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Taxonomies of SOFC material and manufacturing alternatives

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Abstract

Material and manufacturing alternatives for solid oxide fuel cells are listed and analyzed. Specifically, four categories of anode materials, five categories of cathode materials, four categories of electrolytes, and three categories of interconnect materials are presented. Design considerations including operating temperatures and compatibilities among stack materials are also highlighted. Similarly, stack manufacturing options are separated into seven categories and developed into process sequences based on the number and type of firing steps. This work is intended to facilitate material and manufacturing assessments through the consideration of the variety of alternatives prior to capital investment for wide-scale production.

Keywords: SOFC; Design; Materials; Manufacturing; Fabrication

1. Introduction

Fuel cell technologies are expected to substantially reduce oil dependency and environmental impacts compared to conventional combustion-based power generation technologies. Solid oxide fuel cells (SOFCs) have the additional advantages of high efficiency, ability to utilize high temperature exhaust for cogeneration or hybrid applications, and the ability for internal reforming. SOFCs are favored for high-power applications and have also been suggested for distributed power and mobile auxiliary power units. As SOFC developers are already making decisions on design and fabrication options for SOFC systems, a study of the materials and manufacturing options follows.

SOFCs have been developed in both planar and tubular design configurations. First, tubular configurations are comprised of circular or flattened tubes connected in series or parallel to form the stack. The flattened tubular design, or the high-power density (HPD) SOFC developed by Siemens-Westinghouse, offers improvements in electronic conductivity and is expected to support automated production [1]. Second, planar designs are comprised of rectangular or circular plates used to facilitate reactant flows and again combined to form stacks.

When compared to tubular stacks, planar stacks are characterized by higher cell power densities [2]. Adler [3] notes that tubular cells have larger electrical resistances due to the longer distance electrons flow (roughly half the inner circumference of the tube) and have mass and heat transfer issues. Tubular stacks, however, have been proven for longer periods of operation (up to 69,000 h for a single tube). Also, although planar are considered more cost-effective to produce than tubular stacks, planar models are still relatively expensive compared to other power sources [3].

Tubular and planar stacks are comprised of five key types of components: an electrolyte, anode, cathode, interconnect, and seals. The electrolyte at the heart of each cell is a doped solid ceramic oxide that facilitates the generation of oxygen vacancies and carries the charge between the half reactions at the cathode and anode. The cathode (or the air electrode) and the anode (or the fuel electrode) are the sites of each half reaction: oxygen is reduced to oxide ions consuming two electrons at the cathode and fuel is reduced forming two electrons at the anode. The interconnect is the electric link to the cathode and protects the electrolyte

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from a reducing atmosphere. The seals, used in some planar designs, bond components together and provide gas-tightness. Also, whereas the electrolyte, interconnect, and seals are gas tight (directing the flow of reactants), the anode and cathode are porous to enable transport of reactants and products through the components. Also, end plates, current collectors, and other hardware are needed to complete the stack.

An important consideration to both design and manufacturing research for both tubular and planar designs is the reduction of operating temperatures in order to reduce production costs. Specifically, high temperature designs ranging from ∼850 to 1000 °C can be reduced to intermediate temperatures in the range of ∼750–850 °C or even low temperatures of ∼500–750 °C. Lower temperatures allow the use of less expensive and proven metallic interconnects. Lower temperatures also require unproven or very thin electrolytes necessitating special fabrication capabilities, causing a decrease in power density, and limiting internal reforming capabilities. In fact, Ivers-Tiffée et al. [4] suggest temperatures below 600 °C in are not a benefit at all because of minimum reforming temperature requirement.

Works summarizing planar and tubular SOFC design alternatives are provided in textbook format and research works. Specifically, textbooks by Larminie and Dicks [5], EG&G Services [6], Hoogers [7], and most notably Minh and Takahashi [8] and Singhal and Kendall's new release [9] provide summaries of proven and some emerging technologies. Their discussions of SOFC design include descriptions of typical materials use and configurations, the advantages and disadvantages of each design, stack performance relationships, and potential applications issues. More research-oriented discussions provide a review or comparison of typical or novel materials within the context of operating conditions and studies of specific components and can be found in select archival journals and SOFC symposium proceedings. Uncommon is research citing cell and stack performance as a function of materials use, especially in the case of interconnects. The rarest is by far reports of long-term stability of multi-cell stacks.

Summaries of SOFC manufacturing options are provided by Will et al. [10] and Woodward [11]. Specifically, Will et al. provide an analysis of processes based on component thickness and Woodward compares costs for select processes. Also, SOFC manufacturing information for single process-material combinations can also be found again in select archival journals and SOFC symposium proceedings.

This paper presents taxonomies of SOFC materials and manufacturing literature from these and many additional references with an emphasis on material and process alternatives. This work is intended to facilitate material and process selection through the consideration of the variety of design and manufacturing alternatives prior to capital investment for wide-scale production and is part of an environmental life cycle assessment (LCA) of SOFC systems.

2. Taxonomy of SOFC materials

Fig. 1 provides a taxonomy of example SOFC material alternatives. Each class and example material is described as follows for each of the five key stack components.

2.1. Electrolyte materials

In an SOFC, the electrolyte is a solid oxide that forms an O^{2-} charge carrier separating the oxidative and reductive half reactions. In high temperature planar designs, the electrolyte can also function as the support during fabrication. Electrolytes can be categorized as single or bilayer, the latter combining materials to enhance performance. Design requirements for the electrolyte are [3,12–14]:

- ionically conductive (should be characterized by oxygen ion transport numbers close to 1);
- electronically insulating;
- chemically stable at high temperatures;
- chemically stable in reducing and oxidizing environments;
- gas tight/free of porosity;
- production as a uniformly thin layer (to minimize ohmic losses);
- thermal expansion that matches electrodes;
- uses inexpensive materials.

Table 1 provides additional information for the electrolyte materials presented in Fig. 1. Singhal and Kendall [9] note that stabilized zirconia and ceria possessing the fluorite structure has been the most favored SOFC electrolytes with perovskites, brownmillerites, and hexagonal structured oxides as more recent alternatives. Among the candidate materials, zirconia is a relatively cheap base material and is by far the most popular for SOFC electrolyte material. Among the available electrolyte materials, operating temperature is very important to electrolyte performance. This more recently means that low/intermediate temperature planar cells are anode supported because of the electrolyte needs to be comparably thin [1]. At higher temperatures, the electrolyte can be as thick as 150–250 μm because of higher ionic conductivities [1]. Table 2 presents approximate conductivities for select electrolyte materials. Among the materials included and for 600–800 °C, YSB and LSGMC provide the greatest average conductivity. For 800–100 °C, LSGMC and GDC provide the greatest average conductivity.

Badwal and Foger [12] note that with operating temperatures ranging from 800 to 1000 °C, zirconia has good thermal and mechanical shock resistance when doped with yttria, scandia, samarium, and magnesium as Y_2O_3, Sc_2O_3, Sm_2O_3, and MgO. Among the zirconia electrolyte materials, YSZ is the most used SOFC electrolyte. YSZ is characterized by good chemical and mechanical stability with high quality raw materials available [4]. Most common is approximately 8.5% yttria (called CZP [4,12]). Also, although characterized by lower ion conductivity, 3% yttria (called 3YTZ [4]) has been used because of its higher mechanical stability. Many times