TOWARDS THE DEVELOPMENT OF A 25 KW PLANAR SOFC SYSTEM

R. Bolden, K. Föger and T. Pham
Ceramic Fuel Cells Limited
170 Browns Road
Noble Park, VIC 3174, AUSTRALIA

ABSTRACT

Ceramic Fuel Cells Limited (CFCL) commenced its technology demonstration phase in June 1997, after successfully concluding its initial five-year R&D program. With further successful demonstration of stack modules at 1.5 kW and 5.5 kW in size in 1997 and 1998, the Company has rolled out its field demonstration plan for systems up to 100 kW in size. At present, CFCL is working on its first 25 kW system employing CFCL's state-of-the-art stack technology. This paper describes CFCL's efforts in the design and construction of the Company first 25 kW solid oxide fuel cell (SOFC) power generation system. The paper also discusses CFCL's stack technology to be used in this system.

INTRODUCTION

Ceramic Fuel Cells Limited (CFCL) was established in 1992 with a mandate to bring the solid oxide fuel cell (SOFC) technology to full commercialization. In June 1997, the Company completed Phase 1 - its initial five-year R&D program. Phase 2, the technology demonstration phase commenced shortly after, with demonstration plan detailed up to mid-2001.

Following several successful demonstrations of stack modules at 1.5 kW and 5.5 kW in size in 1997 and 1998 (1,2), CFCL has rolled out its field demonstration plan for SOFC systems up to 100 kW in size. At present, the Company is working on its first 25 kW system employing CFCL's state-of-the-art stack technology.

For CFCL, the development of the 25 kW system is a significant step in the journey towards a commercial product. The system will be used initially as a demonstration system to CFCL's shareholders. However, it may have market potential in its own right. Major technical objectives in the development of this 25 kW system are:

• To evaluate the relative merits of various stack and system design concepts.
• To assess the performance of various specialized plant items such high temperature heat exchangers and valves, etc.
• To provide scale-up data to larger systems.

This paper describes CFCL's efforts in the design and construction of our first 25 kW SOFC power generation plant. Additionally, the paper discusses CFCL's stack technology to be used in this 25kW system.
System Configuration

Figure 1 shows the process flow configuration of CFCL's first 25 kW SOFC system.

In this scheme, the natural gas fuel is pre-processed in two stages prior to being fed to fuel cell stacks.

The first stage involves the removal of sulfur-containing odorants in the form of butyl-mercaptans typically present in pipeline natural gas. This is achieved by using the commercially proven two-step desulphurization method that employs cobalt molybdate catalysts and zinc oxide adsorbent (3). The small amount of hydrogen required for the conversion of the mercaptans to hydrogen sulfide is provided externally from hydrogen bottles. For optimal efficiency, desulfurization of the fresh natural gas fuel is carried out at 380°C, which is within the 350°C - 400°C temperature range suggested in a study by Lundberg (4).

The second stage of the fuel pre-processing section of the plant uses adiabatic steam pre-reforming to remove the higher hydrocarbons, ethane and propane. The pre-reformer employs commercially available catalysts that are loaded with a high concentration of Ni particles. The catalyst is active at temperatures as low as 250°C and is also highly resistant to carbon deposition (5). The pre-reforming stage minimizes the risk of carbon
formation as a result of the thermal cracking of the higher hydrocarbons that would have otherwise occurred in the downstream heat exchangers, pipes and the stack itself. Furthermore, this pre-reforming step allows the fuel, now comprising mainly methane and steam, to be preheated up to 650°C, thus reducing thermal gradients in the stack.

Fresh tap water is treated to boiler feed water quality. The treated water is vaporized and superheated to the desired temperature in the steam generator. Steam is generated up to an amount corresponding to a steam to carbon ratio of 2.25. This provision of steam is provided to ensure that there will be sufficient steam to suppress carbon formation near the inlet region of the anode surface where, as a result of the fast kinetics (6,7,8), reforming equilibria are likely to establish very quickly.

Air is filtered and forced through the system and stack using a blower. It is preheated to a temperature that maintains the stack operating temperature at 850°C and oxygen utilization at 50%.

The stack carries most of the reforming load internally so as to optimize thermal usage, and hence overall system efficiency. Hot streams from the anode and cathode exhausts are used to satisfy all internal preheating requirements, as well as for steam raising. The high operating temperature of SOFC stacks demands the use of costly exotic materials for the air and fuel heat exchangers, as well as their associated control valves. This excludes many heat exchangers and control valves that are available off-the-shelf. As a result, for these items, CFCL has engaged various specialist manufacturers to design them to CFCL's specifications.

The small amount of unspent fuel from the stack, H₂ and some CO, is completely combusted in a catalytic converter. The oxidant used in this combustion process is the cathode exhaust whose temperature is further reduced, after the air preheater, in a water-cooled exchanger. This set-up is designed to make sure that combustion in the catalytic converter takes place well below the explosive limit. The thermal energy in the exhausts is further recovered in a closed circuit waste heat recovery system before being discharged to the atmosphere.

The DC power produced from the stacks is converted to AC form using a power conditioner, which is currently being manufactured to CFCL's specifications. It is expected the power conversion loss in this step will be about 7% of the DC power output.

The 25 kW plant uses a remote monitoring and control system with stand-alone PC/PLC controls. The control system has a graphical, menu driven and windows based man-machine interface that will allow easy selection of relevant data on-line, clear-cut monitoring of trends and rapid specifications of plant set points. In addition to normal operation, other operational aspects of the plant such as Start-up, Stand-by, Shutdown and Emergency Stop have also been considered in the development of the control software.

**Key Performance Indicators**

Process modeling of the above scheme producing 25 kW AC power output results in a set of key performance indicators, shown in Table 1.
Table 1. Key performance indicators of the 25 kW system shown on Figure 1.

| Stack Performance | Fuel utilization (%) | 85 |
|-------------------|----------------------|----|
|                   | Oxygen utilization (%) | 50 |
|                   | Temperature - max. (°C) | 850 |
|                   | Current density - ave. (mA/cm²) | 150 |
|                   | Power density - ave. (mW/cm²) | 101 |
| System Performance | Total DC output (kW) | 31 |
|                   | Electrical efficiency (%) | 43 (HHV) |

* Defined as 25 kW/total energy input at the beginning of life.
HHV = High Heating Value.

Since this is the first demonstration system for CFCL in the 25 kW range, the estimated electrical efficiency of 43% (HHV) is highly competitive. Higher electrical efficiency could be achieved by minimizing parasitic losses throughout the system, as well as the AC and DC internal power usage.

Current Status

CFCL has recently completed plant trials of a similarly configured system at the 1.5 kW scale. The aim of this project, known as the Proof-of-Concept System Number 2 (POC2), was to test system configuration concepts, as well as special high temperature plant items that will be scaled up in the 25 kW system. These trials have provided CFCL with valuable design and operating experience, and scale-up data of SOFC systems running on natural gas fuel. The system also pilot tested the control software that had been developed in-house.

The 25 kW plant is presently being assembled. Commissioning tests for various plant items will commence shortly, while plant performance results are expected during the final quarter of 1999.

TECHNOLOGY FOR THE FIRST 25 KW STACK

Cell Technology

CFCL has developed electrolyte-supported cell technology for operation at more than 830°C, and anode-supported technology for operation between 700 and 830°C. Electrolyte-supported cells, at 3 and 8 mole % Y₂O₃-ZrO₂ (3YSZ and 8YSZ) are produced by tape casting, punching to the desired size and sintering in a single firing step that can achieve flatness to within a few microns. LSM cathode and NiO/YSZ anode layers are subsequently deposited onto the cell surface by screen printing and firing. Electrolyte sheets with 50-100 μm thickness (3YSZ) and 130-200 μm (8YSZ), and 50 mm to 150 mm square in size, are produced. A commercial tape-caster and a screen printer are used in the batch production mode.
Operations at more than 830°C significantly restrict choices and increase costs for interconnect materials. CFCL has made a strong push to develop high-performance cell technology operating in the 700-800°C range. Anode-supported cells with 500-700 μm anode supports and 10-30 μm thick electrolyte (8YSZ) layers have been fabricated by laminating tape-cast anode and electrolyte sheets followed by sintering. The company has also established a program on high-performance cathodes for 700-800°C operation.

The superior performance of the anode-supported cells has been demonstrated, and the technology is currently being scaled-up. However, these cells are still fabricated on a laboratory scale, and therefore will not be available for the first 25 kW stacks. Stack designs are being developed which allow interchange between electrolyte- and anode-supported cells.

**Stack Designs**

Based on a detailed cost estimation study, CFCL has concluded that stacks using thick metal plate interconnects formed by machining would never be a cost-effective option, even with cheap steels. Our new design uses thin sheet steel components as interconnect/gas distribution plates. The stack to be put in service in the 25 kW system consists of 8 modules, internally manifolded, with each module containing 30 layers of 4x4 arrays of cells. Each of these cells has an effective area of about 80 cm². The expected total DC power output of this stack is 31 kW. Extensive fluid flow modeling is also carried out to optimize the gas and heat flow distribution in the stack.

**Stacking Technology**

Our cost targets demand the use of low-cost materials for the interconnecting plates, which are the dominant cost components in the stacks. Ferritic-type stainless steels appear most promising with respect to key properties such as corrosion resistance and thermal expansion. An engineering approach is currently being pursued to overcome the poisoning of the cathode as a result of the chromium evaporation from the airside of the interconnecting plates.

Effective and long-lasting seals are obviously important ingredients for a successful operation of planar SOFC stack. These seals must be able to remain effective after numerous thermal cycles that stack is typically subjected to during its lifetime. Seals need to be tailored to the stack design and cell technology. CFCL has developed a number of different sealing concepts based on glass and glass-ceramics for operation below and above 800°C. Production methods for larger scale manufacture have been developed.

**Internal Reforming Cells and Stacks**

Maximizing internal reforming is an effective way of managing the thermal energy distribution in solid oxide fuel cell systems. CFCL has developed anode technology that will promote the steam reforming of methane within the fuel cell stacks in the temperature range from 800°C to 930°C. Figure 2 shows experimental data of a stack operated on pre-reformed natural gas fuel in a mini-proof-of-concept system. This stack
operated at 900°C, 200 mA/cm² and a steam to carbon ratio (S/C) of more than 1.5. Good performance and stability are evident over more than 1000 hours of operation at two fuel utilization levels, 60% and 85%. Additionally, there was no evidence of carbon formation observed during the entire operation.

![Figure 2. Stack performance with internal reforming.](image)

**Prototype Demonstrations**

The new stacking concept was demonstrated in a single cell stack arrangement. This stack was operated for more than 4000 hours with an observed degradation rate of about 1% per 1000 hours. A 10 layer, 2×2 array stack of a similar cell configuration was assembled and fired-up at about the same time. After about 375 hours of operation, an operation mishap occurred that led to air starvation in some layers of the stack. As soon as this happened, the bottom layers started to degrade. However, the top layers still showed stable performance, in line with data from the single cell stack arrangement. Figure 3 shows performance data of layer 3, the best layer from the 10 layer, 2×2 array stack, for more than 3000 hours operating at 820°C. The technology scaled quite well. Further optimization and fine-tuning of the stacking arrangement have been considered for incorporation into the 25 kW system stack module. The stacking design has been finalized. Components for the 31 kW stack for the 25 kW system are currently being manufactured.
SUMMARY

Following successful demonstrations of stack technology at the 1.5 kW and the 5.5 kW scale in 1997 and 1998, Ceramic Fuel Cells Limited (CFCL) is embarking upon a demonstration plan for systems up to 100 kW in size. The Company presently has the immediate technical goal of developing prototype systems in the 25 kW range.

A 25 kW system employing CFCL's state-of-the-art stack module technology is being assembled. Process modeling of this system yields a net electrical efficiency of 43% based on HHV. Given the fact that the system has been designed as a test station, the estimated electrical efficiency is competitive. Commissioning tests of the system will commence shortly, with plant performance results expected during the final quarter of 1999.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge valuable inputs from the Quasar prototype demonstration team and Dr. Khaliq Ahmed for providing the internal reforming stack test results.

Figure 3. Performance of layer 3 in the 10 layer, 2×2 array stack.
REFERENCES

1. K. Föger, B. Godfrey and T. Pham, in *Fuel Cells Bulletin*, No. 5, February 1999 issue, S. Barrett, Editor, p. 9, Elsevier Science Ltd, UK (1999).

2. R. B. Godfrey, K. Föger, S. P. S. Badwal and R. Bolden, in *Proceedings of the 1998 Fuel Cell Seminar*, p. 503, Palm Springs, California (1998).

3. P. J. H. Carnell, in *Catalyst Handbook*, Second Edition, M. V. Twigg, Editor, p. 198, Manson Publishing Ltd, London, UK (1996).

4. W. L. Lundberg, in *Solid Oxide Fuel Cell System Cogeneration System Conceptual Design*, GRI Report No. GRI-89-0162, under contract No. 5068-294-1273, (1989).

5. R. Vannby and S. Winter Madsen, in *Proceedings of the AIChE Ammonia Symposium on Safety in Ammonia Plants and Related Facilities*, paper No. 280f, Los Angeles, California (1991).

6. E. Achenbach and E. Riensche, *Journal of Power Sources*, **52**, 283 (1994).

7. V. D. Belyaev, T. I. Politova, O. A. Mar’ina and V. A. Sobyanin, *Applied Catalysis A: General*, **133**, 47 (1995).

8. A. L. Dicks, R. J. Carpenter, E. Erdle, D. F. Lander, P. D. Lilley, A. G. Melman and N. Woudstra, in *Solid Oxide Fuel Cell Systems Study*, Volume 2, A. G. Melman and N. Woudstra, Editors, Commission of the European Communities Report No. EUR 13103, under contract No. EN 3E-0165-NL, (1991).

Electrochemical Society Proceedings Volume 99-19 87