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A review of solid oxide fuel cell application

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Abstract. Solid oxide fuel cell (SOFC) is an efficient chemical fuel cell, which has been widely used in different fields. The successful application of this technology is of great significance to alleviate the energy crisis, meet the demand of the quantity and quality of electricity, and protect the ecological environment. SOFC has been utilized with gas turbine (GT), homogeneous charge compression ignition (HCCI) and small-scale power generation. This article introduces the characteristics, working principle and engineering application of solid oxide fuel cells in more detail.

1. Introduction

With the advancement of science and technology, energy crisis and the stringent measures on environmental protection, it is important to find a new type of battery with high efficiency and eco-friendly. Fuel cells are recognized by researchers for their unique advantages. First of all, it can directly convert chemical energy into electrical energy. Secondly, it has very high conversion efficiency. The solid oxide fuel cell belongs to the fourth-generation fuel cell. It is a full-solid chemical power generation device that directly converts the chemical energy stored in the fuel and the oxidizing agent at medium and high temperatures into high-efficiency and environmentally-friendly chemical energy. Also, it is considered to be the only future power generating device which is comparable to proton exchange membrane fuel cells [1]. The solid oxide fuel cell can be applied to a variety of fuels and can operate under a variety of fuels including carbon-based fuels. Although SOFC has obvious prospects and advantages as an energy conversion technology, some obstacles must be overcome to commercialize SOFCs. For example, a catalyst with a higher tolerance to fuel impurities is required to improve its efficiency and prevent anode deactivation due to carbon deposits when using carbon-based fuels, long-term operation reliability and durability, sealing issues, stacking and system integration issues.

SOFC has been applied in many fields. Due to the continuous increase in demand for electricity, a considerable amount of power generation is put into use every year in the world. In the next 20 years, the world's demand for electricity will increase exponentially. The location of traditional power plants is usually not a place where electricity is needed, and a power transmission system is essential. Because of the huge cost of the power transmission system, it has not developed synchronously. Especially in developing countries and remote areas, the power system is still in a relatively backward position. Therefore, decentralized power generation technology has received extensive attention around the world. SOFC is a new type of power generation technology that gradually changes the traditional central power supply system into a decentralized power supply system, and directly installs power generation according to the power consumption needs at the location of the household. SOFC-

GT (gas turbines) system has been used in different areas to solve the problem [2]. Another aspect of the demand for electricity is the use of motor vehicles. From electric locks and power windows to climate control in vehicles and even more sophisticated computer tracking systems, the demand for electricity from motor vehicles is increasing [3]. SOFC is currently the world's most popular car auxiliary power supply technology. SOFC/HCCI engine hybrid system was considered to alleviate the pressure of electricity demand on motor vehicles. It can provide power for any demand other than driving. Its application will completely change people's concept of an electric vehicle.

There have been many applications of portable batteries. Figure 1 shows the structure of direct flame solid oxide fuel cells (DF-SOFCs). A major advantage of this type of structure is its simple structure, which requires neither a separator nor a gas storage [4]. The mixture of fuel and air reacts on the surface of the anode and cathode to provide power for the continuous operation of the battery.

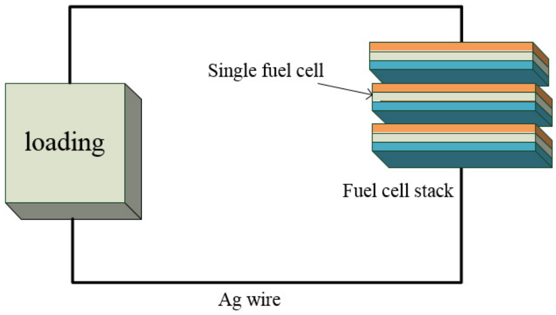

Figure 1. schematic of the 3-cell stack

2. Operating principle

Fig. 2 shows the operating principles of SOFC [5]. Electrochemical charge transfer reaction and reforming reaction occur in SOFC. On the cathode (air electrode), oxygen molecules get electrons and are reduced to oxygen ions. Under the action of an electric field, oxygen ions migrate to the anode through the oxygen vacancies in the electrolyte to perform oxidation reaction with fuel H_2 or CH_4, and electrons generate a current through external circuits. During the chemical reaction, Gibbs free energy (or chemical potential energy) of the global reaction of fuel and oxidant is converted into electricity and heat. The electrochemical reactions that occur on the cathode and anode in SOCF are exothermic. Therefore, when the operating temperature is set, there is also a temperature distribution inside the battery. In the case of cross-flow, the air outlet/fuel outlet is a high-temperature area, or even 200 ℃ higher than the set temperature, causing local damage to the battery and related materials.

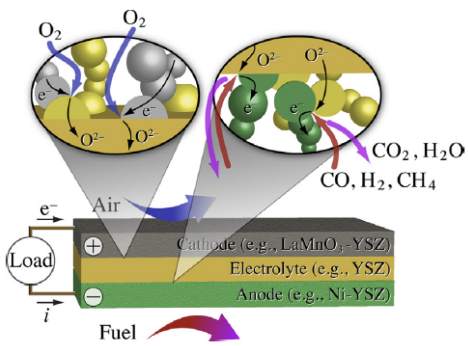

Figure 2. Basic Operating principle of SOFC [5]

3. SOFC-GT combined system

Fig. 3 illustrates SOFC-GT combined system [6]. The fuel and air are allowed to move into the anode and cathode. The fuel and air undergo a chemical reaction in the SOFC, but some of the fuel gas doesn't react. However, the unreacted fuel gas in the SOFC undergoes further reaction in the

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combustion chamber to make full use of the fuel. The high-temperature gas reacting in the combustion chamber is converted to mechanical energy and electrical power through the turbine. The discharged high-temperature gas heats the compressed air in the heat exchanger. Researchers used the perspective of replacing the Brayton cycle combustion chamber to improve the efficiency of the SOFC-GT system. A common way to increase efficiency is to integrate a pressurized SOFC stack with a traditional Brayton cycle. In addition, anode gas recirculation and indirect internal fuel reforming can be used to improve system efficiency. Several different methods can be used, such as reducing the amount of steam required for fuel pre-reforming, reducing the number of stacks required.

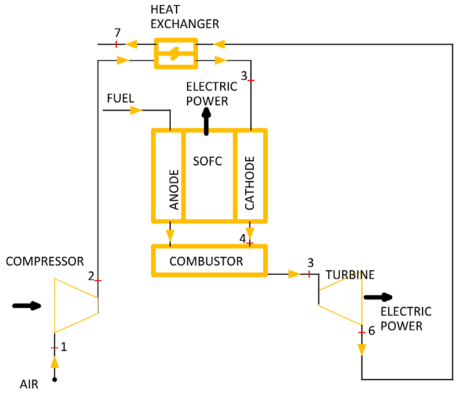

Figure 3. Hybrid SOFC-GT Brayton cycle [6]

4. SOFC/HCCI engine hybrid system

Figure 4 shows the simple working system of SOFC [7]. The system is composed of SOFC, catalytic combustor, reformer, blower, heat exchanger and suction pump. The reformer is combined with the catalytic combustor [8] which can improve the heat exchange efficiency. The fuel reforming process is divided into two parts, one part is reformed in the reformer, and the other part is reformed by a chemical reaction in the SOFC. Fuel and water are preheated by the heat exchangers to provide heat to external devices and equipment. The unused anode exhaust gas and air in the SOFC are combusted and released heat in the catalytic combustor. In order to effectively recycle the heat energy in the exhaust gas, a heat recovery steam generator (HRSG) is installed in the SOFC system to convert the heat from the exhaust gas into high-temperature steam. The temperature of the exhaust gas after passing through the HRSG is lower than 130°C, which does not only ensure multi-level utilization of energy but also keeps the HRSG in a stable working state.

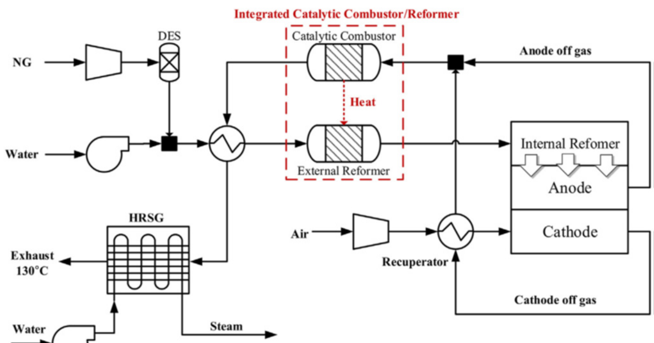

Figure 4. Schematic diagram of the SOFC simple system [7]

Fig. 5 is a schematic diagram of the SOFC/HCCI engine hybrid system [7]. The system is composed of SOFC stack, external reformer, HCCI engine, heat exchanger, blower and pump. HCCI engine replaces the catalytic combustor. The fuel and water are preheated by the heat exchanger and provides heat to the external reformer. The external reformer and the catalytic combustor are combined thermally and mechanically [8], and part of the internal reforming is performed in the SOFC stack. This combination improves the heat transfer between the HCCI engine and the external reformer. The air and smoke eventually run out in the HCCI engine. A heat exchanger is also installed behind the HCCI engine to provide heat from the hot exhaust gas to the external reformer.

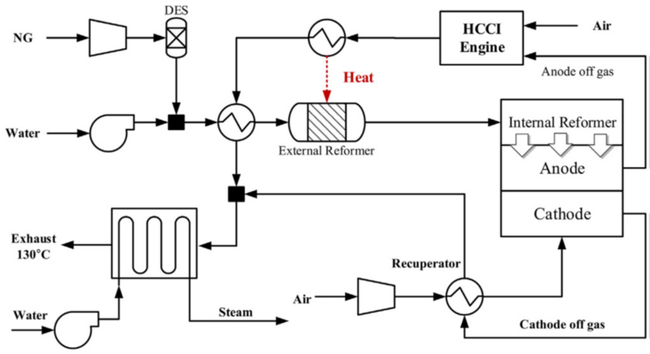

Figure 5. Schematic diagram of the SOFC/HCCI engine hybrid system [7]

The revenue obtained from the thermal energy of the system is included in the calculation of the total revenue requirement [7], the levelized cost of electricity (LCOE) of different systems is calculated, and the results of different systems without incorporating the thermal energy revenue into the calculation are shown in Figure 6. The heat recovered by HRSG is different for different systems, and the levelized cost of electricity will decrease for different systems. In the SOFC simple system, the LCOE decreased by 23.5%, and the LCOE of the SOFC-GT hybrid system and SOFC/HCCI engine hybrid system decreased by 12.0% and 7.8%, respectively. Thermal energy recovery has less effect on SOFC-GT hybrid system and SOFC/HCCI engine hybrid system.

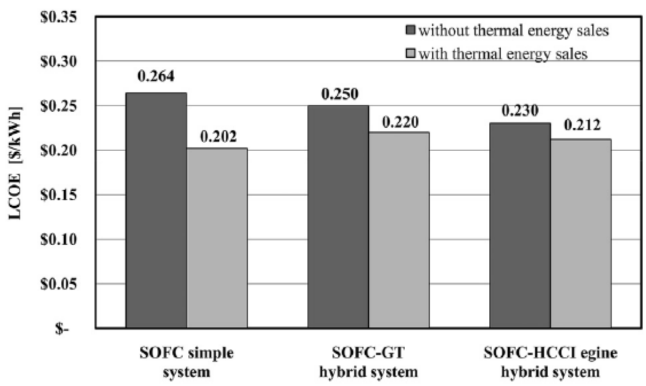

Figure 6. Calculation results of LCOE considering the profit of thermal [7]

5. Portable direct-flame solid oxide fuel cell

DF-SOFCs have the characteristics of rapid startup and shutdown, which is beneficial to the application of small-scale power generation [9]. Sun [9,10] proposes to apply free flame to solid oxide fuel cells. Gaseous fuels (methane, ethane, and propane), liquid fuels (ethanol, butanol, and kerosene), and solid fuels (paraffin and wood) can all be used in power generation of SOFCs. Butane is an alternative fuel for high-energy-density micro fuel cells because it is flammable, colorless, liquefied gas, and safe to store in a mini portable fuel tank. Fig. 7 shows the schematic of direct butane flame solid oxide fuel cell [4]. The fuel cell is placed above the flame, the flame front and the anode (Ni, YSZ) are in contact with each other, and the cathode is exposed in the air. The butane nozzle is used to ignite the fuel and provide a high-temperature flame for the battery. The cathode, anode, and electrolyte are connected. The battery is connected to a porous alumina plate with a cathode inside.

Silver and wires are used as electrical connections to ensure that the anode and cathode of the two batteries are connected. Heating the battery pack by the high temperature provided by the butane flame causes the solvent and binder in the silver paste to evaporate, allowing them to be tightly connected. The collectors of the battery pack are silver paste and silver wire, which minimize the catalytic activity of fuel reforming.

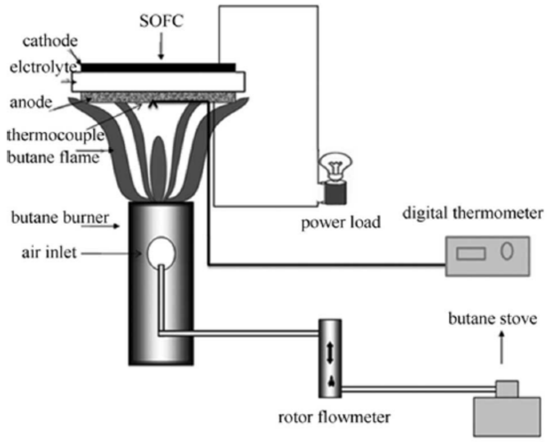

Figure 7. Schematic representation of the direct butane flame solid oxide fuel cell [4]

Fig. 8 shows a flame temperature graphed against the height [4]. Butane gas and air are premixed and enter the premixed combustion device for the reaction. It can be seen from the figure that the maximum flame temperature increases when the flow rate increases. However, the peak is at different positions for different flow rates and the increase in flow rate shifts the flame peak position to the right. Butane flame temperature range from 400-1002℃. The flame temperature depends on the flame position. The fuel cell material is metal and ceramic, which has strong heat conduction. The temperature is stable between 3 and 6 cm. The temperature is relatively stable in this height range; therefore, butane flame can be used as a heating source for SOFC.

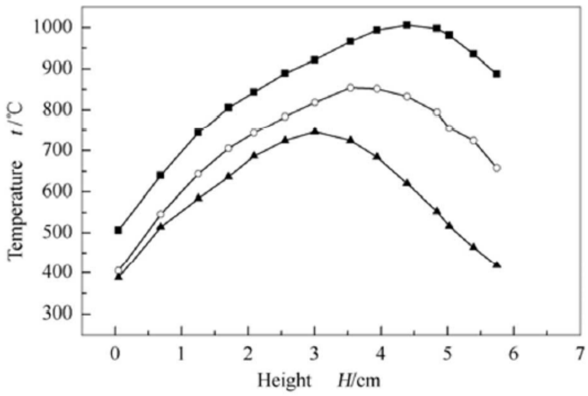

Figure 8. Flame temperature distribution with height under different flow (■: 120 mL/min; ○: 80 mL/min; ▲: 40 mL/min) [4]

6. Conclusion

The successful application in different system is of great significance to alleviate the energy crisis, meet the demand for power quantity and quality, protect the ecological environment and national security. This paper provides a brief review of solid oxide fuel cell and focuses on the SOFC-GT combined system, SOFC/HCCI engine hybrid system and portable direct-flame solid oxide fuel cell. it is found that:

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1. Oxygen gets electrons at the cathode and is reduced and then ionized. The key material for conduction is oxygen ions. SOFC has the advantages of high working efficiency and low pollution, but there are also safety problems such as high local temperature.
2. In the future, the SOFC-GT combined system will replace the traditional power generation plant and become a more efficient and cheaper system that can meet the regional electricity demand.
3. SOFC/HCCI engine hybrid system is a very promising concept, especially in a distributed system, because it improves efficiency and reduces operating costs. The use of thermal energy has the smallest impact on the SOFC/HCCI engine hybrid system and the greatest impact on the SOFC simple system.
4. SOFC has good thermo-mechanical properties, and SOFC battery will be a good choice for portable and rechargeable batteries in the field. The flame temperature in DF-SOFCs increases with the increase of flow rate and the flame temperature of 3~6cm is relatively stable.

References

[1] Seungdoo P, John M V, (2000) Raymond J G. Direct oxidation of hydrocarbons in a solid-oxide fuel cell. Nature, 404 : 265–267.

[2] Cocco D, Tola V. (2009) Externally reformed solid oxide fuel cell–micro-gas turbine (SOFC–MGT) hybrid systems fueled by methanol and di-methyl-ether (DME). Energy, 34: 2124–30.

[3] Choi JH, Ahn JH, Kim TS. (2014) Performance of a triple power generation cycle combining gas/steam turbine combined cycle and solid oxide fuel cell and the influence of carbon capture. Appl Therm Eng, 71: 301–9.

[4] Y G WANG, L L SUN, L H LUO, et al. (2014) The study of portable direct-flame solid oxide fuel cell (DF-SOFC) stack with butane fuel, Journal of Fuel Chemistry and Technology, 42: 1135-1139

[5] J. Hanna,W.Y. Lee,Y. Shi, et al. (2014) Fundamentals of electro- and thermochemistry in the anode of solid-oxide fuel cells with hydrocarbon and syngas fuels.Progress in energy and combustion science,2014,40: 74-111.

[6] McPhail SJ, Aarva A, Devianto H, Bove R, Moreno A. (2011) SOFC and MCFC: Commonalities and opportunities for integrated research. Int J Hydrogen Energy 36 :10337–45.

[7] S.H. Park, Y.D. Lee, K.Y. Ahn, (2014) Performance analysis of an SOFC/HCCI engine hybrid system: System simulation and thermo-economic comparison. International Journal of Hydrogen Energy, 39: 1799-1810.

[8] K.Y. Ahn, Y. Kim,T.G. Chang, SM. Lee, (2012) An experimental study on the reaction characteristics of a coupled reactor with a catalytic combustor and a steam reformer for SOFC systems.International journal of hydrogen energy, 37: 3234-3241.

[9] Horiuci M, Suganuma S, Watanabe M. (2004) Electrochemical power generation directly from combustion flame of gases, liquids, and solids. J Electrochem Soc, 151 : A1402–A1405.

[10] Sun L L, Hao Y, Zhang C M, Ran R, Shao Z P. (2010) Coking-free direct-methanol-flame fuel cell with traditional nickel-cermet anode. Int J Hydrogen Energy, 35 : 7971–7981.