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**HOMOGENEOUS CHARGE COMPRESSION IGNITION  
CONTROL BY THE USE OF  
PLASMATRON FUEL CONVERTER TECHNOLOGY**

L. Bromberg and A. Rabinovich

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Plasma Science and Fusion Center  
Massachusetts Institute of Technology  
Cambridge, MA 02139

and

Hydrogen Microplasmatron Technologies  
Sharon MA 02067

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### **Abstract**

Homogeneous Charge Ignition Compression (HCCI) operation has emissions and efficiency advantages over both spark ignition and compression ignition operation. The main difficulty with HCCI is control of timing. The possible uses of plasmatron fuel converters for controlling HCCI engines are described.

## **I. Introduction**

It has been well established that operation in homogeneous, lean mode results in large decrease of NO<sub>x</sub> and particulate matter emissions. Fundamentally, the reason is the avoidance of regions with either fuel rich regions that generate particulate matter, or stoichiometric conditions that generate high temperature and NO<sub>x</sub> emissions.

The control of this type of discharge has been explored. Successful operation has been obtained, for some operating regions, by the use of late injection into the cylinder, with long ignition times (longer than the times required for fuel injection and for the establishment of a relatively homogeneous charge). Control through stratification of the temperature or fuel charge has been proposed, either by the use of EGR, or by using a heat exchanger to preheat the incoming air using hot exhaust gases. The problem with this approach is that the ignition timing is a strong function of the temperature of the incoming air, as sensitive as 1 crank-angle degree per 4 C difference in the charge air temperature. Very precise control of the temperature is therefore required. In addition, for transportation applications, a very fast response is required, especially at conditions of high power characteristics of merging and passing.

Other methods of control involve variable valve timing (VVT) or variable compression ratio (VCR), both methods require sophisticated engine actuators.

In addition, it has been found that the self ignition is a strong function of the fuel octane rating. Experiments of HCCI using fuels with several values of RON (Research octane number) have been carried out, and it has been found that fuels with lower RON (i.e., more prone to self ignition) have a rather broad operational regime, as opposed to those with a high octane value.

Additives, to either promote oxidation (ozone) or to ignite the fuel (by variation of the the octane rating of the fuel) have also been proposed. The onboard generation of ozone requires substantial electrical power. The variation of the fuel octane rating requires two or more fuels on board, with the inconvenience of carrying and refueling two or more tanks. Mixtures of methane and DME for octane number variation have been explored.

Surrogate reformat has been used in a compression ignition engine. It was found, as expected, that hydrogen and CO fuel does not fundamentally change the operating parameters of the combustion, and therefore can not be used directly for the control of the ignition. This is understandable, since the self ignition temperature (autoignition) of hydrogen requires very high temperature and compression ratios.

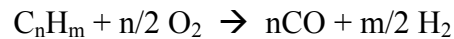
In this writeup, two possible methods of control of HCCI combustion by the use of plasmatron fuel converter methods are described.

## II. Hydrogen Production from Compact Plasmatron Fuel Converter

Plasmatron fuel converters provide electrical discharges in flowing gases of hydrocarbon fuels and air (and/or other oxidants). The resulting generation of reactive species in the flowing gases along with increased mixing accelerates reformation of hydrocarbon fuels into hydrogen rich gas. Plasmatron fuel converters may also be utilized for increasing enthalpy, further accelerating the reaction rates. These conditions facilitate the reforming of a wide range of hydrocarbon fuels into hydrogen-rich gas.

By increasing the reaction rates, plasmatron fuel converters can reduce size requirements for effective reforming, increase speed of response and increase fuel flexibility. A wide range of fuels can be converted to hydrogen rich gas. The boost provided by the plasma can facilitate partial oxidation reactions with negligible soot production and efficient conversion of hydrocarbon fuel into hydrogen-rich gas. Plasmatron fuel converters can alleviate problems associated with catalytic reformation, such as response time limitations, sensitivity to fuel composition, poisoning, soot formation and a narrow operational temperature range.

Under ideal stoichiometric partial oxidation conditions, the partial oxidation reaction is



In this case there is just enough oxygen around to convert all the carbon in the fuel into CO. The partial oxidation reaction is exothermic. In the case of liquids fuels (gasoline, diesel), approximately 15% of the heating value of the fuel is released in the partial oxidation reaction.

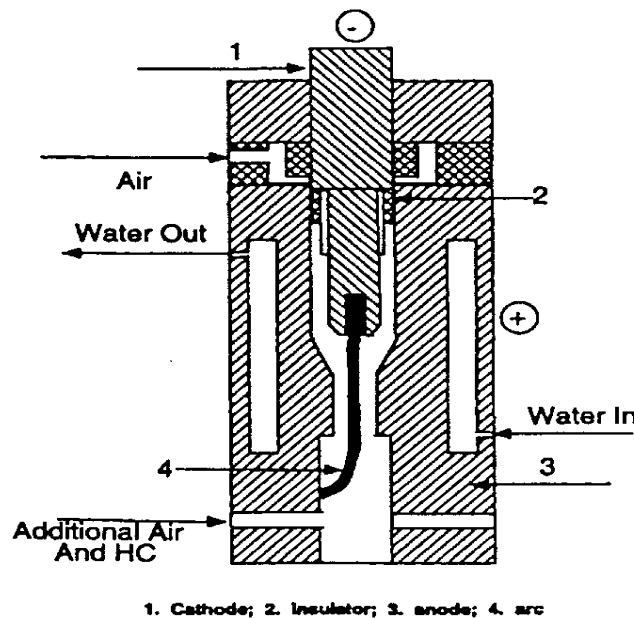


Figure 1. Thermal plasmatron fuel converter

The plasmatron fuel converter provides continuous ignition at the entrance of the fuel, and helps in the gasification of the fuel. By generating radicals throughout the volume, limitations due to slow flame propagation are alleviated, ensuring that the reaction occurs over the whole reactor volume, increasing conversion efficiency and reducing soot formation.

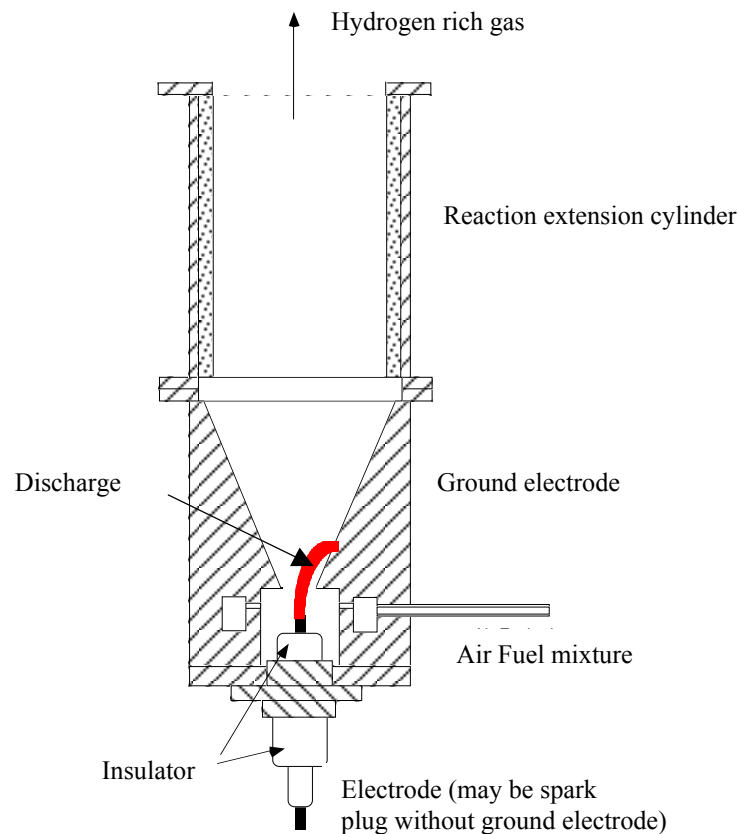


Figure 2. A low current plasmatron fuel converter.

Two types of plasmatron fuel converters have been developed at MIT. One type is based on DC arc technology. These plasmatrons operate at thermal equilibrium (where the electron, ion and neutral temperatures are comparable). The temperature is high (several thousand degrees), requiring substantial electrical heating to maintain the plasma at near atmospheric pressure. This heating facilitates startup of partial oxidation operation at the stoichiometric oxygen to fuel ratio without the need of any additional heat provided by release of chemical energy. These compact thermal plasmas devices operate at relatively low voltages and high currents (e.g. 100 V, >20 A and an electrical power level of 2 kW). The local heating at the electrodes is high, and electrode erosion is minimized by

aggressive water cooling and strong rotation of the anode root. The high power densities at the anode and cathode arc roots reduces the electrode life. Obtaining electrode life greater than 1000 hours appears to be difficult and will require new design approaches. Figure 1 shows a thermal plasmatron fuel converter.

The second type of plasmatron employs a discharge mode with non-equilibrium features allowing operation at much reduced plasma current relative to earlier compact arc plasmatron fuel reformers developed at MIT. The discharge is a nonthermal plasma, with electrons at much higher temperature than the ions and neutrals, which are at near room temperature. This plasma generates relatively low levels of plasma heating. Figure 2 shows a diagram of a low current plasmatron reformer. Air and fuel are continuously injected in a plasma region provided by a discharge established across an electrode gap. The device operates at atmospheric pressure, with air as the plasma forming gas. When operating DC, the cathode can be a heavy duty spark plug. The ground electrode of the spark plug would have been removed. The anode can be a steel or copper cylinder. Neither electrode is water cooled.

Table I shows the parameters of a first generation fuel converter using a low current compact plasmatron. Typical electrical power levels are a few hundred Watts, on the order of 1-2% of the heating value power of the fuel that is processed by the plasmatron fuel converter. This electrical power loss results in a drain of 3 to 5% of the chemical power of the fuel in order to produce the electricity. Most of the heating is provided by the exothermicity of the partial oxidation reaction. The partial oxidation heating can be increased by operating with increased oxygen to carbon ratio (i.e., combusting a fraction of the reformat). This additional heating is specially important during start-up phase of the fuel converter. However, this additional heating decreases the hydrogen yield.

The plasma source is followed by a reaction extension cylinder. For tests with the addition of water, a simple heat exchanger was added downstream from the reaction extension cylinder, both to cool the reformat and to produce steam.

Table 1.  
Parameters of low current compact plasmatron fuel converter

Power	50-300 W
Current	15-120 mA
H <sub>2</sub> flow rate	30-50 liters/min
Height	25 cm
Volume	2 liters
Weight	3 kg

Second generation low current plasmatron fuel converters have recently been tested. In these compact devices both the cathode and the anode have relatively large area, in contrast to the first generation device shown in Figure 2. They produce a discharge over a large volume and have been operated at higher powers than the first generation low current plasmatrons.

This low current device has been used to convert natural gas, gasoline and diesel fuel into hydrogen rich gas. The device showed minimal evidence of soot, even after extended operation. Typical power conversion efficiencies in the partial oxidation mode were 60-85% (ratio of heating value of the product gas to heating value of the fuel). Diesel fuel streams with chemical power levels of 5 to 20 kW have been processed into hydrogen rich gas.

Table 2 shows reforming results for several cases, using the second generation plasmatron fuel converters, at steady state conditions (after about 1 to 2 minutes). Several types of reaction extension cylinders were used with either no catalyst or a catalyst in the reaction extension cylinder. The effect of the presence of water was also studied. The purpose of the water addition is to convert, via a water-shift reaction, a large fraction of the CO generated in the plasmatron fuel converter into additional hydrogen, for those applications where hydrogen is much more preferred than CO. High hydrogen yields higher than 100% (hydrogen in product gas divided by hydrogen in fuel) can be achieved with the use of a catalyst and water shifting. Power conversion efficiencies of close to 90% have also been obtained under certain conditions. However, it is difficult to obtain water onboard vehicles, and this will be a major deterrent to the use of the water shift reaction for onboard applications for internal combustion engines.

Typical second generation low current plasmatron fuel converter parameters are a power level of 300W to 600W, and oxygen/carbon ratio (O/C) of 1.2-1.5, and fuel rate of 0.3-0.5 g/s (corresponding to about 10-20 kW of fuel power).

The composition of the hydrogen rich gas for the cases in Table 2 are shown in Table 3. High concentrations of hydrogen and CO are obtained. It appears to be possible to operate the low current plasmatron fuel converter in modes with minimal production of soot.

Table 2.

Performance of second generation low current plasmatron fuel converter using diesel fuel

	Electrical Power input kW	O/C ratio	H <sub>2</sub> O/C	Fuel Flow rate g/s	Fuel Power kW	Hydrogen yield	Energy Consumption MJ/kg	Power Conversion Efficiency %
Empty reactor no water	0.27	1.32	0	0.26	11	0.64	13	56
Ceramic catalyst no water	0.19	1.51	0	0.48	20	0.75	4	64
Honeycomb catalyst no water	0.23	1.21	0	0.34	14	0.91	6	74
Honeycomb catalyst with water	0.15	1.24	1.78	0.31	13	1.22	3	87

Cases for different catalyst, O/C ratio and presence/absence of additional water.

Table 3.  
Gas composition for cases in Table 2.

	H2 vol.%	CO vol.%	CO2 vol.%	N2 vol.%	CH4 vol.%	C2H4 vol.%
Empty reactor no water	14	16	4.7	64	0.7	0.1
Ceramic catalyst no water	14	17	4.7	64	0.2	0
Honeycomb catalyst no water	19	21	3.3	57	0.3	0
Honeycomb catalyst with water	23	17	6.2	52	1.2	0.4

Previously, diesel fuel has been successfully reformed at  $O/C \sim 1$  using a compact plasmatron reformer that employs a DC arc plasmas [Bromberg2]. However, arc plasmatron reforming utilizes substantially higher electrical powers and currents.

Even when operating at stoichiometric partial oxidation ( $O/C \sim 1$ ), the reaction is exothermic. For the case of liquid fuels, with a composition nearly of  $C_nH_{1.9n}$ , the reaction releases about 15% of the heating value of the fuel. The temperature of the reformat, assuming near adiabatic conditions, is on the order of 1000K. As in the case of the nonthermal plasmatron, with  $O/C > 1$ , the adiabatic temperature is even higher.

### a) Oxidative conversion of diesel by air with a thermal plasma

The combination of partial oxidation reactions with pyrolysis reactions may also produce a product gas with a high heating value.

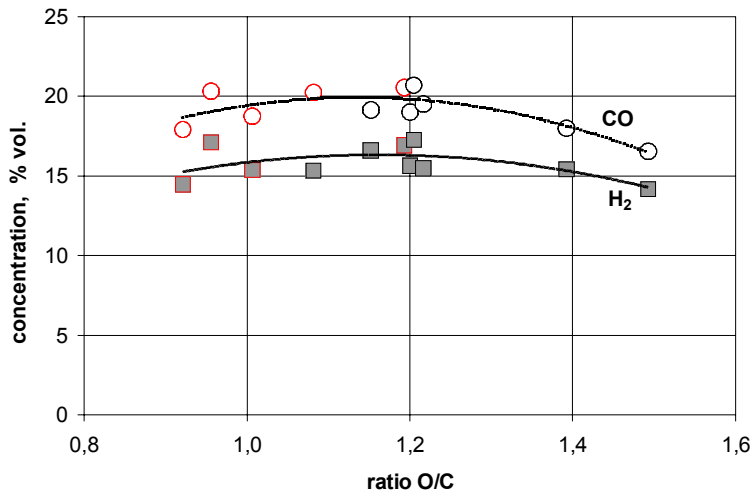


Figure 3. The concentration of  $H_2$  and  $CO$  in the reaction products as a function of the ratio  $O/C$



Typically it is found that the maximum concentration of  $H_2$  was produced at an O/C ratio that was in the neighborhood of 1.2, as shown in Figure 3. Oxidative diesel conversion by air is accompanied by ethylene formation if the O/C ratio drops below 1.2. The concentration of methane is approximately three times lower the concentration of ethylene. This is shown in Figure 4.

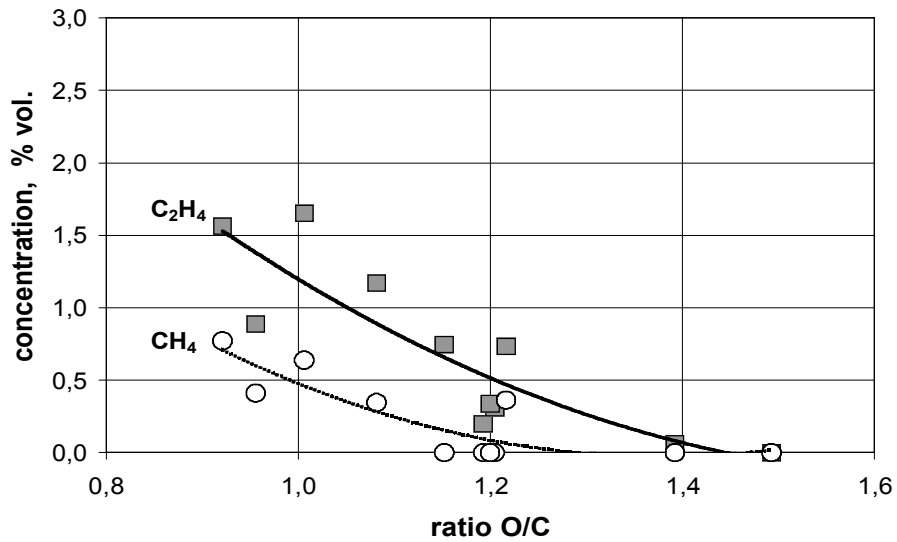


Figure 4. The concentration of  $C_2H_4$  and  $CH_4$  in the reaction products as a function of the ratio O/C.

The reaction products heating value increases with decreasing value of the ratio O/C. The maximum value of heating efficiency is around 85 % even though there is considerable  $C_2H_4$  formation at an O/C ratio of 0.92. This is shown in Figure 5. At the lower O/C ratios higher heating value efficiency are achieved but there may be a serious problem with free carbon formation when the O/C ratio is less than 1.2-1.3.

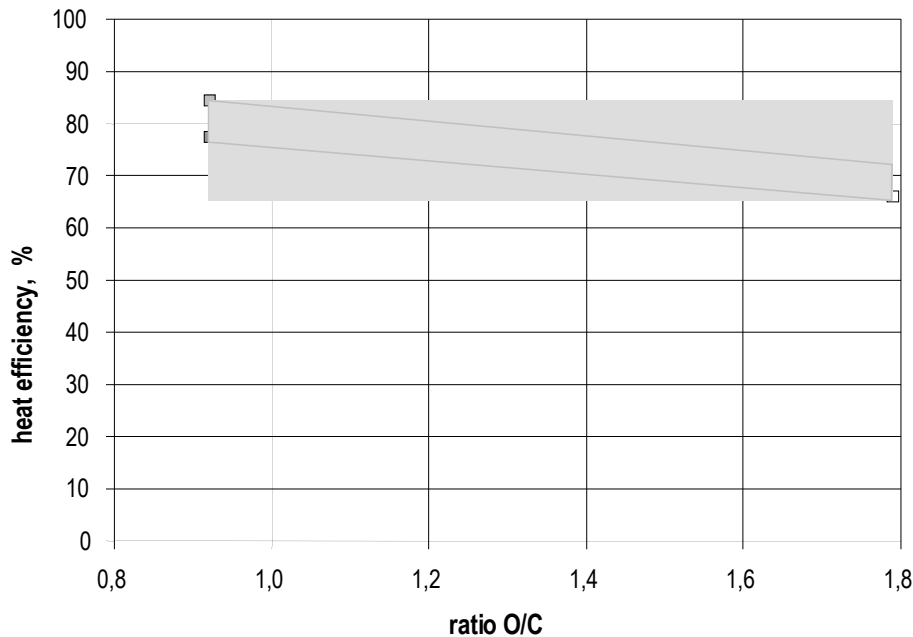


Figure 5. Heating efficiency of the reaction products as a function of the O/C ratio.

A decrease in the ratio  $2O_2/mC_mH_n$  leads to the formation of light hydrocarbons with a low ignition point. The presence of these compounds in the product gas can produce pre-ignition and knocking during engine operation.

### III. Plasmatron aided HCCI operation

It has been previously suggested that hydrogen rich gas could be an ideal fuel for the cold start phase of an engine that when warm operates in HCCI mode. During the cold start the engine could operate as a spark ignition engine, with the low emissions characteristics of engine operating in lean mode.

In this paper, the characteristics of the plasmatron for HCCI applications are discussed. Two of the features of the plasmatron fuel converter features could be useful for control in HCCI combustion are:

1. the exothermicity of the reaction can be used for heating the incoming air with fast response (since the heat is deposited directly in the gas, avoiding heat transfer through metallic or ceramic walls in the heat exchanger, with a resulting time delay.)
2. the octane value of the fuel can be controlled by either use of hydrogen and CO as a fuel additive, or by the production of C<sub>2</sub> compounds, mainly ethylene when operating the thermal plasmatron fuel converter at low O/C ratios.

### a) Temperature control

As described above in the prior art section, the partial oxidation reforming is exothermic, releasing a small fraction of the heating value of the fuel (around 15%). This heat can be used for controlling the temperature of the gaseous charge that is injected in the engine. The temperature is one of a small number of knobs that can be used for controlling the ignition timing in HCCI.

The temperature excursion of the gas into the cylinder depends on the amount of air that is mixed with the reformat. The composition of the air/reformat fuel ratio can be described using the equivalence ratio of this mixture. The equivalence ratio of the air/reformat fuel mixture is defined as the ratio between the reformat fuel/air mixture to that for stoichiometric combustion of the reformat fuel/air mixture. Assuming that 15% of the heating value of the fuel is released, for a fuel of composition near  $C_nH_{2n}$ , Figure 6 shows the temperature excursion of the air/reformat mixture as a function of the equivalence ratio.

During the engine cold start, when the conventional methods of establishing the charge temperature do not work (*i.e.*, EGR or a heat exchanger driven by the exhaust gas), the plasmatron fuel converter can be used to instantaneously increase the charge temperature to the levels required. When the conventional methods are used to increase the temperature of the gas in the cylinder, very low levels of plasmatron fuel reformation could be used to select rather precisely the charge temperature, with a device with fast response..

To increase the charge temperature to the temperatures that are desirable, above 100C, the equivalence ratio of the gaseous mixture should be around 0.1. Since the engine could run at equivalence ratios around 0.5-0.6 to minimize emissions, the maximum required fuel to be processed by the plasmatron fuel converter for startup is on the order of 20% of maximum load. The minimum torque of the engine during startup, when operating the fuel converter for maximum hydrogen yield, is around 20% of maximum torque. At lower loads, the charge temperature would be lower than required for HCCI operation. To operate the engine at lower powers, it would be required to operate the plasmatron in a mode with higher O/C ratios, therefore combusting a fraction of the fuel. Operating the plasmatron in this mode has the advantages of both decreasing the heating value of the reformat fuel (therefore decreasing the engine load) and increasing the enthalpy of the reformat, thus increasing the temperature of the air/reformat fuel mixture.

On the other hand, during the warm phase operation, relatively small values of fuel need to be processed to control the temperature. Assuming that a temperature excursion of 5 K is desirable, then the equivalence ratio of the charge is on the order of .01. If the engine operates at a equivalence ratio of 0.6 (assuming that the engine can be operated at high load in the HCCI mode), then about 2% of the fuel needs to be processed by the plasmatron fuel converter.

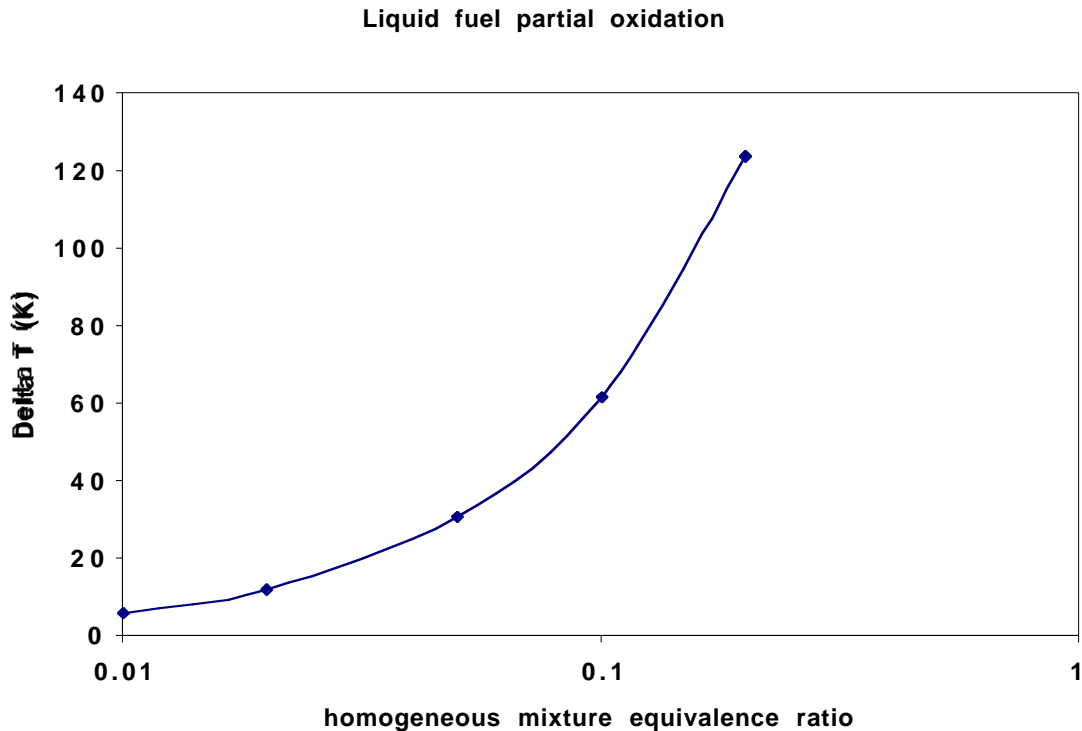


Figure 6. Temperature excursion of the gaseous charge to the cylinder as a function of the equivalence ratio of the air/reformate fuel mixture.

*b) Octane control*

In addition to helping control the temperature in the charge, the plasmatron can be used to generate fuels of different octane value. When operating at  $O/C > 1.2$ , the reformate has a composition similar to synthesis gas, with about 20mol%  $H_2$  and  $CO$ , and small concentration of  $CO_2$ ,  $C_2$ s, water, and the balance nitrogen. The synthesis gas can be used to increase the octane value of the fuel (since hydrogen has a very high octane value, while  $CO$  is similar to that of methane), but requires its use not as an additive but as a substantial fraction of the fuel.

When the  $O/C$  is smaller than 1.2-1.3, it is possible to generate substantial concentration of  $C_2$  compounds, which have very low octane number. In this case, the reformate composition may include an ethylene concentration that can be as high as a few percent. Since the concentration of hydrogen and  $CO$  is on the order of 20%, but since the heating value of ethylene is about 4 times that of the reformate, then

Under ideal circumstances, the process can be written as:



In practice, the process is somewhat less efficient, but for the process of illustration the above is adequate.

The concentration of hydrogen and CO in the reformat, as a function of the concentration of ethane in the reformat, are shown in Figure 7. Since a fraction of the fuel is pyrolyzed into ethylene, the required oxygen, and therefore nitrogen, are reduced. The reduction in the nitrogen concentration is the main reason why the hydrogen and CO concentrations remain relatively constant. This is also demonstrated in the experiments, in Figure 3 above.

Also shown in Figure 7 is the ratio of the heating value of the ethane in the reformat compared to that of hydrogen and CO. Ethane has about 4 times the heating value per mol than does hydrogen or CO.

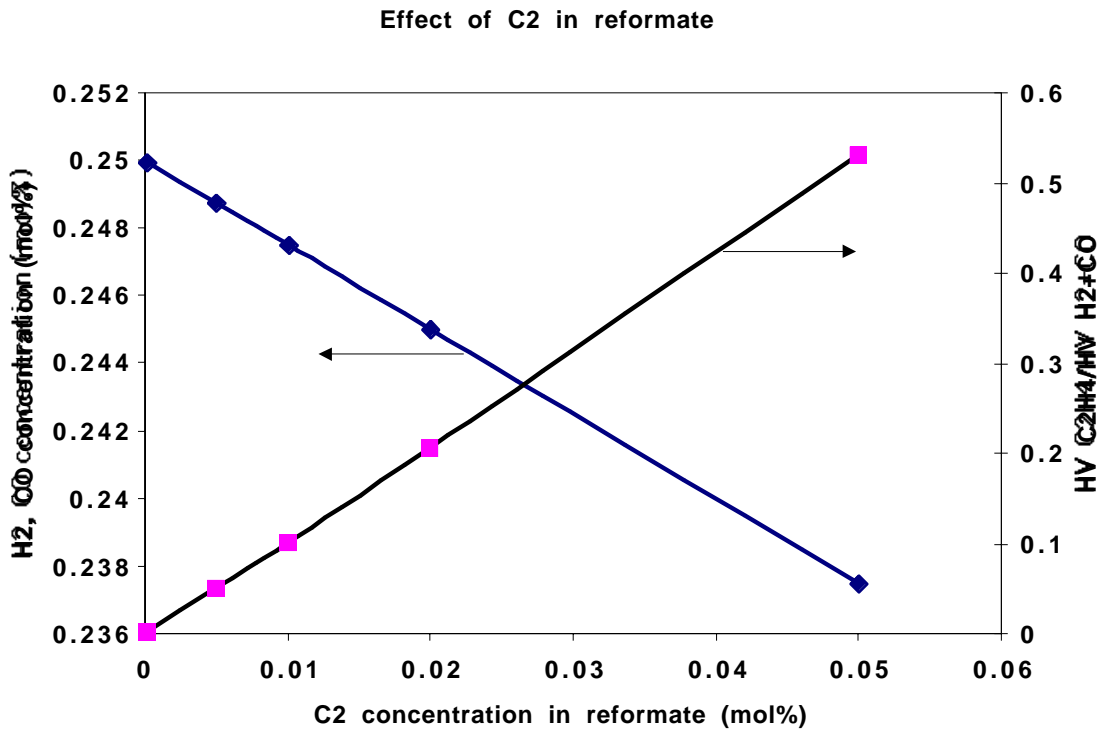


Figure 7. Concentration of hydrogen and CO, as a function of the C2 concentration in the reformat. Also ratio of the heating value of the ethane to that of hydrogen and CO combined.

The reformat can be introduced into the engine to control the ignition timing. Figure 8 shows the fraction of that needs to go through the reformer as a function of the reformat equivalence ratio, as defined above (ratio between the air to engine /fuel reformat to the air/fuel reformat for full combustion of the reformat). There is additional fuel injected into the engine, since the reformat is mainly an additive. It is assumed that the overall equivalence ration in the cylinder (fuel+reformat fuel) is 0.7.

In order to process only about 10% of the fuel, the reformat equivalence ratio is about 0.05 (i.e., about 20 times more air than required for full combustion of the air). The ethane concentration in the cylinder is also shown. For 10% of the fuel to the reformat,

the ethane concentration is about 0.1%. It is not known the ethanes concentration required to control the ignition timing.

The fuel octane rating can therefore be changed via the addition of reformat from a plasmatron fuel converter. The higher the ethylene concentration in the cylinder, the lower the octane number (i.e., the more prone to self ignition).

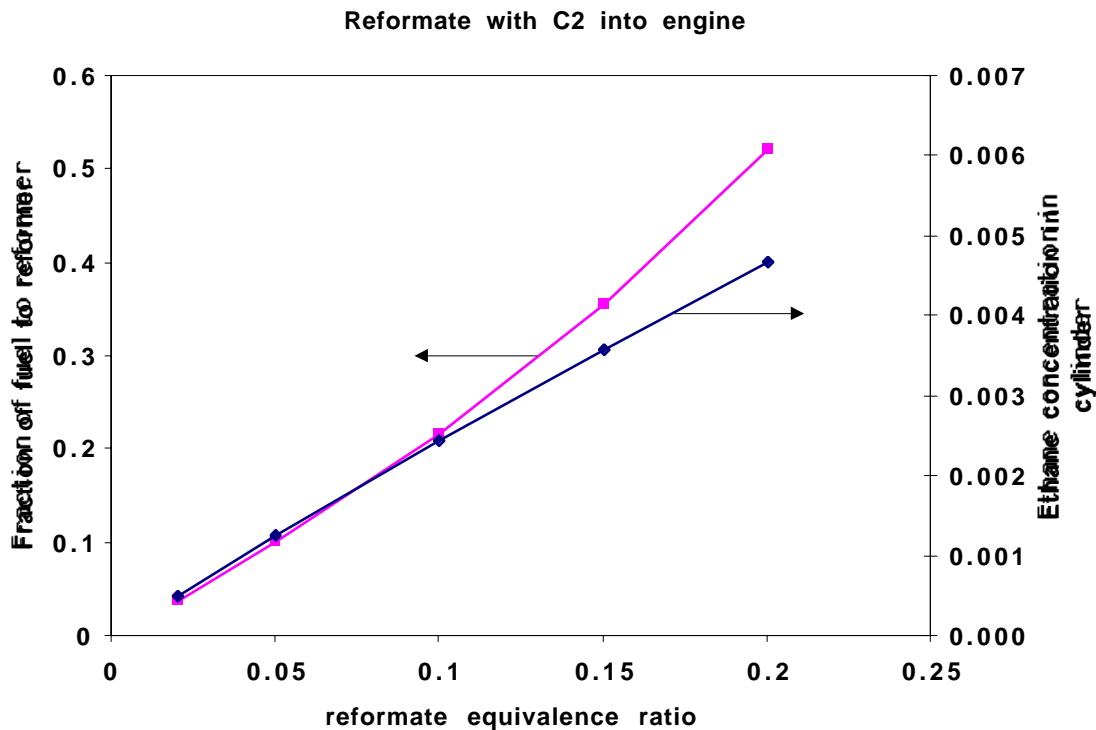


Figure 8. Fraction of the fuel that goes through the reformer as a function of the reformat equivalence ratio. Also shown is the ethane concentration in the cylinder.

The rate of heat release in the engine, needed to avoid knock, can be controlled by the establishment of substantial temperature gradients in the air, as suggested by Noda. In that work it was envisioned that EGR would aid in the generation of the temperature gradients. The use of the reformat can aid in the generation of temperature gradients by not-ideal premixing of the air and the plasmatron reformat.

Although hydrogen has a very high temperature for self-ignition, the presence of hydrogen in the combustion chamber may also help ignition, due to the very small energy required for ignition. Under appropriate set of conditions, the local ethylene ignites the local hydrogen that in turn ignites the local fuel, without the need of flame propagation.

Finally, the reformat non-uniformity in the charge to the cylinder can also be used to control ignition.

#### IV. Conclusion

The uses of fuel reformation, and in particular plasmatron fuel converter, to facilitate control and operation in HCCI mode have been described.

The plasmatron fuel converter can aid HCCI operation by:

- Air charge heating during cold start
- Air-charge temperature control during warm operation
- Octane control, by use of hydrogen and CO as a substantial fraction of the fuel, or use of C<sub>2</sub>H<sub>6</sub> as an additive.

It is necessary to explore these options, both through modeling and through experiments.

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