

Challenges in Fabricating Solid Oxide Fuel Cell Stacks for Portable Applications: A Short Review

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Abstract: Despite being the most efficient and quiet operation type of fuel cells, solid oxide fuel cells (SOFCs) deal with several constraints in terms of fabrication cost, material selection and durability issues due to their high operating temperature. The high operating temperature of SOFCs limits their stationary and large-scale applications. Moreover, these constraints restrict the commercialization of portable SOFCs. Therefore, the operation temperature of SOFCs must be reduced to overcome the aforementioned problems. However, this task is challenging because the operation temperature mainly affects the material preparation and the stack design to produce the electrical power needed for small-scale applications. This paper provides an overview of the challenges faced by each component such as the materials, the design of stack, fabrication cost and related research in fabricating high power SOFC stacks.

Keywords: Solid oxide fuel cell, stacks, materials, cost, portable applications

1. Introduction

Due to depletion of fossil fuels and growing demand of energy consumption, there has been considerable research efforts on developing alternative sources of energy such as biomass, solar, wind and hydrogen [1]. One type of hydrogen energy which is solid oxide fuel cells (SOFCs) were first developed by Gaugain after the discovery of solid electrolytes in 1853. During the 19th century, SOFCs were actively developed. Nernst showed that 15mol% yttria-stabilized zirconia (15YSZ) exhibits high conductivity, and Schotty later proposed that it can be a potential candidate for solid electrolytes. Baur and Presis further proved that YSZ works at 1000 °C [2]. Several

studies used ceramic oxide as the electrolyte and fabricated stacks with various designs to improve its performance. Compared with other types of fuel cells, such as proton-exchange membrane fuel cells (PEMFCs), direct-methanol fuel cells (DMFCs), alkaline fuel cells (AFCs), molten-carbonate fuel cells, and phosphoric acid fuel cells, SOFCs feature a higher efficiency of up to 90% if the heat produced is harnessed and the anode off-gas is recycled to the anode inlet [3] (Figure 1). The relatively high operating temperature of SOFCs allows internal reforming and enhances the kinetics reaction. Moreover, SOFCs can tolerate fuel impurities because of their high operating

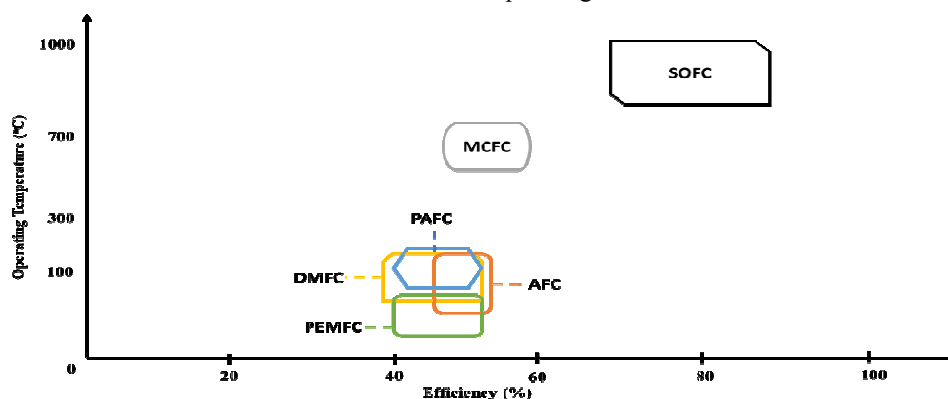


Fig. 1 Technical characteristics of various types of fuel cells [7, 8].

temperature [4]. Therefore, SOFCs are flexible to many types of fuels and not limited to pure hydrogen [5]. A single cell consists of three main components, namely, anode, electrolyte, and cathode [6]. Fuel is supplied at the anode and air at the cathode. At the cathode, oxygen in air is reduced to produce oxygen ions that pass through the electrolyte into the anode. The oxygen ions that reach the anode react with fuel, leading to oxidation. Consequently, electrons are released into the outer circuit and water as the by-product [7]. The basic working principle of SOFCs is shown in Figure 2.

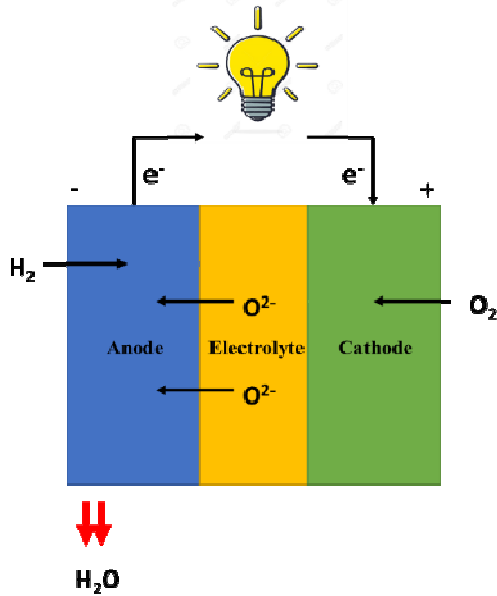


Fig. 2 Basic working principle of SOFCs.

A stack is formed by combining a number of single cells sandwiched by interconnect materials as a current collector. All components must be compatible to prepare a working stack. SOFC stacks have two types, namely, planar and tubular. The planar design has excellent power density because of its effective current collection and low cost fabrication, whereas the tubular design features outstanding mechanical and thermal properties [8]. Due to its capability to operate in high temperature, SOFCs are most likely to be applied by large-scale, stationary applications with power ratings up to megawatt [9]. Over the years, small-scale energy delivering devices (1–20 W) had a spring up need for power sources in portable electronic devices [10]. With the progress in thin film technology and microfabrication, micro-SOFCs are predicted to be developed as battery replacement in small devices [11]. Compared with PEMFCs and DMFCs, micro-SOFCs are foreseen to have better performance in term of specific energy and energy density output. For instance, eZelleron, an innovative company developed a 1–100 W prototype microtubular portable devices. Meanwhile, Ultra Electronics-USSI designed and manufactured SOFC for back up and portable power generation. Their tubular ceramic cell design allows them to offer compact and rugged systems that can operate in the most austere and remote locations. [12]. Figure 3 shows the results of a literature survey on the number of publications about the development of SOFC stacks. These data were obtained by searching the ScienceDirect database for “SOFC,” “stack,” “planar,” and “tubular.” The data demonstrate the ongoing interest in the development of SOFC stacks.

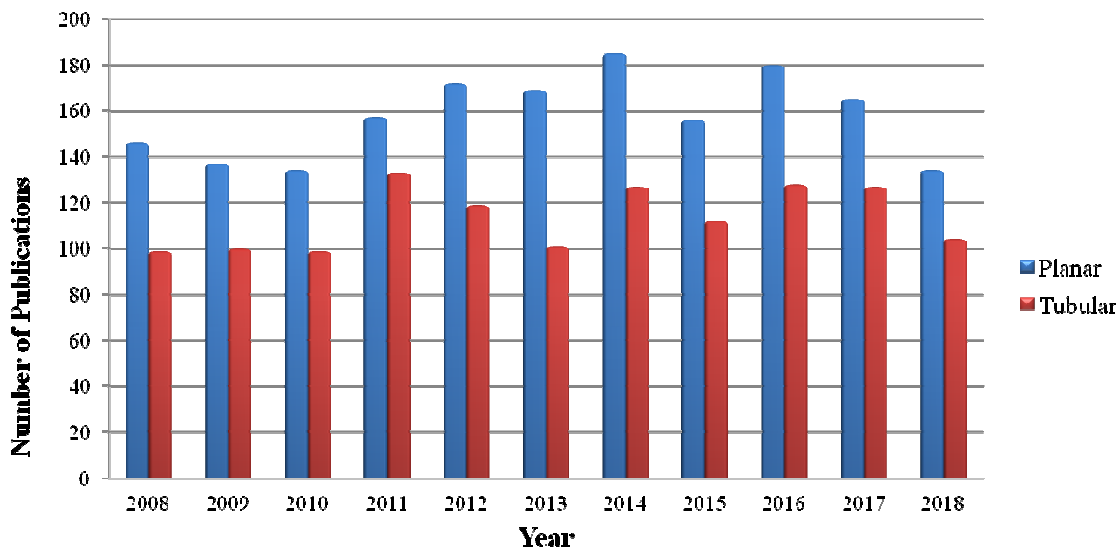


Fig. 3 Ongoing trend of publications on the development of SOFC stacks over the past 10 years. (Keyword search “SOFC”, “Stack”, “Planar” and “Tubular” in <http://www.sciencedirect.com>, August 2018)

2. Material Challenges

Given that SOFCs operate at a high temperature, not all materials are suitable to meet the purpose, and interconnect materials are costly. This major drawback has brought the attention of researchers to lower the operating temperature (<1000 °C). Thus, a new operating temperature zone called intermediate-to-low temperature (IT-LT-SOFC) zone was proposed [13]. A typical IT-SOFC operates below 800 °C, and LT-SOFCs operate below 600 °C [14]. The electrical and catalytic activity, chemical compatibility, and thermal stability of materials should be adjusted to allow SOFC components to operate in a low temperature range.

2.1 Anode

Fuel oxidation takes place at the anode, as shown in Figure 2. In consideration that gas exchange occurs at the gas–electrolyte–anode interface, the anode should have sufficient porosity. Nickel/yttria-stabilized zirconia (Ni/YSZ) has been used for a long time as anode materials and shows excellent performance at high operating temperatures. However, Ni/YSZ is exposed to carbon deposition and contaminant poisoning (mainly by hydrogen sulfide, H₂S) once in contact with reformed hydrocarbon fuels (combined with steam or CO₂). Sulfur is strongly absorbed on the Ni surface and blocks triple phase boundary (TPB) for oxidation. Therefore, a few studies have been carried out to improve sulfur tolerance by surface modification using BZXYb (BaZr_{0.1}Ce_{0.7}Y_{0.1}Yb_{0.1}O_{3-x}) [15] and adding niobium oxide (Nb₂O₅) [16]. At an intermediate operating temperature, nickel/samarium-doped ceria (Ni-SDC) cermet is commonly used. Meanwhile, Jarot et al. [17] reported that samarium-doped ceria carbonate (SDCC) can be a potential material for electrolytes to operate at low temperatures (<600 °C). Mahmud et al. [18] further determined the suitability of SDCCs as anodes and found that these cells feature good bonding between particles and efficient porosity to be anode candidates.

2.2 Cathode

Similar to the anode, the cathode must also have an adequate porosity to transport the oxygen to the cathode–electrolyte interface and must be catalytically active toward oxygen reduction. LSM perovskite (La_{1-x}Sr_xMnO₃) is a commonly used cathode for high-temperature operations. However, this material cannot operate at low temperatures because its high activation energy increases the polarization resistance and decreases the catalytic activity [19]. Thus, ionic–electronic conducting (MIEC) materials are obtained from perovskite-based materials, such as lanthanum strontium cobaltite ferrite (LSCF) and barium strontium cobaltite ferrite (BSCF), to develop a new cathode material for IT-LT-SOFCs. Compared with pure electronic conducting materials that only allow reaction on the TPB, MIEC materials allow oxygen reduction to occur on both surface and bulk path. However, despite the good electrochemical performance of LSCF at a low operating temperature, the

existence of cobalt in this MIEC material increases the thermal expansion coefficient of the cathode and leads to incompatibility with the electrolyte [20]. Thus, various cobalt-free materials have been developed, such as NLNCA oxide (Nd_{0.9}La_{0.1})₂(Ni_{0.74}Cu_{0.21}Al_{0.05})O_{4+δ} [20] and SFT oxide (SrFe_{0.9}Ti_{0.1}O_{3-δ}) [21]. Alternatively, the additional of silver (Ag) into cathode has also been studied extensively to reduce the cathode polarization resistance, hence, will increase the cell performance. Ag is chosen over other noble metals such as platinum (Pt) and palladium (Pd) as it is much cheaper and possesses high electrocatalytic activity, high oxygen reduction rate and stable in both oxidation and reduction environment [22].

2.3 Electrolyte

Unlike the porous structure of electrodes, electrolytes require a dense structure. The electrolyte has to be completely gas-tight, crack free and as thin as possible to avoid the gas leakage that can decrease the cell performance. YSZ and Gadolinium-doped ceria oxide (GDC) are the most typical materials until the ceria oxide take place because of its high ionic conductivity and the ability to operate in lower temperature. Additional carbonate in ceria/carbonate interface acts as a superionic highway enabling the ionic transport and so far, shows the best conductivity. However, the carbonate salts can create a couple of issues such as the coke deposition on the anode which can initiate catalytic deactivation, pore filling, loss of cell performance and weakened durability [23]. Proton conducting electrolyte could be an alternative material as it is having comparable conductivity with ceria/carbonate based electrolytes but the cells' performance in terms of stability and poor capability to carbonation are main challenges for practical applications [24]. Thus far, Barium Zirconium Cerium Yttrium Oxide (BZCY) is a commonly used material. However, it has been reported that BZCY showed instability after exposure to atmosphere containing carbon dioxide and water. To overcome the challenges, co-doping of various rare earth ions such as zinc offers higher proton conductivity and higher stability [25].

2.4 Interconnect

The interconnect can be found on both sides of the anode and the cathode as it sandwiches the single cell to act as the current collector and physical barrier. Therefore, the interconnect is expected to operate in both oxidizing and reducing atmospheres during the operation [26]. Doped lanthanum chromite (LaCrO₃) is a common interconnect material for high-temperature operations. However, the difficult fabrication of LaCrO₃ and expensive cost of lanthanum have directed researchers to replace the traditional ceramic interconnects with metallic alloys to allow low temperature operations [27]. Ferritic stainless steel for instance has become the standard material for SOFC applications. However, there are few serious issues that may affect the stack particularly on the cathode side such as chromium poisoning. Therefore, researchers developed protective coatings to reduce oxide

growth kinetics, increase oxide scale conductivity, improve oxide scale-to-metal adhesion, and inhibit Cr migration [28]. The next challenge is to select the appropriate deposition technique, considering that the quality of coating surface is associated with cell performance. The workability on interconnect materials with complicated gas flow channels should also be considered.

3. Stack Design

The tubular and planar stack designs have inherent advantages and drawbacks. The planar type is favorable because of its high power density and easy fabrication. However, the application of this type of design is limited by the difficult sealing process and by its higher fabrication cost than the tubular type [29]. Conversely, the tubular type offers low fabrication cost, excellent long-term performance, and thermo-cycling stability. Compared with the planar design, the tubular design exhibits much lower power density because of its structural disadvantages resulting from the long current path [30]. Hence, recent studies have combined both planar and tubular types in the forms of flat tubular to achieve maximum benefits from both designs [8]. The different designs of stack are also shown in Figure 5 [27] [31].

fabrication. Therefore, several earlier studies have conducted manufacturing cost analyses for several different SOFC production volumes and system sizes [33][34]. To summarize, the stack cost comprises cell cost (raw materials and production) and balance of stack cost (components surrounding each cell). Numerous studies and cost projections have been performed for automotive fuel cell systems [35] and combined heat and power applications [36]. Direct stack manufacturing costs are mainly modeled for large appliances, whose net electricity capacities range between 1-250 kWe. Overall stack manufacturing costs range from \$166 kW/e to \$5,387 kW/e for a 250 kWe system at 50,000 systems per year. [37]. Dubois et al. [38] performed a comparative and extensive cost study between the fabrication of protonic ceramic fuel cells (PCFC) and SOFC stacks and the study demonstrated the cell raw material cost for SOFCs is 35% lower compared to PCFCs. For the total cost stack, it is shown in Figure 6 that SOFC stack operating in methane fuel at 800°C is estimated to be 27% lower than its PCFC counterpart operating at 500°C whereas for low operating temperature fuel cell, PEMFC, the total cost stack is expected to be much lower than both PCFC and SOFC. Operating at a low temperature enables PEMFC to have a wide variety of material selection resulting in a lower material cost compared to

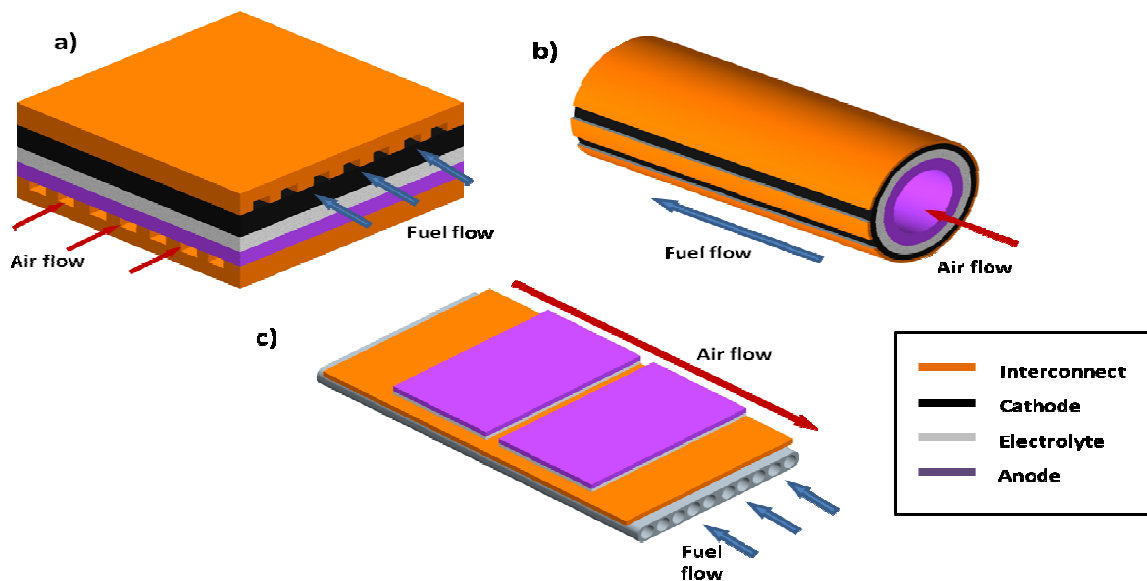


Fig. 5 Schematic diagrams of a) planar, b) tubular and c) flat tubular stack

4. Fabrication cost of solid oxide fuel cell (SOFC) stack

Fuel cells are not yet manufactured in high volumes in spite of the various points of interest over the conventional and alternative power generation sources. This situation arises due to the limitations of mature hydrogen supply infrastructures [32]. Although SOFCs can directly operate with various fuel types, the high manufacturing cost can be the main barrier of fuel cell

high operating temperature fuel cell. Although the stack cost of PEMFC is low, the overall system for this type of fuel cell is relatively high as it only operates with high purity hydrogen [39]. If this is not overcome, there is a higher chance that SOFC will take place in various application fields due to its fuel versatility. In fact, the recent trends in SOFC studies focusing to utilize available

hydrocarbon fuels and reduce the operating temperature (less than 600°C) [40].

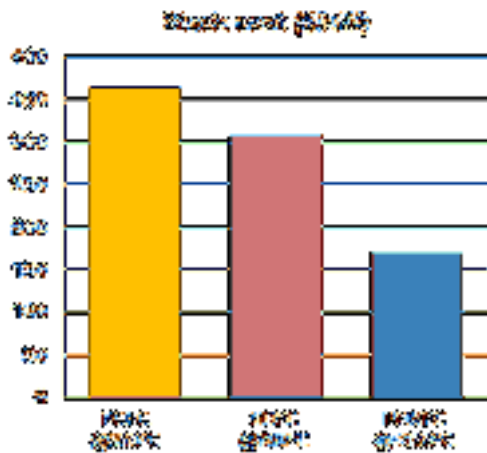


Fig. 6 Total cost distribution of PCFC, SOFC and PEMFC stack

5. Conclusions

The commercialization of SOFCs for portable applications has yet to succeed given the various challenges in material selection and stack design and the high fabrication cost. Considering that micro-SOFCs can only be operated in a reduced operating temperature, advanced knowledge and technology bear importance in fabrication of thin film membranes with a large active area to produce a reasonable power output. In addition to, the material challenges, cost fabrication and stack design, the membrane microstructures for micro-SOFCs depend on parameters such as chemical composition, the deposition technique used, and substrate to ensure good stability and durability for long-term usage. Hence, fundamental issues need to be resolved before it can succeed in the market. The authors note that there remains significant uncertainty in stack cost fabrication associated materials, manufacturing processes and equipment facility. Although wide research have been conducted on fabricating micro fuel cells, with either the materials used or the process involved, extensive research is still needed for commercialization of SOFCs for portable applications.

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