Status of MWth Integrated Gasification Fuel Cell (IGFC) Power Generation System Demonstration in China

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Status of MW_{th} Integrated Gasification Fuel Cell (IGFC) Power Generation System Demonstration in China

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Abstract This paper provides status update of IGFC power generation system being developed at National Institute of Clean-and-Low-Carbon (NICE) at MW_{th} scale. This system is designed to use coal as fuel to produce syngas as a first step similar to integrated gasification combined cycles (IGCC). Subsequently, the solid oxide fuel cell system is used to convert chemical energy to electricity directly through electrochemical reaction without combustion, which is different from IGCC. This system leads to a higher efficiency as compared to a traditional coal-fired power plant. The unreacted fuel in the SOFC system is transported to an oxygen-combustor to be converted to steam and CO_2. Through heat recovery system, the steam is condensed and removed, and CO_2 is enriched and captured for sequestration or utilization, such as co-electrolysis of CO_2 and H_2O using curtailed renewable energy for production of syngas. Comprehensive economic analysis for a typical IGFC system was performed and the results were compared with supercritical pulverized coal-fired (SCPC) power plant, showing the cost of electricity (COE) of IGFC could be up to 20% lower than that by SCPC with CO_2 capture. The SOFC stacks selected for IGFC development were tested and qualified 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 preferred to be 1.68 or higher to avoid carbon deposition inside of the fuel pipe. For lower H_2/CO ratio, steam to CO ratio needs to be higher. Besides, the steam needs to be mixed well with the syngas above 100°C and below the temperatures where carbon formation is thermodynamically favored. The 20kW SOFC power generation unit is being developed with design system conditions of 20 kW maximum power, current density of 0.334 A/cm^2, DC efficiency of 50.41%, and fuel utilization of 80%. A 100kW-level subsystem will consist of 6 x 20kW power generation units, and the MW_{th} IGFC system will consist of 5 x 100kW-level subsystems.

Keywords Integrated gasification fuel cell (IGFC), Solid oxide fuel cell, Stack module, Carbon dioxide capture, Oxygen-combustor

1. Introduction

Due to vast coal reserve and its lower cost, coal-fired power plant provides majority of electricity need in China, which is one of the major sources of CO_2 emission and air pollution. In 2019, China's CO_2 emission is more than the sum of that produced by Europe and the United States. In the Paris agreement signed by international leaders in 2015, Chinese government promised CO_2 emission in China will be peaked in 2035 and then gradually decreased to below 3 Gt by 2050 compared to 9 Gt in 2015 (Jiang, 2017). CHINA Energy is one of the leading energy companies in China and ranks 107 for world 500 companies. Its coal mining is up to 500 MMT per year and the total

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electricity generated by coal-fired power plant is 190 GW per year, about 45% of total electricity by CHINA Energy. The old coal-fired power plant has lower efficiency, up to 35-40% and also generates significant CO_2 emission as well as other contaminants, such as NOx, SO_2, and dust, to cause air pollution. The supercritical pulverized coal (SCPC) power plant has better efficiency, up to 48%. However, its cost is higher if CO_2 is captured and stored.

Integrated Gasification Combined Cycle (IGCC) and Integrated Gasification Fuel Cell (IGFC) power generation system with CO_2 capture are being developed recently to use coal effectively and reduce air pollution and CO_2 emission. Compared to IGCC, the advantage of IGFC is higher efficiency and lower overall cost, especially pressurized system (Braun et al., 2012). IGFC is expected to be the most efficient power generation system in coal-fired power generation system (Liese et al., 2010, Ghosh et al., 2006). A typical IGFC power generation system includes： 1）coal gasification subsystem to convert coal powder to syngas and remove all kinks of impurities; 2) high temperature solid oxide fuel cell system; and 3) CO_2 capture, utilization and storage subsystem. A simple IGFC system is similar to an IGCC system, but the gas turbine (GT) power island is replaced by a fuel cell power module. Since the fuel cell is a system to convert chemical energy to electricity through electrochemical reaction, higher power generation efficiency can be achieved than IGCC. 64.5%(HHV) and 53.6% power generation efficiency have been demonstrated using high-grade bituminous coal and low-grade coal, respectively, by National Institute of Advanced Industrial Science and Technology (AIST) in Japan (Nomura et al., 2011). Developing the IGFC power generation system to convert old coal-fired power plant to green energy form to significantly reduce CO_2 emission and air pollution is an urgent task for CHINA Energy. Since July 2017, National Institute of Clean-and-Low-Carbon Energy (NICE), fully owned by CHINA Energy, has been developing an IGFC demonstration system working with key partners, such as Huaneng Clean Energy Research Institute, China University of Mining Technology Being, Huaqing Inc. etc. High quality coal syngas is being mass-produced at the Coal-to-Oil plant in Yinchuan, Ningxia, one of the subsidiaries of CHINA Energy, which will be used as fuel for the IGFC system being developed by NICE. Therefore, the coal gasification and coal syngas purification processes will not be discussed in this paper. Oxygen-combustion of exhaust fuel from the fuel cell system and CO_2 capture will be discussed in separate paper (Wang, 2021). The development status of the high-temperature solid oxide fuel cell (SOFC) power generation system, including the system concept design and initial experimental results are presented and discussed.

2. Economic analysis of IGFC system

The team first performed comprehensive economic analysis for a typical IGFC systems mentioned in the DOE NETL report (DOE/NETL, 2014) which consists of three main subsystems: 1) coal gasification and removal of variety of impurities; 2) SOFC power generation subsystem with anode loop recycle; and 3) oxygen-combustion and heat recovery system generation (HRSG) for CO_2 capture, see Fig. 1 adapted from DOE/NETL reports (DOE, 2014 & 2015). An ASPEN Plus model was built to estimate costs for Case 1.1 and Case 2.1 in the DOE NETL report using CoP gasifier. Assumptions and parameters being used in the model are listed in table 1. Costing methods were used from various references. First, IGCC with CoP gasifier without CO_2 capture (Case B4A) was used for cost estimates for most non SOFC components. Case B5A was used to evaluate the costs of the Selexol plant and adapt them for IGFC costing cases. Case12F was used for estimating cryogenic separation of CO_2 from other components (DOE, 2015). The QGESS capital cost scaling methodology was used for scaling the components to the size estimated for the IGFC cases (DOE, 2013). The US estimates were converted to CNY using a conversion rate of USD:CNY of 1:6.5. Fig. 2 shows a comparison of a number of cases. The SCPC and SCPC with CO_2 capture estimates have been previously reported in the literature by our previous studies (Surinder, 2018). The SCPC study was used to calculate a capital cost and operating cost reduction factors between US and China. These factors were used to update the IGFC US cases to calculate the China IGFC costs. It is recognized that this is a simplified methodology for calculating IGFC costs in China. A more detailed analysis is suggested for another study where every unit operation is modeled and sized specific for China conditions. Such a work is out of scope for this study. The Base IGFC case is modeled vs Case 1.1 in the DOE study with an SOFC

Table 1 Assumptions for ASPEN Plus model

Case	1.1	1.2	3.1
Anode feed CH4 content (mol%)	5.8	5.8	10.9
SOFC operating pressure (bar)	1	2	8
SOFC degradation rate (5/1000h)	1.5	0.2	0.2
SOFC overpotential (mV)	140	141	70
Capacity factor	80	80	85
SOFC stack cost （CNY/kW）	1463	1463	1463
Inverter efficiency（%）	97	97	97

degradation rate of 1.5%/1000 hrs. The lower degradation rate case is modeled according to Case 1.2 of DOE study with an SOFC degradation rate of 0.2%/1000 hrs. The advanced IGFC case is modeled according to Case 3.1 in the DOE study at a pressure of 8 bars instead of 20 bars used in the DOE study.

A capacity factor of 80% was chosen for Case 1.1, 1.2, CN 1.1 and CN 1.2 and 85% for Case 3.1 and CN 3.1 to compare with DOE NETL cases. The results are shown in Fig. 2. Comparing different cases, it is clear that China based systems are consistently lower in cost vs. US. It is also clear that IGFC costs are higher as compared to SCPC without and with CO_2 capture at an SOFC degradation rate of 1.5%/1000 hrs. The IGFC system can become competitive compared to SCPC with CO_2 capture if SOFC degradation rate can be reduced to 0.2%/1000 hrs. Such SOFC technology has been demonstrated at 250kW level in both US and

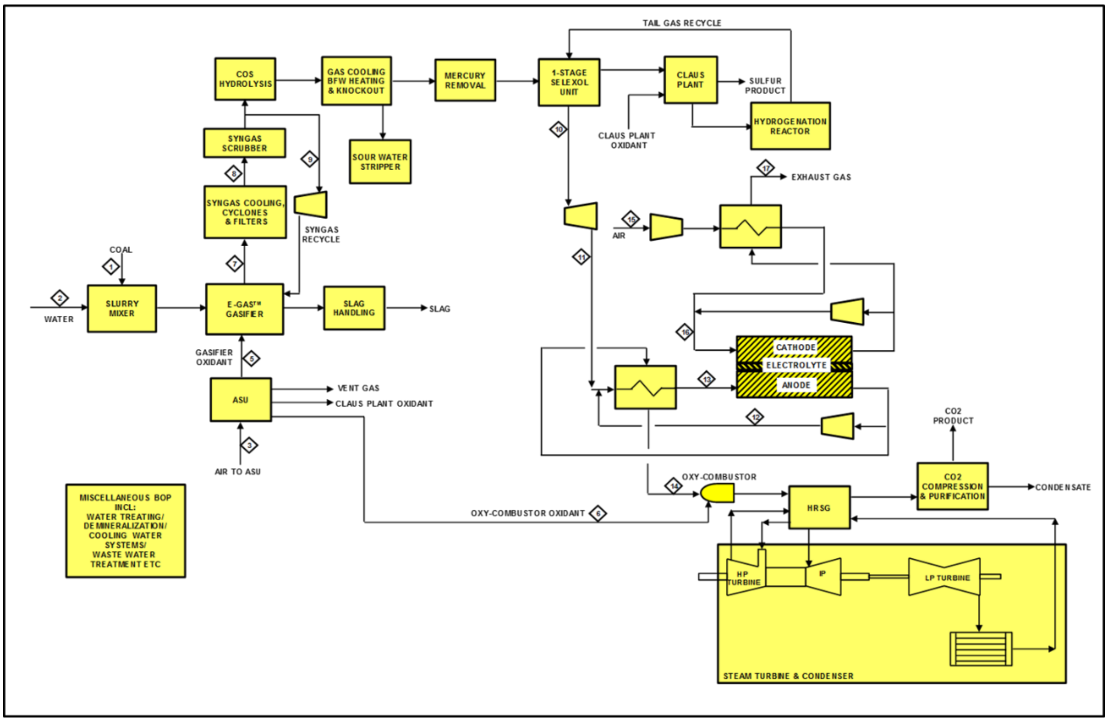


Fig. 1 A typical IGFC system for economic analysis (from DOE/NETL report, 2014)

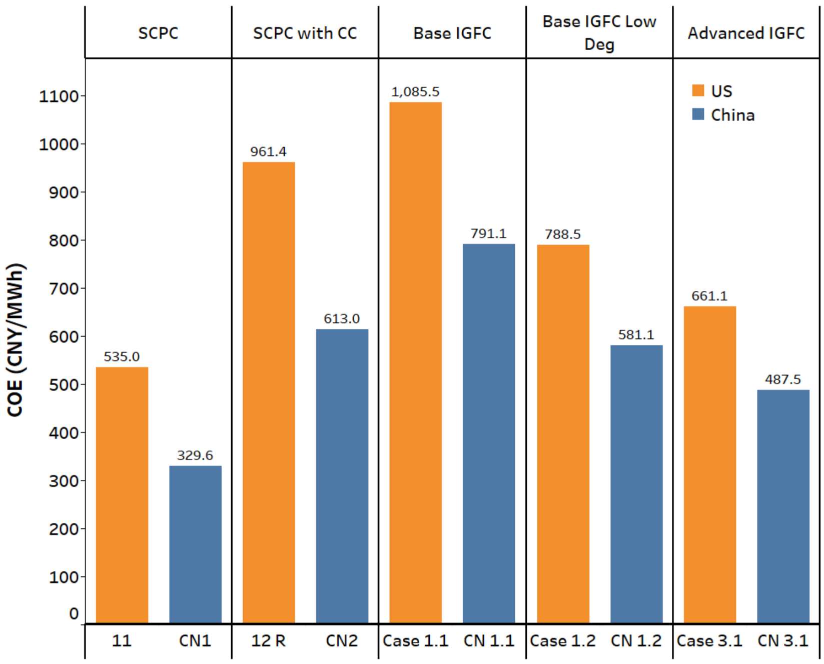


Fig. 2: Cost of electricity (COE) of various IGFC systems cases as compared to SCPC without and with CO2 capture for US and China.

Japan (Kobayashi, 2015). IGFC system at higher pressure indicates reduction in COE further.

3. IGFC system development

3.1 SOFC stack selection and evaluation

Since CHINA Energy is a traditional energy company focusing on mainly coal mining, coal-fired power plant, wind power, hydropower, and solar power recent years, SOFC technology is not available in house. The team communicated many domestic and international SOFC developers intending to get high quality and low cost stack for this program. Based on the considerations, such as quality, availability, cost as well as mass production capability and quality control, the stacks from Elcogen in Finland, Sanhuan in Chaozhou, China, Huaqing in Suzhou, China, and China University of Mining and Technology at Beijing were considered for evaluation. Stack leakage was inspected for all incoming stacks and followed by electrochemical testing using hydrogen fuel between 700-800°C in ambient pressure based on stack specification provided by suppliers. More testing data from Sanhuan stacks were generated due to its availability. All testing stands or systems used for SOFC stack or module testing in this work were designed and built by NICE with suppliers. Fig. 3 summarized testing results (stack voltage and power output vs. current density) of three individual stacks. For stack 1, the stack power output is 981W at current density of 250mA/cm^2, and increased to 1021W at current density of 270mA/cm^2. When current density is higher than 270mA/cm^2, the stack voltage formed a tail, off the trend line. To better understand the effect of testing conditions on stack performance, the stack was tested under different fuel flow rate and all tests were performed at 750°C (stack 2 and 3 in Fig. 3). It can be seen that when the flow rate was increased from 9 SLPM (standard liter per minute) for stack 1 to 12 SLM for stack 2, and 13 SLPM for stack 3, the stack voltage shows good linearity.

The testing data of stack 1 was further analyzed to better understand the stack properties, such as area specific resistance (ASR, ohm-cm^2), and stack performance, such as fuel utilization and DC power efficiency under different testing conditions. The electrochemical reaction on anode side can be expressed as:

$$H_2 + O^{2-} = H_2O + 2e^- \quad (1)$$

The fuel utilization during stack operation is consumed fuel by electrochemical reaction divided by total inlet fuel to the stack which can be written as equation (2) using hydrogen fuel as an example:

$$U_f = n \times \frac{I}{2F} \times \frac{1}{\frac{q_{v\,H2}}{V_m}} \times 100\% \quad (2)$$

where I is current through fuel cell stack, Ampere; F is Faraday's constant, C/mol; n is the number of cells connected in series in the stack, $q_{v\,H2}$ is hydrogen flow rate, liter/s; V_m is molar volume of a gas at standard conditions, liter/mol. The DC power efficiency of the SOFC stack or module can be obtained by:

$$DC_{eff} = \frac{P}{q_{mol} \times Q} \times 100\% \quad (3)$$

Where P is stack power output, watt; q_{mol} is fuel flow rate, mol/s; Q is low heat value of the inlet fuel, J/mol (Q=285,800J/mol for hydrogen).

Fig. 4 summarized average stack ASR, fuel utilization and DC power efficiency vs. current density at average temperature of 750°C with fixed fuel (9 SLPM) and air flow (25 SLPM) rate. It can be seen that, at current density of 250 mA/cm^2, the stack average ASR, fuel utilization, and DC power efficiency are 0.305 ohm-cm^2, 82.7%, and 61.3%, respectively. With increasing current density from 250 mA/cm^2 to 270 mA/cm^2, the stack average ASR, fuel utilization and DC efficiency are increased to 0.420 ohm-cm^2, 90.7%, and 63.4%, respectively, and a tail started to form from

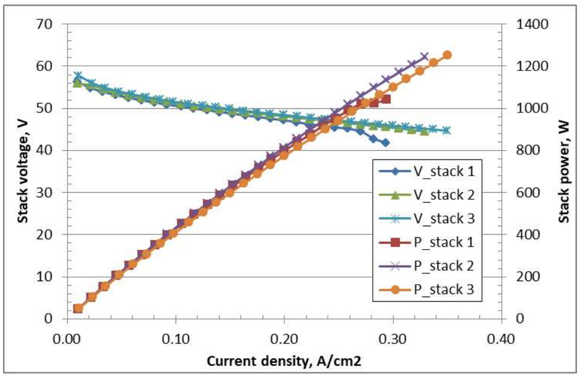


Fig. 3 V-I curves of SOFC stack (fuel flow rate is 9.0S LPM for stack 1, 12.0 SLPM for stack 2, and 13 SLPM for stack 3)

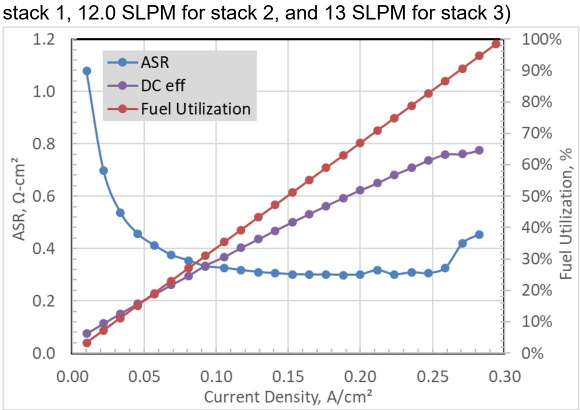


Fig. 4 SOFC stack average ASR, DC power efficiency and fuel utilization vs. current density

voltage vs. current density curve (Fig. 3). Most likely fuel starvation happened at local area within the stack, especially near the stack outlet, when current density is 270 mA/cm^2 or higher with fuel flow rate of 9 SLPM. Generally speaking, ASR curve shows three distinct regions as expected. At lower current density, the cell potential drops as a result of the activation polarization. Since steam has significant effect on anode polarization, such as hydrogen absorption and dissociation on Ni particles, and the charge can be transferred easier under electric field, stack ASR decreased significantly with increasing current density （hydrogen fuel is pure hydrogen and the steam content in the fuel increased with increasing current density）. At moderate current densities, the cell potential decreases linearly with current due to ohmic losses. Therefore, stack ASR is almost no change with current density from 0.1-0.25 A/cm^2. At high current densities (>0.25 A/cm^2), the cell potential drop departs from the linear relationship with current density as a result of a more pronounced concentration polarization. it seems to be safe to operate Sanhuan stack at current density of around 250mA, or fuel utilization of about 80%.

Short term stack durability was also tested up to 540 hours under different conditions (Fig. 5). In period one, the fuel and air flows are 13 SLPM and 36 SLPM, respectively, and then the fuel flow decreased to 10.6 SLPM while keeping constant air flow in period 2. Within both periods, noticeable stack degradation is observed. In period 3, air flow was increased to 69 SLPM while keeping fuel flow no change. In period 4, the stack current was decreased from 24 A to 22 A, and

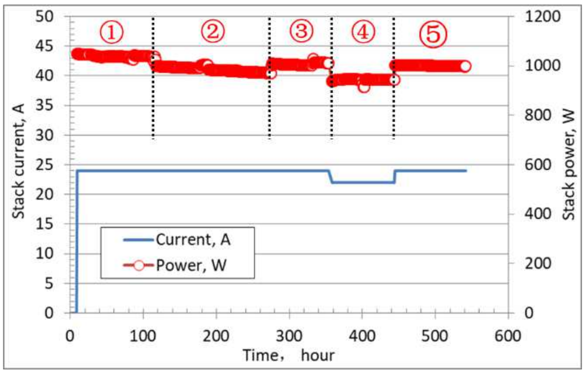


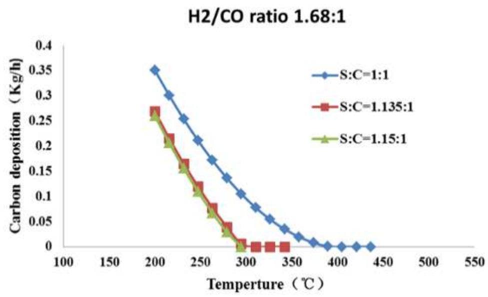
Fig. 5 SOFC stack short term durability at 750^{o}C

back to 24 A for period 5. It can be seen that there is no noticeable stack degradation for periods 3 to 5 even though the duration is not long enough.

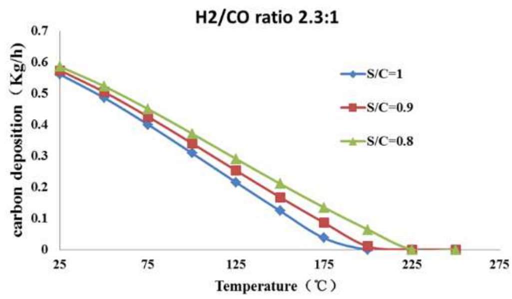
3.2 Design system operation conditions

IGFC system being developed will be operated under coal syngas rather than hydrogen fuel. Therefore, the stack performance under coal syngas needs to be evaluated and the design system operation conditions need to be defined. The coal syngas composition available for IGFC system operation is roughly 61.8%H_2, 36.7%CO, and 1.1%N_2 with minor content of CO_2 and CH_4. Based on thermodynamics, CO intends to form carbon under certain conditions, so called reverse Boudouard reaction, see equation (4), which is exothermal reaction and is thermodynamically favored at temperatures below 500^{o}C based on thermodynamic analysis (Fig. 6). The formed carbon could be deposited on the inner surface of fuel pipe to block fuel flow channel or enter into the stack with fuel gas stream and be deposited on anode surface. The stack performance would be affected under either case. Besides， the contact material and the material surface properties

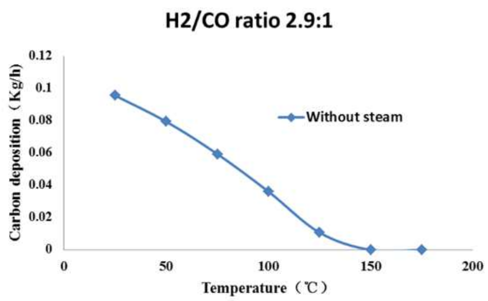
$$CO(g) \rightarrow C(s) + CO_2(g) \qquad (4)$$



(a) H2/CO=1.68 (61.8%H2, 37.7%CO)



(b) H2/CO=2.3:1 (69.7%H_2, 30.3%CO)



（c）H2/CO=2.9:1 (74.4%H , 25.6%CO)

Fig. 6 Potential carbon deposition analysis within fuel pipe for coal syngas with different H_2/CO ratio using ASPEN Plus

may also affect carbon formation. The amount of carbon formation at different temperatures was analyzed using ASPEN Plus for the syngas with different H_2/CO ratio in the syngas (Fig. 6 a-c). When

H_2/CO ratio is 1.68 (61.8%H，37.7%CO)，the high end temperature for carbon formation was decreased from about 400ºC to 300ºC with increasing steam/CO ratio from 1 to 1.15. When H_2/CO ratio is 2.3 (69.7%2，30.3%CO), the high end temperature for carbon formation changed to about 200ºC and the steam/CO ratio, when changing from 0.8 to 1.0, shows no significant effect on carbon formation temperature which is determined by the thermodynamics of the reaction. Above this temperature, the Gibbs free energy change of reaction (4), ∆Ge, is positive and the reaction would not happen. If further increasing H_2/CO ratio to 2.9 (74.4%H_2, 25.6%CO), the highest temperature for carbon formation is decreased to about 150ºC even without steam addition. From kinetics point of view, the reaction speed is too slow at lower temperatures and the reaction (4) may not happen since the fuel gas stream will pass this temperature range with high speed, ~14 SLPM, under system operation conditions.

Stack test was also performed to better understand its performance and behavior under coal syngas (Fig. 7). To make sure this specific stack has the same performance as others under hydrogen, the stack was first tested under hydrogen with flow rate of 13 SLPM at 750ºC. The V/j curve (V_1st H_2) shows good linearity and the stack generated 1252W (P_1st H_2) at the current density of 330 mA/cm^2 indicating a good stack. Then the fuel was switched to simulated coal syngas with composition of 61.8%H_2 and 37.7%CO (steam/CO ratio is 1). The OCV change is as expected due to pO_2 change in fuel stream, and the V/j curve is linear up to the current density of 270 mA/cm^2. Above

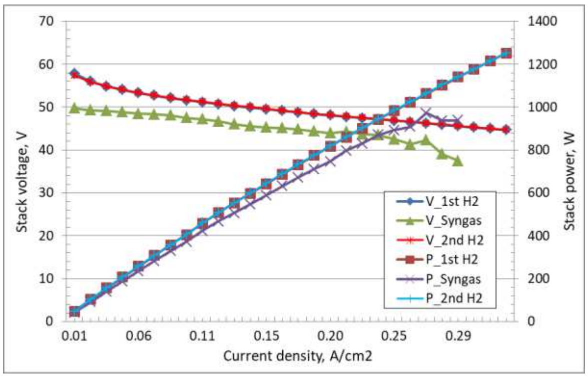


Fig. 7 SOFC stack performance under H2 (flow rate: 13SLM) and simulated coal syngas (61.8%H_2, 37.7%CO, flow rate:13 SLM with steam/CO ratio of 1.1)

that, both voltage and power curve tailed down from the trend line of the original plot. The test was shut-down for inspection. Significant carbon deposition inside of fuel inlet pipe was identified. The stack was reheated to 750ºC under safe gas (5%H_2 balanced with nitrogen), and then being purged with hydrogen at 750ºC and tested again after OCV is stabilized. The V/j curve of the second test under hydrogen (V_2nd H2) generally overlapped with the V/j curve of the first hydrogen test indicating the carbon damage to stack performance is temporary which is recoverable when fuel steam is switched from simulated syngas to hydrogen. The analysis of the test set-up after testing indicates that the steam was added into the fuel stream near the entrance of the furnace where the temperature may possibly be well above the temperature range of carbon formation. That means the carbon has been formed before the steam was added into the fuel inlet pipe.

Second stack test was performed at 725ºC (stack average temperature) using simulated coal syngas (61.8%H_2, 37.7%CO, steam/CO ratio: ~0.7) as fuel to make sure the steam is added into the fuel stream at lower temperature before carbon has been formed. The stack performance was stable during testing and series of tests were successfully completed at current densities between 258.2 and 282.9mA/cm^2 with high voltage per cell (table 2). 1022W stack power and 53.2% DC efficiency were achieved. Fuel utilization is up to 84.6% with no sign of fuel starvation. However, carbon was still observed inside of fuel inlet system during after-test inspection. This is possibly due to the lower steam/CO ratio or insufficient mixing between fuel gas and steam.

Table 2 SOFC stack testing results with syngas

Test No	Current density, mA/cm^2	Voltage/cell, V	Stack power, W	U_f, %	DC eff, %
1	258.2	0.845	943.9	80.7	51.2
2	282.9	0.835	1022.4	82.8	51.9
3	280.6	0.837	1016.3	84.6	53.2

Notes: 1) Operating conditions were controlled by adjusting current density and fuel flow rate, 2) Stack average temperature: 725ºC， 3） Steam/CO ration: ~0.7

4-stack module was tested, after successful single stack testing, using pipeline coal syngas at Coal-to-Oil plant in Yinchuan, Ningxia province. During test, the coal syngas was mixed with partial hydrogen to get a composition with higher H_2/CO ratio of 2.8 (72.9%H_2, 26.0%CO, steam/CO ratio is 1). Module power, fuel utilization, and DC power efficiency are 1.4kW/stack, 84.5%, and 53%, respectively. The module was operated under coal syngas and hydrogen mixture for up to about 350 hours without noticeable degradation trend. Furthermore, the post-test analysis shows no carbon deposition in fuel pipeline. Detailed experimental results will be published separately (Xu, 2021)

Based on thermodynamic analysis and stack performance verification test, the coal syngas composition with H_2/CO ratio from 1.68 to 2.8 could be used as fuel for IGFC power generation system. If the syngas has lower H_2/CO ratio, more steam is required to mix with the coal syngas above 100°C and below the temperatures where the carbon formation is thermodynamically favored inside of fuel inlet pipeline surface to prevent carbon deposition, which may affect system performance if steam content is too high. If the coal syngas has higher H_2/CO ratio, carbon deposition can be prevented with less steam or even no steam in fuel stream. More stack performance data with different coal syngas composition and operation conditions are needed to achieve highest power generation using available coal syngas or managing to get coal syngas composition which may benefit IGFC system power generation and efficiency.

3.3 20kW SOFC power generation unit development

A simplified IGFC system flow chart is shown in Fig. 8, in which pipeline coal syngas is used. Sulfur is removed before syngas enters into SOFC stacks. After electrochemical reaction in the stack, outlet fuel, which still contains about 10-20% flammable, is fed into oxygen-combustor to convert H_2 into steam and CO into CO_2. After going through heat recovery system, steam is condensed and was removed, and CO_2 is enriched to higher than 95% for capture. Based on this flow chart, 20kW SOFC power generation unit has been developing since April 2019 using performance data of single stack and 4-stack module obtained under both hydrogen and simulated or real coal syngas as fuel. The system process flow diagram (PFD) is shown in Fig. 9. To be clarified, this PFD only represents the operation of the 20kW power generation unit under steady state. During system start-up or shut-down, there will have a start-up gas burner to heat up the system to design operation conditions or provide extra heat during system shut-down in order to control the cooling rate. The fuel system consists of a mixing tank to thoroughly mix coal syngas and steam at temperatures above 100°C to prevent carbon formation in fuel inlet before entering into the stack, and a heat exchanger to heat the fuel stream to desired temperature, which is ~700°C for the stack selected for our IGFC system. The fuel flow is single pass without recycle and the design fuel utilization is 80%. The exhaust fuel, after cooling and separating the water from the gas stream, will be fed into an oxygen-combustor to burn the residual fuel and enrich CO_2 higher than 95% for capture, which can be stored or utilized, such as producing H_2-CO syngas through co-electrolysis of carbon dioxide and steam. The detailed experimental results will be published separately (Hanlin, 2021). The stack module includes 4 stack towers and each tower was built from 4 stacks, which is able to generate maximum 20kW power under current density of 336 mA/cm^2 and 171.2 V/stack tower, respectively.

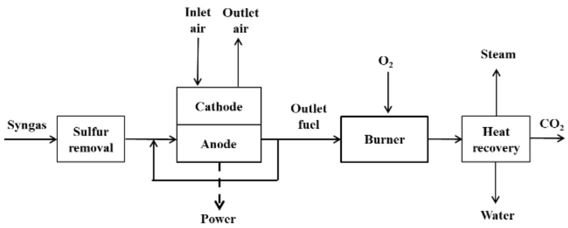


Fig. 8 IGFC system flow chart using pipeline coal syngas

During long term steady state operation, the module was designed to operate at 0.25 A/cm^2 and the power output is 15 kW (see table 3). CFD simulation was conducted to better understand the fuel and air flow within the stack module since it's important for heat management and keeping the healthy stack during operation. The simulation results are promising (Fig. 10). The air flow is pretty uniform and the fuel flow variation is within ±5%, which is acceptable for the system operation under design conditions. Uniform

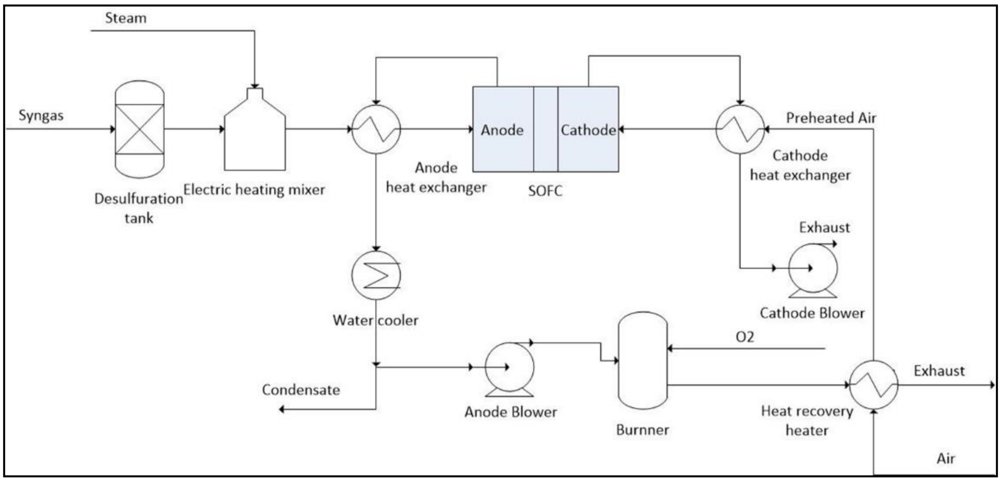
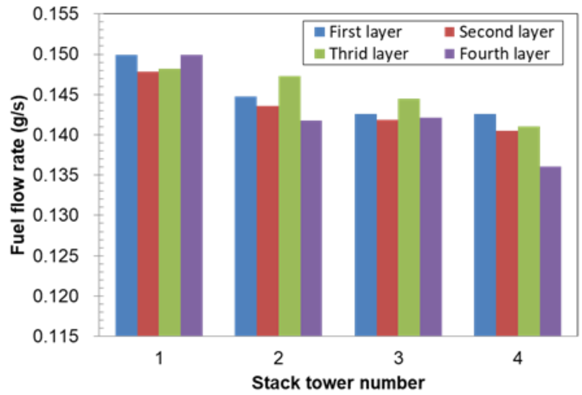


Fig. 9 Process flow chart of the 20kW SOFC system

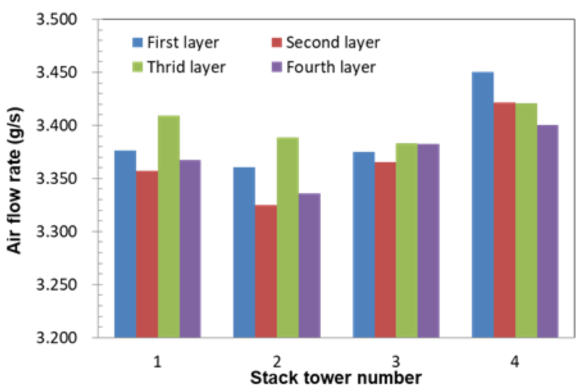
fuel flow will ensure that there will have no fuel starvation in any local area within the stack during system operation. The uniform air flow could ensure that the temperature difference of all stacks in the module can be controlled within specification. That is, the air inlet temperature of each stack is 700ºC and outlet temperature is ≤800ºC to maintain best performance and healthy stack. The cathode loop consists of a gas start-up burner, and the hot exhaust gas can be used to heat up cold air when the system

Table 3 Design operation conditions of 20kW power generation system

	Unit	Design condition	Max. power output
Power output	KW	14.9	20
Coal syngas flow rate	Kg/h	4.89	6.57
Air flow rate	Kg/h	188.13	290
Current density	A/cm^2	0.250	0.336
Stack tower voltage	V	175.6	171.2
DC efficiency	%	51.7	50.41
Fuel utilization	%	80	80
Heat loss	KW	2	2



（a）Fuel flow distribution in SOFC stacks within 20kW module



（b）Air flow distribution in SOFC stacks of 20kW \module

Fig. 10 Gas flow distribution in SOFC stacks of 20kW module

starts at room temperatures. During system steady operation, the inlet air is heated up through a heat exchanger. Fig. 11 shows the assembly sketch of the 20 kW SOFC power generation system excluding the oxygen-combustor. On the back of the sketch, it's a hot box where the SOFC module is installed. The hotbox is designed to keep the fuel cell module at constant temperature during steady state operation through the selection of insulation material to keep minimize heat loss and the control of cathode gas flow rate. The front part is BOP including fuel, air, and safe gas (to protect

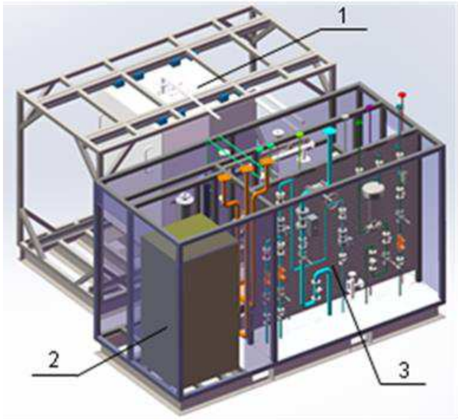


Fig. 11 20kW SOFC power generation system being developed and constructed (1: hotbox with stack module, 2: control and data acquisition, 3: BOP)

SOFC module during emergency shutdown) pipe line, control valves, flow meters, pressure meters etc., inlet fuel and air preheaters, exhaust fuel and air blowers. The corner box is control system. There is no external reformer and the majority of CO in the fuel gas stream expects to be converted to CO_2 within fuel cell stack. This reaction is exothermal and the released heat may help self-sustainable operation of the system. However, the temperature difference between cathode inlet and outlet will be monitored closely to make sure the outlet temperature is not exceeding 800ºC.

3.4 MWth IGFC system concept design

The conceptual design of the 500kW IGFC power generation system is shown in Fig. 12. The system consists of 5x100kW-level subsystems which can be controlled separately and generated DC power is converted to AC power. There are 5-6 SOFC modules within each subsystem which are electrically connected in parallel. If any module goes wrong or needs maintenance, other modules will not be affected and can continue to generate power. Within each module, there are multiple stack towers. These stack towers are electrically connected in parallel. In each stack tower, individual stack is electrically connected in series. The beauty of this design is that any damage, repair，or maintenance of individual stack tower， module， or subsystem will not affect the operation of other stack towers, modules, or subsystem. Based on table 3, the design voltage of the stack tower during steady state operation is 172.2V. This voltage may be too low for direct DC/AC conversion, which may need to be boosted to higher DC voltage before being converted to AC power. The desired DC voltage depends on the technology of advanced DC/AC converter. The small amount of power loss through each DC booster and AC converter will be considered during system design.

The layout sketch of 100 kW-level SOFC power generation system is shown in Fig. 13, which consists of 6 x 20kW fuel cell modules, and each module can generate 15kW DC power during steady state operation. All SOFC modules, including the hotbox, are located on one side of the layout and control system is located on another side. Gas pipe lines, heat exchangers, fuel and air preheaters, blowers etc. are in between them. The footprint of this 100 kW-level SOFC system is roughly 7m x 30m.

Based on the conceptual design and selected SOFC stacks, materials and key components of the balance of plant (BOP), the initial cost model of the 100 kW-level fuel cell system was established, shown in Fig. 14. In which the stack cost is 30.4% which is generally in the ballpark for stack cost percentage in a SOFC power generation system published by other fuel cell developers. However, the stack cost may be slightly higher in our system since we purchased the stacks from supplier and the labor cost for system assembly was counted in other cost rather than materials cost only. The heat exchanger is 7.9% and hotbox is 14.8% which expects to be reduced significantly since it was customized design and built with very small quantities.

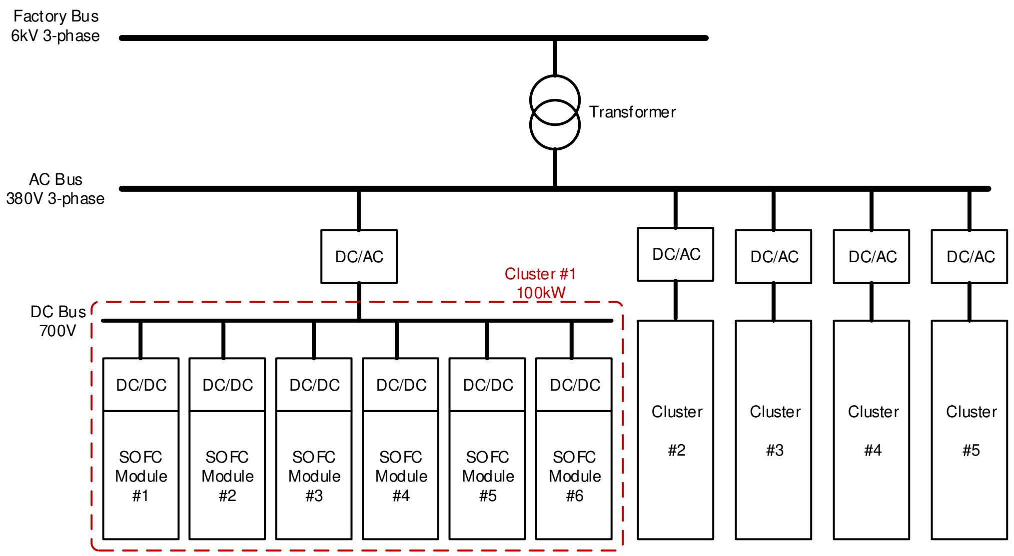


Fig. 12 500kW SOFC power generation system conceptual design which consists of 5 x 100 kW-level subsystem, and each subsystem consists of 5-6 SOFC modules which are electrically connected in parallel.

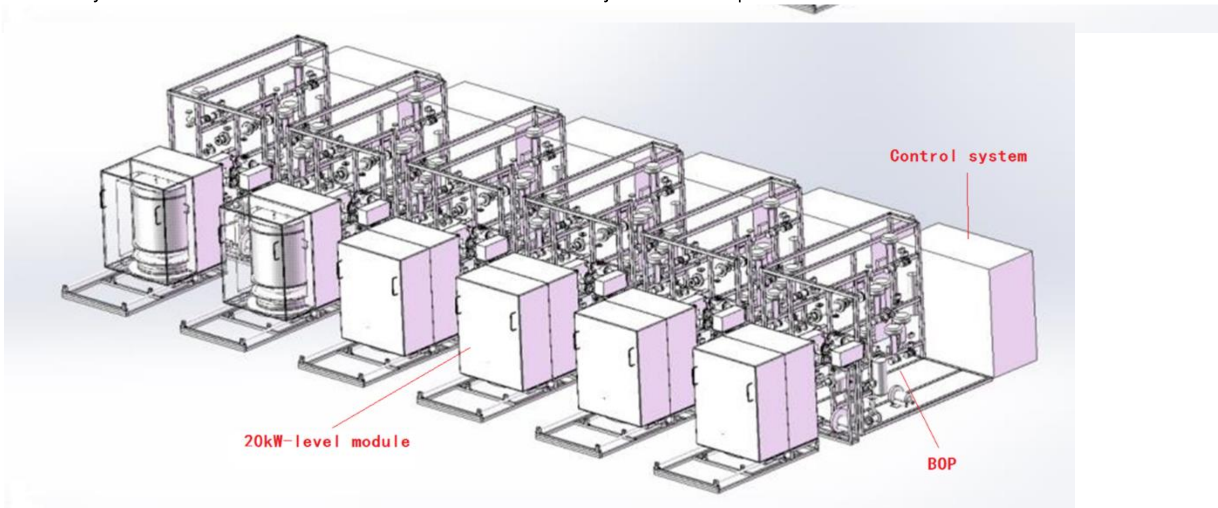


Fig. 13 100 kW-level SOFC power generation system conceptual design (consisting of 6 x 20kW modules for steady state operation)

With mass production, it will become standard product and the cost will be much lower. The major cost seems to be BOP related, such as gas pipe materials, gas flow and pressure control meters, fuel and air preheaters or burner during system start-up, heat exchangers during system steady state operation, blowers to transport exhaust fuel to oxygen-combustor to burn residual fuel to CO_2 and steam for CO_2 enrichment, and the labor cost for system assembly. Since it's a demonstration unit, the overall cost is higher. For commercial product, the system cost, including both materials and labor, can be reduced significantly.

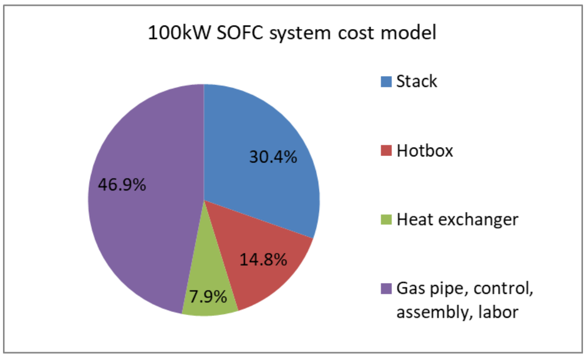


Fig. 14 Cost model of 100 kW-level SOFC system

4. Summary

(1) The economic analysis indicates that the advanced IGFC system (power degradation rate is 0.2%/1000hrs or lower) with CO_2 capture is competitive compared to SCPC, and its COE can be up to 20% lower than that of SCPC. The captured CO_2 can be stored or utilized through co-electrolysis with H_2O to produce syngas again to achieve fuel→electricity→waste→fuel cycle.

(2) Based on testing results, the SOFC stacks selected in this study shows good performance, consistency, and long term stability. Average stack ASR is about 0.31 ohm-cm^2 in hydrogen. Under preferred testing conditions, stack shows no noticeable degradation during more than 500 hours of long term durability test in both hydrogen fuel and coal syngas indicating long service life. When using syngas as fuel, H_2/CO and steam/CO ratio need to be well controlled to avoid carbon deposition inside of fuel pipe. H_2/CO ratio of 1.68 to 2.8 and steam/CO ratio of 1 are acceptable. When H_2/CO ratio is at the lower end, the mixing of steam with syngas is critical.

(3) 20kW SOFC power generation unit is being developed to verify technology feasibility, which consists of four stack towers and each stack tower consists of 4 x 1-1.5kW stacks, the power output of which depends on the fuel type and operation conditions. The maximum power output of the unit is 20kW when using syngas as fuel. The CFD simulation of 20kW module indicates that fuel flow is generally uniform among 16 stacks. Flow variation between stacks is less than ±5%. The 100 kW-level sub-system can be built by duplicating 5-6 x 20kW power generation units, and the MW_{th} IGFC demonstration system (total input energy is MW and power output is 500kW) will consist of 5x100 kW-level sub-systems.

(4) The design operation conditions of the 20kW power generation unit, 100 kW-level sub-system, and the MW_{th} IGFC demonstration system are current density of 250 mA/cm^2 (14.9kW power output for steady state operation) and 336 mA/cm^2 (maximum 20kW power output), respectively, fuel utilization of 80%, DC power efficiency of higher than 50%, stack inlet and outlet temperatures of 700°C and 800°C, respectively, DC voltage output from SOFC stack tower of higher than 171V. DC/DC booster may be required before DC/AC conversion.

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Nomenclature table

Acronym/ Symbol	Description	Unit
ASR	Area specific area	ohm·cm^2
BOP	Balance of plant	
CC	CO_2 capture	
CFD	Computational fluid dynamics	
CN	China	
CNY	China Yuan	
COE	Cost of electricity	CNY/MWh
DOE	Department of Energy	

Eff	Efficiency	%
QGESS	Quality guidelines for Energy system studies	
GT	Gas turbine	
HRSG	Heat recovery system generation	
IGCC	Integrated gasification combined cycle	
IGFC	Integrated gasification fuel cell	
j	Current density	A/cm^2
NETL	National Energy Technology laboratory	
OCV	Open circuit voltage	V
P	Power	W
PLC	Programmable logic controller	
SLPM	Standard liter per minute	
SCPC	Supercritical pulverized coal	
SOFC	Solid oxide fuel cell	
U_f	Fuel utilization	%
V	Voltage	V

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Figures

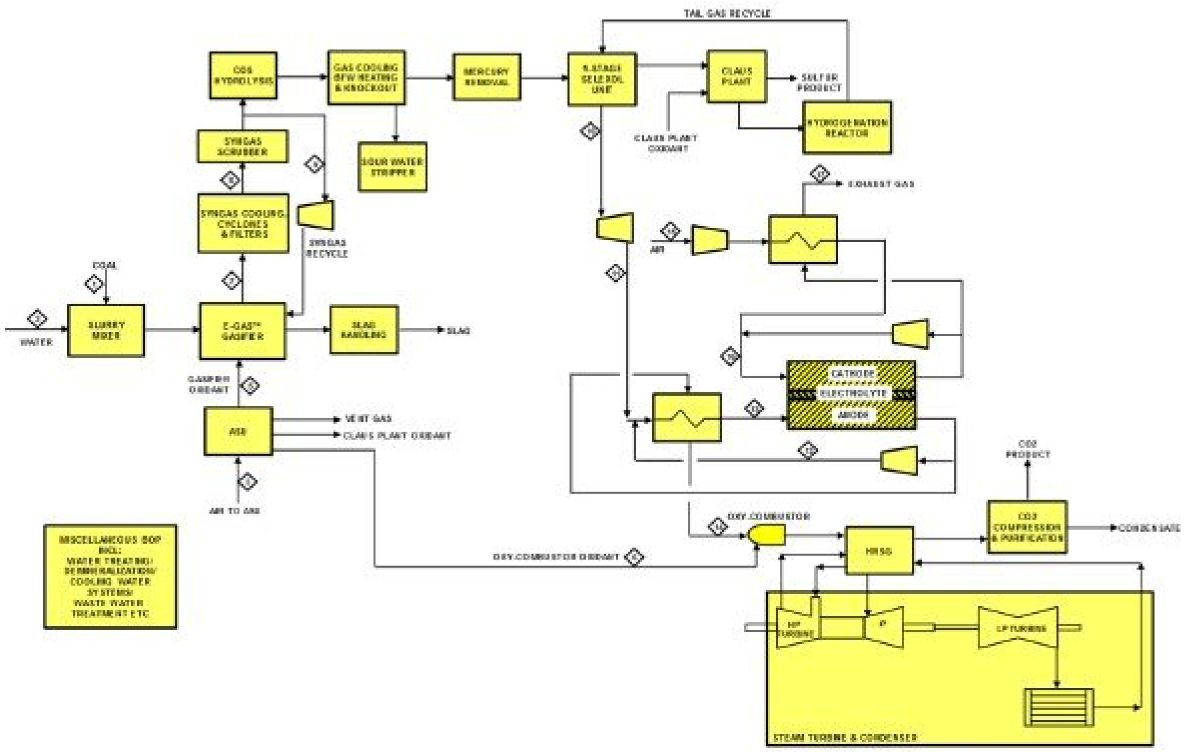


Figure 1

A typical IGFC system for economic analysis (from DOE/NETL report, 2014)

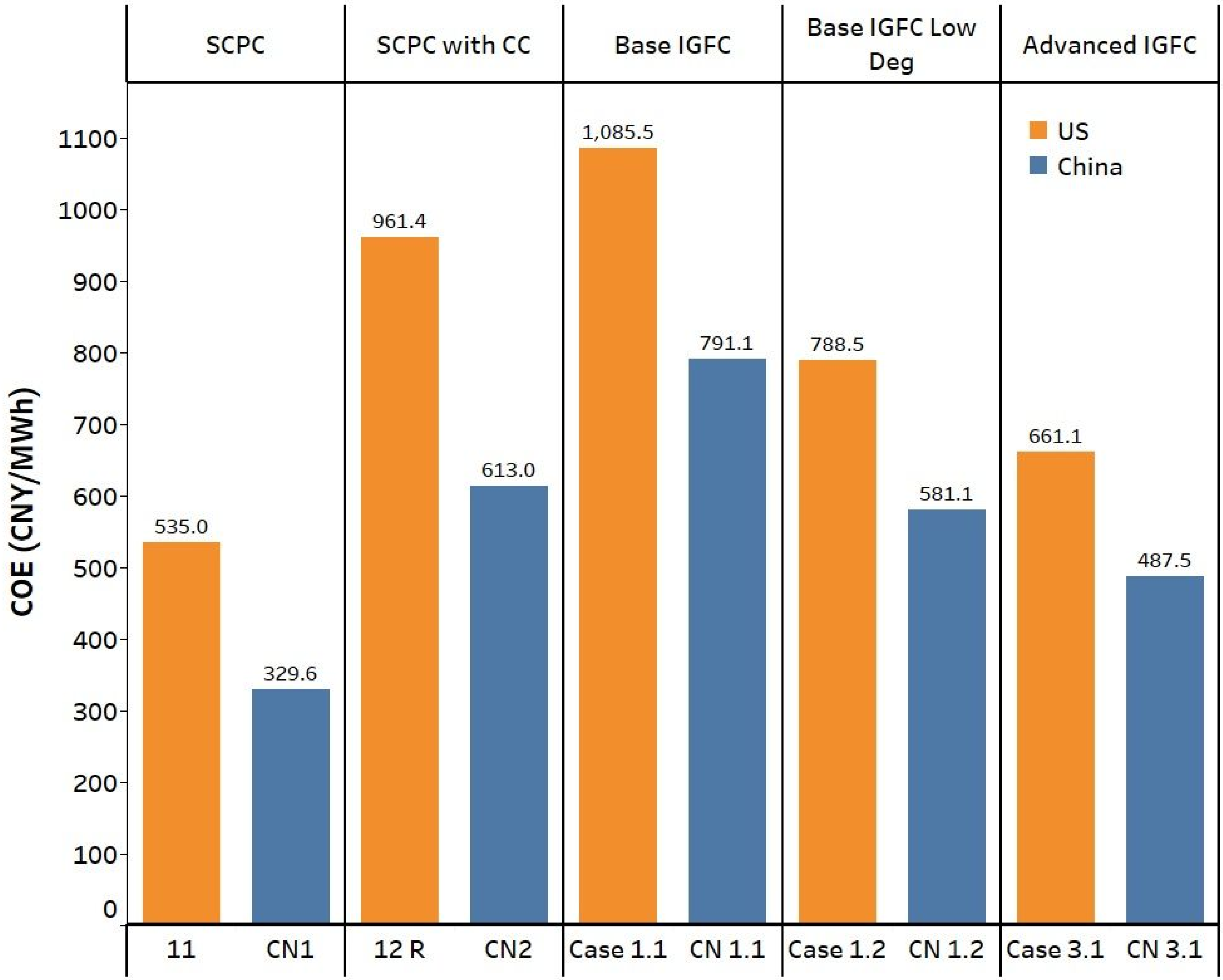


Figure 2

Cost of electricity (COE) of various IGFC systems cases as compared to SCPC without and with CO2 capture for US and China.

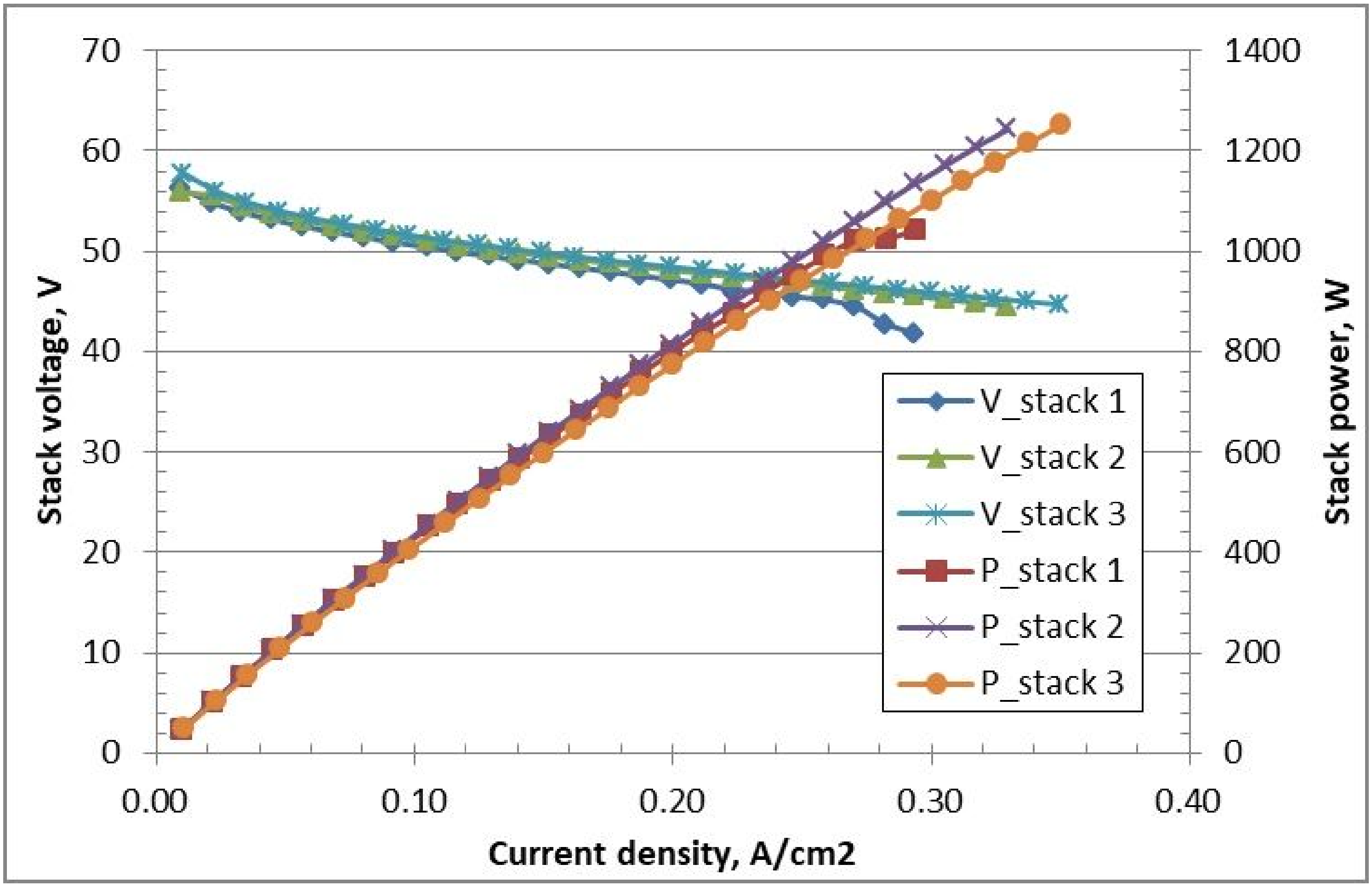


Figure 3

V-I curves of SOFC stack (fuel flow rate is 9.0S LPM for stack 1, 12.0 SLPM for stack 2, and 13 SLPM for stack 3)

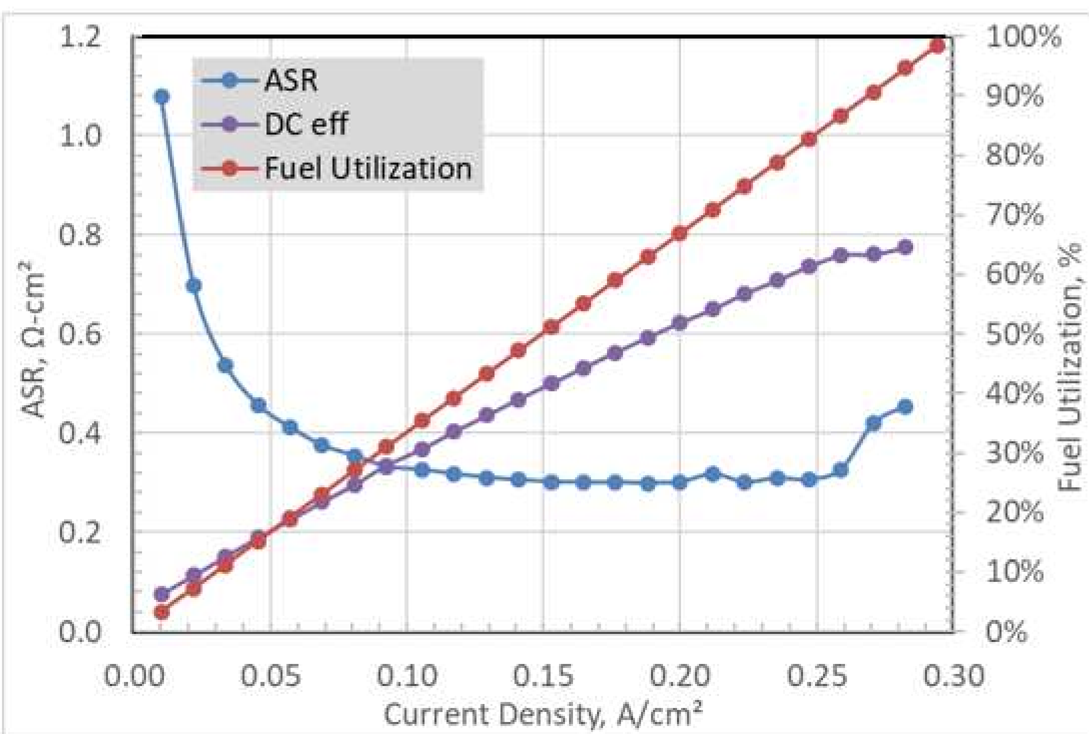


Figure 4

SOFC stack average ASR, DC power efficiency and fuel utilization vs. current density

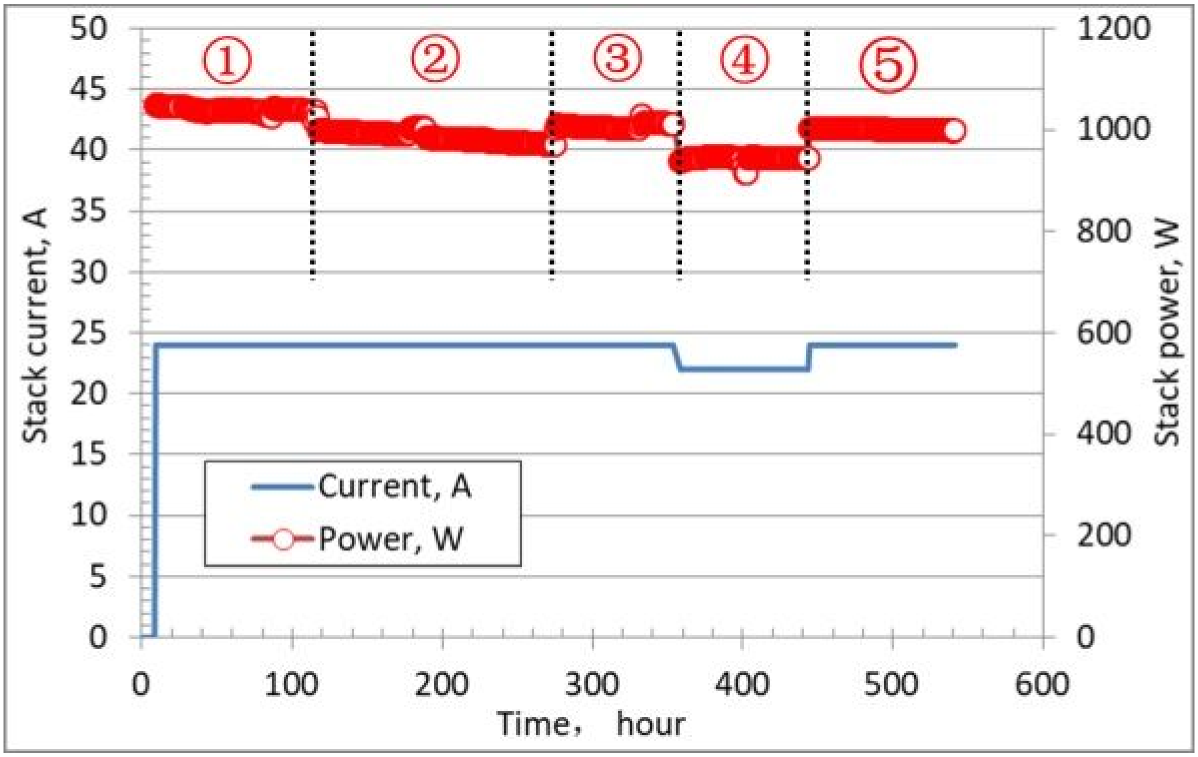
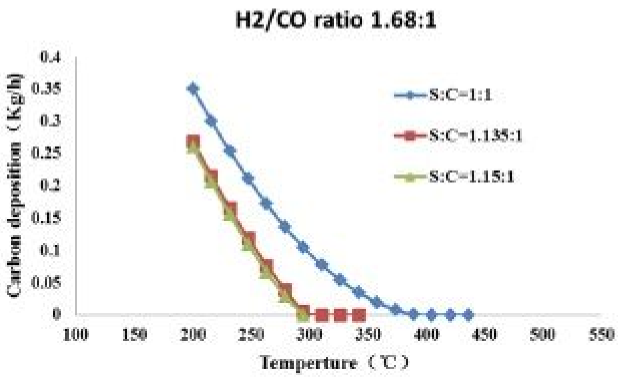
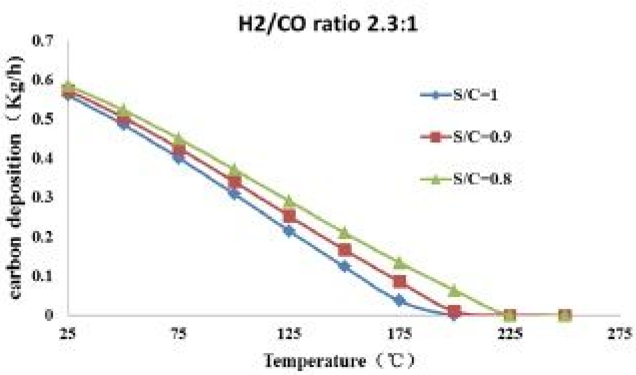


Figure 5

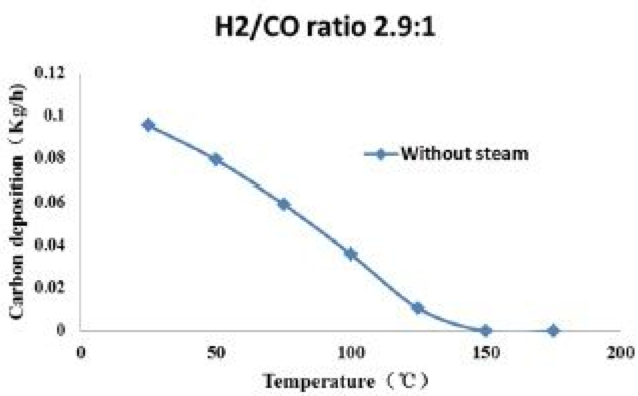
SOFC stack short term durability at 750oC



（a）H2/CO=1.68:1 (61.8%H_2, 37.7%CO)



(b) H2/CO=2.3:1 (69.7%H_2, 30.3%CO)



（c）H2/CO=2.9:1 (74.4%H_2, 25.6%CO)

Figure 6

(a) H2/CO=1.68 (61.8%H2, 37.7%CO). (b) H2/CO=2.3:1 (69.7%H2, 30.3%CO). (c) H2/CO=2.9:1 (74.4%H2, 25.6%CO)

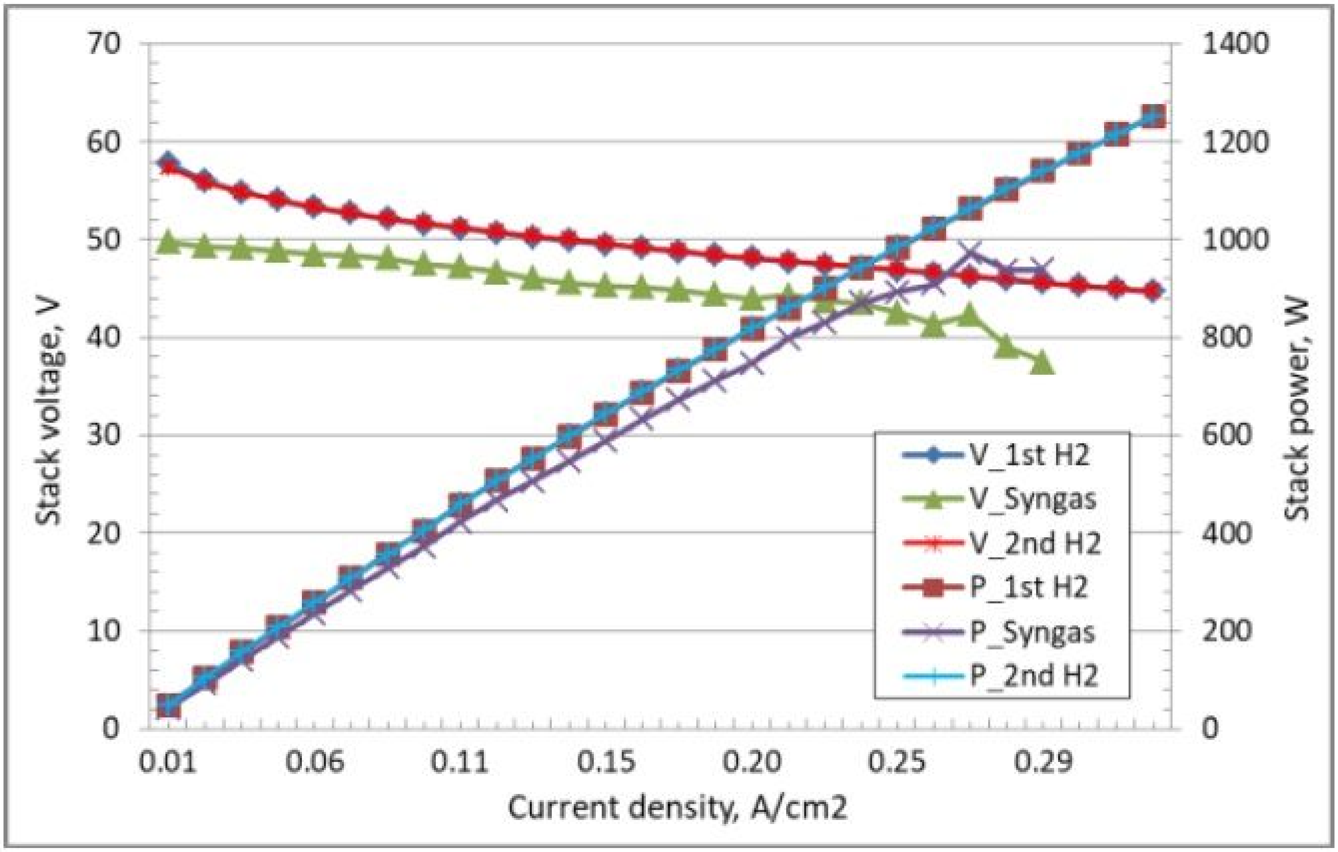


Figure 7

SOFC stack performance under H2 (flow rate: 13SLM) and simulated coal syngas (61.8%H2, 37.7%CO, flow rate:13 SLM with steam/CO ratio of 1.1)

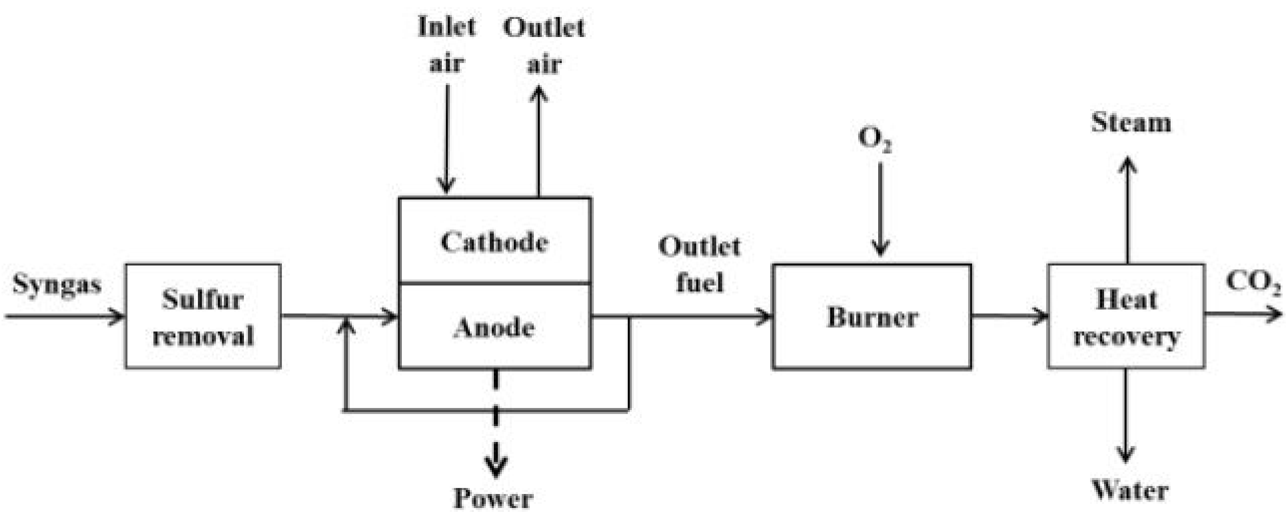


Figure 8

IGFC system flow chart using pipeline coal syngas

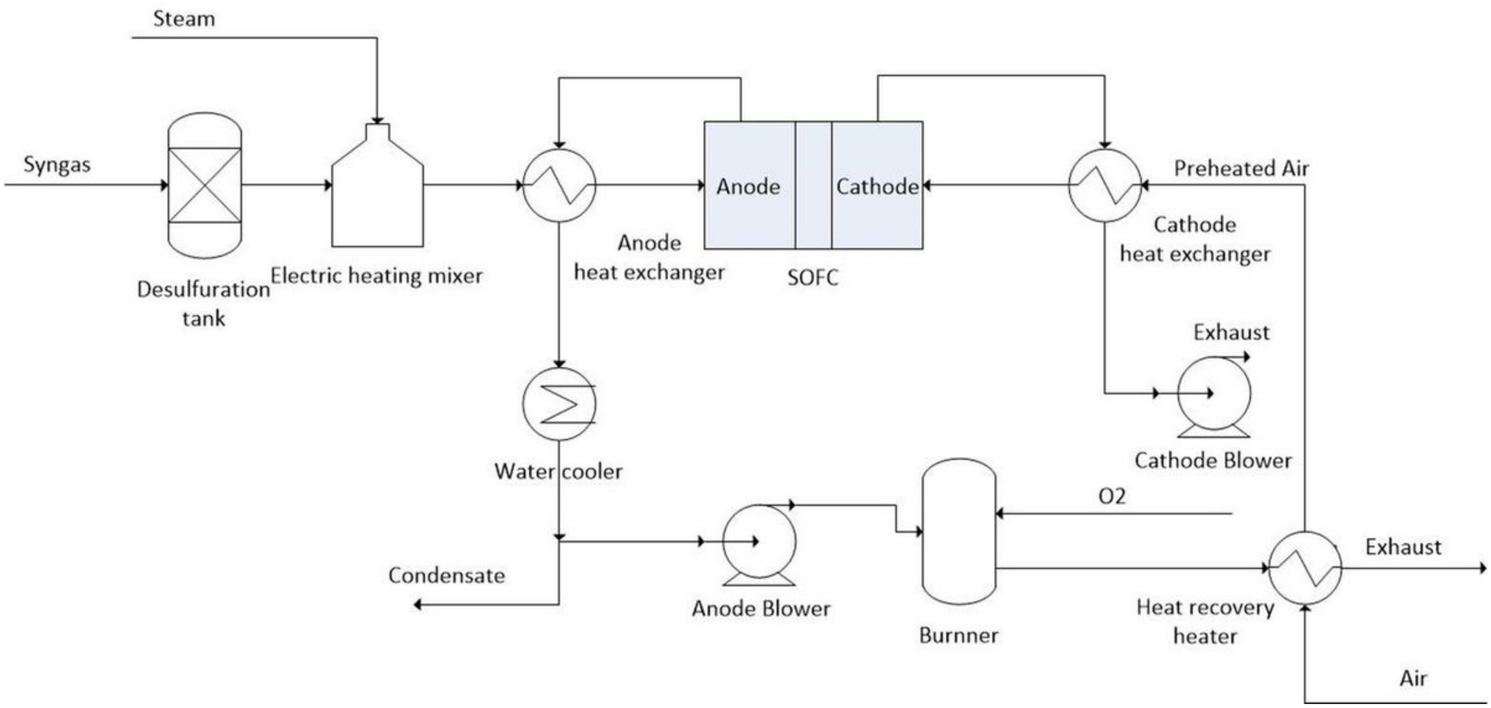
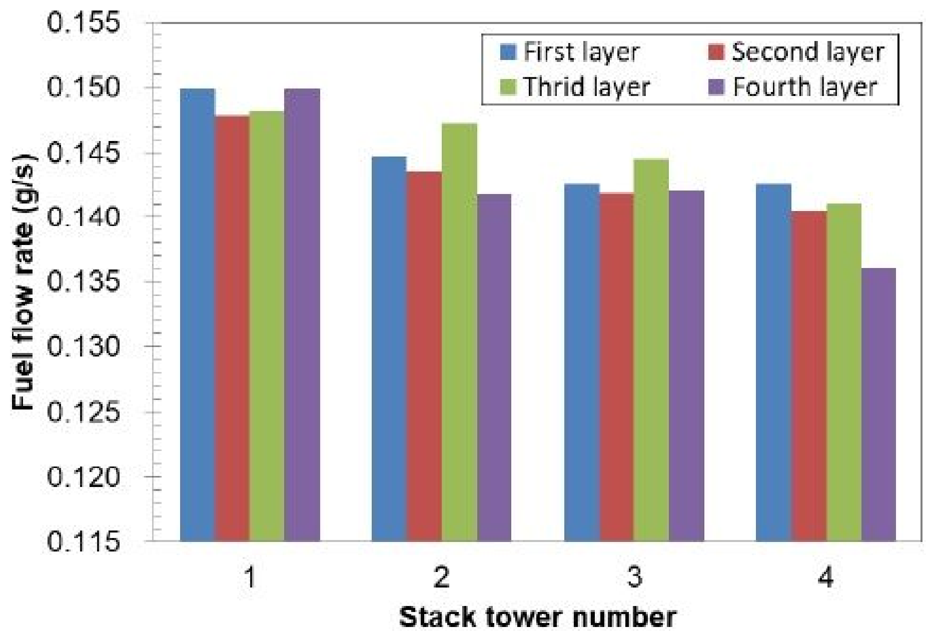
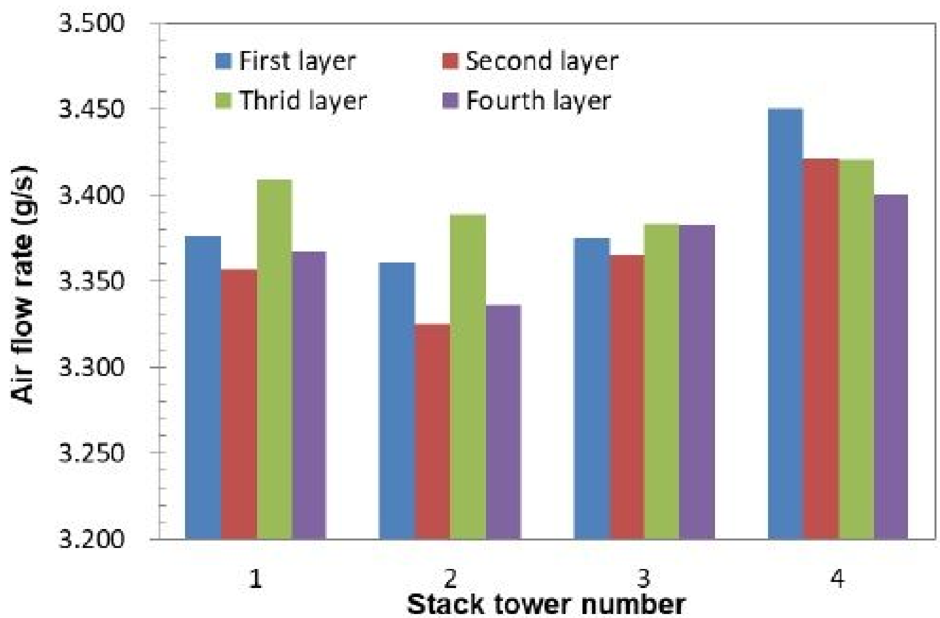


Figure 9

Process flow chart of the 20kW SOFC system



（a）Fuel flow distribution in SOFC stacks within 20kW module



（b）Air flow distribution in SOFC stacks of 20kW module

Figure 10

Gas flow distribution in SOFC stacks of 20kW module（a）Fuel flow distribution in SOFC stacks within 20kW module （b）Air flow distribution in SOFC stacks of 20kW \module .

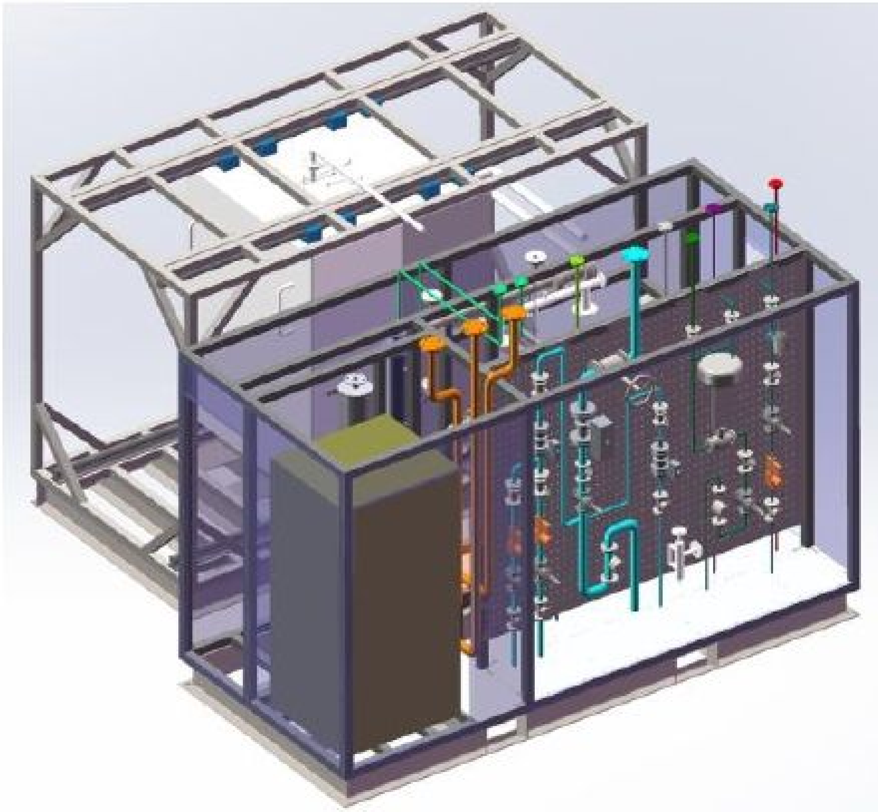


Figure 11

20kW SOFC power generation system being developed and constructed (1: hotbox with stack module, 2: control and data acquisition, 3: BOP)

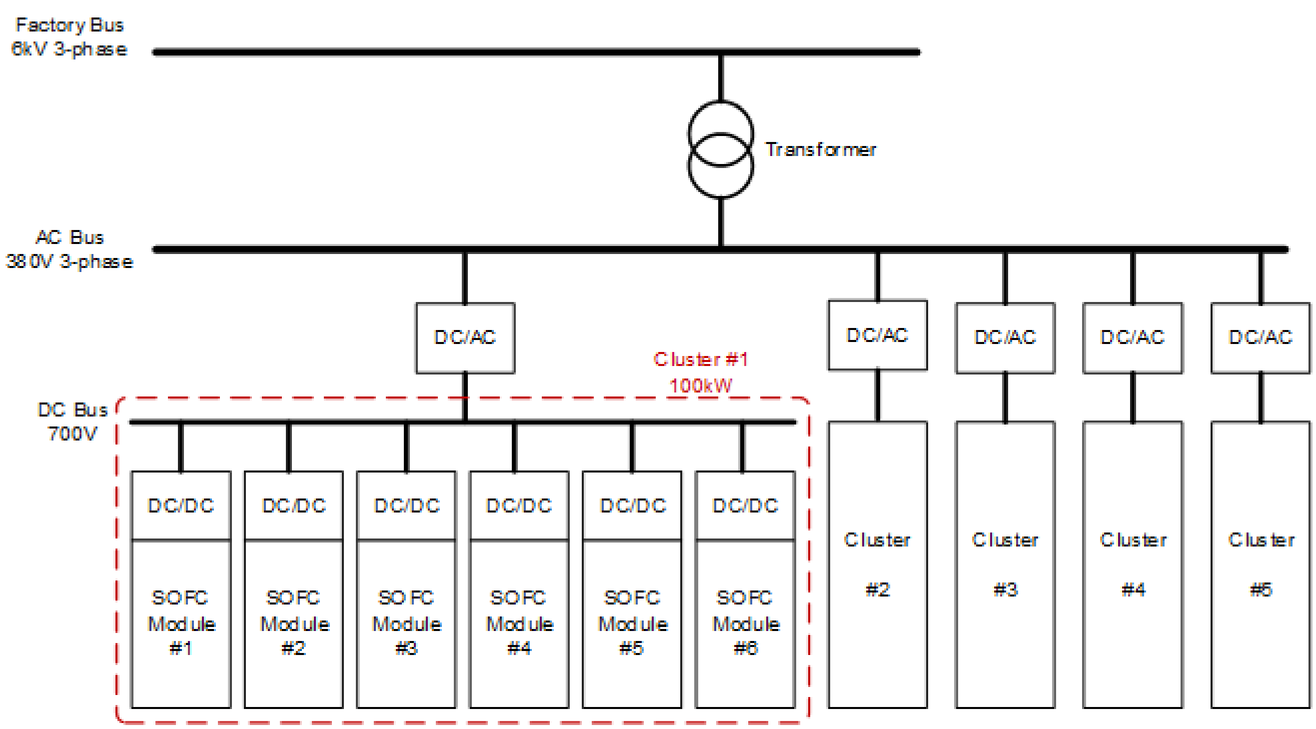


Figure 12

500kW SOFC power generation system conceptual design which consists of 5 x 100 kW-level subsystem, and each subsystem consists of 5-6 SOFC modules which are electrically connected in parallel.

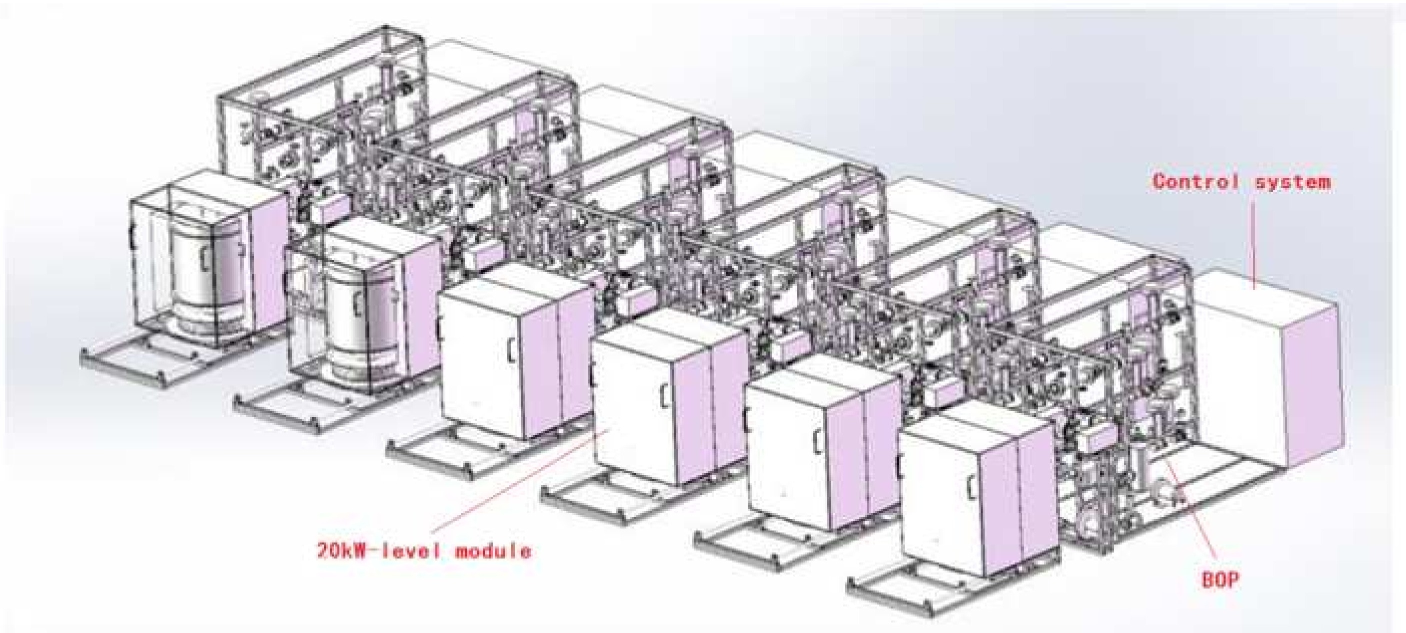


Figure 13

100 kW-level SOFC power generation system conceptual design (consisting of 6 x 20kW modules for steady state operation)

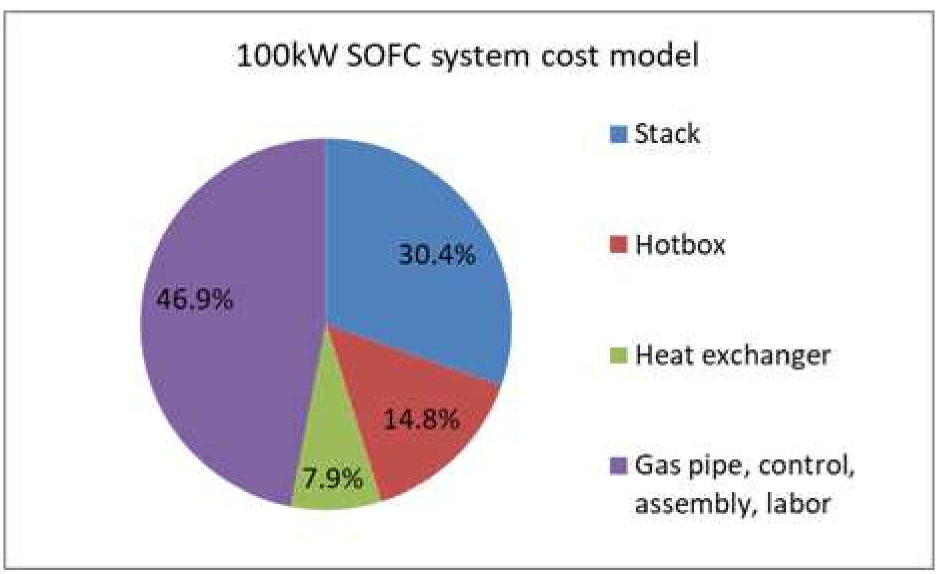


Figure 14

Cost model of 100 kW-level SOFC system