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SOFC system integration activities in NIMTE

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Abstract

The fast depletion of fossil fuel resources and the environmental pollution are the major issues caused by the abundant use of fossil fuels. These issues have led to the exploration of alternative energy conversion systems. Solid Oxide Fuel Cell (SOFC) system has the advantages such as low to zero emissions during operation, flexibility of operation and ease of integration with other systems. Therefore, developing and commercializing a SOFC system attracts much interest.

In China, the biggest SOFC program currently is run by Ningbo Institute of Materials Technology and Engineering (NIMTE), Chinese Academy of Sciences (CAS). In this paper, current status of SOFC system integration in NIMTE is summarized. To accomplish the integration of SOFC system, various BOP components have been developed and manufactured including porous media combustor, reformer, vaporizer, heat exchanger and power electronics. Many efforts have been done to increase the system's performance. The water to methane ratio is an important parameter that affects the reformer's performance. By modifying the vaporizer's structure and controlling its overall heat transfer coefficient, we successfully stabilized the steam supply. A compact methane reformer powered by porous media burner was also manufactured and its performance was investigated. This reformer contains an annulated column metal monolith catalyst in which a porous media is placed inside. Natural gas is burned in the porous media to power the steam reforming of methane that reacts in the metal monolith catalyst. In the annulated column metal monolith catalyst, active component Ni was coated on the metal surface which was used to catalyse the steam reforming reaction. A series of experiments was carried out and results showed that this reformer can work stably and effectively to provide hydrogen for the SOFC system.

With our mass-produced anode-supported SOFC stacks, we have developed a 1kw class and a 5kw class SOFC system for stationary power generation. Both 2 systems use nature gas as fuel. And the calculated power generation efficiency is about 40%. Optimization and a thermally self-sustaining system are still undergoing by improving the structure of heat zone and control strategy. Our target is integrating a 100KW system in the next 5 years.

Introduction

Solid oxide fuel cell (SOFC) was received more and more attention because of its high efficiency, non-pollution and fuel flexibility and was regarded as a promising power generation method in 21st century.

The biggest SOFC program team was built up in Ningbo Institute of Materials Technology and Engineering (NIMTE), Chinese Academy of Sciences (CAS) and there are over 100 full-time staffs in this team. Various BOP components such as porous media combustor, reformer, vaporizer and heat exchanger were developed to integrate SOFC system.

Now we have developed necessary BOP components and a series of experiments were carried out to confirm their performance. We have built up a 1kW-scale and a 5kW-scale SOFC system for stationary power generation based on natural gas supply and the calculated power generation efficiency is about 40%. In future we will go on optimizing the SOFC system in term of a thermally self-sustaining function by improving the structure of stack zone and control strategy. Our following task focus on a 100KW system in the next 5 years.

1. Development of BOP components and stacks

1.1 Porous media combustor

In SOFC system, the self-designed porous media combustor was used to provide heat energy for some processes such as steam reforming reaction of natural gas, vaporization and heating hot area. The porous media combustor contains a pre-mixed chamber and a combustion chamber. Fuel and air were pre-mixed in the chamber before they enter the combustion chamber in which the porous media such as SiC was put inside. This porous media combustor has some advantages[1] such as high power density, stable flame and low NO_x emission etc. Fig.1 shows the porous media combustor and Fig.2 shows the temperature uniformity test results. In the temperature uniformity test of the porous media combustor, 5 thermocouples were distributed uniformly from top to bottom and data was collected by software. The test results showed that temperature uniformity is good in the porous media combustor that will facilitate the steam reforming of natural gas.

Fig.1 Self-designed porous media combustor

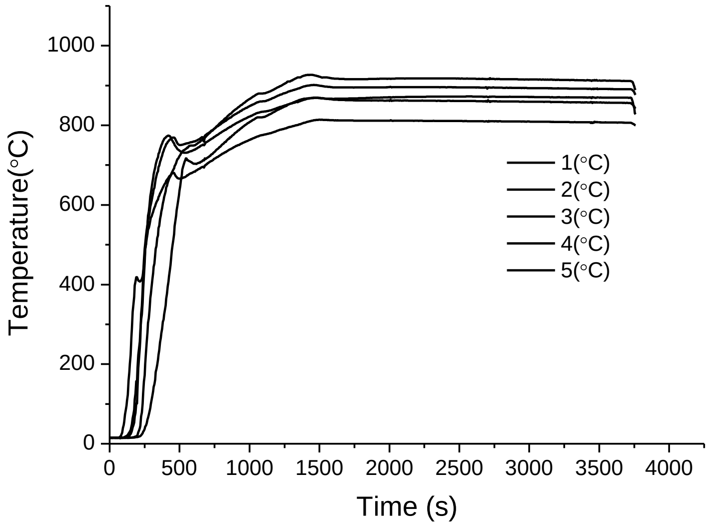

Fig.2 Temperature uniformity test of porous media combustor

1.2 Vaporizer

In steam reforming reaction of natural gas, the natural gas and water are heated up before being introduced to the reformer. The vaporizer was manufactured to vaporize the feed water and to preheat the natural gas. The vaporizer includes a porous media combustor and some coil pipes. By absorbing the energy of the high temperature flue gas from the porous media combustor, the water was vaporized and the natural gas was preheated to a suitable temperature. Natural gas (mainly methane) was used as fuel of combustor. The vaporizer was shown in Fig.3.

Fig. 3 Self-designed vaporizer

Vaporization of water was implemented using self-designed vaporizer and the results were listed in Table 1. In a 5kW SOFC system, the amount of steam is required about 80 g/min in reforming reaction of natural gas. The vaporizer can vaporize 80 g/min water to 443 °C and in which the heat transfer coefficient is 58 W/m^2.K, the efficiency is 73.5%.

Table1 Results of water vaporization test

Water flow (g/min)	Temperature of steam outlet(°C)	Methane flow (SLM)	Air/fuel ratio	Heat transfer coefficient (W/m^2.K)	Efficiency
34	416	3.5	17	48	66.2%
51	406	5.3	17	55	64.8%
80	443	7.5	17	58	73.5%

1.3 Reformer and reforming reaction

The reformer mainly contains an annulated column metal monolith catalyst and a porous media combustor. Natural gas is burned in the porous media to power the steam reforming of methane that reacts in the metal monolith catalyst[2]. In the self-designed annulated column metal monolith catalyst, active component Ni was coated on the metal surface which was used to catalyse the steam reforming reaction. The reformer and the Ni-based monolith catalyst were shown in Fig.4.

Fig.4 Self-designed reformer (left) and the Ni-based monolith catalyst (right)

Hydrogen was introduced into the reformer to reduce the monolith catalyst at 800°C for 3h before reforming reaction. After reduction of the monolith catalyst, the preheated natural gas (mainly methane) and steam were supplied to the reformer as reaction feeds and then the steam reforming reaction of natural was processed. Gas chromatograph was used to analyze the product gas and the results were revealed in Table 2.

From Table 2, it can be seen that when methane flow is 21 SLM, the conversion of methane is 99.3%. The product gas after reaction contains H_2, CO, CO_2 and some residual CH_4. Among the product gases the hydrogen accounts for 74.5%. The hydrogen obtained from steam reforming of methane reaches 67.2 SLM while the methane feed is 21 SLM. The process ability of the reformer is sufficient for 3~5 kW SOFC system while the efficiency of energy utilization is over 30%.

Table 2 Reforming performance of self-designed reformer

Methane flow (SLM)	Amount of hydrogen (SLM)	Gas products（V%）				Conversion of CH_4
		H_2	CO	CO_2	CH_4	
5	16.4	77.0%	16.5%	6.5%	0.04%	99.8%
7	22.6	77.2%	17.3%	5.4%	0.1%	99.5%
14	45.0	75.7%	18.4%	5.8%	0.2%	99.4%
21	67.2	74.5%	19.7%	5.7%	0.2%	99.3%

1.4 Process control and software

Process control in SOFC system such as temperature, pressure and flow rate was carried out base on the control system we developed. A model for a SOFC control system was built up by hardware-in- loop simulation technology. Real-Time Workshop and xPC Target software were used to generate and compile codes from Simulink models, and then download it to an industrial computer with a PC-type processor. The application is run to communicate with I/O boards to receive data from sensors and to send signals to actuators such as mass flow meter, electromagnetic valve *etc*., at the same time, the application can simultaneously transmit data packet to supervisory program by TCP/IP protocol. The model, state flow and software interface were shown in Fig.5~7.

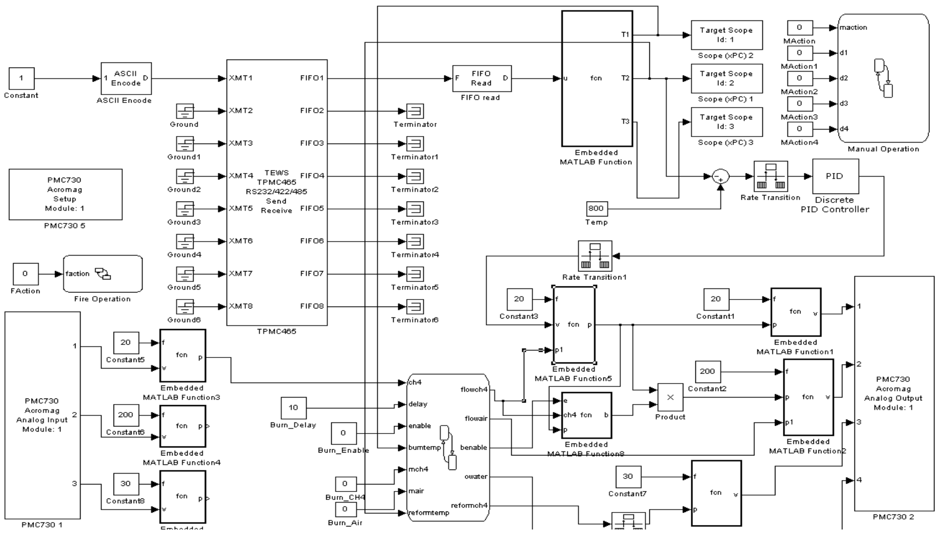

Fig.5 Simulink model

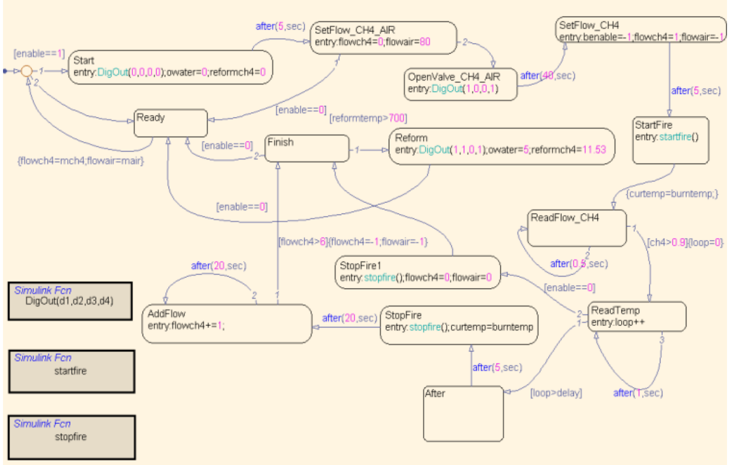

Fig.6 State flow chart

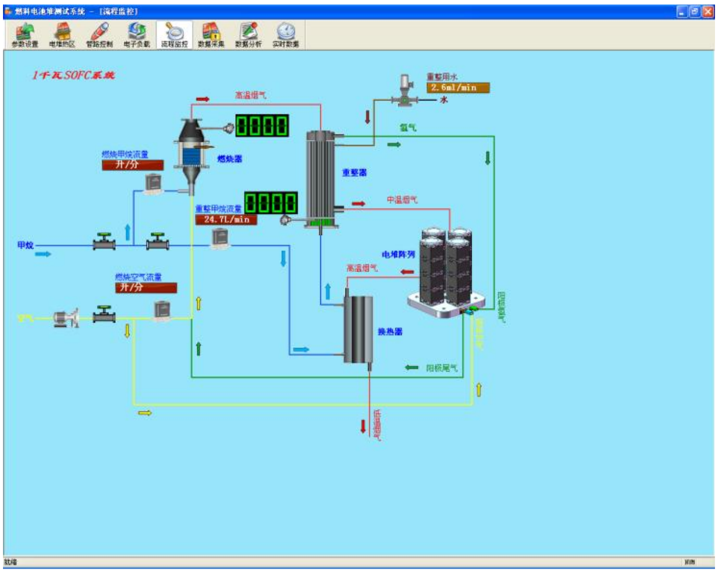

Fig.7 Supervisory program user interface

1.5 SOFC stacks

A series of 30-cell stack were manufactured using anode-supported single cells and the open circuit voltage (OCV) was generally more than 33V as shown in Fig.8. The stacks work stably and the maximum output power of these stacks ranged from 300W to 500W in which the output power density reaches 0.15~0.25W.cm^{-2} at the temperature of 800°C. The degradation rate of short-stack was reduced to 0.18%/100h by improving the contact between the interconnect and the cathode current collecting layer[3] (see in Fig.9). Two, four and eight stack modules were also integrated and the output power reached 700W, 1kW and 2.5 kW, respectively. Strategies to lower temperature difference within stack modules were developed to improve the stability of stack modules.

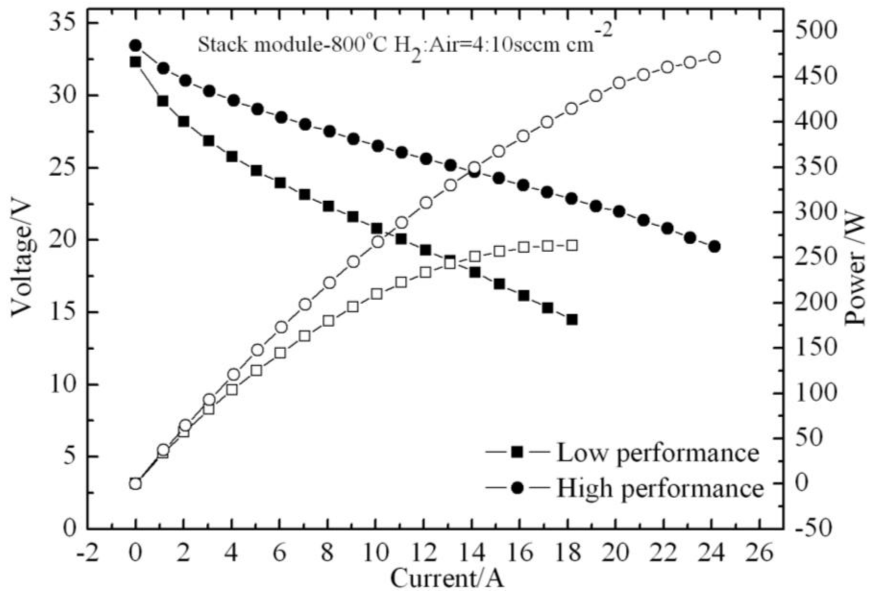

Fig.8 I-V curve of stack module

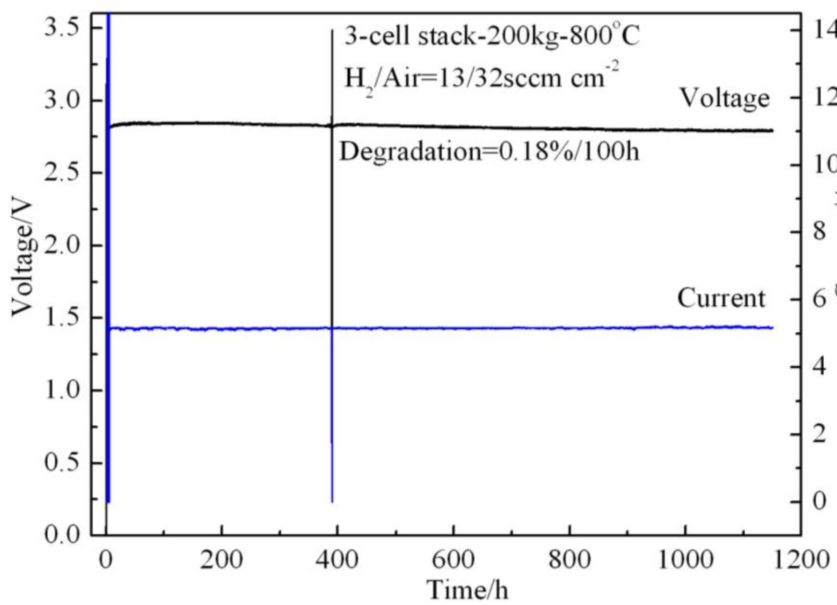

Fig.9 Degradation of short stack

2. SOFC system integration

2.1 Strategies for SOFC system integration

For SOFC system integration, a three-step strategy is carried out by SOFC group in NIMTE. First step: Integrate all the BOP components mentioned above. The point is to make sure that a phase products must meet the needs of the next reaction. During the integration, energy demands in some processes such as vaporization, reforming and heating stack can be meet separately. That is to say, a number of combustors are distributed in SOFC system to provide energy if necessary. Second step: Base on the first step, integrate and optimize the BOP components in order to optimize the energy flow in the system, which means, in this step, energy demands in SOFC system is provided only by the initial energy input(from combustor), without additional energy supply in intermediate processes. The SOFC system run in this step can be regarded as a self-sustained system. Third step: In order to increase the system efficiency, the heat exchange efficiency of each BOP components is considered. And cascade utilization of energy is also employed to optimize the all SOFC system.

2.2 Heat balance of stacks and efficiency of fuel utilization

To estimate the energy balance of our stack zone, energy consumption of SOFC system was investigated. The processes such as steam reforming of natural gas, reaction in stacks, combustion of anode exhaust gas and utilization of waste heat were involved. In this investigation, the air/fuel ratio of reaction in stacks is set to 3:1, the efficiency of power generation is set to 30~50% and the efficiency of fuel utilization is varied from 20% to 80%. Fig.10 shows the calculated results.

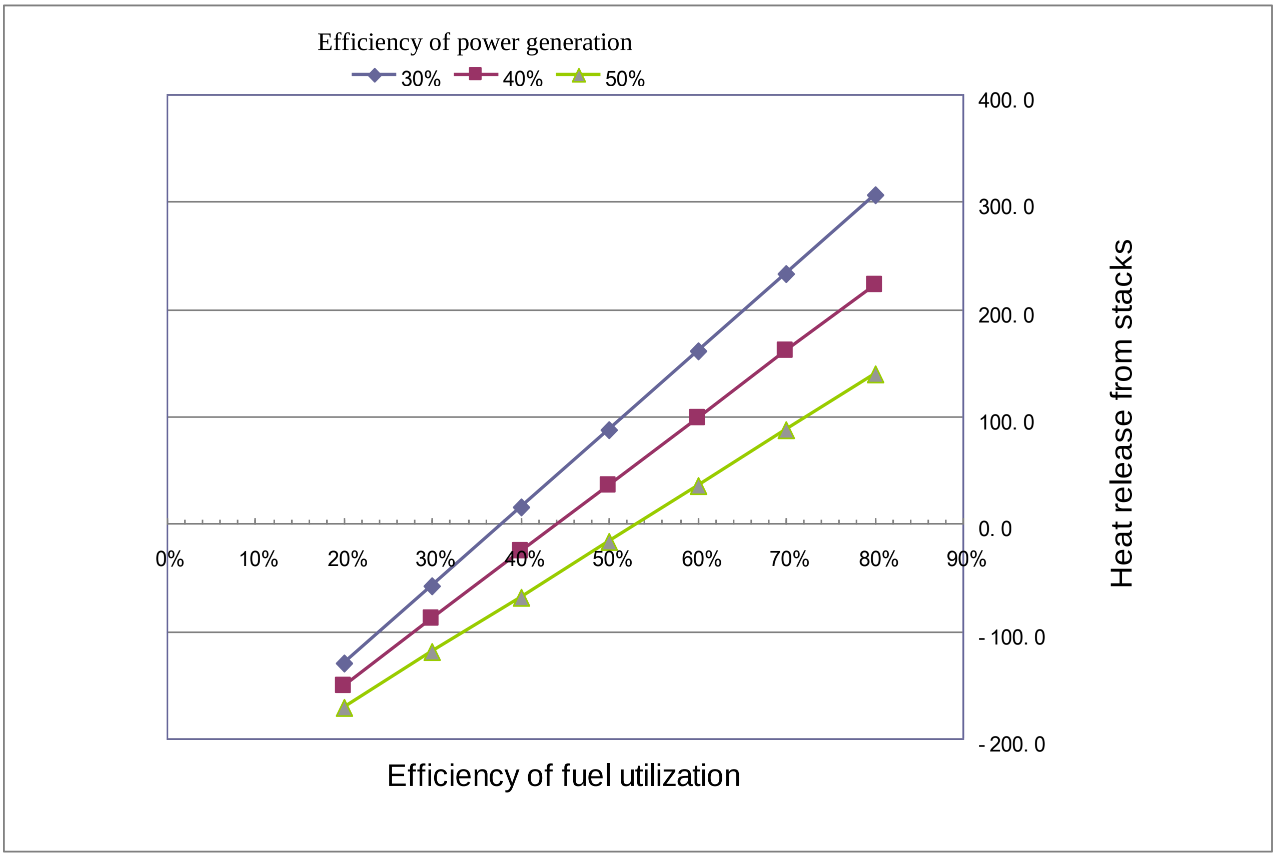

Fig.10 Heat balance of stacks and efficiency of fuel utilization

Fig.10 tells that in our self-sustained SOFC system, only when the efficiency of fuel utilization reaches to the range of 40~50%, then the heat released from the stack is enough to keep the stack zone's temperature stable. Furthermore, to keep the stack zone's temperature stable, the stack zone structure, heat exchanging between air preheater and stack zone should also be seriously considered, because the heat exchanging between air preheater and stack zone is the only method to control the stack zone's temperature.

2.3 SOFC system

The 1kW and 5kW SOFC self-sustained system were designed and manufactured in NIMTE and the efficiency of power generation is about 40%. The 10kW SOFC system was also manufactured and the comprehensive test is in progress. Fig.11 shows the 5kW

SOFC system in NIMTE and this SOFC system mainly contains combustor, vaporizer, reformer, stacks, control cabinet and software. The performance of stacks used in the SOFC system is displayed in Fig.12.

Fig.11 5kW SOFC system in NIMTE

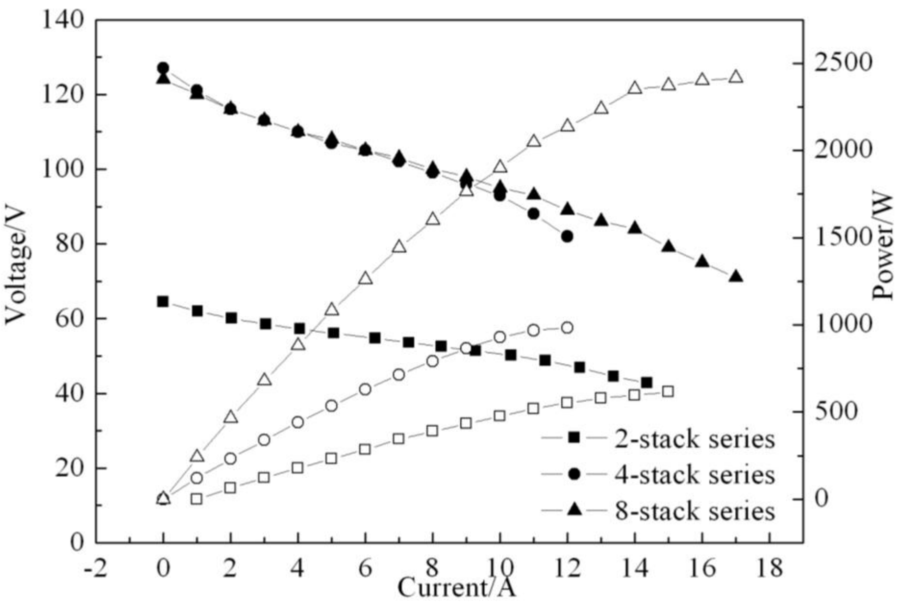

Fig.12 Output power of stack series

3. Summary

A series of SOFC components such as stacks, porous media combustor, reformer, vaporizer and heat exchanger were developed and their performance was investigated. One self-designed reformer can process 21 SLM methane, which is enough to supply our 3~5kW SOFC system. A three-step strategy is proposed for our SOFC integration. Improving efficiency of heat exchange and cascade utilization of energy were two key methods to optimize the SOFC system. A 1kW and a 5kW self-sustained SOFC system were built up in NIMTE and the efficiency of power generation is about 40%. The 10kW SOFC system was also developed and the comprehensive test is in progress.

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References

[1]. D.Trimis, F.Durst. Combustion in a Porous Medium-Advances and Applications. Combustion Science and Technology,1996,121(1-6):153-168.
[2]. Hyun-Seog Roh, Deuk Ki Lee, Kee Young Koo, Un Ho Jung , Wang Lai Yoon. Natural gas steam reforming for hydrogen production over metal monolith catalyst with efficient heat-transfer. International Journal of Hydrogen Energy, 2010, 35(4):1613-1619.
[3]. W.B. Guan, H.J. Zhai, L. Jin, T.S. Li, W.G. Wang. Effect of Contact between Electrode and Interconnect on Performance of SOFC Stacks. Fuel Cells, 2011,11(3): 445-450.