Int J Coal Sci Technol (2021) 8(3):327–334
https://doi.org/10.1007/s40789-021-00443-3

Current status of national integrated gasification fuel cell projects in China

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Received: 20 July 2020 / Revised: 1 February 2021 / Accepted: 20 May 2021 / Published online: 3 July 2021

Abstract Coal has been the main energy source in China for a long period. Therefore, the energy industry must improve coal power generation efficiency and achieve near-zero CO_2 emissions. Integrated gasification fuel cell (IGFC) systems that combine coal gasification and high-temperature fuel cells, such as solid oxide fuel cells or molten carbonate fuel cells (MCFCs), are proving to be promising for efficient and clean power generation, compared with traditional coal-fired power plants. In 2017, with the support of National Key R&D Program of China, a consortium led by the China Energy Group and including 12 institutions was formed to develop the advanced IGFC technology with near-zero CO_2 emissions. The objectives of this project include understanding the performance of an IGFC power generation system under different operating conditions, designing master system principles for engineering optimization, developing key technologies and intellectual property portfolios, setting up supply chains for key materials and equipment, and operating the first megawatt IGFC demonstration system with near-zero CO_2 emission, in early 2022. In this paper, the main developments and projections pertaining to the IGFC project are highlighted.

Keywords Integrated gasification fuel cell (IGFC) · Fuel cell · Coal-based power generation · Near-zero CO_2 emissions

1 Introduction

Coal is the most abundant and low-cost energy carrier on the planet. This makes coal the dominant source for energy as well as greenhouse gas emissions (Wang et al. 2015; Chang et al. 2016; Li et al. 2018). The major greenhouse gases include CO_2, methane, and nitrous oxide (N_2O). Of these, CO_2 levels have increased by more than 40% since the beginning of the Industrial Revolution, from about 280 parts per million (ppm) in the 1800s to 400 ppm today; most of this increase was caused by burning coal. The emission of greenhouse gases leads to global warming, climate change, rising sea levels, decreasing ocean pH, and extreme weather events. The adverse effects caused by global warming require greater power efficiency and lower CO_2 emission for traditional coal-fired power plants (pulverized coal-fired boilers (Bhanarkar et al. 2008; Mao et al. 2014)). In November 2018, the US Department of Energy announced the "Coal FIRST" plan, aimed at developing flexible, innovative, resilient, small, and transformative advanced coal-fired power plants suitable for future energy systems. In May 2019, the US Department of Energy (2019) invested US $100 million in this plan to develop future advanced coal power plants.

Integrated gasification combined cycle (IGCC) power generation systems were designed for higher efficiency and lower CO_2 emissions. The first generation of IGCC systems was developed in the 1970s to mitigate the oil crisis. Commercial IGCC systems were demonstrated in the 1990s (Gräbner 2015). In 2009, the China Huaneng Group launched the first 250-MW-class IGCC demonstration power plant. In 2012, the gasifier was successfully ignited, leading to the generation of electricity. To date, the system

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has reached 41% (lower heat value, LHV) efficiency in operation (Jiao 2009; Lv et al. 2010; Hui 2015). Dry coal powder gasification is one of the key technologies utilized in IGCC systems. Although commercial gasifiers are available, the gasification efficiency, syngas purification, and cost reduction require further research and development.

Fuel cell technology has attracted considerable attention for decades. The fuel cell is an electrochemical device that can directly convert chemical energy into electricity. The integrated gasification fuel cell (IGFC) power generation system combines coal gasification and high-temperature fuel cells, such as solid oxide fuel cells (SOFCs) or molten carbonate fuel cells (MCFCs). The IGFC is able to achieve much greater system efficiency, up to 50%–60%, and lower cost for CO_2 capture and utilization, and is a revolutionary breakthrough compared with traditional coal-based power generation, which relies on the combustion of coal to generate electricity with lower efficiency (Peng and Han 2009; Li et al. 2010; Discepoli et al. 2012). The technology of IGFCs makes near-zero emissions of CO_2 and pollutants more feasible. In 2000, a study by the Solid State Energy Conversion Alliance (SECA) showed that, by using internal CO_2 capture in fuel cells, the economic and environmentally friendly IGFC system could capture 99% CO_2 before emission (Surdoval et al. 2001).

Both the US Department of Energy (DOE) and Japan's New Energy and Industrial Technology Development Organization (NEDO) have been supporting IGFC technology development and application demonstration for some time (Williams et al. 2006; Damo et al. 2019). In 2000, the US DOE established the SECA program to develop 100 MW IGFC systems (Dong et al. 2019). In 2003, a megawatt IGFC power generation system was demonstrated at Wabash River Generating Station by Kentucky Advanced Energy and Fuel Cell Energy. In 2016, the US National Energy Technology Laboratory made medium- and long-term development plans for SOFC technology. Based on the plans, 10 MW and 50 MW IGFC or natural gas fuel cell demonstration systems with carbon capture would be built in 2025 and 2030, respectively.

In 2015, Japan announced a 10 year IGFC development plan with the goal of achieving 55% power generation efficiency by 2025 (Dong et al. 2019). Since 2017, NEDO and Osaki Power Generation Co. Ltd. have cooperated on an IGFC verification project. The project included three phases: (1) oxygen-rich IGCC system verification; (2) verification of the IGCC system with near-zero CO_2 emission; and (3) verification of the IGFC system with near-zero CO_2 emission. The third phase was started in 2019 with two 600 kW IGFC systems. The goal of the phase 3 program is to achieve 47% power efficiency with 90% CO_2 recovery rate. This technology would be applied to 500-MW-class commercial power generation facilities in the future (Shindo 2017). In August 2018, Minister Wang Zhigang of China's Ministry of Science and Technology visited the International Research Center for Hydrogen Energy at Kyushu University and the 250 kW fuel cell demonstration system in Japan. The development of IGFC technology in China is in its very early stages. In 2009, Peng proposed the development of IGFC technology in China (Peng and Han 2009). Later, a novel concept that combined coal gasification, SOFCs, and chemical looping combustion was formulated and evaluated. Based on the model analysis, the net power efficiency of the system is projected to reach 49.8% (based on coal LHV, including energy penalties for coal gasification, oxygen production, and CO_2 compression) (Chen et al. 2015).

The IGFC system with near-zero CO_2 emissions integrates coal gasification, high-temperature fuel cells, and CO_2 capture and utilization. With the support of the Ministry of Science and Technology of China, Chinese researchers proceeded to the design, manufacture, and operation of large-scale coal gasification technology. The system integration design and optimization, operation, and control technology should be finished during the periods of the 10th, 11th, and 12th Five-Year Plans. These will build a solid foundation for further development of IGFC technology. Currently, the development and commercialization of IGFCs has been considered a strategic energy plan by the Chinese government. In the "13th Five-Year Plans for Power Development", there is expected to be a technology breakthrough in improving the efficiency of traditional coal-fired power plants. The development and application of fuel cell technology in stationary power generation systems are also expected.

High-temperature fuel cells, especially SOFCs, are the most promising technology for use in IGFC systems. Fuel Cell Energy, Bloom Energy, Mitsubishi Heavy Industries, and Siemens Westinghouse have demonstrated SOFCs for stationary power generation. Nowadays, SOFC technology is in the early stages of commercialization. The near-term objective is to reduce costs and improve the performance and long-term stability of the SOFC systems (Mastropasqua et al. 2017; Damo et al. 2019). Using SOFC systems, good progress was also made in CO_2 enrichment for carbon capture and storage; 90% and 95% of CO_2 enrichment has been achieved in gas turbine SOFCs (Campanari 2002) and IGFC systems (Li et al. 2012), respectively.

The development of high-temperature fuel cells in China falls behind that in leading countries. Chinese researchers have completed the "Basic research on carbon-based solid oxide fuel cell" program under the "973" project and a kilowatt-class SOFC power generation unit has been successfully developed. However, the remaining challenge is to scale up the smaller SOFC unit to build a larger power generation system. In July 2017, the China Energy Group received an award from the Ministry of Science and Technology under the National Key R&D Program for a program to develop "Integrated gasification fuel cell technology with near-zero CO_2 emission." To complete this project, an industry–university research team was formed, led by the China Energy Group, and including a total of 12 universities, research institutes, and industrial partners, such as the China University of Mining and Technology-Beijing, the China Huaneng Group, and the National Institute of Clean and Low-Carbon Energy. The team has been focusing on key scientific problems and technologies related to IGFCs, such as coal gasification techniques, syngas cleaning processes, high-temperature fuel cell stack and module design, fuel cell system integration and design concepts, and CO_2 capture and utilization. This team is technology innovation-oriented, and the objective of the project is to develop an IGFC technology that can be scaled up for 500 kW system demonstration.

The successful development of an IGFC system will ensure that coal can continue to be used as one of the key energy resources in China in the next couple of decades, before renewable energy becomes the dominant energy source. In the future, traditional coal-fired power plants can be replaced by efficient 100 MW IGFC power generation systems with near-zero carbon emissions.

2 Introduction: IGFC project

2.1 Objectives

The objectives of the IGFC project are to develop IGFC technology with a CO_2 capture or utilization subsystem, using coal syngas as fuel and a high-temperature fuel cell to replace the gas turbine in an IGCC to convert chemical energy to electrical energy directly, which is scalable to larger system, and meanwhile generate intellectual property portfolios for key technologies. At the end of the project, it is intended that a 1 MW_{th}-level (input heat value) IGFC demonstration system with near-zero CO_2 emission will be designed, built, and operated, with CO_2 capture rate $\geq$ 91% and fuel cell power generation efficiency $\geq$ 50%. Based on this technology, a blueprint design of a 100-MW-class IGFC power plant will be developed and analyzed, with the expected target of achieving CO_2 capture rate $\geq$ 90%, fuel cell power efficiency $\geq$ 50%, and overall system efficiency $\geq$ 47%.

Successful completion of the project will help to understand better the design principles and process and engineering optimization of IGFC systems, including all the subsystems, accelerate the commercialization of IGFC technology in China, and eventually achieve the target of CO_2 reduction in the next few decades, which is a revolutionary change from coal-based power generation. Meanwhile, the project will attract private investment to support fundamental research and technology development, which can further improve the performance, cost reduction, long-term durability, and reliability of the IGFC system.

2.2 Scope of the work

The project is focusing on areas of coal gasification and syngas purification, high-temperature fuel cell stacks and module design, CO_2 capture and utilization, and IGFC system design and engineering optimization.

This project comprises five tasks: (1) investigation of the effect of energy conversion and the operation conditions of subsystems on the efficiency of the IGFC system; (2) development of new gasifier and syngas purification equipment and investigation of contaminant formation during coal gasification; (3) technological development of a high-temperature fuel cell power generation system using coal syngas as fuel; (4) investigation of the method of CO_2 capture and utilization for IGFC systems; (5) demonstration of a MW_{th} IGFC power generation system with near-zero CO_2 emission. Tasks 2 to 4 provide technical support and the guidelines for IGFC system design, performance, and operation under task 5. Task 1 is focused on conceptual design, system performance evaluation, and technology scale-up, based on the IGFC system developed under task 5.

2.3 Initial concept of the IGFC system

The IGFC system to be developed consists of three subsystems: (1) coal gasification and syngas purification, to remove different kinds of impurity and obtain high-quality syngas, a mixture of H_2 and CO, which may go through a water–gas shift reactor to convert CO into CO_2 before entering the fuel cell stacks; (2) high-temperature fuel cell stacks, to directly convert the chemical energy of the fuel to electricity, with air going into the cathode side and fuel going into the anode side, and oxygen being reduced to oxygen ions on the cathode side, which are then transported through the electrolyte to the anode side and react with H_2 to form water (as steam) on the anode side; and (3) combustion of outlet fuel from the fuel cell stack via an oxygen combustor to enrich CO_2 for capture and storage or utilization through co-electrolysis of CO_2 and H_2O in a solid oxide electrolysis cell (SOEC). The process for the IGFC system is shown in Fig. 1.

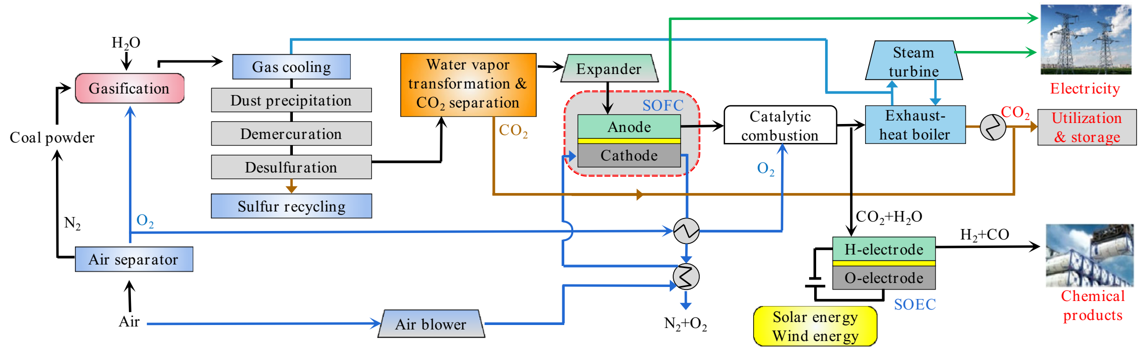

Fig. 1 IGFC system to be developed

3 Major progresses of IGFC project

3.1 Coal gasification purification

To develop new technology for coal gasification and syngas purification, the gasification reaction characteristics of ultrafine coal char particles, the effect of the melting of coal ash on the coal gasification reaction, models to predict the coal gasification processes, the formation mechanism of syngas contaminants, and the pressure-swing adsorption separation of H_2O and CO_2 from syngas at elevated temperatures were studied. The process, from coal to H_2, is shown in Fig. 2.

(1) The method of desulfurization and decarburization using activated carbon at moderate temperatures was selected. The effects of reaction temperature, regeneration method, water vapor content, and water–gas conversion reaction on desulfurization and decarburization were investigated. The desulfurization and decarburization performance using activated carbon adsorbent was also studied by simulating the actual composition, and the macroscopic phenomena observed were explained using microscopic mechanisms. Carbon dioxide can be separated from cleaned syngas, for utilization and storage, through the bypass line after the water–gas shift reactor for CO_2 scrubbing in the IGFC system, as shown in Fig. 1.

(2) An experimental device for mercury removal was set up and mercury removal adsorbents were selected. Aluminum oxide powder with internal micropores and a particle size of 1.00–0.55 mm (specific surface area, 240 m^2/g) and cobalt nitrate were used as the carrier and active component of the adsorbent, respectively. The Al_2O_3 powder was first impregnated with 10 wt% cobalt nitrate and 10 vol% hydrochloric acid solution and then calcined in a nitrogen atmosphere at 500 °C for 2 h. The experimental results showed that an efficiency of mercury removal of up to 90% could be achieved.

(3) The enrichment or dissociation characteristics of inorganic mineral elements, nitrogen, and sulfur in ultrafine coal particles were analyzed. A kinetic study of the gasification reaction of ultrafine coal particles was conducted. A method for calculating gasification reaction dynamics was established, and kinetic parameters, such as reaction rate, activation energy, and pre-exponential factor of CO_2 gasification of ultrafine coal particles at different reaction temperatures and different particle size distributions,

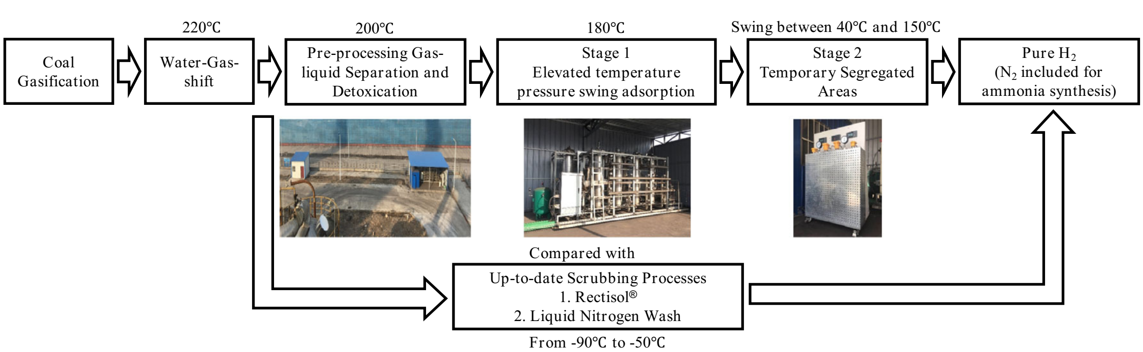

Fig. 2 Overall process from coal to H_2 in the ammonia plant

were obtained. The effect of ash melting on coal gasification was also investigated.

(4) A kinetic model for CO_2 gasification of ultrafine coal particles was developed, and an experimental scheme for coal gasification was established. The kinetic parameters of coal gasification at high temperatures were obtained, from which a distributed activation energy model was established, and the dynamic characteristic parameters were analyzed.

3.2 High-temperature fuel cell

The 5 kW SOFC and 10–20 kW MCFC stacks were tested. Research on the integrated coupling mode and control strategy of 100 kW SOFC and MCFC systems has started, and the design scheme has been optimized. The main progress of the high-temperature fuel cell is summarized as follows.

(1) Based on performance data of the stack, a multi-physical field coupling model of the electric, temperature and flow fields within the SOFC stack was constructed, and the stack design was optimized. Kilowatt-level stacks have operated for more than 1200 h with syngas (H_2, 69.87%; CO, 19.48%; CH_4, 0.29%; CO_2, 10.36%), and the output power was stable at above 725 W. A design concept of a 10–25 kW SOFC power generation system (Fig. 3) based on syngas has been completed. The balance of plant of the power system was built and installed, and the stack module is being assembled at the test site. Commissioning tests will begin soon.

(2) The design of a 5 kW MCFC short stack has been finalized. Material compatibility for scaling up components, such as the MCFC matrix, electrode, and bipolar plate, was optimized, and satisfactory results were achieved. Short stacks of MCFCs with a cell area of 0.2 m^2 were successfully fabricated. The discharge current densities of up to 110 mA/cm^2 at constant voltage were obtained for a single cell and 10 short stacks of MCFCs. A long-term durability test of 10 short stacks demonstrated relatively stable performance over 960 h. Using a single MCFC, the effect of syngas composition and impurities on cell performance was studied. Based on the test matrix and the results, the design operation conditions of the MCFC stack were selected. Recently, a 20 kW MCFC single stack (Fig. 4), with a maximum power output of 21.6 kW, was built and tested, and a stable power output of 16.51 kW was achieved. The start-up procedures, which were determined and optimized using short stacks, were implemented into a 20 kW stack; this ensured mechanical integrity of the stack for improved performance.

Fig. 3 10 kW SOFC system

(3) The initial concept design of the 100 kW MCFC power generation system and its control strategy was completed. The materials and components for cell and stack fabrication to construct a 100 kW MCFC system were ordered.

3.3 CO_2 capture and energy conversion

In accelerating the development of carbon capture, utilization and storage technology is essential for the development of advanced IGFC technology with near-zero CO_2 emissions. In this stage, new methods of CO_2 capture and energy conversion will be explored for off-gas from a high-temperature fuel cell. Two technologies, catalytic combustion and co-electrolysis of CO_2 and H_2O via SOECs, are being developed. The objectives of this task are to develop a kilowatt-level SOEC stack for co-electrolysis of CO_2 and H_2O and build an experimental test rig to verify the catalytic combustion technique. The lessons learned from laboratory-scale testing will help the team scale up the SOEC stack and combustor technology and implement

Fig. 4 20 kW MCFC single stack

them in a MW_{th} IGFC demonstration system. The main progress made in this task is described next.

(1) Exhaust gas catalytic combustion technology: Water-and-CO_2 resistant perovskite and hexaaluminate catalysts for fuel cell off-gas combustion were successfully developed and deposited on a porous ceramic substrate, from which a kilowatt-class SOFC off-gas burner and a testing system were built. The simulated conversion rate of the combustible components (CO, H_2) of exhaust gas is $> 97\%$, as verified by experimental data.

(2) Multidimensional model construction and internal heat and mass transfer mechanism: One-dimensional, quasi-two-dimensional, and three-dimensional SOFC–SOEC stack models were developed, and the effects of the cathode side flow channel and its structure on stack performance were analyzed. The effects of operating parameters, such as conversion rate of CO_2, on the co-electrolysis reaction of CO_2 and H_2O in the SOEC stack, were investigated, and strategies for further optimization were proposed. From the theoretical model and experimental results, the mechanism of CO_2 reduction and conversion to CO in a SOFC–SOEC stack was better understood.

(3) Materials, cell, and stack technology development of SOECs (Fig. 5): New perovskite electrode materials were developed through in situ precipitation of nanoparticles, and showed good catalytic activity for CO_2 reduction and conversion to CO in SOEC cells or stacks. Using new electrode materials, SOFCs and SOECs were successfully fabricated with good quality and high yield, and were also scaled up to produce full-size rectangular cells for stack development. A unique stack design with an open-cathode structure was developed, and can be integrated to produce larger SOFC–SOEC modules for power generation or as electrolysis. A number of kilowatt-

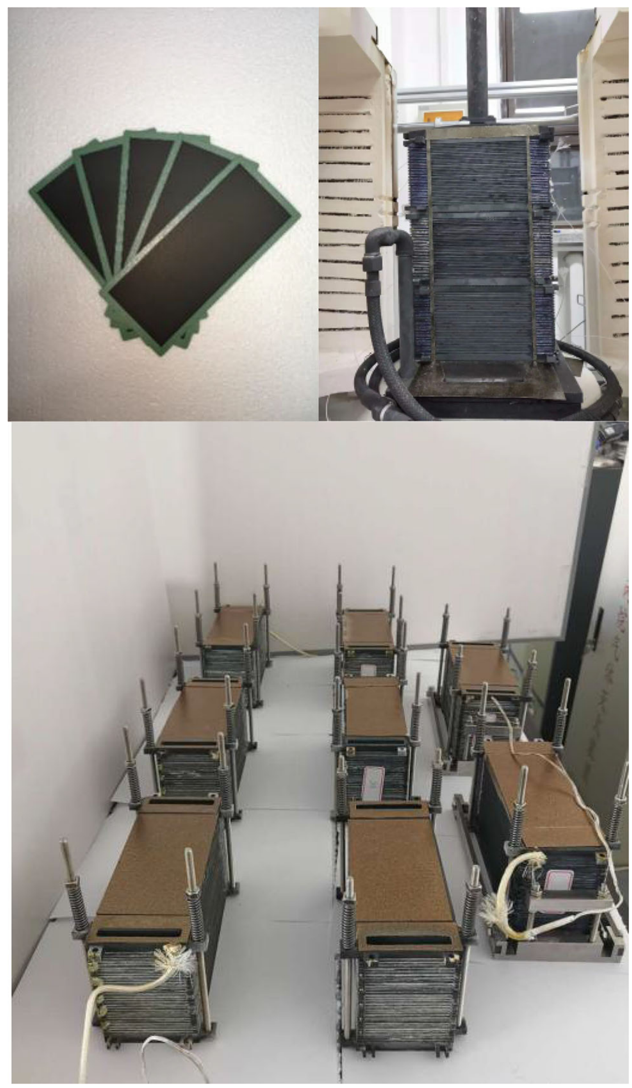

Fig. 5 Single cell, stack, and standardized large-scale assembly of SOEC stacks

level stack tests demonstrated high power output and stable performance. (Fig. 6).

3.4 Demonstration of IGFC system

Comprehensive economic analysis of a typical IGFC system was performed and the results were compared with those obtained for a supercritical pulverized coal-fired (SCPC) power plant, demonstrating that the cost of electricity of IGFC could be up to 20% less than that for a SCPC with CO_2 capture. The SOFC stacks selected for IGFC development were tested under both hydrogen and simulated coal syngas fuel, showing good consistency and stable long-term performance. Experimental results using SOFC stacks and thermodynamic analysis (using Aspen Plus) indicate that the hydrogen to CO ratio of the syngas is preferably 1.68 or higher, to avoid carbon deposition inside the fuel pipe. For a lower H_2:CO ratio, the steam to CO ratio needs to be higher. Moreover, the steam needs to be mixed well with the syngas above 100 °C and below the temperatures where carbon formation is thermodynamically favored. A 20 kW SOFC power generation unit is being developed with a design system condition of 20 kW maximum power, current density of 0.334 A/cm^2, DC efficiency of 50.41%, and fuel utilization of 80%. A 100 kW level subsystem will consist of six 20 kW power generation units, and the MW_{th} IGFC system will consist of five 100 kW level subsystems.

Fig. 6 IGFC test platform and demonstration base

4 Conclusions

A dry method for sulfur–carbon co-decoupling from coal syngas at moderate temperatures was developed and an experimental device for syngas purification was built and tested. The results show that the total sulfur content in the purified gas is less than 0.02 ppm. A 5 kW SOFC and a 20-kW-class MCFC stack were assembled. The MCFC stack was tested continuously for 72 h with a stable power output of >16.5 kW. Full-size cells were developed, and a kilowatt-class SOEC stack was assembled and tested. High-efficiency CO2 conversion was achieved. The preliminary design of the 20-kW-class SOFC power generation unit was completed. The design of the testing site for MWth IGFC system demonstration has just been completed, and the site preparation and construction will start in next couple of months.

During this project, it was demonstrated that IGFC systems are capable of reducing CO2 emissions. The high-temperature fuel cells have demonstrated the feasibility of achieving high power efficiency with traditional fuel. It is expected that in the near future, the coal-fed IGFC will be one of the most promising clean and low-cost energy sources.

Acknowledgements This work was financially supported by the National Key R&D Program of China (2017YFB0601900).

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