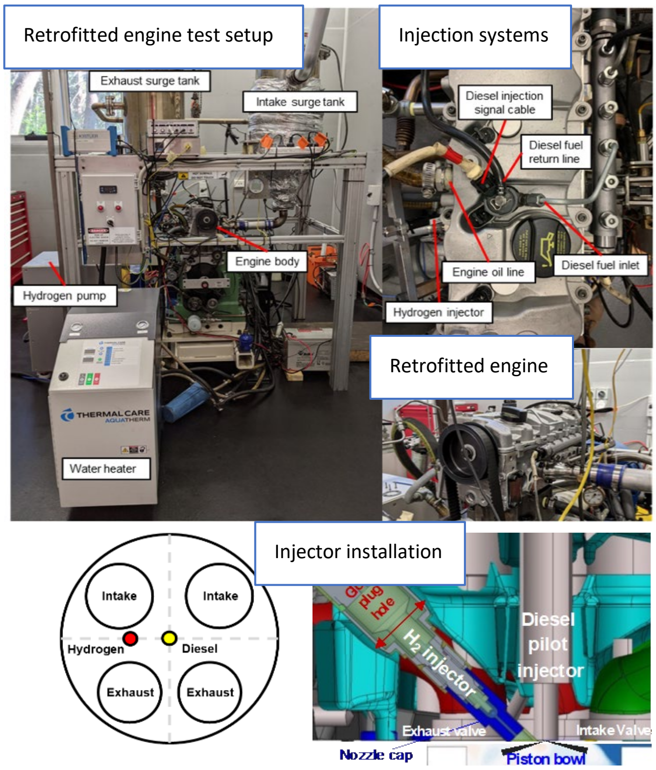


Figure 7 Modified commercial diesel engine with an additional hydrogen direct injector. The engine test facility setup and injection system installation layout are shown in the picture together with an engineering illustration of the single-hole capped hydrogen injector developed for this conversion.

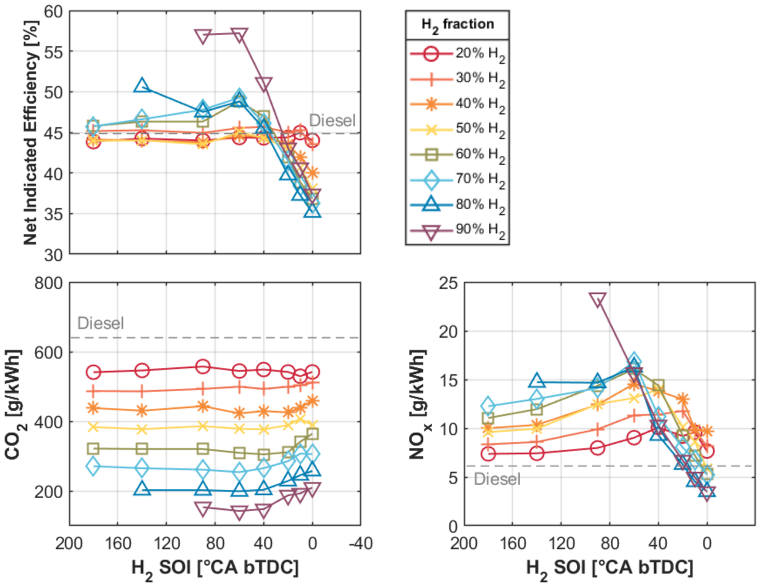


Figure 8 Efficiency and engine-out emissions of carbon dioxide and nitrogen oxides for varied hydrogen start of injection (H2SOI) and hydrogen energy fraction. The diesel baseline is shown as a horizontal line for a comparison purpose. 57.2% thermal efficiency and 85.9% CO_2 reduction is demonstrated.

2.5 The Techno-economics Programme

In this programme, we examined the decarbonisation of three coupled energy sectors: electricity, transport and heating/industry. The sector coupling included the production of hydrogen from each of electricity via electrolysis, the gasification of coal and the reforming of natural gas; the displacement of gasoline/diesel and natural gas by any of these forms of hydrogen; the generation of electricity by gas turbines and reciprocating engines fuelled by either natural gas or any of these forms of hydrogen; and the electrification of the transport fleet. Plausible sensitivities to technological learning, energy efficiency measures, natural gas prices and subsidies for renewables were examined systematically as the coupled systems' total greenhouse gas emissions were reduced to zero.

The observed transition to zero emissions found significant uses for hydrogen from both electrolysis and fossil fuels with carbon capture and storage (CCS). It was found that the plausible rates of technological learning from today to 2050 dramatically reduce the total costs and the land area required for achieving deep abatement mainly due to the projected fall in the costs of wind, solar PV and electrolysis. The combination of hydrogen fuelled reciprocating engines, electrolysis and hydrogen gas storage was also observed to provide lower cost, longer term electricity storage than batteries and pumped hydropower. Nonetheless, the marginal costs of reducing emissions beyond approximately 90% abatement relative to today were found always more than 100 $/tCO_2e$ and land use could increase dramatically. This suggested that negative emission technologies will likely have a role in achieving net-zero emissions in combination with widespread renewable deployment, technological learning and some continued fossil fuel use with CCS.

3. Key highlights and difficulties experienced

3.1 The CFR Programme

Key highlights:

- Hydrogen was found to be significantly more knock-resistant than standard gasolines when providing similar energy to the premixture.
- ASTM octane standards are ill-posed for rating hydrogen-rich fuel blends.
- A modified octane rating method was proposed to rate hydrogen and hydrogen-rich fuel blends at conditions of relevance to practical IC engine operation.

Programme-specific challenges:

- Engine backfire was observed at high intake temperatures, which was due to the necessary homogeneous charge preparation approach used for the ASTM octane rating method.
- Hydrogen's high flame speeds at near-stoichiometric conditions led to high rates of pressure rise, which was mistakenly identified as autoignition by the standard detonation pickup sensor. This, in part, led to assigning unrealistically low octane value to hydrogen.
- At higher compression ratios and near-stoichiometric conditions, charge detonation occurred, which was detrimental to the engine. These events led to peak in-cylinder pressures in excess of 200 bar that are 3-5x higher than those experienced under normal operating conditions.

3.2 The HPC Programme

3.2.1 HPC modelling of the UoM's CFR engine:

Key highlights:

- Auto-ignition was observed to occur in the cases with spark timing before TDC. Temperature stratification in the cylinder was observed, and the formation of initial hotspots in the end gas region occurred near the exhaust valve due to the presence of high temperatures.

- After the first auto-ignition event, the pressure wave generated by the initial hotspots induced the formation of secondary hotspots in the end gas. The combination of these events results in large pressure oscillations of more than 100kPa.

- The laminar flame speed was found to be the key parameter affecting the flame propagation, and the speed of the autoignitive front propagation was 6-10 times larger than that of the premixed flame.

- It was found that a zero-dimensional model for end-gas auto-ignition was able to capture the trends observed in the three-dimensional model and also provided a reasonable estimate of knock point.

Programme-specific challenges:

- The combustion modelling required a lookup table for the laminar flame speed and detailed chemical mechanism to model flame propagation and end-gas auto-ignition. It was noticed that the choice of the models significantly affected the results. This required a careful examination of different models to achieve the best agreement with the experimental data.

- Various boundary conditions had to be applied for the simulations. It was found that 1D GT-POWER simulations were necessary to obtain to boundary conditions for the HPC simulations.

3.2.2 HPC modelling of the UoM's 2nd generation DISI hydrogen-fuelled engine:

Key highlights:

- It was found that advancing spark timing leads to autoignition events near the flame front, immediately merging with the spark-initiated flame.

- For the cases with different injection timing, the flame evolution involved a combination of a spark-assisted flame and an autoignition-generated flame.

- Strong mixture and temperature stratification were present for all cases with different spark and injection timings.

- It was shown that zero-dimensional modelling of the end-gas can capture the autoignition timing if both temperature and mixture stratification are considered.

Programme-specific challenges:

- Computational cost (CPUh) of the simulation had a direct relationship with injection duration. In higher equivalence ratios, it was required to increase the injection duration to deliver the required hydrogen mass into the cylinder. Therefore, the computational modelling of these cases was very challenging.

- 3D-printed injector geometry was complicated and implementing it in the computational domain required a very fine grid size, which could have significantly increased the computational cost. A simplified version of the injector and modified compression ratio were used to avoid this challenge.

3.2.3 HPC modelling of UNSW's 1st generation CI engine:

Key highlights:

- Despite the relative simplicity of the modelling approach that was employed, based on a commercial computational fluid dynamics package, good agreement was obtained for experimental trends.

- Deep analysis of the model results was quite useful to understand how mixture distributions were critical in determining efficiency, NOx emissions, combustion phasing, combustion duration, and unburned fuel emissions.

Programme-specific challenges:

- The main challenges faced were unknown detailed boundary conditions, for example: the details of the hydrogen fuel injection which was not resolved due to unknown internal geometry of the injector, details of the initial state of in-cylinder turbulence at bottom dead centre, and details of the local wall temperatures.

3.2.4 HPC modelling relevant to UNSW's 2ndst generation CI engine:

Key highlights:

- The first direct numerical simulations (DNS) of the ignition of a diesel-relevant fuel (n-dodecane) mixing with a lean hydrogen-air mixture in thermochemical conditions relevant to the 2nd generation engine were carried out, with the intent to gain a detailed, scientific understanding of the resulting ignitions. These simulations required significant fractions of a large supercomputer to execute.

- A key finding was that hydrogen addition slowed the ignition process due to its scavenging of active radical species. Subsequent to ignition, the flame initially evolved in a qualitatively similar way to what has been observed for similar mixing layers without hydrogen, which was not anticipated. Finally, the dual-fuel flames transitioned to lean, premixed type flames with notable diffusive-thermal instabilities. Overall, the results underline how complex combustion can be under these conditions.

Programme-specific challenges:

- It was hoped that three-dimensional DNS could be carried out. This was not possible due to the extreme computational demands of properly resolving very thin flame fronts.

- It was hoped to carry out RANS simulations of the second-generation engine in full. This did not eventuate due to the border closure resulting from the coronavirus pandemic, and the associated staffing challenges.

3.3 The Engine Programme

Key highlights of the SI engine programme:

- Two compression ratios of 12:1 and 14:1 were studied in the DISI engine programme. The engine demonstrated knock-limited performance at both compression ratios, particularly at richer conditions with optimal spark timings, and for the higher compression ratio.

- Retarding the injection timing from early and homogeneous injection demonstrated trade-offs between efficiency, engine power and NO emissions.

- Water injection was found effective in extending the knock limits and enabling higher powers to be attained.

- Water injection was considered to potentially impact autoignition (and hence engine knock) via three potential routes: the charge cooling effect, the thermophysical effect via water modifying the specific heats of the fresh charge, and the kinetic effect via water's third-body interactions. The impact of charge cooling was dominant, with the thermophysical effect also significant but the kinetic effect weak.

- Indicated thermal efficiencies of ~47% were achieved in this programme.

Key highlights of the CI engine programme:

- A commercial diesel engine was successfully retrofitted to build a hydrogen diesel dual-fuel direct injection engine and tested for engine-out emissions and efficiency/performance in a dynamometer facility.

- Two combustion modes were found where generally early to intermediate 180-60 °CA bTDC hydrogen injection timing causes primarily premixed combustion, a crossover point emerges around 40 °CA bTDC and for late injection timings of 20-0 °CA bTDC there is primarily mixing-controlled combustion with a hydrogen diffusion flame.

- A trade-off between engine performance quantified by efficiency and low NOx emissions emerged. The optimised efficiency and NOx were attained at 40 °CA bTDC hydrogen injection timing, at which point the hydrogen charge is intermediate between well-mixed and stratified, enabling fast flame propagation.

- Over 90% hydrogen energy substitution of diesel fuel was achieved with up to 85.9% reduction in CO2 without knock or pre-ignition for hydrogen injection timings 90-0 °CA bTDC.

- Indicated thermal efficiencies of ~57.2% were achieved in this programme through the partial premixing strategy.

Programme-specific challenges – SI engine programme:

- Given the space limitations in the engine head, a small M8 spark plug was used for ignition. The short length of ceramic insulation on this plug combined with high in-cylinder pressures at the time of ignition made the ignition system prone to arcing outside the chamber and therefore cause the engine to misfire. This issue was addressed by significantly reducing the spark gap, applying dielectric grease to the spark plug and also pressurising the back of the plug to increase its electric resistance.

- The engine operation was significantly knock-limited, particularly at the compression ratio of 14:1. This limited the attainable power and efficiency. Water injection into the intake manifold was used effectively suppress end-gas autoignition and extend knock limits.

Programme-specific challenges – CI engine programme:

- The commercial direct injector that was initially trialled featured 6 holes with a diameter of approximately 160 µm. Trials showed this could not exceed a hydrogen energy fraction beyond 50% due to poor control over mixture preparation. Hydrogen mixture formation within the piston bowl was found to be the key to achieve hydrogen energy fraction higher than 90%; this was achieved by adding a single-hole nozzle cap with a 1 mm hole diameter.

- Higher hydrogen energy fraction produced higher NOx emissions up to greater than three times the diesel baseline for 90% hydrogen energy fraction and 90 °CA bTDC injection timing. This was mitigated by controlling hydrogen direct injection timing.

3.4 The Techno-economics Programme

Key highlights:

- The combination of hydrogen-fuelled reciprocating engines, electrolysis and hydrogen gas storage could provide lower cost, longer term electricity storage than batteries and pumped hydropower. This finding has major implications for successful transition to zero emissions energy sector.

Programme-specific challenges:

None.

4. Commentary on commercialisation prospects (including for example, product costings, business model and preliminary market assessment)

Not yet applicable.

5. Summary of knowledge sharing activities completed (e.g. publications, conferences, patents)

Below is the summary of publications completed by the end of this project.

1. Lu Z., Yang Y., Lacey J., Brear M., "Experimental and numerical analysis of hydrogen oxidation in a flow reactor, " *Proceedings of the Australian Combustion Symposium*, Dec. 2019;
2. Lu Z., Jiang J., Yang Y., Lacey J., Brear M., "Hydrogen oxidation near the second explosion limit in a flow reactor, " *the 38th International Symposium on Combustion*, PROCI-S-19-01209, 2020;
3. Mortimer J., Yoannidis S., Poursadegh F., Lu Z., Brear M., Yang Y., Etherington D., Heijkoop M., Lacey J., "An experimental and numerical study of a hydrogen fuelled, directly injected, heavy duty engine at knock-limited conditions," *the ASME Internal Combustion Engine Fall conference*, ICEF2020-2920, Nov. 2020;
4. Mortimer J., Poursadegh F., Brear M., Yoannidis S., Lacey, J., Yang Y., "Extending the knock limits of hydrogen DI ICE using water injection," *Fuel*, 2023, 335;
5. Poursadegh F., Brear M., Hayward, B., Yang Y., "Autoignition, knock, detonation and the octane rating of hydrogen," *Fuel*, 2023, 332;
6. Yosri, R., Palulli, R., Talei, M., Poursadegh, F., Mortimer, J., Yang, Y., Brear, M., "Numerical investigation of a large bore, direct injection, spark ignition, hydrogen-fuelled engine," *International Journal of Hydrogen Energy*, *48*(46), 17689-17702;
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