V.11 Techno-Economic Feasibility of Highly Efficient Cost Effective Thermoelectric-SOFC Hybrid Power Generation Systems

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Objectives

Phase I

- Create innovative integrated solid oxide fuel cell-thermoelectric (SOFC-TE) technical concepts meeting the requirements of 65% electric efficiency and $400/kWe.
- Develop techno-economic models to assess the feasibility of the created concepts using trade studies
- Create specifications for the optimal system and identify the barriers/technology gaps.

Phase II

- Present the detailed technology/issue/solution to be matured that lead the concept going beyond a feasibility analysis in Phase I.

Accomplishments

- Identified the best system configuration with an ambient pressure stack, which serves as an intermediate step in technology maturation toward the optimal pressurized SOFC-TE system to meet the project goals for high-efficiency, coal-based central power plants.
- Created the specifications for the optimal systems, including both the pressurized SOFC-TE and the ambient-pressure SOFC-TE systems.
- Identified the barriers and technology gaps for the deployment of the hybrid systems.
- Created a conceptual framework for Phase II work.

Future Work

Complete the Phase I report and Phase II proposal.

Introduction

A TE material can generate power directly when it is conducting heat from a hot fluid to a cold one, known as the Seebeck effect. In a SOFC, the exhaust fluid leaving the stack and its afterburner typically has a temperature around 800°C. In today's SOFC design, the exhaust heat is usually recovered in a heat exchanger or preheater, to preheat the fuel or air entering the stack. A TE generator can be used for heat recovery as well as converting part of the heat to electricity directly.

This study is concerned with the trade-off between the performance and cost in reaching the overall system performance and cost targets. During the first year of the project, the best system configuration was identified as a pressurized SOFC-TE system. The project focus for the second year includes the product cost and performance specifications for the optimal concept, as well as the evaluation of the technology and identification of cost barrier and enablers.

Approach

A road map was created that shows the intermediate stages from a proof-of-concept unit at 1 kW scale to the ultimate, optimized hybrid system in multi-megawatt coal power plants. Ambient-pressure systems were found to be one of the intermediate stages in the development and maturity roadmap. The optimal ambient-pressure configuration was obtained based on system modeling.

Based on the modeling results, system specifications were created for both the optimal pressurized and the ambient-pressure systems. The technology and cost barriers were evaluated for the deployment of the hybrid system. While the SOFC stack using coal gas as the fuel and the TE technology require development by themselves, the barriers and enablers analysis here focuses on the integration of the SOFC and TE. The plan for Phase II work is being framed and includes the building and testing of a proof-of-concept lab unit.

Results

Optimal Ambient-Pressure SOFC-TE

Due to the fact that the ambient-pressure system does not have a turbine, the exhaust gas leaving the SOFC burner has a temperature of more than 800°C and is higher by approximately 300°C than in the pressurized case. This can be used for power generation with a high stage TE in addition to the TE in a pressurized system. The system diagram is shown in Figure 1.

The system efficiency results are shown in Figure 2. Major parameters affecting the system efficiency include ZT, the figure of merit of the TE materials, and the cold gas flow rate in the low stage TE. The cold gas flow rate at the high stage TE is determined by the SOFC stack. It is approximately equal to the hot gas flow rate and

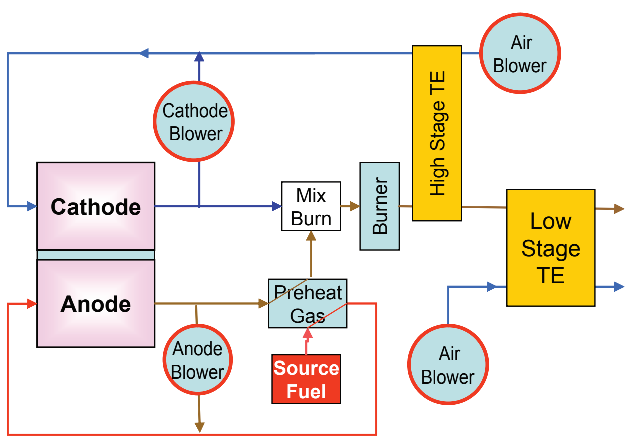

FIGURE 1. Diagram for the Optimal Ambient-Pressure SOFC-TE System

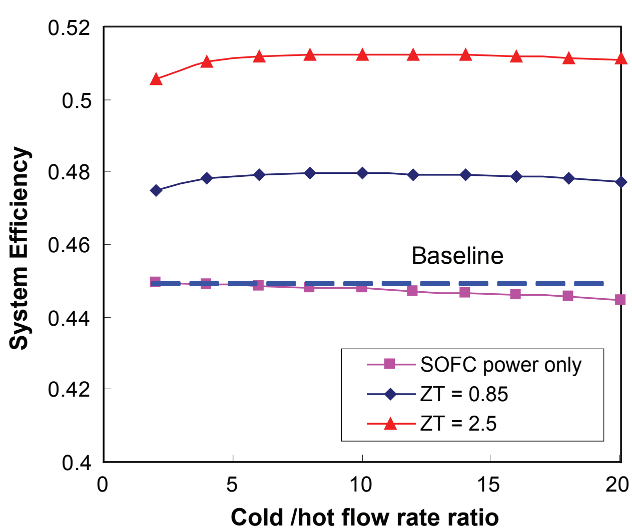

FIGURE 2. Ambient-Pressure System Efficiency at Different Cold Flow Rate and ZT

cannot be changed arbitrarily. Today's state-of-the-art ZT value with high technology readiness level, i.e., in production, is at about 1 at mid-range temperatures [1]. Higher ZT of 3.2 has been achieved in Lincoln Lab [2] but the technology readiness level is low. The electricity generated by the two TE contributes close to 6% points of the overall 51% system efficiency for the ambient-pressure SOFC-TE system.

Cost and Performance Specifications for the Selected Concepts

For this task, the system working principles were described first. The system operation includes five modes: start-up, steady operation, load transition, shut-down and idle.

Major system design requirements are: 1) overall performance requirements, such as system efficiency, overall capacity; 2) transient requirement, mainly the time for start-up, load transition and shut-down; 3) system control, allowing the system to operate in different modes with proper transition and logic control of fuel and air supply; and 4) subsystem or replacement requirements, i.e., time for a component or subsystem replacement.

Based on the system requirements, the components design requirements were defined. Major component requirements are performance specifications such as heat exchanger capacity and fan efficiency. The life of major components was listed and a replacement schedule was created, as shown in Table 1. The factory manufacturing cost specifications were then obtained based on the cost modeling. The cost specifications considered the market size or production volume effect.

Technology Gaps/Cost and Performance Barriers

The major technology gaps to reach the goal of 60% or higher system efficiency arise from the stack, the TE and the system integration. Although development of the standalone SOFC stack and the TE generator are important, the focus of this study is conceptual system definition, modeling and integration. Major cost and performance barriers include:

1) The cathode recycle blower that can withstand the >800°C exhaust temperature.
2) The anode blower that can withstand the same high temperature but with the flow rate 35 times smaller than the cathode blower. An ejector may serve this function but needs to be developed.
3) The air preheater that should have long life, low cost and can resist 800-1,000°C hot gas.
4) The control of coupled turbo-compressor and the stack.
5) Possible carbon deposit due to metastability of the (H_2 + CO) mixture in the fuel supply pipe.

TABLE 1. Replacement Schedule for the Proposed SOFC-TE Optimal Configuration

Component	Life		Replacement or Overhaul Schedule																			
	Years	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SOFC stack	5	1					1					1					1					1
Cathode Blower	2.5	1			1		1			1		1			1		1			1		1
Anode Blower	2.5	1			1		1			1		1			1		1			1		1
Turbine	5	1					1					1					1					1
Air compressor	3	1			1			1			1			1			1			1		
Pressure vessel	3	1			1			1			1			1			1			1		
Air preheater	5	1					1					1					1					1
PCS	5	1					1					1					1					1
BOP	10	1										1										1
Control	10	1										1										1
Insulation	10	1										1										1
Burner	5						1					1					1					1
TE blower	5	1					1					1					1					1
TE	20	1																				

6) A 200 kW SOFC-TE system requires a turbo-compressor of 50-60 kW of net power. Small turbines tend to increase the cost per kilowatt. If multiple SOFC stacks share one turbo-compressor for higher efficiency and low cost, the control between the sharing stacks needs to be coordinated. The piping should be able to resist 800-1,000°C hot gas and have a small pressure drop and good insulation.

7) The power conditioning system (PCS) that can handle the power generated by the SOFC and TE. The components generate DC power at different current and voltage levels. The PCS constitutes about 1/3 of the system cost. A cost-effective solution, e.g., using a plant DC bus, may be a good option.

Phase II Planning

A step-by-step development approach is proposed from today's feasibility study in Phase I to the ultimate application in coal-based central power plants. The conceptual roadmap is shown in Figure 3. This conceptual roadmap involves product development and introduction commensurate with technology maturity. Earlier products generate revenues, a fraction of which can be invested to develop the next and more capital intensive technology.

The first stage of the SOFC-TE development roadmap is a 1 kW scale proof-of-concept unit, which is proposed as part of the Phase II work. This is an ambient-pressure system with moderate technical risks but demonstrates the integration capabilities of the distinct, SOFC and TE, electrical generators while providing the opportunity for, at least, partial validation of system models. The second stage is the development, demonstration, and product design of 1-10 kW units that can be used in residential or defense applications. Process development for cost optimization and reduction would be an important activity starting with this stage. The third stage is the development of units on the order of 100 kW that can be used for commercial building applications, such as large box stores, supermarkets, office buildings, hospitals and schools. The last stage is the coal-based power plant application, where the technology for the key SOFC and TE components is matured, scaled-up, and effectively integrated to convert the heat content of coal gas to electricity efficiently and cost-effectively reaching the capital cost target of $400/kWe.

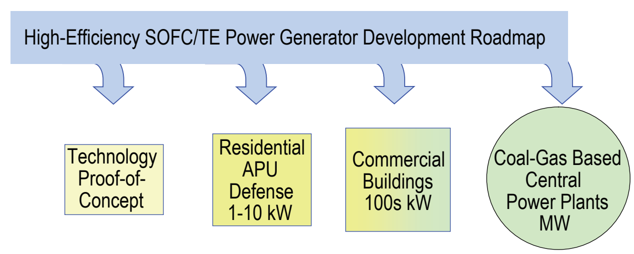

FIGURE 3. Roadmap from Today's Feasibility Study to Multi-MW Coal Power Plant Application

Conclusions

- An ambient-pressure SOFC-TE with 51% system efficiency is identified as a proof-of-concept system demonstrator toward the ultimate SOFC-TE central power plant systems.
- Performance and cost specifications for the optimal systems were created based on modeling.
- Technology and cost barriers were identified.
- A step-by-step approach is being proposed to progressively develop and mature the hybrid SOFC-TE system technology from the Phase II feasibility study to the central power plant application technology readiness level.

FY 2007 Presentations

1. Jifeng Zhang, Benoit Olsommer, Jean Yamanis, Douglas Crane, Lon Bell and Robert Collins, "Techno-Economic Analysis of SOFC-TE Hybrid Power Generation Systems", Presented at the Direct Thermal-to-Electrical Energy Conversion (DTEC) Program Review and Workshop, Coronado, CA, August 29-September 1, 2006.

2. Jifeng Zhang, Benoit Olsommer, Jean Yamanis, Douglas Crane, Lon Bell and Robert Collins, "Techno-Economic Feasibility of Highly Efficient Cost-Effective Thermoelectric-SOFC Hybrid Power Generation Systems", Presented at the 7th Annual Solid State Energy Conversion Alliance (SECA) Workshop and Peer Review, Philadelphia, PA, September 12-14, 2006.

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1. H. Bottner, "Micropelt Miniaturized Thermoelectric Devices: Small Size, High Cooling Power Densities, Short Response Time", ICT 2005, Clemson, SC.

2. Robert F. Service, "Temperature Rises for Devices That Turn Heat Into Electricity", Science 29 October 2004 306: 806-807.