

# **Exploration of a Fuel Cell/Internal Combustion Engine Combined Cycle for High Efficiency Power Generation**

## **(A GCEP Exploratory Project)**

### **Investigators**

Chris F. Edwards, Professor, Stanford University Mechanical Engineering

Mark A. Donohue, Graduate Researcher, Stanford University Mechanical Engineering

John R. Fyffe, Graduate Researcher, Stanford University Mechanical Engineering

Carol Regalbuto, Graduate Researcher, Stanford University Mechanical Engineering

### **Abstract**

Internal combustion (IC) engines serve as a viable small-scale and portable option for electricity generation. While there are several aspects of IC engines that limit their efficiency, one of the major detractors is the unrestrained combustion reaction that is the initial step in the conversion of the chemical bond energy of the fuel into useful work. Another viable small-scale electricity generation device is the fuel cell. Fuel cells use a restrained reaction to oxidize the fuel, whereby the rate of work extraction is directly coupled to the rate of fuel oxidation—a more efficient process than combustion. Fuel cells have some limitations that prevent their more widespread use, however. They have a narrow selection of acceptable fuels and are not able to fully oxidize the input fuel stream, resulting in some amount of unreacted fuel being exhausted. Our proposed system seeks to marry these two devices in a way that is beneficial to both. By operating some of the cylinders of an IC engine upstream of the fuel cell at a very rich equivalence ratio, the engine can serve as a fuel reformer to generate hydrogen from hydrocarbon molecules found in typical fuels. After passing this gas through a shift reactor to lower the carbon monoxide concentration, it can be fed into a fuel cell where a significant fraction of the fuel oxidation will take place. Any unreacted fuel that leaves the fuel cell can then be combusted in the remaining cylinders of the IC engine to ensure that all of the fuel is utilized. Work is underway to determine the operating conditions for each of the devices in the system, as well as the type of fuel cell that lends itself best to this application. Some preliminary experimental data has also been generated in exploring the use of an IC engine as a fuel reformer.

### **Introduction**

The goal of this research is to determine if an efficient, small-scale electricity generation system could be developed by combining an internal combustion engine with a fuel cell. This approach was formulated after exergy analysis of a typical IC engine revealed that significant efficiency gains could be made by reducing the exergy destruction due to combustion [1]. There are two paths that one could take to accomplish this. The first would be to carry out the combustion at an extreme state so that the entropy generation due to combustion would be reduced [2]. The second would be to perform the fuel oxidation in a restrained manner. A restrained reaction has much lower entropy generation than an unrestrained reaction. Therefore, if a large portion of the fuel were to be oxidized in this restrained manner, one could significantly reduce the exergy destruction associated with fuel oxidation. We are interested in the latter as a means of reducing exergy destruction.

Fuel cells use a restrained reaction for electricity generation. Chemical bond energy is converted to electricity by an electrochemical process in which the rate of work extraction is coupled to the rate of reaction. Fuel cells typically use hydrogen as a fuel, which is difficult to store and not as readily available as other fuels such as natural gas or gasoline. However, a system could reform fuels into a syngas usable by the fuel cell. It is not uncommon for fuel cell systems to employ a fuel reformer to generate the hydrogen from other fuel sources, either by auto-thermal reforming or steam reforming. Our system would carry out this reforming step by performing rich combustion in the IC engine. This may lead to lower hydrogen yields than could be achieved in a traditional reformer, but there is the opportunity to extract some work during the expansion stroke in this step. The balance between syngas yield and work output is subject to further investigation. Experimental work is underway to measure exhaust concentrations for rich combustion in a General Motors LS1 engine to gauge possible yields from a production engine.

The second area currently under investigation is the sensitivity of the fuel cell to other species present in rich IC engine exhaust. Conventional proton exchange membrane (PEM) fuel cells can easily be poisoned by carbon monoxide (CO) concentrations above few 10s of ppm. The CO binds to reaction sites, preventing hydrogen from reacting in the fuel cell to generate electricity. Given that the products of rich combustion will have a large concentration of CO, significant aftertreatment of the exhaust would be needed for it to be a suitable fuel for the fuel cell. There are other types of fuel cells that may better lend themselves to this application, though. Currently, high temperature PEM (HTPEM) fuel cells are being investigated. The higher temperatures decreases the risk that the CO will remain bound to the reactions sites, allowing the fuel cell to tolerate CO concentrations up to 3% [3]. This level of CO should be achievable by passing the exhaust gas from the rich cylinders through a shift reactor before entering the fuel cell. This hypothesis will be tested experimentally this summer.

## **Background**

### *Exergy Analysis*

Exergetic analysis of a typical, naturally aspirated IC engine cycle reveals that, of the exergy destroyed, approximately 40% is due to heat transfer, 20% is due to exhaust, and 30% is due to combustion. The exhaust exergy destruction can be reduced by implementing turbomachinery to harness some of the enthalpy remaining in the exhaust, and work is currently underway to reduce the exergy destruction due to heat transfer by employing thermal barrier coatings to minimize heat transfer [1]. Our work here is aimed at reducing the portion of exergy destruction due to combustion in the manner described above. By systematically reducing the exergy destruction in the main contributors to the overall exergy destruction of the system, we can ultimately produce a more efficient engine. If we are successful in reducing the exergy destruction due to heat transfer using thermal barrier coatings, and in reducing the exergy destruction due to combustion by performing a large portion of the oxidation in a fuel cell, it is not unreasonable to expect a system that can operate near 70% exergy efficiency.

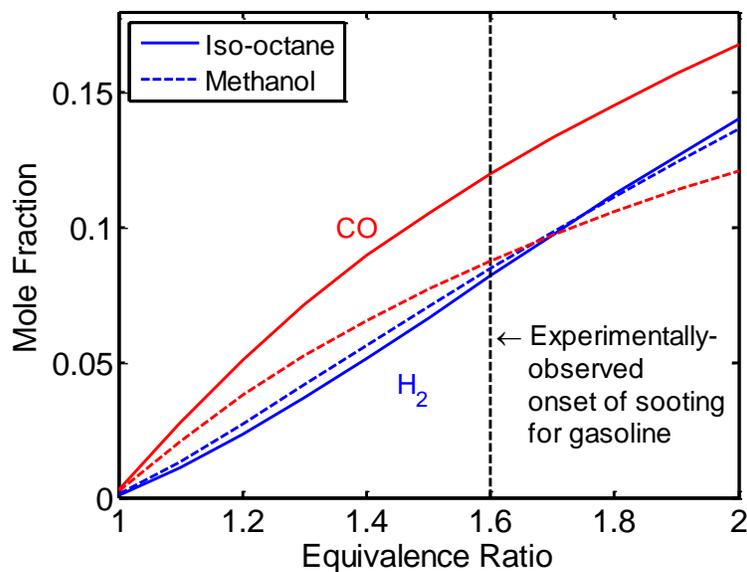
### High-Temperature PEM Fuel Cells

High-temperature PEM (HTPEM) fuel cells use different electrolytic membranes than conventional PEM fuel cells and operate at temperatures between 120°C and 200°C. The higher operating temperatures allow for improved cathode kinetics, better resistance to contaminants such as CO, and easier water management as all the water in the system is in the vapor phase. HTPEM membranes are commercially available and have been tested to determine their ideal operating regimes with respect to power output and CO tolerance. While many tests have been done using HTPEM fuel cell stacks, they have all been as isolated stacks and not as part of a larger system. In our work with a HTPEM fuel cell stack coupled to an HCCI engine, we will be interested in how the fuel cell performance affects the system as a whole.

## Results

### Modeling Fuel Reforming in Internal Combustion Engines

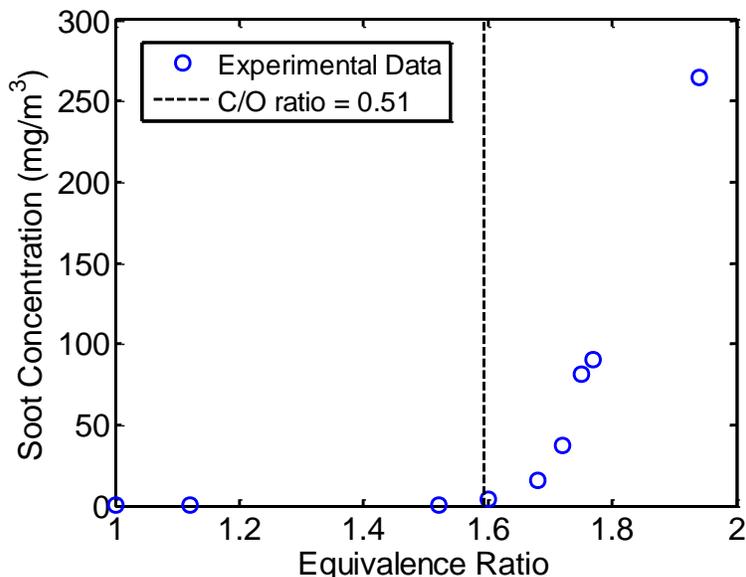
The first step of the investigation involved modeling the fuel reforming process in an IC engine. The modeled reforming process was used to determine CO and H<sub>2</sub> concentrations and the exhaust gas temperatures for a range of equivalence ratios. This information is critical in designing the water-gas shift reactor as well as modeling the entire system. Detailed models of a spark-ignition (SI) engine and a homogeneous-charge compression ignition (HCCI) engine were developed. Additional parameters of interest, such as exergy destruction and equivalence ratio limits for iso-octane and methanol, were also determined using the engine models. Figure 1 shows the modeling results for exhaust gas CO and H<sub>2</sub> concentrations for an SI engine. The CO concentrations for both iso-octane and methanol exceed HTPEM fuel cell limits around an equivalence ratio of only 1.1, suggesting that a water-gas shift reactor would be necessary for any significant amount of fuel reforming in combination with a HTPEM fuel cell.



**Figure 1:** Hydrogen (H<sub>2</sub>) and carbon monoxide (CO) mole fractions in SI engine exhaust versus equivalence ratio for iso-octane and methanol (2000 RPM, Half-Throttle).

### Preparation for Experimental Engine Fuel Reforming

A series of fuel reforming experiments in the General Motors LS1 8-cylinder SI engine are planned for the near future. The expected concentrations of H<sub>2</sub> and CO in the exhaust exceed the 10% and 6% limits for H<sub>2</sub> and CO respectively on the current exhaust gas analyzer equipment in the laboratory. Therefore, a precision dilution system was implemented that could accurately dilute exhaust gas samples up to a 10:1 dilution ratio. The system was calibrated for high accuracy, accounting for the effects of exhaust gas composition.



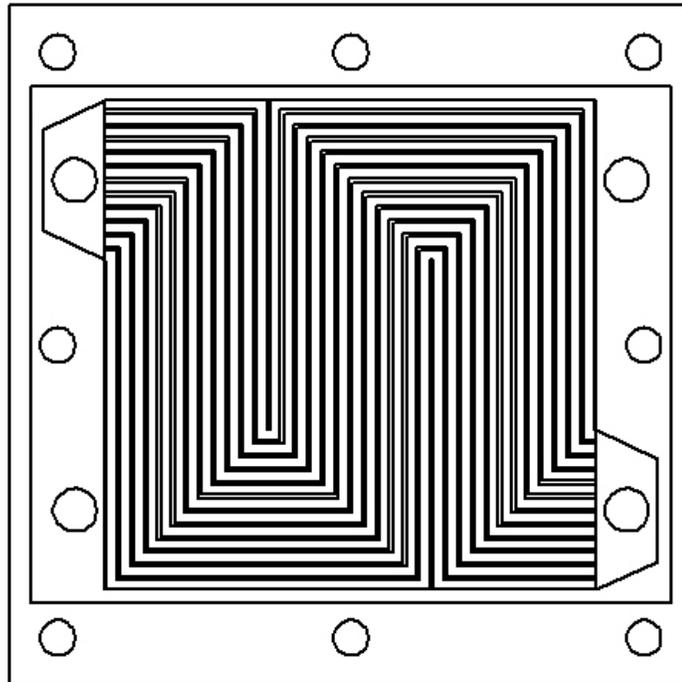
**Figure 2:** Soot concentration versus equivalence ratio for the LS1 engine running on standard gasoline (2000 RPM, Half-Throttle).

HTEPM fuel cells experience catalyst contamination in the presence of soot (solid carbon). Soot measurements using an AVL 415SE Smoke Meter were performed when operating the LS1 engine with gasoline, and similar experiments are planned for methane, methanol, and ethanol to determine the equivalence ratio where soot begins forming. For gasoline, the equivalence ratio where soot begins to form is at  $\phi = 1.6$ . The measured onset of sooting will confine the operating conditions for our overall system.

A flame ionization detector (FID) is used to measure total hydrocarbons in the exhaust gas. The FID detects ions generated during combustion of hydrocarbons in a hydrogen flame, with the ion generation being proportional to the concentration of the hydrocarbons in the flame. Each hydrocarbon has a unique response factor. Alkanes have response factors very near one, not requiring much differentiation between different fuel types. However, alcohols' response factors vary by fuel, so the analyzer's response factor for methanol or ethanol must be determined. Commercial precision methanol-/ethanol-nitrogen calibration gases are not easily obtained. To calibrate the FID, a saturator system was designed to produce a saturated stream of alcohol-nitrogen at a known temperature and pressure. The experimental setup is completed and tests to determine alcohol response factors will be conducted in the near future.

### *HTPEM Fuel Cell Stack Design*

A HTPEM fuel cell stack has been designed and is under construction. The stack will use Celtec®-P membrane electrode assemblies (MEAs) supplied by BASF and custom-designed graphite flow plates to transport the reactant gases around the membrane surfaces areas. The MEAs have active areas of  $45 \text{ cm}^2$  and a peak power output of approximately  $0.5 \text{ W/cm}^2$  for a total peak power output of  $22.5 \text{ W}$  per MEA. (The number of MEAs used determines the power produced by the fuel cell stack.) The split of power generation between the engine and the fuel cell has yet to be determined and will be investigated experimentally.



**Figure 3:** High-temperature PEM fuel cell parallel bipolar plate design with parallel serpentine channels.

### **Progress**

Work is still in the beginning stages, but the development of a more efficient distributed power generation system could significantly reduce greenhouse gas emissions. In addition to the lower  $\text{CO}_2$  output per unit of power that comes with higher efficiency, the proposed system could use alternative fuels such as natural gas or ethanol with significantly lower carbon release than traditional diesel or gasoline. Although the work done so far has focused primarily on gasoline in a typical production engine, this is only intended to be a baseline. As research moves to other fuels, other engines, and other combustion strategies, the system will move towards lower  $\text{CO}_2$  emissions than traditional small-scale generators.

## Future Plans

To date, all experimental fuel reforming work has been conducted on a production engine running on gasoline. After this baseline is set, work will move to a research engine platform where we will have more control over the engine cycle as well as the fuel used. We are particularly interested in the performance of alcohols, not only because of their lower carbon content, but because they can be used at higher equivalence ratios without sooting. Higher equivalence ratios lead to higher syngas yields from the reforming cylinders, which would allow us to oxidize a greater amount of the fuel in the fuel cell.

The fuel cell stack will continue to be constructed, and when complete, will be tested to characterize its performance with respect to power output and CO tolerance. Iterations on design parameters such as MEA size, gasket sealing, and flow plate channels will be made to increase fuel cell performance.

## References

1. Johnson, B. and Edwards, C., "Exploring the Pathway to High Efficiency IC Engines through Exergy Analysis of Heat Transfer Reduction," *SAE Int. J. Engines* 6(1):2013, doi:10.4271/2013-01-0278.
2. Miller, S.L., Theory and Implementation of Low-Irreversibility Chemical Engines. Ph.D. dissertation, Dept. of Mech. Eng., Stanford Univ., Stanford, CA, 2009.
3. Li, Q. et al, "The CO Poisoning Effect in PEMFCs Operational and Temperatures up to 200°C," *J. Electrochemical Society* **150**(12): 2003, doi: 10.1149/1.1619984.

## Contacts

Christopher F. Edwards: cfe@stanford.edu  
Mark A. Donohue: mdonohue@stanford.edu  
John R. Fyffe: johnrf@stanford.edu  
Carol Regalbuto: mcreg@stanford