PARAMETRIC STUDY OF FUEL CELL AND GAS TURBINE COMBINED CYCLE PERFORMANCE

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ABSTRACT
A number of cycles have been proposed in which a solid oxide fuel cell is used as the topping cycle to a gas turbine, including those recently described by Beve et al. (1996). Such proposals frequently focus on the combination of particular gas turbines with particular fuel cells. In this paper, the development of more general models for a number of alternative cycles is described. These models incorporate variations of component performance with key cycle parameters such as gas turbine pressure ratio, fuel cell operating temperature and air flow. Parametric studies are conducted using these models to produce performance maps, giving overall cycle performance in terms of both gas turbine and fuel cell design point operating conditions. The location of potential gas turbine and fuel cell combinations on these maps is then used to identify which of these combinations are most likely to be appropriate for optimum efficiency and power output. It is well known, for example, that the design point of a gas turbine optimised for simple cycle performance is not generally optimal for combined cycle gas turbine performance. The same phenomenon may be observed in combined fuel cell and gas turbine cycles, where both the fuel cell and the gas turbine are likely to differ from those which would be selected for peak simple cycle efficiency. The implications of this for practical fuel cell and gas turbine combined cycles and for development targets for solid oxide fuel cells are discussed. Finally, a brief comparison of the economics of simple cycle fuel cells, simple cycle gas turbines and fuel cell and gas turbine combined cycles is presented, illustrating the benefits which could result.

1. NOMENCLATURE
AC Alternating Current
DC Direct Current
E Cooling effectiveness
H Enthalpy
P Pressure
Q Power or heat flow
q Mass flow
T Temperature
w Coolant mass fraction
η Efficiency

Subscripts
a Air stream
dc DC (direct current)
e Exhaust stream
f Fuel stream
LHV Lower Heating Value

2. INTRODUCTION
There have been several proposals for integrated cycles involving fuel cells and gas turbines, many of which were first considered some time ago (see for example Bloomfield (1977), and Harvey and Richter (1994)). Since fuel cells have not been available at sufficiently high power ratings to make integration with gas turbines a practical proposition, interest in these combined cycles has been largely theoretical until recently. Megawatt scale fuel cells have now been demonstrated, however, and there has accordingly

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been a growth of interest in this field. Combined cycle plant comprising gas turbines and either molten carbonate fuel cells (MCFCs) (Steinfeld, 1996) or solid oxide fuel cells (SOFCs) (Veyo, 1996a) have been proposed. Of particular interest are the systems using SOFCs and gas turbines, as described by Bevy et al. (1996) and elsewhere, in which the compressor section of a gas turbine pressurises the fuel cell and the fuel cell exhaust gas is expanded in the turbine section of the gas turbine. Such cycles have a dual benefit:

- Pressurisation of the fuel cell may be used to improve either its thermal efficiency or its power density (or a combination of both).
- The “waste” heat in the exhaust of the fuel cell is recovered in the turbine.

Studies of SOFC plus gas turbine combined cycles have generally focused upon case studies of specific plant configurations by assessing the performance of a particular fuel cell coupled to a particular gas turbine. In the present paper, more general parametric studies, analysing the performance of a set of cycle configurations over a range of parameters such as pressure ratio and firing temperature, are described. Such analysis potentially allows a number of alternative cycle configurations to be analysed on a consistent basis, as well as identifying which gas turbine and fuel cell combinations might be the most suitable candidates for integration. In addition, the impact of potential developments in both fuel cell and gas turbine technology may be assessed.

This paper describes a basic model for the analysis of fuel cell and gas turbine combined cycles and the use of this model to generate parametric performance maps for a SOFC integrated with a “basic” gas turbine, a recuperated gas turbine, and an intercooled and recuperated gas turbine. The performance maps show cycle efficiency and specific power as a function of cycle pressure ratio, gas turbine firing temperature and fuel cell exhaust temperature. Following this, the economic aspects of such combined cycles are briefly covered, estimating the cost of electricity for optimal cycle configurations, based upon the calculated performance and published cost estimates. Finally a short summary and conclusions are presented.

3. PARAMETRIC STUDIES

All of the cycles discussed in this paper have been analysed using variants of a single cycle model, and it is convenient to first describe the basic cycle model before proceeding to specific cases.

3.a. Basic Cycle Model

Calculations involving complex gas turbine cycles are widely carried out (see for example Chiesa et al. (1995) and Macchi et al. (1995)), and modelling of compressor, turbine, combustor and heat exchanger unit operations does not require extensive explanation. However, the integration of a fuel cell into such a system is a relatively novel feature, and the means by which the fuel cell is modelled merits more detailed discussion.

Figure 1 illustrates the energy and mass transfer processes for a solid oxide fuel cell; these processes are described in more detail than can be covered here, by Appleby and Foulkes (1993) and Gardner (1996).Air supplied to the cathode and fuel (assumed throughout this paper to be methane) is supplied to the anode. Whilst in general the fuel supply pressure $P_f$ could differ from the air supply pressure $P_a$, they are taken here to be equal, in order to maintain a pressure balance across the structural elements of the cell. In reality, differing pressure losses through the fuel cell may mean that slightly different pressures are required, but since the fuel mass flow is substantially smaller than the air mass flow, the overall impact of this on the work of compression will be small. Within the fuel cell, oxygen ions are transferred from the air stream to the fuel stream by conduction in the fuel cell electrolyte; oxidation of the fuel proceeds via an intermediate reforming step (see for example Gardner (1996)). A portion of the lower heating value (LHV) of the oxidised fuel is converted to electrical energy, available as DC electricity at the fuel cell terminals, and the remainder is converted to heat. Some of this is lost to the environment through the walls of the fuel cell and the remainder is carried away in the exhaust streams. It should be noted, as emphasised by Gardner (1996) and others, that the fuel cell is not “Carnot limited”. One of the principal reasons for the high efficiency of the fuel cell and gas turbine combined cycles to be described below, is the lower irreversibility of the electrochemical oxidation process when compared to conventional combustion.

As illustrated in Fig. 1, it is assumed here that the exhaust fuel and air streams are mixed, and any unburnt fuel is combusted in the mixing chamber, as in the fuel cell stack design described by Veyo (1996b). The DC electrical power, $Q_{dc}$, is given by:

$$Q_{dc} = \eta_{el} \cdot \Phi \cdot Q_{LHV}$$  \hspace{1cm} (1)
where $\eta_f$ is the gross fuel cell efficiency, $Q_{\text{H}}$ is the lower heating value of the fuel and $q_f$ is the fuel mass flow. The baseline fuel cell efficiency $\eta_f$ used in these studies is 52% at atmospheric pressure, based upon DC cell voltages given by Beve at al. (1996) for a current density of ~350 mA/cm².

As mentioned above, one of the main advantages of the SOFC plus gas turbine combined cycle is the fact that pressurisation of the fuel cell leads to increased efficiency. Beve et al. (1996) give data for the increase in cell voltage with operating pressure at a given current density. Based on this data, a relationship of the form:

$$\eta_f = 0.52 \left[1 + \frac{29}{650} \log P\right] \quad P \leq 1 \text{ atm}$$ (2)

is used for the variation of cell efficiency with operating pressure $P$ (atm).

The majority of the analysis described below assumes that the fuel cell exhaust temperature remains constant at a value of 850°C (as used by Veyo (1996a)) and consequently the operating temperature of the cell is assumed not to vary greatly. However, in certain cases, variation of exhaust temperature is permitted. As discussed by Hirschenhofer et al. (1994), the impact of varying operating temperature upon the efficiency of a SOFC is not well established. Equilibrium thermodynamic considerations suggest that efficiency should fall with increasing temperature, whereas kinetic considerations favor a rise in efficiency with increasing temperature. For the present work it has been assumed that, over a relatively small temperature range at least, efficiency is roughly independent of operating temperature. While it is acknowledged that this is not entirely satisfactory, more detailed information on the operation of SOFC stacks at a range of temperatures is required before a better model may be developed. Furthermore, as illustrated by Nathanson (1996), the relationship between fuel cell exhaust temperature and operating temperature is highly dependent on the details of the particular stack design.

Further aspects of the fuel cell performance assumptions are detailed in Table 1. Note that the pressure loss is assumed to apply equally to the fuel and air streams and is "flange to flange", including all manifolding.

### Table 1: Fuel Cell Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Efficiency (@ 1 atm)</td>
<td>52%</td>
</tr>
<tr>
<td>Power Electronics Efficiency</td>
<td>96%</td>
</tr>
<tr>
<td>Fuel Utilisation</td>
<td>85%</td>
</tr>
<tr>
<td>Heat lost to Environment</td>
<td>2% ($q_r-Q_{\text{env}}$)</td>
</tr>
<tr>
<td>Pressure Loss ($q_f/P_f$)</td>
<td>3%</td>
</tr>
</tbody>
</table>

### Table 2: Plant Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Efficiency (Polytropic)</td>
<td>88%</td>
</tr>
<tr>
<td>Turbine Efficiency (Adiabatic)</td>
<td>88%</td>
</tr>
<tr>
<td>Turbine Stage 1 Pressure Ratio</td>
<td>2</td>
</tr>
<tr>
<td>Combustor Pressure Loss</td>
<td>3%</td>
</tr>
<tr>
<td>Intercooler Pressure Loss</td>
<td>3%</td>
</tr>
<tr>
<td>Recuperator Effectiveness</td>
<td>85%</td>
</tr>
<tr>
<td>Recuperator Pressure Loss (Each Side)</td>
<td>3%</td>
</tr>
<tr>
<td>Inlet Air Conditions</td>
<td>1 atm, 15°C</td>
</tr>
<tr>
<td>Inlet Fuel Conditions</td>
<td>1 atm, 15°C</td>
</tr>
<tr>
<td>Gearbox Efficiency</td>
<td>98.5%</td>
</tr>
<tr>
<td>Generator Efficiency</td>
<td>98.5%</td>
</tr>
<tr>
<td>Fuel LHV</td>
<td>50019 kJ/kg</td>
</tr>
</tbody>
</table>

A simple model for gas turbine cooling is used, similar to that described by El-Masri (1987), in which the cooling air mass flow (assumed to be taken entirely from compressor discharge) is chosen depending upon the mainstream temperature, the coolant temperature and a metal temperature of 800°C, according to the effectiveness curve shown in Fig. 2.

If the mainstream temperature is less than 800°C then clearly no coolant is required. Two coolant streams are used: the first returned upstream of the first stage of the turbine to represent cooling of the first fixed blade row, and the second returned downstream of the first stage of the turbine to represent the remainder of the cooling requirement. This is a relatively simple model and is conservative in that higher metal temperatures and lower coolant flows could be tolerated in an advanced turbine. However, the majority of the studies described below involve gas turbines with relatively low turbine inlet temperatures and small cooling requirements, so that the overall system performance is not overly sensitive to the cooling model.
3.b. Cycle Studies

Many of the SOFC plus gas turbine combined cycles described in the literature (for example Bevc et al. (1996), Nathanson (1996), and Ali and Moritz (1996)) include a number of components in addition to the basic gas turbine and fuel cell, such as intercoolers, recuperators and reheat combustors. The simplest cycle involving only a fuel cell and gas turbine is first analysed here, before a recuperator and then an intercooler are added.

3.b.i. Fuel Cell Plus Gas Turbine. The simplest cycle in which a gas turbine is used to pressurise a fuel cell is shown in Fig. 3. Compressor discharge air is supplied directly to the fuel cell cathode and fuel cell exhaust gas passes to the gas turbine combustor. Additional fuel may be supplied to the gas turbine combustor where required.

![Diagram of Fuel Cell plus 'Basic' Gas Turbine](image)

**Figure 3: Fuel Cell plus 'Basic' Gas Turbine**

Clearly the use of such a generic model does not necessarily accurately represent the performance of specific gas turbines. The component efficiencies used in the model are likely to be slightly optimistic in predicting the performance of some existing small industrial gas turbines. However, they represent a realistic target for new turbines and are consistent with those used elsewhere (Bevc et al., 1996).
Figure 4. shows the efficiency and specific power of this cycle for a range of cycle pressure ratios and gas turbine combustor outlet temperatures (COTs), with a constant fuel cell exhaust temperature of 850°C. It is apparent that increasing gas turbine combustor outlet temperature reduces overall cycle efficiency. This is because the fuel cell is a more efficient device than the gas turbine and it is therefore preferable to use the entire fuel supply in the fuel cell. Firing the gas turbine in this cycle is somewhat akin to supplementary firing of the heat recovery steam generator (HRSG) in a conventional (gas turbine/steam turbine) combined cycle, which will always reduce cycle efficiency (see for example Horlock (1992)). The optimum pressure ratio is moderate, ~18. The peak efficiency predicted here, ~68%, is comparable with those suggested elsewhere for more complex cycles (Veyo, 1996a).

For interest, the published (Gas Turbine World, 1995) pressure ratios and firing temperatures of a number of small industrial gas turbines are shown on Fig. 4. However, it must be emphasised that the performance indicated will not necessarily correspond precisely to that calculated for a cycle using the gas turbine in question due to differences in component efficiencies.

The major problem with an unrecuperated cycle of this nature is that the air supply to the fuel cell is relatively cool, except at the highest pressure ratios. It must be assumed that, in order to maintain acceptable temperature gradients and associated thermal stresses, there will be some lower limit on the temperature at which air may be supplied to the fuel cell. This will clearly depend upon the individual cell. Lines at which fuel cell inlet air exceeds 400°C and 500°C are shown in Fig. 4., indicating that the minimum pressure ratio for the cycle is likely to be around 23 which is slightly higher than the optimum pressure ratio of 18.

For an open cycle gas turbine, since the overall size of a turbine is largely governed by the airflow, specific power will generally give a qualitative feel for the specific capital cost of a cycle. However, such a simple relation is not immediately apparent for the fuel cell plus gas turbine combined cycle. In particular, since the fuel cell is likely to be rather more costly than the gas turbine, the proportion of the overall power output produced by the fuel cell will have a rather greater impact on the specific cost of the cycle. For the 18:1 pressure ratio cycle above, the fuel cell provides 83% of the total power if no fuel is fired in the gas turbine, falling to 67% with an 8% point drop in efficiency, if the gas turbine inlet temperature is increased to 1150°C. Thus, whilst there is no thermodynamic motivation for firing fuel in the gas turbine, there may well be a significant capital cost benefit.

**Figure 5: Fuel Cell plus 'Basic' Gas Turbine Performance Map with No Fuel Fired in the Gas Turbine Combustor**
Figure 5 shows a similar performance map, in this case assuming that no fuel is fired in the gas turbine combustor, but that fuel cell exhaust temperature is allowed to vary. Different SOFC developers have published exhaust temperatures ranging from 850°C (Veyo, 1996a) to 1000°C (Nathanson, 1996). The main point of interest here is that the overall cycle efficiency increases with increasing fuel cell exhaust temperature. Extending the analogy with a conventional combined cycle gas turbine (CCGT), it might be expected that there would be a value for the fuel cell exhaust temperature at which peak efficiency was achieved. However, this limit has not been reached here, and further increases in temperature were not felt to be realistic. This result is significant, since low exhaust temperatures are a development target for standalone SOFC operation. Whilst not conclusive, due to the simple model for variation of SOFC efficiency with temperature, this analysis suggests that higher exhaust temperatures should be the development target for combined cycle operation (despite the associated additional cooling requirements).

3.b.ii. Fuel Cell Plus Recuperated Gas Turbine. Figure 6 shows an extension to the cycle described above to include a recuperator. Heat is transferred from the gas turbine exhaust to compressor discharge air upstream of the fuel cell inlet. The performance of the recuperator is as detailed in Table 2. This cycle is similar to those described by Beve et al. (1996), Nathanson (1996), Ali and Moritz (1996) and White (1996).

Figures 7 and 8 show cycle efficiency and specific power for cases with constant fuel cell exhaust temperature and unfired gas turbine combustor respectively. As expected for a recuperated cycle, the optimum pressure ratio falls to a much lower value, ~5. Recuperated cycles are not possible for pressure ratios greater than around 14 here, due to the low turbine exhaust temperature at the relatively low firing temperatures considered. The use of a recuperator implies that the air inlet temperature to the fuel cell is generally higher, so that excessively cool air supply is less likely to be a problem.
Perhaps the most significant aspect of these results is that the peak efficiency is only slightly greater, by around 1% point, than that obtained with the unrecuperated cycle. This implies that it may well be more cost effective to construct a cycle without a recuperator, which is frequently a relatively high cost item. However, since the unrecuperated cycle uses a higher pressure ratio, the pressure vessel required to house the fuel cell is likely to be more costly. The fraction of the total power generated by the fuel cell in the peak efficiency case with an 850°C fuel cell exhaust temperature is ~77%, approximately 6% lower than the equivalent unrecuperated case. Assuming that the fuel cell specific capital cost is generally higher than that of the gas turbine, this is likely to further offset the cost of the recuperator in this configuration.

3.b.iii. Fuel Cell Plus Intercooled and Recuperated Gas Turbine. Figure 9. shows a further extension to the cycle, introducing a stage of intercooling between the high pressure (HP) and low pressure (LP) compressors. The performance of the intercooler is as detailed in Table 2. The LP compressor pressure ratio is chosen to minimise the overall compressor work in each case.

Figures 10. and 11. show cycle efficiency and specific power for cases with constant fuel cell exhaust temperature and unfired gas turbine combustor respectively. These results do not differ greatly from the preceding case, although as expected the optimum pressure ratio shifts to a slightly greater value (around 7) and the air temperature at inlet to the fuel cell falls. The overall peak cycle efficiency is marginally higher than the previous case, by ~1.5% points, although it is clearly questionable whether such a small gain would justify the inclusion of an intercooler. The fraction of the total power generated by the fuel cell in the peak efficiency case with an 850°C fuel cell exhaust temperature is also very similar to the equivalent case without intercooling, ~6% lower. This would yield only a very marginal cost benefit for this configuration.
**Figure 10:** Fuel Cell plus Intercooled Recuperated Gas Turbine Performance Map with Constant Fuel Cell Exhaust Temperature

**Figure 11:** Fuel Cell plus Intercooled Recuperated Gas Turbine Performance Map with No Fuel Fired in the Gas Turbine Combustor
4. ECONOMICS IMPLICATIONS

Detailed plant cost estimates are beyond the scope of this paper. However, a realistic estimate of the cost and performance of a small gas turbine can be obtained from published data (Gas Turbine World, 1995). Typical cost and efficiency for 1, 3 and 10 MW gas turbines are given in Table 3.

Table 3: Representative Published GT Costs and Efficiency

<table>
<thead>
<tr>
<th>Specific Cost</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MW</td>
<td>1030 $/kW</td>
</tr>
<tr>
<td>3 MW</td>
<td>760 $/kW</td>
</tr>
<tr>
<td>10 MW</td>
<td>590 $/kW</td>
</tr>
</tbody>
</table>

Notes:
1. Costs are increased by 50% compared with those given in Gas Turbine World (1995) to allow for turnkey installation.
2. Efficiencies are reduced by 1% point compared with those given in Gas Turbine World (1995) to allow for inlet and exhaust losses.

Fuel cell costs are inevitably less well established, since SOFC stacks are not as yet commercially available. However, a figure of around $1000/kW for an installed stack is frequently mentioned in the literature. Here it is assumed that such a figure is realistic and that it will not vary greatly with power rating over the range 1-10 MW. The fuel cell performance model used in this paper gives an efficiency of 50% nett AC, LHV for a standalone atmospheric pressure fuel cell.

It is assumed that an overall cycle efficiency of 65% is realistic for a SOFC plus gas turbine combined cycle, based upon the above analysis, and that the fuel cell provides 70% of the power output. The overall cost is taken as being simply equal to the sum of the costs of the gas turbine and standalone fuel cell which make up the system.

Using these cost and performance assumptions, and using a discount rate of 12%, a plant life of 15 years, a gas cost of $3/MMBtu and an annual operation and maintenance (O&M) cost of 10% capital cost, the cost of generation for these systems can be estimated following the method outlined by Horlock (1992). This yields the results given in Table 4.

Table 4: Cost of Electricity (CoE) Comparison

<table>
<thead>
<tr>
<th></th>
<th>Standalone FC</th>
<th>Standalone GT</th>
<th>Combined Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoE at 90% Utilisation</td>
<td>5.2 $/kWh</td>
<td>5.1 $/kWh</td>
<td>4.5 $/kWh</td>
</tr>
<tr>
<td>CoE at 60% Utilisation</td>
<td>6.7 $/kWh</td>
<td>6.1 $/kWh</td>
<td>5.9 $/kWh</td>
</tr>
<tr>
<td>CoE at 30% Utilisation</td>
<td>11.4 $/kWh</td>
<td>8.8 $/kWh</td>
<td>10.3 $/kWh</td>
</tr>
</tbody>
</table>

Figure 12 shows the results of an extension of the above analysis to cover a range of power ratings and utilizations. Costs and efficiencies for fuel cell and gas turbine systems in the range 1-10 MW were obtained by interpolation in the values discussed above. The cost of electricity was then calculated at each power rating and utilisation. The figure shows the regions in which each system gave the lowest cost of electricity.

5. DISCUSSION

This paper has described the assessment of the performance of a number of SOFC plus gas turbine combined cycles for a range of cycle parameters. The principal conclusions are:

- Relatively low firing temperature gas turbines give the highest overall cycle efficiencies when integrated with SOFCs.
- The use of gas turbines with higher firing temperatures reduces the fraction of the power generated in the fuel cell and potentially reduces the specific cost of the system.
- The addition of extra complexity into the cycles, specifically intercoolers and recuperators, gives a relatively small increase in cycle efficiency, and the extra cost may well not be justified.
- A simple analysis suggests that the cost of electricity for a fuel cell plus gas turbine combined cycle is lower than that of either the fuel cell alone or the gas turbine alone at a power rating of ~10 MW and lower.
There is clearly scope to extend this work further. In particular a more
detailed model of the fuel cell is required, probably focusing upon a
particular design of stack. This should model some of the internal heat
transfer, in order to relate fuel cell operating temperature more directly to
exhaust temperature, and include the effect of temperature on both
performance and life. This could then be used for more detailed thermo-
economic optimisation, varying the operating parameters of the fuel cell
more extensively than has been carried out here, in order to identify the
most cost-effective combined cycle. Finally, Ali and Moritz (1996) have
discussed some of the practical design issues involved in integrating a gas
turbine with a SOFC, and more detailed consideration of the points raised
is undoubtedly required.

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