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Tubular SOFC and SOFC/Gas Turbine Combined Cycle Status and Prospects

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# TUBULAR SOFC AND SOFC/GAS TURBINE COMBINED CYCLES--STATUS AND PROSPECTS

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Presently under fabrication at Westinghouse for EDB/ELSAM, a consortium of Dutch and Danish utilities, is the world's first 100 kWe Solid Oxide Fuel Cell (SOFC) power generation system. This natural gas fueled experimental field unit will be installed near Arnhem, The Netherlands, at an auxiliary district heating plant (Hulp Warmte Centrale) at the Rivierweg in Westervoort, a site provided by NUON, one of the Dutch participants, and will supply ac power to the utility grid and hot water to the district heating system serving the Duiven/Westervoort area. The electrical generation efficiency of this simple cycle atmospheric pressure system will approach 50% [net ac/LHV]. The analysis of conceptual designs for larger capacity systems indicates that the horizon for the efficiency of simple cycle atmospheric pressure units is about 55%.

An increase in operating pressure to ten atmospheres will yield about a ten percent increase in cell voltage, hence efficiency. At three atmospheres, the voltage increase is about half that at ten atmospheres. Previously reported conceptual design activity (1,2) for pressurized 3 MW and 5 MW SureCELL™ SOFC/Gas Turbine (PSOFC/GT) power plants operating at a pressure ratio of 8.8 and utilizing a highly efficient two shaft intercooled and recuperated gas turbine yielded combined cycle efficiencies of 61% and nearly 70%, respectively. The performance estimates for these plants have been refined, considering a reduction in SOFC power lead losses that is based upon recent experimental data, and a higher recuperator effectiveness of 93%. In addition, for the 3 MW plant, performance has been estimated for the case in which the reheat combustor at the power turbine inlet is not fired.

The objectives of the analyses reported herein were fourfold. The first was to document the improved performance potential of the two shaft turbine cycle given access to a better recuperator and lower lead losses, and the second objective was to assess the performance of PSOFC/GT combined cycles in the 3 MW plant application that are based on the use of a simple single shaft gas turbine having a design-point turbine inlet temperature that closely matches the temperature of the SOFC exhaust gas, about 850 C. The third objective was to estimate the performance potential of smaller combined cycle power plants employing a single SOFC submodule, and the fourth objective was to evaluate the cogeneration potential of such systems.

As in the previously reported analyses, the basic building block for an SOFC system is the 100 kW (atmospheric pressure) SOFC generator module (1152 cells, each 22 mm diameter by 1500 mm active length), now in manufacture. Using two such building blocks, each with an additional cell row (96 cells), an SOFC submodule was configured with 2496 tubular AES SOFCs in a common canister. This submodule has a nominal capacity of 600 kW dc at nine atmospheres pressure, and pressurized SOFC modules housing one, three, or four such submodules comprise the SOFC systems in the PSOFC/GT power plants that are discussed below.

Two cycles for pressurized SOFC/GT power plants based on a two-shaft gas turbine were described previously (2). In that gas turbine, the first shaft functions as a zero-net-power hot-gas generator, and ac power (1.4 MW) is produced by the power turbine on the second shaft. The gas generator is equipped with two stages of intercooled compression, and the compressor turbine has an inlet temperature requirement (861 C) that is very close to the temperature that is available at the exhaust of an SOFC module. The power turbine design inlet temperature is 863 C, and it is normally achieved by burning natural gas fuel at a reheat combustor. An 88%-effective recuperator in this regenerative gas turbine cycle contributes to its high operating efficiency (43%, LHV).

When a pressurized SOFC module with three SOFC submodules is placed ahead of the high pressure combustor in this cycle, the SOFC operating point can be selected such that no fuel is required by the combustor. This leads to a PSOFC/GT plant rating of approximately 3 MW net ac. Similarly, a second module of identical design can be installed ahead of the low pressure reheat combustor and operated such that the flow of fuel to that combustor is also zero. In that case, a plant of nominal 4.5 MW rating results. Equipping each SOFC module with a fourth submodule results in more power from the plant, in excess of 5 MW, and higher efficiency. Updated performance estimates for the 3 MW and 5 MW power plants are summarized in Table 1; the estimates are based on the reduced lead losses and a 93% effective recuperator.

Table 1. PSOFC/GT (Two-Shaft) Power Plant Performance Estimates

| **Plant** | 3 MW-class | 5 MW-class | 3 MW-class, Unfired Power Turbine |
|---|---|---|---|
| Current Density, mA/cm2 | 496 | 410/344 * | 582 |
| SOFC Fuel Utilization, % | 90 | 90 | 80 |
| SOFC Power, MW ac | 1.82 | 3.98 | 2.01 |
| Gas Turbine Power, MW ac | 1.41 | 1.40 | 1.15 |
| Plant Net ac Power, MW | 3.21 | 5.36 | 3.15 |
| Plant Efficiency, Net ac/LHV | 63.1 | 71.5 | 64.5 |

* HP module/LP module

The table also presents performance estimates for the case in which the power turbine in the 3 MW-class plant is not fired. To maintain the design inlet temperature at the compressor turbine inlet without the need to fire the HP combustor, the selection of a new SOFC operating point at a higher cell current is required. With this relatively high current, the best plant efficiency is achieved with a reduced utilization.

In another conceptual design approach to achieving a PSOFC/GT power plant of approximately 3 MW capacity, a single-shaft gas turbine of nominally 1.2 MW rating has been applied. The design pressure ratio for this turbine is 6.36, and the turbine inlet temperature is 868 C. The SOFC module was configured using three 600 kW submodules as in previous analyses. To integrate the SOFC module and the gas turbine, the gas turbine inlet temperature and pressure ratio values were retained, but the system mass flow was reduced about 14%. The gas turbine has no intercooler, but it is recuperated. and the plant performance estimates summarized in Table 2 were done for a recuperator effectiveness of 93%. The estimates indicate that a plant based on a single-shaft gas turbine can achieve power and efficiency performance that is similar to that for the two-shaft power plant.

Table 2. PSOFC/GT (Single-Shaft) Power Plant Performance Estimates

| | |
|---|---|
| Current Density, mA/cm2 | 550 |
| SOFC Fuel Utilization, % | 80 |
| SOFC Power, MW ac | 1.95 |
| Gas Turbine Power, MW ac | 1.03 |
| Plant Net ac Power, MW | 2.93 |
| Plant Efficiency, Net ac/LHV | 63.7 |

Again utilizing a single-shaft gas turbine basis, but with a lower power rating, and a pressurized SOFC module housing only one submodule, a MW-class PSOFC/GT power plant can be configured that will also achieve very attractive performance. Figure 1 shows design-point performance for the plant operating with an SOFC fuel utilization of 85%, and for a low pressure ratio that may permit indoor installation. At each point on the curve the SOFC system configuration is fixed as indicated above, but the gas turbine sizing is allowed to change from point to point in response to changes in the SOFC operating point and the air mass flow requirement. Given a cell current density at each point on the curve, the SOFC stoichs requirement (3.5 minimum) was adjusted to maintain the recuperator effectiveness at 93%. The selection of a particular design-point on the curve for a specific application will of course depend on economic considerations.

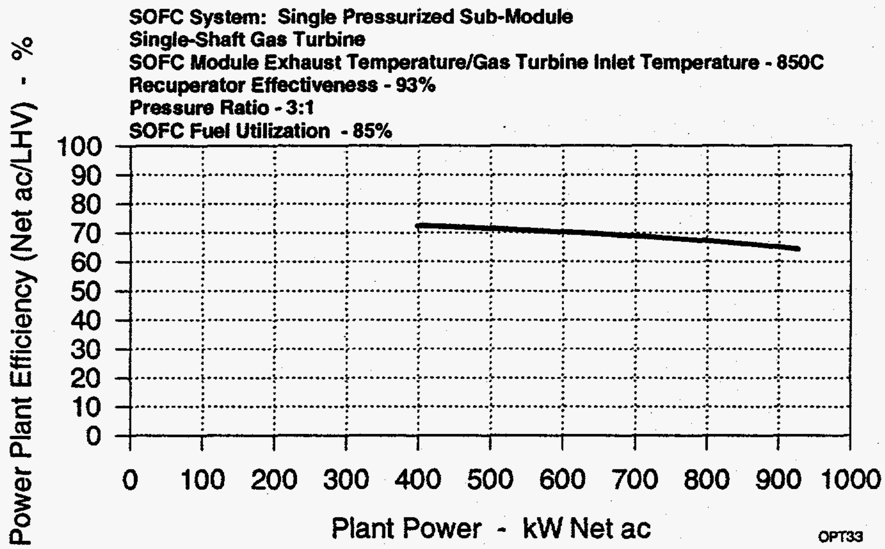


Figure 1. MW-class PSOFC/GT power plant performance estimates.

For the Figure 1 analysis, the distribution between SOFC power and gas turbine power range from 81%/19% at the low-power point, to 66%/34% at the highest power.

This same small power plant could also be equipped with a heat recovery steam generator (HRSG) and a hot-water heater for cogeneration application. Plant performance estimates are provided in Figure 2 for the case in which the HRSG/water-heater combination is positioned at the recuperator exhaust exit. Again, these estimates are the result of a design-point analysis in which the SOFC system consists of a single SOFC submodule, but the gas turbine and heat recovery system sizing is variable. The features of a fixed plant design would depend on economics. HRSG steam conditions at each point on the curves were fixed at 10 atm (abs), 10 C superheat, and the exhaust temperature at the water heater exit at 70 C. Hot water temperatures in the 120-140 C range will be achieved depending upon the water mass flow rate. It is noted that the thermal performance of the heat recovery system is affected by the arrangement of equipment. For example, higher steam temperatures could be achieved by placing the superheater ahead of the recuperator. An air bypass around the recuperator would also affect thermal performance.

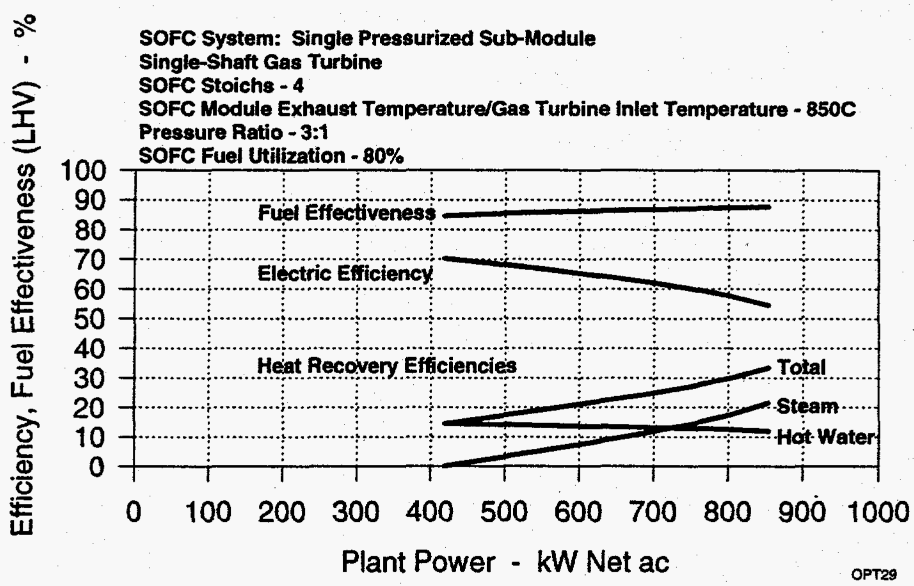


Figure 2. MW-class PSOFC/GT cogeneration system performance estimates.

Since the PSOFC/GT combined cycle can be configured to achieve very high levels of efficiency at capacity levels two orders of magnitude smaller than non fuel cell systems, the SureCELL™ PSOFC/GT is the ideal distributed power generator, and the concept has attractive cogeneration potential. Widely dispersed and located near load centers, SureCELL™ systems could contribute to a world wide reduction in carbon dioxide production because of their inherent efficiency. Using desulfurized fuel, and with minimal fuel combustion, the SureCELL™ system would also produce significantly less NOx and SOx than non fuel cell alternatives. The addition of the gas turbine as the bottoming cycle to the SOFC adds an increment of output without the consumption of additional fuel thereby yielding the higher efficiency. More importantly perhaps, the relatively low technology level of the turbine required results in the addition of this capacity and efficiency increment at far less cost than would be possible with fuel cells alone.

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