II.2 Solid Oxide Fuel Cell Coal-Based Systems

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Objectives

- Develop and optimize a design of an integrated gasification fuel cell (IGFC) power plant incorporating a solid oxide fuel cell (SOFC)/gas turbine (GT) hybrid system that will produce highly efficient, environmentally benign and cost-effective electrical power from coal.
- Design and analyze an IGFC plant operating at both pressurized and ambient pressure conditions.
- Perform component gap analysis to identify performance requirements that exceed current capabilities.

Accomplishments

- Developed a design for an IGFC power plant capable of producing ~500 MW of power from Pittsburgh No. 8 coal at an efficiency of 50% relative to the higher heating value (HHV) of the coal, while isolating 90+% of the carbon in the coal.
- Designed and analyzed two different versions of the IGFC plant.
  - The "baseline" system uses an SOFC operating at ambient (1 atm) pressure producing 67% of plant gross power, a heat recovery steam generator and steam turbine system (HRSG/ST) producing another 30%, and an expansion turbine providing the balance. At GE's baseline SOFC performance targets, this system achieves 44% efficiency.
  - The pressurized system, where the SOFC operates at 15 atm, dispenses with the expansion turbine (as the syngas pressure does not need to be reduced before the SOFC) and adds a GT. In this configuration, the SOFC produces 62% of the gross power, with the rest divided evenly between the GT and ST. This system achieves 50% HHV efficiency at baseline SOFC performance targets.
- Performed SOFC performance sensitivity analysis on baseline system. Results of analysis indicate 50% HHV efficiency can be achieved by improving SOFC performance. SOFC requirements that yield 50% efficiency are extremely challenging, but not inherently impossible.
- Identified component performance requirements that are beyond today's capability.

Introduction

A high-level conceptual design and analysis of IGFC power plants of ~500 MW capacity was performed with two different plant architectures:

1. The "baseline" system, in which the SOFC operates at ambient pressure. This system contains no gas turbine; excess heat from the fuel cell cycle is used to generate steam in a HRSG for a ST.
2. The "pressurized" system, which contains a SOFC and GT, both operating at ~15 atm pressure, in addition to the HRSG/ST.

Both systems use a coal gasification system based on GE's gasification technology. In all cases, the systems were designed and component performance targets set in order to meet or exceed the Department of Energy's (DOE's) program requirements, as shown in Table 1. In the analysis, the Phase III requirements of 50% HHV efficiency and 90% CO_2 isolation were targeted.

TABLE 1. DOE Coal-Based Hybrid Minimum Requirements

	Phase I	Phase II	Phase III
End Date	**FY 2008**	**FY 2010**	**FY 2015**
Fuel	**Coal-Derived Hydrogen or Syngas**		
Cost (Power Blocks)	$600/kW	$400/kW	$400/kW
Efficiency (Coal HHV)	40%	45%	50%
CO_2 Isolated	90%	90%	90%
Validate Test (hours)	1,500	1,500	>25,000
Degradation (/1,000 hrs)	≤ 4.0%	≤ 2.0%	≤ 0.2%

As the Phase III targets are aggressive and will not be realized in hardware for several years, the performance targets of several system components (most notably the SOFC stack) have been set beyond current capabilities. Therefore, there are significant technology gaps that must be closed in order to achieve the results described here.

Approach

In a previous GE study, an IGFC plant design capable of 90% CO_2 isolation was developed and analyzed [1]. The down-selected design from that study, with CO_2 separation taking place downstream of a pressurized SOFC, was chosen as the original baseline concept for the present study. Several alternative approaches were proposed and considered [2]. Eventually, a single design was selected as the most promising for detailed analysis. This design is the "pressurized system" referred to in the Introduction. During the course of this work, DOE requested a study of an unpressurized system. The system selected for this study, the "baseline" system of this report, is very similar to (and simpler than) the pressurized system.

The IGFC concepts were modeled to identify component performance levels required to meet the 50% efficiency requirement. The goals of the analysis were as follows:

- Define the potential of the concept to meet the 50% goal
- Identify key technical gaps
- Perform sensitivity analysis on the effect of key performance assumptions on the system efficiency
- Flow down performance requirements to the SOFC development team

A general approach adopted at the start of the project was to limit technical risk to the SOFC subsystem, using conventional technology for all other parts of the system. However, this approach proved untenable, particularly for the baseline system, because the performance required of the SOFC was deemed unreasonably aggressive, even considering substantial technology development. Therefore, several system components have performance targets beyond current capabilities, including the SOFC stack, coal gasifier, CO shift, inverter, and steam turbine. In some cases, the performance cannot be achieved today because of purely technical limitations. In others, the performance can be achieved only at prohibitive cost. Regardless, technology advances are required to realize the full set of requirements.

Results

System Performance Summary

The performance for each system analyzed is shown in Table 2. Note that all cases shown include 90+% CO_2 isolation, as required. With baseline stack performance targets, the pressurized system is capable of achieving the 50% HHV efficiency target. The baseline system, however, has an efficiency of only 44.9% at these conditions. While this performance is adequate to meet Phase I and Phase II requirements (40% and 45%, respectively), significant improvement is required to reach 50%. This target can be achieved by increasing the SOFC performance requirements, using a "Super" SOFC.

TABLE 2. Performance Summary for Baseline and Pressurized Systems

Power Summary, MW			
	Baseline System	Baseline System with "Super" SOFC	Pressurized System
Coal Feed, HHV	1047.1	1047.1	1047.1
Total Gross Generated Power	542.5	592.9	585.8
Total Parasitic Power	71.9	69.7	64.9
Net System Power	470.6	523.2	520.9
System Efficiency	44.9%	50.0%	49.7%

Key Technology Gaps

The analysis described requires several system components to provide performance that represents advancement over current technology capability or that requires verification beyond that performed to date. These parameters, therefore, represent the technology risks (and in some cases, the cost risks) associated with achieving 50% HHV efficiency in an ambient-pressure IGFC system. Several of these key technology gaps will be discussed further here.

Coal

As specified by the DOE minimum requirements, this study has been based on a high-rank bituminous coal, Pittsburgh No. 8, which meets these criteria. Using other, lower-rank coals, will invariably result in a lower system efficiency. This is not a technology risk per se, but a factor that must be considered during development (and one that integrated gasification combined cycle developers are beginning to struggle with currently).

Gasifier

The quantity of oxygen required from the air separation unit (ASU) for gasification is a significant efficiency driver. In current systems, the oxygen-to-carbon ratio in the gasifier is ~0.96. An improvement of approximately 10% is assumed in this analysis. Such an improvement will likely require advances in gasifier design and slurry mixing. More detailed study of the issues involved here is needed, but the technical risk is deemed high.

Syngas Coolers

The conventional radiant syngas cooler (RSC) used in today's gasification systems produces saturated steam with an exit temperature of ~650°F. In the IGFC system described in this report, the RSC generates superheated steam with an exit temperature of 850°F. As a result, the convection syngas cooler (CSC) will also see superheated steam and higher temperatures. The modification is not believed to represent a major gap in technology. However, the higher operating temperatures will likely require a change in materials sets and represents a cost challenge. New high-temperature materials may need development; alternatively, cost reductions in current materials may enable achieving these targets. Thus, the risk is considered moderate.

High Temperature CO Shift

Today's CO shift reactors commonly operate with excess steam to avoid forming methane and other carbon-containing byproducts. In this analysis, no such byproducts are produced despite a steam-to-carbon near the equilibrium stoichiometry and much lower than the values >2 typically used. Realizing such capability will require either major advances in catalyst capability or a change to new shift methods, such as the separation membrane approaches under development at GE and elsewhere. This is a high-risk technology gap.

SOFC

Unsurprisingly, most of the gap separating current technology from 50% efficient IGFC systems will need to be filled by SOFC development. The SOFC parameters required to achieve the target efficiency are all extremely challenging. Given the reasonable assumption that power densities >0.5 W/cm^2 are required to make IGFC systems economically viable, the cell voltage and fuel utilization requirements are extremely challenging. GE has made good progress toward these targets recently. Recent tests in simulated high-hydrogen syngas have achieved 0.480 W/cm^2 at 0.80 V and 84% fuel utilization, which could lead one to believe that success is near. However, these results were achieved in a single cell at a uniform temperature of 800°C, while the IGFC air temperature rise means that the average cell operating temperature must drop (or methods of controlling degradation at temperatures >800°C must be developed). Also, achieving high fuel utilization in a large stack comprising 100+ cells is at the very least a major engineering challenge, as design and manufacturing specifications must be set to ensure that cell-to-cell flow variation is almost nonexistent. The risk of achieving the SOFC performance targets is still extremely high.

SOFC Recycle

The IGFC design calls for ~50% recycle of the SOFC air. The recycle fraction is a huge driver on efficiency as it dramatically reduces the fresh air flow requirement and therefore the main compressor parasite. Blowers for the required temperatures (800+°C) do not exist at present and will need development. This is largely a reliability and cost challenge as opposed to a technology challenge, since rotating machinery operating at these temperatures does exist. However, the reliability and cost risks are significant.

Conclusions and Future Directions

SOFC power plants operating on coal have the potential to achieve up to 50% HHV efficiency while isolating the carbon from the coal for later sequestration or transport. This performance represents a 25% efficiency improvement over today's planned IGCC systems as well as a significant emissions advantage.

A highly efficient IGFC system that does not require SOFC pressurization or integration between the SOFC and a GT has been analyzed. It seems likely that a system such as this could be demonstrated far earlier than a pressurized system with a GT, since the former avoids a number of engineering and operational challenges. The results indicate that such ambient-pressure systems would be valuable not just for demonstration purposes, but have the potential to be economically viable in their own right.

Realizing the benefits of these plants will require significant technology development over the next decade. By far the most important developments needed are in the SOFC itself. The dramatic performance improvements of the last several years must continue and be joined by similar advances in cost reduction and degradation minimization.

References

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