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Configuration and Performance of Fuel Cell-Combined Cycle Options

Authors:
Lawrence K. Rath
Patrick H. Le
Frederick A. Sudhoff

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Configuration and Performance of Fuel-Cell Combined-Cycle Options

L.K. Rath, P.H. Le, and F.A. Sudhoff
U.S. Department of Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, WV 26507

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Abstract

The natural gas, indirect-fired, carbonate fuel-cell-bottomed, combined cycle (NG-IFCFC) and the topping natural-gas/solid-oxide fuel-cell combined cycle (NG-SOFCCC) are introduced as novel power-plant systems for the distributed power and on-site markets in the 20-200 megawatt (MW) size range. The novel NG-IFCFC power-plant system configures the ambient pressure molten-carbonate fuel cell (MCFC) with a gas turbine, air compressor, combustor, and ceramic heat exchanger.

The topping solid-oxide fuel-cell (SOFC) combined cycle is not new. The purpose of combining a gas turbine with a fuel cell was to inject pressurized air into a high-pressure fuel cell and to reduce the size, and thereby, to reduce the cost of the fuel cell. Today, the SOFC remains pressurized, but excess chemical energy is combusted and the thermal energy is utilized by the Carnot cycle heat engine to complete the system.

ASPEN performance results indicate efficiencies and heat rates for the NG-IFCFC or NG-SOFCCC are better than conventional fuel cell or gas turbine steam-bottomed cycles, but with smaller and less expensive components. Fuel cell and gas turbine systems should not be viewed as competitors, but as an opportunity to expand to markets where neither gas turbines nor fuel cells alone would be commercially viable. Non-attainment areas are the most likely markets.

Background

Because of the abundance and relatively low cost of natural gas, gas turbine systems are well accepted in the power generation community. There are many advantages to using gas turbine systems. Nominally clean fuels are required to protect the turbine machinery, so the systems tend to also produce low pollutant levels. When bottomed with a steam turbine, the energy from the exhaust stream can be used to inexpensively produce electric or cogeneration power. In addition, gas turbines provide low maintenance and rapid startup.

There is, however, a limit to their use imposed by material properties — the temperatures needed to achieve high efficiency exceed what current materials can reasonably provide. While rapid strides have been made in the last few decades to achieve 50 to 56 percent efficiency for the lower heating value (LHV) gas turbine combined cycles, values above 62 percent appear to be difficult to achieve. Over the next 10 years, the U.S. Department of Energy's (DOE's) Morgantown Energy Technology Center (METC) will co-sponsor research on its Advanced Turbine System (ATS) Program to develop large, utility-scale units that are expected to achieve gas/steam cycle systems at 62 percent efficiency. A simple advanced gas turbine system is illustrated in Figure 1. These improvements will be made possible if new

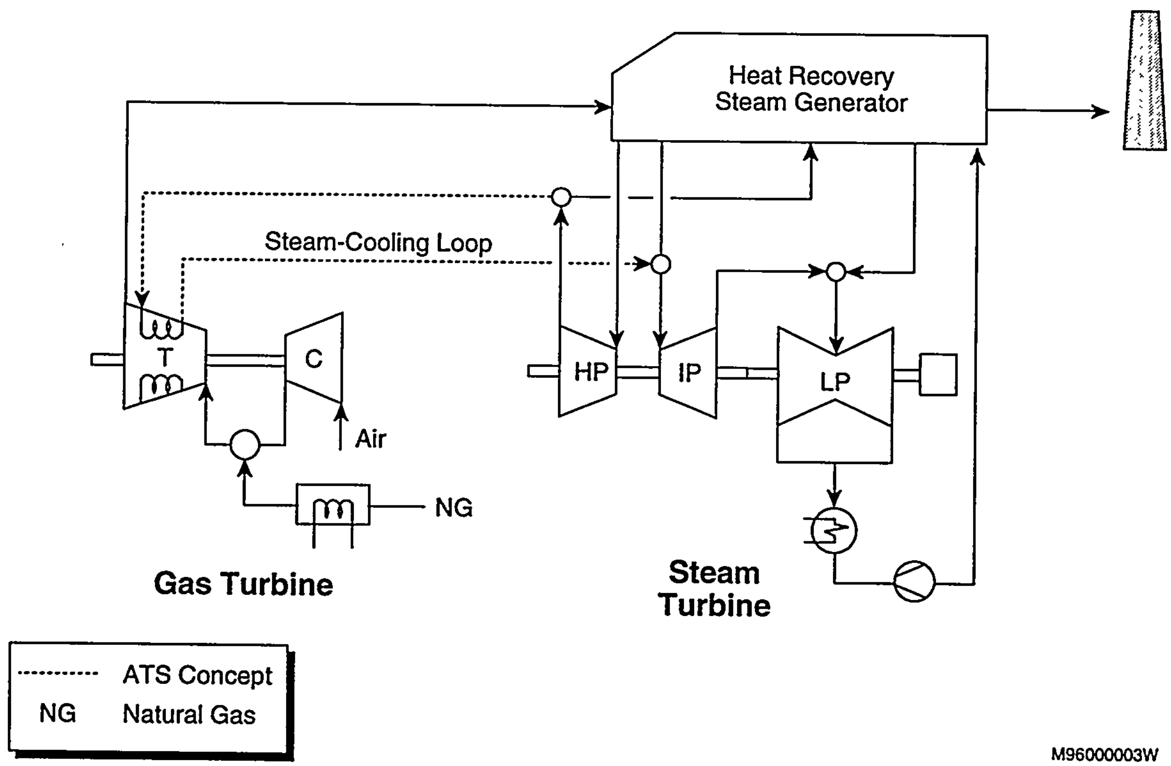

Figure 1. Simple Advanced Gas Turbine System

high-temperature materials are developed as planned. Such thermal systems can achieve higher efficiencies if the turbine inlet temperature is increased by approximately 150 to 200 °C. However, it will then become ever harder to meet the environmental standards because nitrogen oxide (NO_X) production tends to increase non-linearly with increases in temperature. A new breakthrough technology is needed to achieve higher efficiencies and maintain low pollutant levels. This technology is the fuel cell.

DOE has identified both fuel cells and advanced gas turbines as preferred sources of future electric power. DOE/METC is investigating the possibility of bringing both of these technologies together for the first time. Table 1 compares the system efficiencies of the power generation technologies discussed in this paper.

Table 1. Comparison of Power Generating Technologies

Technology	Configuration	LHV%	HHV%
GTCC uility size	gas turbine-hrsg	56	51
ATS utility size	adv. gas turb-hrsg	62	56
SOFC-ST	fuel cell-hrsg	63	58
MCFC-ST	fuel cell-hrsg	65	60
NG-IFCFC	GT-fuel cell-hrsg	74	67
NG-SOFCCC	fuel cell-GT-hrsg	74	67

Fuel-Cell Technology

The different types of fuel cell use different types of electrolytes as the principal component by which power is converted, and the type of fuel cell is named after the electrolyte. The fuel cell is a device that oxidizes fuel directly into electrical power without the enthalpy of combustion raising the temperature (Appleby and Foulkes 1989). In the MCFC, the oxidizer (air and carbon dioxide [CO_2]) passes through a semi-permeable membrane to the fuel compartment or anode where it electrochemically reacts with the fuel. Similarly, in the SOFC, the oxidizer (air) passes through a semi-permeable membrane to the anode and electrochemically reacts with the fuel. Figures 2 and 3 illustrate the basic MCFC and SOFC systems.

In the MCFCs, electrons are released at the anode/electrolyte interface by the reaction of hydrogen ions with carbonate ions. Water, CO_2, and heat are released by the anode reaction. Carbonate ions are created at the cathode/electrolyte interface by the electrochemical reaction of oxygen, CO_2, and two electrons. MCFC stack designs incorporate either internal or external manifolding. Internal and external reforming of methane to hydrogen and CO_2 are being

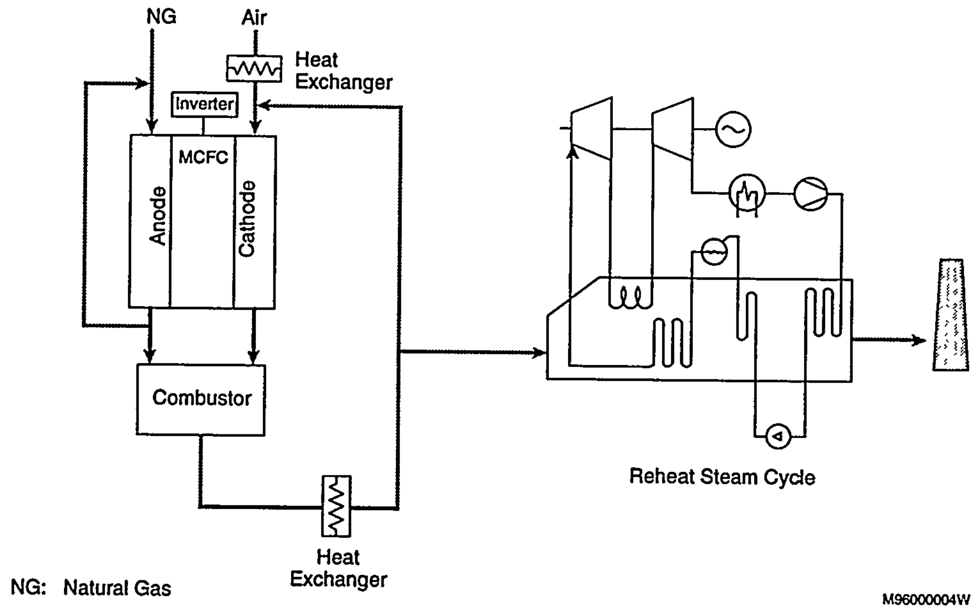

Figure 2. Basic Molten-Carbonate Fuel-Cell System

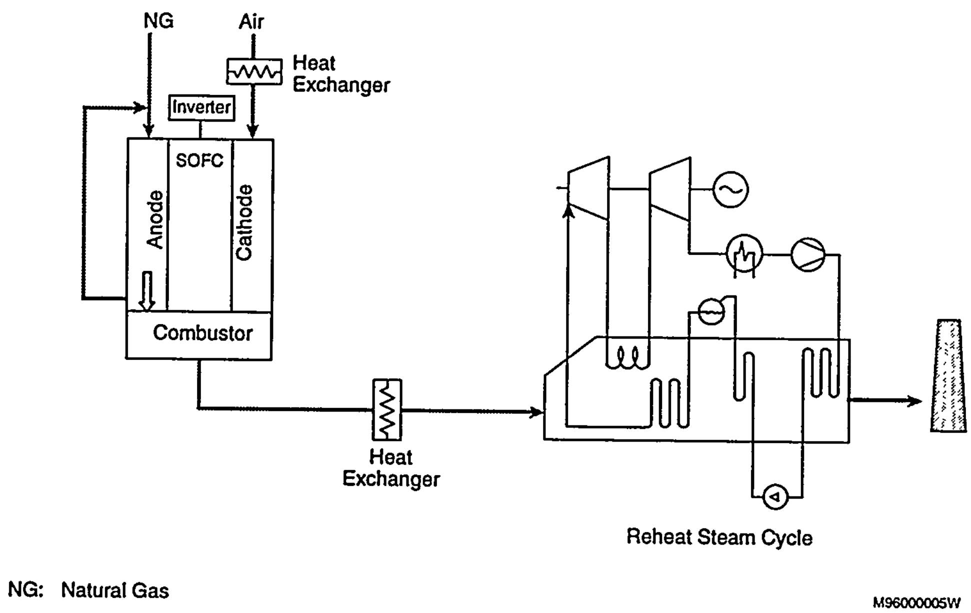

Figure 3. Basic Solid-Oxide Fuel-Cell System

considered in several commercialization concepts. All MCFC concepts employ flat cell components in the cell package (i.e., anode, matrix to hold carbonate, cathode, current collector, and separator plate). Energy Research Corporation and MC-POWER Corporation are leading MCFC manufacturers.

The MCFC was selected for the novel bottomer configuration because the temperature required for its operation is nominally about the same as that of the gas turbine exhaust. MCFCs operate at about 550 °C (1,050 °F), while SOFCs may operate at 1,000 °C (1,832 °F). Recognizing the synergism, we examined the possibility that the clean air exhaust from the turbine could drive the fuel cell. This would all but eliminate a need for a heat exchanger to couple the two units. Figure 4 illustrates the NG-IFCFC system.

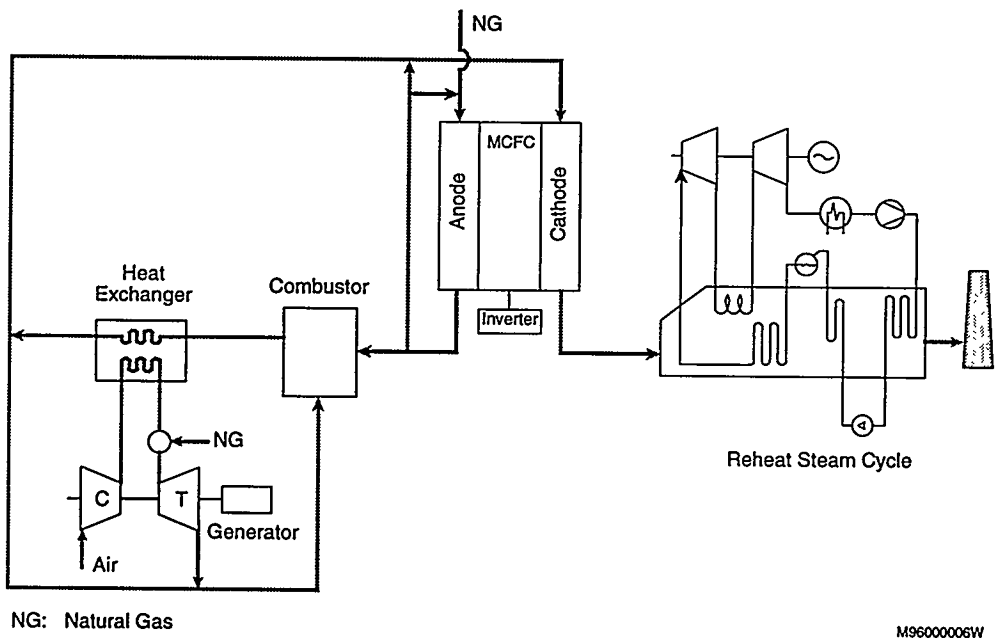

Figure 4. Natural Gas/Indirect-Fired Carbonate Fuel-Cell System

In the SOFC, electrons are released at the anode/electrolyte interface by the reaction of hydrogen and oxygen ions. Water and heat are released by the anode reaction. Oxygen ions are created at the cathode/electrolyte interface by the reaction of oxygen and two electrons. The solid state character of all SOFC components means that there is no restriction on cell configuration. Westinghouse Electric Corporation is the developer of the most common tubular bundle configuration. Ztek, Incorporated, and others are researching a flat plate or monolithic design. The SOFC can operate at pressures ranging up to 30 atmospheres. Carbon monoxide (CO) or ammonia, poisons to other fuel cells, can be used as a fuel in the SOFC.

The SOFC was selected for the topper configuration because the fuel cell operates satisfactorily under high pressure and the fuel-cell exhaust is about 1,000 °C (1,832 °F). About 50 percent of the fuel is converted to electrical energy in the SOFC. High-temperature fuel-cell exhaust drives the expansion turbine where most of the remaining chemical energy is captured. Once again, the coincidence of the synergistic effects leads to elimination of several heat exchangers. Figures 5 and 6 illustrate the NG-SOFCCC system. Slight modifications to the compressor exhaust flow stream result in a less expensive steam cycle and slightly improved system efficiency for the system shown in Figure 6.

Advantages to both types of fuel cell, such as environmental friendliness, make them the ideal power system of the future: NO_x, sulfur oxide, CO, and other pollutant exhaust products are insignificant. As attempts are made to improve the efficiency of gas turbines, ever higher temperatures will also be needed to compete with fuel-cell efficiency. These high temperatures will cause an increase in NO_x emissions. This will not occur with fuel cells, which release chemical energy as a stream of electrons rather than thermal energy. Fuel-cell efficiencies are controlled by Gibbs' Free Energy rather than by high-temperature operation. Some chemical energy is unconverted and some heat is generated by the fuel cell. This provides a source of conventional heat energy that can be used by a traditional heat engine. Thus, ultimately, to achieve 70+ percent LHV power efficiency, we must unite the two prime mover systems.

There are other operational benefits to fuel cells. They will operate efficiently in small sizes and even at partial loads, and because of this, are ideal for distributed power generation. These benefits in turn result in the potential to completely eliminate high voltage lines, reducing health concerns.

Status of Fuel-Cell Commercialization

Fuel-cell technology has evolved from small, curious, laboratory cell tests in the 1980s to fuel-cell-stack demonstration testing of complete systems (Williams and George 1990, 1991; Energy Research Corporation 1987). Systems testing is the precursor to commercialization, and small units in the 100-kilowatt (kW) range are commercially available. Thus, the fuel cell is no longer a technology of the distant future. Stack life for the MCFC has been extended from 100 hours in the early 1980s to some 5,000 hours for small stacks in recent years. Testing is underway to warrant MCFC units for 25,000 hours, and within several years, vendors expect to warrant their units for 40,000-hours operation. The largest MCFC stack now being manufactured and tested is 2-MW size.

Tubular and planar SOFC testing is still behind the MCFC in terms of stack size. However, single tubular SOFCs have been tested for 50,000 hours. Stacks up to 100 kW have been demonstrated. For monolithic SOFCs, a type of planar SOFC, higher power densities appear feasible. These units potentially will provide eight times the power of present fuel cells in half the stack volume.

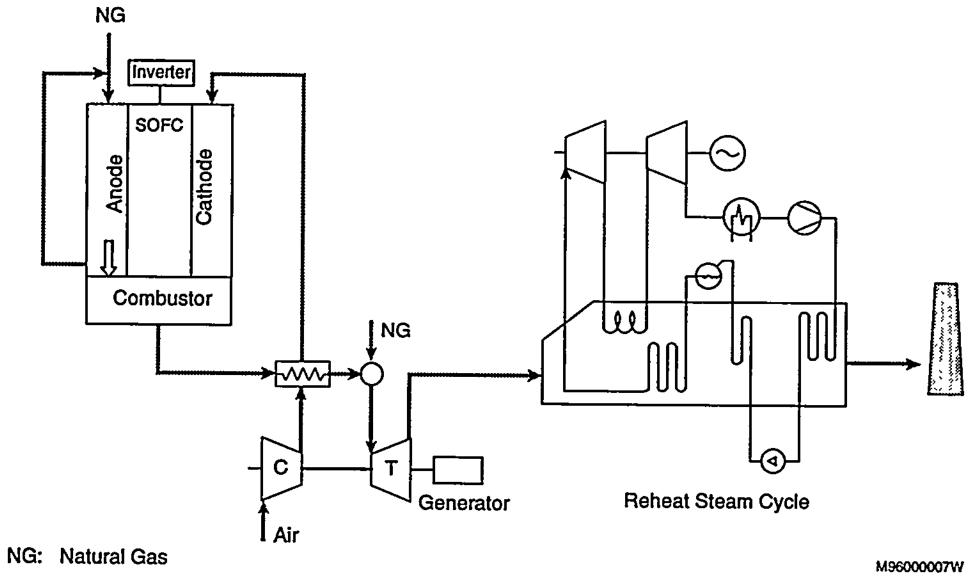

Figure 5. Natural Gas/Solid-Oxide Fuel-Cell Combined-Cycle System, Alternative 1

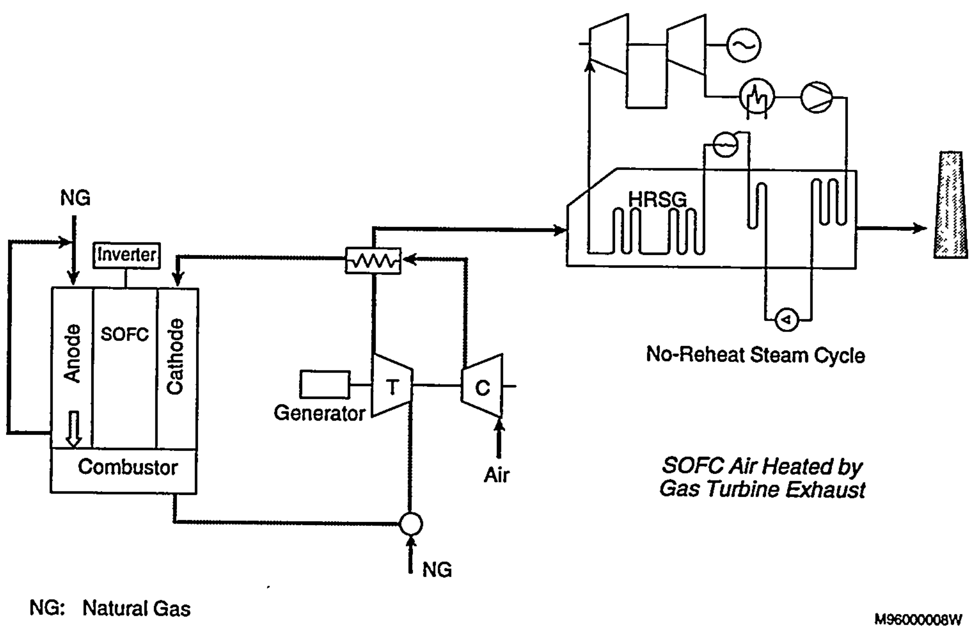

Figure 6. Natural Gas/Solid-Oxide Fuel-Cell Combined-Cycle System, Alternative 2

Power Conversion Configurations

While a fuel cell is extremely efficient, not all of the fuel's energy is electrochemically converted to electric power. About 50 percent of the fuel that comes into either an MCFC or SOFC is converted to electric power. The excess fuel is then consumed in a secondary combustor to generate thermal energy for the expansion turbine or additional thermal energy for the bottoming steam cycle. Moderate- to high-temperature product streams and other exhaust streams always result from the fuel conversion, and these energy streams have to be thermally converted to electric power. Two possible configurations that compare ways of using the fuel-cell exhaust stream energy are shown in Figures 4 to 6.

Many other configurations are possible. The NG-IFCFC configuration in Figure 4 shows the compressed air for the gas turbine being heated by the exhaust of the fuel cell by passing through a heat exchanger. The air is further heated by an off-base combustor to turbine inlet conditions. Only hot air passes through the turbine.

Combustion products from the turbine, exiting at approximately 500 °C (950 °F), nominally drive a steam cycle. The turbine exhaust is best utilized in the NG-IFCFC system as part of the oxidant feed to the MCFC. CO_2, provided by the combustor exhaust, is combined with the turbine exhaust and is passed to the fuel-cell cathode. Ultimately, the fuel-cell cathode exhaust is at higher temperatures than the turbine exhaust, and hence, it could be used more effectively by a steam turbine. The waste heat is effectively shared by two power sources in the NG-IFCFC, thereby increasing the overall cycle efficiency.

As an alternative, a gas turbine could be used to provide a high-temperature, pressurized air stream that then passes into a pressurized SOFC. The NG-SOFCCC system in Figure 5 shows this configuration, where the SOFC is a topper for the high-pressure gas turbine. Total system air and fuel are first compressed and processed through the fuel cell. Fuel is supplied to the anode and compressed air is supplied to the cathode. The pressurized fuel-cell exhaust is further heated by completing the combustion of exhaust gases. At the turbine operating pressure, the combusted fuel-cell exhaust is next processed to the gas turbine. The expansion turbine captures the remaining expansion energy. Depending on the turbine inlet temperature and pressure ratio, the exhaust is at 425 to 500 °C (800 to 950 °F).

An alternative system is presented in Figure 6. In this configuration, the turbine exhaust is used to heat the inlet air to the fuel cell. This improves the efficiency of the fuel cell, but reduces the efficiency of the heat-recovery steam generator by supporting a generic no-reheat steam cycle. The system efficiency is slightly higher and system cost is lower using this configuration.

There is little difference in the cost performance trade-off between the MCFC and SOFC units. The gas turbine units are similar. Both systems still have the exhaust stream from the fuel cell to deal with. The exhaust stream temperature in the NG-IFCFC system is high and can be used to generate a reheat steam cycle. In the NG-SOFCCC configuration, the turbine exhaust is probably best utilized by heating the compressor discharge air; turbine exhaust temperatures are high enough to provide a fair Rankine bottom cycle. DOE is examining these and other configurations to evaluate which provide the most effective utilization of the fuel-cell exhaust stream.

Advantages of the Fuel-Cell Combined-Cycle System

Many hardware limitations are overcome using integrated gas-turbine/fuel-cell systems compared to using either a gas turbine or a fuel cell bottomed with a steam turbine. Problems overcome and advantages of the fuel-cell combined-cycle systems include:

- Operating at ambient pressure, the MCFC provides thermal energy for an efficient reheat steam-bottoming cycle, using cathode exhaust stream energies.
- Gas turbine provides flexibility to move available heat from the fuel-cell exhaust into first; the Brayton cycle and then, the Rankine cycle.
- The fuel cell provides high efficiency at lower temperatures, where a Carnot cycle engine is ineffective.
- Fuel-cell combined-cycle systems provide a way of optimizing system economics through fuel flexibility without turbine cleanup problems.
- MCFC exhaust is approximately 600 to 700 °C (1,110 to 1,300 °F), which increases the performance of the indirect-fired system.
- The recycle stream is combusted and used to preheat compressor discharge air, reducing the amount of fresh fuel consumption required to obtain the gas turbine inlet temperature.
- At high compression ratios, a heat exchanger is not required for pre-heating the fuel-cell air.
- The combustor in the indirect-fired cycle operates with high-temperature exhaust air, which makes the system prone to fuel-bound NO_X. This effect is partially mitigated by using partially consumed air from the fuel cell as a product.
- Fuel-cell exhaust can be added effectively into the pre-mixed system, reducing NO_X formation.
- The pressurized fuel cell reduces SOFC and balance of plant (BOP) costs.

The potential benefits are obvious. A calculated LHV efficiency of about 74 percent is possible for a NG-SOFCCC operating under high pressure, including thermal losses as well as losses for auxiliary equipment. A primary benefit of coupling the two power generation systems is that the overall costs of fuel-cell systems could be lowered significantly, allowing for an early introduction of the technology.

Synergistic effects will open markets to the combined heat-engine/fuel-cell system. Fuel-cell and gas-turbine systems should not be viewed as competitors, but as an opportunity to expand into environmental markets in non-attainment areas. This would allow the fuel cell to be introduced with a system that has a high response, low cost, and fuel flexibility. And the gas turbine could then meet stringent emission regulations. However, for systems with increased efficiency, the availability of high-temperature (ceramic) heat exchangers is still problematic and becomes a critical issue.

Cycle Efficiency Calculations

As separate systems, both the advanced turbine and the fuel cell have reached the pinnacle of high efficiency. Theory and ASPEN simulations support combining these two power generation systems to produce a super efficient system. Calculations were carried out by DOE using the ASPEN code modified to calculate the conversion of chemical to electric power, as well as the conversion of thermal energy to electric power. Although higher steam-turbine efficiency is expected to be available by the turn of the century, we conducted this ASPEN study assuming current steam-turbine technology. Hence, the calculations reflect a conservative viewpoint.

Calculations of the primary systems show that the LHV efficiency of an MCFC bottomed by a steam cycle could achieve roughly 65 percent. The simulations of the high-pressure NG-SOFC bottomed by a steam turbine show about 63 percent efficiency. Calculations are based on firing the fuel cell with a stoichiometric mixture of methane and air. For a natural gas, indirect-fired, gas turbine, steam-bottomed system, the efficiency is expected to be about 55 percent. A high-pressure gas turbine was used in the system simulations. For both systems, calculations include reasonable assumptions of parasitic losses for the compressor, turbine, and fuel-cell sub-systems.

When the combination system was analyzed, the hot air from the gas turbine was exhausted into the fuel cell as the bottomer, as well as into the off-base combustor. The products all eventually exhausted into a steam Rankine cycle. The turbine air was in excess of what can be used by the fuel cell since hot air must be used by the off-base combustor.

Various splits of the exhaust air to the fuel cell and the off-base combustor are being considered because the ratio has a tremendous effect on the cost and efficiency of the system. Heat to raise the turbine air to the inlet temperature is supplied by a heat exchanger using the fuel product gases from the off-base combustor. Since this combustor does not need natural gas, the fuel can be almost any reasonable fuel, adding fuel flexibility that is otherwise not available to a stand-alone fuel-cell system. The design assumes a 10-percent pinch and high-temperature materials for the first few tube rows to accommodate the high temperatures. Costs of the heat exchanger unit are not expected to be unduly great because much of the recuperation can be done with metal tubes.

The calculations indicate the efficiency of the combination power systems can be greater than 73 percent for the NG-IFCFC or MCFC bottomer, and possibly as high as 74 percent for the pressurized NG-SOFCCC topping cycle. System efficiency differences are not significant. Every effort was made to simulate the fuel-cell-gas turbine system using the same premises. Unfortunately, MCFC and SOFC systems required different gas turbines, resulting in different fuel cell to turbine ratios, steam cycle temperatures, etc. For this preliminary analysis, efficiencies were assumed to be equal, although cycle efficiency is known to decrease with smaller scale units.

Parasitic losses could reduce any of these system efficiencies. Higher efficiencies are possible by using greater fractions of turbine exhaust air in the carbonate fuel cell. The larger the fraction of air in the fuel cell instead of the combustor, the more the two systems act in series instead of in parallel, and the better the composite performance. The NG-SOFCCC operates completely in series, and fuel cell to turbine ratios are greater in the NG-SOFCCC. Thus, the efficiency increases because the fuel-cell power output increases and the efficiency of the fuel cell is greater than that of current turbines. However, the system costs also increase. Optimization will be determined by the market place and this will tend to favor the turbine. We have not tried to optimize this balance. We only indicate that the use of the lower efficiency turbine system will not compromise the combination system efficiency.

Discussion

The electric power in Figure 4 was assumed to be provided by a MCFC operated at ambient pressure, a current design gas turbine, and a steam cycle. In an indirect-cycle, air exhausts from a gas turbine and provides a natural source of heated air for the fuel cell. Thus, the MCFC operates properly with air that is preheated to approximately 550 °C (1,025 °F); this is the normal temperature for gas turbine exhausts operated at between 8 and 30 atmospheres.

A high efficiency is projected if all the energy from the cathode recycle stream of the fuel cell can be used by the Brayton cycle instead of the Rankine steam cycle. This comes about from two factors being present in the indirect-cycle configuration:

1. The cathode recycle heat provides energy that heats the compressor discharge air rather than ambient air, and thus, gains a net power compared to the usual fuel-cell configuration; and

2. The fuel-cell exhaust stream passes into the combustor and again provides heat to the compressor discharge air.

In the NG-SOFCCC configuration of Figures 5 and 6, the SOFC is operated at high pressure. Typical anode and cathode inlet temperatures approach 550 °C (1,050 °F), fuel-cell operation is at about 800 °C (1,500 °F), and the final exhaust temperature is near 1,000 °C (1,832 °F). The galvanic fuel-cell efficiency decreases with increases in temperature as projected using the Nernst equation. At high temperatures, the reaction kinetics are improved and fuel-cell resistance losses are decreased. The tradeoff for the fuel cell is that the voltage, power, and surface area dictate operation at higher temperatures.

Summary

The NG-IFCFC and NG-SOFCCC are introduced as novel power-plant systems in the distributed power and on-site markets at 20 to 200 MW size. The NG-IFCFC power-plant system configures the ambient pressure, carbonate fuel cell with a gas turbine, air compressor, combustor, and part-ceramic heat exchanger. The NG-SOFCCC power-plant system configures a high-pressure fuel cell with a high-pressure gas turbine and a steam turbine. ASPEN performance results indicate efficiencies and heat rates for the NG-IFCFC and NG-SOFCCC are similar. Key parameters such as temperatures and pressures are within current limits of industrial practice. The efficiencies are comparable to conventional MCFC or SOFC steam-bottomed systems, but with smaller and less expensive components.

The potential benefits are obvious. High electrical conversion efficiencies are possible. The combination of fuel cells and Carnot cycle systems provides a cost-effective new system with greater flexibility to meet local demands. Competing manufacturers of gas turbines and fuel cells must work together to integrate this technology into the most efficient and cost-effective system possible. Much work remains to be accomplished. DOE and METC are the ideal organizations to lead this development because of their system analysis capabilities, experience with heat engines and fuel cells, and the lead in identifying the fuel-cell/heat-engine concept.

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