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Views & Comments

Current Status and Future Prospects of Fuel Cells in China

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1. Background

The need for green, low-carbon, and sustainable development has become a global consensus [1]. In China, low-carbon and green energy reformation presents many difficulties and challenges. On the one hand, as the largest energy producer and consumer in the world, China is facing the serious problem of carbon dioxide (CO_2) emissions caused by large-scale coal-based fossil energy exploitation [2,3]. On the other hand, due to the intermittency and volatility of electricity from renewable energy itself and the uneven geographical distribution of the renewable energy resources in China, the problem of the storage and peak shaving of large-scale renewable energy must be urgently resolved. Therefore, there is a critical need to develop revolutionary technologies for energy conversion and storage in order to meet China's grand energy challenges.

Hydrogen energy has significant advantages, such as net-zero CO_2 emissions, energy storage capacity, safety, and controllability; in addition, it is an energy interconnection medium and can be deployed and utilized in many fields such as transportation, industry, and construction. Hydrogen energy can integrate traditional fossil energy with renewable energy to achieve a smooth transition between the two sources of energy [4]. Fuel cell technology is a key link in the application of hydrogen energy, as fuel cells can combine hydrogen energy and electrical energy, which will be an important option to solve China's carbon emission problems.

2. An introduction to fuel cells

A fuel cell is a power generation device that directly converts the chemical energy of the fuel into electrical energy. Depending on the type of electrolyte used, fuel cells can be classified into solid oxide fuel cells (SOFCs), proton-exchange membrane fuel cells (PEMFCs), molten carbonate fuel cells (MCFCs), phosphoric acid fuel cells (PAFCs), and alkaline fuel cells (AFCs) [5]. At present, global fuel cell supplies mainly comprise PEMFCs and SOFCs, which have a wide variety of power applications ranging from portable and transportation power systems to large-scale stationary power systems, as shown in Fig. 1.

This work highlights the current status of domestic and global PEMFC and SOFC development, discusses existing problems in PEMFC and SOFC technology in China, summarizes the key tasks to be addressed in the PEMFC and SOFC industry supply chains, and provides an outlook on safeguard measures and policy recommendations. Actively developing fuel cell technology will stimulate China's supply-side energy reform, promote the energy technology revolution, and establish a technical foundation for the early realization of China's goals of achieving a carbon peak and carbon neutrality.

3. Development status of PEMFCs

PEMFCs have many advantages, such as a low operating temperature, fast start-ups, and a broad range of applications, particularly in the transportation industry. The governments of Europe, the United States, Japan, and the Republic of Korea and large automobile companies have taken fuel cell vehicles as an important development direction. As of the end of 2020, the number of hydrogen fuel cell vehicles in the world reached 34 218 [6]. In regard to global hydrogen fuel vehicle development types, hydrogen fuel cell vehicles are mainly passenger vehicles. The development of small fuel cell passenger cars technology has enabled the development of large fuel cell commercial vehicles such as hydrogen fuel cell heavy-duty trucks and forklifts. On an international level, the initial commercialization of many PEMFC materials and components has been achieved. The power of a single fuel cell system has been developed from 30–60 to over 150 kW, and the platinum (Pt) loading has been reduced to 0.1 $g{\cdot}kW^{-1}$. At present, the main focus of PEMFC development is in the direction of high power, low noble metal catalyst loadings, low cost, and a long life [7].

The development of fuel cell vehicles has important strategic significance for ensuring national energy security, creating a low-carbon emission reduction environment, and promoting the transformation and upgrading of the automobile industry. In recent years, China's domestic fuel cell industry chain has entered a fast growth stage, but China's fuel cell vehicles are mainly commercial vehicles. As of the end of 2020, China had 7729 hydrogen fuel cell commercial vehicles—a number that is increasing rapidly [6]. In the future, hydrogen energy and fuel cell technology will have broad application prospects in the locomotive and shipping industries.

Thus far, China has mastered the key materials of PEMFCs and the core technology and manufacturing process for PEMFC stacks.

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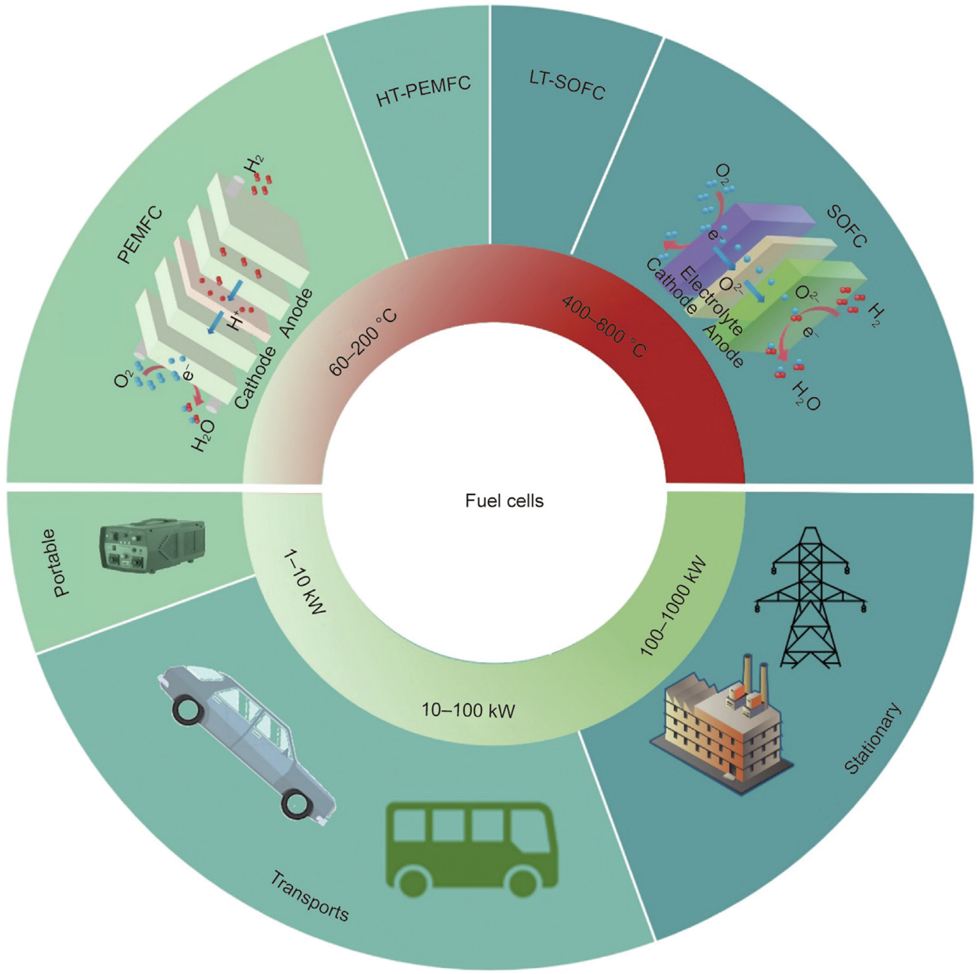

Fig. 1. Schematic diagram of the applications of fuel cells. HT-PEMFC: high–temperature PEMFC; LT-SOFC: low–temperature SOFC.

The overall performance of China's fuel cell systems has gradually approached the international first-class level and is in a stage of concurrent technological development. Domestic fuel cell stacks are gradually being produced by enterprises such as the State Power Investment Corporation (SPIC) Hydrogen Energy Company, Shanghai Hydrogen Propulsion Technology Company, Sunrise Power, and Weichai Power.

The number of hydrogen refueling stations (HRSs) affects the application of PEMFC technology. As of the end of 2021, there were 659 HRS in operation around the world, 183 of which were in operation in China. However, China's commercial-vehicle-oriented development route does not depend on the number of hydrogen stations in the initial stage of commercialization.

Many basic research studies on PEMFCs have been conducted in China. Based on a bibliometric analysis, out of a total of 15 020 research publications on PEMFCs between 2008 and 2018, the United States made the greatest contribution of 3009 (around 20% of the total publications). China's contribution came next, with a contribution of 2480 (more than 16% of the total publications) [8].

Chinese enterprises are major players in PEMFC vehicles, systems, and stacks, but few enterprises are involved in manufacturing fuel cell parts and components, especially the most basic key materials and components such as proton-exchange membranes, carbon paper, catalysts, air compressors, and hydrogen cycle pumps. Although domestic enterprises in the system area have started to catch up with the international level, there is still a significant gap in reliability and durability compared with international advanced products, and China's access to some key parts and materials still depends on imports. There is an urgent need for China to strengthen its domestic basic fuel cell research and the research and development of innovative materials, components, and new technologies. It is also essential for China to realize the domestic manufacturing of key materials and components, improve the power density of fuel cells and stacks, and lay a foundation for catching up with the advanced global development status of fuel cells.

In general, conventional low-temperature PEMFCs (LT-PEMFCs) are operated at temperatures below 100 °C, and they present critical water management problems that require intricate flow field designs due to the existence of both water vapor and liquid water in the system. LT-PEMFCs require extremely pure fuel (i.e., hydrogen) with few or no impurities in order to forestall catalyst poisoning; moreover, the reformate gas must be processed via a water gas shift to reduce the carbon monoxide (CO) content to below 10 ppm (1 ppm = 1 cm^3/1 m^3). LT-PEMFCs also suffer from restricted oxygen mass transport at high current density, resulting in large polarization. In recent years, high-temperature PEMFCs (HT-PEMFCs; 120–200 °C) have attracted increased attention due to their advantages over LT-PEMFCs, such as their ease of heat and water management, because there is no liquid water in HT-PEMFCs, and the improved poisonous gas endurance of their catalysts, which allows reformate gas to be directly used as fuel [9].

4. Development status of SOFCs

SOFCs can use hydrogen as fuel and do not require a fuel with high purity. In particular, they can operate directly using various carbon-containing fuels (e.g., natural gas, biomass gas, gasoline, diesel, ethanol, etc.) [10] that are compatible with existing energy supply systems. SOFCs, which are also known as ceramic fuel cells, have an all-solid-state ceramic structure with a lifetime of up to 100 000 h. Their modular design is easy to install, has high electrical efficiency under different power ratings, and easily improves the flexibility and security of grid operation. The drawbacks of SOFCs include their high-temperature operation—which affects the range of materials selection and the lifetime damage due to materials degradation—and their slow start-up speed. The most common application field of SOFCs is stationary power generation, including small household combined heat and power (CHP), data center backup power stations, and industrial stationary power stations. Among these applications, large-scale distributed power generation and integrated gasification fuel cell (IGFC) systems with near-zero CO_2 emissions will become the main research direction in the future.

The United States, Europe, Japan, and other developed countries and regions have always occupied the global leading positions in SOFC technology. After decades of tackling key technical problems, several SOFC companies with distinctive technologies and commercial products have emerged, such as Bloom Energy of the United States, Kyocera of Japan, Ceres Power of the United Kingdom, SOLIDpower of Italy, and Elcogen of Estonia [11,12]. Among these companies, Bloom Energy, which is funded by venture capital, is currently the most successful fuel cell company in SOFC commercialization. Its SOFC products have a single-output power range of 100–250 kW, and their electrical conversion efficiency can reach as high as 65%. Bloom Energy has provided a safe and reliable power supply for the large data centers of dozens of global Fortune 100 companies, such as Apple, Walmart, and the Bank of America. In 2020, Bloom Energy and Samsung Heavy Industries signed a joint development agreement to design and develop fuel cell ships, realizing their vision of clean energy for ships and a more sustainable maritime transportation industry. Japan's Kyocera began developing proprietary ceramic technologies for SOFC applications in 1985. In 2011, the company began the mass production of a household kilowatt-level SOFC cogeneration system with a total efficiency of over 90% (lower heating value (LHV)). At present, the number of installations continues to increase while the price gradually decreases.

Foreign SOFC research and development mainly focus on reducing costs and improving stability; in comparison, China's research and development have started late and are still in the preliminary exploration stage. In recent years, China has made great progress in the development of key SOFC materials and single cells. Chaozhou Three-Circle Co., Ltd. (CCTC) has become the core supplier of Bloom Energy's SOFC electrolyte, based on the company's expertise in ceramic manufacturing. During the 12th Five-Year Plan period, a project led by the China University of Mining and Technology-Beijing completed the first SOFC-oriented National Key Basic Research Development Plan (973 Plan). The demonstration projects of the National High Technology Research and Development Program of China (863 Program) (which involved 5 kW system and 25 kW stack projects) were respectively undertaken by the Dalian Institute of Chemical Physics, the Ningbo Institute of Materials Technology and Engineering, the Huazhong University of Science and Technology, and the Shanghai Institute of Ceramics. However, a complete breakthrough in efficient, reliable, and consistent cell stack and system integration technology has not been achieved, causing China to fall far behind foreign countries in terms of SOFC commercialization. During the 13th Five-Year Plan period, large energy companies such as China Energy Group, State Grid, and Weichai have started SOFC research and development, creating a good opportunity for SOFC development in China.

In July 2017, China Energy Group and the China University of Mining and Technology-Beijing were awarded a grant from the Ministry of Science and Technology under the National Key Research and Development Program to develop "integrated gasification fuel cell technology with near-zero CO_2 emissions" [13]. The core of this project is the development of high-temperature SOFC technology. IGFC is a power generation system that combines an integrated gasification combined cycle (IGCC) with high-temperature fuel cells. IGFC is expected to further improve the efficiency of coal gasification power generation, reduce the cost of CO_2 capture, and simultaneously achieve near-zero emissions of CO_2 and pollutants. It is a fundamentally transformative technology for coal power generation.

China has not yet publicly reported a long-running SOFC commercial system. SOFC research in China mainly focuses on breakthroughs in key materials, processes, design and component technologies, and the construction of demonstration projects. For example, the current IGFC demonstration project was established by the China Energy Group in Ningxia. In 2022, the 100 kW IGFC test demonstration system passed an expert field assessment. Furthermore, CCTC reported a 100 kW SOFC system demonstration whose alternating current (AC) power generation has a net efficiency as high as 64.1%. Since the 14th Five-Year Plan, with the development of hydrogen energy and fuel cells, a series of policies have been introduced in China, and SOFC technology has entered a period of rapid development.

The first key issue in SOFC research and development is that the SOFC operate at high temperatures, which bring many degradation problems of the components. SOFC technology is a typical "high-threshold" technology [14], which involves electrochemistry, materials science, mechanical engineering and other related theories. However, domestic industrial development proprietary information cannot be well shared. In terms of basic research, most domestic universities or enterprises operate alone and can only carry out work within their ability in their familiar research fields. They have not collaboratively formed a joint force to establish a good theoretical and technical system.

Second, China started SOFC research and development late, with insufficient investment and insignificant industrial participation. Although a considerable number of SOFC-related papers have been published in China, key technical SOFC research combined with practical applications is relatively weak in China, resulting in a slow commercialization process. In sharp contrast to China, industrial, academic, and governmental interaction was fundamental for SOFC development in the United States and Japan [15]. For example, the United States has established a Solid-State Energy Conversion Alliance (SECA) program for SOFC development, which consists of three parties: industrial teams, core technology teams, and federal agencies. These parties coordinate their activities and cooperate in order to jointly promote the development and commercialization of SOFC products. Since 2002, the average annual investment in SOFCs in the United States has been maintained at more than 30 million USD, and the cumulative investment of Bloom Energy in the United States has exceeded 1 billion USD.

5. Strategic thinking and development path for fuel cells

Fuel cells are important technical enablers for future energy transformation. Therefore, for a long time in the future, China will need to continue to strengthen its fundamental and applied fuel cell research, emphasize fuel-cell-related engineering, enhance the fuel cell process and equipment research and development, and promote the formation of fuel cell industry. It will also be necessary to continually improve China's fuel cell industry supply chain, gradually expand the scale of fuel cell system demonstrations, increase the maturity of fuel cell technology, improve the construction of fuel cell regulations and standards, strengthen top-level fuel cell planning and design, and advocate policies to guide the fuel cell industry. Finally, China will need to establish low-cost material, component, and system and production industry chains for fuel cells in order to realize the commercial operation of fuel cells without subsidies.

At present, with the rapid progress of fuel cell technology, China has achieved the level of producing high-power PEMFC stack and system, and the PEMFC development path has been gradually clarified in order to greatly reduce costs while improving the performance and lifetime of fuel cells. Most of the key materials and components in PEMFCs are imported, which seriously restricts the manufacturing cost of fuel cells and makes it impossible to ensure a secure supply of key materials in future commercialization processes. Therefore, the current key task in China's industrial development is to vigorously promote the formation of fuel cell stacks and key material industry chains with independent intellectual property rights, which will ensure technical support for and the production capacity of the commercial development of PEMFCs.

Given that domestic SOFC technology is not yet fully mature and there is an urgent need for demonstration, the development of a 100 kW SOFC power generation unit as soon as possible during the "14th Five-Year Plan" period is undoubtedly the most suitable direction, as this will lay a foundation for the scale of megawatt-level and even 100 MW-level power generation systems in the future. The 100 kW power generation unit is widely used in urban data centers and distributed power generation applications, biomass gas power generation in rural and remote areas, and large-scale coal gasification fuel cell power generation.

5.1. Key tasks in the PEMFC industry chain

Key tasks must be completed in the PEMFC industry chain, as follows:

(1) Improvement of the performance and specific power of PEMFC stacks, enhancement of the durability and reduction of the cost of PEMFCs (especially for commercial vehicles), and improvement of the domestic supply of key core materials in PEMFC stacks;

(2) Development of HT-PEMFC technology, research on high-temperature/high-contaminant tolerance and high-altitude environmental adaptability technologies, consolidation of the new HT-PEMFC material system, and promotion of PEMFC production and large-scale PEMFC application.

5.2. Key tasks in the SOFC industry chain

The following key tasks must be completed for the enhancement of the SOFC industry chain:

(1) Development of low-cost, high-performance single-cell technology, research on the application of SOFCs using carbon-containing or ammonia fuel [16], research on electrode activity improvement and contaminant erosion mechanisms under working conditions, development of LT-SOFCs in areas such as proton conductor materials and key technology, and development of accelerated life testing technology and methods;

(2) Efficient, consistent, and reliable cell stack design and integration technology, including recyclable and repairable ceramic–metal sealing technology, low-cost stainless-steel material development, and oxidation-resistant coating technology;

(3) IGFC system technology development such as high-power module integration technology and thermal management technology, system integration technology, and related control strategies;

(4) Expansion of SOFC industrial applications such as transportation and marine applications and strengthen the hydrogen production technology via solid oxide electrolysis cells (SOECs).

6. Safeguard measures and policy suggestions

To promote the development and early commercialization of fuel cell technologies, China needs to strengthen its top-level fuel cell design, exercise nationwide strategic planning, and continue to support basic scientific and key technological research on fuel cells. At the same time, based on its national context, China must adhere to multiple application scenarios and early demonstrations, and carry out fuel cell commercial application demonstrations according to local conditions.

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