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Electrochemical performance of a short tubular solid oxide fuel cell stack at intermediate temperatures

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HIGHLIGHTS

- The single cells fabricated for the stack show similar power performances.
- Stack power output in series, parallel and their mixed arrangements was similar.
- Using mixed parallel-series configurations can offer a suitable current or voltage.
- Mixed parallel-series configurations can be fixed in case any fuel cell fails.
- A damaged cell can be replaced in a module not to damage the overall performance.

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ABSTRACT

A short stack composed of six micro-tubular fuel cells was fabricated in order to study its electrochemical performance under different electrical connection configurations (parallel, series and parallel-series) at intermediate temperatures. Two cells were in the Ni-YSZ/YSZ/Pr_2NiO_4-YSZ system and four were in the Ni-YSZ/YSZ/Nd_2NiO_4-YSZ configuration, of which one failed following testing at 600 °C. Overall, individual cells had similar performance delivering 202, 302 and 340 mW/cm^2 at 600, 650 and 700 °C, respectively. The stack delivered a maximum of 7.40, 10.32 and 11.56 W at these temperatures. No significant differences were found among different arrangements. However, as expected, the stack performance was most affected by the malfunctioning cell under a series arrangement at 600 °C. Since the parallel-series configuration delivers an intermediate voltage and current and similar power to the parallel or series connections, it can be more suitable for stack assembly. Such an arrangement also offers the possibility of replacement of a stack module in case a cell fails in that module during operation. A repairable fuel cell stack eliminates the negative economic impacts caused by a malfunctioning cell which, in extreme cases, can lead to the complete loss of the valuable energy conversion device.
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1. Introduction

Fuel cell technology is one of the cleanest and most efficient techniques for converting the chemical energy of fuels into electricity [1]. The solid oxide fuel cell (SOFC) or in other words a ceramic fuel cell is a widely investigated device by researchers across the world to eliminate the environmental pollution caused by fossil fuels. The potential market competitiveness of SOFCs arises from: efficiency, flexibility in choice of fuel gas (hydrogen, hydrocarbons), solid and modular construction that has no moving parts, high operating temperature (produces high quality heat as a by-product which can be used for cogeneration), no precious metals involved in fabrication and a potential long life expectancy of more than 40,000–80,000 h [2,3].

The two main fuel cell designs are planar and tubular configurations. Despite the lower power density of tubular fuel cells compared with the planar design, they are preferred since tubular fuel cells require less sealing, show superior thermo-mechanical properties, withstand more thermal cycles and require less start up/shut down time [4–6]. Micro-tubular SOFCs (μt-SOFCs) have a diameter of less than 5 mm which due to their small diameter show a high power density (power density is proportional to the reciprocal tube diameter) and rapid start-up and cool-down time. The micro-tubular design has been seriously considered for portable applications such as cell phone where planar cells cannot be

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used [7–9]. A great example of high thermal shock resistance of tubular fuel cells is shown by Du et al. [10]. They fabricated a tubular stack which could withstand more than 50 thermal cycles when single cells were heated at a rate of 550 °C/min to the operating temperature.

The power generated by a single tubular fuel cell is too small for many applications, which necessitates investigation into the design and fabrication of fuel cell stacks for commercial adoption of SOFC technology. Fuel cell stacks have diverse applications such as stationary power generation and in the transportation industry, as shown in Fig. 1. Micro-tubular SOFCs with power output of 1–100 W are being developed by eZelleron for application in portable devices. Ultra Electronics-USSI designs tubular SOFC stacks for back up and portable power for use in oil and gas pipelines and remote sensors as well as for military applications. For instance, the D350 is a compact 350 W SOFC generator for application in expeditionary activities and remote battery charging. Fuel cell stacks producing 10 kW and above are appropriate for stationary applications, while 1–5 kW range stacks can be used for both mobile and stationary (mainly residential) applications. Stacks in the range of 100–500 kW are suitable for distributed power generation, such as Bloom Energy's 400 kW installation on Google's main campus in Mountain View, California.

In the early 1990S, Singhal and Kendall fabricated thin (100–200 μm) YSZ electrolyte supports for application in μt-SOFCs [11]. Following that, Alston et al. [12] from Kendall's research group designed one of the first μt-SOFC stacks, which consisted of 1000 zirconia electrolyte cells assembled into racks of 40 cells. The racks were connected in series, with parallel arrangement of tubes within each rack. The fuel cells were able to withstand 200 °C/min temperature rise, but delivered low power of 0.082 W/cm^2 at 850 °C due to the high ohmic resistance of the electrolyte support. Since then different research groups have attempted to develop different types of anode supported tubular fuel cells stacks. For instance, Lee et al. [5] developed a 700 W anode supported micro-tubular SOFC stack by stacking 36 fuel cells (each 20 cm long) arranged into bundles (of six) which formed a modular type stack. The stack generated a power density of 0.38 W/cm^2 at 750 °C using H_2 as fuel and a multi-layered cathode composed of LSM and LSCF, and showed a long term durability of over 400 h.

The Ni-YSZ/YSZ/YSZ-LSM system has been the desired system for many researchers due to the proven long term stability of its components. For instance, using this cell configuration, Sammes et al. fabricated a 100 W modular stack using 40 single cells [13]. Ding and Liu designed a two cell stack segmented in parallel which produced 1.78 W/cm^2 at 800 °C [14]. Bai et al. made two cone shaped cells stacked in series which produced 3.7 W at 800 °C [15]. Lim et al. fabricated a stack using 30 bundles connected in series in which each bundle contained two flat tubular fuel cells connected in parallel and managed to produce 921 W at 750 °C [16]. More recently, Ye et al. fabricated a short stack using two cells connected in series and produced 5.8 W and 4.9 W power output at 850 °C in hydrogen and ethanol fuels, respectively [17]. Suzuki et al. fabricated a short stack using five fuel cells of the type Ni-GDC/GDC/GDC-LSCF which produced 2.8 V OCV and 1.5 W at 500 °C for portable applications [18].

Sarkar's research group from Alberta Innovates-Technology Futures (AITF) published several patents on stack system design during 2004–2010 [19–22]. As presented originally in [23] and shown in Fig. 2, his suggested SOFC based power generator consists of a fuel reformer, modular SOFC stacks, a catalytic combustor, air blower, a thermal recuperator and a power conditioning unit/DC to DC converter. Electrical systems and sensors monitor the whole process to ensure that the system was operating under its optimum conditions. The stack was self-sustained and an in-house designed catalytic burner provided sufficient heat to take the stack to its operating temperature. Using the catalytic combustor, no external heat source was needed. From this design, they fabricated a stack consisting of 60 anode supported μt-SOFCs [23] as shown in Fig. 3a. Humidified hydrogen and air were fed to the anode and cathode, respectively. Fuel was injected into the open end of each cell using an Inconel tube. A machined glass-ceramic was used as the cell holder and a mica gasket provided suitable sealing. A catalytic burner was embedded between the cells to start up the stack as shown in Fig. 3b. To improve the temperature uniformity inside the stack, a high emissivity foil surrounded the stack and a high emissivity coating covered the current collector surface of each cell cathode. The stack ran for 1000 h without any major problem when it faced several on/off stages. The total generated power reached 20 W which was lower than expected. This was attributed to sagging Inconel fuel inlet tubes which touched the anode surface

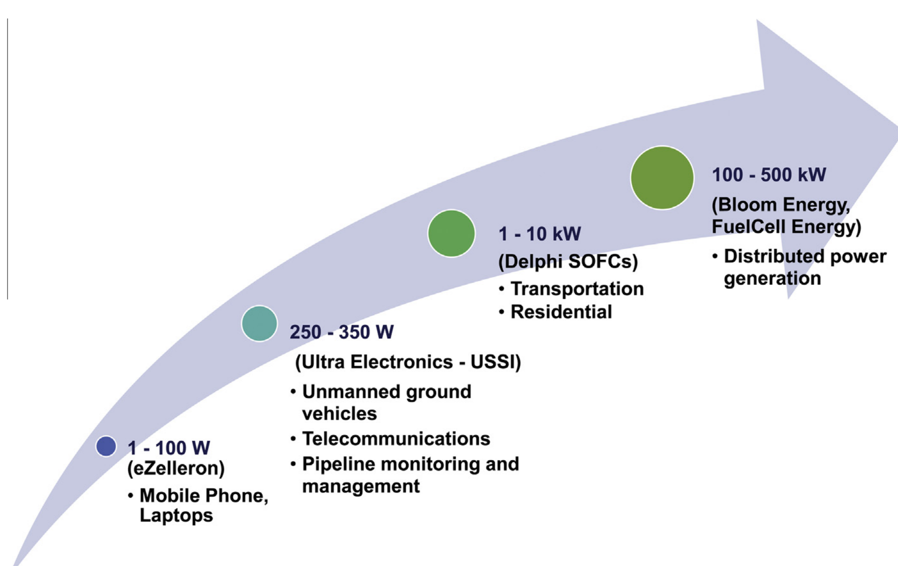

Fig. 1. Applications of SOFC stacks according to their power rating. Manufacturer names appear in parenthesis.

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