Review of Materials for Solid Oxide Fuel Cell

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Abstract. The solid oxide fuel cell (SOFC) is one type of electrochemical device that can gain electrical energy by straightly converting the chemical energy from the fuel. After atomic, thermal, and hydropower, it is known as the fourth power generation technique. The energy conversion is through an electrochemical reaction; thus, the Carnot cycle effect is not able to limit the transfer efficiencies of fuel cell, which means the efficiency will be high. As the most energy-efficient devices, Using fuel cell technology, power may be produced at up to 60% efficiency (even comparing with cogeneration). Hydrogen can be the energy source of the SOFC, which can react with the oxygen from atmosphere and produce water. This process is without greenhouse gas emissions. In the study of the fuel cell, the material study is one of the essential parts. This review briefly presents the research progress of electrolytes and electrode material of SOFC as well as their significance to SOFC technology.

Keywords: SOFC; Electrochemical device; Fuel; Energy conversion.

1. Introduction

The SOFC is a technology which is attracting popularity today because of its superior power-generating capabilities that boast sufficient electrical efficiency for autos and home appliances. Due to the working principle of SOFC, there are many other kinds of fuel besides the hydrogen can be the fuel sources for the SOFC. For example, since ammonia is carbon-free, it is also considered to be used in the fuel cell as the hydrogen carrier. With the development of the ammonia fuel cell, it can be used in many fields like transportation, wastewater treatment, life cycle analysis, and so on [1]. With the increasing attention paid to environmental issues in today's society. Because of its great efficiency and minimal environmental impact when in operation, fuel cells are frequently suggested [2].

In the study of the fuel cell, the material study is one of the essential parts, which includes the anode material, cathode material, and electrolyte material. Many ceramic materials are being studied or in an application, but they both face tradeoffs. For example, higher conductivity and better stability are found of the Scandia-stabilized zirconia (ScSZ) in material design of SOFC electrolytes compared with Yttria-stabilized-zirconia (YSZ). Still, the availability and price of Scandia are issues [3]. This review presents the recent progress of the material for SOFCs.

2. Structure of SOFC

Typically, cathode, anode and electrolyte are the three essential elements in a SOFC system. It is made possible for the fuel, typically gas, to be added to the anode and an oxidant from the atmosphere to enter the cathode. In order for fuel cells to operate, the induced gases must be capable of electrochemical oxidation and reduction. The electrolyte develops a gradient of chemical ion potential, which is the primary source driving its operation and producing direct current (DC) electrical energy in the outside circuit. Figure 1 shown below gives the brief schematic diagram.

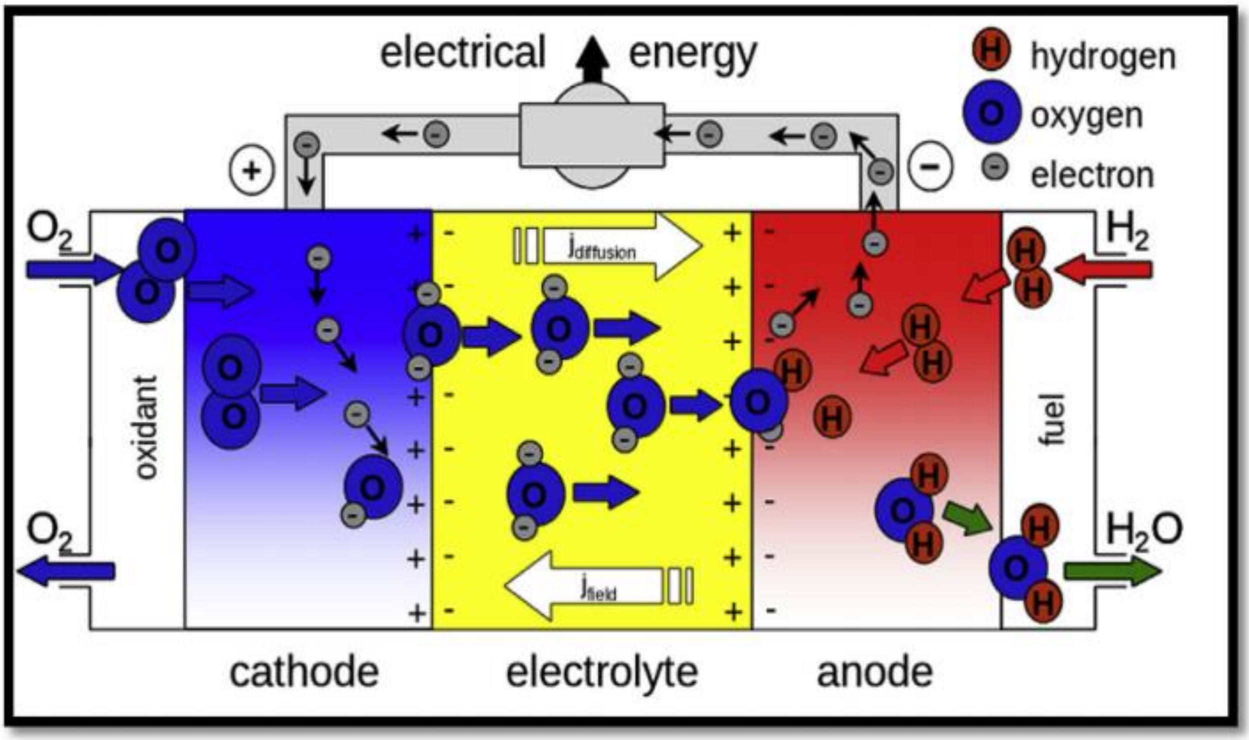

Fig 1. Schematic diagram of SOFC.

According to the SOFC working principle, REDOX reaction happens at the electrodes, the anode has the oxidation, while the oxidant occurs the reduction at the cathode [4]. The material design for the fuel cells components should be followed the following requirements:

For electrolytes:

1. Higher conductivity for ions, protons, or oxides should be included in the electrolyte materials. For electrolyte with a thickness of 10-100 m, 0.01-0.1 S/cm of conductivity is ideal. If the solid electrolyte carries less oxide, there will be significant ohmic losses, which will result in nonlinear conducting qualities.

2. The solid electrolyte material should have low electronic conductivity since excessive electronic conductivity leads to electrons leakage, more voltage loss, and insufficient power production.

3. The mechanical strength and thermal stability of the solid electrolyte need to be strong.

4. Chemical, phase, dimensional, and morphological stability are requirements for solid electrolyte material.

5. Low price and easy for fabrication.

For Anode:

1. The anodic reactions are enhanced by a triple-phase barrier with a high surface area. The triple-phase border is the location of the electrochemical reaction (TPB).

2. A prominent porosity microstructure, which speeds up gas transit and reaction byproduct production. [5, 6].

3. To be effective thermally with electrolytes, cathode, and other structures. It must be stable, have high electronic conductivity, and have a high level of electro-catalytic activity.

For Cathode:

1. To avoid concentration polarisation, a cathode should have enough porosity to permit fast transport of molecular oxygen (O_2) to the active sites (where O_2 is converted to O_2∀).

2. To reduce ohmic losses when the electrons are used in ORR, high electrical conductivity for an excellent cathode system is essential, often greater than 100 S cm^-1.

3. To prevent excessive thermomechanical stresses, the cathode's thermal expansion coefficient (TEC) must be equivalent to that of other cell components.

Based on these principles, a lot of materials have been designed for SOFC. The following pages will introduce the recent progress and several examples of each component.

3. Electrolyte materials

In order to lower the current leakage in SOFCs, a ceramic material or thick layer of solid oxide electrolyte is utilized. This material has the ability to transport oxygen ions and little to no electrical conduction [7]. The materials must be stable mechanically and chemically [8, 9], and they must be compatible with electrodes, like cathode and anode. According to Fig. 2 shown below, the SDCC superionic transport mechanism is driven by the coexistence of proton and ionic conductive phases.

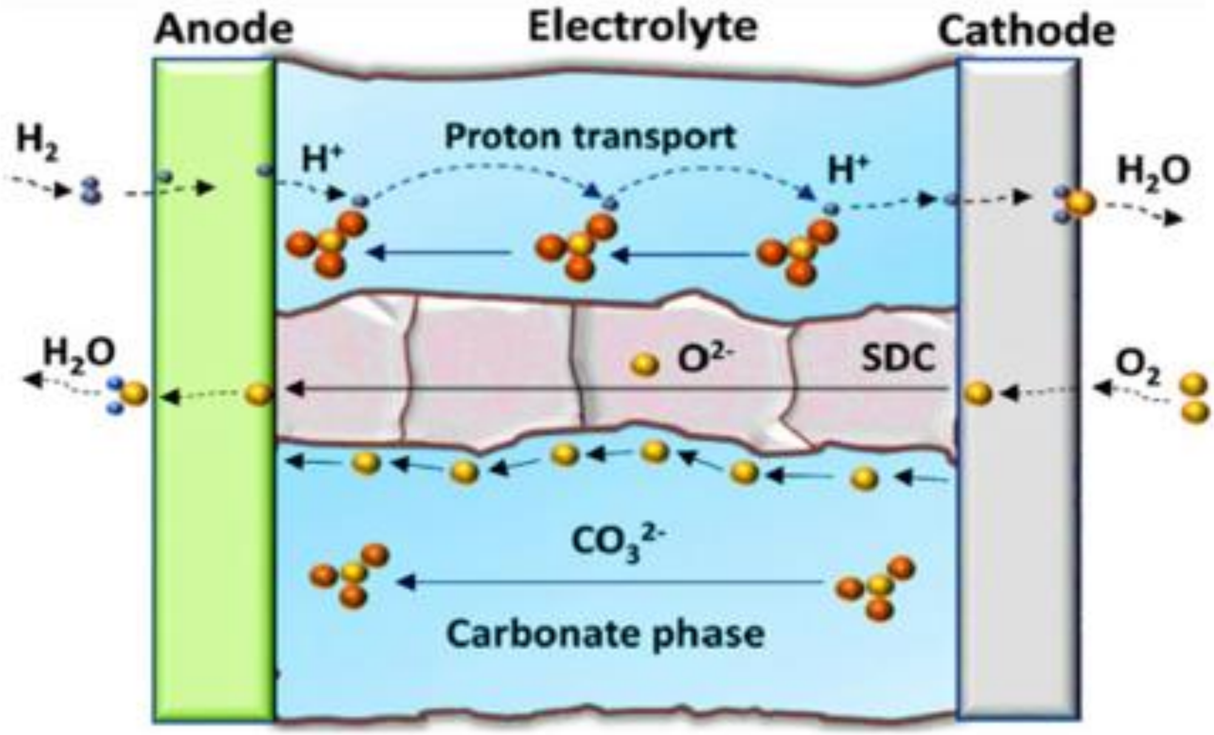

Fig 2. Diagram of ionic & proton conductions.

Numerous ceramic materials have been developed during the past ten years to function as electrolyte materials. One of them is Yttria-stabilized zirconia (YSZ), which is frequently utilized in SOFC as a solid electrolyte material. In comparison to YSZ, Scandia-stabilized zirconia (ScSZ) has demonstrated greater stability and better ionic conductivity [5]. Scandia is a useful material for SOFCs electrolytes, but its cost and availability are its two main drawbacks [5]. Material selection for electrolytes needs to be traded off, thus, more new types of material need to be designed for wide application fields.

$Sc_2O_3 - ZrO_2$ (ScSZ) based electrolyte systems have been studied more recently because it has a better ionic conductivity comparing with YSZ when the operating temperature is low. A small defect is form by the small difference in the Sc^{3+} radius and Zr^{4+} radius in ScSZ. This small defect results in a compact crystal structure with a high concentration of mobility. ScSZ still has a drawback, if the operating temperature is below 500 °C, the conductivity will be equally even lower than YSZ. This is because the low temperature increases the activation energy. For the SOFC whose operating temperature is around 500 °C, which is called intermediate temperature SOFC (IT-SOFC), grain boundary becomes another noticeable factor. Because within the reducing temperature, the grain boundary will increase [6]. To enhance the grain boundary, nanostructure materials were created.

Ceria doped-based electrolyte system is designed within the need of decreasing operating temperature. Ceria is a dopant for fluorite structures. Compared with zirconia, Ceria dopant has better ionic conductivity when the operating temperature is low, and the polarization resistance is lower as well. A significant issue with ceria-doped electrolytes for electrical conduction at low partial pressures of oxygen (O_2). When it is in a reduced environment, Ce^{4+} will be converted to Ce^{3+}. During this, electrons will transfer through the electrolyte. It will cause short circuits and decrease the open circuit voltage [7].

Besides the two electrolyte systems introduced above, there are many other materials for electrolytes studied such as LSGM, LSCF, LSTF, and GDC-based electrolyte systems. The general design principle is mentioned above. Within the wider application demand, IT-SOFCs even low-temperature SOFC (LT-SOFC) attract a lot of interest. Solving the conductivity issues of electrolytes at low temperatures is the goal of the academic circle to conquer [10].

4. Electrodes materials

The microstructure is a key factor in SOFC technology when choosing an anode material [8]. The material's microstructure affects the electrochemical performance of the electrodes. Fuel oxidation, including that of H_2 and natural gas, happens at the anode. The general principle of electrode materials design has mention in the previous pages, when all these factors are considered together, SOFCs with excellent performance is made possible. The oxidation reaction's polarisation losses will be reduced as well. Kröger-Vink equation [9] shown below gives the oxidation of [8, 9]:$H_2 + O_{YSZ}^{2-} = H_2O + 2e^- + V_{\ddot{O},YSZ}$

Ni-based anode system's electrochemical action is the compared to other pure metallic electrodes, like Pt and Ru, when the $\mathrm{H_2}$ based oxidation reaction happens. Comparing of the thermal expansion coefficient, Ni's is $13.3 \times 10^{-6} \cdot \mathrm{K}^{-1}$ whereas YSZ's is$10.5 \times 10^{-6} \cdot \mathrm{K}^{-1}$, which is decreased in the composite material to ensure thermal compatibility [8]. A method that creates increased reaction sites by adding YSZ to porous Ni to create cermet lowers polarisation resistance while also inhibiting the coarsening and development of Ni grains [8, 10]. However, Ni used as an anode material has drawbacks. Additionally, at T<700 °C, there is a strong likelihood that Ni may partially transform into NiO, which would cause instability in the cermet microstructure [8].

$Ce_{0.6}Gd_{0.4}O_{2\pm\delta}$ (CGO) and $\mathrm{Y_{0.2}Ti_{0.18}Zr_{0.62}O_{1.9\pm\delta}}$ (YZT) ceramic's electrochemical properties are determined they're by a reported method using mixed ionic conductivity. The polarization resistance of YZT was indicated $0.7\,\Omega/\mathrm{cm}^2$ when the operating temperature is 1300 °C, whereas polarisation resistance of two ceramic electrodes without sintering was indicated $0.44\,\Omega/\mathrm{cm}^2$ & $0.37\,\Omega/\mathrm{cm}^2$ correspondingly. According to Cowin et al review, for a composite or cermet to perform better as an anode, it must possess a variety of qualities which are mentioned in the previous contents.

$\mathrm{ABO_3}$ Perovskite structure is integrated with A- and B- cations. It has unique properties. Thus, this structure is widely used in the cathode system. Due to the same size of the O_2 ion and the occupancy of the octahedral voids (1/4 parts) by B- cations, the big A- cations in the perovskite form a cubic close-packing structure. Due to the order of distortion and partial replacement in the sub-lattices of both A- and B-cations, the electronic characteristics of perovskite material may change.

Other materials are in the study as well, like LSCM anode systems, Metal fluorite cermets, miscellaneous electrode systems and so on.

5. Conclusion

Because of the fuel flexibility and real power-generating equipment with low environmental effects, SOFCs have been examined all over the world. This review article will briefly discuss the electrolytes and electrode material of SOFC as well as their significance to SOFC technology. In addition, this review takes few SOFC material example for each component to present the problem and the direction of the researchers' efforts. The development of higher-performing materials that can operate at low temperatures requires a lot more attention. This will make SOFC technology more significant. Cost-cutting is still a major issue with SOFC technology, though.

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