V.I.1 Diesel-Fueled SOFC System for Class 7/Class 8 On-Highway Truck Auxiliary Power

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Protonex, LLC, Broomfield, CO

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Project End Date: December 31, 2009

Objectives

Design, develop, and demonstrate a practically sized, diesel-fueled solid oxide fuel cell (SOFC) auxiliary power unit (APU) configured to provide electrical power for sleeper cab auxiliary loads of on-highway trucks to meet the requirements for cost, size, weight, fuel efficiency, and operation on diesel fuel.

- Develop ultra-low sulfur diesel (ULSD) fuel processor.
- Develop fuel cell that operates on ULSD catalytic partial oxidation (CPOX) reformate.
- Design, build and test APU under real-world conditions.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Durability
(B) Cost
(C) Performance

Technical Targets

This project is to develop APU systems for heavy truck applications to reduce idling of the main engine. The following lists the current DOE 2010 auxiliary power units and truck refrigeration unit targets and the actual 2006 proposal targets in ()s:

- Cost: $400/kWe (1,500 $/kW)
- Specific power: 100 W/kg (17 W/kg)
- Power density: 100 W/L (8 W/L)
- Efficiency @ rated power: 35% (25%) (lower heating value basis)
- Cycle capability: 150 cycles (10 cycles)
- Durability: 20,000 hours (1,500 hours)
- Start-up time: 15-30 min (60 min)

Accomplishments

Developed:

- Low-cost balance-of-plant (BOP) concepts and compatible systems designs.
- Identified low-cost, high-volume components for BOP systems.
- Demonstrated efficient SOFC output power conditioning.
- Demonstrated SOFC control strategies and tuning methods.

Demonstrated:

- Operation meeting SOFC APU requirements on commercial ULSD fuel.
- SOFC system operations on dry CPOX reformate.
- Successful start-up and shut-down of SOFC APU system without inert gas purge.

The SOFC APU demonstration was carried out at the Cummins Power Generation (CPG) facility in Minneapolis, Minnesota on February 26, 2010. The demonstration was successfully completed on February 27, 2010 including the necessary steady-state, transient, and peak power operation tests. Table 1 lists the results against project objectives.

TABLE 1. Results Against Project Objectives

Objective	Target	Demonstrated
Operation on Liquid Fuel	ULSD	ULSD
Average Power (Net DC)		1,100 Watts
Average Power (Net AC)		820 Watts
Combined Heat and Power (CHP)		>4 kWatts
Peak Power (Net DC)		1,250 Watts
Specific Power (Net DC)	17 W/kg	9 W/kg
Power Density	8 W/L	3 W/L
Start-up Time (Cold)	1 hour	1 hour
Efficiency @ Rated Power	25% lower heating value	11% lower heating value
In-Vehicle Demonstration	Operation on a Class 8 Truck	Operation on Truck Hardware in Lab

DC - direct current; AC - alternating current

Introduction

With the onset of anti-idling legislation and the rising cost of fuel one potential early adopter for SOFC fuel cell technology is the on-highway truck APU application. First, an SOFC APU could provide the same electrical source as a conventional internal combustion engine-based APU. Second, it has the potential to improve exhaust emissions, fuel efficiency, reduced transmitted noise and vibration, and provide heating for both cabin and engine.

This project was directed at designing, building and demonstrating a ULSD-fueled SOFC APU installed in an on-highway truck to supply AC power for cabin loads, engine heating, and battery charging during rest periods.

Approach

The plan to complete the objectives of the project included identifying the overall truck system performance, power electronics, heating, battery, fuel cell system, and fuel cell hot zone requirements.

The APU design used a novel dry CPOX reformer that requires no water. The APU is a modular design, based on four ~600 W (gross) modules, yielding ~2 kW net DC power. The scale up of fuel cell modules to 600 W and the development of the diesel CPOX reformer was to have been accomplished by modifications to a pre-existing 250 W SOFC module. CPG was responsible for project management, system design, packaging, all cold BOP equipment including air and fuel supply and metering, vibration isolation, power electronics and controls. Protonex built the hot modules, including stacks, reformers, heat exchangers, tail-gas combustors and insulation packages.

Results

Since last year's report, we fabricated and tested two generations of complete SOFC modules and operated those modules on both hydrogen/nitrogen mixtures and on reformed liquid fuels. In addition to tests of full-scale stacks and modules, we also tested sub-scale modules and fuel processor components.

Each module in the APU was a complete, independent hot zone containing a tightly-integrated stack, fuel processor, recuperative heat exchanger and tail-gas combustor inside an insulation package. The stacks used 66 tubes, each Ø10x135 mm. The first round of modules were delivered to CPG in the third quarter of Fiscal Year (FY) 2009, the second round used for the demonstration in the first quarter of FY 2010.

In FY 2009, Protonex began testing subscale stacks on liquid fuels to determine proper set-points for the fuel processor and cathode air flow to enable reliable startup and shutdown of stacks on liquid fuels. These tests included operation on both ULSD and low-sulfur kerosene fuels. Each thermal cycle was between 180°C and 720°C with heating and cooling times of approximately 40 minutes each. The power was very stable over these cycles, with less than 1% power loss over 10 thermal cycles.

CPG completed the BOP air delivery system fabrication for the four module fuel cell system. The system includes one cathode air blower, one CPOX air boost blower, four cathode flow control valves, four anode control valves, eight air mass flow sensors. The system achieved the required flow characteristics for the modules. CPG utilized low-cost automotive components in this fuel cell development application to prove a reduced cost bill of materials.

CPG revised the power electronics topology to eliminate the DC-DC boost. The revised topology was simpler and provided an overall efficiency improvement of 3-4%.

Identified and tested a group of inexpensive waste heat recovery exchanger designs that provide the required cab heating with an effectiveness of ≥95% and pressure drop of <2" water over the required range of operating conditions. From a previous study it is known that the cab requires about 5 kW of heat during a peak winter event. The heat exchanger is capable of transferring the required amount of heat at a very high effectiveness at all flow conditions.

The final demonstration occurred on February 26th, 2010 (Figure 1) with the results shown in Table 1. The key performance parameters are:

FIGURE 1. SOFC APU Demonstration Article at CPG

1. Operation meeting SOFC APU requirements on commercial ULSD fuel.
2. SOFC systems operating on dry CPOX reformate.
3. Successful start-up and shut-down of SOFC APU system without inert gas purge.
4. AC power output sufficient to operate 12,000 BTU air conditioning system.

The test consisted of heating each module individually for convenient monitoring, and allowing the entire system to achieve a steady state. Note that the system is capable of starting all modules simultaneously if desired. The steady-state DC power production was 1,500 W gross with approximately 380 W of parasitic losses for a net production of 1,120 W. A peak power loading of 1,680 W with a net output of 1,225 W was recorded for 10 minutes higher peak loading of the modules is possible, the peak loading was not limited by inherent module capability, rather it was limited by the thermal balance. Future systems could be designed for higher firing rates and power production with moderate design modifications to the heat exchangers, fuel feed system and thermal insulation package.

After the peak loading, the system continued in steady-state DC power operation for 10 hours, simulating the rest period over which a Class 7/8 APU would operate. At the end of this time the power output was 1,490 W gross and 1,110 W net.

The system was then transitioned to AC loading for 1.5 hours. The AC loading required the modules to be connected in series electrically; thus forcing the same current through all modules and reducing total power by 3%. The larger change in parasitic losses was due to the inverter efficiency of ~85%. The power produced

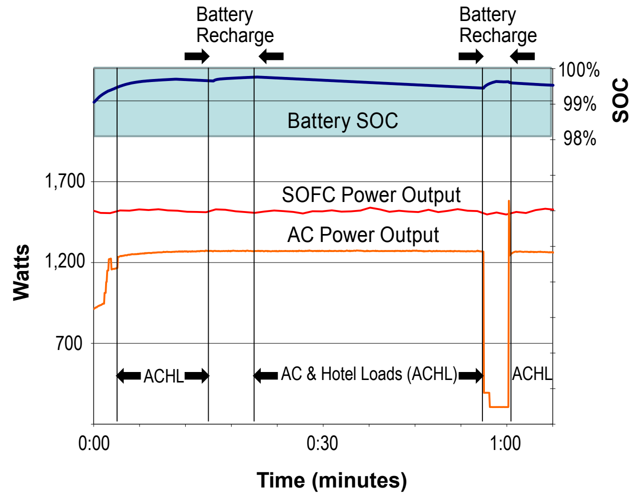

FIGURE 2. Average AC power Produced by SOFC Sub-System on ULSD during Final Testing at CPG

during this period is shown in Figure 2, 1,460 W gross and 820 W net at the end of the test. This allowed the air conditioning, lighting and additional DC loading thus simulating a truck "hotel" load to all operate simultaneously from power generated by the SOFC sub-system.

Conclusions and Future Directions

Summary

- During FY 2010 the project fabricated and delivered the second generation of SOFC modules with significantly improved performance and stability. These modules were demonstrated and characterized on both hydrogen and reformed liquid fuels.
- Demonstrated the viability of a dry CPOX approach at the stack and module level.
- Built and tested two complete 4-module sets for testing.
- Completed conceptual design of higher-power (~1 kWe) module.
- Completed SOFC APU unit fabrication and demonstration.
- Project work completed in the second quarter of FY 2010

Discussion

At the conclusion of the SOFC APU project the technology may be seen to be approaching the necessary requirements for creating successful commercial implementation(s) in mobile power markets in the five- to ten-year range.

Key technical obstacles for commercial implementation were addressed in this project:

- Diesel fuel reforming without water (including sulfur handling): The Protonex module demonstrated short-term operation on commercial ULSD without supplementary water or water recycling under controlled oxygen-to-carbon ratio conditions.
- Cost: The implementation of low-cost automotive control components was demonstrated through novel adaptations to achieve required accuracy and resolution. Stereolithography components demonstrated potential for cost-effective integration of multiple functions in tooled components. A commercial, low-cost, high efficiency cathode blower was matched to system requirements.
- Performance: The APU power unit demonstrated the potential to produce required mission levels of power generation from a package envelope comparable to current production APU products.

Durability and efficiency are two areas that require additional development to reach commercial requirements. Observed levels of stack degradation during this project are recognized to be inadequate to support a commercial product and are the object of ongoing development at Protonex.

Observed system efficiency, while comparable to small diesel gensets operating at light-load conditions, needs improvement to maximize economic benefits. Observed efficiency was negatively impacted in three areas:

1. Tubular stack elements performed below expectations, especially at higher levels of fuel utilization. Projections were based on performance of the previous smaller tubes.
2. Carbon-free operation of the CPOX reformer required higher than expected O/C ratios, lowering effective reformer efficiencies
3. The BOP was sized to the projected stack power. Operation at the lower power levels demonstrated by the prototype stacks resulted in an effectively oversized BOP.

After some experience in control of full SOFC fuel cell systems it is apparent that proper mechanical system design allows utilization of low-cost sub-system components and reduces parts count.