Developing a Thermodynamic Fuel Cell

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Objectives

Demonstrate a combustion-based approach to electrical generation, maximizing the thermodynamic cycle and thus achieving high efficiency and near-zero emissions, while facilitating a path to hydrogen and hydrogen-rich fuels utilization.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cell Transportation Systems section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year R,D&D Plan:

- D. Fuel Cell Power System Benchmarking

Approach

- Analyze significant components of the thermodynamic fuel cell, including homogeneous charge compression ignition (HCCI) combustion, linear electrical generation and two-stroke cycle charging, employing experimental and computational means.
- Design major sub-systems based on achieving maximum electrical conversion efficiency and minimal operating emissions.
- Integrate components into a full-scale prototype with a rated power output of 30 kW.
- Demonstrate the device's operating performance and fuel versatility.

Accomplishments

- Experimentally established the potential of HCCI combustion using a free piston configuration (30-kW, 2-kW sizes) to realize significant improvements in thermal efficiency and NO_x emissions.
- Computationally analyzed, designed and constructed a full scale linear alternator. Collaborated with Magnequench, Int. to design and manufacture a similar, but significantly different linear alternator at no cost to Sandia.
- Reconfigured a 4-cylinder Caterpillar engine to test the performance of the two linear alternator designs at full power output.
- Computationally developed an optimized gas transfer system with respect to the thermodynamic fuel cell's operating characteristics and two-stroke cycle dynamics.
- Investigated the performance of a hybrid thermodynamic fuel cell/turbine system.
- Completed preliminary designs for a 4-kW free piston gas compressor (Sandia funded).

Future Directions

- Measure and evaluate linear alternator performance. Modify/adjust configurations based on dynamic testing.
- Investigate additional scavenging designs incorporating late, port fuel injection for short-circuited emissions control. Verify computational results using a free piston, single-stroke scavenging experiment.
- Develop control schemes to facilitate nominal operation.
- Integrate components into a full-scale demonstration prototype.
- Form industrial consortium for commercial application.

Introduction

High efficiency, low emissions electrical generators will lead to a path for renewable hydrogen-based fuel utilization. Electrochemical fuel cells are generally considered to be ideal devices for these applications, where hydrogen or methane is used as the fuel. However, the extensive development of the internal combustion engine, and the existence of repair and maintenance industries associated with piston engines, provide strong incentives to remain with this technology until electrochemical fuel cells are proven reliable and cost competitive.

The thermodynamic fuel cell is based on utilizing homogeneous charge compression ignition (HCCI) combustion of very lean ($\phi \sim 0.3$) fuel-air mixtures to approach ideal Otto cycle performance (the most thermodynamically efficient option for piston engines). HCCI is extremely rapid (nearly constant-volume), with numerous ignition points occurring throughout the charge; chemical kinetics dominate while there are no flame propagation or fuel diffusion requirements [1]. In addition, virtually any fuel-air mixture can be used, with NO_x emissions controlled through sufficient charge dilution and rapid expansion of the combustion gases [2]. Sandia's concept, illustrated in Figure 1, employs a free piston/linear alternator combination to facilitate direct electrical generation, thus enabling electronic control of the HCCI process and therefore the performance of the fuel cell. Structural integrity (for high peak pressures), design simplicity and cost issues are addressed with this unique design.

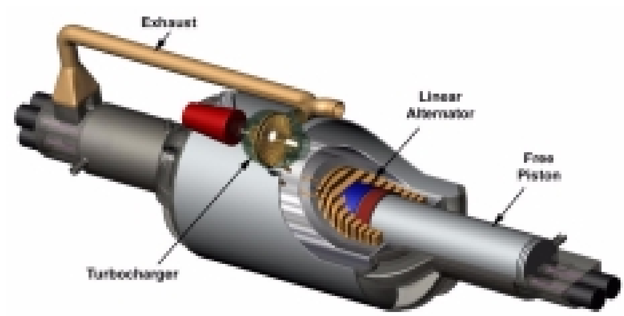

Figure 1. Thermodynamic Fuel Cell

Approach

This research project aims to investigate and resolve critical issues involved in developing the thermodynamic fuel cell. The end goal is to construct a full-scale prototype that can demonstrate the device's efficiency and emissions potential, as well as its fuel versatility. Major processes of HCCI combustion, linear electrical generation and two-stroke cycle charge delivery have been investigated in previous years using both experimental and computational means. The objective has been to verify the capabilities of the critical components while determining the factors that will affect the performance of the integrated configuration.

During fiscal year 2003, efforts were made to continue to design, build and test various components, and to further develop industrial partnerships; commercial relationships are expected to facilitate the rapid transfer of this technology to the marketplace after concept demonstration. Work this year focused on aspects of the linear alternator and the scavenging system, as well as additional studies investigating the benefits of a combined thermodynamic fuel cell / turbine hybrid system.

Results

The alternator test rig, illustrated in Figure 2, became operational this year, with issues regarding the piston's integrity seemingly resolved. A test procedure has been developed and preliminary data acquired using the Magnequench constructed alternator, without the inclusion of the permanent magnets. The magnets will be attached to the piston next and tests run under both load and no-load conditions. A switching mechanism will need to be developed to achieve the rated output for this design (as explained in previous FY reports); however, comparison with Magsoft FLUX2D software's performance predictions and an evaluation of its accuracy should be possible in the coming months.

Multi-dimensional modeling of the scavenging system was employed to analyze and design an optimal arrangement; this configuration will be fabricated and tested using a single-cycle experiment. Figure 3 illustrates an arrangement expected to give very good performance (charge replacement greater than 90%, with fuel trapping capabilities near 100%). In this "stratified-scavenging" design, an initial charge of fresh air (yellow) flushes the combustion products from the cylinder (orange), while a rich fuel-air mixture (blue) is introduced late in the gas transfer process. A late, port fuel-injected configuration to be investigated in FY 2004 represents a natural progression in this component's development and should improve short-circuiting controllability.

Figure 2. Alternator Test Rig

Full cycle thermodynamic modeling utilizing zero-dimensional representations of the in-cylinder processes, the free piston dynamics, and assumed efficiencies for a turbocharger/compressor combination, was used to conduct a feasibility study analyzing a thermodynamic fuel cell/turbine combination [3]. Simulations were conducted over a range of possible boost pressures, from 1.2 bar through 3.0 bar. The results indicated that the emissions performance is unchanged for these variations; however, the free piston dynamics can be significantly altered by an increase in cylinder pressure. For the highest boost case, the frequency increased 45%. In addition, the combustion pressures were also calculated to be sensitive to any boost, with the peak pressure increasing to 445 bar (from 230 bar) for the 3.0 bar boost case.

The performance improvements for the hybrid system are presented in Figure 4. The changes in generating efficiency (↑7% at 2.5 bar) and power density (↑38% at 3.0 bar) with increasing boost pressure are plotted. It can be seen that there is a maximum efficiency that can be reached in this hybrid arrangement due to the performance limit of current turbocharger and compressor technologies. The power density, on the other hand, did not seem to have a limit for the conditions investigated.

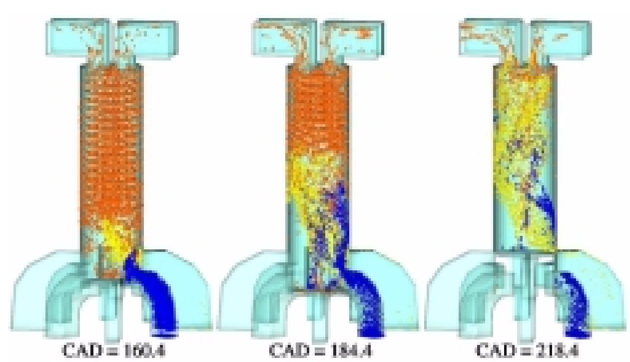

Figure 3. Calculated Stratified-Scavenging Flows

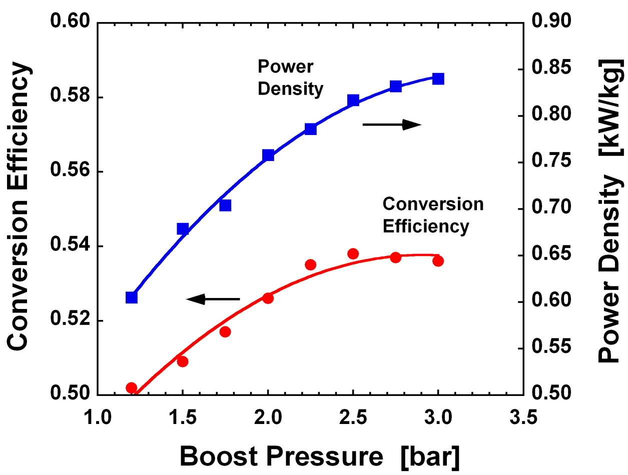

Figure 4. Fuel-to-Electricity Conversion Efficiency and Power Density vs. Boost Pressure

Conclusions

- The thermodynamic fuel cell represents a near term (2010) option for achieving the DOE's Hydrogen, Fuel Cells and Infrastructure Technologies Program goals of significantly advancing the operating efficiency and emissions performance of electrical generating devices, while creating a path for renewable hydrogen-based fuel utilization.
- A prototype design is moving forward, with the performance of each major sub-system being quantified.
- To date, no unsolvable barriers have materialized.

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3. Van Blarigan, P. and Goldsborough, S., "Free Piston Generator/Turbine Systems - Advanced Hybrid Systems," Proceedings of the 14th Annual U.S. Hydrogen Meeting: Energy Security through Hydrogen, National Hydrogen Association, March 4th-6th, Washington, DC, 2003.

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2. Goldsborough, S., "Toward the Development of an Advanced, Rapid Combustion Electrical Generator", Alfred University, April 17th, Alfred, NY, 2003.
3. Goldsborough, S., "Toward the Development of an Advanced, Rapid Combustion Electrical Generator", Marquette University, March 27th, Milwaukee, WI, 2003.
4. Van Blarigan, P. and Goldsborough, S., "Free Piston Generator/Turbine Systems - Advanced Hybrid Systems," 14th Annual U.S. Hydrogen Meeting: Energy Security through Hydrogen, National Hydrogen Association, March 4th-6th, Washington, DC, 2003.
5. Goldsborough, S. S. and Van Blarigan, P., "Optimizing the Scavenging System for a Two-Stroke Cycle Free Piston Engine for High Efficiency and Low Emissions: A Computational Approach," SAE Paper 2003-01-0001, March 3rd, Detroit, MI, 2003.
6. Goldsborough, S. S. and Van Blarigan, P., "Optimizing the Scavenging System for a Two-Stroke Cycle Free Piston Engine for High Efficiency and Low Emissions: A Computational Approach," International Multidimensional Engine Modeling User's Group Meeting at the SAE Congress, March 2nd, Detroit, MI, 2003.
7. Van Blarigan, P. and Goldsborough, S., "Ideal Otto Cycle Implementation of HCCI Combustion," U.S. Department of Energy HCCI Meeting, Sandia National Laboratories, January 30th, Livermore, CA, 2003.

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Special Recognitions & Awards/Patents Issued

1. Van Blarigan, P., "Free-Piston Engine," US Patent # 6,199,519 B1
2. Harry L. Horning Memorial Award, Society of Automotive Engineers, 1998