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Effects of pressurization and temperature on power generating characteristics and impedances of anode-supported and electrolyte-supported planar solid oxide fuel cells

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HIGHLIGHTS

- Pressurized anode-/electrolyte-supported planar SOFCs are measured at 750–850 °C.
- At any given p (1–5 atm) and T, ASC has roughly twice higher power density than ESC.
- Both ASC and ESC performance improve with increasing p and T.
- ASC is more sensitive to pressurization than ESC having larger power increments.
- Measured electrochemical impedances explain these ASC & ESC performance data.

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ABSTRACT

Power generating characteristics of pressurized anode-supported cell (ASC) and electrolyte-supported cell (ESC) are measured using the same single-cell stack setup, a planar full cell sandwiched by a pair of rib-channel flow distributors. Both ASC and ESC apply the same flow rates ($Q_{anode} = 0.5$ slpm $H_2 + 0.4$ slpm N_2 and $Q_{cathode} = 0.9$ slpm air) measured at three operating temperatures ($T = 750$ °C, 800 °C, 850 °C), each T under five pressures ($p = 1, 2, 3, 4, 5$ atm), having a total of 30 data sets for comparison. It is found that under loaded conditions, ASC has much larger increments in power densities, about three folds higher, than ESC due to pressurization. As T increases from 750 °C to 850 °C at 0.7 V, power densities of ASC/ESC increase from 175/97 mW cm^{-2} to 309/193 mW cm^{-2} at $p = 1$ atm, while at $p = 5$ atm, the increases of power densities are 281/137 mW cm^{-2} to 476/250 mW cm^{-2}, showing a stronger temperature dependence than pressurization. Corresponding electrochemical impedance spectra show that the better cell performance of ASC is attributed to both lower ohmic and polarization resistances found in ASC than that in ESC.

1. Introduction

Our modern society urgently needs much better electrical power generation systems, i.e. much higher efficiencies and much lower emissions than current conventional systems, in order to improve effectively many deteriorative environment and energy problems that we are facing today. As such, one promising candidate, a pressurized solid oxide fuel cell (PSOFC) integrating with a gas turbine or micro gas turbine (MGT), has been proposed and developed, having the highest efficiency up to 70% among only a few available hybrid power generation systems [1]. The feasibility of such hybrid PSOFC-GT or -MGT power system was demonstrated [2–5] during the past decade. For instances, Siemens established a demo project of a 220 kW PSOFC-MGT hybrid power system (PH220) in 2002 [2,3]. The Korea Institute of Energy Research reported a smaller hybrid power system (5 kW PSOFC integrated with 25 kW MGT) in 2006 [4]. And the Mitsubishi Heavy Industries run a 200 kW hybrid PSOFC-MGT combined-cycle power plant in 2011 [5]. Clearly, significant progresses on such hybrid power system have been achieved, but there are still technical challenges to be solved before a stable operation among different components of such hybrid PSOFC-GT or -MGT power system can be assured [6].

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One important technical challenge is the detail information of PSOFC, especially on the impact of pressurization and the effect of operating temperature to power generating characteristics and electrochemical impedances of PSOFC, which are still rather limited in literature. This motivates the present study.

Two main configurations of SOFCs are tubular and planar [7]. For simplicity, this study only discusses planar SOFCs, which have higher cell performance and lower fabrication cost than tubular SOFCs [7,8]. Furthermore, there are two types of planar SOFCs, i.e. electrolyte-supported and electrode-supported (either anode or cathode), depending on which material is the dominant component. The electrolyte-supported cell (ESC) has lower manufacturing cost and better mechanical robustness than that of the anode-supported cell (ASC) or the cathode-supported cell (CSC) [e.g., 9,10]. But ESC has higher ohmic losses and lower power densities than ASC or CSC, because ESC has a much thicker electrolyte than ASC or CSC [e.g., 11,12]. As to the electrode-supported SOFCs, ASC is preferred over CSC, since the former has higher power densities than the latter, especially at reduced operating temperatures [12]. Hence, the present study selects both planar full ESC and ASC as benchmark cells to measure the effect of operating temperature on these two different supported cells under elevated pressure conditions.

Specifically, the present work measures power-generating characteristics and electrochemical impedances of pressurized ASC and ESC using the same “single-cell stack” setup, a planar full cell (square area of 50 × 50 mm^2) sandwiched by a pair of rib-channel flow distributors (interconnectors). Such “single-cell stack” term was also used previously (e.g, [13–18]). Note that the merit of the present study is to apply the same experimental procedures and conditions, i.e. same flow rates, pressure, temperature, for both ASC and ESC cases, so that a direct comparison on power densities and electrochemical impedance spectra (EIS) between ASC and ESC can be measured. Results on EIS data at a fixed operating temperature ($T = 850$ °C) were recently reported [19], where experiments were carried out in a high-pressure, high-temperature SOFC test facility [18,19]. In this work, we will report new modifications of such high-pressure, high-temperature SOFC test facility and present new results on the effect of operating temperature to power generating characteristics and EIS of these single-full-cell stack-like ASC and ESC units. There are 30 data sets in total for comparison. Each of both ASC and ESC cases includes 15 data sets at three operating temperatures ($T = 750$ °C, 800 °C, 850 °C) and at each T with five different pressures (p) varying incrementally from 1 atm to 5 atm. Hence, effects of pressure and temperature on cell performance of both ASC and ESC can be scrutinized, which are important to pressurized SOFCs that are still limited in literature.

The next section describes a pressurized SOFC test facility with an emphasis on new modifications. Also described are the material information of ASC and ESC and associated experimental procedures and conditions. Results of power-generating characteristics and EIS of high-pressure single-full-cell stack-like ASC and ESC units are presented in Section 3, showing the effect of operating temperature on the cell performance of pressurized SOFC. Finally, conclusions are offered in Section 4.

2. A pressurized SOFC test facility

Fig. 1a presents a pressurized SOFC test facility, including an inner temperature-controlled furnace (central portion) that is resided in a newly established outer pressurized stainless steel vessel (see the left real photographs taken from top and front views). As can be seen from the top view photo, the new outer pressurized vessel applies a new gear device for easily sealing the vessel's cap without using any screws and bolts. Since the outer stainless steel vessel's cap is quite heavy, very difficult to open it up by one man. An extended weight-balance component connected to the vessel's cap with bearings that can move with the vessel's cap (see the front view photo) is used, so that the vessel's cap is very easy to open and close for test and maintenance purpose. Furthermore, an extended stainless steel supporting frame is welded on the lower portion perimeter of the outer pressurized vessel, just below the extended weight-balance component, so that the vessel can firmly stand on the ground at all times even when the vessel's cap is fully opened. The present SOFC test facility can be pressurized up to 10 atm.

Inside the furnace (see the central portion of Fig. 1a), there are several assembly parts, including from inside out a full planar cell (positive electrode-electrolyte-negative electrode, PEN), either ASC or ESC with the same reactive area of 40 × 40 mm^2, a supporting metallic (crofer 22-APU) frame, and platinum and nickel meshes on anode and cathode for current collection (see the exploding sketch on the bottom right of Fig. 1a). Then the PEN, the metal frame, and current collectors are sandwiched by a pair of rib-channel flow distributors (interconnectors) made of aluminum oxide materials on both anode and cathode sides to form a single-full-cell stack-like unit. It should be noted that the use of the metallic frame is to provide the mechanical support for PEN, which also acts as a separator to prevent the possible cross-leakages between fuel and oxidant from both feed and exhaust headers of interconnectors [16,17]. Such single-cell stack-like unit is again sandwiched by two ceramic housing units for air and fuel inlets and outlets. We apply a serpentine heating pipe system (see the central portion of Fig. 1a) to assure uniform heating of the supplied fuel and air gases. Other parts of the high-pressure SOFC test facility, such as mass flow controllers and power and impedance measuring devices, are not shown, and the reader is directed to Ref. [18] where the detail information can be found.

The top central and right portions of Fig. 1a show the information of ASC and ESC which were purchased from H. C. Starck (ASC 3 and ESC 2), each including two real photographs of PEN on both cathode and anode sides together with the schematic diagram of cathode, electrolyte, and anode with thickness information. Concerning the synthesizing process of the two different supported cells, ESCs can be manufactured by tape casting the electrolyte, followed by a cutting and sintering step, before both electrodes are deposited by screen printing and subjected to a final sintering step. As such, the number of sintering steps for ESCs can be minimized to only two. But ASCs are generally manufactured with three sintering steps (pre-sintering of substrate, electrolyte densification, and cathode sintering) and a flattening step is frequently necessary to minimize the bending caused by the different sintering behavior of the electrolyte, anode and substrate [20]. In general, ESCs are cheaper to manufacture than ASCs. Fig. 1b shows the cross-sectional morphology SEM images of both ASC and ESC with material information. Hence, the present testing full cells contain three different layers, i.e. the anode: porous NiO/YSZ of 470–565 μm (ASC) and/or porous NiO/GDC of 30–50 μm (ESC), the electrolyte: dense YSZ of 4–6 μm (ASC) and/or dense TZ3Y of 80–110 μm (ESC), and the cathode: porous LSM/YSZ-LSM double layer of 30–60 μm (ASC) and/or 30–50 μm (ESC), respectively. Same as our previous studies [18,19,21], the present study applies a seal-less single-cell stack by using appropriate load plates to obtain a good electrical contact between the PEN and the two current collectors without bolts. This arrangement can avoid the difficult matching problem of thermal expansion coefficients among different components of the stack.

Like our previous studies [16–19,21], the present study applies the same testing procedures proposed by Haanappel & Smith [22] for the start-up and cell performance measurements. In all