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**Onboard Plasmatron Generation
of
Hydrogen Rich Gas
for
Diesel Engine Exhaust Aftertreatment
and Other Applications**

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ABSTRACT

Diesel plasmatron reformer technology can provide substantial throughputs without the need of using a catalyst. The use of the special plasma facilitates robust non-catalytic conversion of diesel fuel into hydrogen rich gas with hydrogen yields that could be sufficient for NO_x trap regeneration applications. Higher yields can be obtained with the use of a catalyst. Plasmatron reformers could also be used for manufacturing of ethene, which could be useful as a selective reducing agent. In addition, plasmatron reformer technology can be used for converting a range of biofuels into hydrogen rich gas. These fuels include various oils. This capability may improve the prospects for use of renewable fuels in a variety of vehicular applications. This paper discussed the status of plasmatron diesel fuel reformers and possible applications to diesel engine exhaust aftertreatment.

Onboard Plasmatron Generation of Hydrogen rich Gas for Diesel Engine Exhaust Aftertreatment and Other Applications

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I. Introduction

Plasmatron reformers can provide attractive means for conversion of diesel fuel into hydrogen rich gas. The hydrogen rich gas can be used for improved NO_x trap technology and other aftertreatment applications [1].

Plasmatron reformers developed at MIT use a special low power, low current electrical discharge to boost partial oxidation conversion of hydrocarbon fuels into hydrogen and CO. This reformer technology provides the advantages of

- Rapid startup and response to transient conditions
- Efficient conversion
- Compact size
- Relaxation or elimination of reformer catalyst requirements
- Capability to process difficult to reform fuels

Diesel plasmatron reformer technology can provide substantial throughputs without the need of using a catalyst. The use of the special plasma facilitates robust non-catalytic conversion of diesel fuel into hydrogen rich gas with hydrogen yields that could be sufficient for NO_x trap regeneration applications. Higher yields can be obtained with the use of a catalyst. Plasmatron reformers could also be used for manufacturing of ethene, which could be useful as a selective reducing agent. In addition, plasmatron reformer technology can be used for converting a range of biofuels into hydrogen rich gas. These fuels include various oils. This capability may improve the prospects for use of renewable fuels in a variety of vehicular applications. This paper discussed the status of plasmatron diesel fuel reformers and possible applications to diesel engine exhaust aftertreatment.

II. Reformation

Plasmatron fuel converters operate through the generation of a continuous discharge where fuel enters the reformer. This discharge provides large volume reaction initiation of the reforming reaction. The discharge generates numerous localized regions of intense heating (even though the resulting spatially averaged temperature increase can be quite modest), as well as large number of radicals that promote the reaction. The discharge and the subsequent exothermic reactions generate enough energy for the gasification of the remaining liquid fuel.

The plasma induced turbulence also improves the mixing of the air/fuel mixture, as well as mixing of those regions where partial oxidation has started with those regions where conversion has yet to begin. Thus, reactions occur over essentially the entire reformer volume facilitating high conversion efficiency, in a device with small volume. Rapid heating of the fuel and good air/fuel mixing are also helpful in the minimization of soot production.

In some circumstances, the plasma energy can be used to provide additional enthalpy increase of the air/fuel mixture. This capability can be utilized to meet demanding requirements, such as rapid startup and quick transient performance.

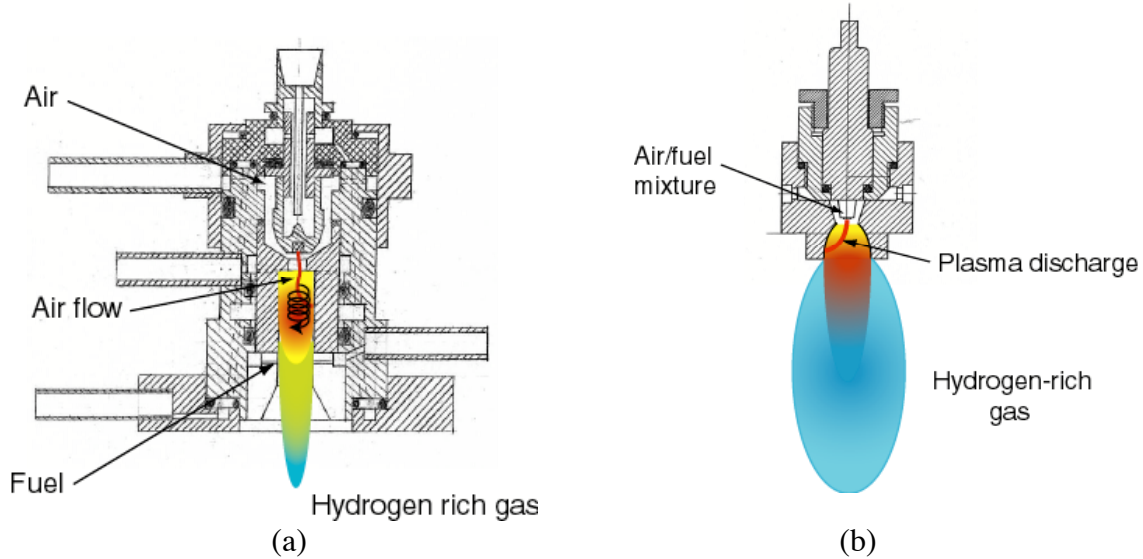


Figure 1 Schematic diagrams of plasmatron fuel converters developed at MIT. (a) Thermal plasmatron (High current, high power, water cooled electrodes, circa 1999); (b) Low current plasmatron (Low current, low power, long electrode lifetime Circa 2001)

Present plasmatron development at MIT involves low current plasmatron reformers. Typical parameters of operation for a low current plasmatron reformer are given in Table 1. The electrical power can be varied, and the device has been operated at powers from 50 W to > 800 W. We have used this type of device to generate a reformat with an equivalent heating value power of 10-40 kW, from diesel and other heavy hydrocarbons. The power supply is current controlled, and the plasma current entry in Table 1 refers to the average value after breakdown.

Table 1.
Low current plasmatron operating parameters.

| | | |
|----------------|-----------------|---------|
| Power | W | 300-600 |
| Plasma Current | A | .1-.4 |
| H2 flow rate | slpm | 40 |
| Length | cm | 40 |
| Volume | cm ³ | 2000 |
| Weight | kg | 3 |

III. Diesel fuel reforming

Characteristics of thermal and low current diesel fuel plasmatron reformers are shown in Table 2. The thermal plasmatron operates at ~100V, 15A DC using an arc plasma, while the low current plasmatron reformer operates at 500-1000V, 0.2-0.8 A AC.

Table 2
Diesel Plasmatron Reformer Parameters

| | | Thermal plasmatron 1999 | Low current plasmatron 2001 |
|-----------------------------|-----|-------------------------------|-----------------------------------|
| Electrical power | W | >1500 | 100-800 |
| O/C ratio | | ~1 | 1.2-1.4 |
| Fuel flow rate | g/s | 0.6 | 0.4 |
| Hydrogen yield | | 0.9 | .5-.9 |
| Power conversion efficiency | | 0.9 | 0.85 |
| Reformate temperature | K | 1200 | 1000-1300 |

The reformate composition for homogeneous (nuncatalytic) and catalytic reforming (where the fuel first passes through the discharge which precedes a catalyst) for the low current plasmatron is shown in shown in Table 3. The ratio of oxygen to carbon atoms in the air/fuel mixture is 1.2-1.4. The thermal plasmatron was operated without a catalyst.

Table 3
Reformate parameters for low current plasmatron

| | Homogeneous | Catalytic |
|-------------------------------|-------------|-----------|
| Concentration (vol %) | | |
| H2 | 8% | 18% |
| CO | 15% | 22% |
| C2's | 3% | 0.6% |
| Conversion | | |
| H2 in fuel to Hw in reformate | 50% | 80% |
| C in fuel to C2's | 25% | 5% |
| Energy conversion efficiency | 75% | 70% |
| Reformate temperature (K) | 1000 | 850 |

IV. Biofuels reforming

As is the case with diesel fuel, bio-oils are difficult to properly reform because of their propensity to generate soot in the partial oxidation process.

Plasmatron reformer conversion of a number of biofuels has been investigated. Corn oil, canola oil and soy oils have been studied. Ethanol has also been reformed.

Table 4 shows results of tests using a thermal plasmatron fuel converter. These tests are being extended to include use of a low current plasmatron reformer.

Table 4
Plasmatron fuel converter reforming of biofuels
Thermal plasmatron

| | CANOLA | CORN OIL |
|---------------------------------------|--------|----------|
| Fuel flow rate (g/s) | 0.3 | 0.47 |
| Hydrogen concentration (% vol) | 25.6 | 23 |
| Methane concentration (% vol) | 1.7 | 7.6 |
| Carbon Monoxide concentration (% vol) | 26 | 18.6 |
| Carbon Dioxide concentration (% vol) | 0.3 | 2.1 |
| Hydrogen yield | 92% | 84% |

V. Diesel aftertreatment exhaust applications

Potential diesel exhaust aftertreatment applications using plasmatron generation of hydrogen rich gas include:

- NO_x absorber catalyst regeneration
 - NO_x regeneration
 - Sulfur regeneration
- Hydrocarbon regeneration of SCR catalyst
- Onboard ammonia manufacturing

These potential applications are briefly described below. The SCR regeneration by hydrocarbons, and the ammonia production applications are speculative at this time, but merit further study.

a) NO_x Absorber Catalyst Regeneration using Diesel plasmatron reformer

The regeneration process of the NO_x absorber trap uses a reductant. Hydrogen rich gas is a significantly stronger reducing agent than diesel, with reduced fuel penalty compared with diesel fuel. Although this is important in itself, a potentially more important advantage of using hydrogen as a reductant, instead of diesel fuel, is due to the fact that hydrogen can regenerate traps at lower catalyst temperature than possible with straight diesel fuel. This is important for trap regeneration under conditions where catalyst does not warm up sufficiently, such as urban drive cycles.

As a consequence of the use of a stronger, more efficient reductant (higher concentration of hydrogen), it should be possible to decrease the regeneration time and the fuel penalty. This could be particularly important for the case of a single leg NO_x trap configuration (only one trap, regenerated on-line). In this case decreasing the regeneration time could have an especially significant beneficial effect on the fuel penalty. In either the case of single or tandem leg configuration, plasmatron diesel fuel reformers can operate with the

engine exhaust as the source of the oxidizer. This minimizes the amount of fuel required for generating the hydrogen rich gas or the high temperatures required for regeneration.

In addition, using hot hydrogen rich gas, Parks [2] has obtained good desulfurization at lower temperatures in a net reducing atmosphere. A comparison of desulfurization performance using reformat and diesel fuel has yet to be performed.

b) Light Hydrocarbon catalyst regeneration

The regeneration of certain NOx catalysts requires light hydrocarbons. The diesel plasmatron reformer, when operated in the homogeneous mode, can produce large amounts of ethylene. Unfortunately, we have not been able to create slightly heavier hydrocarbons, such as propane, which seem to be more effective in catalyst regeneration, such as in the case of nonthermal plasma aftertreatment.

Table 5 shows the results of operation a low current plasmatron reformer (with improved reactor) for optimal production of C2's. In this case, it is possible to have carbon conversion to C2's of about 30%. The measured energy conversion efficiency (heating value of the reformat divided by the heating value of the fuel) is higher than in the case of high hydrogen yields.

Table 5
Homogeneous plasmatron conversion for production of light hydrocarbons
Improved reactor configuration

| | |
|-----------------------------|------|
| Electrical power (W) | 500 |
| Reformat composition | |
| H2 | 9.5 |
| CO | 15.2 |
| CO2 | 4.1 |
| N2 | 63.5 |
| CH4 | 3.4 |
| C2H4+C2H6 | 3.1 |
| C2H2 | 0.1 |
| Yields | |
| CmHn to H2 | 44% |
| CmHn to CO | 58% |
| CmHn to C2's | 28% |
| Reformat thermal efficiency | 88% |
| Reformat power (HHV, kW) | 36 |

c) Onboard ammonia manufacturing

Diesel fuel plasmatron reformers have potential for onboard ammonia generation for SCR catalytic regeneration. Two options for manufacturing of ammonia are:

1. Ammonia production from hydrogen rich gas ($N_2, H_2 \rightarrow NH_3$)
2. Ammonia from onboard generated NO ($NO, H_2 \rightarrow NH_3$)

In both approaches, a plasmatron fuel converter might provide the hydrogen required for the ammonia manufacturing. The practicality of using these processes is uncertain. Proof of principle experiments for these options have not been performed.

A system scheme based on approach 2 is shown in Figure 2. NO, from engine exhaust, with additional NO generation from a thermal arc discharge, is converted to ammonia by reacting it with hydrogen over a catalyst. One source of system inefficiency comes from the arc requirement for increasing the NO concentration in the exhaust gas (to minimize the free oxygen). A second inefficiency comes from the hydrogen/CO required to remove the free oxygen prior to converting the NO into ammonia. However, even with these parasitic inefficiencies, system fuel penalties on the order of a few percent might be obtained under appropriate assumptions.

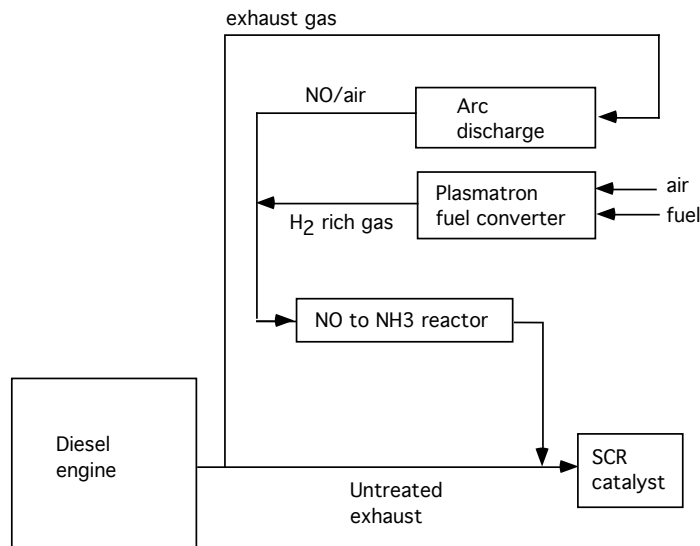


Figure 2. Onboard manufacturing of ammonia from NO and hydrogen.

VI. Conclusions

Plasmatron reformers can provide substantial advantages in converting diesel fuel and other difficult to reform fuels (e.g. bio-oils) into hydrogen rich gas.

Use of the hydrogen rich gas could significantly improve prospects for practical utilization of NOx traps, both for NOx removal from the trap, and for periodic desulphurization of the trap.

Diesel fuel plasmatron reformers might be also used to generate gases with relatively high concentrations of ethylene. This gas could be used for aftertreatment systems that utilize hydrocarbon driven SCR. Another possible application is onboard generation of ammonia. The ammonia could be used in conjunction with SCR catalysts. However, these concepts are speculative at the present time.

Progress is continuing in improving the operating characteristics of low current diesel fuel plasmatron reformers.

Acknowledgements

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