Experimental Evaluation of SI Engine Operation Supplemented by Hydrogen Rich Gas from a Compact Plasma Boosted Reformer

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ABSTRACT

It is well known that hydrogen addition to spark-ignited (SI) engines can reduce exhaust emissions and increase efficiency. Micro plasmatron fuel converters can be used for onboard generation of hydrogen-rich gas by partial oxidation of a wide range of fuels. These plasma boosted microreformers are compact, rugged, and provide rapid response. With hydrogen supplement to the main fuel, SI engines can run very lean resulting in a large reduction in nitrogen oxides (NO_x) emissions relative to stoichiometric combustion without a catalytic converter. This paper presents experimental results of a microplasmatron fuel converter operating under variable oxygen to carbon ratios. Tests have also been carried out to evaluate the effect of the addition of a microplasmatron fuel converter generated hydrogen in a 1994 production 2.3L four-cylinder SI engine. The tests were performed with and without hydrogen-rich gas produced by the plasma boosted fuel converter with gasoline. Approximately two orders of magnitude reduction in NO_x due to very lean operation was obtained under certain conditions. An advantage of onboard plasma- boosted generation of hydrogen is that it is used only when required and can be readily turned on and off. Substantial NO_x reduction should also be obtainable by heavy exhaust gas recirculation (EGR) facilitated by use of hydrogen-rich gas with stoichiometric operation.

INTRODUCTION

Decreasing emissions from motor vehicles and increasing efficiency is a necessary step toward improving air quality and decreasing greenhouse gases. Internal combustion engines for transportation constitute the single largest consumer of imported oil and are also a major source of ozone-producing gases such as NO_x that affect urban areas. A variety of potential improvements are presently being investigated: lean-burn engines; increased compression ratio; improved catalyst formulations; use of close coupled catalysts; new types of exhaust treatment; electric and fuel-cell powered vehicles; and alternative fuels.

A concept that could substantially reduce emissions is onboard hydrogen generation using microplasmatron fuel converters. Plasmatrons are electrical gas heaters that make use of the conductivity of gases at high temperature. Microplasmatron fuel converters are compact, rugged, can be used with a variety of fuels and provide rapid response. Large reductions in emissions from SI engines are possible using the hydrogen-rich gas produced by plasmatron conversion of hydrocarbon fuel. Increased flame speed in the cylinder extends the lean limit of SI engine operation [1]. The combination of increased flame speed and lower flammability limits of hydrogen can thus stabilize combustion during lean operation.

Very lean operation could reduce engine NO_x production by a factor of one hundred relative to stoichiometric operation [2,3,4]. Hydrogen addition could also be used to reduce NO_x emissions by facilitating use of increased exhaust gas recirculation (EGR) [5]. Onboard production of hydrogen is also attractive for reduction of cold start emissions, as well as for catalyst regeneration and post treatment.

Concepts for use of plasmatron generated hydrogen-rich gas in spark ignition engines have been discussed in previous papers [6-9]. Engine experiments have also performed using bottled synthesis gas [2, 3, 4, 10], and with conventional reformers operating on methane [11] or ethanol [12,13]. To the knowledge of the authors, this paper reports the first use of a compact plasma boosted reformer to convert gasoline into hydrogen rich gas which is then combusted in an internal combustion engine resulting in a large decrease in air pollutants.

The paper presents experimental results of gasoline reforming with a plasmatron operating under partial oxidation conditions. Recent progress on decreasing the electrical energy consumption and increasing the yield of the microplasmatron fuel converter, by improved designs, are discussed. Following a brief description of the plasmatron operation, methods to improve the plasmatron efficiency and the overall process are briefly described. Electrical energy requirements and hydrogen yields are reported. Results of experiments on the use of a microplasmatron fuel converter with a 2.3 L, four cylinder SI engine at the Advanced Propulsion Technology Center of the Oak Ridge National Laboratory are then described. Finally, applications of the microplasmatron fuel converter on-board vehicles are briefly described.

COMPACT PLASMA BOOSTED REFORMERS

Plasmatrons provide ohmic heating of gases to elevated temperatures. At these temperatures the gas is partially ionized. Plasmatrons provide highly controllable electrical heating of this gas. The increased temperatures, ionization levels and mixing provided by plasmatron heating accelerate reformation of hydrocarbon fuels into hydrogen rich gas. The high temperatures can be used for reforming a wide range of hydrocarbon fuels into hydrogen-rich gas without the use of a catalyst. It thus is possible to eliminate problems associated with catalyst use, such as narrow operating temperature, sensitivity to fuel composition, poisoning, and response time limitations.

By increasing the reaction rates, plasma heating could significantly reduce size requirements for effective reforming, increase speed of response and increase fuel flexibility. A wide range of operation is possible, from partial oxidation to steam reforming. The boosting of the reaction rate would occur by creation of a small very high temperature region (5000-10000 K) where radicals are produced and by increasing the average temperature in an extended region.

The additional heating provided by the plasma can ensure a sufficiently high number of chemically reactive species, ionization states, and elevated temperatures for the partial oxidation reaction to occur with negligible soot production and with a high conversion of hydrocarbon fuel into hydrogen-rich gas. The effective conversion of hydrocarbon fuel is aided by both the high peak temperature in the plasma and the high turbulence created by the plasma.

A plasma boosted reformer can be made very small because of the high power density. The rapidly variable plasmatron parameters (energy input, flow rate, product gas composition, etc) make this technology very attractive for application to the dynamic demands for hydrogen-rich gas production in vehicles. It should be possible to practically instantaneously produce hydrogen-rich gas for use during cold startup. Throughout the driving cycle, rapid changes in hydrogen-rich gas flow can be accommodated by variation of plasmatron parameters. [8]

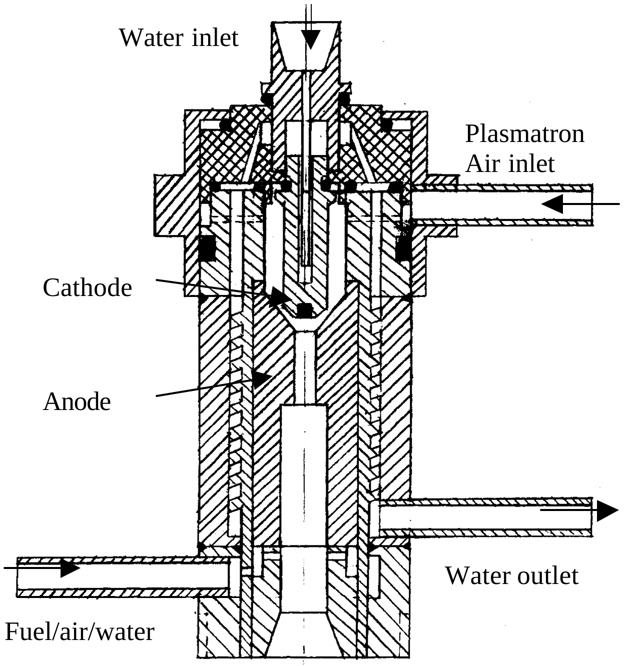

Figure 1. Plasmatron fuel converter device. Reaction extension cylinder and heat exchanger are not shown.

Figure 1 shows a diagram of a multi kilowatt plasmatron. The device operates at atmospheric pressure, with air as the plasma forming gas. The plasmatron operates in DC mode. The plasmatron consist of copper cathode with a hafnium tip, and a copper tubular anode [14]. The electrodes are separated by an electrical insulator made out of fiberglass (G-10). The cathode and anode are water cooled, and this cooling represents a sink of energy. Measurements on the water temperature rise indicate that the plasmatron is about 70–80% efficient. The cathode has a tip made of hafnium. Hafnium allows operation on air as the plasma forming gas. The hafnium tip has a high electron emissivity and relatively long lifetime at current less than ~100 A.

The plasma arc ignites across the electrode gap. Air is injected tangentially upstream from the electrodes to produce a vortex that elongates the plasma inside the tubular anode. The anode root of the arc is in constant rotation in order to minimize electrode erosion. The hydrocarbon fuel and additional air are injected downstream from the electrodes. The mixture of hot air and vaporized hydrocarbons enter the plasma reactor where the reaction takes place.

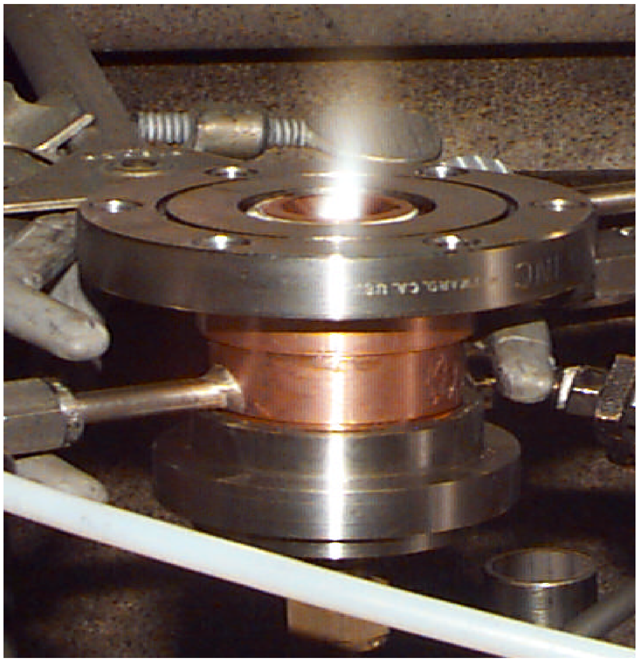

Figure 2. DC arc microplasmatron operating in air without fuel.

Figure 2 shows a photograph of the plasmatron without a reaction extension cylinder, operating on air at about 1.5 kW. The plasma jet is pointing upwards. During reforming operation, fuel and additional air are injected downstream from the stainless steel flange shown in the Figure 2.,

Figure 3 shows a microplasmatron fuel converter that includes a reaction extender and a heat exchanger. The heat exchanger can be used to simultaneously cool down the hydrogen-rich gas and to preheat the incoming air and fuel. Preheating the air/fuel reduces the electrical energy requirement to the plasmatron and increases the hydrogen yield. Work is continuing in the development of high efficiency, high temperature heat recuperator. Simple calculations show that the use of preheat can half the electrical power requirements to the plasmatron.

A typical microplasmaton fuel converter includes a steel tube 4 cm in diameter and 15 cm long thermally insulated by fiberglass felt and steel screens. The samples of hydrogen rich gas are cooled down and analyzed using gas chromatography (GC). Table I shows the typical plasmatron range of operating parameters for a DC arc device. Materials that could be used in various components of the plasma boosted reformer are copper, zirconium and molybdenum. Conversion efficiency, electrode life, size, and weight are key feasibility issues and require detailed experimental investigation.

Table 1. Parameters of conventional DC Arc plasma boosted reformer.

Power	1.5-10 kW.
Voltage	120-140 V DC
Current	15-75 A DC
Flow rates	
Air	0.5-1.5 g/s
Fuel	0.3-0.5 g/s

The setup used in the experiments described below with the engine is shown in Figure 3. The plasmatron is followed by a reaction extension cylinder, a simple heat exchanger (not cooled for the present experiments), and a gas-to-water heat exchanger, used to cool the reformate.

GASOLINE AND DIESEL REFORMING – Using a DC arc microplasmatron fuel converter, conventional fuels were very efficiently converted to hydrogen rich gas, with an electrical power input of ~10% of the heating value of the fuel. However, with heat regeneration and with improved reactor design, it is estimated that the required electrical energy input to the microplasmatron fuel converter will be on the order of 5% of the heating value of the fuel. Furthermore, the reactor showed no evidence of soot, even after extended operation. Innovations to further decrease the energy consumption and to further simplify the microplasma reformer are described at the end of this discussion.

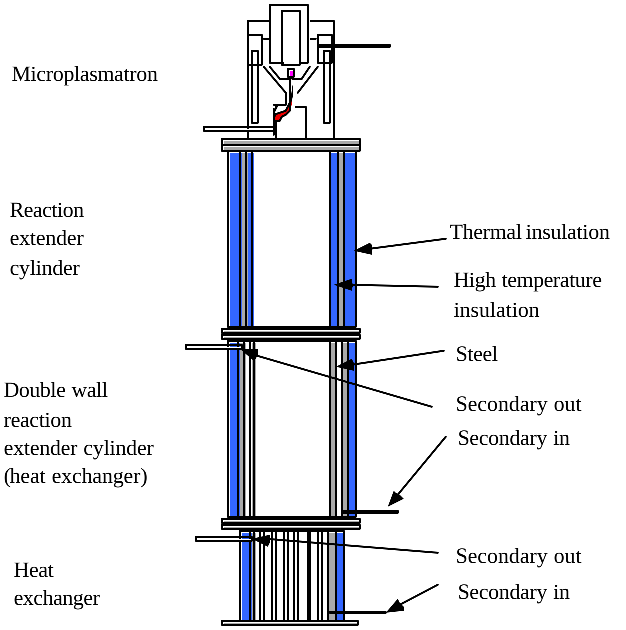

Figure 3. Microplasmatron with reaction extender cylinder and two heat exchangers.

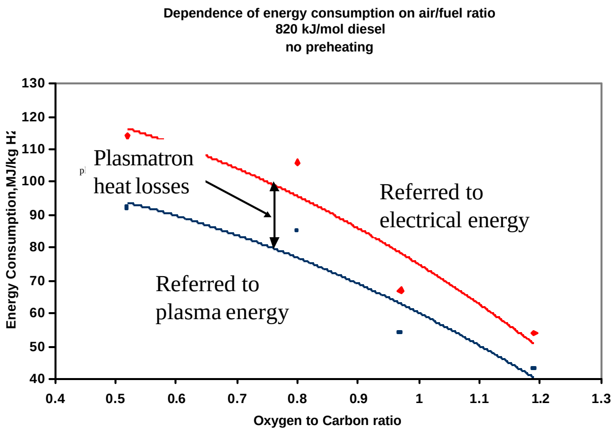

Figure 4. Energy consumption for plasma diesel reforming as a function of the oxygen to carbon ratio.

Figure 4 shows the specific energy consumption of the hydrogen rich gas produced by the DC Arc micrplasmatron fuel converter, in units of MJ/kg H_2 for diesel fuel. The hydrogen and light hydrocarbon yield as a function of oxygen to carbon ratio is shown in Figure 5. At the higher oxygen to carbon ratios, the process becomes more exothermic. For a given specific electrical power input, the increase temperature increases the yield (as shown in Figure 5) and decreases the specific energy consumption.

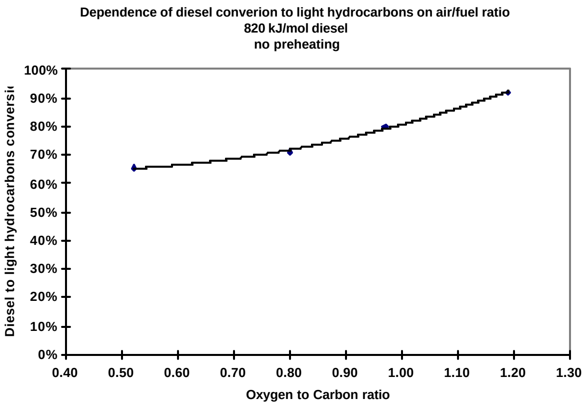

Figure 5. Hydrogen and light hydrocarbon yield as a function of the oxygen to carbon ratio.

The experiments described above were conducted at constant power. The power requirements and the reformate composition were relatively insensitive to the flow rates as long as the specific power input (power/unit mass) and air/fuel ratios are kept constant. Under these circumstances, although the residence time decreases (because of the higher throughputs) increased efficiency of the system makes up for the decreased residence time. Figure 6 shows the composition of the reformate for diesel as the fuel, as a function of the oxygen to carbon ratio. The hydrogen concentration is relatively constant.

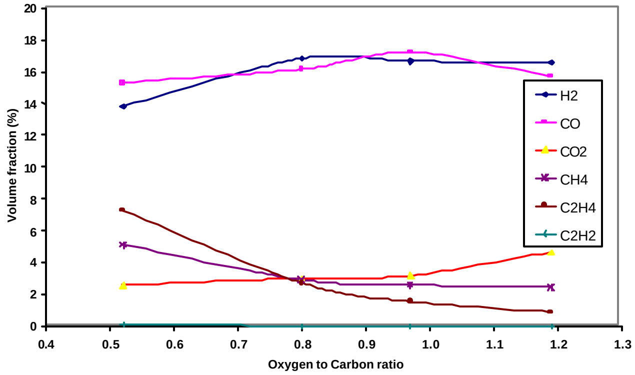

Figure 6. Composition of reformate as a function of the oxygen to carbon ratio, for diesel fuel. Balance is N

Microplasmatron fuel converters have substantial dynamic range. The lower power is determined by the maximum voltage capability of the power supply (the voltage increases with decreasing current), while the highest power is determined by erosion of the electrodes. It is expected that a dynamic range of a factor of 10 is possible without substantial modification to the plasmatron device. This is sufficient to provide the required change in throughput for conventional engines. For hybrid vehicles, with engines operating at constant or near constant conditions, the plasmatron fuel converter would operate at near constant conditions, with air/fuel/power management requirements that are much simpler than for conventional drive.

ENGINE EXPERIMENTS

An improved compact plasma boosted reformer was installed and tested on a production in-line four-cylinder SI gasoline-fueled engine (1994 General Motors Quad-4) at Oak Ridge National Laboratory (ORNL)). The Quad4 has a 2.3 L displacement, 9.2 cm bore, 8.5 cm stroke and compression ratio of 9.5. This engine is port-fuel-injected and does not utilize a turbocharger or exhaust gas recirculation. The engine was coupled to a 130 kW (175 hp) eddy-current (Power Dyne, Inc.) dynamometer for engine speed and load control. Engine control management was carried out with a TEC-II control system (Electromotive, Inc.) The TEC-II provided access to all calibration parameters (raw fuel curve, enrichment, spark advance, and exhaust O_2) for proper engine operation. The TEC-II control allows the user to set desired air/fuel ratios (lean, rich, and stoichiometric). It can also adjust the fuel automatically to maintain stoichiometric air/fuel ratio by monitoring the exhaust gas oxygen.

Along with engine operating parameters and in-cylinder pressure, engine out regulated emissions (CO, HC and NO_x) and PM were measured at each operating point. Total mass concentration and rate of PM was measured with a Tapered Element Oscillating Microbalance (TEOM, R and P Co. Model 1105). A scanning mobility particle sizer (SMPS, TSI, Inc.) measured PM size and number. CARB Phase II certification grade gasoline was used for engine and plasmatron operation. The gasoline equivalent air/fuel ratio was measured with a universal exhaust gas oxygen (UEGO) sensor (Horiba MEXA 110) in the exhaust stream. Therefore during reformate addition, the reported equivalence ratio is actually slightly higher because of partial combustion in the microplasmatron.

The microplasmatron was operated with a constant gasoline throughput of 0.25 g/s. The reformate was cooled down to room temperature by a low pressure shell-in-tube heat exchanger. The composition of the microplasmatron output was continuously monitored using a conventional tailpipe emissions monitor (Horiba MEXA 554). Table 2 shows the measured parameters of the microplasmatron during experiments conducted at ORNL and MIT. The electrical power input to the microplasmatron was about 2% of the heating value of the fuel processed. This microplasmatron incorporated several design improvements which will be discussed in a later publication.

Experiments were conducted at two engine operating conditions: the first one at 2300 rpm and 4.2 bar brake mean effective pressure (BMEP); and the second one at 1500 rpm and 2.6 bar BMEP. Maximum brake torque (MBT) spark timing was defined for both operating conditions at stoichiometric conditions with the engine in closed-loop control mode. Once the MBT spark timing was defined for each condition, spark timing remained fixed as air/fuel ratio was increased with the engine in open-loop control mode. BMEP was also kept constant as air/fuel ratio was increased.

Table 2. Operating conditions for the microplasma reformer.

	at MIT (GC)	at ORNL (Horiba)
Power, W		270
Fuel flow rate, g/s		0.25
Composition of reformate		
CO	20%	18-21%
CO2	3.5%	4%
CH4	0.5%	
C2H4+C2H6	0.2%	
H2	16%	
N2	60%	
HC (ppm)		260-410

Reformate was introduced into the engine via the intake manifold downstream of the throttle. The overall hydrogen addition was relatively small, being about 4% of fuel heating value at the 2300 rpm condition and about 9% at the 1500 rpm condition. The maximum reformate flow rate was determined by heat removal limitations of the plasmatron reactor. Bench top tests are being conducted in the laboratory to remove this limitation.

RESULTS AND DISCUSSION

Figures 7 and 8 show the Coefficient of Variation of the gross Indicated Mean Effective Pressure (COV of IMEP) as a function of equivalence ratio for the two operating conditions. Both cases of baseline operation (without reformate addition) and the case with reformate addition are shown in the figures. The equivalence ratio in these figures has been determined from the exhaust gas composition. The presence of hydrogen in the engine substantially reduces the COV of IMEP, even at the 2300 rpm condition, when the reformate addition is a small fraction of the total fuel.

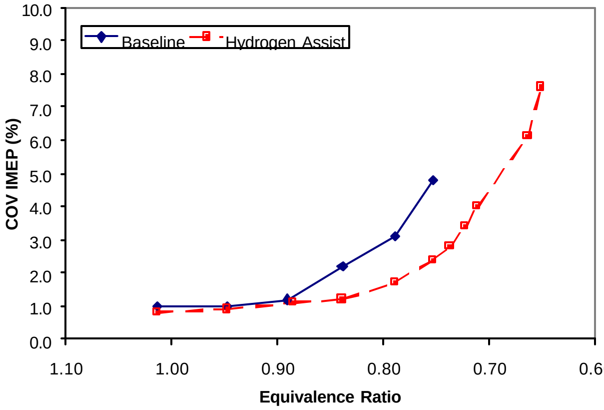

Figure 7. COV of IMEP as a function of exhaust equivalence ratio (1500 rpm, 2.6 bar BMEP).

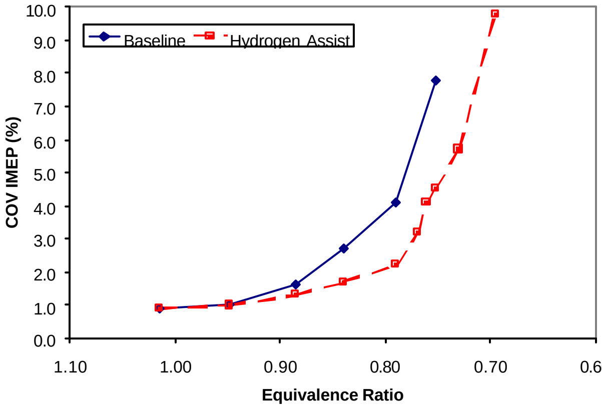

Figure 8. COV of IMEP as a function of exhaust equivalence ratio (2300 rpm, 4.2 bar BMEP).

Figures 9 and 10 show the NO_x emissions as a function of the COV of IMEP. The plots illustrate the reduction of NO_x emissions within acceptable levels of cycle-to-cycle combustion variations (3 to 5% COV of IMEP). The NO_x concentration decreases with the reformate addition for a given COV of IMEP, even with relatively small reformate addition. At a COV of 5%, NO_x is reduced by a factor of about a hundred relative to the stoichiometric baseline (with no EGR) by the addition of plasma boosted reformer generated hydrogen at 1500 rpm engine operation. The baseline case does not include effects of operating with EGR without hydrogen. For a stoichiometric baseline with EGR, the difference in NOx emissions would be a factor of 50. Higher reformate addition may be necessary, especially for the higher load cases. The plasma boosted reformer is presently being modified to provide increased hydrogen generation.

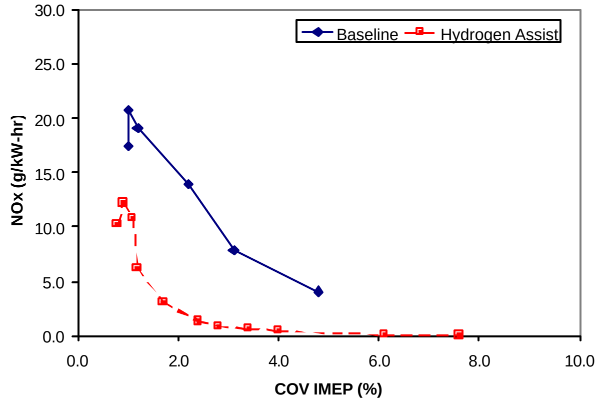

Figure 9. NOx emissions as a function of the COV of IMEP (1500 rpm, 2.6 bar BMEP).

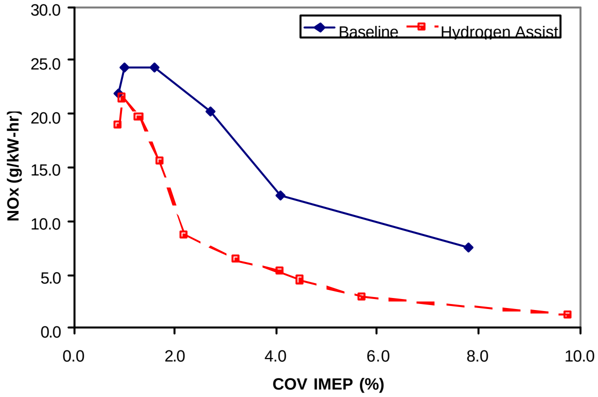

Figure 10. NOx emissions as a function of the COV of IMEP (2300 rpm, 4.2 bar BMEP).

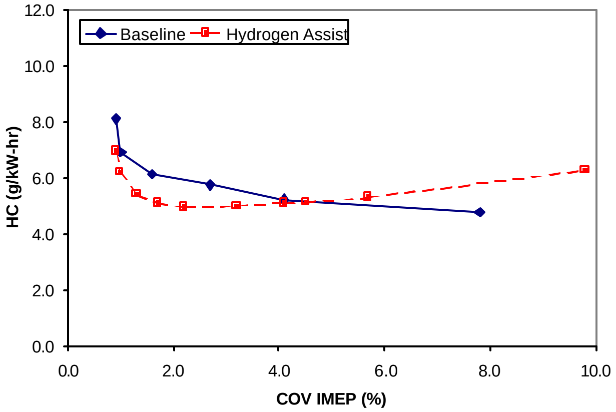

Figure 12. Hydrocarbon emissions as a function of the COV of IMEP (2300 rpm, 4.2 bar BMEP).

The corresponding concentration of hydrocarbons is shown in Figures 11 and 12, for the 1500 and 2300 rpm operating conditions, respectively. Decreases in HC emissions of about 20-30% are possible. Larger effects could be possible with the additional of increased amounts of hydrogen rich gas.

Particulate mass emissions as measured by the TEOM showed very low values for both the baseline and reformate addition cases. Figure 13 shows the relative mass emissions decrease from the baseline stoichiometric case. Although the TEOM was approaching its lower sensitivity limits, the trend is still clear; decreasing equivalence ratio leads to lower PM mass emissions. In addition to PM mass, PM size distribution was measured. Figure 14 shows that there appears to be an *increase* in particle number with decreasing equivalence ratio. Although this seems to contradict the PM mass emissions decrease, the proportion of larger diameter (and heavier) particles decreases with decreasing equivalence ratio.

DISCUSSION

The addition of reformate stabilized lean operation resulting in lower NO_x emissions. Similar results should be obtainable with reformate addition at high EGR levels. Actually, the exhaust gas has a larger heat capacity than air (due to the higher concentration of tri-atom molecules in the exhaust gas), and therefore NO_x reduction with EGR should be larger than with air [1]. Tests are being planned to investigate the effects of EGR with reformate addition.

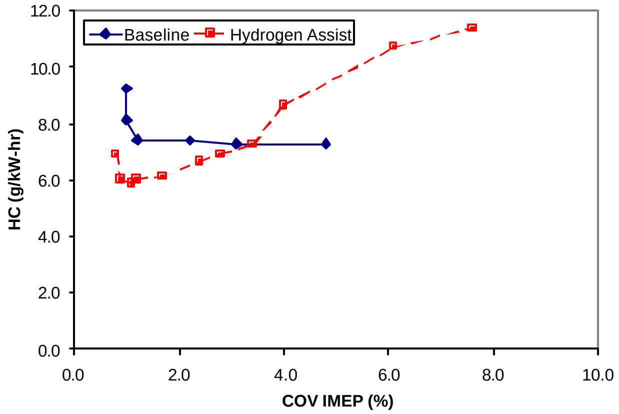

Figure 11. Hydrocarbon emissions as a function of the COV of IMEP (1500 rpm, 2.6 bar BMEP).

In a similar fashion to other reformer concepts such as those used for reforming ethanol [12,13], the plasma boosted reformer is also ideally suited for cold-start operation, due to the fast turn on time of the plasma. Even in the absence of air/fuel preheat in the plasmatron system, the overall efficiency of the system should be comparable to that in present engines. The time of operation without preheat and with a high fraction of fuel to the plasmatron is limited to the cold start and is thus very small. During cold start a high fraction of the fuel would be converted into hydrogen-rich gas. As soon as the catalyst is warmed up, the fraction of processed fuel would be decreased.

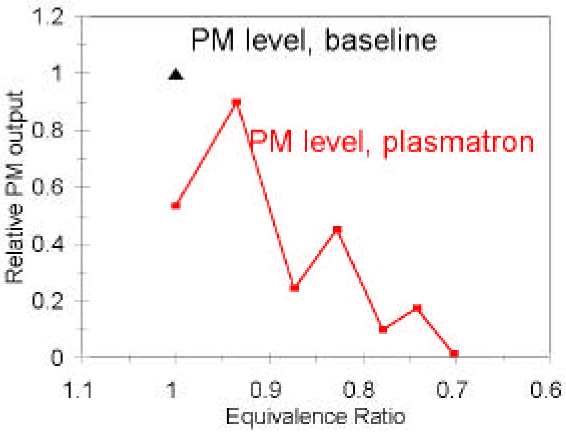

Figure 13. Relative PM emissions as a function of equivalence ratio (1500 rpm, 2.6 bar BMEP).

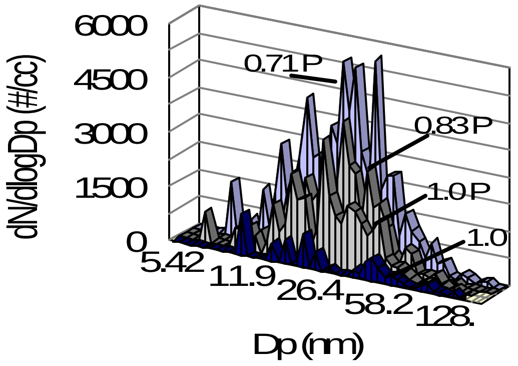

Figure 14. Particle size distribution for four different equivalence ratios (designated by labels) at 1500 rpm, 2.6 bar BMEP. P designates microplasmatron assist. Note the overall numbers are very low.

FUTURE IMPROVEMENTS

There are several approaches for improving the performance of the plasma fuel converter. Heat recovery has been mentioned, and should result in decreased energy consumption and increased conversion of the fuel. Heat regeneration tests are underway in the bench-top system.

In addition, it is possible to improve the performance by use of improved plasma source. Recently, tests using a low current plasma device have resulted in greatly decreased energy consumption (by a factor of 5), with comparable hydrogen yields. The new device also substantially increases electrode lifetime and significantly simplifies the required power supply. The configuration is still being characterized, and will be described after it is more thoroughly investigated

CONCLUSION

Onboard generation of hydrogen-rich gas using a plasma boosted microreformer could provide important new opportunities for significantly reduced emissions. A compact plasma boosted reformer was successfully integrated with a gasoline engine on an engine test stand. SI engine experiments were carried out to determine the effect of reformate addition on emission and efficiency. A NO_x emissions reduction of approximately two orders of magnitude was obtained under certain conditions. The plasma boosted microreformer operated reliably for the relatively long duration of the experiments (>6 hours per day), operating on gasoline. Additional effort is required to decrease the electromagnetic noise, as well as to better integrate the microplasmatron fuel converter with the engine. The rapid response, as well as the robustness to fuel characteristics and ambient temperature, make the plasma boosted microreformer suitable as a fuel converter for a variety of onboard applications.

ACKNOWLEDGMENTS

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