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## **A Study on Performance and Emissions of a 4-stroke IC Engine Operated on Landfill Gas with Syngas Addition**

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### **ABSTRACT**

The aim of this study is to investigate the suitability of landfill gas (LFG) as an alternative fuel for an internal combustion (IC) engine and how to reduce pollutants emissions from LFG operations by adding syngas to LFG. The effect of CO<sub>2</sub> fractions in LFG on the engine performance and exhaust emissions such as CO, UHC and NO<sub>x</sub> are experimentally determined, and a simulated LFG (50% CH<sub>4</sub> and 50% CO<sub>2</sub>) mixed with a simulated syngas consisting of H<sub>2</sub> and CO (H<sub>2</sub>/CO = 2) is also studied. The Honda GC160E engine connected with a small generator which functions as different electrical loads is used for this study. When CO<sub>2</sub> fraction in LFG changes from 0% to 50% at 0.8 kW load condition, CO and UHC emissions increase from 241.8ppm to 802.1ppm and from 35.6ppm to 113.4ppm respectively, while NO<sub>x</sub> emission decreases from 126.7ppm to 99.8ppm. In case of LFG (50% CH<sub>4</sub> and 50% CO<sub>2</sub>)-syngas (H<sub>2</sub>/CO = 2) mixtures, 5% addition of syngas to LFG at 0.8 kW load condition reduces CO, UHC and NO<sub>x</sub> emissions from 802.1ppm to 203.1ppm, from 113.4ppm to 11.1ppm and from 99.8ppm to 64.5ppm, respectively. However, when more syngas is added to LFG (10% and 15% syngas in fuel mixture) it does not measurably reduce these emissions any further.

Keyword: Landfill gas, LFGTE, emissions reduction, catalysis

### **INTRODUCTION**

Landfills are the largest human-generated source of methane emissions in the United States. Because methane is both potent and short-lived, reducing methane emissions from municipal solid waste (MSW) landfills is one of the best ways to achieve a near-term beneficial impact in mitigating global climate change. LFG electricity projects capture ~85% of the methane emitted from a MSW landfill. In addition to reduced price volatility, an LFG to electricity (LFGTE) project provides two GHG emissions reduction opportunities. First, it requires methane from the landfill to be collected, thereby preventing the gas from escaping into the atmosphere. Second, it displaces the CO<sub>2</sub> emissions from the fossil fuels that would otherwise have been used. A good example of this is the S.C. Johnson & Son' Waxdale plant in Wisconsin which anticipates a cut in the consumption of electricity and natural gas by 50% and greenhouse gas emissions reduction by nearly the same amount i.e. 30,000 tons per year [1] via a LFGTE project.

Transactions have already taken place both internationally and in the United States to generate revenue through the sale of GHG credits. For example, as far back as 1999 Zahren Alternative Power Corporation (ZAPCO) sold

2.5 million tons of CO<sub>2</sub> emission credits from 20 LFGTE projects in the United States to Ontario Power Generation, Inc. in Canada [2]. In June 2001, the Dutch utility Nuon purchased more than 300,000 tons of CO<sub>2</sub> emission credits from a GSF Energy LFGTE project in New Jersey [3]. It is important to note, however, that the market for CO<sub>2</sub> emission reduction credits is just beginning to develop globally, and the accounting standards and methodology for measuring and inventorying emissions and related offsets are still in their very early stages of development.

Use of LFG however is plagued by low/fluctuating BTU content resulting in lack of flame stability, increased emissions and compromised fuel efficiency (due to need for supplemental fuel to compensate for the lower BTU content). Emissions waivers are often required before LFGTE projects can be permitted. The resulting economic considerations arising from the cost for upgrading fuel, the additional expenses for using specialized power generators coupled with permitting costs have prevented widespread use of LFG. In view of these factors LFG is commonly flared off. This generates CO<sub>2</sub> (also a greenhouse gas) without efficiently utilizing the energy in the LFG.

Another consideration is that due to the low BTU content of LFG most engines need to be modified considerably to accept it as a fuel source. In addition, once modified, those engines prefer a consistent composition of the fuel (e.g. 50% methane and 50% carbon dioxide). Often fuel conditioning has to be done if the LFG composition varies. That is if the methane content drops, secondary fuel may have to be added to ensure continuous and stable combustion to allow the engine to operate. Not only is the participatory mechanism of H<sub>2</sub> in emissions reduction understanding limited, especially for low BTU fuels, but also the concept of partially reforming LFG has rarely been examined. The presence of CO<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>O and some O<sub>2</sub> in the fuel stream makes the reactants unique with regards to previously examined high energy gaseous fuels such as natural gas, propane, etc.

It is known that supplementing combustion processes with hydrogen results in lowered emissions of nitrogen oxides, soot, hydrocarbons and carbon monoxide as well as improved combustion stability. However, availability of hydrogen for these processes remains elusive. Advantages of running a natural gas fueled engine with varying hydrogen content in the fuel have been well documented [4,5]. Bell and Gupta [6] have done an extensive review of prior work with hydrogen-supplemented feeds and have also reported their experience with hydrogen additions of 5, 10 and 15% to a natural gas fueled spark ignition (SI) engine. NO<sub>x</sub> emissions as low as 0.11 g/hp-hr were reported over a relatively broad range of equivalence ratios along with associated reduction in CO and HC. The supporting arguments for reduced NO<sub>x</sub> are primarily a combination of lower in-cylinder temperatures due to leaner operation and the much faster flame speeds associated with hydrogen. It is anticipated that 15–30 molar % of H<sub>2</sub> in the fuel should result in considerable improvement in lean limit stability and consequently result in a significant reduction of NO<sub>x</sub>, CO and HC emissions [7].

Different types of reforming devices which produce hydrogen have been developed. For instance, Heywood et al. [8] have been developing a plasma assisted H<sub>2</sub> generation device (Plasmatron) which has shown greater than 80% NO<sub>x</sub> reduction in a gasoline fueled SI engine with potentially increased engine efficiency. Other work by Hydrogen Consultants, Inc. of Littleton, Colorado, has also demonstrated that methane blended with only 5% hydrogen (Hythane<sup>®</sup>) can result in NO<sub>x</sub> and CO reduction of up to 50%. Work at Sandia's Combustion Research Facility [9] has identified that "The development of H<sub>2</sub> and H<sub>2</sub>-blended hydrocarbon fuels will boost the use of alternative fuels and lead to cleaner burning turbines." By extension, introducing H<sub>2</sub> in to IC engine fuels will allow them to operate in a more fuel-lean, premixed mode, which is an effective means of reducing NO<sub>x</sub> emissions due to the lowered flame temperature while maintaining reliability.

While the advantages of H<sub>2</sub>-spiking of the fuel are numerous, the major hurdle is in demonstrating a feasible and practical means of making H<sub>2</sub> available without compromising system efficiency and/or adequately addressing challenges with control aspects of injecting, mixing and igniting the reactive mixture. Onboard H<sub>2</sub> storage poses uniquely difficult problems. Plasma assisted devices from Lynntech,

Inc. and MIT are plagued by serious efficiency and size penalties and have to overcome significant other hurdles (e.g. electrode corrosion) before they can be considered practical. Currently there are other companies that are developing hydrogen injection schemes to reduce NO<sub>x</sub> emissions, primarily from gas turbine combustors. For example, PSM, a subsidiary of Calpine is considering using hydrogen injection to augment the emissions reductions they obtain with their LEC-III dry low NO<sub>x</sub> combustor [10]. However, the approach that they are pursuing is to use hydrogen from facilities that would otherwise flare it. While this approach is viable and makes sense, it requires a hydrogen supply that is considered waste. The move toward a carbon neutral fuel supply and with the interest in a hydrogen economy growing, it is unlikely that there will be many hydrogen supply facilities to meet their need. This paper will present emissions results of a 5-hp, 4 stroke Honda GC 160E engine operating on simulated landfill gas and LFG mixed with various ratios of syngas.

## EXPERIMENTAL

The following experimental work was conducted to evaluate and examine the direct use of landfill gas and the addition of hydrogen, carbon monoxide and simulated synthesis gas in a small internal combustion engine in terms of the engine performance and exhaust emissions at different electrical load conditions.

A Honda GC160E-QHA, gasoline (spark ignition) type engine, connected to a small generator was fueled on simulated landfill gas. For the purpose of this study, the carburetor, fuel tank, and fuel pump were detached and removed from the engine. The mixture of fuel and air was fed directly into the engine cylinder. An aluminum plate with a ½ inch threaded hole for pipe fitting was fabricated and fixed to the engine. Four gases were used to create various simulated gaseous fuels: CH<sub>4</sub>, CO<sub>2</sub>, H<sub>2</sub>, and CO. Air was used for oxidants. CH<sub>4</sub>, CO<sub>2</sub>, H<sub>2</sub> and CO were fed from each gas cylinder (*TechAir*, 99.97%, 99.995%, 99.999%, 99.9%, respectively), and laboratory air was used. The supplied gases were monitored through rotameters made by Fisher & Porter Co., to ensure precise control. Pressure gauges were connected with each in order to accurately calculate mass flow rate of the gases. The range of conditions tested covered pure methane as a baseline to a simulated landfill gas (50% CH<sub>4</sub> & 50% CO<sub>2</sub>) with 25% increments of CO<sub>2</sub> addition. Hydrogen and carbon monoxide were introduced separately ranging from 5 to 15% to determine the effect of each. Finally a equal ratio of hydrogen and carbon monoxide was introduced into a simulated landfill gas to determine the effect of reformed landfill gas to syngas.

The engine was directly connected to a PRAMAC EG2800 electric generator. In this test, the term load is used to mean the measured electric power produced by the electric generator. A bank of several light bulbs was used to vary the electric load produced by the generator. To increase the engine loading more bulbs were powered, to decrease the engine load fewer bulbs were powered. This "load board" then consisted of sixteen different light bulbs of 100 – 200

watts each, wired in parallel, with every two bulbs sharing a switch, to allow easy load variation for flexible testing. To measure the power the engine electric generator produced, a Wattsup pro power meter (model # 99333) was used to continuously monitor the power output of the engine during testing.

Emission analysis was conducted with an ENERAC 700 continuous monitoring unit. The instrument's probe was inserted into the exhaust flow. A pump located inside the device draws a small amount of sample of the main exhaust gas. The sample was dried before entering the analyzer, via an onboard water trap and filtered for particulate matter.

The overall schematic of the test system is shown in Figure 1.

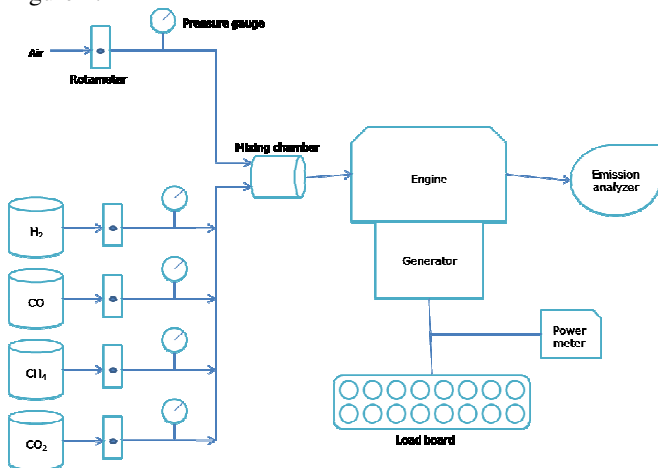


Figure 1. Schematic of LFGTE test system

## RESULTS & DISCUSSIONS

The engine was tested over a range of CH<sub>4</sub>, CO<sub>2</sub>, CO and H<sub>2</sub> concentrations resulting in 52 completed tests. The discussion here will only highlight the primary findings of the testing in terms of CO, UHC and NO<sub>x</sub> emissions. It should be noted that the emissions from the Honda test engine operating on methane were compared to emissions from commercially operating LFGTE systems and were comparable. Therefore, results from this study can be considered representative of what would be expected in field operation.

A primary consideration when determining the production of emissions from combustion systems is the temperature at which the combustion occurs. While measurements are ideal they are not possible to obtain without extreme modifications to the engine which also will likely impact the performance. Therefore an adiabatic flame temperature calculation was done to ensure that changes in gas composition did not change the maximum possible combustion temperature. Figure 2 shows the results of those calculations as a function of engine load.

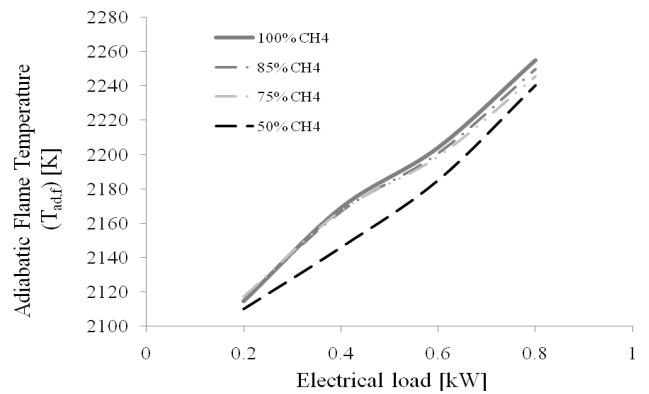


Figure 2. Adiabatic flame temperature calculation for compositions from pure methane to simulated LFG

The calculations show that over the tested range, based on inlet gas composition, temperature of 300 K and total flow rate, which had to be adjusted for each composition, the calculated adiabatic flame temperature was nearly constant except the mixture of 50% CH<sub>4</sub> and 50% CO<sub>2</sub> at 0.4kW load: about 23 °C less than other mixtures. This indicates that changes in emissions observed can be attributed to impacts of gas composition and the resulting chemistry of combustion rather than temperature effects.

The emissions of CO and unburned hydrocarbon (UHC) are indicative of combustion performance. Since CO and UHC are produced when the combustion is not complete, more CO and UHC emissions typically result when there is poor mixing of the fuel and air, not enough residence time or lower combustion temperature (although very high temperature will also result in high CO, UHC emissions will be very low). In Figure 3, CO emission measurements are presented as a function of CO<sub>2</sub> amount in the inlet fuel. For each measurement the engine was loaded at reproducible points to yield comparable conditions. 0% CO<sub>2</sub> fraction means pure CH<sub>4</sub> fuel.

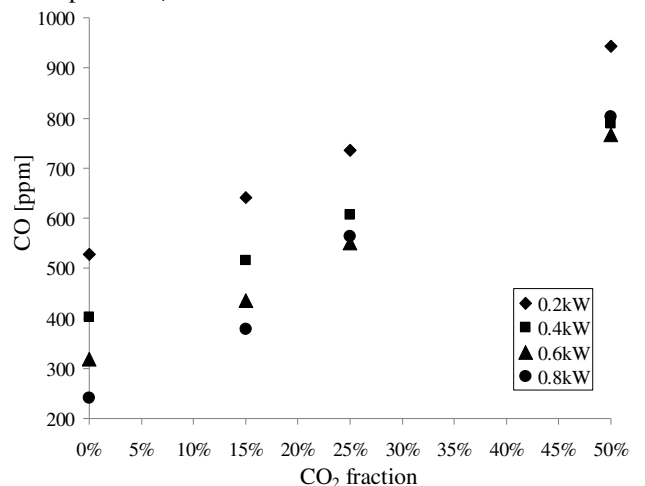
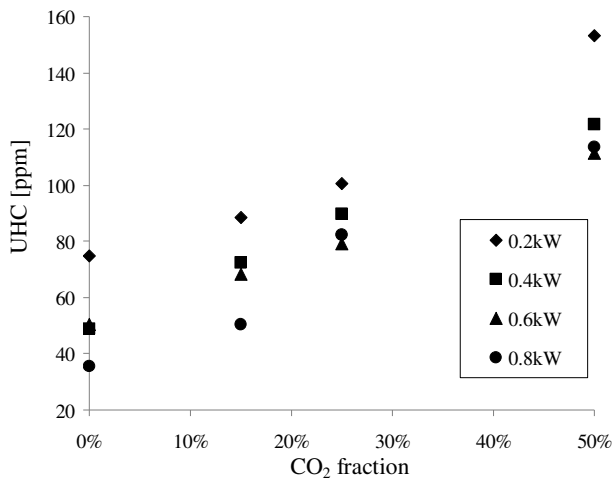


Figure 3. CO emissions measurements with CO<sub>2</sub> composition in the inlet fuel

Figure 3 shows the CO emissions increase by 80% for the 0.2 kW load condition and to nearly a factor of 2 for

the 0.8 kW condition as the CO<sub>2</sub> composition is increased (0% to 50%) which means fuel quality deteriorates, with the highest level measured at the simulated LFG composition, i.e. 50% CO<sub>2</sub>. In addition, as the load is increased (0.2kW to 0.8kW) the CO emissions decrease by about 15% which is expected since an increase in load results in slower engine speed, thus more residence time in the combustion chamber. It is interesting to note the convergence of the emissions as composition of LFG is approached.

The UHC emission data are shown in Figure 4 as a function of CO<sub>2</sub> concentration (0% to 50%) in the inlet fuel mixture. The data follow the same trend as the CO emissions which are expected if incomplete combustion is occurring due to slow reactions resulting from dilution effects. The UHC measurements also include CH<sub>4</sub> emissions; therefore, it is difficult to discern if the CH<sub>4</sub> is just passing through the engine or it is partially reacted. Again, as the CO<sub>2</sub> in the inlet fuel mixture increases (fuel quality becomes lower), the UHC emissions rise from below 80ppm to 150ppm for 0.2 kW load condition.

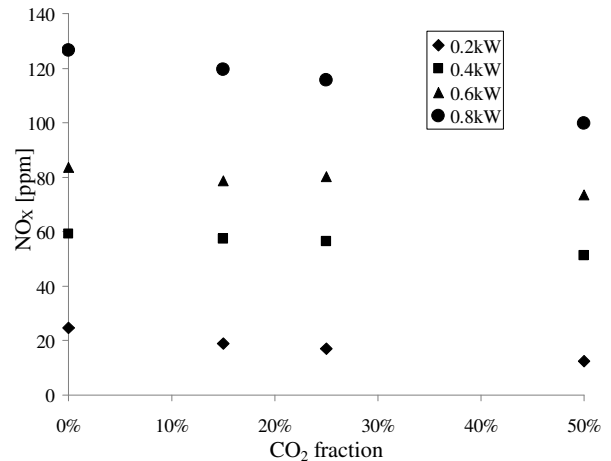


**Figure 4.** UHC emissions measurements with CO<sub>2</sub> composition in the inlet fuel

The last major emissions components from IC engines are NO<sub>x</sub>. Since the testing utilized pure CH<sub>4</sub> and CO<sub>2</sub> for making various fuel mixtures, there were no contaminants such as H<sub>2</sub>S; therefore, SO<sub>x</sub> emissions were not produced. NO<sub>x</sub> is formed via three main pathways for fuels without nitrogen components, which landfill is one. The primary mechanism is thermally initiated and controlled, also called the Zeldovich mechanism. High temperatures cause the nitrogen, from the air, to dissociate into nitrogen radicals, thus becoming very reactive and combine with oxygen to form NO. Further reactions in the combustion chamber and downstream in the exhaust convert some of the NO to NO<sub>2</sub>, thus NO<sub>x</sub>. While this mechanism does not become significant until temperatures exceed 1500°C (1800 K), it is exponential in temperature so once engaged it quickly becomes the biggest contributor. Another mechanism is the Fenimore, or prompt NO<sub>x</sub> route. Here fuel radicals such as CH<sub>3</sub> and others react with diatomic nitrogen from the air to

form a CHN molecule and a nitrogen radical. This chemically produced nitrogen radical then can react with oxygen the same way as occurs in the Zeldovich mechanism. Finally, there is the nitrous mechanism which is engaged at high pressures that are found in the combustion cylinders. Here diatomic nitrogen reacts with an oxygen radical to form N<sub>2</sub>O, which can then reduce to NO and participate in the NO to NO<sub>2</sub> mechanism in the system.

Shown in Figure 5 are NO<sub>x</sub> emissions measured as a function of CO<sub>2</sub> concentration. The largest effect was at the 0.2 kW load condition where the NO<sub>x</sub> concentration decreased from 24.8ppm to 12.4ppm when CO<sub>2</sub> fraction changes from 0% to 50%. Referring back to Figure 2, adiabatic temperature, the all load conditions are near or above 2100K for all CO<sub>2</sub> concentrations. For example, 0.2kW averages 2114K, 0.4kW averages 2162K, 0.6kW averages 2197K and the 0.8kW averages 2248K. Therefore, these conditions have the thermal (Zeldovich) mechanism more engaged which likely dominates the production of NO<sub>x</sub> formation compared to the other pathways at these temperatures.



**Figure 5.** NO<sub>x</sub> emissions measurements with CO<sub>2</sub> composition in the inlet fuel

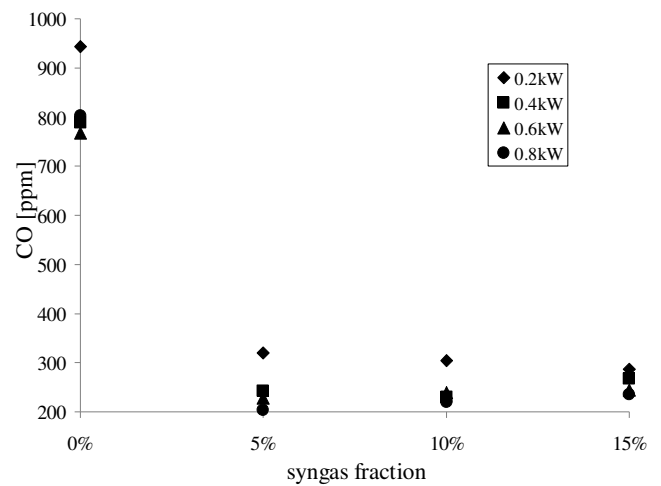
Since the introduction of CO<sub>2</sub> was designed not to much change the adiabatic temperature, see Figure 2, the major effect of CO<sub>2</sub> is dilution of radical or reactant concentrations. Temperatures above 1800K cause the diatomic nitrogen to dissociate forming nitrogen radicals. While CO<sub>2</sub> addition does decrease the nitrogen radical concentration, since the nitrogen concentration in the system is high, ~70%, the addition of CO<sub>2</sub> does not significantly impact the nitrogen content. For example, the pure methane condition has 74% nitrogen and the simulated LFG (50% CH<sub>4</sub>, 50% CO<sub>2</sub>) has 69% nitrogen. Thus, there is ample nitrogen content to dissociate at the high temperatures to maintain a critical nitrogen radical pool which maintains the Zeldovich mechanism contribution. Quantitatively this can be seen at the 0.4 and 0.6kW conditions where the addition of 50% CO<sub>2</sub> only reduces the NO<sub>x</sub> by ~13% on average. The 0.8kW load condition does show a more pronounced decrease in NO<sub>x</sub>, approximately 20% at 50% CO<sub>2</sub> condition. While this is not expected, it may be due to CO<sub>2</sub> dissociation at the higher

adiabatic temperatures providing CO and oxygen radicals. In this case, CO behaves as a reductant and will impact NO<sub>x</sub> formation. This is consistent with thermodynamic calculations that show at 1500K CO<sub>2</sub> barely dissociates while at 1800K CO<sub>2</sub> dissociates by 0.031 % and at 1880K CO<sub>2</sub> dissociates by 0.067%, which is 3 times the amount at 1800K. This amount may be above a threshold that engages a CO + N route to form CON, which upon further reaction forms CO<sub>2</sub> and N<sub>2</sub>, effectively tying up the nitrogen radicals, preventing them from forming CHN molecules.

It is clear that as the engine operates on more diluted fuel and therefore the energy content decreases, the emissions increase for CO and UHC by nearly two times, yet the NO<sub>x</sub> emissions decrease by 50% only for the low load condition (0.2kW) but only about 20% for the other loads (0.4, 0.6 and 0.8kW) with increasing CO<sub>2</sub> fraction in the inlet fuel mixture. There are many ways to reduce the emissions prior to release into the atmosphere via conventional post-combustion clean up methods. However, many of these methods result in reduced power output due to pressure drop increases and could potentially add significant expense. The method discussed here is to convert part of the methane in the LFG to H<sub>2</sub> and CO (syngas) via a very compact partial oxidation reactor. The major advantage of this reactor is that it generates the syngas in-line or in-situ without reducing the power output. This allows for a more reactive mixture to enter into the engine, thus allowing stable engine operation on LFG with considerable variations in the CH<sub>4</sub> – CO<sub>2</sub> ratios.

The addition of syngas to hydrocarbon fuels changes both the chemical and physical processes occurring in flames, which, in turn, improve flame stability, reduce pollutant emissions, and without reducing combustor efficiency. This arises primarily due to higher flame speed and lower ignition temperatures of the H<sub>2</sub>. The mixture of unreacted LFG, H<sub>2</sub> and CO is substantially more reactive than the pure LFG fuel. This allows ignition and stable combustion of the fuel at significantly lower temperatures and lower  $\phi$ . Thus, carbon based particulates, CO, UHC and NO<sub>x</sub>, primarily formed in the combustion chamber due to non-homogeneous combustion characteristics, are reduced. To quantify these effects a syngas composition was matched to a previous study by Kohn et al. [11] that converted LFG in an auto-thermal catalytic reformer. This composition was recreated using pure CO and H<sub>2</sub>, mixed with the simulated LFG (50% CH<sub>4</sub> and 50% CO<sub>2</sub>) and tested in the Honda engine to compare the emissions output with those measured on only methane and carbon dioxide mixtures.

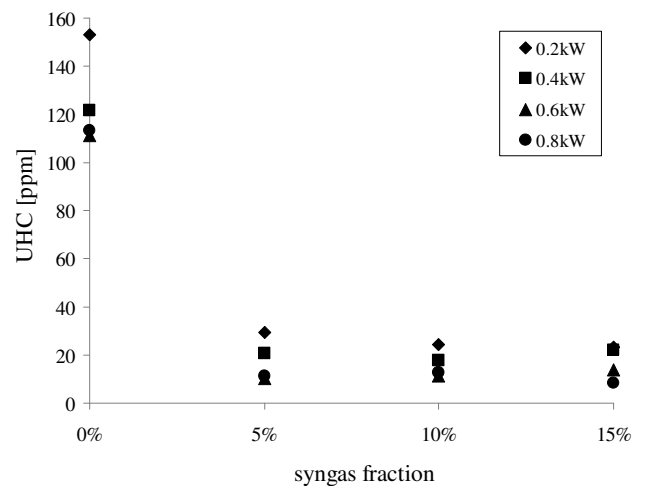
In general, the addition of syngas having the ratio of H<sub>2</sub>/CO=2 decreases the emissions significantly but only to a certain point. Figure 6 shows the measurements of CO emissions as a function of syngas mixed with the simulated LFG fuel and introduced into the engine together. In Figure 6, the 0% syngas condition is the same data shown on Figure 3 at the 50% CO<sub>2</sub> condition.



**Figure 6.** CO emissions measurement for simulated LFG with varying amounts of syngas addition to the combustion

Clearly, the addition of as little as 5% syngas with the simulated LFG composed of 50% CH<sub>4</sub> and 50% CO<sub>2</sub> reduces the CO emissions by nearly a factor of three for all load conditions. Interestingly more syngas does not measurably reduce the emissions any further. This may be an indication of the fluid dynamics within in the cylinder governing the emissions production.

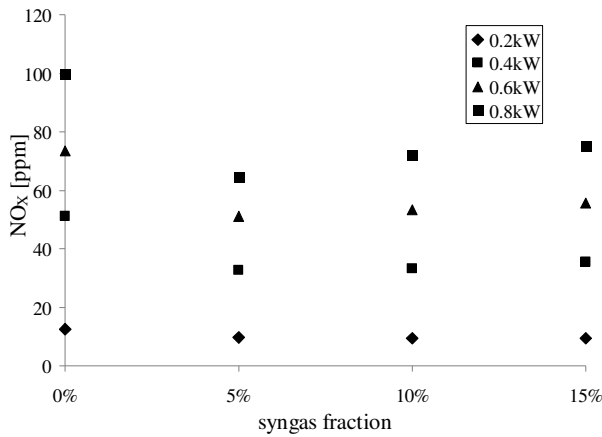
A similar trend is shown for UHC emissions production with syngas addition. Figure 7 shows the measured UHC emissions as function of syngas mixed with the simulated LFG. Again, the data at 0% syngas is the same data shown in Figure 4 at 50% CO<sub>2</sub> fraction.



**Figure 7.** UHC emissions measurement for simulated LFG with varying amounts of syngas addition to the combustion

Here again, the emissions are reduced by approximately a factor of five at all load conditions. Similar to the CO emissions data, an increase of syngas beyond 5% does not have a noticeable effect on the emissions output.

Finally the emissions for  $\text{NO}_x$  are shown in Figure 8 as a function of syngas added to the LFG fuel. Again the major emissions reduction occurs with the addition of 5% syngas with little improvement as more syngas is added.



**Figure 8.**  $\text{NO}_x$  emissions measurement for simulated LFG with varying amounts of syngas addition to the combustion

The reductions for  $\text{NO}_x$  are not as dramatic as the reductions in CO and UHC. This is consistent with the idea that the combustion on LFG is not very robust thus producing significant amounts of products of incomplete combustion but does not produce significant amounts of  $\text{NO}_x$ . Figure 8 shows the reduction in  $\text{NO}_x$  only about 40% at the most when 5% syngas is added. Moreover, there is a slight increase in emissions for the higher loads (0.4, 0.6 and 0.8kW) as the syngas fraction is increased from 5% to 15%. It is currently unclear if this is a real effect an artifact of the experiment. It is outside of the measurement error so it displays a real trend.

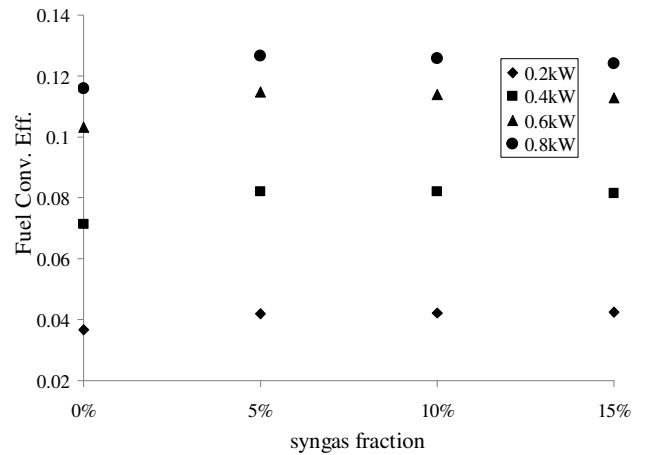
Finally, to demonstrate the effects of syngas addition are truly related to improvements in combustion stability and robustness, a comparison of fuel conversion efficiency was calculated. The fuel conversion efficiency is defined as the ratio of engine power output to the heat release rate of the fuel, as follows:

$$\eta_f = \frac{P}{\dot{m}_f Q_{HV}} = \frac{3600}{\text{sfc} Q_{HV}}$$

$Q_{HV}$  is the lower heating value of the fuel [MJ/kg of fuel]. sfc means the specific fuel consumption, defined as follow:

$$\text{sfc} = \frac{\dot{m}_f}{P}$$

$\dot{m}_f$  is the mass flow rate of fuel [g/hr], and P is the engine power output [kW] [12]. Figure 9 shows the results of the fuel efficiencies as a function of syngas introduced with LFG mix.



**Figure 9.** Fuel conversion efficiency as a function of syngas mixed with simulated LFG (50%  $\text{CH}_4$ -50%  $\text{CO}_2$ )

Figure 9 shows the fuel conversion efficiency remaining relatively stable for all syngas fractions introduced. Therefore, the reductions in emissions can be attributed to the hydrogen and carbon monoxide creating a more reactive mixture allowing the combustion to be more complete.

## CONCLUSION

The CO and UHC emissions increased while the  $\text{NO}_x$  emissions decreased with the presence of  $\text{CO}_2$  in fuel mixtures. The increase in engine loads resulted in the decrease in the emissions of CO and UHC and the increase in the emissions of  $\text{NO}_x$ . The syngas addition to LFG not only improved the fuel conversion efficiency but also reduced pollutant emissions because of  $\text{H}_2$  and CO in syngas allowing more complete combustion in the engine cylinder. It is found that 5% syngas addition was most effective to reduce pollutant emissions, and more syngas did not significantly decrease the emissions.

## ACKNOWLEDGEMENT

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