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SOLID OXIDE FUEL CELL POWER SYSTEM CYCLES

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ABSTRACT

Reviewed are power system concepts employing the solid oxide fuel cell (SOFC) at atmospheric pressure in simple cycle; in an atmospheric pressure hybrid cycle with a gas turbine (SOFC/GT); and in a pressurized SOFC/GT hybrid (PSOFC/GT). Estimates of power system performance are presented and discussed. Simple atmospheric pressure SOFC systems designed for combined heat and power (CHP) application can approach 50% electric generation efficiency (net AC/LHV) and 80% fuel effectiveness [(net AC + useful heat)/LHV]. Pressurized SOFC systems with intercooled, recuperated, and SOFC-reheated GT cycles can approach 70% electric generation efficiency, while the atmospheric pressure SOFC/GT hybrid cycle and a simple pressurized SOFC/GT cycle can approach 55% and 60% generation efficiency, respectively. These high levels of efficiency are extraordinary in that they are achievable at the MW capacity level.

INTRODUCTION

SOFC power and CHP systems can be configured based upon the atmospheric pressure simple cycle, atmospheric pressure SOFC/GT hybrid cycle, and pressurized SOFC/GT hybrid cycle concepts. In labeling these concepts, the pressure designation refers to the pressure at which the SOFC generator module is operated, and the term "hybrid" indicates that the generator is integrated with a gas turbine. At the present time, a 100 kWe CHP system, representing the current generation of Siemens Westinghouse atmospheric pressure systems, is installed at a utility site in the Netherlands. The maximum electric generation efficiency for that system is 47% (net AC/LHV). Taking credit for the district-heating hot water (cold return temperature = 323K, hot supply temperature = 393K) produced as well as for the electric power, the system's fuel effectiveness approaches 75%, and it is noted that with additional heat transfer surface, and for an application offering a lower cold return temperature, the fuel effectiveness would exceed 80%. The atmospheric pressure SOFC can be integrated thermally with a gas turbine, increasing the electric efficiency to 50%-55% due to the additional power that is provided by the turbine. By pressurizing the SOFC generator, and employing the simplest integration with the gas turbine, system efficiencies of 60% or higher are projected - see, for example, Bevc et al (1996) and Stephenson and Ritchey (1997). As shown by the present paper, and also by Massardo and Lubelli (1998) and Campanari and Macchi (1998), efficiencies of 70% and higher are estimated for more complex cycles.

Early SOFC power and CHP systems were designed to operate at atmospheric pressure. Presently underway at Siemens Westinghouse is the fabrication of a 250 kW pressurized hybrid power system for Edison Technology Solutions. In addition, conceptual design studies are being done to develop the high-efficiency pressurized SOFC hybrid system concept, and also the atmospheric pressure SOFC hybrid concept. Work in these study areas is reviewed in this paper. Features of the three cycle concepts are discussed, and performance estimates for power and CHP systems based on the concepts are presented.

CYCLE BACKGROUND

Simplified cycle diagrams for the three SOFC power system types are presented in Figure 1. For the power systems considered in this paper the fuel is desulfurized natural gas, the SOFC generator exhaust temperature is 1120K, and the SOFC air inlet temperature will typically be 800K, regardless of the system type.

In the atmospheric-pressure cycle (Figure 1a), process air for the SOFC generator is provided by a conventional motor-driven blower. The air is preheated by heat recovered from the SOFC generator exhaust at the recuperator, and additional heat required to meet SOFC air temperature requirements is provided by the air heater. The SOFC generator in this system operates near atmospheric pressure,

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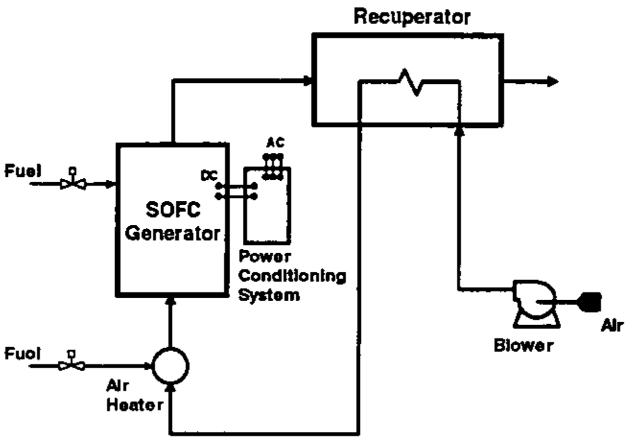
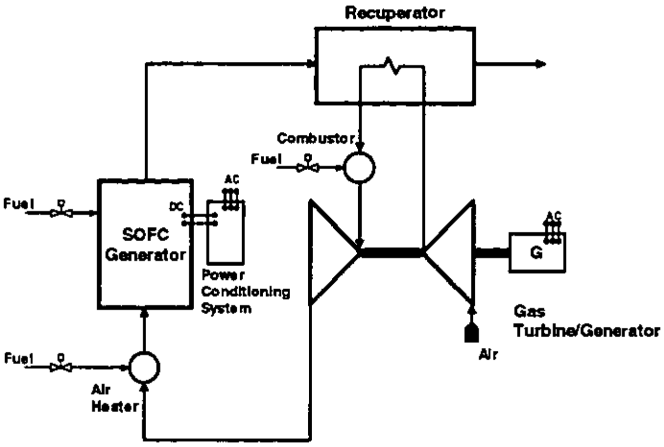
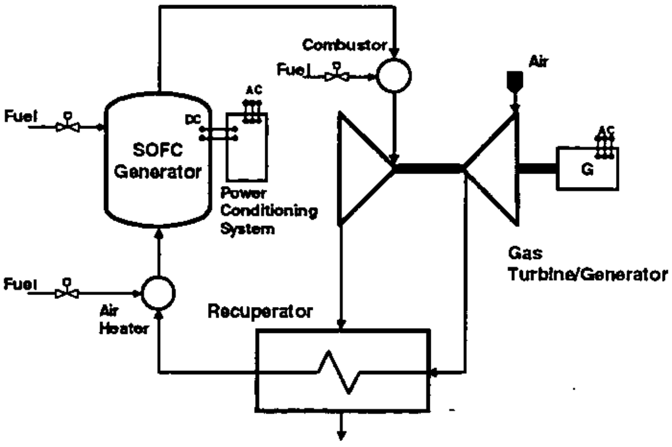


a. Atmospheric pressure simple cycle.



b. Atmospheric pressure hybrid cycle.



c. Pressurized hybrid cycle.

Figure 1. SOFC Power System Cycle Concepts.

with its pressure being above atmospheric by only the sum of the recuperator gas-side and exhaust duct pressure drops; typically, that sum will be less than 0.07 bar. A relatively low generator packaging cost is an advantage of the atmospheric-pressure system. In addition, the system is simple. The only continuously moving parts are in the air blower; as a result, high system reliability is expected.

The atmospheric pressure hybrid cycle (Figure 1b) builds on the atmospheric-pressure system by supplanting the motor-driven blower with a turbine-expander-driven compressor. The heat input required by the turbine Brayton cycle is provided via the recuperator, which recovers that heat from the low-pressure, high-temperature SOFC exhaust. The expander delivers more power than is required by the compressor, and the surplus shaft power is harnessed by an alternator. Since more power is produced by the SOFC/GT system, due to the addition of the turbine-alternator and the elimination of the parasitic blower motor, a higher system efficiency will be realized than could be achieved by the SOFC generator alone. System efficiency will maximized if there is no firing of fuel at the GT combustor or the air heater. As with any staged energy conversion cycle, highest cycle efficiency is achieved if the fuel energy supplied to the system is processed by all energy-converting stages of the system - in this case there are two, the SOFC generator and the turbine alternator. Since the SOFC generator still operates at near atmospheric pressure, the low-cost generator housing is retained. It is noted that the SOFC generator oxidant in this system is the turbine exhaust. This oxidant will be normal air if there is no need for GT combustor firing. However, if firing would be required for peak-power purposes, there will be a small efficiency penalty as a result of running the SOFC generator on vitiated air.

The pressurized hybrid cycle is depicted in Figure 1c. In this cycle, the SOFC generator is pressurized, operating on recuperatively heated air coming from the compressor discharge. A power system based on this cycle achieves an increased power output and higher efficiency relative to a simple atmospheric pressure SOFC system for two reasons. The first is the increased system power output that is provided by the addition to the cycle of the turbine-alternator and the elimination of the parasitic blower motor. The second is the increased SOFC voltage and power output that come from pressurizing the SOFC generator. Cell voltage, and hence, SOFC power and efficiency, increase with pressure; the relationship of cell voltage with pressure is logarithmic, and much of the increasing-voltage benefit is achieved in the pressure range of 1 bar (abs) to 10 bar (abs). The SOFC process air in the pressurized hybrid is preheated with heat recovered from the turbine exhaust, and is air regardless of whether or not the turbine combustor is fired. Maximum cycle efficiency is achieved when firing is avoided, and when there is no need for heat input at the air heater.

Note that in each system concept, air heater firing will also introduce vitiated air to the SOFC generator. Air heater operation is required during system startup, and possibly during part-load operations.

CYCLE PERFORMANCE COMPARISONS

To highlight the effects of cycle differences on power system performance, Table 1 summarizes the performance at the maximum efficiency operating point for power systems that are based on the three cycle types, but which employ SOFC stacks identical in con-

Table 1
Comparison of Peak-Efficiency Performance Estimates.
(Single SOFC Stack of 100 kW class)

Parameter			
System Type	Atmospheric Pressure SOFC Simple Cycle	Atmospheric Pressure SOFC Hybrid Cycle	Pressurized SOFC Hybrid Cycle
Cell Current Density, mA/cm²	180	265	287
SOFC Generator Pressure, bar (abs)	1.08	1.08	2.4
SOFC DC Power, kW	120	158	176
SOFC AC Power, kW	109	145	162
Gas Turbine AC Power, kW	-	30	40
System Net AC Power, kW*	102	170	197
System Efficiency (Net AC/LHV), %	47	53	56

* Net AC Power = Gross AC - parasitic power losses (blower, fuel compressor, system controls)

figuration and cell number. The SOFC generator in each system is composed of a single 1152-cell stack of the design used in the EDB/ELSAM 100 kWe SOFC CHP system, which is installed at the NUON test site in the Netherlands — see Kuipers (1998) and Veyo (1998).

Note that the peak efficiency estimates for the hybrid cycle systems both occur at higher cell currents than for the simple atmospheric-pressure SOFC system. Maximum-efficiency operation occurs at the thermally self-sustaining operating point, where no supplemental fuel needs to be added at the air heater to maintain SOFC temperature. In the SOFC/GT hybrid cycles this condition must occur at higher cell currents since the SOFC inlet air is heated at a lower-temperature point in the cycle.

Table 1 indicates that the hybrid cycle systems will generally achieve higher electric efficiencies than the atmospheric pressure system, and they will generate more power in the process. They present, therefore, the opportunity for lower capital costs ($/kW), and for lower costs of electricity due to both the lower capital costs and the improved fuel economy.

MW-CLASS PRESSURIZED SOFC HYBRID CYCLE POWER SYSTEM PERFORMANCE ESTIMATES

A cycle diagram for a pressurized SOFC hybrid cycle CHP system based upon a single-shaft gas turbine is presented in Figure 2. The heat recovery system, in additinn to preheating SOFC air and fuel for a hot-desulfurization process, is also equipped for the production of steam for an industrial process and hot water for district heating application. A once-through steam generator is depicted, which was assumed to operate, for these calculations, at 9 bar (abs) and with 10K - 15K of steam superheat. A gravity circulation steam generator could alternatively be applied. With the gas turbine designed for a pressure ratio of 3.0:1 at a TIT of 1170K, the exhaust temperature at the recuperator exit will be in the 480K - 650K range, depending upon the SOFC operating point. The water flow rate to the water heater is modulated to maintain the heater exit water temperature at 390K. Performance estimates for the MW-class CHP system are presented in Figure 3. The gas turbine combustor for these calculations is fired to maintain the 1170K TIT. Higher electric efficiencies, peaking at approximately 60%, with less recovery of useful heat, would result if the combustor were not fired.

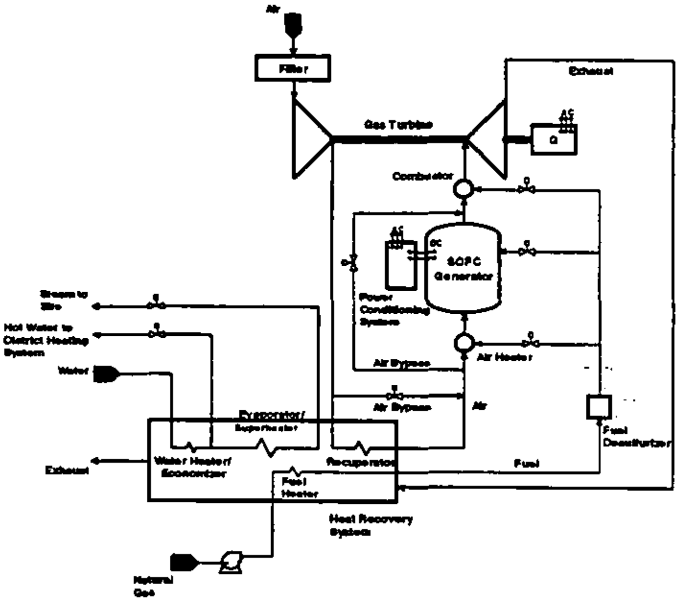


Figure 2. Pressurized SOFC Hybrid CHP System Cycle.

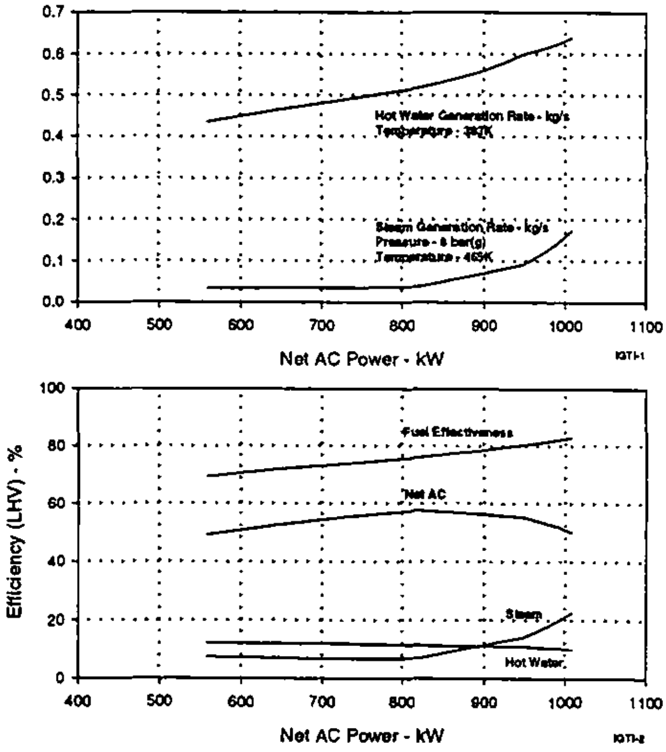


Figure 3. Pressurized Hybrid Cycle CHP System Performance Estimates. Fired Turbine Combustor.

20 MW HIGH-EFFICIENCY PRESSURIZED SOFC HYBRID CYCLE PERFORMANCE ESTIMATES

A pressurized SOFC hybrid cycle is presented in the Figure 4 that can provide the basis for a power system of very high electric efficiency. The compressor is intercooled, and the turbine is SOFC-reheated and recuperated, which contribute to increased turbine power output as well as to higher turbine cycle efficiency. An SOFC generator is placed ahead of each combustor, and the generator operating points are selected such that the heat provided by the two generators is just sufficient to produce the required turbine inlet temperatures, without the need for the firing of fuel at either combustor. Studies are underway to develop the conceptual design for a 20 MW net AC power system that is based on this cycle. Performance is being evaluated, a plant component arrangement concept is being developed, and the power system commercial installation cost and cost-of-electricity are being estimated. Preliminary performance estimates are summarized in Table 2. The projected efficiency will exceed 70% in a dry system, with no need for a Rankine bottoming cycle. The gas turbine equipment for this system is being specified by Rolls-Royce Allison.

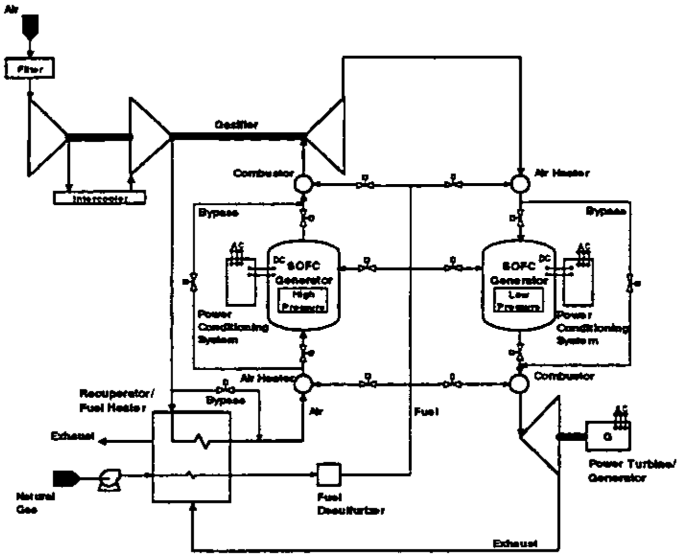


Figure 4. High-Efficiency Pressurized SOFC Hybrid Power System Cycle.

A 20 MW power system is also being evaluated that uses a cycle similar to the one shown in Figure 2 (less the steam generation components), but which applies a Solar Turbines Mercury 50 gas turbine configured to integrate with a pressurized SOFC generator. The Mercury 50 engine was developed by Solar Turbines as part of the DOE Advanced Turbine Systems (ATS) program. It operates with a combustor firing temperature of 1450K, a compressor pressure ratio of 9.0:1, generates 4.5MWe, and is recuperated. The pressurized hybrid power system that results from the application of this engine is currently estimated to operate with an efficiency in the low 60's (dry system, no Rankine bottoming cycle). Due to the engine's high power output, and the resulting need for a smaller SOFC complement to achieve a desired total power output, a key attribute of the system is expected to be its relatively low cost. Because of the high exhaust temperature, a Rankine bottoming cycle could be added, or the system could be applied to CHP duty. With the bottoming cycle, the estimated electrical generation efficiency is approximately 67%, and in CHP service the system fuel effectiveness estimate exceeds 80%. Performance estimates for a 10MW power system that employs a single Mercury 50 are presented in Table 3. It is noted that for integration with a Rankine bottoming cycle of realistic capacity, multiple 10 MW PSOFC/ATS-GT systems may be required.

Table 2
High-Efficiency Pressurized SOFC Hybrid Cycle Power System Performance Estimates

High-Pressure SOFC	
Operating pressure	6.2 bar (abs)
DC power	8.7 MW
Low-Pressure SOFC	
Operating pressure	2.5 bar (abs)
DC power	7.9 MW
Total SOFC DC Power	16.6 MW
Total SOFC AC Power	16.0 MW
Compressor Pressure Ratio	6.0:1
Gasifier Turbine Inlet Temperature	1117K
Power Turbine Inlet Temperature	1117K
High-Pressure Combustor Fuel Flow	0
Low-Pressure Combustor Fuel Flow	0
Gas Turbine AC Power	3.8 MW
System Net AC Power	19.5 MW
System Efficiency (Net AC/LHV)	70%
System Exhaust Temperature	470K

Table 3
High-Efficiency Pressurized SOFC/ATS-GT Hybrid Cycle Power System Performance Estimates

Cycle Type	PSOFC/ ATS-GT	PSOFC/ATS-GT with Rankine Bottoming Cycle	PSOFC/ ATS-GT CHP
Compressor Pressure Ratio	9:1	9:1	9:1
Compressor Air Intake Rate, kg/s	12.8	12.8	12.8
Turbine Inlet Temperature, K	1450	1450	1450
SOFC Exhaust Temperature, K	1120	1120	1120
SOFC Gross DC Power, MW	7.0	7.0	7.0
SOFC Gross AC Power, MW	6.8	6.8	6.8
Gas Turbine Gross AC Power, MW	4.2	4.1	4.1
Steam Turbine Gross AC Power, MW	-	0.6	
System Net AC Power, MW	**10.7**	**11.2**	**10.6**
System Efficiency (Net AC/LHV), %	**64**	**67**	**64**
Recuperator Exit Exhaust Temperature, K	616K	631	631
Heat Recovery for CHP Application (Steam & Hot Water), MWt	-	-	1.3
Fuel Effectiveness, %	**-**	**-**	**85**

CONCLUSION

SOFC technology can be applied in a variety of ways to configure both power and CHP systems that will operate with a range of electric generation efficiencies. An atmospheric pressure cycle, capable of efficiencies in the 45%-50% range, can be the basis for a simple, reliable CHP system. Integrating with a gas turbine to compose an atmospheric pressure SOFC hybrid cycle system, the simplicity of the atmospheric pressure SOFC technology is retained, and moderately high efficiencies in the 50%-55% range can be achieved in either power or CHP systems. The pressurized SOFC hybrid cycle provides the basis for the very high electric efficiency power system. Applying conventional gas turbine technology, power system efficiencies in the 55%-60% range will be achieved by the pressurized SOFC hybrid cycle, and CHP systems based upon the cycle are also possible. When the pressurized SOFC hybrid cycle system is based on a more complex turbine cycle, for example, one that is intercooled, reheated, and recuperated, electric efficiencies of 70%, or higher, are projected.

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