DIESEL ENGINE ASSISTED WITH REFORMER GAS

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ABSTRACT

Research on the utilization of alternative fuels in internal combustion engines (ICE) has increased in recent years. This increase is driven largely by energy and environmental factors including the scarcity and economic swings of fossil fuels and also increasing CO_2 emissions causing global climate change. An alternative fuel that has the potential of mitigating these issues is reformer gas. The focus of this work is to investigate the effect of varying reformer gas composition on the combustion and emissions of a compression ignition (CI) engine operating on diesel fuel with reformer gas addition to the intake manifold. The experiments were performed on an overhead valve (OHV) Lister Single cylinder engine. The reformed gas used was simulated from bottled H_2 and CO gases and the proportions were varied using a timed port fuel injection system. Compare to the diesel fuel base line, the cycle efficiency increases as the amount of reformer gas increases. Varying reformed gas composition does not have a significant effect on the NOx emissions with the engine operating at low load. However at high load there was an increase (10%) of NOx emission. Regarding to H2 and CO emissions as are escaping in the exhaust gases, at low load there is a fraction of the reformed gas that is not being burned. At high load there is still a fraction leaving through the exhaust pipe but not much as low load. These results are promissory and applicable because reformed gas can be produce from a variety of different feedstocks, and allow for reformed gas production to be tailored to a specific region's localized resources.

Key words: Reformed Gas, Biomass, CI engines

1. Introduction

Research on the utilization of alternative fuels in internal combustion engines (ICE) has increased in recent years. This increase is driven largely by energy and environmental factors including the scarcity and economic swings of fossil fuels and also increasing CO_2 emissions causing global climate change. An alternative fuel that has the potential of mitigating these issues is synthesis gas.

Synthesis gas, also known as syngas, producer gas, or reformer gas, is a mixture of gases typically containing hydrogen and carbon monoxide as the fuel component of the gas, with the balance being made up of carbon dioxide, water, and nitrogen. Syngas can be produced from a variety of different feedstocks such as coal, biomass, or natural gas, and can be produced by various methods including gasification or partial oxidation. This flexibility in production and feedstock allows for syngas production to be tailored to a specific region's localized resources. The problem with having a variable feedstock and production method, however, is that the syngas composition (H_2/CO ratio) can vary greatly. This high variability in composition can have implications for combustion in IC engines.

The focus of this work is to investigate the effect of varying syngas composition on the combustion and emissions of a compression ignition (CI) engine operating on diesel fuel with syngas addition to the intake manifold. This operating regime is similar to a traditional dual fuel diesel engine. Dual fuel engines are typically modified CI engines that use the diesel fuel as a pilot ignition source. The gaseous fuel is injected with the intake air and is the primary fuel source. Over 80% of the power can be generated from the gaseous fuel. The dual fuel engine approach allows the utilization of fuels, like hydrogen and carbon monoxide, which typically will not burn in a CI engine. This work differs from the dual fuel engine approach, because the primary fuel is the diesel fuel and the secondary fuel is the syngas mixture.

For CI engines, the ignition of the primary fuel (i.e., which is typically the gaseous fuel in dual-fuel CI combustion) is activated by the in-cylinder conditions. Some fuels, i.e., syngas, do not have good enough ignition quality to enable ignition. Therefore, two fuels must be used [12],[13]. First a pilot fuel, which could be for example diesel fuel, is injected, resulting in ignition and a rise of the temperature in the combustion chamber. Then, the second fuel, which could be for example syngas, is injected and ignites as pilot fuel temperature increases [10]. In this method a large quantity of hydrogen cannot be used, since syngas will replace the air, thereby reducing the air available for diesel combustion [14]. The use of syngas has been questioned due to some perceptions, namely (a) auto-ignition tendency at a higher compression ratio and (b) a large de-rating in power due to the energy density being low [3]. However, these perceptions need to be reviewed carefully. The arguments against the classical view in favour of better knock resistivity are as follows. Firstly, the fact that that the laminar burning velocity is high due to the presence of hydrogen might reduce the tendency of knock [3]. Secondly, as the hydrogen self-ignition temperature is 858 K, compared to diesel of 453 K, it allows a larger compression ratio to be used for hydrogen in internal combustion engine [15]. Finally, the presence of inert gases in the syngas (CO_2 and N_2) might suppress the pre-flame reactions that are responsible for knocking on account of increased dilution [3].

In addition, there is a general perception that as syngas is a low-density energy fuel, the extent of de-rating in power would be large when compared to high energy density fuels. This could be misleading because what needs to be accounted for by way of comparisons is the mixture energy density [16] and not the fuel energy density. Hydrogen has the highest energy to weight ratio of all fuels [11] and it might be possible to reduce de-rating by working with engines of higher compression engines as it was mentioned before.

The influence of CO in the syngas has not been document extensively. The engine exhaust gas from the diesel operation contains increased concentrations of H_2 and CO. The concentrations of unburnt H_2 and CO in the engine exhaust gas depend highly on the engine operating condition with increased concentrations mainly seen at low engine loads [5]

2. Experimental Setup

2.1 Engine Test Stand

The experiments were performed on a Lister single cylinder engine. The engine is a water-cooled, naturally aspirated, four stroke indirect injected (II) diesel engine. The dynamometer consists of a 110 v D.C. shunt wound interpolar machine without cooling fan. Table 1 shows the specifications of the engine.

Table 1: Engine Specifications

Bore (mm)	96
Stroke (mm)	114
Compression Ratio	Adjustable 4:1 to 22:1 by a Variable Compression Unit
Engine Speed (RPM)	800 - 1800
Swept Volume (L)	0.765
Injection System	Indirect injected (Pump-Line-Nozzle)

The syngas used was simulated from bottled H_2 and CO gases and the proportions were varied using a timed port fuel injection system. The fuel injection system consisted of a Siemens 3RG-4021 inductive sensor which was mounted to the engine valve cover to sense when the intake valve opened. This sensor was used as a trigger input for a two channel BNC 555 pulse-delay generator which sent signals to two Quantum PQ2-3200 gaseous fuel injectors, via National Semiconductor LM1949 injector drivers. The syngas mixtures (H_2 and CO) were injected into the intake manifold throughout the duration of the intake stroke. This was done to prevent any build-up of H_2/CO mixture within the intake manifold. The hydrogen line had a flame arrestor to prevent any flashback of the hydrogen-air mixture.

The engine air flow rate was measured using a Merriam 50MW20-2 laminar flow element. The diesel fuel flow rate was determined by measuring the amount of gravity fed fuel flow through a burette in one minute intervals. Hydrogen and carbon monoxide fuel flows were measured using Alicat m-series mass flow meters.

In-cylinder pressure was measured using a Kistler 6123 pressure transducer coupled to a 504E Kistler charge amplifier. A National Instruments 6062E data acquisition card was used with Labview 8.6.1 to acquire the high speed in-cylinder pressure data. The in-cylinder pressure and IMEP data were calculated based on a 100 cycle average. A US Digital HB6M rotary optical encoder with 1800 CPR resolution was used as an external clock. A Wolff Controls injector needle lift sensor was used to sense injector needle motion.

2.2 Emissions

The oxides of nitrogen (both NO and NO_2) were measured using a California Analytical Instruments (CAI) model 600 HCCD chemiluminescence analyzer. Carbon monoxide was measured using a Horiba PIR-2000 CO analyzer for concentrations above 1500 ppm and a Rosemount model 880 CO analyzer for concentration below 1500 ppm. The hydrogen in the exhaust was measured using an Agilent 6890 Gas Chromatograph (GC). The GC column used was a 30m X .530 um X 25 um molecular sieve (part number 19095p-ms6). This column was selected give good separation for H_2, O_2, N_2, CO, along with other species. The hydrogen in the exhaust was measured only for the 100% H_2 and the diesel only conditions, and was not measured for the remainder of the syngas tests. The GC column was kept at a constant 40 C temperature during the testing.

2.3 Testing Conditions

Ultra-low sulfur diesel (< 15 ppm sulfur) fuel was used as the main fuel component for these experiments. The syngas was simulated using various proportions of high purity (> 99.99%) hydrogen and carbon monoxide from high pressure gas bottles. Table 2 shows the conditions which were tested.

Table 2: Test matrix

Diesel Substitution (%)	Part Load (IMEP = 2 bar)			Moderate Load (IMEP = 4 bar)		
	Gaseous Proportion (vol.)		IMEP (bar)	Gaseous Proportion (vol.)		IMEP (bar)
	H_2 (%)	CO (%)		H_2 (%)	CO (%)	
0	0	0	2	0	0	4
10	100	0	2	100	0	4
10	75	25	2	75	25	4
10	25	75	2	25	75	4
10	0	100	2	0	100	4
20	100	0	2	100	0	4
20	75	25	2	75	25	4
20	25	75	2	25	75	4
20	0	100	2	0	100	4
40	100	0	2	100	0	4
40	75	25	2	75	25	4
40	25	75	2	25	75	4
40	0	100	2	0	100	4

Two IMEP conditions were tested; 2 bar and 4 bar IMEP, which represented a part load (~33% load) and a moderate load (~66% load) condition, respectively. The diesel only conditions were selected as the base cases, by which the rest of the cases were determined from. The testing began by bringing the engine up to temperature and determining the amount of diesel fuel flow required to give 2 bar IMEP. Once this flow rate determined, the other conditions (10%, 20%, and 40% diesel substitution) were selected by reducing the diesel flow rate by 10%, 20%, or 40% and adding either hydrogen, carbon monoxide, or both to bring the IMEP back up to 2 bar. This way the substitution percentage is based on either mass or energy fraction. The same was repeated for the 4 bar IMEP condition.

The proportions of hydrogen to carbon monoxide were determined on a volume basis. The four H_2/CO proportions (100%/0%, 75%/25%, 25%/75%, 0%/100%) were selected to give a wide range of the fuel component of syngas that can be expected from various feed stocks and production methods, along with the extremes of straight hydrogen and straight carbon monoxide.

3. RESULTS AND DISCUSSION

In this experiment various proportions and amounts of hydrogen and carbon monoxide were injected in the intake manifold of a compression ignition engine operating on diesel fuel. The engine was operated at 2 bar and 4 bar IMEP while measuring the cycle efficiency and exhaust emissions such as NO_x, NO_2, CO, and unburned H_2 emissions.

3.1 Cycle Efficiency

Figure 1 and Figure 2 show how the cycle efficiency varies for various diesel fuel substitution amounts with the engine operating at 2 and 4 bar IMEP, respectively. The baseline diesel only condition, represented by the dashed line, had a cycle efficiency of 34.6% for the 2 bar IMEP condition and 39.6% for the 4 bar IMEP condition. The plots show that for all the cases tested, the cycle efficiency is below the diesel only base condition, which indicates that the gaseous fuel is not burning as well as the diesel fuel. For both the 2 bar and 4 bar IMEP conditions, as the diesel fuel substitution amount is increased the cycle efficiency decreases for all of the syngas proportions tested. For the 2 bar IMEP case, the cycle efficiency varies from 10 – 25 % less than the base diesel only case. The 4 bar IMEP case, however, shows a cycle efficiency variation ranging from 5 – 18% less than the base diesel only case. This demonstrates that there is better gaseous fuel utilization at the higher 4 bar IMEP condition. This has been reported in the literature [4]. At low load, the efficiency for the engine operation with syngas was considerably lower compared to the operation on diesel fuel only due to inefficient burning of CO and H_2. However as load increases, the efficiency becomes almost close or greater to the base line.

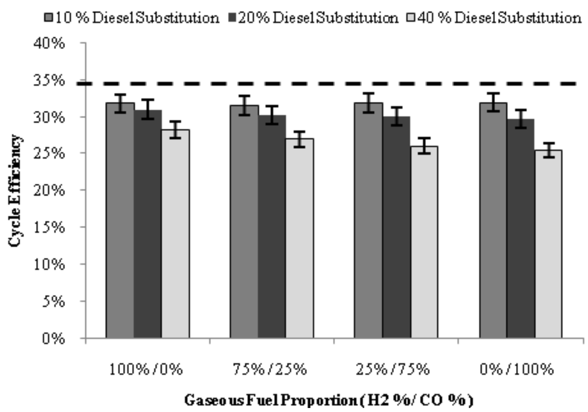

Figure 1: Cycle Efficiency at 2 bar IMEP

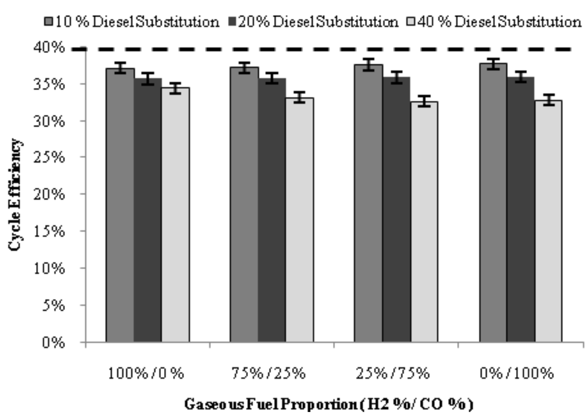

Figure 2: Cycle Efficiency at 4 bar IMEP

Figure 3 and Figure 4 show how the the cycle efficiency changes by varying the ratios of hydrogen to carbon monoxide in the syngas mixture with the engine operating at 2 bar and 4 bar IMEP, respectively. For 10 % diesel substitution for both the 2 bar and 4 bar IMEP cases, the syngas proportion does not seem to have an effect on cycle efficiency and the cycle efficiency remains constant at 31.7% +/- 0.2 and 37.4% +/- 0.3, resepectively. As the diesel fuel subsititution is increased to 20%, however, there is a slight cycle efficiency reduction with increasing carbon monoxide proportion for the 2 bar IMEP case. The cycle efficiency drops from 31.0 % for the straight hydrogen condition, to 29.7% for the straight carbon monoxide condtion. The cycle efficiency drop becomes more apparent at the 40% diesel substitution condition for both 2 bar IMEP and 4 bar IMEP cases. The 2 bar IMEP, 40 % diesel substitution case shows a steady drop with increasing carbon monoxide fraction from 28.3% for the straight hydrogen conditon, down to 25.4% for the straight carbon monoxidecondition. The 4 bar IMEP, 40% diesel substitution condition shows a cycle efficiency drop from 34.4% for the straight hydrogen (100% H2) condition to 33.1% for the 75% / 25 % (H_2/CO ratio) condtion. This intial cycle efficiency drop with carbon monoxide addition is much greater than the cycle effeciency reductions seen with further increasing carbon monoxide fractions.

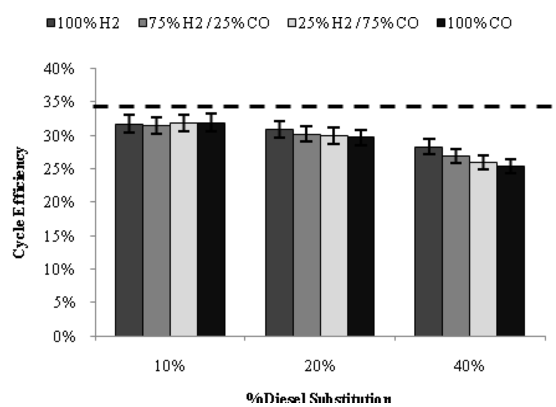

Figure 3: Showing effect of varying syngas composition on cycle efficiency with engine operating at 2 bar IMEP

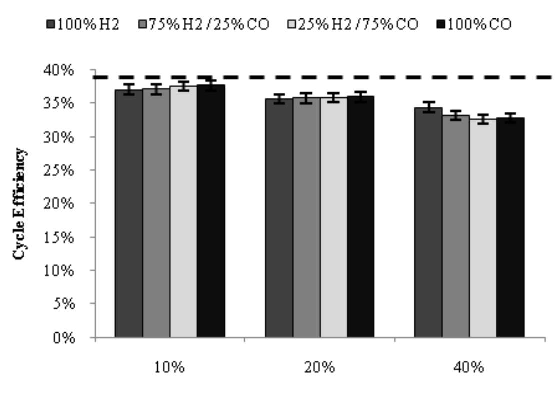

Figure 4: Showing effect of varying syngas composition on cycle efficiency with engine operating at 4 bar IMEP

It is evident that the cycle effieciency is reduced as the gaseous fuel equivalence ratio is increased for the 2 bar and 4 bar IMEP conditions. For the 2 bar IMEP case, the gaseous fuel equivlence ratio varied from 0 for the diesel base case, to 0.03, 0.05, and 0.11, for the 10%, 20%, and 40% diesel fuel substitution cases, resepectively. For the 4 bar IMEP case, the gaseous fuel equivalence ratio varied from 0 to 0.16. There is a clear dependence of a reduction in cycle efficiency with increasing gaseous fuel equivelence ratio, independent of the syngas fuel composition.

The reduction in cycle efficiency with syngas addition from the baseline diesel conditon is directly related to the amount of unburned mixture escaping with the exhaust gases. The overall syngas-air mixture was extremly lean during all of the tests, ranging from 0.025 – 0.16. This very lean mixture would not be capable of sustaining flame propogation outside the diesel fuel flame region. In traditional diesel dual fuel engines, the diesel fuel is used as a pilot igniton source for the gaseous fuel mixture. Gomes Atunes et al [6] reported the improved performance when using dual fuels and HCCI compared to the conventional diesel engine mode. It should be noted that dual operation on 20% diesel fuel and 80% hydrogen (on an energy basis) increased the shaft output by 21.5% compared to diesel mode. The gaseous fuel concentrations are typically high enough to sustain flame propogation throughout the combustion chamber, outside of the diesel fuel diffusion burning process. Figure 5 shows how the exhaust emissions of hydrogen and carbon monoxide increase with increasing gaseous fuel equivalence ratio. The conditions shown are for the 100% CO and 100% H_2 tests at 2 bar and 4 bar IMEP. This shows that the unburned syngas mixture is proportional to the fuel concentration present in the intake manifold. The trend is linearly increasing, which means that the gaseous fuel equivalence ratio threshold where flame propogration outside of the diesel flame jet has not occurred.

3.2 NOx Emissions

Figure 6 and Figure 7 show the NO_x emissions with various syngas proportions and amounts with the engine operating at 2 bar and 4 bar IMEP, respectively. The dashed lines represent the diesel only baseline condition. Figure 6 shows that varying syngas compostion does not have a significant effect on the NO_x emissions with the engine operating at 2 bar IMEP. The overall NO_x emissions remain near the baseline diesel only condition of 415 ppm. Figure 7 shows the NO_x emissions at 4 bar IMEP, where the baseline diesel only condition has a NO_x emission of 700 ppm. For all of the syngas conditions tested at 4 bar IMEP, the NO_x emissions are higher than the baseline diesel only case. It is also shown that as the diesel fuel subsititution amount is increased, the NO_x emissions also increase at 4 bar IMEP, to a maximum of 891ppm for the straight carbon monoxide, 40% diesel substitution case. For the 4 bar IMEP, 40% diesel substitution case, the NO_x emissions steadily increase as the carbon monoxide fraction is increased in the syngas mixture, from 812 ppm for the straight hydrogen condition, to 891 for the straight carbon monoxide condtion.

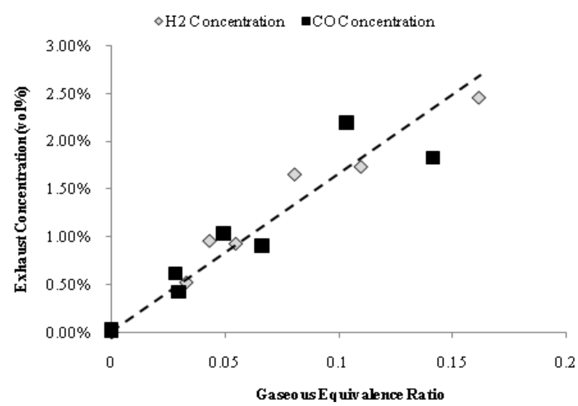

Figure 5: Increasing Exhaust Emissions of H_2 and CO with increasing gaseous fuel equivalence ratio at 2 bar and 4 bar IMEP

The NO_x emissions shown in Figure 6 and Figure 7 show that for the 2 bar IMEP condition, the NO_x emissions remain relatively unchanged with sygnas addition, however for the 4 bar IMEP condition, the NO_x emissions increase with increasing diesl fuel substitution.

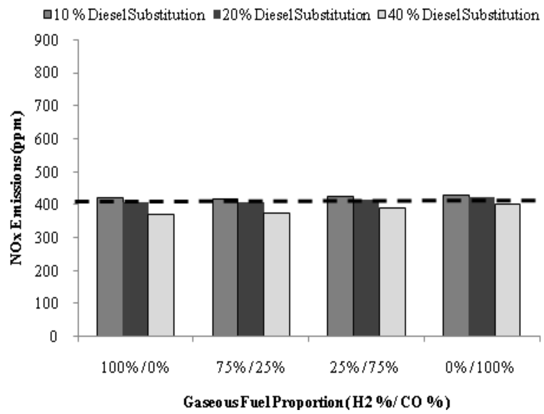

Figure 6: NO_x emissions at 2 bar IMEP

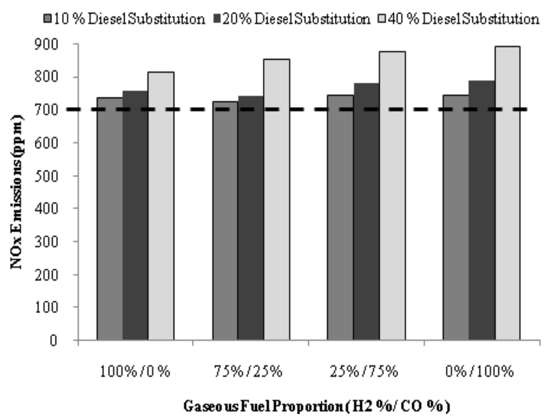

Figure 7: NO_x Emissions at 4 bar IMEP

The relatively constant NO_x emisisons seen at lighter load are consistent with previous work with hydrogen only addition [18] and a the lighter load. As the load is increased to 4 bar IMEP the trend of increasing NOx emissions with increasing diesel fuel substitution would indicate an increase in the flame temperature of the diesel fuel flame jet. It seems that at these higher diesel fuel substitution amounts the compositoin of the syngas mixture does not matter, and a NO_x increase will be seen. Varde and Frame [17] reported that a low levels of hydrogen addition (e.g., 5 to 10% of the total energy injected as hydrogen in the intake air) there were reductions in smoke emissions at part load and NOx emissions were unchangeable. At higher loads and higher levels of hydrogen addition, NOx emissions increased.

3.2 CO and H_2 Emissions

Figure 8 and Figure 9 show the CO emissions at 2 bar and 4 bar IMEP, respectively. For both load conditions, the CO emissions increase significantly as the CO fraction is increased in the syngas. This means that there is a significant fraction of the syngas that is not being burned as is escaping as an unburned mixture. For the 2 bar IMEP condition, the amount of unburned CO escaping with the exhaust ranged from 48- 54 % of the CO injected with the intake air. This means that only roughly 50% of the gaseous mixture was being burned. For the higher load 4 bar IMEP condtion, the amount of unburned CO escaping with the exhaust ranged from 30 – 37% of the CO injected with the intake air. This means that at the higher load condition, a greater amount of the gaseous mixture is being burned, between 63 – 70%.

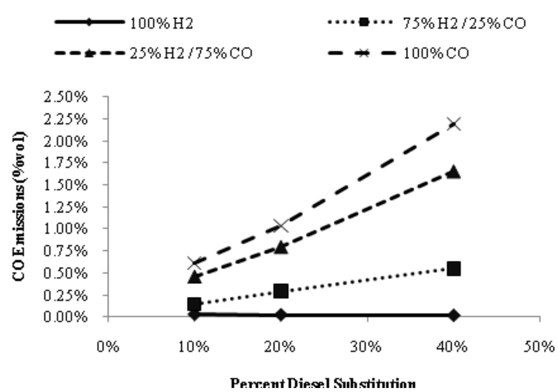

Figure 8: CO Emissions at 2 bar IMEP

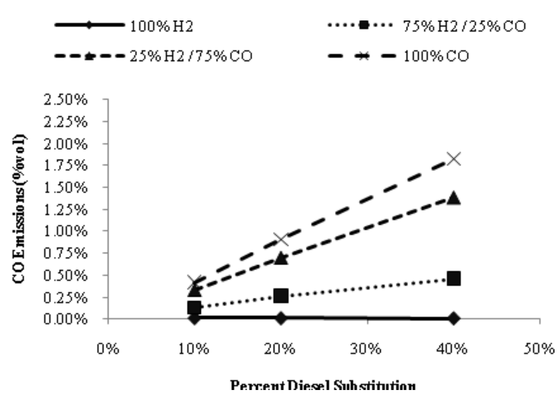

Figure 9: CO Emissions at 4 bar IMEP

Figure 10 shows the unburned hydrogen emissions for the 100% hydrogen conditions at 2 bar and 4 bar IMEP. The unburned hydrogen in the exhaust was only measured for the syngas compositon made up of 100% hydrogen. The unburnded hydrogen in the exhaust increases with increasing diesel substituion amount for both 2 bar and 4 bar IMEP conditions. The higher load 4 bar IMEP condition has a maximum unburned hydrogen concentration of 2.5% in the exhaust at 40% diesel substitution while the 2 bar IMEP condition has a maximum of 1.7%.

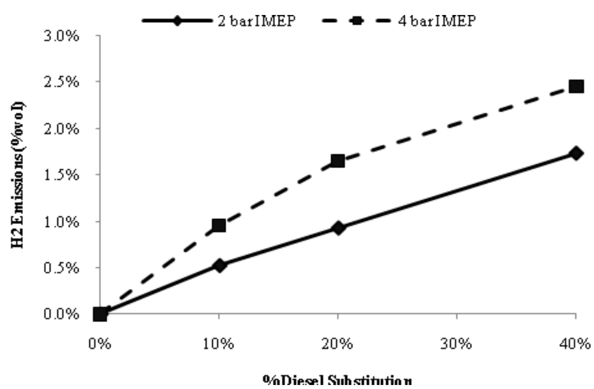

Figure 10: H_2 Emissions at 2 bar and 4 bar IMEP

Figure 11 shows the CO emissions for the baseline diesel only case and also the conditions where the syngas compositions were made up of 100% hydrogen.

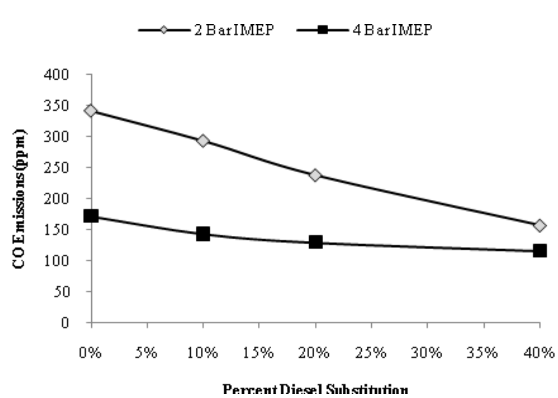

Figure 11: CO Emissions for 100% H_2 condition at 2 bar and 4 bar IMEP

The CO emissions for the 2 bar IMEP cases were higher than the 4 bar IMEP cases, and for all of the conditions tested, the CO emissions decreased with increasing diesel substitution amount. For the 2 bar IMEP condition, the CO emissions ranged from 350 ppm for the diesel base case and steadily decreased to 155 ppm at the 40 % diesel substitution amount. For the 4 bar IMEP condition, the CO emissions were 170 ppm for the diesel base case and decreased to 115 ppm at the 40 % diesel substitution case.

4. Conclusions

From the previous analysis, it is concluded that:

- Syngas can be an alternative for compression ignition engines
- There is a significant decrease of NOx emissions at low loads when the engine is running with mixtures of syngas.
- It is possible to substitute partially diesel fuel by syngas without a decrease of efficiency and an increase of harmful emissions.

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