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Effect of Hydrogen Fumigation in a Dual Fueled Heavy Duty Engine

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Abstract

Concerns over the impact of road transport emissions on the climate have led to increased focus on how CO_2 emissions could be reduced from the sector. This is of particular concern in the commercial vehicle sector, where engine downsizing and electrification have limited benefit due to the vehicle duty cycle. In this paper, we present results from an experimental program to investigate the impact of dual fueling a heavy duty engine on hydrogen and diesel. Hydrogen is potentially a zero carbon fuel, if manufactured from renewable energy but could also be manufactured on the vehicle through steam reformation of part of the liquid fuel. This opens a novel pathway for the recovery of waste heat from the exhaust system through the endothermic steam reformation process, improving the overall system efficiency. For these concepts to be viable, it is essential the dual fueled combustion system is both thermally efficient, and does not increase toxic emissions such as NO_x. The test program reported studied the impact of hydrogen injection into the engine intake system with and without Exhaust Gas Recirculation (EGR). The baseline engine was calibrated to achieve Euro VI NO_x emissions with various aftertreatment strategies. The impact of displacing diesel with increased quantities of hydrogen was studied. The results are compared with a conceptual model of the hydrogen – diesel combustion process presented in the paper.

Introduction

The internal combustion engine is likely to remain the primary power plant in heavy duty commercial vehicle applications for the foreseeable future [1]. A combination of economic pressure to reduce fuel costs and legislative pressure to reduce CO_2 emissions will drive changes to the powertrain to increase efficiencies from around 40-45% today to 50% or higher in the future [1, 2]. To achieve these ambitious targets, radical changes to the combustion system, overall vehicle architecture and fuel have been proposed and are being studied by a number of researchers [1-3]. In this paper we consider the impact of dual fueling a low emissions diesel engine with hydrogen introduced into the intake system, often referred to as fumigation. This provides two pathways for the reduction of CO_2 emissions (see figure 1);

- Displacing the fossil fuel with hydrogen manufactured from a renewable source
- On board manufacture of hydrogen by steam reforming of liquid diesel fuel, enabling the use of waste exhaust heat to improve system efficiency

Dual fueling the vehicle with hydrogen and diesel would reduce the cost and package implications of on board storage of hydrogen by reducing the amount of hydrogen required, yet still provide an overall reduction in CO_2 emissions from the vehicle. The size of the hydrogen storage tank can be then tailored to the available space and energy storage density of the hydrogen tank, without compromising the range of the vehicle.

Reformation of the liquid fuel into syngas is also attractive as an estimated 20% increase in the calorific value of the fuel could be achieved through steam reforming of part of the fuel and the recovery of waste heat from the exhaust to provide thermal energy for the reforming process in a process that effectively converts thermal energy to chemical energy. The syngas will be a mixture of many compounds, but principally hydrogen (70%) and CO (25%). For the current study, only the effect of the main hydrogen component was tested to simplify the experiment to facilitate fundamental understanding of the hydrogen component combustion process. Future work is planned using syngas.

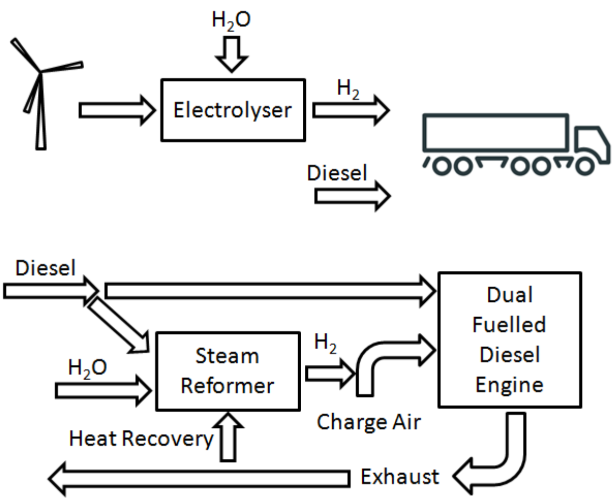


Figure 1: Potential energy pathways for hydrogen supply to the engine

Both hydrogen supply pathways have merit, but to be effective it essential that the hydrogen fueled engine can operate at least as efficiently as a conventional Diesel fueled engine, within toxic emissions limits. On this subject, the literature is mixed. Gatts [4] and Liew [5]conducted extensive work on a commercial Euro III Cummins engine and Mack engine operating at Euro IV. The engine calibration was not adjusted from the diesel only set up. Dependent on the operating point and hydrogen concentration, NO_x emissions and brake efficiency were seen to either increase or decrease, with no clear trend reported. Some hydrogen slip was reported, particularly at light load conditions and low hydrogen concentrations. Other researchers working on light duty engines have shown similarly mixed results [6-8]. In some cases, a slowing of the combustion process was reported [8]. This was interpreted as a delaying of the formation of OH radicals, delaying ignition and the hydrogen having a similar effect to EGR on the combustion process. Recent work on a light duty single cylinder by Talibi [9] observed similar trends but proposed a different interpretation of the results. Talibi suggested the NO_x response could be explained by considering the local flame temperatures of the two fuels. Overall, there is not a clear picture of how a Diesel – hydrogen engine operates and could be optimized to delivery high efficiency at low NO_x emissions across the operating envelope.

In this paper, we present a hypothesis for how a homogenous mixture of hydrogen will combust in a compression ignition Diesel engine dual fueled with diesel. The experimental set up of an advanced single cylinder heavy duty engine is described, including details of how the engine was modified to enable hydrogen to be introduced to the intake system. The engine was equipped with a low NO_x combustion system, compatible with Euro VI emissions levels and the Delphi F2E fuel system, capable of 3000 bar injection pressures. The results of the experimental program are described including experiments with and without EGR and advanced and retarded combustion strategies. The experimental results are then compared with the conceptual model. The paper concludes with a discussion on the impact of the test results on the viability of a diesel – hydrogen fueled commercial vehicle.

Conceptual model of hydrogen-Diesel combustion

Gaseous fueled engines, ignited by a diesel pilot injection have been described in the past. However, the concept described here differs in that the diesel injection remains the main contribution of the fuel energy. Test work reported in this paper examined the effect of hydrogen fumigation up to 8.2% hydrogen concentration by volume in the inlet manifold where the contribution of the two fuels by energy is roughly equal. The combustion chamber contains a homogenous mixture of hydrogen and air, into which the diesel is injected. To investigate how the two fuels will burn, it is important to first understand the ignition and combustion properties of the two fuels (Table 1).

	Diesel	Hydrogen
Stoichiometric Air Fuel ratio	14.5:1	34.3:1
Lower Flammability Limit (LFL)	6.8% (by mass)	4% (by volume)
Auto ignition temperature [10]	~315°C	~565-582°C
Laminar lame speed (1bar)	0.5-1.0m/s [11]	3-5 m/s [12]

Table 1: Comparison of Ignition Properties

From table 1, it can be seen hydrogen will burn much more quickly and at a much lower concentration than diesel. However, the autoignition temperature of hydrogen is higher than diesel and so it may possible to ignite a hydrogen mixture from a diesel flame prior to autoignition of the hydrogen mixture from the compression process alone. The hydrogen – diesel engine is a hybrid of a compression and spark ignited engine, having fuel in both a homogenous (hydrogen) and stratified (diesel) state. To aid understanding of the combustion processes, a ‘three mode’ conceptual model is proposed (figure 2):

Mode 1 Hydrogen pre-ignition: The hydrogen concentration is above the LFL, cylinder conditions exceed hydrogen ignition requirements before auto-ignition of the diesel injection. In this mode, the hydrogen will auto-ignite from multiple sites in a Homogenous Charge Compression Ignition type of combustion mode and in extreme cases in a ‘knock’ combustion mode resulting in rapid heat release and rise in cylinder pressure.

Mode 2 Lean Hydrogen: The hydrogen concentration is below the LFL. Hydrogen will only combust through mixing with the diesel diffusion flame. The rate of combustion is therefore controlled by the rate of homogenous air/hydrogen mixing with the diesel flame.

Mode 3 Rich Hydrogen: The hydrogen concentration exceeds the LFL, whereas the in cylinder conditions are below the ignition conditions for the hydrogen prior to ignition of the diesel fuel. In this mode, a laminar flame will develop in the hydrogen – air mixture initiated from the Diesel diffusion flame.

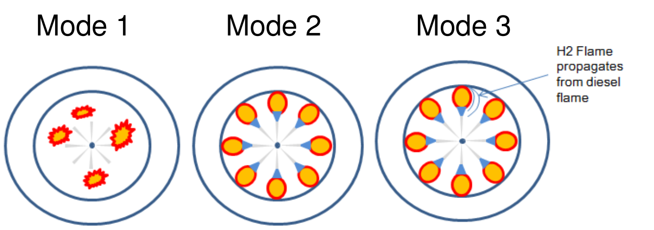


Figure 2: Conceptual model of the hydrogen – Diesel combustion system

The hydrogen combustion process is therefore controlled by (a) which side of the LFL the hydrogen concentration is and (b) whether the in cylinder conditions exceed the auto-ignition conditions of hydrogen. A test program was defined to span these conditions to test the validity of the proposed model.

Description of the Engine Test Facility

The test program was undertaken in the University of Brighton’s heavy duty engine test facility. The test engine was a Ricardo Proteus (see figure 3), with key parameters summarized in table 2. The combustion chamber was of the quiescent open chamber type, typical of modern heavy duty Diesel engines. The fuel system was the Delphi F2E pumped injection system, capable of 3000 bar injection pressures.

The test facility was modified to convert the engine for hydrogen fumigation of the intake system (figure 4). This included the inclusion of a flame arrestor and bursting disk in the intake system and hydrogen injection system. A suitable hydrogen injector could not be found capable of injecting against the expected pressures in the intake manifold. Instead, a Horiba SEC Z552MGX mass flow controller was used to regulate the flow of hydrogen into the intake system of the engine. The hydrogen was introduced well upstream of the intake ports in a bend via a perforated tube to promote good mixing with the charge air.

Figure 3: Proteus engine installed at the University of Brighton test facility

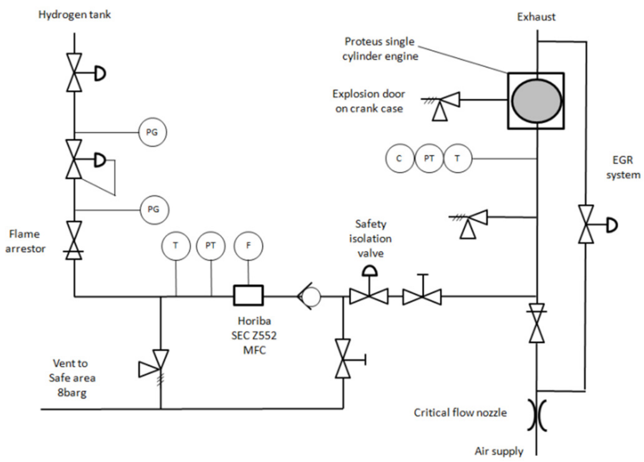


Figure 4: Diagram of Hydrogen system

Bore	131.1mm
Stroke	150mm
Compression ratio	16:1
Swept volume	2l
Swirl	Quiescent
Combustion chamber	Open Chamber
Diesel injection system	Delphi F2E Pumped Injector

Table 2: Engine Characteristics

The engine crank case was fitted with a bursting disk to protect the system against an explosion in the crank case and the test cell was fitted with a hydrogen detector to protect the facility against a hydrogen leak. Air flow into the engine was supplied by a separate air compressor. The air flow was regulated via a set of four nozzles, operated in a choked condition. This enabled the air flow into the engine to be set independently of fluctuations in the intake pressure due to pressure pulsations or the introduction of different quantities of hydrogen.

Test program

The test program was defined to (a) improve understanding of the hydrogen – Diesel combustion process and (b) investigate the viability of the combustion system for application in future heavy duty road transport applications.

It was decided to fix the engine load and speed at a representative condition and concentrate testing on different fuel injection strategies and intake conditions. A load of 195NM at 1250rpm was selected, representative of the A50 condition on the ESC drive cycle [13]. This is a typical motorway cruise condition for long haul truck engines. Test swings were defined as follows:

- Hydrogen concentration to span either side of the LFL (4%)
- Advanced and retarded diesel injection timing, phased to start combustion at Top Dead Center (TDC) and retarded 10° from this timing for the baseline Diesel only case
- No EGR and 20% EGR

The test program is summarized in table 3.

	Timing[1] (°ATDC)	AFR[2] (-)	EGR (%)	H_2 concentration (%Vol)	Intake temperature (ºC)
1	-6 (advanced)	25:1	0%	0-10%[3]	20
2	4 (retarded)	25:1	0%	0-10%[3]	20
3	-6 (advanced)	25:1	20%	0-4%	40
4	4 (retarded)	25:1	20%	0-4%	40

Table 3: Test matrix

[1] Defined as the timing of the electronic pulse to the injector

[2] Defined for 100% diesel (no hydrogen) case

[3] Increased until the onset of knock

The intake manifold temperature was lowered to the minimum possible with the available coolers. It was planned to increase the temperature to demonstrate the transition from mode 3 to mode 1, by increasing the charge air temperature to achieve auto-ignition of the hydrogen mixture prior to diesel ignition. However, as reported later in the paper, hydrogen ignition (mode 1) was achieved at the lowest achievable temperature and so further testing at higher temperatures was not undertaken.

The test program was performed by first setting the engine in Diesel only mode. This enabled the inlet air flow to be set, which was then held constant whilst different quantities of hydrogen was injected into the intake system. The start of diesel injection was held constant and the period reduced to maintain constant load with the introduction of increased quantities of hydrogen. The effective air fuel ratio would therefore change during the swing, but the mass flow of air (and therefore oxygen) would remain constant. The hydrogen was progressively increased until a knocking type of combustion was observed, and then reduced progressively back to zero to check repeatability of the test points. For the EGR swings, the back pressure on the engine was controlled at 1.1 times the intake pressure and the EGR rate set for each condition by modulating a valve between the intake and exhaust system. As hydrogen was added to the intake system, the intake pressure will rise due to the increase in inlet mass flow. The back pressure and EGR valve settings were then adjusted to maintain the required EGR rate. EGR was defined as the ratio of inlet to exhaust CO_2 concentration, as measured using a Horiba 7170 emissions analyzer:

$$EGR(\%) = 100\,\frac{CO_{2\,intake} - CO_{2\,ambient}}{CO_{2\,exhaust} - CO_{2\,ambient}}$$

It should be noted that the displacement of carbon from the fuel through the injection of hydrogen at constant load will change the carbon concentration in the exhaust products, increasing the mass flow of exhaust gas required to achieve a given EGR rate. Other researchers [14] have proposed that hydrogen has similar properties to EGR in reducing the inlet charge oxygen concentration. For the research reported here, we elected to maintain a constant CO_2 balance and any additional effect of the hydrogen in the inlet system would be observed in the exhaust emissions. Carcal research grade diesel (RF0608B5) was used throughout the program.

Data processing

The low speed measurements were averaged over a 1 minute period. Cylinder pressure measurements were captured on a high speed logger and the average of 100 cycles taken. The experimental results were post processed as follows:

- The brake power was corrected for ambient conditions as per ISO 1585
- The inlet mass air flow was calculated from the pressure difference across the critical flow nozzles, in accordance with BS EN ISO 9300:2005
- The brake specific NO_x was calculated from the exhaust concentration, correcting for humidity as per R49, ISO8178, CFR Part 89 etc.
- The brake thermal efficiency (BTE) was calculated from the diesel and hydrogen fuel flows, assuming a lower heating value of 42,660kJ/kg for diesel and 121,000kJ/kg for hydrogen

The critical measurement was the change in BTE, which depends on many factors including the accuracy of the two fuel flow meters, temperature stability of the fuel and the accuracy of the load measurement. Considering these factors, a maximum error of ±2% was determined in the calculation of the BTE.

Experimental Results

Baseline Case – No EGR

Cylinder pressure and 5% burn angle results for the advanced and retarded timing cases are shown in figures 5 and 6. For the advanced timing case, two modes of combustion are observed as the hydrogen quantity is increased. Below the LFL (<4%), the cylinder pressure traces are very similar, indicating no appreciable change in the rate of heat release with the addition of hydrogen to the charge air. Similarly, the 5% burn angle is unchanged as diesel fuel is displaced with hydrogen. However for the advanced timing case, above the LFL, the 5% burn angle is observed to advance by 0.5°. As the diesel injection timing is unchanged, this is due to either pre-ignition of hydrogen before ignition of the main diesel charge or advance of diesel ignition due to modification of the ignition process by the hydrogen. Hydrogen pre-ignition is considered more likely, as the advance in the 5% burn angle is only observed above the LFL, when the hydrogen-air mixture can support combustion. The rate of cylinder pressure rise and hence heat release and maximum cylinder pressure (P_{max}) also increase above the LFL. A rise in motoring cylinder pressure was also observed, due to the higher inlet manifold pressure with the increased mass in the intake with the introduction of hydrogen. For the retarded injection timing tests, the advance in the 5% burn angle is more pronounced (1.6°) but there is much less effect on the shape of the cylinder pressure curve and hence bulk rate of heat release. The more pronounced advance of the 5% burn angle for the retarded injection case is due to the longer residence time of the hydrogen-air mixture at peak cylinder temperature conditions prior to ignition of the diesel fuel, enabling more time for the hydrogen to ignite before ignition of the diesel charge, or interact with the diesel ignition chemistry. The observed behavior is consistent with a transition from the 2nd (lean hydrogen) to 1st (hydrogen auto-ignition) modes shown in figure 2 as the hydrogen concentration is increased beyond the LFL, however the above mentioned interaction with the diesel ignition process cannot be discounted.

Brake thermal efficiency results shown in figure 7 indicate a drop of 1% point in BTE for a 4% addition of hydrogen for both advanced and retarded timing tests. The observed change is within the expected errors of the experiment (±2%), but was found to be repeatable and consistent between different test conditions and therefore cannot be ignored. Other researchers have reported similar results, in the range of 1-3% drop in BTE. The drop in BTE was attributed to incomplete combustion of the hydrogen, referred to as hydrogen slip [4, 6]. It was not possible to measure directly hydrogen in the exhaust system so this hypothesis has yet to be verified, but is considered the most likely explanation for the observed results.

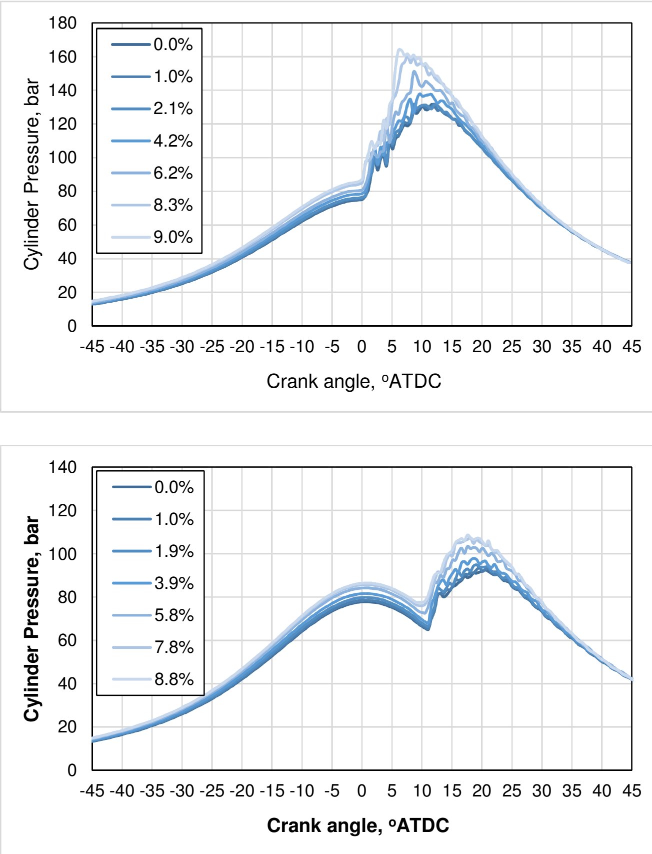


Figure 5: Cylinder Pressure Results (a) advanced timing (b) retarded timing without EGR for different hydrogen concentrations (by volume)

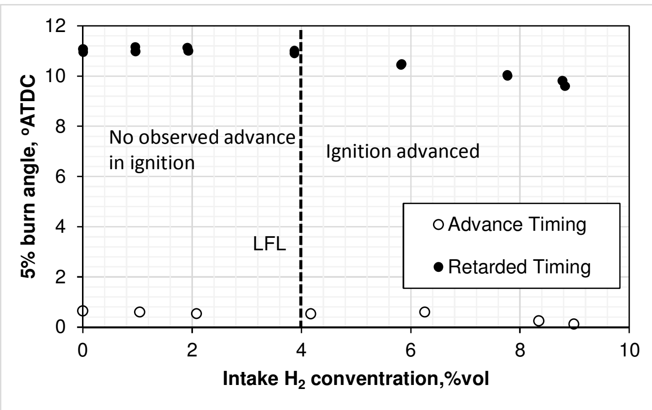


Figure 6: 5% burn angle data for the advanced and retarded timings without EGR against hydrogen concentration

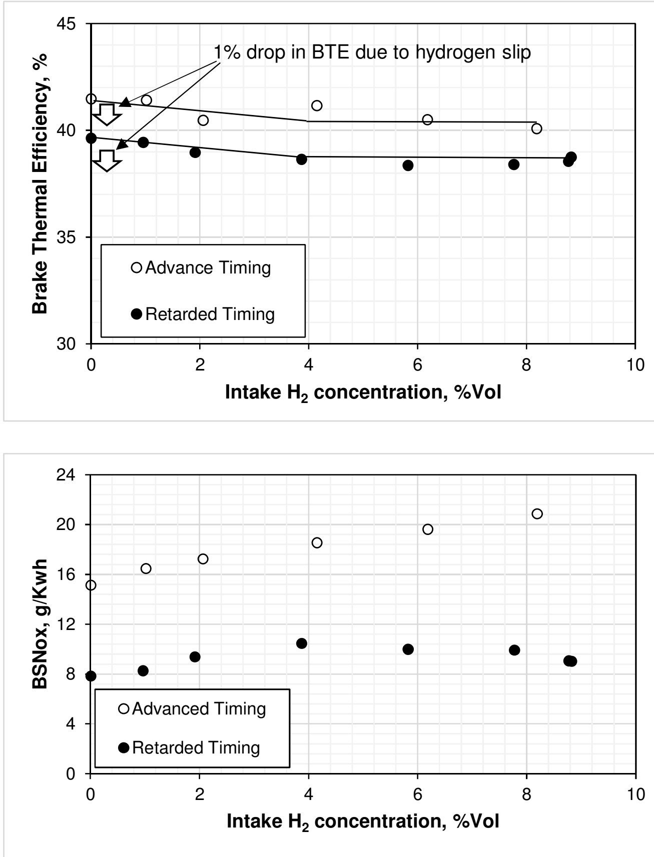


Figure 7: Brake thermal efficiency (a) and NO_x (b) results from hydrogen swings without EGR for advanced and retarded timings

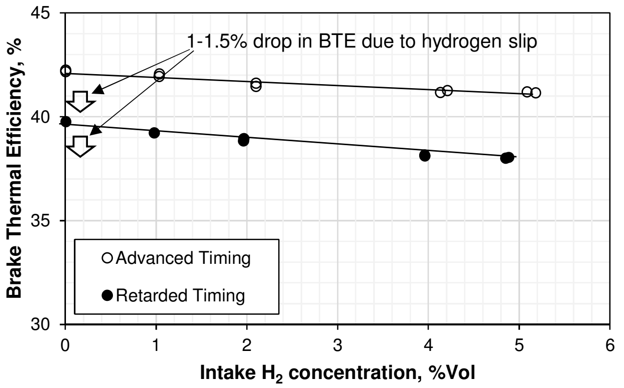
The BTE shown in figure 7a is observed to be constant above 4% hydrogen concentration (above the LFL). Above 4% concentration, combustion of the air-hydrogen mixture is possible and so less hydrogen slip would be expected. However, hydrogen trapped in the crevice volumes would still not be expected to burn and so some slip is expected, increasing with increased hydrogen concentration. The balance of these two competing effects observed in the test data is no net reduction in BTE above the LFL. The same trends were observed for the advanced and retarded injection timing cases.

The NO_x emissions for the retarded timing case (shown in figure 7b) were observed to rise then fall above 4% hydrogen concentration. Similar results were observed by Liu [14], and was attributed to a combination of changes in flame temperature and interaction of the hydrogen with the NO_x formation chemistry, in particular a change in the NO_2/NO_x ratio. However, for the advanced timing case, a steady increase in NO_x was observed up to the point when a knocking type of combustion was observed (>8.3% concentration).

EGR Case

Figure 8b shows NOx emissions for tests with EGR. The results demonstrate that, as expected, the introduction of EGR significantly reduces the Diesel only NO_x emissions, from 15.1 to 6g/kWhr at the advanced timing and from 7.8 to 2.5g/kWhr at the retarded timing. The BTE results (figure 8a) follow a similar trend to the non EGR case up to the LFL, with a 1 to 1.5% drop in BTE. Within the accuracy of the fuel consumption measurement, this is essentially the same result as observed without EGR. Hydrogen concentrations above the LFL were not studied with EGR due to the risk of ignition in the inlet manifold.

The advanced timing NO_x results are also similar to the non EGR case, with NO_x increasing with increasing levels of hydrogen fumigation. A small increase in NO_x was also observed for the retarded case, but much less than observed for the advanced condition. In both cases, the EGR remains an effective NO_x control strategy. It is worth noting the engine out NO_x emissions, even with 4% hydrogen addition are within Euro IV limits (ie typical engine out levels for a Euro VI engine with SCR).



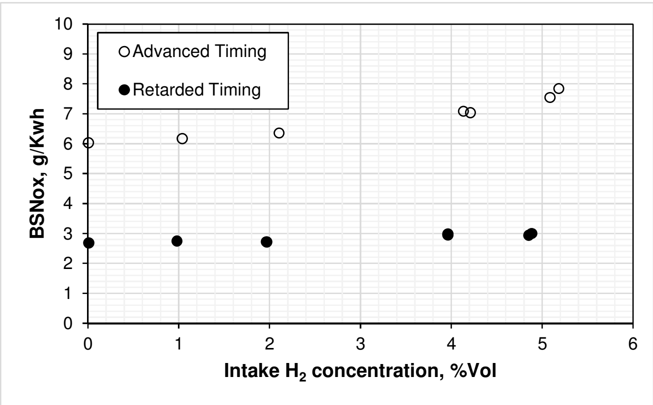


Figure 8: Brake thermal efficiency (6a) and NO_x (6b) results from hydrogen swings with 20% EGR for advanced and retarded timings

Discussion of Results

Emissions Results

Euro VI requires ultra low cycle NO_x emissions of less than 0.4g/kWh across the cycle. This could be achieved 'engine out' using very high levels of EGR and high pressure injection, but with significant implications to the efficiency and architecture of the engine. OEM's have therefore used SCR aftertreatment as an effective means of controlling NO_x. The test program was set up to cover the two NO_x control approaches seen in the European market:

- High efficiency (>95% conversion) SCR without EGR
- Modest efficiency (~90%) SCR with modest levels of EGR

Considering the NO_x results presented earlier, Euro VI NO_x emissions are achieved with either strategy with significant displacement of diesel by manifold injected hydrogen. Retarded injection timings, with the associated fuel consumption penalty are required for the non EGR case, whereas an advanced timing strategy is possible with modest levels of EGR. This implies hydrogen fumigation could be implemented with minimal change to the engine emissions control system and calibration. The gradual change in NO_x (at levels low enough to achieve Euro VI) with hydrogen concentration also means the engine calibration would need minimal adjustment to the quantity of hydrogen used. With reference to the two pathways for hydrogen to be supplied to the vehicle, this is a significant result. Considering the first option of hydrogen as a second fuel. In the event a vehicle was in operating in a region with an undeveloped hydrogen distribution network, the vehicle could operate in Diesel only mode preventing the vehicle from being stranded due to the unavailability of hydrogen. This would make the introduction of hydrogen dual fueling much less risky to both OEM's and vehicle operators, removing range anxiety. Considering the second option of on board fuel reforming, the supply of hydrogen will be dependent on the transient performance of the reformer. As the reformer requires waste heat, thermal transience on vehicle start up and load variations (such as climbing followed by descending a hill) will impact the supply of hydrogen. The fact that the calibration is relatively insensitive to a varying supply of hydrogen implies that the system will be tolerant to the likely transient performance of the reformer.

Thermal Efficiency and Carbon Emissions

In all cases, a 1-1.5% drop in BTE was observed between the Diesel only case and the hydrogen – Diesel cases. As previously mentioned this is within the experimental accuracy of the fuel flow measurements and so is not strictly statistically significant but is systematically observed in all cases. Referring to the conceptual model for hydrogen combustion, at concentrations below the LFL, the homogenous mixture of hydrogen can only burn by interacting with the diffusion flame through mixing of the air/hydrogen mixture with the flame. Some hydrogen will not be burnt due to incomplete mixing and will appear as un-burnt fuel in the exhaust and would explain the observed drop in BTE. Referring to the conceptual model proposed in figure 2, any of the air-hydrogen mixture that is not consumed in the Diesel flame will not burn and will slip through to the exhaust system. Other researchers have reported similar results, but generally a larger drop in BTE of the order of 1-3% points. The baseline combustion system in the current research is well optimized, with a good match of the in cylinder air motion and fuel system, achieving near zero particulate emissions. This is indicative of good air-diesel fuel mixing, and high air utilisation. A fuel injection pressure of 2000 bar was selected for the current work, based on a previous extensive optimization study [15]. Although lower than the 3000 bar capability of the F2E system, this pressure provided the best result at the A50 condition. This pressure is still much higher than those used in previous studies where less advanced fuel systems were available. It is therefore likely the combination of high rail pressure matched to the in cylinder charge motion to promote good mixing is also favorable for the hydrogen-diesel combustion system. The high level of matching of the air motion and fuel system of the baseline engine is therefore likely to promote more complete combustion of the hydrogen and may explain low BTE penalty compared to previous studies. Further work is required to verify this hypothesis, to study further the interaction of air – hydrogen and diesel fuel mixing.

For the non EGR NO_x control strategies, the BTE was insensitive to the concentration of hydrogen in the intake system above the LFL. This would suggest that high levels of diesel can be displaced without significantly affecting the thermal efficiency of the engine within emissions limits. At 4% hydrogen, 25% of the Diesel is displaced and 50% at the upper limit of 8.2% hydrogen used in the present research. This means, that if the hydrogen is supplied through a low carbon source, a significant reduction in CO_2 emissions could be achieved through dual fueling the engine with hydrogen and diesel. Keeping the hydrogen concentration below the LFL is attractive as it minimizes the risk of ignition in the intake system, suggesting a 25% reduction in CO_2 could be practically and safely achieved.

Comparison with Conceptual Model

A conceptual model of hydrogen Diesel combustion was proposed at the beginning of this paper. The experimental data broadly supports the model as follows:

Mode 1 (hydrogen auto-ignition). The cylinder pressure traces and 5% burn angle data show evidence of early ignition with the introduction of hydrogen above the LFL. This is interpreted as pre-ignition of hydrogen due to the in-cylinder conditions exceeding the auto-ignition temperature for the hydrogen – air mixture prior to ignition of the main diesel charge. However, this could also be due to advance of the diesel ignition due to interaction of hydrogen with the diesel auto-ignition process. Further work is required to understand the ignition process of the hydrogen-diesel engine and define the exact mechanism. At concentrations between 4% and 8%, the pre-ignition of the hydrogen did not result in a 'knock' type of combustion, and is more consistent with a HCCI type of combustion process. Above 8%, knock was observed and testing was not undertaken at these conditions to prevent damage to the engine.

Mode 2 (lean hydrogen). Below the LFL, there is no evidence of combustion prior to ignition of the main diesel charge and the cylinder pressure trace with hydrogen is very close to the Diesel only case. This implies the rate of combustion is controlled by air-hydrogen and iesel fuel mixing. The BTE results suggest a high level, but still incomplete combustion of the hydrogen controlled by mixing of the air-hydrogen mixture with the diesel flame.

Mode 3 (rich hydrogen). Even at manifold temperatures low enough to prevent the bulk air exceeding the hydrogen auto-ignition temperature (20°C), it was not possible to prevent pre-ignition of the hydrogen-air mixture above the LFL. It is widely reported that hydrogen has a low ignition energy and so would be easily ignited by any hot spots in the combustion chamber or hot residual gases trapped in the chamber and further heated during compression. Mode 3 may therefore be unachievable at the compression ratios required to ignite diesel and hence not observed.

Conclusions

An experimental program was successfully undertaken to investigate the impact of hydrogen fumigation of the intake system of a low emissions heavy duty combustion system. Significant quantities of hydrogen could be safely added, up to 8.2% by volume, representing the displacement of 50% of the Diesel charge without knock.

The engine could be calibrated to achieve NO_x emissions compatible with Euro VI emissions limits. This was achieved by either retarding the injection timing without EGR, or the addition of 20% EGR with an advanced timing strategy. The NO_x emissions increased with higher quantities of hydrogen over a wide range of concentrations up to 8.2% for these calibrations, but still within Euro VI limits. It is concluded a robust hydrogen-diesel calibration can be achieved that is compatible with the ultra-low NO_x levels required for Euro VI with SCR exhaust aftertreatment. At the selected calibrations, the BTE was observed to drop by 1% point which was attributed to hydrogen slip, this 1% drop was insensitive to hydrogen concentration.

It was proposed that the lower drop in BTE observed compared to other researchers was due to more complete combustion of hydrogen due to good mixing of the air-hydrogen mixture with the diesel fuel. The injection pressure available from the F2E system is higher than that used by other researchers and could promote improved mixing of the diesel and hydrogen-air mixture. Further research is in progress to investigate the impact of injection pressure on the performance of the hydrogen-diesel combustion system and air-fuel mixing.

It is concluded that if hydrogen can be produced from a zero carbon source, a significant reduction in CO_2 emissions of up to 25% could be safely achieved with minimal change to the engine calibration and architecture. An alternative pathway for the supply of hydrogen through on board fuel reformation is also possible, opening a new method for waste heat recovery if a suitable steam reformation system can be developed.

References

1. Stanton, D.W., *Systematic Development of Highly Efficient and Clean Engines to Meet Future Commercial Vehicle Greenhouse Gas Regulations.* SAE Int. J. Engines, 2013. **6**(3): p. 1395-1480.
2. Suckuckert, M., *Improved vehicle fuel efficiency for further emissions reduction*, in *10th Integer Emissions Summit.* 2014: Dusseldof.
3. Schreier, H.L., W., Theissl, H., Decker, M., *Potentials and challenges for next generation HD diesel Engines*, in *SAE Heavy Duty Diesel Emissions Control Symposium*. 2014: Gothenburg.
4. Gatts, T., et al., *An experimental investigation of H2 emissions of a 2004 heavy-duty diesel engine supplemented with H2.* International Journal of Hydrogen Energy, 2010. **35**(20): p. 11349-11356.
5. Liew, C., et al., *Exhaust emissions of a H2-enriched heavy-duty diesel engine equipped with cooled EGR and variable geometry turbocharger.* Fuel, 2012. **91**(1): p. 155-163.
6. Tira, H.S., et al., *Influence of the addition of LPG-reformate and H2 on an engine dually fuelled with LPG–diesel, –RME and –GTL Fuels.* Fuel, 2014. **118**(0): p. 73-82.
7. Shin, B., et al., *Hydrogen effects on NOx emissions and brake thermal efficiency in a diesel engine under low-temperature and heavy-EGR conditions.* International Journal of Hydrogen Energy, 2011. **36**(10): p. 6281-6291.
8. Shin, B., et al., *Investigation of the effects of hydrogen on cylinder pressure in a split-injection diesel engine at heavy EGR.* International Journal of Hydrogen Energy, 2011. **36**(20): p. 13158-13170.
9. Talibi, M., et al., *Effect of hydrogen-diesel fuel co-combustion on exhaust emissions with verification using an in–cylinder gas sampling technique.* International Journal of Hydrogen Energy, 2014. **39**(27): p. 15088-15102.
10. *Alcohol's and Ethers*. 1988, Washington: American Petroleum Institute.

11. Chong, C.T. and S. Hochgreb, *Measurements of laminar flame speeds of liquid fuels: Jet-A1, diesel, palm methyl esters and blends using particle imaging velocimetry (PIV).* Proceedings of the Combustion Institute, 2011. **33**(1): p. 979-986.
12. Ravi, S. and E.L. Petersen, *Laminar flame speed correlations for pure-hydrogen and high-hydrogen content syngas blends with various diluents.* International Journal of Hydrogen Energy, 2012. **37**(24): p. 19177-19189.
13. Verbeek, R.P., Ligterink, N.E., Dekker, H.J. *Correlation Factors between European and World Harmonized Test Cycles for heavy-duty engines*. [cited 2015 6th June]; Available from: http://ec.europa.eu/enterprise/sectors/automotive/files/projects/report_whtc_correlation_en.pdf.
14. Liu, S., et al., *An experimental investigation of NO2 emission characteristics of a heavy-duty H2-diesel dual fuel engine.* International Journal of Hydrogen Energy, 2011. **36**(18): p. 12015-12024.
15. Morgan, R., Auld, A., Banks, A. Lenartowicz, C., *The benefits of high injection pressure on future heavy duty engine performance*, in *12th International Conference on Engines & Vehicles*. 2015, SAE 2015-24-2441: Capri.

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Definitions/Abbreviations

BTE	Brake thermal efficiency
EGR	Exhaust gas recirculation
HCCI	Homogenous Charge Compression Ignition
LHV	Lower heating value
TDC	Top dead center