The Role of Solid Oxide Fuel Cells in Advanced Hybrid Power Systems of the Future

by David Tucker, Michael Shelton, and A. Manivannan

In pursuing the implementation of highly efficient, emission-free power, the U.S. Department of Energy (DOE) is looking to the development of hybrid power systems that make use of the coupling of an electrochemical device with a heat engine, or more specifically, a solid oxide fuel cell (SOFC) and a gas turbine.[1-4] The synergies of coupling these systems in a hybrid configuration provide the potential for reaching the highest possible electric conversion efficiency ever realized.[5] As such, advanced hybrid power systems that incorporate a fuel cell and a gas turbine represent fossil or renewable energy production technology that provide the opportunity for a significant improvement in generation efficiency.[6] An example of a simplified process diagram of the power cycle in a hybrid fuel cell gas turbine is shown in Fig. 1.

While much of the DOE-sponsored research focuses on improving the performance of solid oxide fuel cells, a hardware simulation facility has been built by the Office of Research and Development at the National Energy Technology Laboratory (NETL) to explore both synergies and technical issues associated with integrated hybrid systems. The facility is part of the Hybrid Performance (Hyper) project, and is made available for public research collaboration with universities, industry, and other research institutions. The Hyper facility is capable of simulating high temperature fuel cell systems from 300 kW to 700 kW coupled with a 120 kW turbine. The purpose of the Hyper project is to specifically address this higher risk research by combining the flexibility of numerical simulation with the accuracy of experimental hardware.[7] An illustration of the Hyper facility is shown in Fig. 2.

The Hyper facility makes use of pressure vessels and piping to simulate the volume and flow impedance of the cathode and a burner controlled by a real-time fuel cell model running on a dSpace hardware-in-the-loop simulation platform to simulate the fuel cell thermal effluent. The hardware used to simulate the fuel cell is integrated with a 120 kW Garrett Series 85 auxiliary power unit (APU) for turbine and compressor system. The APU consists of single shaft, direct coupled turbine operating at a nominal 40,500 rpm, a two-stage radial compressor, and gear driven synchronous generator. The electrical generator is loaded by an isolated, continuously variable 120 kW resistor load bank. The compressor is designed to deliver approximately 2 kg/s of air at a pressure ratio of about four. The project facility makes use of two counter flow primary surface recuperators with a nominal effectiveness of 89% to preheat the air going into the pressure vessel used to simulate the fuel cell cathode volume.[8] A more detailed description has been provided previously.[7,9] A picture of the facility is shown in Fig. 3.

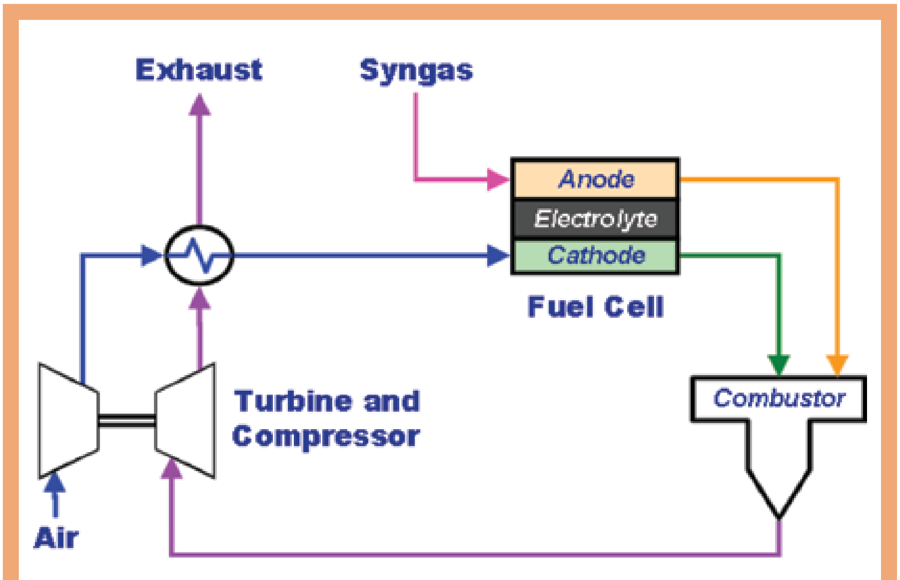

Fig. 1. *Simplified flow diagram of a representative direct fired, recuperated fuel cell gas turbine hybrid system.*

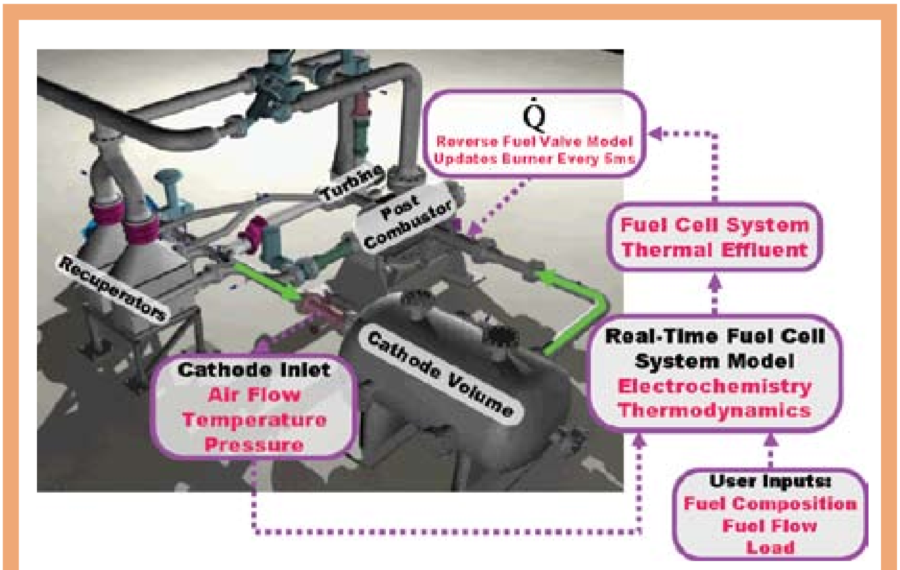

Fig. 2. *Illustration of the Hybrid Performance (Hyper) simulation facility at NETL.*

Fuel Cell Model

A real-time computational model is used to simulate the fuel cell portion of the hybrid. The model is used to dynamically calculate the thermal effluent of a stack based upon measured Hyper flow conditions and user set points, and assumes the use of coal syngas as a fuel, as shown in Fig. 4. In

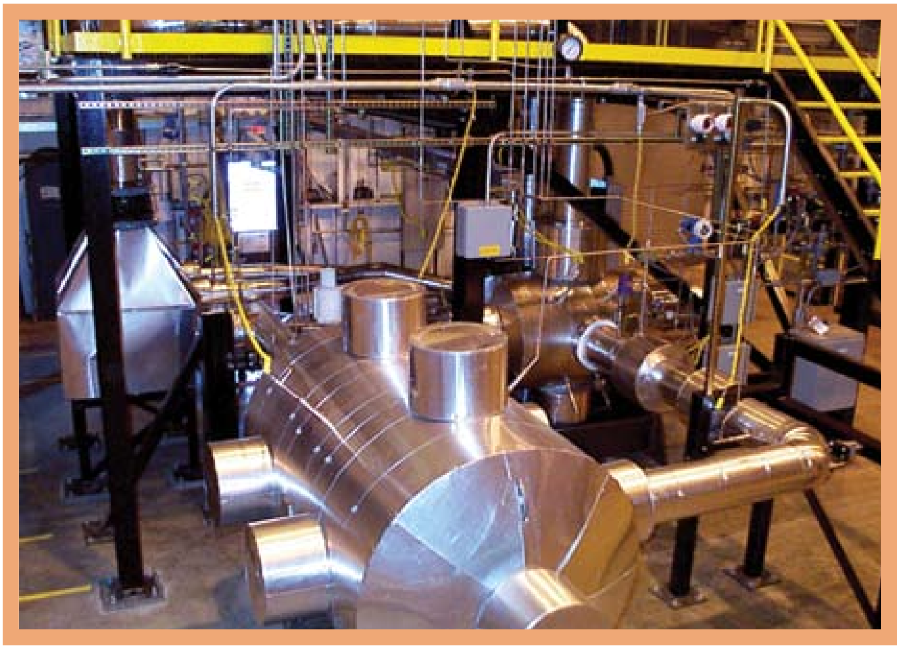

Fig. 3. *A photograph of the Hyper facility at NETL (the cathode volume is shown in the foreground).*

earlier studies, natural gas was used as a fuel source and was reformed to hydrogen and carbon monoxide before entering the fuel cell. For steady state system mapping studies, the model can be used off-line and driven to a steady condition that matches the corresponding steady state process conditions of the Hyper facility hardware for each valve position and specified turbine load. A more detailed description of the model is published elsewhere.[10]

As shown in Fig. 4, the numerically simulated section consists of the planar solid oxide stack, anode recycle, a pre-combustor, and an anode off gas post-combustor. For previous studies the stack size was fixed and composed of 3225 cells to target a range of electrical power generation varying between 228 kW and 687 kW. Computationally, only a single 20 cm x 20 cm cell is modeled with the inlet and outlet streams scaled by the 3225 factor. The range of fuel cell operating conditions used during the tests is specified in Table I.

To further expand the capabilities of the Hyper facility, a distributed 1D model of a solid oxide fuel cell capable of real-time operation has been developed at the Georgia Institute of Technology and implemented in the Hyper dSpace platform. This facilitates determination of dynamic temperature, species concentrations, and current density profiles along the cell during transient system events. Testing is currently underway to examine system response to fuel cell load changes and compressor dynamics resulting in fuel cell cathode airflow transients. The results are expected to be useful in developing control strategies to mitigate undesirable or damaging operating conditions.

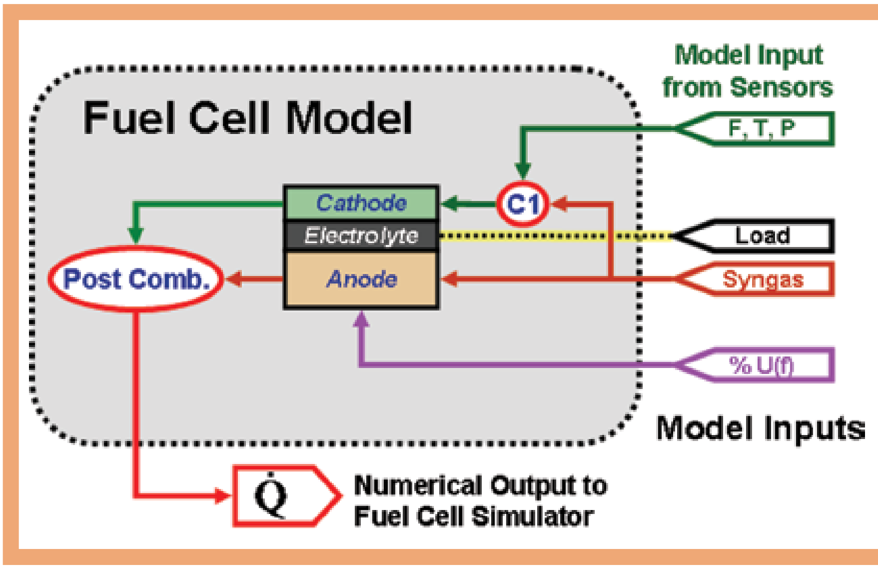

Fig. 4. *Diagram of the Hyper facility real-time fuel cell model.*

Synergies

Efficiency.—The most apparent synergy of integrating a fuel cell and a gas turbine is the gain in total system efficiency. Quite simply, using a turbine to recover electricity from the waste heat of the fuel cell system allows for an increase in total system efficiency. The total system electric efficiency is shown by the lines in Fig. 5 for a combination of topping and bottoming cycle efficiencies. For hybrid systems, the fuel cell is generally used as the topping cycle with the turbine in a bottoming configuration, as shown for the direct fired case illustrated in Fig. 1.

However, a hybrid system generally has efficiencies that are greater than the simple sum of its parts (up to 60% HHV of coal). Cathode cooling airflow for thermal management in a solid oxide fuel cell represents a significant parasitic loss to the electrical efficiency in this component. Integration with a gas turbine provides this airflow without reduction in efficiency. The incorporation of exhaust gas recuperators can provide pre-heat for the fuel cell and still further improve the efficiency of the turbine cycle. In a similar fashion, the turbine cycle allows the fuel cell to be operated under pressure, improving fuel cell performance without a parasitic cost.

System Flexibility and Energy Security.—The need for preheating fuel cell cathode cooling flow is facilitated by the integration of a recuperated turbine cycle which operates at low pressure ratios and relatively low turbine inlet temperatures. Such lenient requirements preclude the need for complex turbine technologies such as turbine blade cooling associated with high temperature operation or even inter-stage compressor cooling required for high pressure ratios.

Gasification technologies are driven to more challenging operation at higher pressures by the requirement for a hydrocarbon rich syngas with a higher volumetric energy content for improved efficiencies in standard power cycles found in integrated gasifier combined cycles (IGCC), for example. An SOFC, on the other hand, is capable of achieving excellent performance using hydrogen (H_2) and carbon monoxide (CO) as a fuel source, eliminating the requirement for complicated gasification technology and opening up the possibility of fuel flexible systems operating at high efficiency.

Since high system efficiency can be achieved even if the turbine in the cycle does not produce electricity,

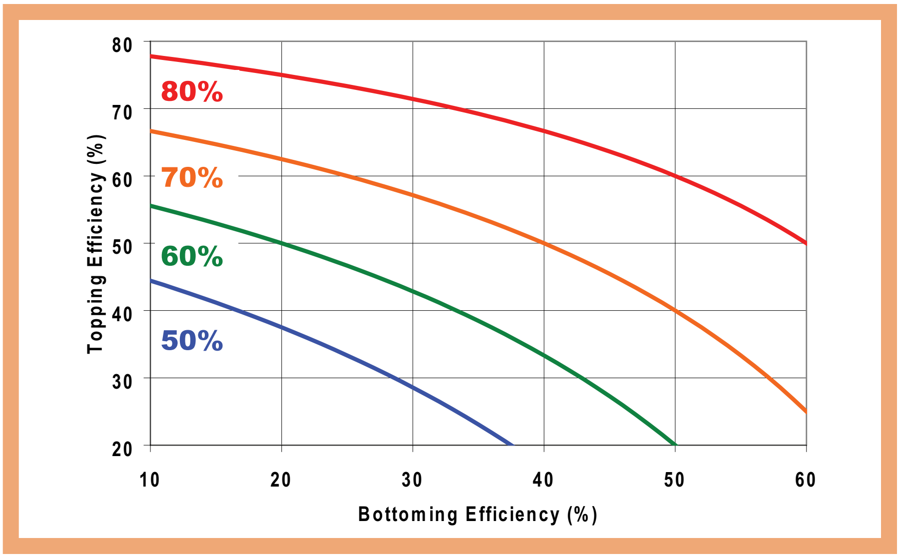

Fig. 5. *Total system efficiency as a function of topping and bottoming cycle efficiencies.*

there is the possibility of maintaining a low cost spinning power reserve and peaking demand. If the fuel cell is base loaded at a nominal condition without the turbine loaded to its maximum capacity, there exists the potential for handling peak load demands by auxiliary firing of the turbine without a significant reduction in total system efficiency. A spinning reserve could also be maintained without parasitic drain on fuel supplies. If sufficient turndown can be demonstrated, because the fuel cell is an electrochemical device, recovery from a full load reject could be accomplished in a matter of minutes instead of days. In recent studies using the Hyper facility to map fuel cell turbine operating envelopes, a system operating range representing a possible turndown of 69% was demonstrated.[11] The implementation of fuel cell turbine hybrid technology could result in more flexible power systems and a significant contribution to energy security in the U.S.

Table I. Range of fuel cell parameter values.

Parameter	Range	Nominal Value
Cell Voltage (V)	0.746 to 0.816	0.746
Load Current (Amps)	90 to 276	220
Stack Power (kW)	228 to 687	529
Stack Fuel Utilization	0.59 to 0.90	0.80
Single Pass Fuel Utilization	0.50	0.50
Stack Efficiency (% HHV)	34 to 44	40.4
Cell Temperature (K)	1,133	1,133
Stack Number of Cells	3,225	3,225
Total Stack Mass (kg)	4,515	4,515
Heat Capacity of Stack (kJ/K)	2,134	2,134
Syngas Fuel to Stack (kW)	534 to 1,631	1,310
Syngas to C1 Combustor (kW)	0 to 288	0

Technical Challenges

Control of Cathode Airflow.—If such systems are to be realized in stationary power generation in the near future, integration and control technology must be developed and proven. Recent work has shown management of cathode airflow to be critical to fuel cell performance and effective control of hybrid systems.[12,13] Previous studies at NETL have shown that small transient changes in cathode airflow can have a dramatic effect on system performance.[14] The effect of flow perturbation due to compressor dynamics or valve operation was shown to be more significant than fuel cell inlet temperature excursions resulting from load variations.[14] It is likely off-design operation of hybrid systems will require careful management of cathode flow.

Compressor Stall and Surge.—The introduction of pressure losses between the compressor and turbine decreases the compressor surge margin and puts the fuel cell at risk for exposure to the pressure dynamics associated with compressor surge. This event represents the greatest risk to the fuel cell in the system because pressure variations are sufficient to damage the turbine and destroy the fuel cell. The use of compressor bleed air during startup was shown to be effective in increasing compressor mass flow and avoiding stall and surge during startup, and a base condition was established for future tests of other control strategies.[15] Currently, the possibility of using the other bypass valves in the Hyper facility to increase surge margin is being examined.

Currently, plans are underway to expand the Hyper facility to include a gasifier capable of utilizing either fossil or renewable fuel sources, as shown in Fig. 6. A recent numerical simulation conducted at the lab showed that capturing the CO_2 upstream of the fuel cell anode did not reduce system efficiency as would be expected.[16] The energy requirement for steam and CO_2 capture was offset by an increase in fuel cell performance operating on a hydrogen-rich syngas without anode recycle (since carbon deposition is not an issue), and an increase in turbine performance due to elevated turbine inlet temperatures.

About the Authors

David Tucker is the Project Leader and principal investigator for the Hybrid Performance (Hyper) project at the U.S. Department of Energy, National Energy Technology Laboratory (NETL). Previous to his employment at NETL, Dr. Tucker had a diverse career in academia and industry. His research interests and experience include fuel cell turbine hybrid systems, solid oxide fuel cell cathode development, coal structure and catalytic liquefaction, flash pyrolysis of

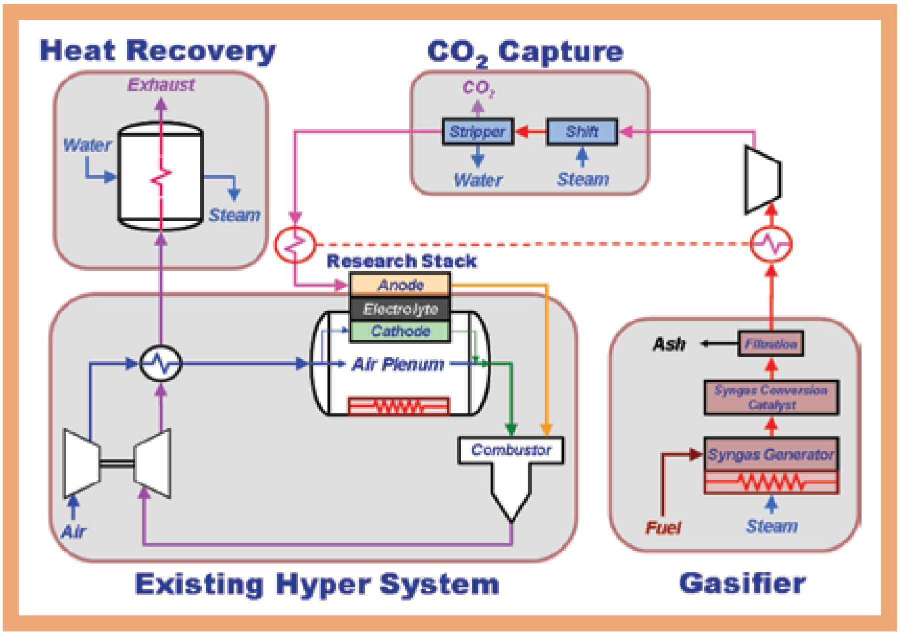

Fig. 6. *Proposed modifications to the Hyper facility for expanding the scope of hybrid system exploration.*

lignite and biomass, and heterogeneous catalysis in gasification. Dr. Tucker maintains several research collaborations, and participates as an adviser in the NRC Research Associateship Programs. He may be reached at david.tucker@netl.doe.gov.

Michael S. Shelton is a professional engineer and CEO of SpectraCADD, LLC. Previously, as the senior engineer for Trans-Alaska Pipeline System, Mr. Shelton focused his efforts in Alaska on arctic engineering and the special engineering issues faced daily by the Alaskan people. Mr. Shelton has research interests in fuel cell turbine hybrids and the application of high temperature structural materials and computational fluid dynamics to this field. Mr. Shelton also serves on several professional engineering committees responsible for developing industry codes standards. He may be reached at michael.shelton@jacobs.com.

A. Manivannan is a materials scientist at the U.S. Department of Energy, National Energy Technology Laboratory (NETL). Prior to joining U.S. DOE, Dr. Manivannan was a faculty member of the Physics Department, West Virginia University, where he currently serves as an adjunct professor. He has carried out research in multidisciplinary areas in materials science for more than 25 years in academia. His research interests and expertise include materials for energy conversion and storage involving photoelectrochemical cells, solid oxide fuel cells, electrochemical energy storage devices such as Li-ion batteries, supercapacitors, and thermoelectric materials, catalysts, etc. Dr. Manivannan has been active in performing several international research collaborations and participates as an adviser in the NRC Research Associateship Programs. He may be reached at manivana@netl.doe.gov.

References

1. Report to Congress, "FutureGen Integrated Hydrogen, Electric Power Production and Carbon Sequestration Research Initiative," U.S. DOE, Office of Fossil Energy, March 2004.
2. M. C. Williams, J. Strakey, and W. Surdoval, *J. Power Sources*, **159**, 1241 (2006).
3. U.S. Department of Energy, "Fuel Cell-Coal Based Systems," U.S. DOE Funding Opportunity Announcement, DE-PS26-05NT42346 (2005).
4. R. A. Dennis, G. S. Samuelsen, M. C. Williams, N. T. Holcombe, and A. W. Layne, "The National Energy Technology Laboratory's Hybrid Power Systems Program," 2002 ASME Turbo Expo, Amsterdam, The Netherlands (GT-2002-30668).
5. W. Winkler, P. Nehter, M. C. Williams, D. Tucker, and R. S. Gemmen, *J. Power Sources*, **159**, 656 (2006).
6. Systems Analysis of an Integrated Gasification Fuel Cell Combined Cycle; http://www.netl.doe.gov/energy-analyses/pubs/IGFC%20Combined%20Cycle%20Final%20Report.pdf
7. D. Tucker, E. Liese, J. G. Van Osdol, L. O. Lawson, and R. S. Gemmen, "Fuel Cell Gas Turbine Hybrid Simulation Facility Design," 2003 ASME International Mechanical Engineering Congress and Exposition, New Orleans, LA.
8. M. E. Ward and M. D. Stephenson, "The Primary Surface Recuperator - Durability and Applications," International Gas Turbine Congress, Kobe, Japan (1999).
9. D. Tucker, L. O. Lawson, and R. S. Gemmen, "Characterization of Air Flow Management and Control in a Fuel Cell Turbine Hybrid," Proceedings of the ASME Power Conference, PWR2005-50127 (April 2005).
10. E. A. Liese, T. P. Smith, C. L. Haynes, and R. S. Gemmen, "A Dynamic Bulk SOFC Model Used in a Hybrid Turbine Controls Test Facility," 2006 ASME Turbo Expo, Barcelona, Spain, GT2006-90383.
11. D. Tucker, E. A. Liese, and R. S. Gemmen, "Determination of the Operating Envelope for a Direct Fired Fuel Cell Turbine Hybrid Using Hardware Based Simulation," 2009 International Colloquium on Environmentally Preferred Advanced Power Generation, Newport Beach, California, ICEPAG2009-1021 (February 2009).
12. A. Traverso, A. F. Massardo, R. A. Roberts, J. Brouwer, and G. S. Samuelsen, "Gas Turbine Assessment for Air Management of Pressurized SOFC/GT Hybrid Systems," First European Fuel Cell Technology and Applications Conference, Rome, Italy, EFC2005-86228 (December 2005).
13. C. Stiller, B. Thorud, O. Bolland, R. Kandepu, and L. Imsland, *J. Power Sources*, **158**, 305 (2006).
14. D. Tucker, T. P. Smith, L. O. Lawson, and C. Haynes, "Evaluation of Cathodic Air Flow Transients in a Hybrid System Using Hardware Simulation," Proceedings of the 4th International Conference on Fuel Cell Science, Engineering, and Technology, FUELCELL2006-97107 (June 2006).
15. D. Tucker, L. O. Lawson, and R. S. Gemmen, "Evaluation of Hybrid Fuel Cell Turbine System Startup with Compressor Bleed," 2005 ASME Turbo Expo, GT2005-68784.
16. E. A. Liese, "Comparison of Pre-Anode and Post-Anode Carbon Dioxide Separation for IGFC Systems," 2009 ASME/IGTI Turbo Expo, GT2009-59144.