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REVIEW ARTICLE

EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF COMBINED HYDROGEN AND DIESEL COMBUSTION ON THE EMISSION OF DIESEL ENGINE

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Experimental Investigation of the effects of combined Hydrogen and Diesel combustion on the emission of Diesel Engine

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1. INTRODUCTION

This paper will look at the exhaust gas emissions based on a gravimetric analysis, from combined hydrogen/diesel combustion. Ultimately the aim of this investigation was to determine if a combination of hydrogen induction and exhaust gas recirculation (EGR) could be used to simultaneously reduce the carbon monoxide, total unburnt hydrocarbons and nitrogen oxides emissions. This being the case, an operating strategy for each of the investigated speeds and loads has been proposed.

2. EXPERIMENTAL TEST MATRIX

2.1 Emissions Tests

In order to investigate the effects of combined hydrogen/diesel combustion with EGR addition, various levels of EGR and hydrogen addition were used. The EGR levels were varied between 0% and 40%, where the engine was capable of running this level, in 5% steps.

Hydrogen was supplied and the levels were varied between 0 and 10% volume of the inlet charge, in 2% vol. steps. In the case of running both hydrogen and EGR, the hydrogen always replaced air.

Two engine speeds were run, 1500rpm and 2500rpm, and 3 engine loads.The 3 engine loads were 0 bar BMEP, 2.7 bar BMEP and 5.4 bar BMEP. Since not all combinations of the speeds and loads were capable of supporting the maximum levels of hydrogen and EGR, Table 1 shows the achieved levels for each operating point .

Operating Point	Hydrogen Level	0% vol.	2% vol.	4% vol.	6% vol.	8% vol.	10% vol.
1500 rpm 0 bar		40 % EGR	30% EGR	30% EGR	Not run	Not run	Not run
1500 rpm 2.7 bar		40% EGR	35% EGR	40% EGR	10% EGR	Not run	Not run
1500 rpm 5.4 bar		30% EGR	30% EGR	30% EGR	15% EGR	15% EGR	10% EGR
2500 rpm 0 bar		40% EGR	40% EGR	35% EGR	Not run	Not run	Not run
2500 rpm 2.7 bar		40% EGR	40% EGR	40% EGR	35% EGR	Not run	Not run
2500 rpm 5.4 bar		15% EGR	15% EGR	15% EGR	15% EGR	Not run	Not run

Table 1 Experimental Test Matrix

3. RESULTS AND DISCUSSION

3.1 Emissions

3.1.1 Carbon Monoxide Emissions

As can be seen from Figure 1, carbon monoxide emissions decrease with an increase in hydrogen percentage. This is true for all loads. The increase in hydrogen means there is a lower percentage of hydrocarbons available for combustion, resulting in lower carbon monoxide emissions for the same load output. This alone cannot fully explain the reduction in CO emissions. It is more likely that the nature of the more complete mixing of the fuel and air brought about by the ignition delay results in more complete combustion. As can be seen from the case of the high load lines in Figure 1, the use of EGR increases CO emissions, but the use of hydrogen goes some of the way towards offsetting this.

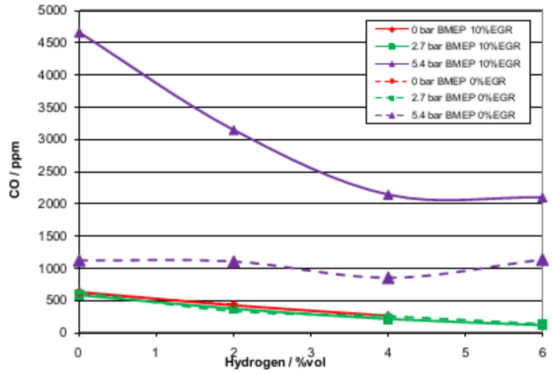

Figure 1 Carbon Monoxide emissions at 2500rpm

As was seen with the 2500 rpm case, carbon monoxide decreases with hydrogen addition in the case of 1500 rpm, as shown in Figure 2. There is however a spike in CO production at 8% vol. Hydrogen induction at 5.4 bar BMEP. This is due to the onset of unstable combustion, and therefore the increase in products of incomplete combustion.

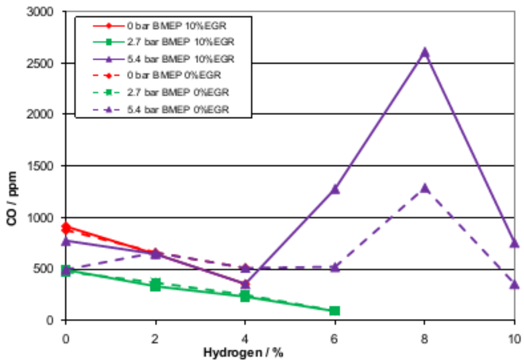

Figure 2 Carbon Monoxide emissions at 1500rpm

3.1.2 Nitrogen Oxide Emissions

As can be seen from Figure 3 nitrogen oxides are mainly increased by the increasing hydrogen. This is to be expected with the increased premixed combustion experienced with hydrogen combustion. However, in the case of no load with 10% EGR it can be seen that NOX actually decreased. Unfortunately, this is also the higher limit of using hydrogen with no load, so a way would have to be found to allow stable combustion.

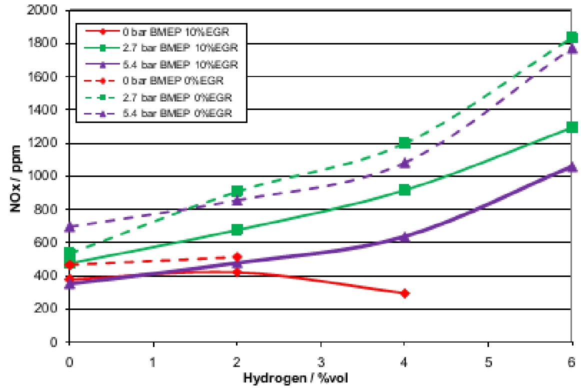

Figure 3 Nitrogen oxides emissions at 2500rpm

Since the production of NOX is controlled by both the in-cylinder temperature and the flame speed, the introduction of hydrogen influences NOX production in more than one way. Hydrogen increases the ignition delay, resulting in faster combustion due to the better mixing of the fuels. This high temperature combustion would be expected to increase the NOX production. It would also be expected that as the mixture became leaner, and the flame speed slower, the time allowed for NOX formation would be increased. The introduction of hydrogen does indeed increase the air/fuel ratio, for example in the case of high load at 2500 rpm and 10% EGR it increases from 16.6 at 0% vol. Hydrogen all the way up to 30.0 at 4% vol. hydrogen, but the chemical kinetics is far too complex for the air/fuel ratio alone to account for the increased production of NOX.

For the 1500 rpm case, the trend appears to be more complicated, as shown in Figure 4. The NOX emissions for the no load and high load case actually decrease up to 4% vol. hydrogen addition. This is clearly due to the slower rates of in-cylinder pressure rise rates at these levels. Lower portions of diesel fuel burned during the premixed phase of combustion leads to lower NOX production as the in-cylinder temperatures are lower.

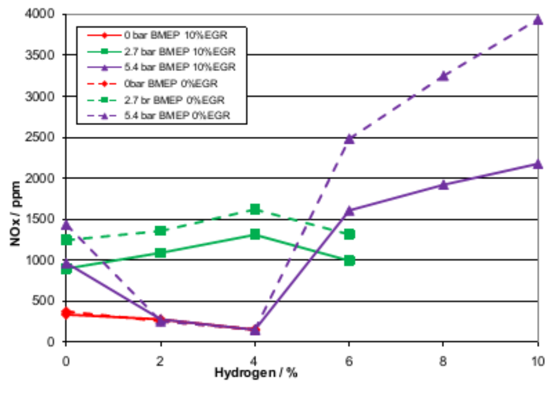

Figure 4 Nitrogen oxides emissions at 1500rpm

3.1.3 Total Unburnt Hydrocarbon Emissions

The total unburnt hydrocarbons (THC) decrease with hydrogen until the combustion becomes unstable. This can be explained by the lower carbon content in the supplied fuel, but also the more complete combustion. Whenthe point of unstable combustion is reached, a sharp rise in the unburnt hydrocarbons can be observed, as is shown in Figure 5, around the 4% vol. hydrogen for both medium and high loads. The point at which unstable combustion is reached changes with both load and speed. The effect of EGR on the THC is a general increase with increasing EGR. The high load 2% vol. hydrogen result is unexpected and needs further investigation.

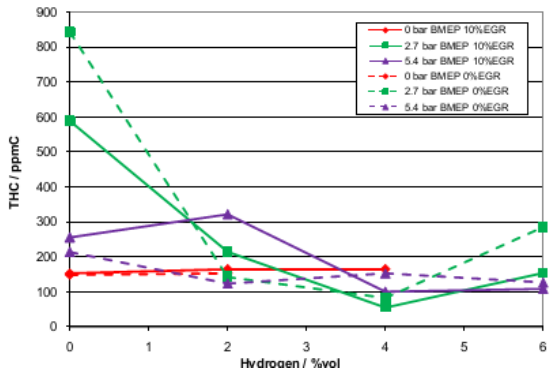

Figure 5 Total unburnt hydrocarbons at 2500rpm

Generally, the THC emissions decrease with hydrogen addition. The point where unstable combustion is reached does vary between the 1500 rpm and 2500 rpm cases, as is shown by Figure 5 and Figure 6.The onset of unstable combustion for the 1500 rpm case at 5.4 bar BMEP can be seen to be between 6 and 8 % vol. Hydrogen induction. The increase in THC emissions at 4% vol. Hydrogen addition for the 2.7 bar BMEP case reflects the dramatic decrease in maximum in-cylinder pressure rise rate. At this point the advantage provided by the premixed nature of combustion is lost.

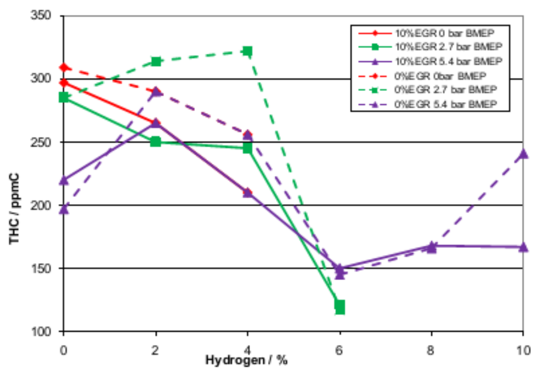

Figure 6 Total unburnt hydrocarbons at 1500rpm

3.1.4 Filter Smoke Number

The measurement of the filter smoke number (FSN) was hampered by the increased water contained in the hydrogen/diesel exhaust. This led to problems within the instrument where the paper used to collect the exhaust became soggy and broke during some measurements. It can still be seen from Figure 7 that the FSN decreases with hydrogen. The FSN always increases with EGR, but this effect is almost negated when EGR is combined with high levels of hydrogen addition. The fact that the 10% EGR shows lower smoke numbers with increasing hydrogen levels when compared to the 0% EGR might seem to be a surprising result. This can be explained by the change in nature of the particulate matter produced. Without hydrogen the PM is mainly sooty in nature, and is black. With hydrogen the PM grows more gummy and colourless as the hydrogen level increases. This shows a shift from long chain carbon molecules towards shorter chain volatile organics.

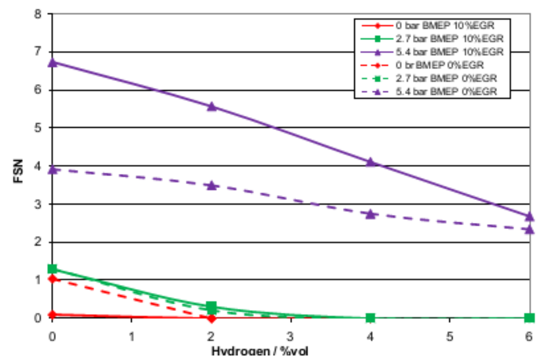

Figure 7 Filter smoke number at 2500rpm

Similarly for the case of 1500 rpm, the filter smoke number is heading towards zero with increasing hydrogen addition, as is shown in Figure 8. However, it can clearly be seen that the anomaly around 8%vol.Hydrogen induction. This is caused by the onset of unstable combustion.

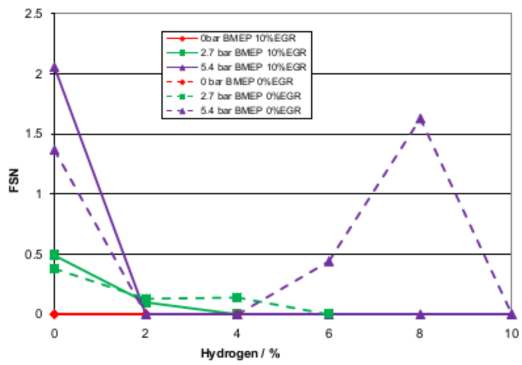

Figure 8 Filter smoke number at 1500 rpm

3.1.5 Specific Emissions

The emissions have been presented above in terms of the absolute values measured in this particular case.This has been necessary in order to examine the relationship between the hydrogen induction and the effects of load, as it is not possible to calculate the specific emissions at the no load case.

Figure 9 shows the expected decrease in CO emissions with hydrogen addition. This is particularly apparent in the high load case in combinationwith EGR. The mechanism for decreasing CO has two components. Firstly the addition of hydrogen as fuel reduces the carbon available in the cylinder. Secondly the premixed nature of the hydrogen/diesel combustion means there is more complete combustion, resulting in higher water and carbon dioxide emissions, rather than the incomplete combustion counterparts.

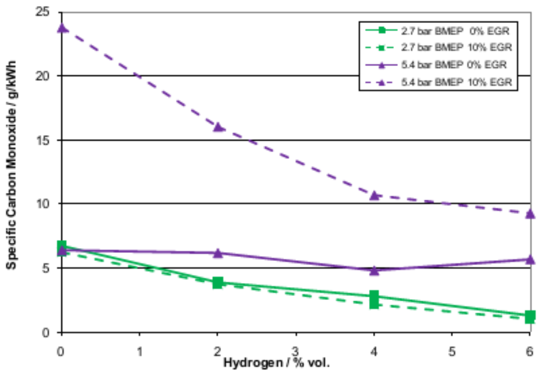

Figure 9 Specific Carbon Monoxide emissions at 2500rpm

Figure 9 Specific Carbon Monoxide emissions at 2500rpm Figure 10 shows the increase in NOX emissions with hydrogen addition. It is important to note however, that the high load specific emissions of NOX are lower than that of the medium load. The mechanisms for NOX production during hydrogen combustion need further investigation.

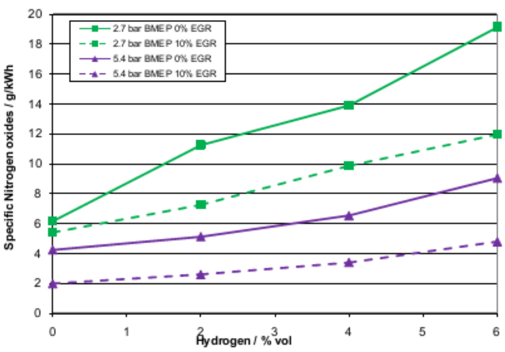

Figure 10 Specific Nitrogen oxides emissions at 2500rpm

3.2 Efficiency

3.2.1 Thermal Efficiency

The fuel conversion efficiency (thermal efficiency) was calculated using equation [Stone (1992)].

$$\eta = \frac{BP}{(\dot{m}_{fdiesel} \times CV_{diesel}) + (\dot{m}_{fH_2} \times CV_{H_2})}$$

Where BP is the brake power and CV is the fuel calorific value (the calorific value of hydrogen is more than double that of diesel, ie. 120kJ/g for hydrogen compared to 45kJ/g for diesel [Zumdahl (1995)]). As shown Figure 11, the efficiency is increased with hydrogen addition for both 2.7 and 5.4 bar BMEP, with maximum gains using EGR of around 8% at 2500 rpm.

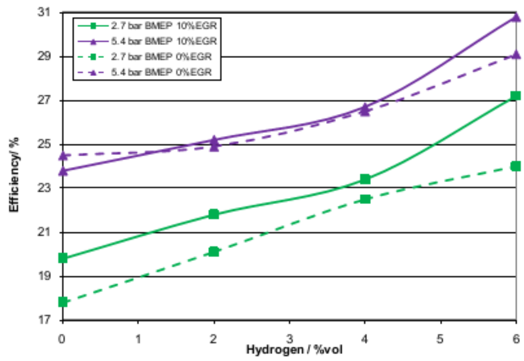

Figure 11 Thermal efficiency at 2500rpm

For the 1500rpm case however, the trend was not so good. As can be seen in Figure 12, the efficiency is increased with the addition of hydrogen apart from the anomaly around 6- 8% vol. Hydrogen addition at 5.4 bar BMEP. As has been discussed in the previous sections, there is something interesting happening at this point which needs further investigation to fully explain.

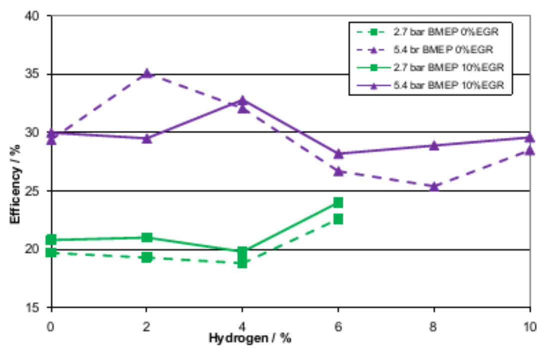

Figure 12 Thermal Efficiency at 1500rpm

It has to be mentioned here that in the case of an engine with on-board generation of hydrogen the overall fuel conversion efficiency of the engine/reformer system will also depend on the fuel reforming process efficiency and not only on the engine combustion process. Never the less, the obtained increased efficiencies show a clear benefit of hydrogen addition in terms of engine fuel conversion efficiency.

3.2.2 Energy Consumption

As the hydrogen level increases, the diesel fuel consumption decreases. This is partly due to the fact that the hydrogen is providing energy to the reaction, but also more of the diesel is being fully utilised, resulting is less wasted energy. As a way of visualising this effect, the total energy supplied the cylinder was calculated.The total energy was calculated using the measured mass fuel flow rate of the diesel fuel and the volumetric fuel flow rate and the density of the hydrogen. As can clearly be seen in Figure 13, the total energy required to maintain the load decreases with hydrogen addition. This effect is more pronounced as the load increases. It is also important to note that the total energy needed to maintain the load is lower with EGR than without. The combined use of EGR and hydrogen delayed the onset of unstable combustion. This phenomenon needs further investigation to understand the chemical kinetics dictating the combustion.

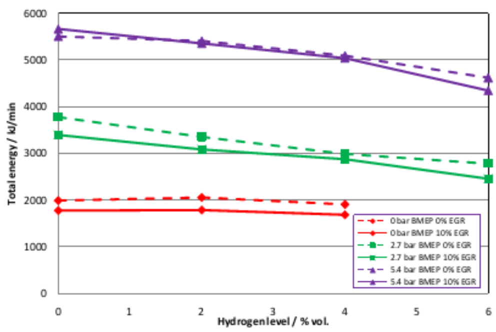

Figure 13Total energy supplied to the engine at 2500rpm

As is shown in Figure 14 a similar effect is observed at 1500rpm. It is clear that at the no load case at 1500 rpm, the combustion is unstable, and therefore more energy must be supplied to maintain the engine operation during misfire. Again the energy consumption is lower with EGR than without, and the decrease with hydrogen addition is clear.

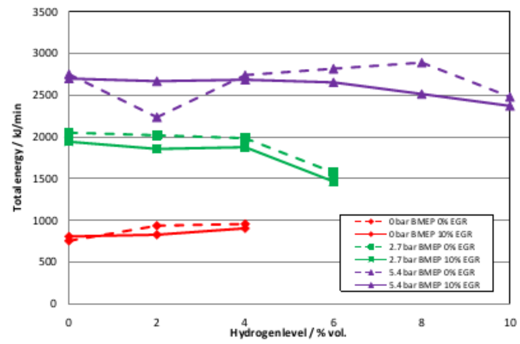

Figure 14 Total energy supplied to the cylinder at 1500rpm

The percentage of energy supplied by the hydrogen as the hydrogen levels increased was also calculated. Figure 15 clearly shows the higher percentage of energy supplied by the hydrogen with EGR. At 2500rpm the onset of unstable combustion occurs when the percentage of energy supplied by the hydrogen passes 50% for the lower load cases. In order to maintain a higher load, the maximum levels of hydrogen addition are lower, around 30% maximum.

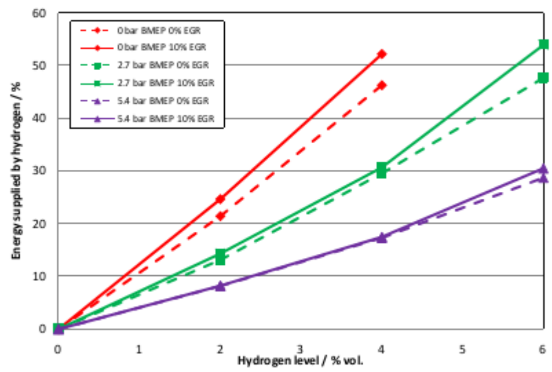

Figure 15 Percentage of total energy supplied by the hydrogen at 2500rpm

In the case of 1500rpm higher percentages of energy supplied by the hydrogen was possible, as shown in Figure 16. The onset of unstable combustion was with about 60% of the supplied energy coming from the hydrogen induction. For the medium and no load cases, the percentage of total energy supplied by the hydrogen is slightly higher with EGR than without, as the mass fuel flow rate of diesel fuel is lower with EGR than without.

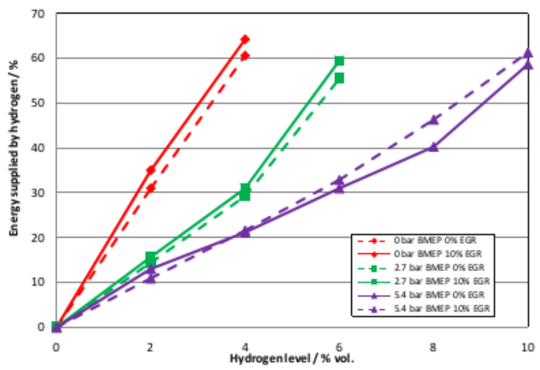

Figure 16 Percentage of total energy supplied by hydrogen at 1500rpm.

4. SUMMARY

This paper has covered the investigation of the effects of hydrogen addition on the exhaust gas emissions.

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