FACILITATION OF HCCI COMBUSTION OF BIOGAS AT MODERATE COMPRESSION RATIOS BY APPLICATION OF FUEL REFORMING AND INLET AIR HEATING

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Abstract

The HCCI shows large benefits in NOx emissions and fuel economy, but is difficult to achieve and control in engines with moderate compression ratios when natural gas and particularly biogas are used as fuel. It has been shown in literature that the addition of hydrogen translates into the lowering of the auto-ignition temperature during the compression stroke. A major effort is being devoted to developing further the fuel reforming technology which facilitates the auto-ignition of hydrocarbon fuels in Homogeneous Charge Compression Ignition engines. The fuel used in this study was simulated biogas which contained 67% CH_4 and 33% CO_2 by volume. Investigations were made into HCCI feasibility using inlet heating alone, HCCI feasibility using inlet heating and addition of simulated reformed fuel, feasibility of H_2 production using fuel reforming and a full closed loop test including on-line H_2 production. All HCCI results were compared to spark ignition baseline results. HCCI combustion for biogas shows significant improvement in NO_x emissions and efficiency over SI combustion. However, it is difficult to achieve with biogas and was only stable with both reformed fuel addition and intensive inlet heating.

Keywords: HCCI, CAI, biogas, natural gas, hydrogen, exhaust gas fuel reforming.

1. Introduction

HCCI combustion technology is the subject of extensive research within the automotive industry because of its potential to improve efficiency and emissions (particularly NOx) of internal combustion piston engines. HCCI technology has been available since 1979 and was originally applied to two stroke engines (Onishi et al. 1979) to try and overcome the problems of unstable combustion at part loads caused by the poor scavenging. More recently research has been focused on applying this technology to four stroke engines, which is the case for this study.

Increasing environmental concerns regarding the use of fossil fuels and global warming have prompted researchers to investigate alternative fuels. One such alternative is the use of bio-fuels, which can be derived from biomass. This study looks into the use of biogas, which is the product of the fermentation of organic matter and is therefore produced in great quantities at landfill sites, farms and sewage works as a matter of course. Biogas composition is typically about 2/3 methane CH_4 and 1/3 carbon dioxide CO_2 by volume. The large amount of CO_2 has the effect of diluting the inlet fuel/air charge much in the same way that EGR

does. This results in characteristically long burn durations, poor efficiencies and low NO_x emissions for biogas fuel in comparison to methane using SI combustion.

HCCI combustion being investigated here, differs radically from SI combustion since combustion initiation is caused by raising the temperature of the fuel/air mixture to it's autoignition temperature. This is usually achieved by inlet heating or using high compression ratios, effectively promoting knock, something to be avoided in spark ignition engines. The combustion speed/duration is then controlled by charge dilution. The benefits of HCCI are that combustion duration is typically much shorter than SI, making for good thermal efficiency, and the large amount of dilution combined with near-homogeneity of the charge reduces peak temperatures resulting in low NO_x emissions. Enabling the HCCI would therefore improve the thermal efficiency of a biogas fuelled engine and at the same time improve NO_x emissions further.

Studies by the Birmingham FPS Group and other researchers using natural gas / methane fuel (Peucheret and Wyszynski 2004, Xu et al. 2004, Christensen et al. 1997 and 1999) have shown that high inlet temperatures and/or high compression ratios are needed to achieve HCCI. One way of reducing the required temperature is addition of hydrogen to the inlet charge (Olsson et al. 2002). It has been shown in the FPS Group research for natural gas/methane fuel that this hydrogen can be provided in sufficient quantities by fuel reforming using a suitable catalyst (Allenby et al. 2001, Peucheret and Wyszynski 2004). Since biogas is largely methane, it should behave in a similar way, except that any sulphur compounds need to be removed first as these are a known poison for reforming catalysts. The catalyst can be located on board for vehicle use, or local to the engine for stationary engine applications. Following on from the previous studies using methane as quoted above, and from the expected behaviour of biogas fuel, 4 main tasks were chosen for this study.

1. Biogas base line SI tests for comparison
2. HCCI feasibility with inlet heating and hydrogen addition.
3. Feasibility of H_2 production using fuel reforming.
4. Closed loop system, using fuel reforming to provide H_2.

2. Equipment

All engine tests were carried out using a "Medusa" single cylinder research engine, built at Birmingham but based on the design by Richard Stone of Oxford University, of bore 80 mm and stroke 88.9 mm with a modified Rover K series cylinder head. Compression ratios used were 10.5:1 using a standard Rover piston, 12.5:1 using a racing piston, and 15:1 using a specially modified piston blank that was designed and machined in house. A Kistler 6125A pressure transducer was fitted flush with the wall of the combustion chamber connected via a Kistler 5011 charge amplifier to a National Instruments data acquisition card fitted in an IBM compatible PC. A shaft encoder was used to provide synchronisation crank angle degrees. Analysis software was developed in house using the LabVIEW programming environment. The engine was run in different modes and air/fuel ratios while the coefficient of variation of IMEP was kept below 5% whenever possible. Carbon dioxide, carbon monoxide, unburned hydrocarbons, oxygen and NO_x emissions were recorded using various standard emissions equipment. A 3 kW electric air heater was installed in the intake duct to preheat the air required for biogas or natural gas HCCI operation. The heater was located upstream of both the fuel entry port and the exhaust gas recirculation loop. The flowrates of the supplied gaseous fuels were monitored using a Roxspur rotameter gas flow meter.

3. Experimental procedures and results

3.1. Baseline SI results

For all baseline tests standard Rover 9 mm lift cams were used with conventional valve timing. Fuelling was kept at stoichiometric (i.e. lambda = 1) and ignition timing was set at each load point to achieve peak cylinder pressure at 15 degrees after top dead centre. Load was regulated by throttling the intake in the conventional manner. Biogas tests were carried out at a compression ratio of 15:1 for direct comparison with the biogas HCCI results, while the available natural gas SI baseline are at CR = 13. Basic results are presented in Table 1 below.

Four main points can be seen from analysis of the baseline SI results.

a) NO_x emissions in SI Biogas combustion are low, particularly in comparison with Natural Gas SI results. This is due to the extra mass of the CO_2 in the fuel acting as a thermal buffer and lowering combustion temperatures thus reducing the rate of formation of NO_x. Due to the long burn duration of biogas fuel it was found that peak cylinder pressure could be set earlier than 15 degrees atdc without inducing knock or raising NO_x levels. In practice advancing ignition would have raised efficiency at the expense of NO_x and retarding ignition would have had the opposite effect. From the above results it seems that the carbon dioxide content of biogas fuel has a similar effect on combustion to the diluting effect of EGR. The effects of EGR on combustion are well known as it is a common strategy for reducing NO_x emissions.

b) The indicated efficiency at between 9% and 21% is very low.

c) The 10% to 90% burn duration at around 50 degrees is longer than for a conventional fuel. Burn duration is conventionally around 30 degrees for natural gas and 25 degrees for gasoline. It was expected that the dilution of the inlet charge with CO_2 in the biogas fuel would slow down combustion, so this long burn duration is not surprising.

d) The coefficient of variation (COV) exceeds the acceptable limit of 5% at all but one of the load points. Again this is as expected from a fuel with a large inert component that dilutes the intake charge.

Table 1. Baseline Biogas SI and Natural Gas SI results.

Biogas baseline SI at CR =15 1500 rpm	IMEP (bar)	NO_x (ppm)	Indicated Efficiency %	10%-90% burn (CAD)	COV of IMEP (%)	Natural Gas baseline SI at CR=13 1500 rpm	IMEP (bar)	NO_x (ppm)
							2.34	1385
	1.169	67	8.8652447	50	15.85		2.52	1628
	1.707	113	11.794542	50	8.97		2.79	1800
	2.28	198	14.467678	49	6.48		3.13	1920
	2.85	203	17.041256	46	5.73		3.25	2016
	3.34	284	19.231483	47	3.96		3.6	2100
	3.8	356	20.728545	47	5.04		4.3	2540

3.2. Biogas HCCI feasibility tests with inlet heating and H2 required to achieve HCCI

All biogas HCCI tests were done at 15:1 compression ratio. HCCI combustion requires elevated in-cylinder temperatures after inlet valve closure, in order to promote auto ignition of the fuel/air mixture. The combustion rate after ignition is controlled by charge dilution in the form of trapped residuals or excess air.

There are 2 main methods of achieving HCCI combustion:

Method 1: Short duration and low lift cams (lift 3mm, duration 140 degrees crank angle) are employed on engine inlet and exhaust. The inlet timing regulates airflow into the engine (and therefore load) without throttling, and the short duration exhaust cam causes hot exhaust gas to be trapped in the cylinder after exhaust valve closure. The principle is that the trapped hot exhaust gas mixes with the fresh charge entering the cylinder, thus heating it up to promote auto ignition while also providing enough dilution to control the burn rate once combustion starts. This method should minimise the inlet heating needed to achieve HCCI. This is the method normally used at Birmingham University.

Method 2: Conventional cam lift and timing are used without throttling. Intensive inlet heating is needed to promote auto ignition. Using this method the engine is run with large amounts of excess air, which controls the combustion rate, and the load is regulated by the amount of fuel injected. This method can be effective, especially when inlet temperatures of more than 200 degrees are needed with Method 1, since at these temperatures, the trapped exhaust gas is no hotter than the intake air at inlet valve opening.

It was found that using *Method 1* (low lift cams, internal EGR trapping, lambda near stoichiometric) it was not possible to achieve HCCI combustion without H2 addition, even when heating the inlet charge to 250°C. Using mixtures of natural gas and biogas allowed HCCI operation at some load points, but this was very hard to achieve, and combustion was not very stable. As a first step towards finding out if fuel reforming could be of use in enabling HCCI with biogas it was decided to add pure hydrogen to the inlet charge, as a replacement to biogas fuel in equal energy terms. The tests were performed with cam timing of 140 deg because it had previously been found that these timings required the least inlet heating when running with natural gas fuel. It can be seen that HCCI has been successfully achieved with an inlet temperature of 250°C and H_2 flow rates of 1.5 and 2 litres per minute. HCCI was not possible with H_2 flow rates lower than 1.5 l/min. It can be seen that NO_x emissions were at least an order of magnitude lower than baseline. However with H_2 flow rates of 1.5 l/min, the COV was unacceptably high (above 5%), particularly when running at stoichiometric air fuel ratio. Combustion with 2 l/min H_2 addition was stable.

Table 2. Biogas HCCI results with low lift 3mm cams and H2 addition, all at 1500 rpm

IMEP (bar)	NOx (ppm)	Indicated efficiency (%)	COV of IMEP (%)	Hydrogen flow (l/min)	Intake temp (°C)	AFR (lambda)
				1	250	
2.6	26	19	5.71	1.5	250	1.03
2.6	9	18	11.29	1.5	250	1
2.5	42	21	1.98	2	250	1.02
3	53	20	1.94	2	250	1

Due to the high inlet temperatures needed, and the difficulty in achieving HCCI with biogas using *Method 1*, it was decided to try *Method 2* (intake heating only, conventional valve events, high lambda) for comparison. Results are shown below in Table 3 and Figures 1 and 2. The power needed to heat the inlet charge was calculated by assuming that the engine had a volumetric efficiency of 100% and that the inlet air temperature was raised by 210 °C, from 20 °C to 230 °C. It can be seen from the results that by using *Method 2*, successful HCCI operation was achieve d over a range of load points using an inlet temperature of 230 °C and 1 l/min H2 addition to replace the equivalent natural gas fuel by energy.

The "knee" in Figure 1 (the graph of NO_x vs. IMEP for high lambda *Method 2*) seems spurious; however it is still evident that the NO_x emissions are cut by at least 50% using this strategy. It can also be seen in Figure 2 that indicated efficiency using *Method 2* is around twice as high for HCCI combustion of biogas than for SI. One reason for this is likely to be due to the shorter burn duration in HCCI mode. When the power needed to heat the inlet charge was included in the efficiency calculations the efficiency obviously dropped, but was still 1.5 times higher than baseline across the load range.

Table 3. Biogas HCCI results with high lift 9mm cams and H_2 addition, all at 1500 rpm

| IMEP (bar)	H_2 addition (l/min)	Intake Temp (°C)	COV of IMEP (%)	AFR (lambda)	10%-90% burn duration (CAdeg)	NO_x (ppm)	Indicated efficiency (%)	Heating Requirement (W)	Overall Indicated Efficiency (%)
0.8	1	230	24.08	3.79	11	1	14.722	1568	9.73064
1.34	1	230	5.04	3.21	10	6	22.05	1568	15.1162
1.62	1	230	3.37	2.71	9	9	24.106	1568	17.0384
1.89	1	230	3.13	2.5	11	8	25.667	1568	18.6186
2.2	1	230	2.47	2.18	8	87	27.477	1568	20.381
2.29	1	230	2.36	2.13	7	80	26.474	1568	20.0216
2.98	1	230	2.98	2.09	11	64	32.066	1568	24.6671
1.22	0.5	230	47.7		25	42	12.458	1568	9.69786
2.76	0		6.18		36		18.656	1568	15.6979
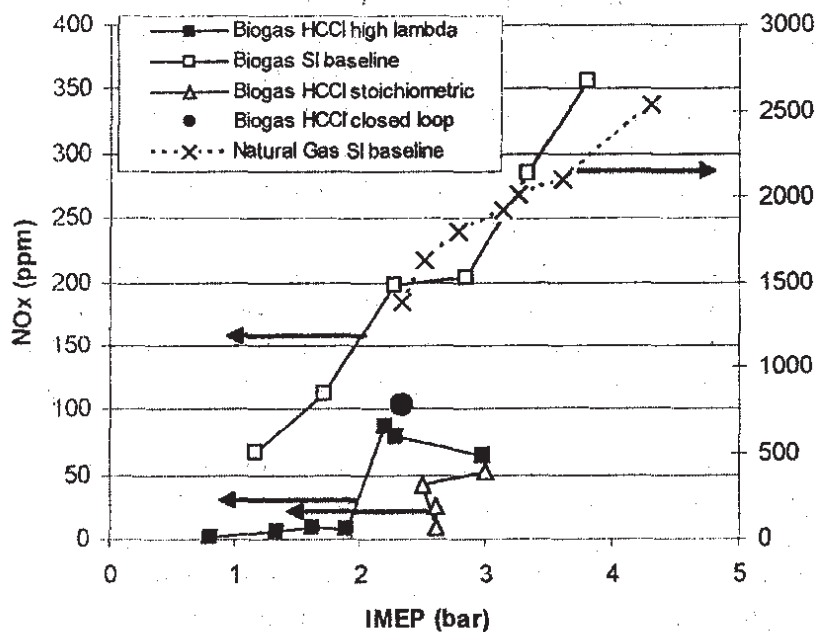
Figure 1. NO_x emissions for Biogas HCCI vs. IMEP at 1500 rpm using high and stoichiometric lambda with H_2 addition compared with baseline SI biogas operation and natural gas SI baseline (values for the latter mode on right hand vertical axis).
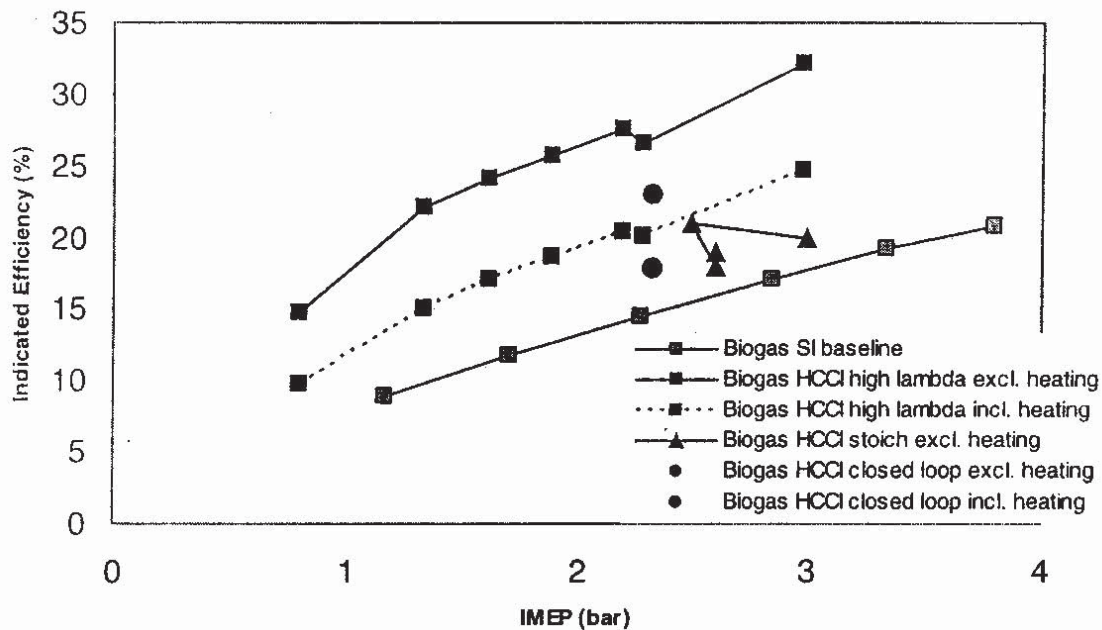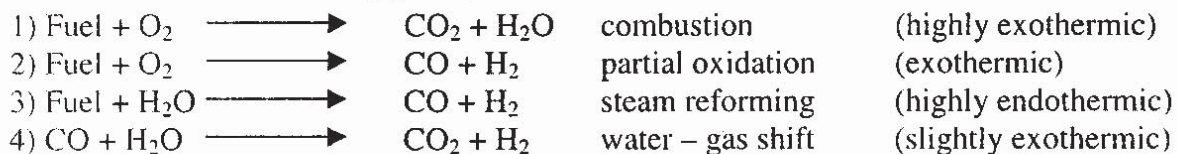
Figure 2. Indicated efficiency for Biogas HCCI vs. IMEP at 1500 rpm using high and stoichiometric lambda with H_2 addition compared with baseline SI biogas operation.

3. 3. Feasibility of H2 supply using biogas fuel reforming

Work at Birmingham University has looked over the years into using hydrogen as an additive to the inlet of an I.C. engine in order to improve different modes of combustion. Carrying hydrogen on board poses obvious problems. A solution is to produce H_2 on board using fuel reforming. Much research is being done globally into hydrocarbon fuel reforming technology principally as a source of hydrogen for fuel cells. However for vehicle fuel blending, it has been shown (e.g. Allenby et al. 2001, Peucheret and Wyszynski 2004) that H_2 can be made in sufficient quantities using exhaust gas fuel reforming. Engine exhaust gas is a source of water and heat, and in some cases O_2 so when it is contacted with fresh fuel it can be used as a reactant for the following principal reactions:

1) $Fuel + O_2 \longrightarrow CO_2 + H_2O$ combustion   (highly exothermic)
2) $Fuel + O_2 \longrightarrow CO + H_2$ partial oxidation   (exothermic)
3) $Fuel + H_2O \longrightarrow CO + H_2$ steam reforming   (highly endothermic)
4) $CO + H_2O \longrightarrow CO_2 + H_2$ water – gas shift   (slightly exothermic)

Reactions 2 and 4 produce hydrogen but are exothermic, so give off heat. This means that the calorific value of the reformer outlet stream will be less than the inlet. Reaction 3 is endothermic. This reaction needs energy input to proceed, but will produce an outlet stream with higher calorific value than the inlet. The goal of fuel reforming is to make H_2 as efficiently as possible. The best case would be to utilise the heat in engine exhaust gas to promote reaction 3 or being able to find a balance between exothermic and endothermic reactions so that there is no net heat release from the fuel. Studies have shown that steam reforming requires a large amount of energy to be effective, and temperatures of 700 degrees are recommended for successful conversion of methane to H_2, however water gas shift and partial oxidation are possible at typical HCCI exhaust temperatures of 400 °C.

The fuel reforming equipment consisted of 2 monolith catalysts one 65mm long and one 75mm long, both 25mm in diameter supplied by Johnson Matthey plc. The catalyst is a nickel free formulation containing precious metals promoted by metal oxides. The catalysts were

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contained in a 25mm diameter stainless steel tube housed in a temperature controlled furnace. Flows of fuel, exhaust gas and air through the catalyst were controlled using glass tube flow meters. For the open loop feasibility tests, air, fuel and exhaust gas were supplied to the reformer, and then analysed and exhausted. A block diagram of the system is shown in Figure 3.
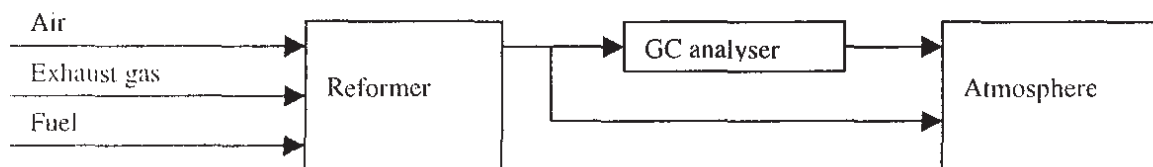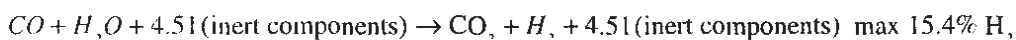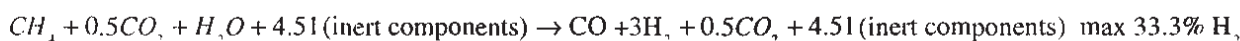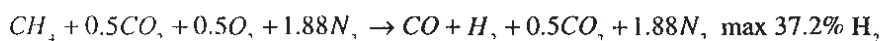

Figure 3. Open loop reforming system

Biogas tests were performed using exhaust gas from an engine running on natural gas fuel, but using bottled simulated biogas in the reformer. Natural gas was chosen mainly for reasons of economy, as the exhaust gas composition when running on natural gas differs little from exhaust gas composition when running on biogas. The main equations for biogas reforming are:

$$CH_4 + 0.5CO_2 + 0.5O_2 + 1.88N_2 \rightarrow CO + H_2 + 0.5CO_2 + 1.88N_2 \quad \text{max } 37.2\% \ H_2$$

$$CH_4 + 0.5CO_2 + H_2O + 4.51(\text{inert components}) \rightarrow CO + 3H_2 + 0.5CO_2 + 4.51(\text{inert components}) \quad \text{max } 33.3\% \ H_2$$

$$CO + H_2O + 4.51(\text{inert components}) \rightarrow CO_2 + H_2 + 4.51(\text{inert components}) \quad \text{max } 15.4\% \ H_2$$

Initial tests were tried with exhaust gas / fuel ratios appropriate for steam reforming without air addition, but hydrogen yield was minimal, less than 1%. Tests were then performed with air addition, which promoted partial oxidation and also helps to raise catalyst temperature. Reformer inlet temperatures were kept at levels similar to typical engine-out temperatures of exhaust gas in HCCI operation, i.e. 400 °C, and reformer space velocities were maintained at approx. GHSV = 8700 h^{-1}. Hydrogen yield for different H_2O to CH_4 ratios (assuming 19% H_2O in exhaust gas from stoichiometric natural gas fuelling and 66% CH_4 in biogas) is shown in Figure 4.

The results show that the greatest yield of H_2 was obtained with partial oxidation alone, i.e. with no exhaust gas added. Seeing as partial oxidation gave the highest yield of H_2 it was decided to find the optimum ratio for H_2 production using partial oxidation alone. Results shown in Figure 4 illustrate that up to 15% H_2 can be produced by partial oxidation of the fuel, the maximum being at the O_2:CH_4 ratio of 0.5, which incidentally is the theoretically correct ratio for partial oxidation. This set of results, which shows an H_2 yield of 14.4% at an O_2:CH_4 ratio of 0.4 is at odds with the previous set which gave an H2 output of 6.7%, at the same settings. It was originally thought that the small amount of sulphur in the natural gas used as the fuel in the engine to supply exhaust gas would not adversely affect the catalyst, however it seems likely that this assumption was not correct. This would explain the difference in results used. For future reference it would be prudent to always use a zero sulphur fuel or a sulphur trap for reforming. In a more detailed study of fuel reforming using methane (the major component of biogas) it was found that it was possible to achieve auto thermal reforming with an H_2 output of about 6% (Peucheret and Wyszynski 2004).
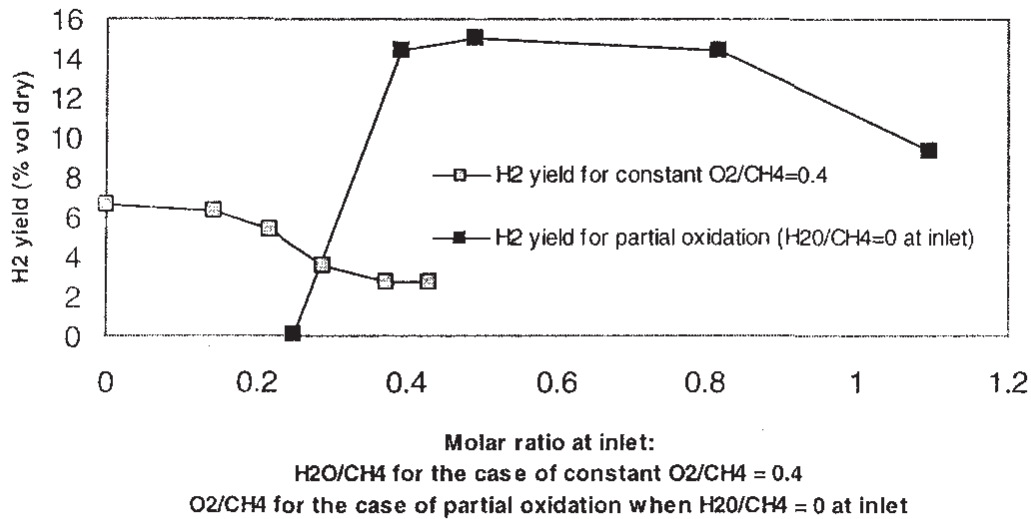
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Figure 4. Hydrogen yield in open loop reforming of biogas. Reformer inlet temp. 400 °C, GHSV = 8700 h⁻¹

3. 4. Closed loop system, using fuel reforming to provide H_2

A block diagram of the system used is shown in Figure 4. The dashed line between engine and reformer is to show that although exhaust could be added to the reformer, only fuel and air were added in this experiment. The mini reformer as used for the open loop experiments was used as the feed source of reformed gas for the engine.
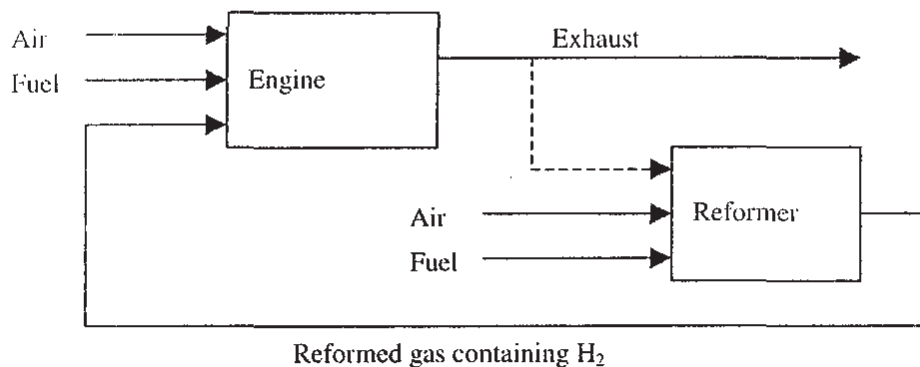

Figure 4. Closed loop reforming system

The test point chosen was to use 12 l/min biogas into the engine and an initial inlet temperature of 230 °C as these values were previously successful with H_2 addition as seen in Table 3. The volume flow of reformer product gas was regulated by assuming that the total volume of product gas had the same volume as the inlet gases. This assumption was thought to be reasonable because even for total conversion of biogas using partial oxidation, the volume of the outlet would be only 12.9% greater than the inlet due to composition changes. The initial flow rate of reformer gas was chosen to be 8 l/min, which is about 10% of the volume of air that reacts with the fuel added (note that achieving HCCI using *Method 2* – i.e high lambda and inlet heating with H_2 addition means a lot of induced air remains un-reacted after combustion so this is very different to 10% of inlet charge). From this starting point trial and error was used to try and find a successful operating point. It was decided to use partial oxidation for this feasibility study as it gives the highest H_2 yield. It was found that the original estimate of 8 l/min of reformed gas did not promote HCCI, so the flow rate of reformer gas was increased keeping air fuel ratios the same to encourage HCCI combustion. At 13 l/min

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flow rate into the reformer and with an 16.1% H_2 in the reformed gas the engine HCCI was stable. Using partial oxidation of fuel in the reformer means that the system as described above is more of a chain with the reformer product gas being fed into the engine but no exhaust re-circulating back to the reformer. However, using high lift cams and using lean air:fuel ratios as described in *Method 2* results in exhaust gas containing a large proportion (50%+) of air. Results are shown in Tables 4 and 5, and the NO_x and efficiency points are added in Figures 1 and 2.

Table 4: Closed loop biogas HCCI results	
rpm	1500
Excess air ratio (lambda)	1.798
Biogas flowrate into engine (l/min)	12
Hydrogen flowrate into engine (l/min)	0
Intake temp ("C)	233
Exhaust CO (% vol dry)	0.06
Exhaust HC (ppm hexane equiv.)	453
Exhaust CO_2 (% vol dry)	8.1
Exhaust O_2 (% vol dry)	10.67
Exhaust NOx (ppm)	103
Exhaust temp ("C)	395
IMEP (bar)	2.33
10% burned (deg atdc)	-1
10%-90% burned (CA deg)	8
COV of IMEP (%)	2.09
Indicated engine power (W)	1310
Energy/unit time in biogas (W)	4341
Energy/unit time in biogas into reformer (W)	1447
Indicated efficiency (%)	23
Heating requirement (W)	1568
Overall efficiency (%)	17.8144

Table 5: Reformer conditions for closed loop operation	
Exhaust gas flowrate into reformer (l/min)	0
Air flowrate into reformer (l/min)	9
Reformer inlet temp. ("C)	445
Reformer outlet temp. ("C)	640
Furnace set temp. ("C)	400
H_2 at reformer outlet (% dry vol.)	16.10%
Molar O_2 : CH_4 ratio at reformer inlet	0.705
Hydrocarbons (ppm hexane equiv.)	1139

4. Conclusions

It is difficult to achieve HCCI combustion using biogas fuel, but it is possible. However, intensive inlet heating and H2 addition are required. Benefits are at least 50% reduction in NO_x and improved engine efficiency by up to 50%. Similarly, in close loop operation at 2.33 bar IMEP with NO_x emissions of 103 ppm and an efficiency of 17.8% including fuel into the reformer and heating for the inlets, these results compare very favourably with baseline SI tests at 2.28 bar IMEP where NO_x was 198ppm and efficiency was 14.4%.

Acknowledgements

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