V.D.3 Development and Demonstration of a New-Generation High Efficiency 1-10 kW Stationary Fuel Cell System

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Objectives

Technical Barriers

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

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

Technical Targets

This project is developing novel fuel processing, proton exchange membrane (PEM) fuel cell technologies and integration strategies in order to achieve DOE targets for integrated stationary PEM fuel cell power systems for year 2011.

- Electrical energy efficiency at rated power – 40%
- Combined heat and power (CHP) energy efficiency at rated power – 80%
- Cost – $750/kW (in volume production)
- Durability – 40,000 hours lifetime

Approach

The approach used to develop the new-generation 1-10 kW_e CHP unit that achieves the high-efficiency, high-durability and low-cost targets simultaneously includes a bold optimization and integration of existing Intelligent Energy (IE) technology platforms. The CHP unit will be based on IE's open architecture integration philosophy that maintains a high purity hydrogen interface between the hydrogen generation and fuel cell subsystems. The fuel cell subsystem will be derived from IE's 2 kW CHP platform and its advanced 10 kW auxiliary power unit platform that achieves 60% efficiency on pure hydrogen. An innovative hydrogen generation subsystem will be developed to support the aggressive cost and performance targets, but will leverage IE's experience from two validated technology platforms: IE's 100 to 500 W_e membrane reformer (MR) that achieves 99.9+% purity with seven different fuel types, and its 10 kW_e steam reformer integrated with a fast cycle pressure swing adsorption (PSA) hydrogen purification system. Both of these hydrogen generation platforms currently achieve efficiencies in the ~65% range. IE has been investigating significant improvements in these technologies to increase hydrogen generation efficiency to over 70% and a new breakthrough adsorption enhanced reformer (AER) that can achieve efficiencies of 75 to 80%. The greatest challenge of the development will be to achieve an optimized balance between increased stack performance (high cell voltage at high current densities), low-cost cell components, increased hydrogen generation efficiency (high fuel conversion, lower steam/carbon ratios, maximum recuperation of heat and water vapor, and high hydrogen recovery factors), low parasitic power components and efficient grid connected inverter, and least cost balance-of-plant (BOP) in a fully integrated system.

IE has developed two fuel cell platforms both using internally humidified metallic bipolar plates with fewer parts and more compact than the competition. For the low power systems (<1.5 kW), IE uses air-cooled (AC) stacks and for high power systems (>2 kW), IE uses evaporatively cooled (EC) stacks.

Accomplishments

- Membrane reformer reached 53% efficiency.
- Tubular steam reformer projected efficiency of 67%.
- Validated novel approach to AER.
- Through a combination of enhanced MEA, diffuser optimization and reduced bipolar plate interfacial resistance, fuel cell electrical efficiency at 96 A (0.5 A/cm^2) has been improved by 6.2% against the program baseline.
- Design, manufacture and validation of high efficiency power management device for use with fuel cell system air delivery sub-system.
- Design and manufacture of high efficiency direct current to direct current converter for system self-start and battery charge application.

Results

Fuel Processors Development

1. Membrane Reformer

IE fabricated and tested a 10-membrane module (MR7) reformer and collected H_2 flux data. Ethanol reforming was conducted in the scaled-up membrane reformer (9X scale-up) with a goal to demonstrate production of 5-7 SLPM of high purity H_2. The membrane reformer consisted of a single hardware that integrated the operations of steam reforming, catalytic combustion, water-gas shift and H_2 separation in a single unit. While operating at an upstream pressure of 11 bar, downstream pressure of 0.25 bar, 610°C, 2,700 h^{-1} gas hour space velocity , steam to carbon = 4.5 (low value compared to others), 5.5 SLPM of H_2 was produced in a stable fashion (Figure 1). C, H and O closures were 8%, 12% and 16% respectively. The excess condensed water was very clear and did not contain trace of unconverted alcohol or other intermediates. The BOP components (heat exchangers etc.) were not optimized during this test, and so reformer thermal efficiency was about 53% (target >60%). A second test with system level modifications is under way.

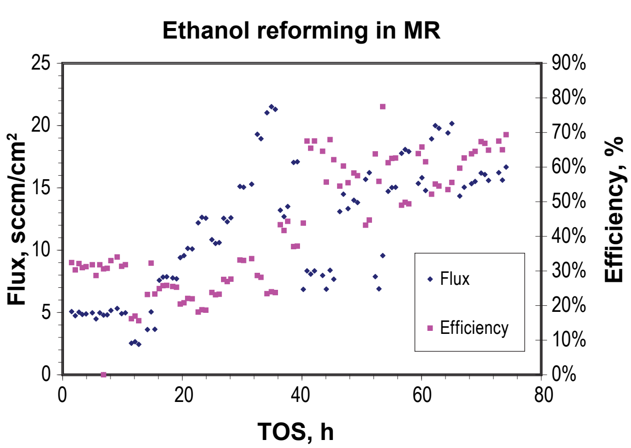

FIGURE 1. Meso Membrane Reformer: Summary of Flux and Efficiency

2. Steam Reformer

IE built and tested with methane a low-cost tubular steam reformer and tested ethanol in another tubular reactor. Design and fabrication of the new Hestia reactor was completed in order to address increased efficiency. Improvements included (1) operation at higher pressures, which will enhance hydrogen recovery through the pressure swing adsorption process, (2) a new low-pressure drop catalytic combustor design that will lead to reduced parasitic power loads, and (3) simplification of assembly and balance of plant. Reactor operation began in December 2007 and optimization continued in 2008. Efficiencies were successfully increased to ~67% (expected H_2 generation efficiency is based on reformer test results and potential PSA recoveries).

The reactor heat exchange capabilities and operation at a couple of different loads were characterized. Operational experience was documented for use in the system balance of plant components. The controls system was updated for ease of operation and functionality. Most of the testing was on natural gas but steady state steam reforming was also performed on a tubular reactor resulting in gas concentration near equilibrium at the exit of the reformer.

3. Adsorption Enhanced Reformer

IE has chosen a low-temperature (~500°C) adsorption enhanced reformer that uses hydrotalcites (KHTC) rather than the high-temperature (600-800°C) adsorption enhanced reformer that uses calcium oxide-calcium carbonate cycle [1-4].

IE has found a proprietary, unique and novel approach to regeneration of the spent sorbent bed that is more energy efficient than that was indicated in the Air Products and Lehigh efforts.

Dr. Armin Ebner and Dr. Jim Ritter of University of South Carolina as a subcontractor to IE have modified and updated their PSA code for simulating AER. The model matched the data in that it shows H_2, CH_4, and then CO_2 breakthrough.

Dr. Winny Dong and her team at California Polytechnic (CalPoly) University, Pomona synthesized xerogels of MgO as potential sorbents, which are being evaluated at IE. Dr. Mingheng Li of CalPoly has done simulations of AER and SMR.

IE built, tested and established proof-of-concept in a 1-tube cyclic adsorption enhanced reformer. Typical AER result from this test rig is shown in Figure 2.

IE has found that the KHTC charged in the AER had been cycled for over 150 times with no apparent loss of activity or capacity.

IE is building a larger AER tube to get longer AER time than the current one wherein pure H_2 (CO_2-free and CO-free) is produced prior to regeneration.

IE is designing a multi-tube cyclic AER with solenoid valves for obtaining continuous H_2 production and the cycle timing data needed to design rapid cycle rotary valves for the AER.

4. Fuel Cell Development

Efficiency enhancement of the fuel cell system has been addressed in a number of areas; fuel cell performance, parasitic losses and power electronics efficiency. From a cost reduction perspective, work focused on the design and preliminary testing of a pressed plate variant of the evaporatively-cooled architecture; this offers considerable cost-reduction at volume provided the performance is comparable with existing hardware.

Diffusion media trials in single cells produced good results in two areas; in the first, parametric testing of media with varying bulk polytetrafluoroethylene (PTFE) and front face (coating). PTFE content showed that electrical efficiency gains could be achieved over the benchmark, while the media tested all showed reduced resistance to air flow and hence reduced air pressure drop (Figure 3) contributing to lower system parasitic power through reduced compressor power requirements.

MEAs from three suppliers were tested initially in single cells, two suppliers then delivered enhanced versions for further single-cell and then short-stack trials. MEA optimization was achieved by changing to more suitable ionomers and by down-selecting variant electrode technologies; further gains were made by reducing membrane thickness which supplier testing has shown does not necessarily compromise membrane life but confirmation of this in IE hardware is required. Recent development has focused on the use of new alloys and coatings for bipolar plates. Ex situ testing identified a number of materials with contact resistances approaching that of gold; these were initially proven in single cells and then the better performing options were tested in short stacks. Most recently, single-cell tests have been carried out using the most promising combinations of developments and one of two scheduled short stacks has begun testing. Figure 4 shows the performance of this stack against the benchmark performance at the beginning of the project. At 0.5 A/cm^2, mean cell voltage is 0.713 V compared with 0.635 V for the benchmark data, equating to an increase in stack operating efficiency from 52 to 57%. Furthermore, if this performance is replicated in a 192 cell stack operating at 0.635 V, then the projected power output would be increased from 11.85 kW to 22.2 kW, i.e. the power output at 0.635 V could be increased by ~87%.

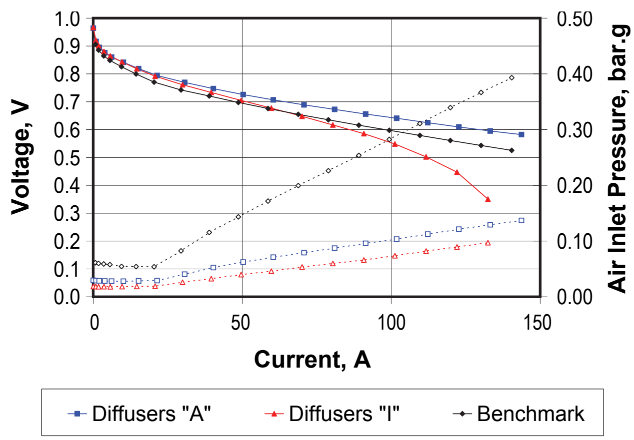

FIGURE 3. Mean Cell Voltage vs Current of IE Fuel Cell

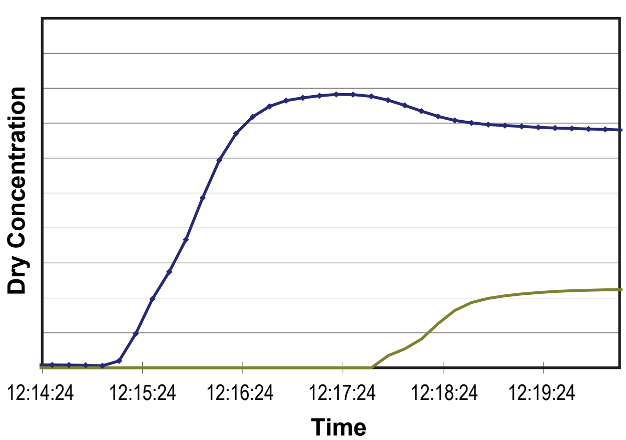

FIGURE 2. Test Data from AER System Showing Delayed Breakthrough of CO_2

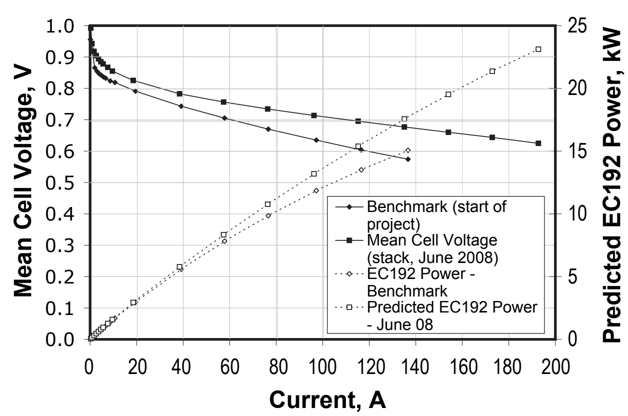

FIGURE 4. Single Cell Tests of Most Promising Combination of Improvements

A pressed plate version of the EC architecture has been designed and tested. A revised power management configuration has also been designed and tested.

5. System Modeling

Comparative systems evaluation on the three reformers and IE's EC PEM fuel cell with the partnership with Sandia National Laboratories (SNL) has begun. Collaboration with SNL to assess potential performance of possible system architecture, as a part of SNL's contribution to IEA-HIA Task 18, was launched in March 2008. A system model was adapted to capture IE's approach and the initial results show 35% fuel-to-electric efficiency based on historical Hestia steam reformer data, new fuel cell data and parasitic power losses.

SNL is now considering other system architectures – MR and AER, and continuing to update models with experimental data.

Conclusions and Future Directions

IE has evaluated two different PEM fuel cells (AC and EC) and various ways to improve their efficiencies and to reduce cost. We have shown the fuel cell efficiency can be improved from around 50% to 57%.

IE has built and continuing to evaluate at component level, three different reformers/fuel processors and purifiers to produce high purity hydrogen: steam reformer (+PSA), membrane reformer and adsorption enhanced reformer. IE has formed research alliances with universities (CalPoly-Pomona, University of South Carolina), SNL and many commercial partners, most notably with Scottish Southern Energy for demonstrating a CHP system. In early March, Intelligent Energy signed a landmark joint venture (JV) agreement with Scottish and Southern Energy, the second largest supplier of electricity and natural gas in the United Kingdom (UK). The JV Company called IE CHP (UK & Eire) Ltd will develop clean and reliable, fuel-cell based, CHP systems for the light industrial, commercial and residential markets in the UK and Ireland.

In early August, in consultation with DOE, IE will down-select the technology options for the demonstration system – such as the EC Fuel Cell at 5 to 10 kW_e together with an appropriate Hestia SMR+PSA and arrive at the decision to go forward towards designing and building the demonstration system in Year 2. IE will choose a demonstration site in consultation with DOE and the project partners by mid-part of Year 2 for demonstration in Year 3. In the event the most developed platform falls slightly short of 40% on the overall electric efficiency (H_2 generation at 70% x fuel cell at 57% = 39.9%), IE intends to develop in parallel the AER that would potentially allow higher H_2 generation efficiency close to 80% which would enable potentially to get more than 45% overall electric efficiency.

FY 2008 Publications/Presentations

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2. Sircar, et al., I&EC Res., 46, 5003-5014 (2007)] and one in press [J. Hydrogen Energy, 33 (2008)].

3. Sircar, S., Kratz, W.C.: Simultaneous production of hydrogen and carbon dioxide from steam reformer off-gas by pressure swing adsorption. Sep. Sci. Technol. 23, 2397 (1988).

4. Sircar, S., Hufton, J.R., Nataraj, S.: Process and apparatus for the production of hydrogen by steam reforming of hydrocarbon. U.S. Patent No 6,103,143 (2000).