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Performance test of a 5 kW solid oxide fuel cell system under high fuel utilization with industrial fuel gas feeding

Ming Xu[1] · Hanlin Wang[1] · Mingxian Liu[2] · Jianning Zhao[3] · Yuqiong Zhang[2] · Pingping Li[1] · Mingliang Shi[2] · Siqi Gong[1] · Zhaohuan Zhang[1] · Chufu Li[1]

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Abstract As the demand for green energy with high efficiency and low carbon dioxide (CO_2) emissions has increased, solid oxide fuel cells (SOFCs) have been intensively developed in recent years. Integrated gasification fuel cells (IGFCs) in particular show potential for large-scale power generation to further increase system efficiency. Thus, for commercial application of IGFCs, it is important to design reliable multi-stacks for large systems that show long-term stability and practical fuel gas for application to industrial equipment. In this work, a test rig (of a 5 kW SOFC system, with syngas from industrial gasifiers as fuel) was fabricated and subjected to long-term tests under high fuel utilization to investigate its performance. The maximum steady output power of the system was 5700 W using hydrogen and 5660 W using syngas and the maximum steady electrical efficiency was 61.24% while the fuel utilization efficiency was 89.25%. The test lasted for more than 500 h as the fuel utilization efficiency was larger than 83%. The performances of each stack tower were almost identical at both the initial stage and after long-term operation. After 500 h operation, the performances of the stack towers decreased only slightly under lower current and showed almost no change under high current. These results demonstrate the reliability of the multi-stack design and the prospect of this SOFC power-generation system for further enlarging its application in a MW_{th} demonstration.

Keywords Solid oxide fuel cell (SOFC) · Integration gasification with fuel cell (IGFC) · Gasification · Stack tower

1 Introduction

As the demand for green energy with high efficiency and low carbon dioxide (CO_2) emissions has increased, solid oxide fuel cells (SOFCs) have become an attractive technology (Choudhury et al. 2013) The advantages of such cells include the fact that a variety of fuels and electrolyte materials can be used and they show high electrical efficiency, full utility of heat and quiet operation (Secanell et al. 2011). They have an electrical efficiency of about 60% under normal operation and up to 90% when combining heat and power operation (Ud et al. 2016). They can also be integrated with another power-generation source, as well as water heating and cooling devices used in residential homes (Sadeghi et al. 2015). To expand their application to a large scale, their integration with gasification systems using coal or biomass as feedstock shows potential (Moosavian et al. 2013; Radenahmad et al. 2020; Subotic et al. 2019); of particular interest are integrated gasification fuel cells (IGFCs).

Most studies on SOFCs have focused on materials for the development of the anode, electrolyte and cathode as well as performance tests (Hossain et al. 2017; Radenahmad et al. 2016). Cells have continually been studied to improve their chemical stability and electrochemical performance. SOFC stacks consisting of multi-layer cells are starting to receive more attention to widen the application

✉ Chufu Li
chufu.li@chnenergy.com.cn

[1] National Institute of Clean-and-Low-Carbon Energy, Beijing 102209, China

[2] Shenhua New Energy Company, Ltd, Beijing 100007, China

[3] Coal To Oil Branch Company, Ningxia Coal Industry Group, Yinchuan 750411, China

of SOFCs, although few studies have been conducted to date. Lim et al. fabricated and characterized a flat, anode-supported, tubular SOFC stack that operates at an intermediate temperature and reported a maximum power of nearly 921 W at 750 °C using hydrogen ($H_{2)}$ (fuel utilization ratio = 25.2%) (Lim et al. 2010). Fang et al. conducted durability tests and investigated degradation behavior of a 2.5 kW SOFC stack with internal reforming of LNG (Fang et al. 2013). They also tested two stacks of different designs under high fuel utilization of up to 90% using humidified hydrogen or 10% pre-reformed LNG as fuel and found that high fuel utilization introduced polarization and a high risk of fuel starvation (Fang et al. 2015). The fuel utilization ratio of their system was 64%–80%, mostly about 70%, while the feeding fuels of the anode side were H_2 or simulated reformate gas and the stability test was is more than 5000 h under 700 °C. The Edison R&D center built a 5 kW SOFC system and conducted a life test for 1500 h at a fixed power output of 1500 W over four start-up/shutdown cycles and the system power was up to 3000 W during the first test sessions (Barrera et al. 2008).

Studies have also explored the combination of SOFCs with gasification to widen their application to more fields. A pressurized 5 kW anode-supported planar SOFC power-generation system was constructed with a pre-former for a fuel cell/gas turbine hybrid system (Lim et al. 2008). The output was 4.7 kW using the preformed gas, but increased to 5.1 kW at 3.5 atm. Modelling of a common SOFC–gas hybrid turbine system illustrated a significant increase in efficiency, with an electrical efficiency of up to 50% and better syngas utilization compared to the implementation of each single technology (Bang-Moller et al. 2010). Subotic et al. (2019) discussed the applicability of SOFC technology for coupling with biomass-gasifier systems, using single commercial SOFCs of industrial size fueled with different representative producer gas compositions of industrial relevance at two relevant operating temperatures. The results showed that feeding the SOFC with a producer gas from a downdraft gasifier, at an operating temperature of 750 °C represented the most favorable setting, considering system integration and the highest fuel utilization.

However, there are few commercial SOFC stacks available on the market. To demonstrate an SOFC power-generation system at the MW scale, hundreds of stacks should be well assembled and the fuel gas must be distribute to each stack to prevent fuel starvation. When coupled with gasification, the long-term durability of such stacks should be tested, as most research has used simulated gas.

To address these issues, in this study, we fabricated a test rig (of a 5 kW SOFC system, with syngas from industrial gasifiers as fuel) to explore the feasibility of a MW class IGFC. As syngas was used as fuel for the anode side, it could lead to fast degradation due to impurities such as hydrogen sulfide or tars as well as coke deposition (Lebreton et al. 2015; Cavalli et al. 2018; Ricoul et al. 2018; Aravind et al. 2008). Thus, a long-term test using industrial syngas under high fuel utilization was conducted to investigate the influence of syngas on the performance of the stacks.

2 Experimentals

2.1 Test rig

Our test rig is shown in Fig. 1. It consists mainly of two parts, a fuel gas supply system and a hotbox (Fig. 2). The supply system provides H_2, syngas, N_2 and stream for the anode of the stacks and air for the cathode. The hotbox consists of a heating furnace and four SOFC stacks assembled in parallel in a heating furnace. The nominal power of the SOFC stack is designed to be about 1 kW for syngas and H_2. The test rig was operated at a oil synthesis plant of the Ningmei Coal to Liquid Company in Ningxia Province and all of the fuels were provided by industrial equipment. The current of stacks were adjusted with two ITEC IT8904 electronic loads.

In the hotbox, four SOFC stacks were divided into two groups (i.e., two stack towers) and two stacks of each stack tower shared one gas distributor. For both the anode and cathode side, two branches of feeder fueling gas connected with the inlet of each distributor. The tail gases were collected into the outlet of the distributor and released out of the heating furnace. The heating furnace had four heating walls and the temperature was controlled at a precision of 1 °C. The current and power of each stack tower was controlled using an electronic load.

Fig. 1 Photo of the test rig

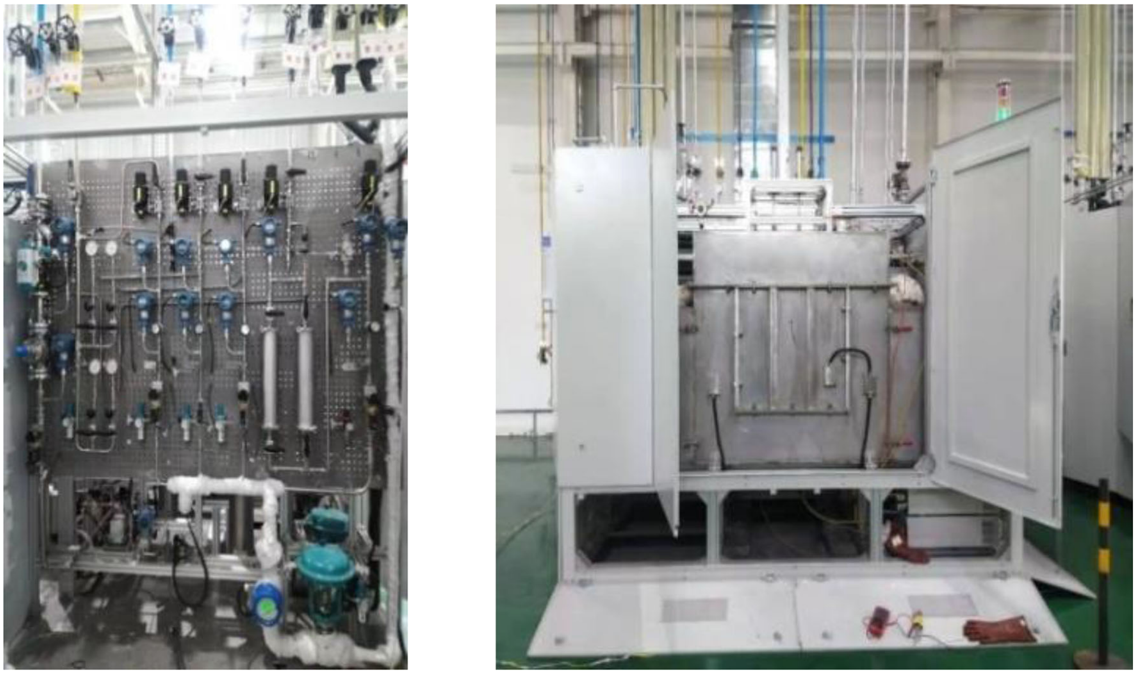

Fig. 2 Photos of the fuel gas supply system and the hotbox

2.2 Test methods

A schematic of the experimental setup is shown in Fig. 3. H_2 and syngas from 4 million tons/a coal-to-liquid (CTL) industrial plant were used as fuel gas supplied to the anode side. Practical stream was added to syngas and its molar flow rate was equal to CO in the syngas to prevent coke deposition. Nitrogen was used as an inert gas for the anode side. The air used as an oxidant for the cathode was also provided by the CTL plant. The flow rates of the gases were controlled using mass flow controllers. The purity of hydrogen was 99.9% and the components of syngas are listed in Table 1. The syngas was desulfurized before entering the stacks.

Table 1 Components of syngas used for the anode side

Component	H_2	CO	N_2	CH_4	Ar
Weight (mol%)	61.774	36.711	1.125	0.372	0.018

Note: CO: carbon monoxide; $N_{2:}$ nitrogen; CH_4: methane; Ar: argon.

As the stacks have been reduced before experimental, a mixture of nitrogen and hydrogen is used as shielding gas for the anode side while air is also used for the cathode side at the start up stage after the stacks were assembled. The inlet pressure of the shielding gas and air were regulated with pressure-control valves and the inlet temperature was controlled using pre-heaters. To save energy, the tail gas

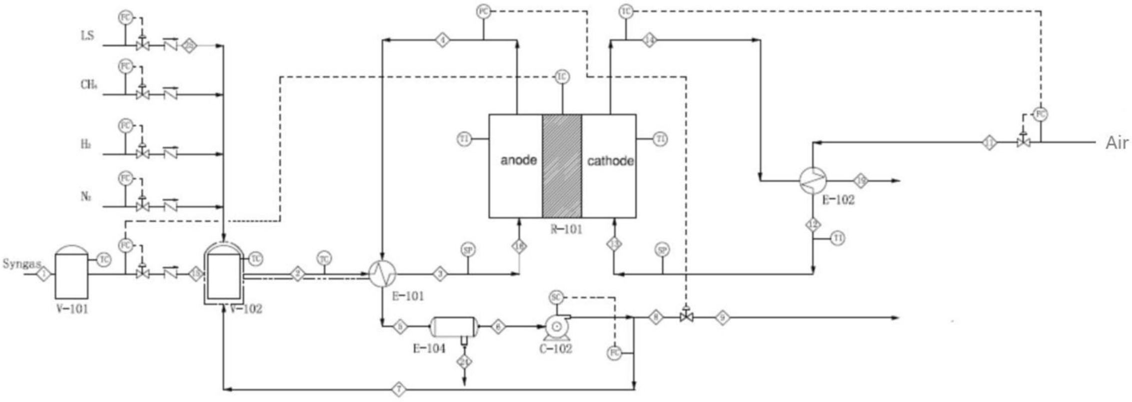

Fig. 3 Schematic of experimental setup

flowing out of the stacks transferred heat to the feeding gas flowing into the stacks via a high-temperature heat exchanger. The increasing rate of stacks temperature was controlled within 30 °C/h. As the system temperature increased, the flow rate of cooling water of the secondary heat exchanger was regulated to maintain the temperature of the tail gas out of the system and fans were used to maintain the system pressure. When the temperature of the stacks reached the working temperature, it was maintained for 1 h and the shielding gas was shifted to fuel gas. During the test, the current was increased to produce more heat. Thus, the flow rate of air was also modified to keep the system temperature stable. As no previous experiments using syngas as the fuel gas for stacks before, test of hydrogen was performed initially and then hydrogen was changed to syngas. In both cases, the furnace was operated at 770 °C.

3 Results and discussion

3.1 Performance verification of stack tower design

As the power-generation system consists of two stack towers and each tower consists of two stacks, the feasibility of the stack tower design was first assessed. As shown in Fig. 4, according to the curves of I–V and I–P, the average open circuit voltage (OCV) was 62.35 V and this decreased to 41.89 V when the current increased to 34 A. The system power reached the target value (i.e., 5 kW) when the current was 29 A. The consistency between the two stack towers was characterized according to the electronic load data of each stack tower, as shown in Fig. 5. The voltage and power of each stack tower under the same current was almost the same for the entire test range. As shown in Fig. 6, the area specific resistance (ASR) of the system stabilized at about 0.35 Ω cm^2 as the current density increased up to 200 mA/cm^2 The maximum current density was about 350 mA/cm^2 and the fuel utilization was greater than 90%. These data indicate that the stack design performed reliably.

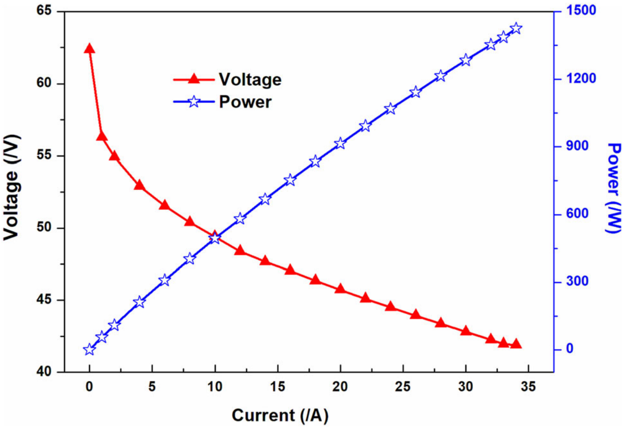

Fig. 4 Average performance of multi-stacks

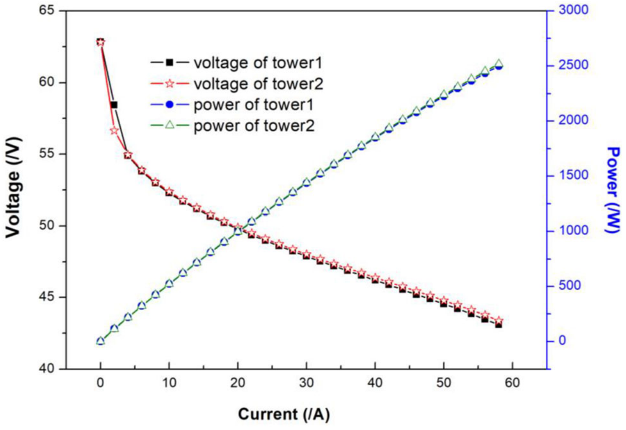

Fig. 5 Performance comparison of two stack towers

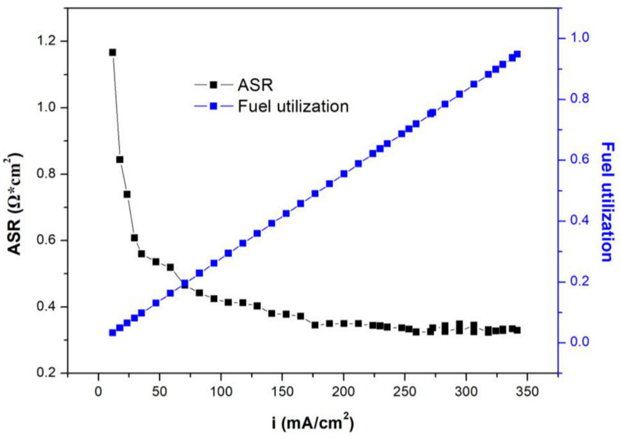

Fig. 6 ASR of the test rig

3.2 Performance results of a long-term test

A long-term performance test using hydrogen and syngas as fuel was conducted. The result for hydrogen are shown in Fig. 7. As the fuel flow rate increased, the output power increased from 3700 to 5700 W. The operation data were very stable with few fluctuations.

The results for syngas are shown in Fig. 8. As the fuel flow rate increased, the output power increased from 4500 to 5600 W. The currents under different scenarios were very stable while there were fluctuations in the output power. These were caused by fluctuations in the feeding stream flow rate as the pressure of the stream from the plant was not very stable.

The long-term performance test lasted about 600 h and an overview of the results is presented in Fig. 9. Ten

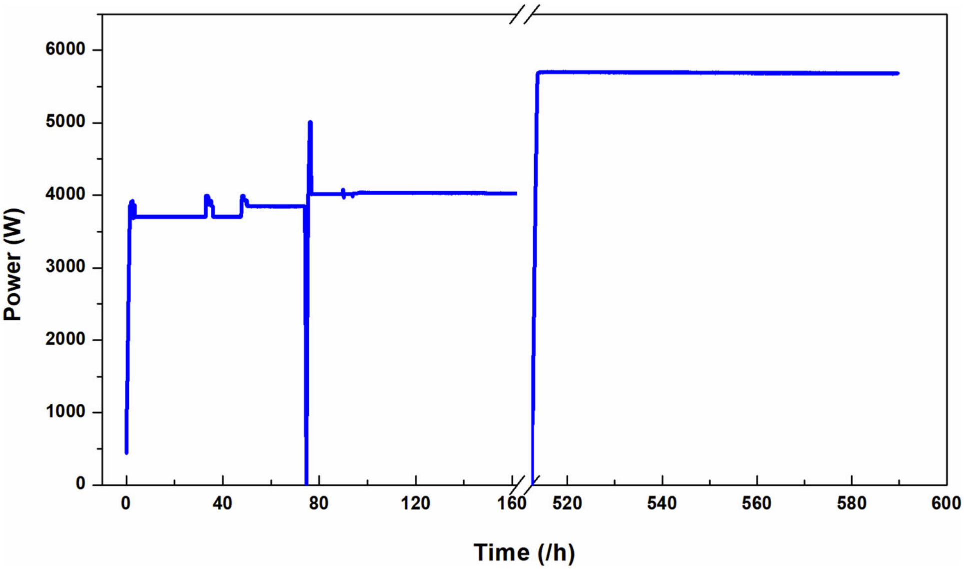

Fig. 7 System performance using H_2 as feeder fuel

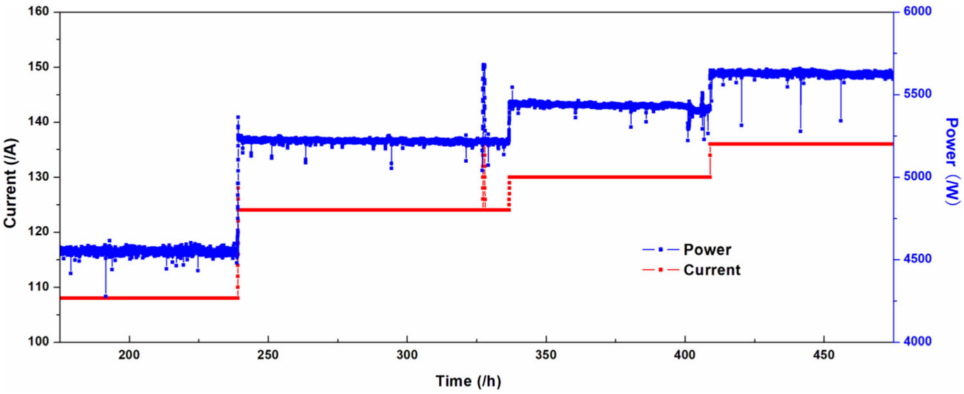

Fig. 8 System performance using syngas as feeder fuel

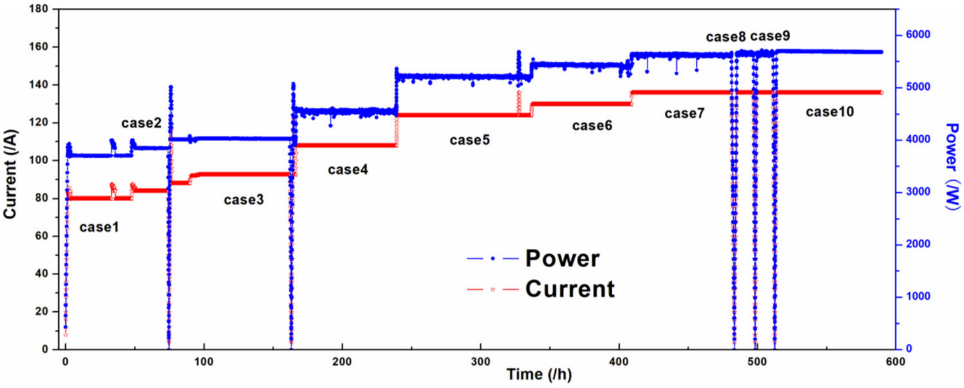

Fig. 9 Overview of long-term performance test results

different feeding conditions were applied and the data are listed in Table 2. Electrical efficiency E_f was calculated considering the input heat of fuels Q_{in} and output electric power P_{out} as $E_f = P_{out}/Q_{in}$. Fuel utilization efficiency U_f was calculated using the following equation:

Table 2 Feeding conditions and the results of E_f and U_f

Case	H_2 flow rate (slm)	Syngas flow rate (slm)	H_2/CO ratio	Current (A)	Power (W)	E_f (%)	U_f (%)
1	52	–	–	80	3700	43.25	59.70
2	40	–	–	84	3840	58.35	81.49
3	40	–	–	92	4030	61.24	89.25
4	–	47.5	3.04	108	4560	56.15	88.22
5	–	57.67	3.13	124	5220	52.98	83.43
6	–	60.5	3.13	130	5430	52.53	83.38
7	–	62.5	3.13	136	5630	52.73	84.43
8	–	62	2.53	136	5660	53.11	85.12
9	–	62.75	3.36	136	5660	52.90	84.10
10	61.9	–	–	136	5700	55.95	85.23

$U_f = I/[N_{\text{fuel}} \cdot F \cdot 2(x_{H_2} + x_{\text{co}})]$, where I is the current, F is the Faraday constant and x is the fraction of fuel.

First, hydrogen was used as a feeder fuel to start the system at a low fuel utilization level. Once the system reached stable operation, the fuel flow rate was increased and the current was increased accordingly to keep the fuel utilization efficiency above 80%. At this point, the system was operated for 500 h. When using syngas as the feeder fuel, the ratio of H_2/CO was adjusted to investigate its influence on system performance. As shown in Table 2, the maximum electrical efficiency was up to 61.24% and the corresponding fuel utilization efficiency was 89.25% during steady operation with hydrogen feeding. When using syngas, the maximum electrical efficiency was up to 56.15% and the corresponding fuel utilization efficiency was 88.22%. The maximum output power during steady operation was 5700 W for hydrogen and 5660 W for syngas, while the electrical efficiency for hydrogen was about 2% greater than that for syngas. No obvious influence of the H_2/CO ratio was found in the experiment; the operation time may have been too short and this should be further investigated.

Performance comparison of stack tower 1 of initial stage and after 500 h operation is shown in Fig. 10. The voltage and power decreased slightly at low current after 500 h of operation compared to its initial stage, while the performance was almost the same as initially when the current was increased above 50 A. The results for stack tower 2 shown in Fig. 11 illustrate a similar tendency. As shown in Fig. 12, a comparison of the two stack towers after 500 h of operation shows almost the same performance, with only a slight difference when the current was greater than 60 A. The results also illustrate the long-term stability of stack towers and the whole system.

4 Conclusions

A test rig (of a 5 kW SOFC system, with syngas from industrial gasifiers as fuel) was fabricated and subjected to long-term tests under high fuel utilization to investigate its

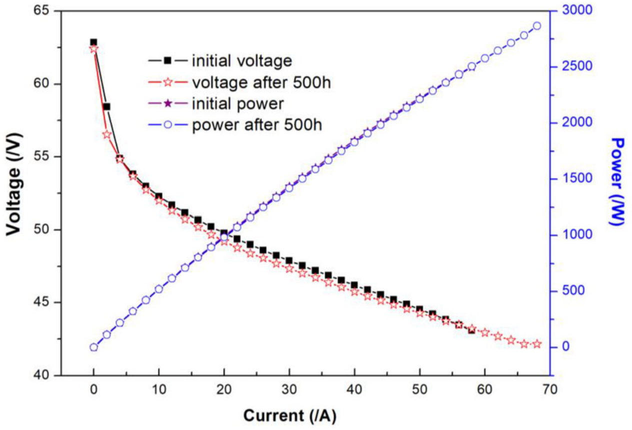

Fig. 10 Performance of stack tower 1 for 500 h of operation

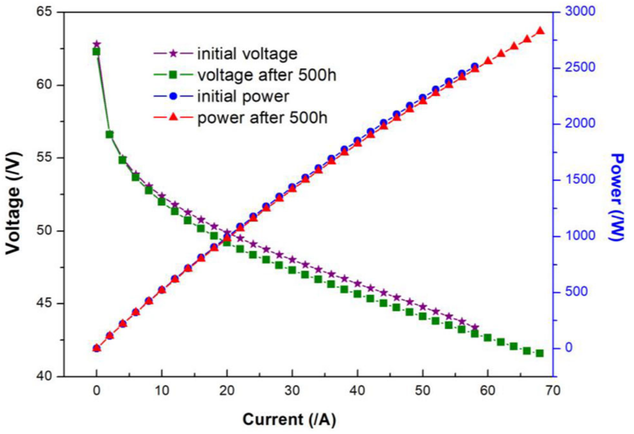

Fig. 11 Performance of stack tower 2 for 500 h of operation

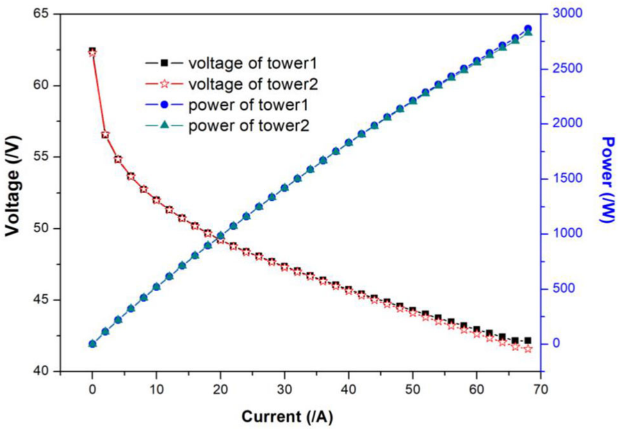

Fig. 12 Performance comparison of stack towers 1 and 2 after 500 h of operation

performance. The maximum steady output power was 5700 W when using hydrogen and 5660 W when using syngas and the maximum steady electrical efficiency was 61.24% while the fuel utilization efficiency was 89.25%. The fuel utilization efficiency larger than 83% lasted for more than 500 h. The mean performance of the stack towers was better than that of either stack alone and the performances of each tower were almost identical. After 500 h operation, the performances of both towers decreased only slightly under lower current and almost did not change under higher current. These results illustrate the reliability of the multi-stack design and the potential of the SOFC power-generation system in further enlarging its application for a MW_{th} demonstration.

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