HYDROGEN REFORMATION IN A LARGE, FAST-MOVING SPARK PLUG INDUCED PLASMA DISCHARGE

September 7, 2003
Princeton University

Advisor: S. Suckewer
Tech Support: N. Tkach
Experimentalist: Bryan Chu

INTRODUCTION:

It is well known that the addition of hydrogen gas to an automobile's fuel supply increases efficiency and also reduces polluting emissions. As demonstrated by a team at MIT, the introduction of hydrocarbon fuel into a continuous plasma discharge results in the production of hydrogen rich gas by the following partial oxidation reaction:

$$2C_nH_m + nO_2 \rightarrow 2nCO + mH_2 \quad (1)$$

By using this reaction, they managed to create a wine bottle sized device with a 60-85% power conversion efficiency known as the "plasmatron." The plasmatron is usually placed in between the fuel tank and the combustion chamber.

However, with the advent of the TSI spark plug design (S. Suckewer, E. Durbin), the need for a separate plasmatron became questionable as the spark discharge characteristics of the TSI could be modified to match those of the DC arc employed in the plasmatron. The only addition required would be a fuel delivery system for the spark plug.

The production of hydrogen would not be the only advantage of this direct injection spark plug; it could also theoretically reduce electrode erosion. According to Suckewer, electrode erosion is due mainly to high-speed electron bombardment. The addition of fuel molecules will increase the local molecular density and thus decrease the mean free path (average distance between collisions for a gas molecule) defined by:

$$\ddot{e} = \frac{1}{\sqrt{2}\partial d^2 n_v} \quad (2)$$

where d is the molecular diameter and n_v is the number of molecules per unit volume. In addition, because of the high-density concentrations, mobile electrons released during the discharge will have less space to accelerate and will not impact the center electrode at such a high speed, thus reducing electrode wear.

EXPERIMENTAL SETUP:

Spark Plug:

Fuel delivery to a spark plug is a very difficult task because of the multiple sealing, heat transfer, and pressure requirements. An existing spark plug was modified in accordance with budget and manufacturing constraints. The final plug we chose was the NGK B5HS because of its bulbous sidewall and "hot" deep-reach ceramic design, allowing us to drill above the threads. The following is a schematic of the plug. The NGK electrode is made of a copper core and nickel tip. The ceramic is alumina silicate.

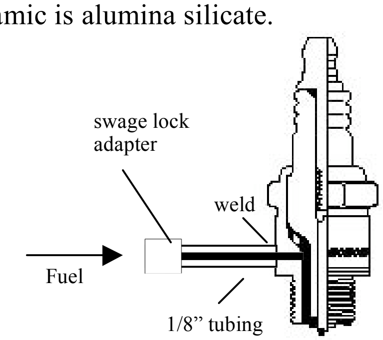

Fig. 1: Modified NGK B5HS

A small hole was drilled into the side of the plug, which was fitted with a 1/8" OD stainless steel tube. The tube was then silver soldered to the plug. Further modification was required in order to reproduce the TSI effect. The customary J-type outer electrode extension was removed and a steel sleeve was inserted inside the plug to decrease the electrode gap and to steer the fuel into the plasma discharge.

Fuel Delivery:

We initially believed that a modified Ficht Marine Onboard Direct Fuel Injector could be used to deliver the fuel through the spark plug. Rated at an injection pressure of 200 psi, it should have had no problem. However, because of the torturous travel through the stainless steel tube and 90 degree turn at the spark plug and the fact that the Ficht delivered an atomized instead of directed spray, the fuel remained trapped within the plug and dripped out at a very low pressure and rate.

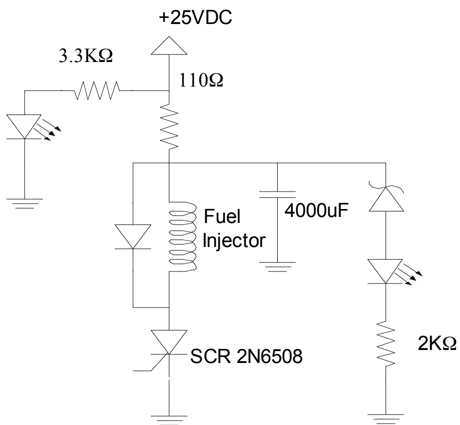

Fig. 2: Ficht Driver Circuit

The above is a schematic of the circuit used to drive the Ficht. A trigger pulse to the gate of the SCR causes the capacitor to discharge and the solenoid windings of the fuel injector to energize, forcing the magnetic plunger down which propels the fuel.

Our next approach was to use a nitrogen-assisted design somewhat similar to the Orbital air-assisted direct injection design. By using four valves controlled by separate solid-state relays we were able to blast the fuel through our entire contraption and have it emerge in a fine high-pressure mist into atmospheric pressure with a nitrogen pressure of 60 psi.

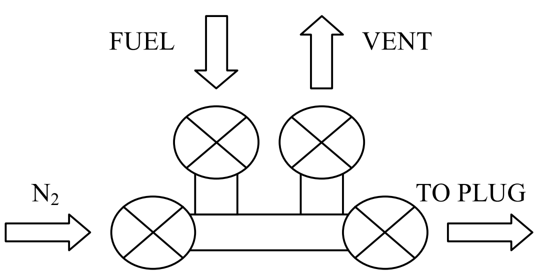

Fig. 3 Fuel Injector

The valves were ordered from McMaster-Carr and were rated for liquid at pressures up to 300 psi. The connections between them were made using Swage-lock adapters and 1/8-inch stainless steel tubing. The valves were switched straight to a 120 VAC wall outlet. The following figure shows a timing diagram for the fuel injector.

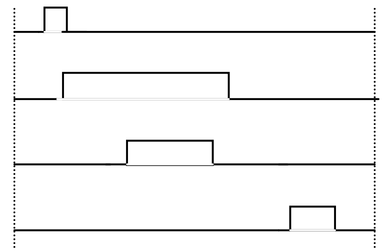

Fig. 4 Fuel Injector Timing Diagram

As can be seen, the vent is open during the entire fueling process. In the original circuit design, the vent and fuel valves were linked by an OR gate so that the activation of the fuel valve would automatically open the vent. However, because of jitter instabilities, we had to remove the logic gate and make do by overlapping the timing values

Chamber and Window Design:

The spark plug was held in a modified vacuum vessel with two specially designed end caps. The following is a schematic of the original design.

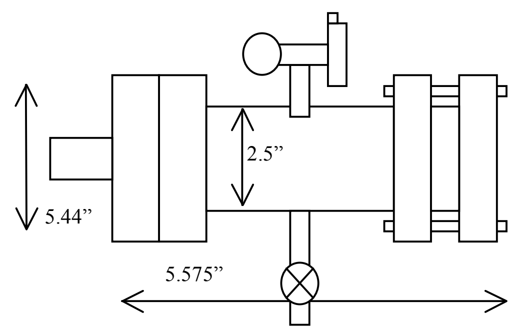

Figure 5: Chamber

The plug is screwed down into the left end cap and light from the spark is allowed to travel through the lexan window trapped between the two flanges that are the right end cap. A pipe thread drilled in the center of the vessel tees off to a pressure gauge and a safety blowout valve. The blowout valve has a pressure range between 50-200 psi. On the opposite side a welded tube leads to a screw valve, which is used to regulate the inlet pressure flow.

The transmittance of various windows proved to be an important property. We needed a window that could withstand the high pressures, transmit the proper amount of light, and also resist the bombardment of the injected fuel and nitrogen. In all, we tested three different windows; a glass vacuum viewing window, a

0.945” thick, 4.5” diameter plexi-glass flanged disk, and a 0.375” thick, 3” diameter piece of lexan. While the glass window transmitted light admirably, it failed the pressure test miserably, shattering at a chamber pressure of 100 psi. The plexi-glass window could withstand the high pressures but soon became cratered and pockmarked and stopped transmitting light properly. The lexan window proved to be the correct one for this experiment withstanding pressures of 300 psi for over an hour.

PROCEDURE:

Verification of Intensity Multiplication:

To verify that the addition of fuel would result in the multiplication of luminance of the spark we focused the light onto a photodiode and measured the intensity traces on an oscilloscope. The resulting peak intensity voltage increased by a factor of 10 when fuel was added as compared to the spark with no fuel at all. The optimal delay time was found to be 0.5 seconds between fuel injection and then spark. For this part and the remainder of the experiment the chamber pressure was held at 40 psi while the nitrogen used to inject the fuel was at 80 psi.

Alignment and Gathering of Spectra:

The spark plug was held in a pressure chamber with one end cap adapted to the plug and the other end cap holding a lexan window to allow the passage of light. Directly in front of the window was a 3” quartz lens (f.l. =7”.) followed by a 2” surface mirror angled at 45 degrees. Light from the spark was focused by the lens and bounced off the mirror onto the spectrometer slit.

Because of the noise generated with each shot of the spark plug, we decided to use Polaroid film to image the spectra instead of a CCD. The Polaroid was then scanned into a computer and read and analyzed using MATLAB’s image processing toolbox.

Each of the Polaroids has five positions which spectra can be imaged upon. The fact that the spectra could not be imaged real-time (which is possible on a CCD) required much advance planning. The entire fuel-spark cycle took 5 seconds. In order to keep track of shots, the trigger to the fuel injector was connected to a timer that cut power after the completion of the timing cycle so the experiment was autonomous once started. This proved to be very useful for our longer exposures, because it eliminated the need to watch the same repetitive procedure for times as long as five minutes.

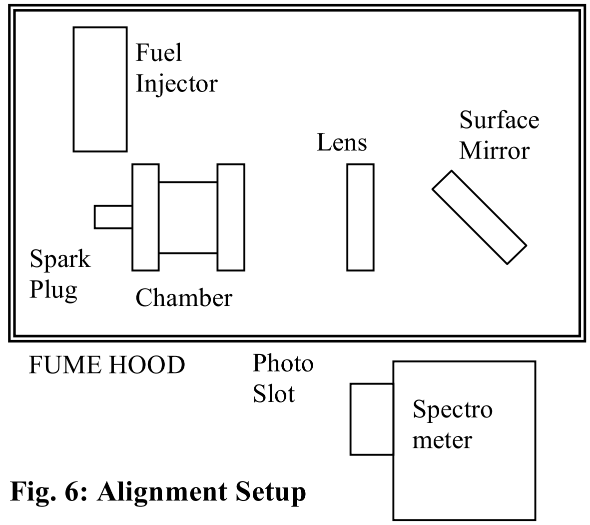

Fig. 6: Alignment Setup

.

Note the use of the fume hood to mitigate the smell of gasoline. As an added safeguard, the traditional plexiglass shield was replaced with a much sturdier piece of lexan.

DATA ANALYSIS:

Calibration of the spectra was performed by use of a mercury lamp. A plot of grayscale intensity (0-255) versus wavelength (angstroms) for a single Polaroid is shown below.

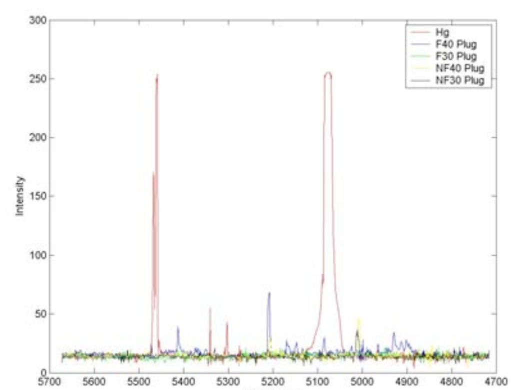

Fig. 7: Intensity Profile of Spectra

The two peaks of the mercury lamp represent the strong mercury lines at 5460.74 Å and 5073.04 Å (the second order result of 2536.52Å.) In order to confirm the production of hydrogen we searched for the classic

Hydrogen Balmer series transitions at 6562.8, 4861.3, 4340.5, and 4101.7 Å. Preliminary spectra scans at 5000 and 4500 Å yielded very unpromising results, intensities <20 on a scale of 255. However, spectra centered at 4100 Å gave rise to very strong gamma and delta hydrogen transitions. The following table illustrates the intensity of hydrogen lines based on the number of spark exposures.

Angstroms	4340.4	4101.8
10 shots	69	52
20 shots	100	64
30 shots	82	118
No Fuel (300 shots)	17	19

Table 1: Hydrogen Line Intensity Levels

OBSERVATIONS AND FUTURE WORK:

The original chamber design was very hard to purge of fuel. The multiple ledges gave the fuel many places to puddle. In addition, the only exit in the chamber was a 0.464-inch diameter hole. Moreover, the only methods of purging used, vacuum suction, and high-pressure nitrogen were ineffective because of the misaligned flow paths. Removing one of the end caps was unacceptable because of the possibility of introducing a leak upon reattachment as well as the prohibitive amount of time the process required. The next-generation chamber solves this problem by incorporating a fuel drain with an exit diameter of 1.5 inches that is also on the bottom so the force of gravity can be used to full advantage. In addition, the new chamber has no ledges that will allow the fuel to be trapped on. Finally, the addition of a single throw, double pull switch allows a constant stream of nitrogen to be blown through the plug to assist in the fuel cleaning process.

Upon dismantling the first chamber and removing the spark plug we noticed that the electrode and surrounding ceramic were covered in black soot, indicating the presence of carbon. This assured us that even though we had not been able to find all of the hydrogen lines, hydrogen must have been liberated, because the carbon deposits were evidence of the breakdown of the original hydrocarbon fuel.

Currently, we are working on implementing the next generation pressure chamber so that comparison of the spark with fuel and without can be made more readily. We also plan to investigate the effect of the nitrogen spike that accompanies the fuel injection on the spark. From our spectral data, it can already be seen that higher pressure sparks result in more intense and also smeared spectra. Isolation of these effects could give us a clue as to whether dynamic or static transportation of fuel to the plug's electrodes is preferable. Finally, it is our hope to compare these results with those of a port injection setup (i.e. where fuel is sprayed across the side of the plug, which is common in many marine applications.)

REFERENCES:

1. Horowitz and Hill, *The Art of Electronics.* Cambridge University Press. 1989.

2. L. Bromberg, D.R. Cohn, A. Rabinovich and N. Alexeev. *Hydrogen Manufacturing Using Low-Current, Non-Thermal Plasma-Boosted Fuel Converters.* Proceedings of the Symposium on ENERGY FOR THE 21ST CENTURY: HYDROGEN ENERGY. April 2001, San Diego, CA.

3. NGK Spark Plugs 1997 Master Catalog.

4. Purcell, Edward M. *Electricity and Magnetism.* Mc-Graw Hill: Boston, MA, 1985.

5. Tipler, Paul A. *Physics for Scientists and Engineers.* Third Edition, Volume 2. Worth Publishers, New York, NY 1991.