HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF HYDROGEN ENHANCED COMBUSTION IN SI AND CI ENGINES ON PERFORMANCE AND EMISSIONS

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ABSTRACT

Hydrogen enhanced combustion (HEC) is promoted as an end-user add-on that has the capability of reducing both engine tailpipe emissions and fuel consumption. An experimental investigation was carried out to measure the effects of HEC in typical engines through laboratory dynamometer testing. Three engines – (1) a carburetted petrol engine, (2) a fuel injected petrol engine and (3) a diesel engine – were tested to investigate the effects of adding hydrogen to the air intake of the engines and measure the effects on performance and emissions (HC, CO and CO_2). The engines were tested at different engine speeds and loads to simulate a wide range of operating conditions. The hydrogen was produced from the electrolysis of a solution of distilled water and sodium hydroxide using two different electrolyser designs. The electrolyser constructions were suitable for automotive applications, that is, small in size and consuming current within the capability of a typical car alternator. Both the hydrogen and oxygen that were produced by electrolysis were added to the engine‘s intake during the tests. Results showed that the addition of HHO is most effective in stabilizing and enhancing the combustion of lean air-fuel mixtures inside the petrol injected engine, allowing for lower HC, CO and CO2 emissions. Thus hydrogen enhanced combustion could play a role in stabilizing lean burn petrol engines.

INTRODUCTION

Cassidy [1] investigated the effect of adding small amounts of hydrogen to a carburetted petrol engine. The results showed that for all equivalence ratios, the addition of small amounts of hydrogen significantly increased the flame speed during combustion. The increase was more pronounced as the equivalence ratio decreased. The same experiments showed that at an equivalence ratio of 0.69 the flame speed of a petrol-air mixture with some added hydrogen (0.07 mass fraction) was as fast as the flame speed of a petrol-air mixture at an equivalence ratio of 0.98 The effect of hydrogen on flame speed is confirmed by experiments carried out by Ivanič et al. [2]. Similar experiments by Conte and Boulouchos [3], who have studied the effects of adding increasing amounts of reformer gas composed of 21% H_2, 24% CO and 55% N_2, have indicated an increase in the rate of heat release with a shortening of the interval required when more reformer gas was added.

As a result of faster combustion, the engine’s efficiency and power output increase because the actual combustion process becomes closer to the reversible constant volume heat addition as modelled by the Otto and Dual cycles. In fact, experiments by various researchers have shown that when adding hydrogen the engine’s efficiency increases. Ji et al. [4] tested a petrol engine at 1400rpm at different loads for two AFRs (λ=1.2 & λ=1.4). For the two AFRs, 3% by gas intake volume of hydrogen was added and increases in the thermal efficiency of the engine were observed. The increase in efficiency due to the addition of hydrogen relative to operation on petrol only was greater for the leaner mixture.

Efficiency increases and specific energy consumption reductions with hydrogen addition were also observed at all load conditions by Saravanan and Nagarajan [5] in a diesel engine running at 1500rpm and equipped with hydrogen port injection. The increases in efficiency and reductions in specific fuel consumption changed with hydrogen injection timing, while diesel injection timing was kept constant. The efficiency at 75% of full load increased from 21.6% for diesel only operation to 25.6% when an optimized hydrogen flow rate of 7.5 lpm was added. By adding 0.78% hydrogen-oxygen by intake gas volume of a small single cylinder diesel engine, Samuel and McCormick [6] reported a 5.4% decrease in fuel consumption, signifying an increase in the engine's efficiency. Bari and Esmaeil [7] also saw increases in the efficiency of a diesel engine as more hydrogen-oxygen gas was added to its intake. The increases observed were of 2.6%, 2.9% and 1.6% for loads of 19kW, 22kW and 28kW respectively at a constant speed of 1500rpm. However, no more increases in efficiency were observed when more than 5% by total equivalent diesel content of hydrogen-oxygen gas were added. Higher peak pressures located closer to TDC as a result of the faster and improved combustion of diesel with added hydrogen produce a higher effective pressure for the same fuel supply, increasing the engine's efficiency [7]. Dülger and Özçelik [8] tested an on-board electrolysis unit producing 20 litres per hour of hydrogen-oxygen gas on four cars for fuel economy, resulting in savings of 43% for a 1993 Volvo 940, 36% for a 1996 Mercedes 280, 26% for a 1992 Fiat Kartal and 33% for a 1992 Fiat Doğan.

Conte and Boulouchos [3] have reported an increase of 34% in efficiency of the petrol engine when the petrol was completely substituted with reformer gas, lower gains in efficiency were observed for lower petrol-reformer gas substitution levels. However, an analysis on the net efficiency gain showed that the reformer efficiency should be of at least 80% in order to obtain a net increase in efficiency for lean limit and EGR limit mixture operation. Similarly, Ivanič et al. [2] have seen up to 12% increases in efficiency when adding 30% plasmatron gas to a lean mixture but when the losses of the plasmatron (assumed as 84% efficient) were considered this gain was reduced to 7%. This meant that the increase in efficiency due to leaning without adding hydrogen was slightly higher but it also meant that a net increase in efficiency could still be achieved using the plasmatron and that the engine could be run at leaner mixtures, thus resulting in reduced pollutant emissions. Thus a very important consideration is whether the gain in efficiency is enough to compensate for the energy required to produce the hydrogen.

Hydrogen addition reduces the cycle-to-cycle variations in SI engines by stabilizing the combustion process even for very lean mixtures [1][3]. In lean mixtures the excess air provides more oxygen to fully oxidize the fuel while at the same time lower peak combustion temperatures are reached. The lower combustion temperatures result in a greater specific heat ratio because net dissociation losses are reduced and thus higher thermal efficiencies can be achieved [1] while heat losses across the cylinder wall to the cooling system are also reduced [9]. Using hydrogen combustion enhancement to stabilize lean petrol engine operation would also allow for higher compression ratios because hydrogen suppresses engine knock [2] while lean mixtures are more resilient to knocking than stoichiometric ones [10].

For these reasons Ji and Wang [11] have investigated the effects on the lean burn limits of a hydrogen-petrol engine. In their experiments the lean limits of the engine were extended to a combined lambda (for an air-hydrogen-petrol mixture) of 1.55, 1.97 and 2.55 for hydrogen intake gas fractions of 1%, 3% and 4.5% respectively when the engine's original lean limit was at a lambda of 1.45.

When adding hydrogen at a constant AFR the in-cylinder temperature increases for both SI and CI engines [1][7]. The higher temperatures promote the oxidization of HCs, PM and CO and thus their emissions are reduced. Moreover, the increased presence of hydrogen increases the rate of formation of the OH radical which helps oxidize HCs, PM and CO better [3][11][12].

Hydrogen also reduces the quenching distance inside the cylinder [11] and therefore lesser HCs are emitted because the wall quenching and crevice HC formation mechanisms are dependent on the quenching distance [13][10]. One other way of reducing HC and CO emissions by hydrogen addition when maintaining the output power constant is by the replacement of some of the carbon based fuel during combustion with carbon-free hydrogen [7]. The reduced carbon content therefore reduces HC, CO and also CO_2 in a manner similar to lean operation. The experiments by Ji and Wang [11], Conte and Boulouchos [14], and Bari and Esmaeil [7] have resulted in a drop in HC and/or CO emissions by the engines under test. Yilmaz et al. [15] also added hydrogen-oxygen gas to a diesel engine and reported an average reduction of 5% and 13.5% in HC and CO emissions respectively with an average increase in torque output of 19.1%.

The effect of hydrogen addition on HC and CO emissions does not always result in their reduction. Saravanan and Nagarajan [16] found that the addition of hydrogen increased HC emissions from 28ppm when running on diesel only to 31ppm at 25% of full load while at 75% of full load the emissions with and without hydrogen were similar. However, CO and exhaust smoke were reduced by adding hydrogen, even when EGR was added for up to 75% of full load. Samuel and McCormick [6] also noticed no change in CO emissions and an increase in smoke and HC emissions when adding hydrogen-oxygen to their diesel engine but the changes in HCs where within the uncertainties of the readings and therefore no definitive conclusion could be arrived at. The results obtained by Cassidy [1] show that hydrogen enhancement produced lower HC emissions for equivalence ratios above 0.8 and higher HC emission for lower equivalence ratios while CO emissions were reduced for all equivalence ratios. When experimenting with lean mixtures, Ji and Wang [11] found that the addition of hydrogen gas resulted in increased CO emissions in close to stoichiometric lean mixtures. This was attributed to the faster reaction of hydrogen with oxygen in air compared to petrol resulting in oxygen depleted zones within the mixture and also because of the longer post-combustion period (resulting from the faster combustion) that cooled the in-cylinder gases before being exhausted thereby reducing the rate of CO oxidization into CO_2.

The aim of this experimental work was to investigate the effects of hydrogen addition in engine air intake on performance and exhaust emissions.

NOMENCLATURE

AFR	[kg/kg]	Air Fuel Ratio
ATC		After Top Centre
BTC		Before Top Centre
DOI		Duration of injection
EGR		Exhaust Gas Recirculation
HEC		Hydrogen Enhanced Combustion
HHO		Hydrogen Hydrogen Oxygen
IMEP	[bar]	Indicated Mean Effective Pressure
LHV	kJ/kg	Lower Heating Value
lpm	[l/min]	Litres per minute
MAP	[kPa]	Manifold Absolute Pressure
MBT		Minimum timing for Best Torque
rpm	[/min]	revolutions per minute
SA	[degrees]	Spark Advance
TDC		Top Dead Centre
λ		Equivalence ratio

GENERAL EQUIPMENT SETUP

A schematic representation of the setup used during the tests can be seen in Figure 1. The data from the dynamometer, engine and the Plint exhaust gas analyser were monitored and logged via a LabVIEW program every 100 ms. The data from the KANE exhaust gas analyser was recorded manually every 10 seconds.

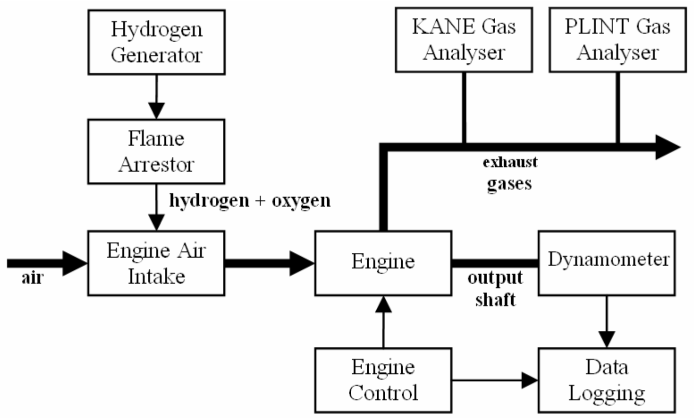

Figure 1 General equipment setup schematic

ENGINES USED FOR THE TESTS

Three different engines were used during the tests in order to obtain a clearer picture of the effects of adding hydrogen in different kinds of engines. The following table illustrates the specifications of the engines used. The testing modes used for each engine are described in later sections.

Table 1: Engine specifications

	Engine 1	Engine 2	Engine 3
Manufacturer	Ford	Ford	Peugeot
Total Displacement	≈ 1000cc	1392cc	≈ 1900cc
Bore	*	77.24mm	85mm
Stroke	*	74.30mm	88mm
No. of Cylinders	4	4	4
Compression Ratio	*	9.5:1	18:1
Air Intake	Natural Aspiration	Natural Aspiration	Turbocharged
Fuel	Petrol	Petrol	Diesel
Fuel System	Carburetted	Fuel Injection	Common Rail HDi
Air-Fuel Mixture Control	Fixed, $\lambda \approx 1$	Programmable ECU	Throttle Controlled
Ignition Timing Control	Mechanical	Programmable ECU	Manufacturer ECU
Dynamometer	Stuska Water Brake	Plint Electric Generator	Froude Water Brake

* Unavailable data

EMISSIONS ANALYSING EQUIPMENT

A modified Plint RE200 and Kane Auto 2-2 gas analysers were used to measure the concentrations of CO, HC, CO_2 and O_2 in the exhaust gases as shown Table 2. The emission readings could be assumed to be on a dry basis since the pipes connecting the gas analysers to the engine exhaust pipe were long enough to condense the water vapour present. Both analysers were calibrated before testing.

Table 2: Exhaust gas analysing equipment

Gas	Gas Analyser	Measurement Unit	Measurement Technique
CO	Kane Auto 2-2	% of exhaust gases	Non-dispersive Infrared (NDIR)
HC	Kane Auto 2-2*	ppm (by volume, based on C_6)	Non-dispersive Infrared (NDIR)
	Plint RE200	ppm (by volume, based on C_3)	Non-dispersive Infrared (NDIR)
CO_2	Plint RE200	% of exhaust gases	Non-dispersive Infrared (NDIR)
O_2	Plint RE200	% of exhaust gases	-

* used to verify trends in HC data from the Plint gas analyser

HYDROGEN GENERATORS

Two hydrogen generators (alkaline electrolysers) were used during the tests producing different flow rates of hydrogen-oxygen (HHO) gas. For both generators a solution of distilled water and sodium hydroxide (NaOH) was used as an electrolyte. Table 3 shows the specifications of the two generators as used during the tests.

Table 3: Hydrogen-oxygen generator specifications as used during the tests

Property	HHO Generator 1	HHO Generator 2
Solution Used (% wt NaOH)*	0.105%	12.04%
HHO Flow Rate	0.3 lpm	1.67 lpm
Energy in H_2 (based on LHV)	35 W	190 W
Efficiency	10.06%	48.01%
Solution Temperature	40-50°C	45-55°C
Electrode Material	Stainless Steel, 0.8mm	Stainless Steel, 1.0mm
Electrode Orientation	Horizontal	Vertical
Active Electrode Area	1508 mm^2	12100 mm^2
Electrode Spacing	5mm	15mm
Number of Cells	4	5
Supply Voltage	13.75 V	13.75 V
Total Current Draw	24.73 A	29.36 A
Power Consumption	340 W	404 W
Cell Voltage	13.75 V	2.75 V
Cell Current	6.18 A	29.36 A
Cell Current Density	0.0041 A/mm^2	0.0024 A/mm^2
*The solution used for the two generators was different because of the differences in cell voltage and current arising from the differences in their designs.		

Both generators were calibrated and tested before being used in the tests using solutions of different concentrations (% by weight of NaOH) to correlate the current consumption, hydrogen-oxygen flow rate and solution temperature. The results obtained for the two generators were different and are discussed in more detail in the following sections. The maximum allowable current draw for both generators was set to 30A, assumed to be the continuous current limit of a car's standard alternator. Further details of the generators including the designs of the in-house built Generator 2 can be found in Zammit [17].

TESTING PROCEDURES

For each test mode the following procedure was followed: i) engine tested at stable conditions without hydrogen-oxygen addition; ii) engine tested at stable conditions with hydrogen-oxygen gas addition; iii) move on to the next test mode. After all the test modes were completed, the first test without hydrogen addition was repeated to make sure that the recorded values would match the original corresponding values and thus ensure no distortions were present in the data. All the engine parameters were kept constant or according to the manufacturer's specifications except for the ones listed in Table 4 to Table 6 for each engine respectively.

Engine 1 was tested at different speeds and loads with 0.3 lpm and 1.67 lpm hydrogen-oxygen addition as shown in the following Table 4.

Table 4: Engine 1 test matrix

	MAP [kPa] (% of full load)			
Engine Speed [rpm]	**Idle**	**2200rpm**	**2800rpm**	**3200rpm**
0.3 lpm HHO addition	33 kPa (0%)	65 kPa (46%)	78 kPa (64%)	78 kPa (64%)
1.67 lpm HHO addition	31 kPa (0%)	66 kPa (49%)	70 kPa (54%)	70 kPa (54%)

Engine 2, was tested at different speeds and loads with 1.67 lpm hydrogen-oxygen addition at varying AFRs and spark timings which were varied via a Reata Engineering programmable ECU and monitored via LabVIEW software. The AFR was varied by changing the duration of injection (DOI) in steps of 0.2ms. The test matrix can be seen in Table 5. The ranges of DOI were chosen so that different mixtures varying from slightly rich up to the leanest mixtures that would provide stable operation would be tested with hydrogen-oxygen addition. The leanest allowable mixture was determined by the smallest DOI at which HC emission readings were stable.

Table 5: Engine 2 test matrix

HHO Addition: 1.67 lpm		**Spark Advance [°Crank Angle BTC], DOI [ms]**			
Engine Speed	**MAP[kPa] %full load**	**40°**	**30°**	**20°**	**10°**
1500rpm	60 kPa (40%)	6.0-4.4ms	6.0-4.4ms	6.0-4.6ms	6.0-5.0ms
	80 kPa (68%)	7.6-5.2ms	7.6-5.2ms	7.6-5.4ms	7.6-5.8ms
2650rpm	60 kPa (40%)	6.2-4.4ms	6.2-4.4ms	6.2-4.8ms	6.2-5.4ms
	82 kPa (71%)	9.0-6.0ms	9.0-6.2ms	9.0-6.4ms	9.0-7.0ms

Engine 3 was tested at different speeds and loads with 1.67 lpm hydrogen-oxygen addition, as seen in Table 6.

Table 6: Engine 3 test matrix

HHO Addition: 1.67lpm					
Engine Speed	Idle	1510rpm	1550rpm	1995rpm	2040rpm
MAP	104 kPa	120 kPa	108 kPa	122 kPa	141 kPa

The hydrogen-oxygen flow rates used during the tests were comparable to those used by Dülger and Özçelik [8] for the first hydrogen-oxygen generator and by Yilmaz et al. [15] and Samuel and McCormick [6] for the second generator. These flow rates were also chosen because of the fact that excessive hydrogen addition could produce more NO_x while currents in excess of 30A would be required, consuming significant amounts of power. In addition, the purpose of the tests was not to test the engine with hydrogen as a secondary fuel but as an additive to enhance combustion.

RESULTS FROM TESTS ON ENGINE 1

The torque readings for operation with and without the addition of 0.3 lpm HHO gas can be seen in Table 7. The results show minor improvements in output torque by 1.8% and 0.75%, corresponding to increases in power output of 0.18kW and 0.13kW, at 2200rpm and 2800rpm respectively while at 3200rpm a loss in torque of 2.18% was observed. The observed increases in power output are less than the 0.4kW required to produce the HHO.

Table 7: Torque readings & uncertainties for engine 1 with 0.3lpm HHO

	without HHO		with 0.3lpm HHO	
Test Mode	**Torque [Nm]**	**± Uncertainty [Nm]**	**Torque [Nm]**	**± Uncertainty [Nm]**
2200rpm, 65kPa	43.253	0.190	44.030	0.233
2800rpm, 78kPa	59.008	0.444	59.451	0.258
3200rpm, 78kPa	60.927	0.350	59.597	0.329

The addition of more HHO had little effect on the performance of the engine. The readings obtained with 1.67 lpm HHO addition are shown in Table 8. The only increase in output torque, of just 0.96Nm corresponding to a 2.17% increase, was observed at 2200rpm. This increased the power output of the engine by 0.22kW. At 2800rpm the addition of more HHO produced a reduction of 1.44% in torque while at 3200rpm the reduction in torque observed was of 0.28%.

Table 8: Torque readings & uncertainties for engine 1 with 1.67lpm HHO

	without HHO		with 1.67pm HHO	
Test Mode	**Torque [Nm]**	**± Uncertainty [Nm]**	**Torque [Nm]**	**± Uncertainty [Nm]**
2200rpm, 66kPa	44.279	0.452	45.240	0.469
2800rpm, 70kPa	49.574	0.950	48.862	0.659
3200rpm, 70kPa	49.872	0.725	49.732	0.704

The increases in output torque for both 0.3 lpm and 1.67 lpm HHO addition at the lower speeds could be explained by the higher flame speed and shortened combustion caused by hydrogen. The loss in torque observed at the higher speeds could also be a consequence of faster combustion which shifts the peak pressure BTC. As the engine speed is increased the spark timing is advanced because the duration of combustion increases [10]. Since the spark advance in the distributer was done automatically with the spring/mass system, it could have been advanced too early before MBT. The variation of spark advance with engine speed, and the effects of different quantities of hydrogen addition and engine load on combustion duration caused the differences observed in torque output between the two amounts of HHO addition.

Table 9 and Table 10 show the measurements of HC, CO_2 and CO emissions from Engine 1 with and without 0.3 lpm and 1.67 lpm HHO addition respectively.

Table 9: Pollutant emission readings & uncertainties for engine 1 with 0.3lpm HHO addition

	Measurement			Measurement Uncertainties		
Pollutant	**HC**	**CO_2**	**CO**	**HC**	**CO_2**	**CO**
Unit	ppm	%	%	± ppm	± %	± %
Speed, Load	**without HHO**					
Idle	3044.1	15.331	8.428	5.292	0.012	0.986
2200rpm, 65kPa	1689.9	17.575	3.903	1.831	0.008	0.451
2800rpm, 78kPa	1446.0	18.837	3.530	1.951	0.007	0.420
3200rpm, 78kPa	1352.8	19.398	3.453	1.380	0.003	0.413
Speed, Load	**with 0.3 lpm HHO addition**					
Idle	2979.9	15.299	8.700	5.330	0.011	1.018
2200rpm, 65kPa	1633.3	17.832	4.148	1.228	0.008	0.479
2800rpm, 78kPa	1391.1	19.107	3.689	0.909	0.005	0.431
3200rpm, 78kPa	1247.9	19.415	3.760	1.085	0.004	0.443

Table 10: Pollutant emission readings & uncertainties for Engine 1 with 1.67lpm HHO addition

	Measurement			Measurement Uncertainties		
Pollutant	**HC**	**CO_2**	**CO**	**HC**	**CO_2**	**CO**
Unit	ppm	%	%	± ppm	± %	± %
Speed, Load	**without HHO**					
Idle	2670.0	16.755	5.088	2.63	0.01	0.665
2200rpm, 65kPa	1758.1	18.208	4.065	1.09	0.01	0.491
2800rpm, 78kPa	1504.4	19.427	3.650	0.31	0.94	0.430
3200rpm, 78kPa	1370.7	19.982	3.581	1.28	0.00	0.420
Speed, Load	**with 1.67 lpm HHO addition**					
Idle	2780.7	16.675	5.455	2.25	0.01	0.654
2200rpm, 65kPa	1675.8	18.554	4.500	1.17	0.01	0.505
2800rpm, 78kPa	1442.0	19.501	3.894	0.31	0.94	0.454
3200rpm, 78kPa	1301.1	19.993	3.770	1.20	0.00	0.441

The HC emissions were reduced with engine speed and load for both operation without and with flows of HHO gas. In general, the addition of HHO has reduced the emissions of HCs, with the only exception being at idle when 1.67 lpm HHO increased HC emissions by 4.15%. The reductions in HC emissions are probably caused by the higher flame speed and diffusivity of hydrogen resulting in more complete burning of the fuel to form more CO and CO_2 as discussed later. The lower quenching distance of hydrogen could have helped burn more of the HCs found in crevices and at cylinder walls [4].

The biggest reduction in HC emissions, by 7.76%, was observed when 0.3 lpm HHO gas was added at 3200rpm. At 2200rpm and 2800rpm the reductions in HC emissions resulting from the addition of 1.67 lpm HHO were higher than those achieved when 0.3 lpm were added. With 0.3 lpm HHO the HC emissions were reduced more as the engine speed increased starting from a reduction of 64ppm HC at idle to 105ppm HC at 3200rpm. When 1.67 lpm HHO were added the effect on HC emissions was more complex, starting with an increase in HC emissions at idling to reductions of 4.68% and 4.14% at 2200rpm and 2800rpm respectively, ending with a reduction of 5.08% at 3200rpm.

Apart from at idling the addition of HHO gas resulted in slightly higher emissions of CO_2, signifying that some extra carbon was being oxidized and which could be related to the reduction in HC emissions. However, the observed changes were very small, with the biggest being observed at 2200rpm with 1.67 lpm HHO and amounting to an increase by 1.90%.

At all test conditions the addition of HHO gas resulted in increases in CO emissions. The addition of 0.3 lpm HHO gas resulted in a maximum increase of 8.90% at 3200rpm while the lowest increase was by 3.23% at idle. On the other hand, the largest increase by the addition of 1.67 lpm HHO gas was by 10.71% at 2200rpm and the lowest increase was by 5.25% at idle.

Thus the higher HHO flow rate resulted in higher CO emission increases. This is also confirmed by the higher average increase in CO/CO_2 ratio of 0.016, caused by the 1.67 lpm addition compared to the 0.013 average increase caused by the 0.3 lpm addition. A possible explanation could be that the higher amount of HHO improved combustion and thus promoted the oxidation of carbon but the increase in temperature and concentration of oxygen were not high enough to fully oxidize it into CO_2. The effectiveness of the fuel-air mixing inside the cylinder could have also had an effect in this respect [11].

RESULTS FROM TESTS ON ENGINE 2

The addition of HHO gas had a measurable effect on the output torque of engine 2. At 1500rpm 60kPa MAP, the addition of 1.67 lpm HHO produced a reduction in the engine's maximum output torque by 1% at 40° SA and increases of 2.1%, 3.9% and 12.4% at SA of 30°, 20° and 10° respectively, it also resulted in a consistent increase in output torque for almost all AFRs and spark timings. In many cases the increased torque resulted in increases in output power greater than the 0.19kW that the complete combustion of the added hydrogen would have given. This signifies that the addition of hydrogen has improved the combustion efficiency. Figure 2 shows the effect on the efficiency when HHO gas was added. The maximum efficiency was increased by 2.3%, 4.2%, 6.3% and 9.3% resulting in reductions in specific fuel consumption of 22.46, 36.21, 57.45, 133.53g/kWhr for spark timings of 40°, 30°, 20° and 10° BTC respectively.

Another interesting fact that was observed in the data was that for all spark timings the AFR at which the output torque reached a value of zero was higher when HHO was added. In fact with HHO addition leaner mixtures have been tested, showing that the increased flame speed produced by hydrogen stabilized combustion and extended the lean limit, particularly at 1500rpm.

At 1500rpm and a MAP of 80kPa, refer to Figure 3, unlike the case where the MAP was 60kPa, for 40° and 30° SA a reduction in output torque was observed for some AFRs. A possible explanation for this could be that since higher loads and hydrogen both increase the flame speed, the peak combustion pressure could have shifted more towards BTC. At 30° SA the addition of HHO initially produced increases, then decreases and then again increases in torque as the AFR was increased. This could be explained by the fact that the flame speed of hydrogen increases as the mixture is made leaner [18] while that for petrol is highest at close to stoichiometric and decreases as the mixture is made leaner or richer [1]. Thus for rich and lean mixtures the combined effect on flame speed would keep the peak pressure location close to TDC and/or ATC while at slightly lean mixtures the peak pressure could be pushed BTC as a higher flame speed results. This would result in increased torque with HHO addition at the rich and lean mixtures while at stoichiometric and slightly lean mixtures a reduction would be observed. For 20° and 10° SA the effect on torque was similar to that observed at 60kPa MAP.

A reduction of 1.3% at 40° SA and increases of 2.3%, 3.7% and 12.4% at 30°, 20° and 10° SA respectively in maximum output torque were observed at 1500rpm and 80kPa. This caused the maximum efficiency, shown in Figure 55, to be reduced by 4.5% at 40° SA while at 10° SA it was increased by 7%. These resulted in an increase in specific fuel consumption by 19.23g/kWhr at 40° SA and a reduction of 46.33g/kWhr at 10° SA.

The addition of HHO gas at 2650rpm and 60kPa MAP reduced the maximum output torque at 40° SA by 5.6% while at 30°, 20° and 10° SA the torque was increased by 0.8%, 6.8% and 6.6% respectively, refer to Figure 4. However for most AFRs, the output torque and thus power, were less when HHO was added at 30° and 20° SA, possibly for the same reasons as explained earlier.

The results for the tests carried out at 2650rpm and 82kPa MAP, show that the addition of HHO gas had a lesser effect on the engine's performance, refer to Figure 5. In fact the changes in maximum output torque were a reduction by 0.9% and increases by 1.7%, 2.1% and 0.4% for spark timings of 40°, 30°, 20° and 10° BTC respectively. However, even though small, these changes produced the largest increases in output power of all the test modes.

The increases in maximum efficiency for SA of 40°, 30°, 20° and 10° were of 1.0%, 0.9%, 0.8% and -0.1% resulting in reductions in the specific fuel consumption of 4.94g/kWhr, 4.53g/kWhr, 4.64g/kWhr and 0.90g/kWhr respectively.

The HC emissions at 1500rpm and 60kPa MAP show that the effect of HHO addition had the largest effect at a SA of 40° BTC. The reduction was greatest at an AFR of 14.2 and amounted to an actual reduction of 128ppm in HC i.e. a reduction of 7.92%. The biggest reduction in terms of percentage was 8.29% and was observed at an AFR of 14.8.

The reductions in HC emissions got progressively smaller as the mixture was made leaner.

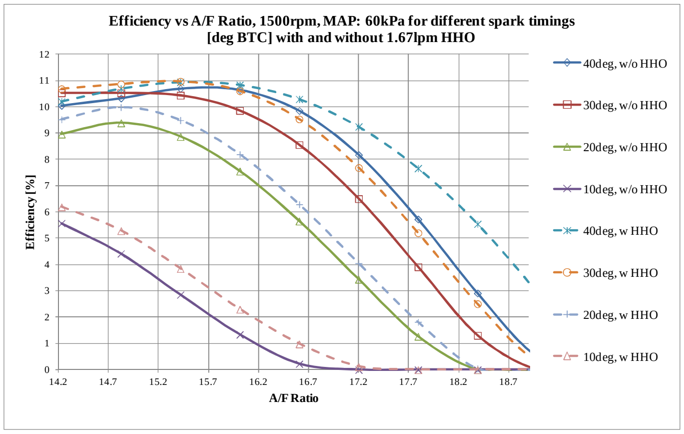

Figure 2: Engine 2 efficiency, 1500rpm 60kPa

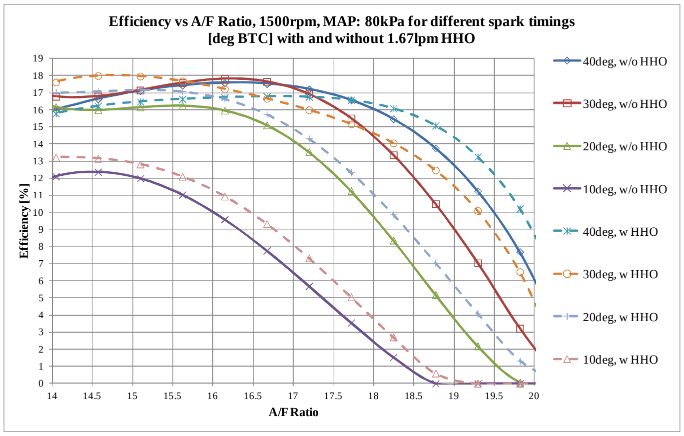

Figure 3: Engine 2 efficiency, 1500rpm 80kPa

At a SA of 30° and 10° the HC emissions with HHO were slightly higher than those without it. At 30° SA this was caused by some misfires that occurred during that test which raised the average HC emissions. At 10° SA the increase in emitted HCs could be due to the reduced mixing time when hydrogen-oxygen gas was added which would not be compensated by more efficient burning. In lean mixtures the flame propagates slower than in rich ones and thus more time is available for the non-combusted mixture to mix before being engulfed by the flame resulting in low HC formation. Since HHO increases the flame speed, particularly at lean conditions, the time available for pre-mixing would be less resulting in higher HC formation because at low load and engine speed the combustion temperatures would be relatively low and HC oxidation would not be as promoted as it would be at higher loads and faster speeds. The effect would be similar to having advanced the spark timing. In petrol engines, the increase in HC emissions with HHO addition would therefore be peculiar to low speed and load operation. In fact the same behaviour was only noticed at idling during the testing of engine 1 with 1.67 lpm hydrogen-oxygen addition.

The same behaviour was not observed when the MAP was increased to 80kPa at the same engine speed meaning that the increased in-cylinder pressures and temperatures caused by the higher load promoted the oxidization of HCs resulting in similar emissions for 30-10° SA with and without HHO. This could also explain why the reductions in HC emissions with HHO addition were low at 1500rpm but bigger at 2650rpm, as will be seen later on. At 40° SA a reduction by 14.42% in HC emissions was observed at 1500rpm, 80kPa MAP causing an actual reduction in emissions of 260ppm while at an AFR of 18.8 and SA of 20° the emissions were reduced by 18.13% – the highest percentile reduction.

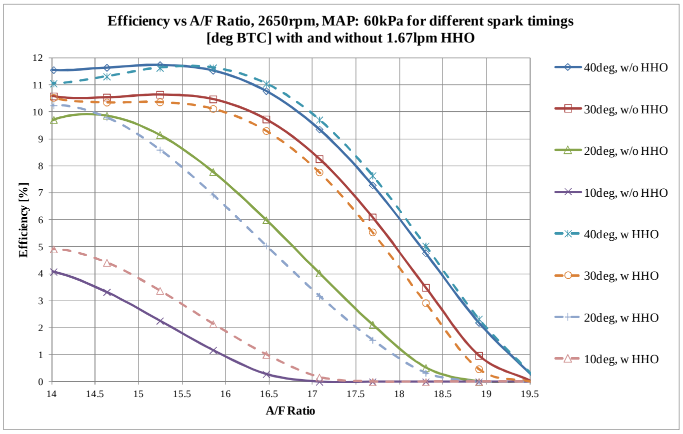

Figure 4: Engine 2 efficiency, 2650rpm 60kPa

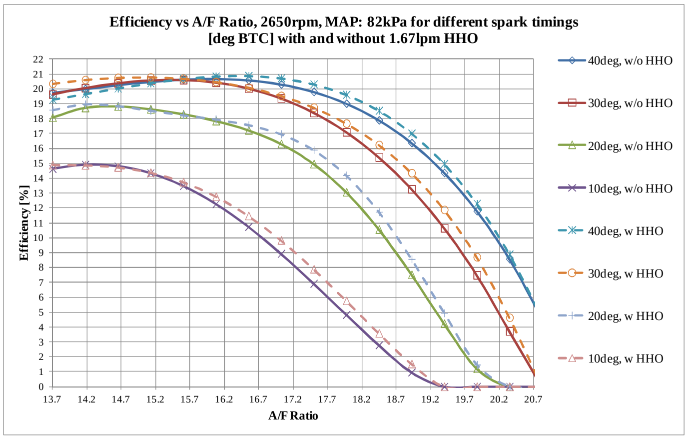

Figure 5: Engine 2 efficiency, 2650rpm 82kPa

At 2650rpm and 60kPa MAP the most significant reductions in emitted HC were observed. At an AFR of 16.5 and 30°, adding HHO gas reduced the HC emissions from 1058ppm to 683pmm, a reduction of over 35%. A reduction of 408pmm was also observed at an AFR of 14.6 and 40° SA. For all spark timings the observed reductions were highest at the richer mixtures and decreased as the mixture became leaner. Unlike at 1500rpm the combustion temperatures at the higher engine speed contribute to the oxidation of HC during the longer post combustion period resulting from HHO.

At 2650rpm and 82kPa MAP the reductions in HC emissions were less than those noticed at the same engine speed and lower load even though significant reductions for all spark timings tested were observed. The highest observed reduction was of 25.54% at a SA of 10° and an AFR of 16. In this test condition, the oxidation of HCs was already high and thus the effect of HHO addition was less marked.

The increased oxidation of HCs resulted in increased emissions of CO_2 as would be expected. At 1500rpm, 60kPa MAP the most significant increase in CO_2 emissions of 3.74% occurred at 40° SA at an AFR of 14.2, which coincided with the largest actual reduction in HC emissions. The increase of CO_2 with hydrogen-oxygen addition was somewhat consistent for all AFRs and SA with an average increase of 2.72%.

At 1500rpm and a MAP of 80kPa, reductions in CO_2 emissions were observed when HHO was added. For each SA the reductions in emissions decreased gradually to turn into an increase as the AFR was increased. However the changes observed were very small with the average increase being 0.47%. This very small change tallies with the similar emissions of HCs observed with and without HHO.

The CO_2 emissions increased with HHO addition in a similar manner during the tests performed on the engine at 2650rpm with MAPs of 60kPa and 82kPa. Peak CO_2 formation shifted towards richer mixtures when HHO was added for both loads at 2650rpm. At 60kPa MAP, the increase in CO_2 emissions was the greatest at an AFR of 14.6 and SA of 30° resulting in a 3.78% increase. At MAP of 82kPa, the greatest increase, of 9.5%, was observed at an AFR of 13.7 and SA of 40°.

The increased emissions of CO_2 with HHO addition indicate that more complete combustion has taken place. In general the measurements showed that the emissions of CO decreased with increasing AFR and increased with HHO addition. SA also influenced the emissions of CO but its effect on the emissions became less with higher engine speed and load. The increases in CO could be the result of insufficiently high temperatures to fully oxidize the HCs and/or due to the increased concentration of CO_2 which would increase the concentration of CO due to dissociation, even at weak mixtures [19].

The CO/CO_2 ratio was used to determine if the increases in CO were due to the partial combustion of HCs or due to the increased CO_2 concentration. The differences between the CO/CO_2 ratios without and with HHO addition for the given test conditions were therefore calculated. The differences in the CO/CO_2 ratio at 1500rpm were mostly positive meaning that the combustion temperatures were not high enough to fully oxidize the HCs. At 2650rpm and lower load the differences in CO/CO_2 ratio, vary from positive to negative meaning that the prevailing CO formation mechanism was dependent on the AFR and SA (thus CO formation kinetics could have played a role too).

RESULTS FROM TESTS ON ENGINE 3

The addition of hydrogen-oxygen gas in the diesel engine resulted in very small improvements in the output torque of the engine as seen in Table 11. The biggest increase of 1.45% occurred at the near idle condition. The improvements in torque decreased as the engine speed and load increased, possibly because of the reduced energy input contribution by hydrogen when compared to the total energy input at such conditions.

Table 11: Torque readings & uncertainties for engine 3

Engine 3	without HHO		with 1.67lpm HHO	
Speed, Load	Torque [Nm]	± Uncertainty [Nm]	Torque [Nm]	± Uncertainty [Nm]
Idle: 934rpm, 104kPa	11.36	0.004	11.52	0.003
1550rpm, 108kPa	41.03	0.013	41.28	0.012
1510rpm, 120kPa	103.57	0.023	104.11	0.026
1995rpm, 122kPa	73.08	0.019	73.17	0.018
2040rpm, 141kPa	120.109	0.019	120.359	0.019

During the tests the fuel consumption was also recorded but as shown in Table 12 the addition of hydrogen-oxygen had no appreciable effect on the specific fuel consumption.

Table 12: Engine 3 specific fuel consumption

Speed, Load	Idle: 934rpm, 104kPa	1550 rpm, 108kPa	1510 rpm, 120kPa	1995 rpm, 122kPa	2040 rpm, 141kPa
s.f.c without HHO	468.01 g/kWhr	247.73 g/kWhr	207.60 g/kWhr	220.05 g/kWhr	215.13 g/kWhr
s.f. c. with 1.67 lpm HHO	461.34 g/kWhr	246.26 g/kWhr	206.51 g/kWhr	219.80 g/kWhr	214.69 g/kWhr

In all cases, the measured increases in torque correspond to a much lower increase in power output than the added power input supplied by hydrogen (0.19kW) and thus were more likely caused by this extra energy input rather than by improved combustion, even though the addition of hydrogen could provide a more homogenous combustion.

The emissions of pollutants in the diesel engine were not affected strongly by the addition of hydrogen-oxygen as shown in Table 13. However it is to be noticed that the emissions of CO and HC of the diesel engine are already very low at all conditions when compared to those of the two petrol engines.

The measurements showed that contrary to the petrol engines and to what would be expected from more homogenous combustion, the addition of hydrogen-oxygen gas in the diesel engine resulted in a slight increase in HC emissions. The biggest increase in emissions occurred at 1510rpm and amounted to 25.29ppm, corresponding to a 7.98% increase. The only reduction in HC emissions, of 1.32%, was observed at idling. A possible explanation could be that the addition of hydrogen promoted the burning of some lubricating oil or/and hydrogen reacted with CO to produce some light HCs as discussed by Conte and Boulouchos [3].

The emissions of CO_2 were also reduced slightly by a maximum of 2.34% at idling while at 1550rpm and 2040rpm no significant change was seen. The CO_2 emissions at 1510rpm and 1995rpm increased by 1.93% and 0.9% respectively.

Table 13: Pollutant emission readings & uncertainties for Engine 3

	Measurement			Measurement Uncertainties		
Pollutant	**HC**	**CO_2**	**CO**	**HC**	**CO_2**	**CO**
Unit	ppm	%	%	± ppm	± %	± %
Speed, Load	**without HHO**					
Idle: 934rpm, 104kPa	156.59	11.513	0.062	0.360	0.002	0.010
1550rpm, 108kPa	138.88	11.665	0.100	0.355	0.002	0.013
1510rpm, 120kPa	316.91	15.576	0.115	0.483	0.004	0.015
1995rpm, 122kPa	236.07	14.597	0.103	0.382	0.002	0.014
2040rpm, 141kPa	406.16	16.911	0.123	0.787	0.001	0.016
Speed, Load	**with 1.67lpm HHO**					
Idle: 934rpm, 104kPa	154.53	11.243	0.071	0.348	0.003	0.010
1550rpm, 108kPa	148.14	11.665	0.099	0.370	0.001	0.013
1510rpm, 120kPa	342.20	15.877	0.111	0.577	0.004	0.013
1995rpm, 122kPa	245.68	14.728	0.100	0.393	0.002	0.013
2040rpm, 141kPa	431.71	16.921	0.100	1.013	0.001	0.013

The emissions of CO followed the inverse trend of HC emissions where they increased at idle and decreased at all the other test conditions. At idle the increase in CO was of 13.58% while the highest reduction in CO was of 18.75% and occurred at 2040rpm. However, it is to be noted that since the CO emissions are very small the percentage changes can be very big even if the actual reduction would be minimal. For instance at 2040rpm the actual difference between the readings of CO% in the exhaust gases was of only 0.023% resulting in a reduction of 18.75% from the no HHO addition case because at the latter condition the actual reading was of 0.123%. This is also indicated by the higher uncertainties of the CO readings.

CONCLUSION

Increases in the power output with HHO addition have been observed for all the engines. The most significant increases were observed in the petrol engines (engines 1 and 2) but depending on the engine speed, load and ignition timing even power losses were observed. Both increases and losses in power output could be attributed to the faster flame speed induced by hydrogen addition.

Increased output power was also observed for engine 3 when HHO was added but the changes were insignificant and close to the measurement uncertainties. The small changes relative to the petrol engines could be due to the engine‘s efficient injection system and because in CI engines combustion occurs spontaneously at various locations unlike in SI engines where the flame starts at the spark plug and propagates through the rest of the mixture. Thus in CI engines the flame speed is not as determining as it is in SI engines.

In all test modes the increased power output of engines 1 and 3 with hydrogen addition was not enough to compensate for the power required to generate the hydrogen. In the case of engine 2 this depended on engine speed and load, the AFR and SA. A comparison of operation at peak efficiency and peak power output with and without HHO addition showed that in most cases the increase in output power was still not enough to produce the hydrogen, even if a 75% efficient hydrogen generator was to be used.

The test results showed, in agreement with the findings of other researchers, that hydrogen addition produced the best effects at lean mixture operation and retarded spark timing (SA ≤ 20°BTC). Generally at these conditions the increase in power output was more than the power needed to generate the hydrogen but since engine 2 was not designed for lean operation this did not coincide with peak output power and efficiency. HHO addition also extended the lean limit of the engine under many of the testing points.

HHO addition also allowed for operating engine 2 at more retarded spark timings thanks to the faster flame speed, thus allowing for better air-fuel mixing before combustion, improving its efficiency and producing fewer pollutants.

In conclusion, the results showed that the addition of HHO is most effective in stabilizing and enhancing the combustion of lean air-fuel mixtures inside the petrol injected engine, allowing for lower HC, CO and CO_2 emissions. Thus hydrogen enhanced combustion could play a role in stabilizing lean burn petrol engines.

ACKNOWLEDGMENTS

The help of Noel Balzan who has modified the Plint exhaust analyzer as well as helped with the LabView programming is greatly acknowledged. Andrew Briffa was also instrumental in utilizing the engines and dynamometers. Funding from the University of Malta research grants is also appreciated.

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