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A 1000-cell SOFC reactor for domestic cogeneration

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Abstract

A cogeneration system was built using 1000 cells with the intention of supplying 30 kW of hot water and 500 W of power. The basis of the cogenerator was the small tubular SOFC design. 8Y zirconia was mixed into a plastic paste and extruded to form thin-walled tubes. The process produced a zirconia material with high strength and good electrical properties. After drying and firing to full density, electrodes were coated onto the inner and outer surfaces of the electrolyte, then sintered. Current collecting wires were wound around the tubular cells and the tubes were assembled into a reactor. Either hydrogen or a premix of natural gas and air was fed through the tubes and ignited by a hot wire. The ignition shock did not damage the cells in any way. Cycling was achieved within minutes. A steel heat exchanger/recuperator was used to feed hot air to the cell stack. The electrical output was measured via a potentiostat. © 1998 Elsevier Science S.A.

Keywords: SOFC reactor; Domestic use; Cogeneration; Zirconia

1. Introduction

The colloidal process has recently been established as one of the most economical methods for making ceramics with good thermal and mechanical properties [1,2]. Traditional techniques, such as melt forming and vapour deposition, produce ceramics with excellent properties but are slow and expensive. Cheaper routes such as powder pressing produce materials with inferior properties [3]. The self supporting SOFC electrolyte device described in this paper requires both high strength and good thermal shock characteristics [4]. The electrolyte undergoes vigorous handling procedures in the preparation of a fuel cell and thus needs high strength. The cells must then survive rapid heating and cooling from room temperature to more than 700°C in minutes. They therefore need good thermal shock resistance.

The ceramic material chosen for this application was yttria stabilized zirconia. Zirconia stabilized with 3 mol% yttria (3Y) produces excellent mechanical properties, but cracks on thermal cycling and has a poor oxygen ion conductivity. Increasing the yttria content increases the O^{2-} ion conductivity, but decreases the mechanical strength and toughness. By producing the ceramic via the colloidal process the mechanical properties were sufficiently improved to be used in this application.

Producing ceramics using the colloidal process involves grinding a powder, suspended in a liquid medium such as water or an organic solvent, with a dispersing agent keeping the fine particles separate once the agglomerates have been broken down. Binder and plasticisers are then added to the system in order to achieve the required rheology for extrusion. It is important to maintain the stability of the dispersion throughout this addition. Excess liquid is then removed in a controlled way, leaving a paste which can be moulded to the required dimensions, in this case zirconia tubes shaped by extrusion. The extruded zirconia tubes can then be sintered and made into fuel cells.

Previous research at Keele University reported in the literature [5] has directly led to the development of the 1000-tube SOFC reactor. This includes information gathered from a 200-cell reactor, and from a 20-tube lab rig. The 1000-tube reactor used the same tubular fuel cells as the earlier design, allowing rapid temperature cycling. The cells were put into individual racks, which were then assembled in modular fashion to build the whole reactor (Fig. 1). The reactor was insulated with ceramic fibre and fitted with thermocouples for temperature control. Natural gas fuel and air were fed to the reactor under computer control. After ignition, air was mixed with the fuel to allow partial oxidation to take place in the fuel cells prior to the electrochemical reaction. The computer also controlled ignition, air/fuel premix, temperature, normal and emergency shut down and data logging. Exhaust heat from the reactor

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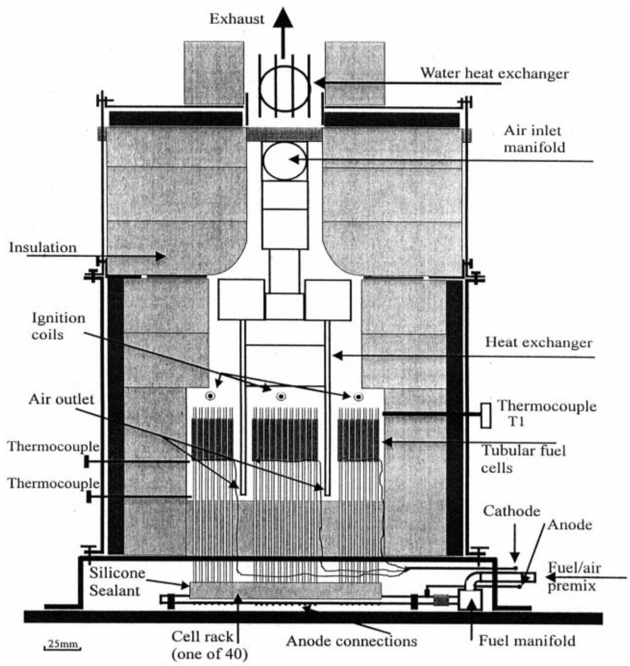

Fig. 1. Schematic of the 1000-tube SOFC reactor.

could be used for water heating while the electrical power could be fed to a battery and solid state DC to AC converter.

2. Experimental

Sheets of 8Y material made via the colloidal process were dried by tapecasting. These sheets were prepared by Viking Chemicals (Denmark), (S. Markland, personal communication). The dry tapes were rehydrated for 30 min in 100% humidity. The rehydrated tapes were then mixed to ensure an even consistency of solvent throughout the material to guarantee good extrusion using a ram extruder. Composition of the tapes was reported previously [6]. Once the tubes were extruded they were dried in ambient conditions and sintered to 1420°C. The sintered tubes had a wall thickness of 0.2 mm and an internal diameter of 2.0 mm. Extruded rods were also produced to give additional strength information (Fig. 2). The strengths of the rods and tubes were assessed using a three point bend test (Lloyd Instruments LRX) with a span of 20 mm and a load cell of 50 N. The tubes were also tested by cycling the temperature from 400 to 800°C and back over a period of 2 min. This was repeated many times as shown in Fig. 3.

The application of electrodes and interconnects to the zirconia fuel cell tubes was described in [7]. The cells for this reactor were made with an active length of 3.0 cm. The 1000 fuel cells were assembled into 40 racks of a new compact design. Each rack has a tubular gas distribution manifold with a flow restrictor for each tube to provide even gas flow across the rack. The fuel cells were fitted over the restrictor tubes and sealed with silicone rubber cement, this junction being outside the hot area of the reactor. The method also provided a useful degree of flexibility during subsequent handling. The racks were assembled individually into the 1000-tube reactor, the construction method allowing easy removal of a rack in the event of failure (Fig. 1). The cathode part of each rack was insulated from its neighbour by sheets of Saffil while the base of the reactor was sealed against heat loss by Saffil wool. For test purposes, hydrogen was fed to the racks from a common manifold while air was fed to the reactor from an air blower via a heat exchanger. The heated air raised the temperature of the

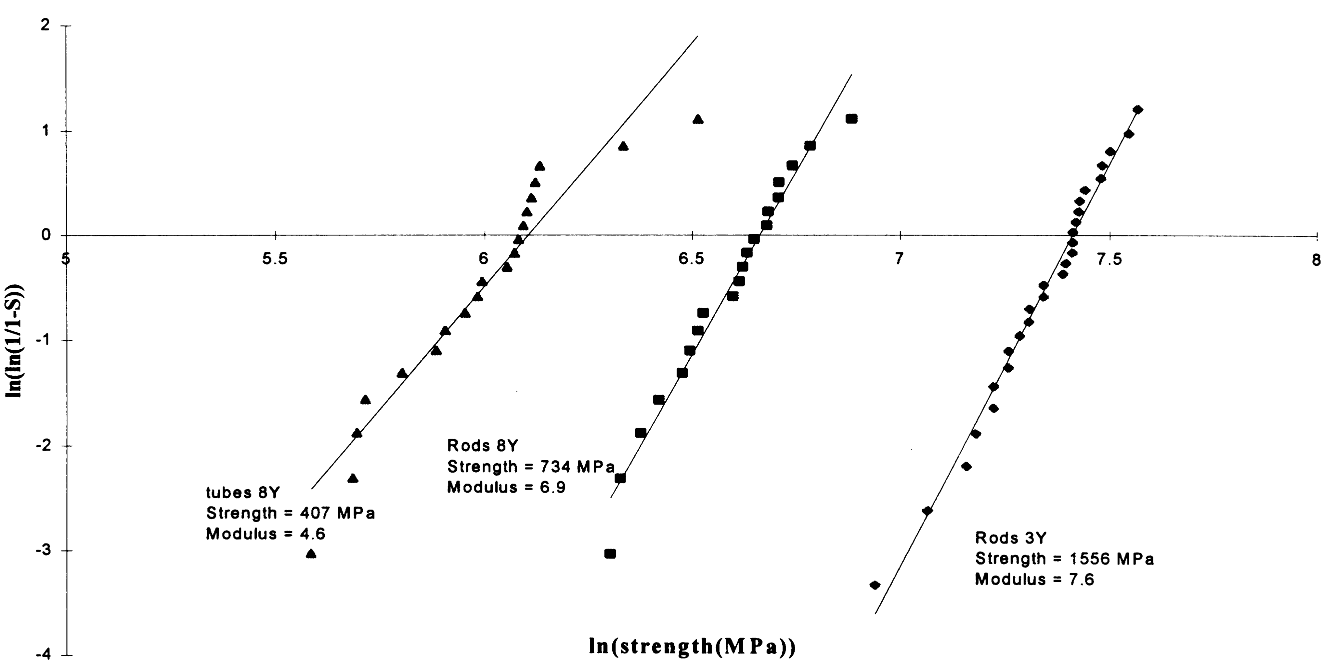

Fig. 2. A Weibull plot of 8 mol% yttria stabilized zirconia tubes with plots of 3 and 8 mol% yttria stabilized zirconia rods.

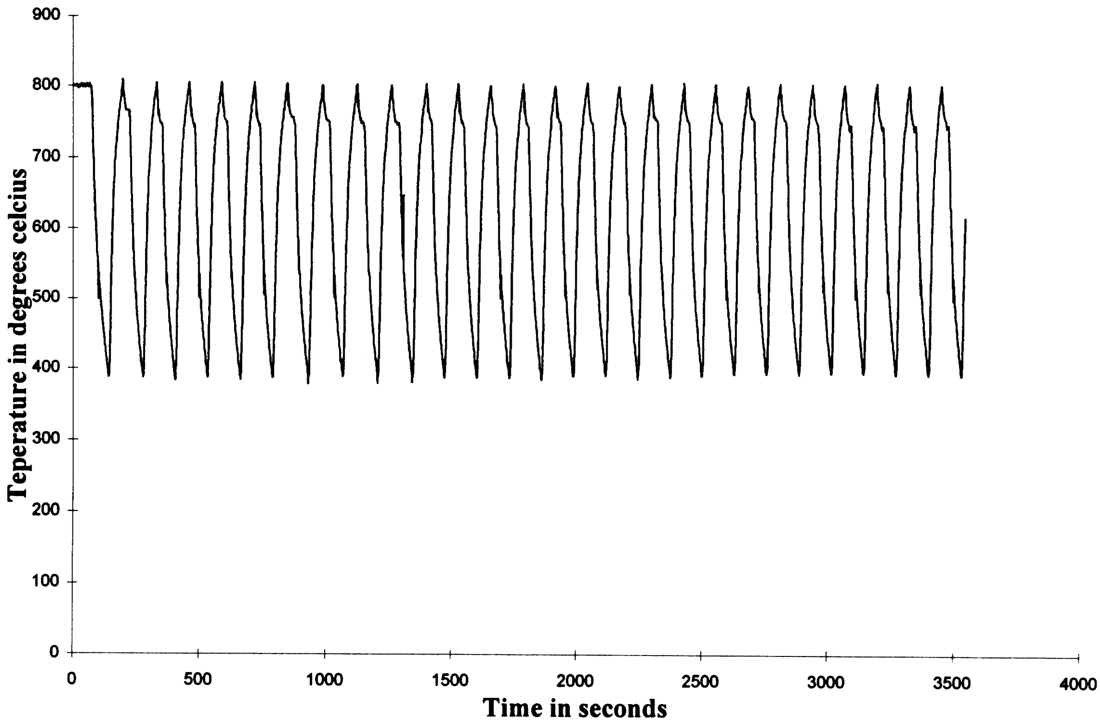

Fig. 3. Temperature cycle of the cells used in the reactor.

reactor to its operating temperature of 700–800°C. Ignition was accomplished using a hot wire igniter. The temperature of the reactor was measured from the thermocouple T1, the computer maintaining the preset temperature by varying the air flow. No additional heat source was required. Experiments were also performed using a premix of natural gas and air replacing the hydrogen fuel. Tubular cells were started on natural gas, and after ignition the air premix was gradually increased so that partial oxidation could occur on the nickel cermet anode upstream of the cells. The tubes in each rack were connected in parallel while the racks were connected in series to build the voltage to a useful figure. The hot flue gases could be used to heat a domestic central heating boiler while the electrical output could be fed to a battery and DC to AC converter.

3. Results and discussion

Results of the three point bend test of the 8Y tubes and both the 3Y and 8Y rods are shown in Fig. 2. The 8Y tubes had a mean strength of 407 MPa but this was misleading as the thin-walled ceramic exhibited crushing failure rather than tensile fracture. Therefore 8Y rods of the same material were tested, giving a mean strength of 734 MPa with a Weibull modulus of 6.9. These values were encouragingly higher than previous figures reported in the literature. 3Y rods gave even higher strength as expected, but the material was unsatisfactory due to low oxygen conductivity and cracking failure during temperature cycling tests [8].

Prior to installation in the 1000-tube reactor, one of the fuel cells from each batch was tested using hydrogen as fuel. A typical result obtained at 800°C and 0.5 v was a current of 285 mA/cm^2 or a power of 142 mW/cm^2. Hot wire ignition was carried out 50 times without any tube failures. Electrical performance remained constant throughout these tests.

Fig. 3 shows 25 cycles of a typical cycling experiment. The system was heated at 200°C/min to 800°C when the ratio of air to fuel was adjusted by the computer to maintain the temperature for 20 min before the cooling cycle was started. From Fig. 3 it can be seen that the cells were cooled to 400°C and heated again to the operating temperature of 800°C in 140 s. The cells survived the rapid heating and cooling without failure. This was repeated for hundreds of cycles.

The cells were built into 40 racks of 25 tubes each as

Table 1

The electrical performance of 10 racks, 25 cells each, from the 1000-cell cogenerator

Rack no.	Open circuit voltage	Current @ 0.5 V and 800°C	Current (mA/cm^2)
1	1.21	7.08	150
2	1.19	7.59	161
3	1.21	7.09	151
4	1.21	7.27	154
5	1.2	8.59	182
6	1.22	7.62	162
7	1.22	7.90	168
8	1.17	9.25	196
9	1.21	7.54	160
10	1.19	7.27	154

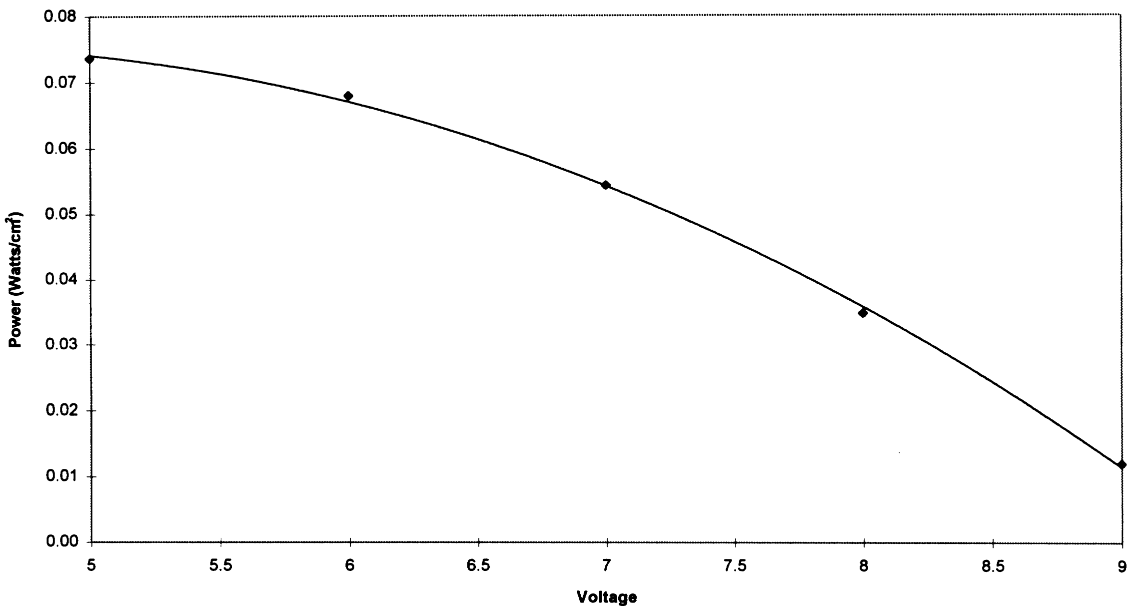

Fig. 4. Power density results for a set of ten racks (250 cells) in the 1000-cell reactor generating at 850°C.

described above. The racks were tested at 800°C and 0.5 v using hydrogen as fuel. Results from ten racks are shown in Table 1. Only 10 racks could be tested at a time on the potentiostat because of power limitations.

Fig. 4 shows the power variation with voltage for the ten racks operating on hydrogen at 850°C. During scale-up from single cells to a rack of cells, the specific output declined. This could have resulted from irregular gas flow, non-uniform temperatures or extra resistances in the connections. Cells were also tested on natural gas premixed with air, for comparison with hydrogen fuel. The electrical power output dropped by 25% in this case.

4. Conclusions

The colloidal process has been used to make zirconia electrolyte tubes. The tubes had an external diameter of 2.4 mm, a wall thickness of 0.2 mm and an average strength of 407 MPa. A 1000-tube SOFC reactor has been built from cells made from these tubes. The reactor was cycled between 400 and 800°C. The tubular fuel cells survived 200°C/min temperature rise without failing. Electrical current has been drawn. The reactor has produced 82 mW/cm^2 of power at 850°C.

Acknowledgements

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