INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 4, Issue 1, 2013 pp.73-84
Journal homepage: www.IJEE.IEEFoundation.org

Design and development of major balance of plant components in solid oxide fuel cell system

Wen-Tang Hong[1], Tzu-Hsiang Yen[2], Cheng-Nan Huang[1], Hsueh-I Tan[1], Yu Chao[1]

[1] Institute of Nuclear Energy Research Atomic Energy Council, Taoyuan County 32546, Taiwan, ROC.
[2] Green Technology Research Institute, CPC Corporation, Chia-Yi City 60036, Taiwan, ROC.

Abstract
The balance of plant (BOP) of a Solid Oxide Fuel Cell (SOFC) system with a 2 kW stack and an electric efficiency of 40% is optimized using commercial GCTool software. The simulation results provide a detailed understanding of the optimal operating temperature, pressure and mass flow rate in all of the major BOP components, i.e., the gas distributor, the afterburner, the reformer and the heat exchanger. A series of experimental trials are performed to validate the simulation results. Overall, the results presented in this study not only indicate an appropriate set of operating conditions for the SOFC power system, but also suggest potential design improvements for several of the BOP components.

Keywords: SOFC; gas distributor; afterburner; reformer; heat exchanger.

1. Introduction

Due to dwindling oil resources and mounting concerns regarding global warming, the demand for power-generation systems with a high efficiency and low emissions is becoming an increasing concern. Solid oxide fuel cells (SOFCs), which convert the chemical energy in fuels such as hydrogen, methane and butane into electricity via an oxidization process, are regarded as a promising solution for large-scale electrical generation applications. SOFCs have a high efficiency and are almost entirely nonpolluting. Furthermore, they contain no moving parts, and are therefore vibration-free and extremely reliable. Significantly, SOFCs can operate with many different input fuels, and therefore resolve many of the technical challenges associated with proton exchange membrane fuel cells (PEMFCs), which can use only hydrogen as the input fuel. However, SOFCs require an extremely high operating temperature in order to achieve a sufficient power output, and thus the problems of material selection and component design present major challenges [1-3].

In an SOFC system, the fuel oxidization reaction produces two by-products, namely water and heat. In combined heat and power (CHP) systems, the heat energy is captured for downstream heating purposes, i.e., the plant generates both electricity and heat simultaneously. In practice, the gas exiting the anode exhaust of a SOFC system contains a small amount of unreacted fuel since the stack does not have a 100% fuel conversion efficiency. Chung *et al*. [4, 5] showed that the overall efficiency of a SOFC system could be increased from 50% to 68% by re-circulating the partial fuel and steam exiting the anode exhaust. Lisbona *et al*. [6] proposed a model for evaluating the performance of a CHP SOFC system and for exploring potential control strategies aimed at improving the system efficiency under part-load operations.

Fontell *et al*. [7] conducted a conceptual study of a planar SOFC system for CHP applications and showed that a system efficiency of around 55~85% (electrical co-generation) could be obtained by optimizing the stack and BOP components. In a later study [8], the same group showed that the harmful emissions of a 1-5 kW SOFC system could be reduced by using a catalytic burner to maintain the flue gas temperature at around 700°C. Finnerty *et al*. [9] developed a novel three-way catalytic system for SOFC applications comprising an in-situ pre-reformer catalyst, the fuel cell anode catalyst and a platinum-based combustion catalyst, respectively. The results showed that the system could be successfully integrated with the SOFC stack using either methane or butane as the input fuel.

Porous media afterburners provide an efficient means of ensuring the complete conversion of the SOFC off-gases during nominal operation and of pre-heating the cathode intake air during long-term operation. Compared to conventional combustion systems, porous media burners have a number of significant advantages, including lower emissions, a wider variable dynamic power range, greater combustion stability, and a freer choice of geometry. Yen *et al*. [10] investigated the optimal operating conditions of a porous media afterburner integrated with a 1 kW SOFC system fed by a natural gas reformer. It was shown that under optimal operating conditions, the afterburner could operate in a long-term, continuous fashion without the need for cooling air or any additional fuel other than that provided by the anode off-gas.

The Institute of Nuclear Energy Research (INER), Taiwan, has recently constructed a 2 kW SOFC system comprising a reformer, a SOFC stack, an afterburner, a fuel heat exchanger and an air heat exchanger. As with any SOFC system, the performance of the INER SOFC system is dependent not only on the design and operating conditions of the fuel cell stack, but also on the design and operating conditions of the BOP components (e.g., the afterburner, reformer and heat exchanger). Accordingly, the objective of the present study is to identify the optimal temperature, pressure and mass flow rate in the major BOP components so as to identify potential design improvements in the INER SOFC system in the future. In practice, optimizing the SOFC system performance using an experimental trial-and-error approach is both time consuming and expensive. Thus, in the present study, the optimal temperature, pressure and mass flow rate in the various BOP components are analyzed using the General Computational Toolkit (GCTool) software package developed by Argonne National Laboratory [11]. Having identified the optimal operating conditions for each of the BOP components, a series of experimental investigations are performed to analyze the performance of the various BOP components.

The remainder of this paper is organized as follows. Section 2 describes the use of GCTool in determining the optimal operating parameters for the SOFC stack, afterburner, reformer and other BOP components. Section 3 presents the detailed designs of the various BOP components in the INER SOFC system. Section 4 presents and discusses the experimental results. Finally, Section 5 provides some brief concluding remarks.

2. Optimization of SOFC operating parameters using GCTool

In many SOFC systems, the gas exiting the anode exhaust is combusted in an afterburner in order to provide a heat source for cogeneration purposes or to pre-heat the fuel cell during warm-up. In addition to providing a heat source, the post-stack combustor also ensures the virtual elimination of all the residual hydrogen and CO remaining in the off-gases following the oxidation process. Thus, the combustor further limits the harmful emissions of the SOFC system. The design route is calculated beforehand by using GCTool to conduct the SOFC system design and the optimal operating conditions between thermal components are revealed. In the present study, the afterburner and all the other major components in the BOP are analyzed and optimized using GCTool.

2.1 Stack electrical conversion efficiency and fuel utilization

The electrical conversion efficiency E_f of an SOFC stack is defined as

$$E_f = \text{Power Output/Input Energy (LHV)}, \quad (1)$$

where LHV is the lower heating value of the fuel. In the SOFC system at INER, the stack has a potential output power of 2 kW and an electrical conversion efficiency of more the 40%. In practice, not all of the fuel which enters the stack reacts with the cathode gas. In other words, the anode off-gas contains a certain amount of residual fuel. The components of the high-temperature anode off-gas are not easily analyzed using direct experimental methods. The alterative way to obtain the reacted fuel value is through the stack output current. Thus, the fuel utilization coefficient of the SOFC stack is generally evaluated in terms of the stack output current, i.e.,

$$U_f = I \times n_{H2} / R_{H2} \tag{2}$$

where I is the stack output current, n_{H2} is equal to 0.018655 mole/(hr. Amp.) and R_{H2} is the molar flow rate of the input fuel (hydrogen).
Figure 1 presents a flow chart showing the major steps in the GCTool procedure used to optimize the SOFC system design in such a way as to achieve a single stack output power greater than 1 kW and an electrical conversion efficiency of more than 40%. In the beginning, according to the single cell P-I-V curve to find the long term operation of voltage, current, active area and cell number.

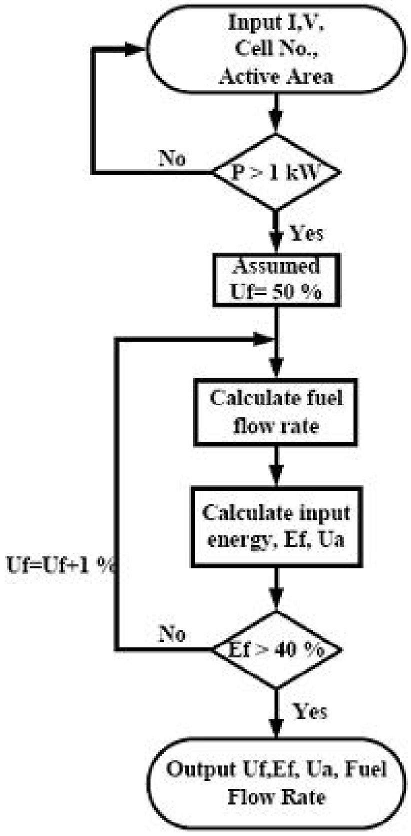

Figure 1. Flow chart showing GCTool optimization procedure for single stack output power of 1 kW (or more) and electrical conversion efficiency of 40% (or more)

2.2 GCTool analysis of BOP
The INER SOFC system is fed by a natural gas reformer, in which the water and oxidant flow rates are determined in accordance with a steam-to-carbon ratio (S/C) of 1.7 and an oxidant-to-carbon ratio (O/C) of 0.3. Following completion of the optimization process shown in Figure 1 (yielding a cell voltage and current density of 0.78 V and 400 A/cm^2, respectively), the stack fuel utilization was found to be 64.2% and the electrical conversion efficiency to be 44%. Moreover, the SOFC stack output power was equal to 2.28 kW and it meets the target. The optimal SOFC stack operating parameters are summarized in Table 1.
Figure 2 illustrates the GCTool optimization results obtained for the various components in the INER SOFC system. The results enable the temperature, pressure and mass flow rate of all the major components in the SOFC to be determined. Once these optimal operating conditions have been defined, the BOP components (e.g., the flow distributor, afterburner, fuel reformer and heat exchanger) can be designed accordingly. In other words, the GCTool results not only indicate an appropriate set of operating conditions for the SOFC power system, but also provide a reference against which to verify the experimental results.

Table 1. Optimal SOFC stack operating parameters

Cell Number	90
Current Density, mA/cm^2	400
Voltage, V	0.78
Active Area, cm^2	81
Power output, W	2278
Reformer N.G. flow rate,LPM	8.38
Reformer Air flow rate, LPM	7
Reformer Water flow rate, c.c./min	12.2
Cathode Air flow rate, LPM	164
Uf, %	64.2
Ef, %	44.2
Temperature, ^{o}C	750

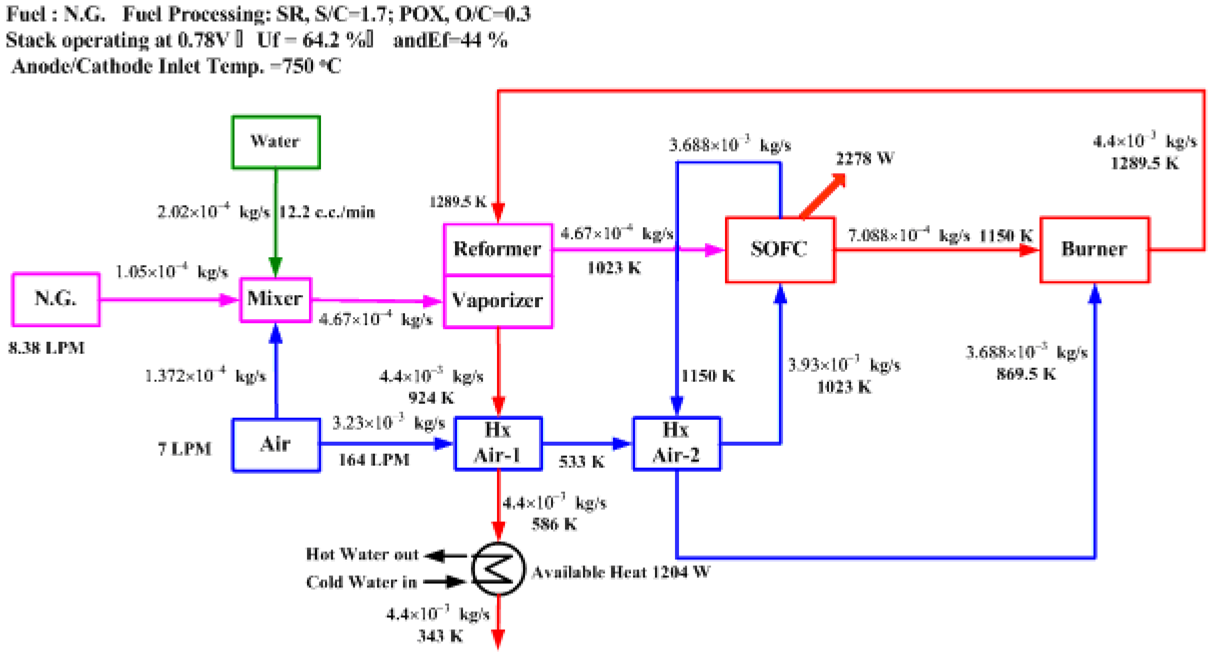

Figure 2. GCTool calculation results for 2 kW SOFC BOP system. (S/C=1.7, O/C=0.3, fuel utilization = 64.2%, electrical conversion efficiency = 44%)

3. Design of SOFC BOP components

The BOP components of a SOFC system account for between 50% and 70% of the total system cost. Due to the high operating temperature of SOFC, the material of all BOP components should own the resistant to thermal shock. Of the various BOP components, the flow distributor, afterburner, gas reformer and heat exchanger play particularly crucial roles in determining the SOFC system performance. The detailed designs of each of these components in the INER SOFC system are described in the following subsections.

3.1 Flow distributor

In general, an SOFC system comprises an array of duplicate stacks arranged in rows. For each stack, the anode and cathode sides have two inlets and one outlet. In other words, each stack contains a total of six inlet/outlet flow channels. Since a typical SOFC system has multiple stacks, designing an appropriate layout of the inlet/outlet flow manifolds presents a major challenge. Specifically, the manifold layout should balance the competing requirements of a compact physical size, a straightforward fabrication and assembly process, and low system heat losses.

The SOFC system developed by INER comprises two stacks. Thus, a total of 12 pipelines (6 pipelines per stack) are required to connect the system to the facility given a traditional manifold design. However, as shown in Figure 3, the flow distributor in the INER SOFC system is designed in such a way that just four pipelines are required. This unique design not only reduces the overall system size, but also ensures a more uniform flow (see simulation results presented in Figure 4 and the variation between input flow rate of two stack is about 0.11% totally).

3.2 Afterburner

Figure 5 presents a schematic diagram showing the heat transport within the afterburner. As shown, the afterburner comprises a mixing chamber (A) and two porous-media sections, namely an upstream fine-pore section (B) and a downstream large-pore section (C). In the SOFC system, the anode off-gas, containing a residual amount of unburned fuel, is fed to the afterburner and combusted with the cathode off-gas. The combustion process recovers the unspent energy from the fuel exiting the SOFC and uses this energy to minimize the load imposed on the input side of the SOFC by providing the energy required to reform the input fuel (methane). In other words, the afterburner not only limits the release of harmful emissions to the environment, but also improves the overall efficiency of the SOFC system.

Yen *et al*. [10] investigated the performance of an afterburner integrated with a 1 kW SOFC system fed by a natural gas reformer. It was shown that the afterburner was capable of operating in a long-term, continuous fashion without the need for cooling air or any additional fuel other than that provided by the anode off-gas given an anode off-gas temperature of less than 650 ^{o}C, a cathode off-gas temperature of less than 390 ^{o}C, and a flame barrier temperature of less than 700 ^{o}C. However, a cooling air supply was required to minimize the risk of flame propagation toward the inlet region of the afterburner; resulting in flash back. Consequently, the afterburner temperature was reduced, and thus the ability of the afterburner to supply heat to the gas reformer on the inlet side of the stack was also reduced.

Figure 6 illustrates the non-premixed afterburner used in the INER SOFC system. As shown, the anode-off gas and cathode-off gas are introduced separately (i.e., unmixed) into the burner and are subsequently combusted; resulting in the emission of a high-temperature flue gas. The afterburner avoids the flash back problem since the anode-off gas and cathode-off gas are unmixed. Therefore, in designing the afterburner, the primary objective is simply to maximize the temperature of the flue gas. Notably, the operating conditions of the non-premixed afterburner are more easily adapted in response to changes in the SOFC system performance than those of a traditional premixed afterburner.

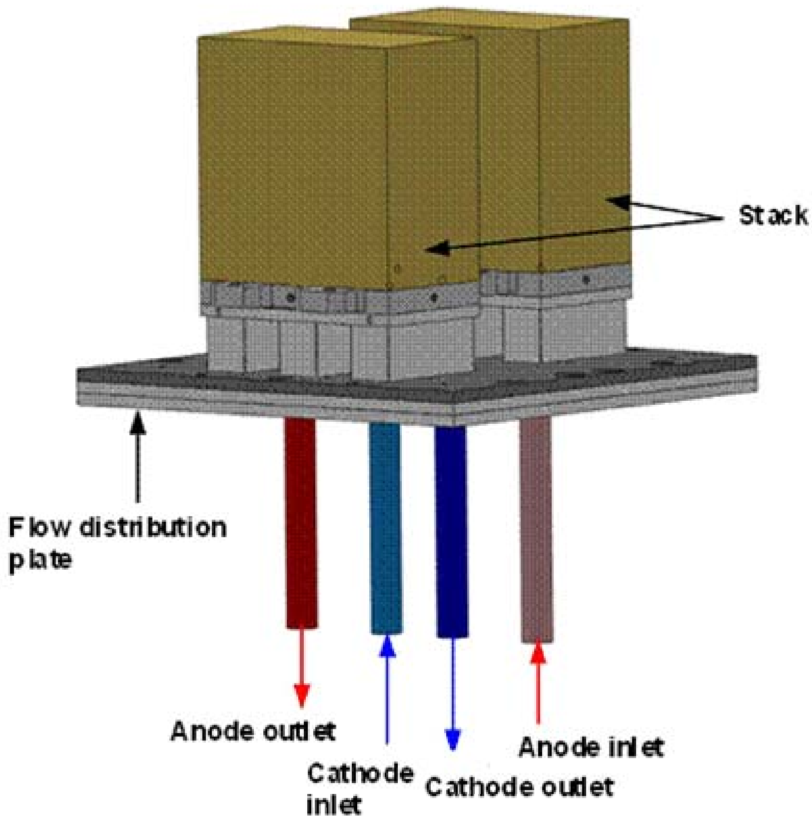

Figure 3. Novel gas flow distributor design

Figure 4. Grid distribution and boundary settings for gas flow distributor

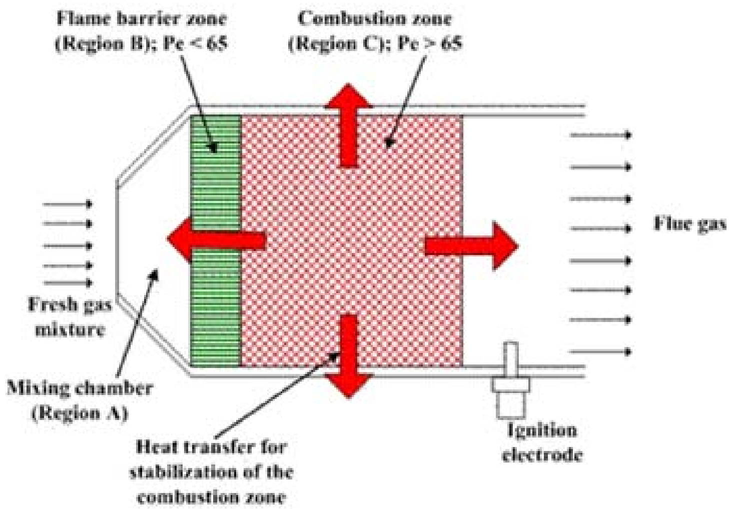

Figure 5. Schematic illustration of traditional porous media afterburner

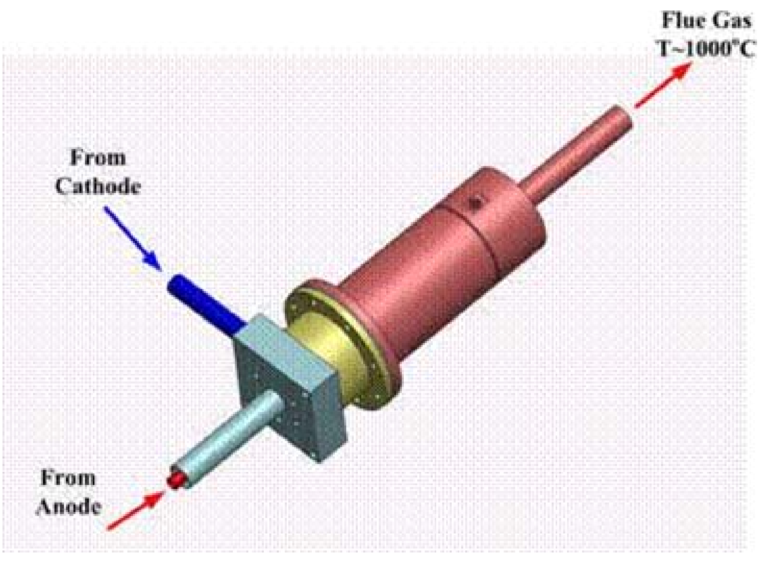

Figure 6. Non-premixed afterburner

3.3 Reformer

In general, natural gas can be reformed to a hydrogen-rich gas by either steam reforming or partial-oxidation reforming. In the INER SOFC system, the reforming process is performed using a combination of these two methods by feeding both steam and an oxidant (air) into a catalytic reactor together with the natural gas. In the present study, the reformer temperature was set at 780 ^{o}C, while the steam and oxidant flow rates were determined in accordance with a steam-to-carbon ratio (S/C) of 1.7 and an oxidant-to-carbon ratio (O/C) of 0.3, respectively. As shown in Figure 7, the hydrogen concentration of the reformate gas remained at a constant value of around 60-65% over the first 1500 hrs following system start-up.

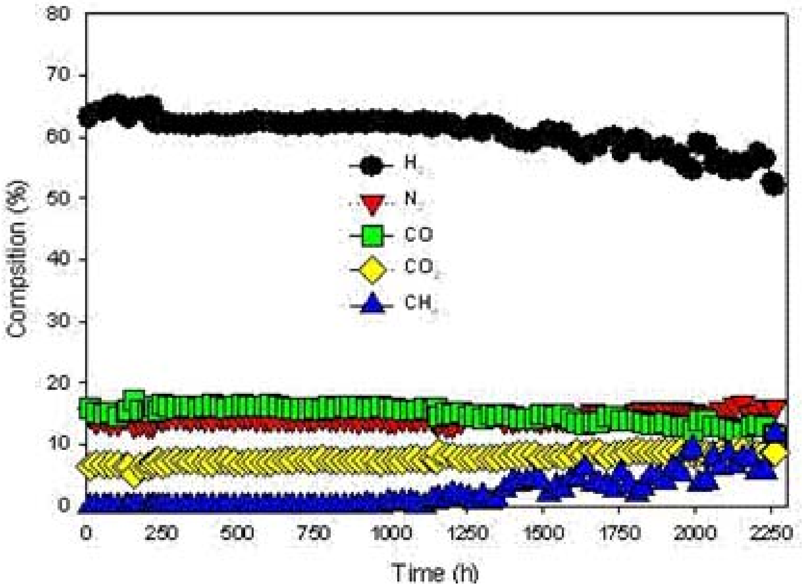

Figure 7. Time-varying composition of reformate gas given S/C= 1.7, O/C=0.3 and T=780 ^{o}C

In obtaining the results presented in Figure 7, the reactant gas was passed over a $Pt/CeO_2/Al_2O_3$ catalyst and the required reaction heat was supplied by an electrical heater. The design of reformer should go a step further and meet the requirements: (1) system long term operation and (2) recovery the system waste heat for itself operation. However, the use of an electrical heater reduces the overall SOFC system efficiency. Thus, in the present study, the SOFC system at INER was equipped with a reformer in which the heat required to achieve the reforming reaction was supplied by the flue gas of the afterburner. As shown in Figure 8, the hot flue enters the reformer zone and then passes through the vaporizer zone, where it prompts a reaction between the methane, steam and oxidant (air). The hydrogen-rich gas is then passed to a heat exchanger before entering the SOFC stack.

Figure 8. Non-electrically heated reformer

3.4 Heat exchanger

In the INER SOFC system, the hot cathode off-gas exiting the stack is passed through a flat plate heat exchanger, where it preheats the reformed fuel prior to its ingress into the SOFC, and then flows into the afterburner. The rate of heat transfer in the heat exchanger is given by Eq. (3), where U is the overall heat transfer coefficient and A is the heat transfer area along the length of the exchanger [12].

$$Q=UA\Delta T_{lm}. \quad (3)$$

The average temperature difference ΔT_{lm} across the heat exchanger (generally referred to as the logarithmic mean temperature difference, LMTD) is equal to

$$\Delta T_{lm}=\frac{(T_{h,i}-T_{c,o})-(T_{h,o}-T_{c,i})}{\ln\left(\frac{T_{h,i}-T_{c,o}}{T_{h,o}-T_{c,i}}\right)} \quad (4)$$

where the subscripts *h*, *c*, *i* and *o* denote *hot*, *cold*, *inlet* and *outlet*, respectively. It represents the relationship between the temperature difference between the hot and cold gas streams at inlet and the temperature difference at the outlet end. Figure 9 compares the cold side absorbed heat and UA (the product of "U" and "A" in Eq. (3)) value of a commercial heat exchanger with that of INER- Kaori design (fabricated in cooperation with Kaori Heat Treatment Company, Taiwan). The results show that the INER-Kaori design improves the cold side absorbed heat and UA value by 18% and 24%, respectively, compared to the commercial design.

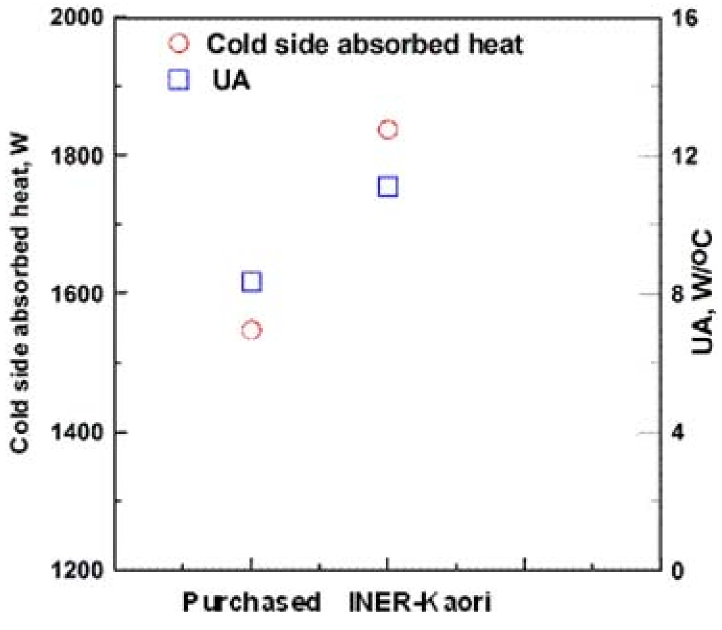

Figure 9. Cold side absorbed heat and UA value of commercial and INER-Kaori plate heat exchangers

4. Experimental results and discussions

Figure 10 presents a schematic illustration of the experimental arrangement used to characterize the transient and steady-state performance of the 2 kW SOFC system. The experimental parameters were set in such a way as to simulate a fuel utilization of U_f = 0.642. The experimental setup did not actually include the stack and the experimental settings were established in accordance with the GCTool results presented in Figure 2. As described in the previous section, the residual (unreacted) fuel in the anode off-gas was recuperated via combustion in the afterburner, and the resulting heat was supplied to the reformer. During the experiments, the gas and liquid mass flow rates were controlled using a digital Alicat control unit. Meanwhile, the temperatures at various points in the experimental system were regulated by a Eurotherm PID controller.

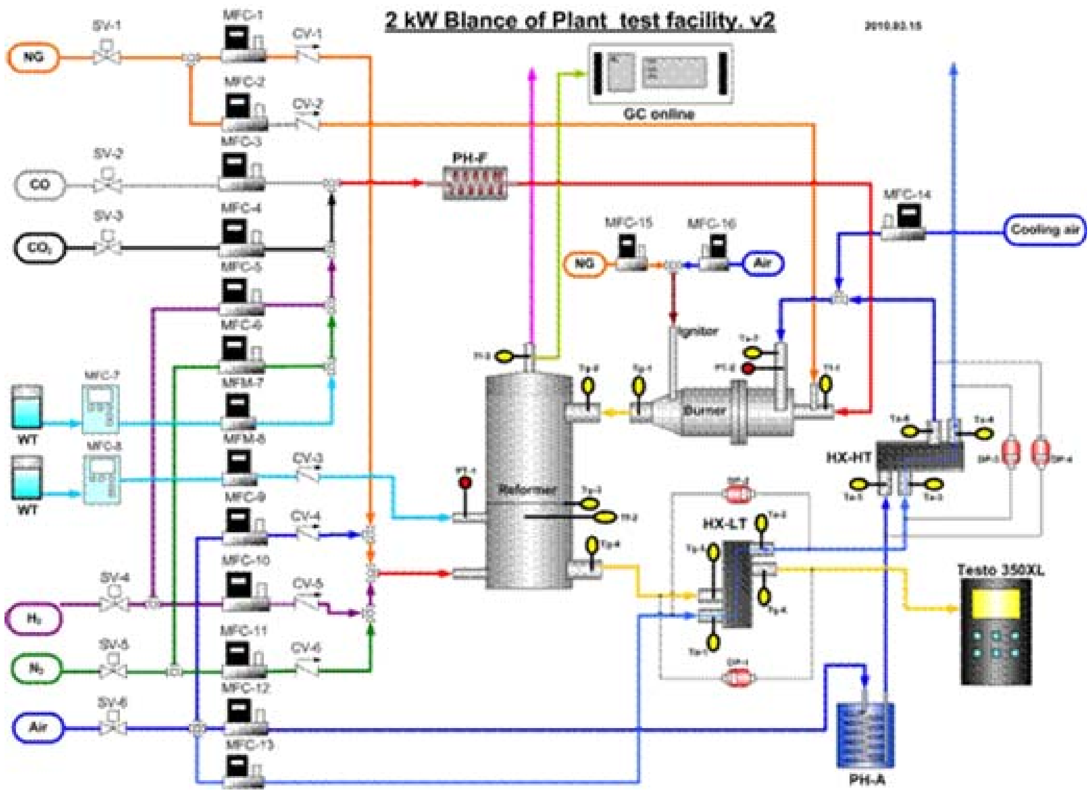

Figure 10. Schematic illustration of 2 kW SOFC experimental system

The cathode off-gas (air) was supplied by a compressor and was pre-heated to a specified temperature by a pre-heater before entering the afterburner. Meanwhile, the anode off-gas was produced by heating liquid water to the point of gasification in a pre-heater and then mixing the resulting steam with hydrogen, nitrogen, carbon monoxide and carbon dioxide provided by a gas supply system. As with the cathode off-gas, the anode off-gas was pre-heated prior to ingress into the afterburner. Note that the desired temperature of the anode off-gas at the afterburner inlet was regulated using a Eurotherm PID controller and HX-HT.

Figure 11 shows the temperature distribution in the non-premixed afterburner given an anode off-gas inlet temperature of 750^{o}C and fuel utilization 64.2%. It is seen that the maximum temperature within the afterburner is 965^{o}C and the outlet temperature is 874^{o}C. In general, the results show that the temperature distribution is relatively uniform and the combustion zone is retained within the porous media zone. There is also no cooling air flow for flash back concern need for a cooling air flow. Consequently, the flash back problem is resolved. Figure 12 shows the temperature distribution and reformate gas composition in the reformer. As shown, the inlet temperature is equal to 805^{o}C and the dry base composition of the reformate gas is as follows: 57.9% hydrogen, 13.9% carbon monoxide, 4.2% methane, 15.3% nitrogen and 8.7% carbon dioxide.

As shown in Figure 13, the cathode air was pre-heated in a two-step procedure using the INER-Kaori flat plate heat exchanger. The inlet temperature was found to be 692^{o}C, i.e., close to the desired stack operating temperature of 750^{o}C. Comparing the results presented in Figures 7 and 12 for the electrically-heated reformer and afterburner-heated reformer, respectively, it is seen that the hydrogen content in the electrically-heated reformer is around 12% higher than that in the afterburner-heated reformer. The superior performance of the electrically-heated reformer is due to the high (780^{o}C) and uniform temperature distribution throughout the reformer. By contrast, in the afterburner-heated reformer, the inlet temperature is around 805^{o}C while the outlet temperature is around 605^{o}C. In other words, the temperature is both lower and less uniformly distributed than in the electrically-heated reformer. The results suggest that the outlet temperature of the afterburner (874^{o}C) is not sufficiently high to meet the reformer reaction requirements despite the fact that the maximum temperature within the afterburner is 965^{o}C. In improving the performance of the INER SOFC system in the future, this problem will be resolved by rearranging the position of the afterburner or developing a novel integrated burner-reformer design.

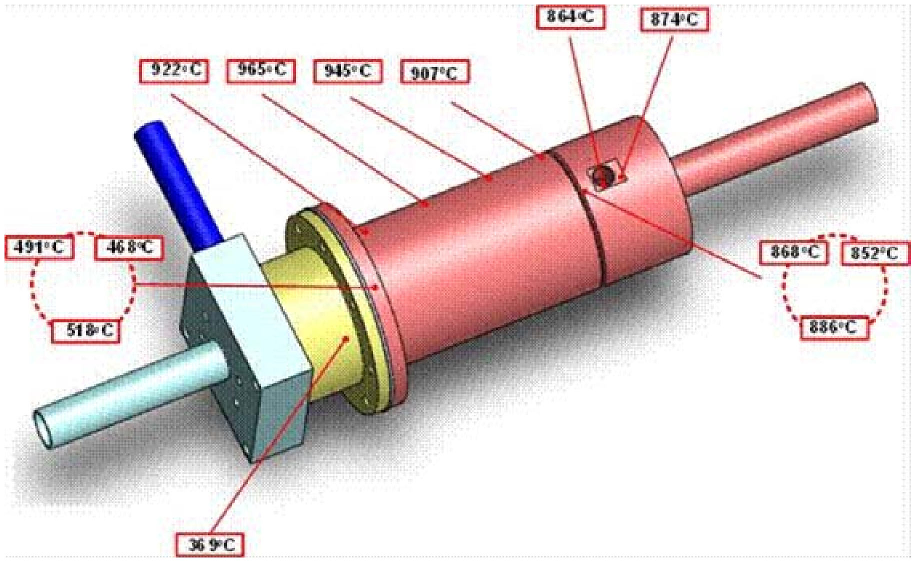

Figure 11. Temperature distribution in non-premixed afterburner

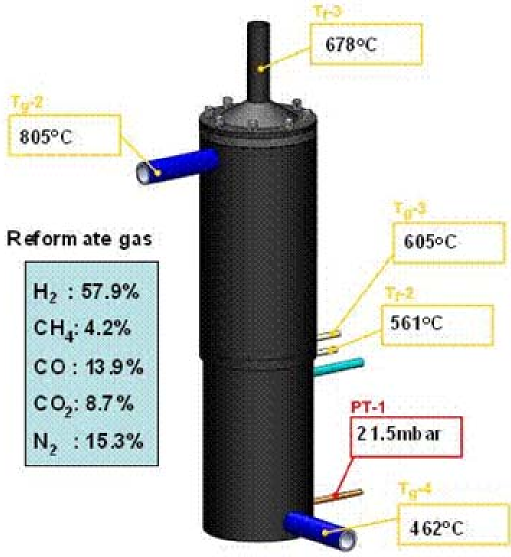

Figure 12. Temperature distribution and reformate gas composition in reformer

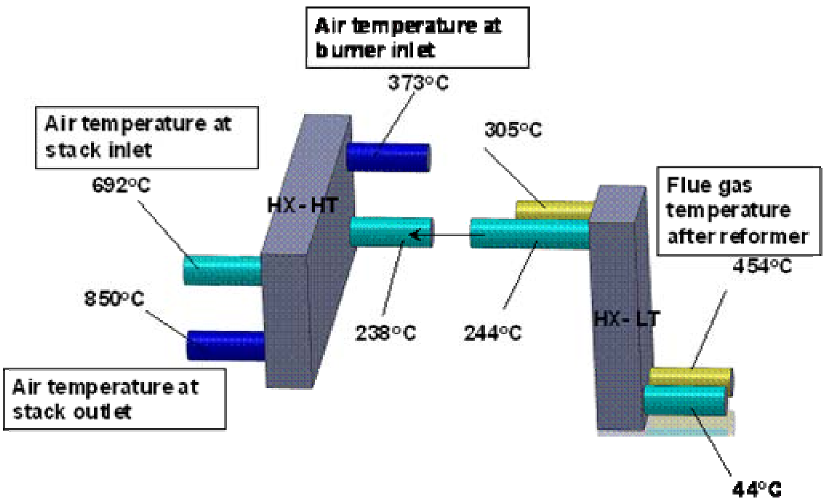

Figure 13. Temperature distribution in high temperature (HT) and low temperature (LT) regions of flat plate heat exchanger

5. Conclusions

SOFC systems are highly complex. Thus, in order to understand the overall system performance, it is necessary to comprehend the behavior of all the individual components. This study has performed numerical simulations to optimize the operating parameters of the 2 kW SOFC system at INER, Taiwan. The performance of the optimized SOFC system has then been examined experimentally. The experiments have focused particularly on the performance of the flow distributor, afterburner, gas reformer and heat exchanger. The experimental results are of benefit in validating the GCTool predictions for the optimal operating conditions and in identifying potential design improvements in the future. The major conclusions of this study can be summarized as follows:

(1) The flow distributer design renders the system more compact and reduces the system heat loss. The design not only results in a higher system efficiency, but also assures a more uniform flow distribution than conventional gas manifold designs.

(2) The non-premixed afterburner design avoids the flash back problem and achieves a uniform temperature distribution within the burner. Moreover, the operating parameters of the afterburner are more easily adapted in response to SOFC system changes than a traditional premixed afterburner.

(3) The afterburner-heated gas reformer improves the overall system efficiency by recuperating the residual fuel in the anode off-gas. However, the temperature within the gas reformer is not only lower than that in a traditional electrically-heated reformer, but is also less uniformly distributed. As a result, the hydrogen content in the reformate gas produced in the afterburner-heated reformer is lower than that in an electrically-heated reformer. Consequently, the development of a combined afterburner / reformer design will be addressed in a future study.

(4) The performance of the INER-Kaori designed flat plate heat exchanger is comparable with that of a commercial product.

References

[1] Appleby A. J., Foulker F. R., Fuel Cell Handbook, Van Norstand Reinhold, New York, 1989.

[2] Stanley W. A., Direct Energy Conversion, Allyn and Bacon, Inc., Boston, 1982.

[3] Larminie J., A. Dicks, Fuel Cell Systems Explained, John Wiely & Sons, Ltd, England, 2000.

[4] Chung T. D., Chyou Y. P., Hong W. T., Cheng Y. N., Lin K. F., Influence of energy recuperation on the efficiency of a solid oxide fuel cell power system, Energy & Fuels 2007, 21, 314-321.

[5] Chung T. D., Hong W. T., Chyou Y. P., Tu D. D., Lin K. F., Lee C. H., Efficiency analyses of solid oxide fuel cell power plant systems, Applied Thermal Engineering, 2008 28, 933-941.

[6] Lisbona P., Corradetti A., Bove R., Lunghi P., Analysis of a Solid Oxide Fuel Cell System for Combined Heat and Power Applications under Non-nominal Conditions, Electrochimica Acta, 2007, 53, 1920-1930.

[7] Fontell E., Kivisaari T., Christiansen N., Hanse J. B., Palsson J., Conceptual study of a 250 kW planar SOFC system for CHP application, J. Power Sources, 2004, 131, 49-56.

[8] Fontell E., Jussila M., Hansen J. B., Palsson J., Kivisaari T., Nielsen J. U., Wärtsilä–Haldor Topsøe SOFC Test System, Extended abstract presented in SOFC-IX, Quebec, Canada, May 15 – 20, 2005.

[9] Finnerty C., Tompsett G. A., Kendall K., Ormerod R. M., SOFC system with integrated catalytic fuel processing, J. Power Sources, 2000, 86, 459-463.

[10] Yen Tzu-Hsiang, Hong Wen-Tang, Huang Wei-Ping, Tsai Yu-Ching, Wang Hung-Yu, Huang Cheng-Nan, Lee Chien-Hsiung, Experimental investigation of 1 kWsolid oxide fuel cell system with a natural gas, J. Power Sources, 2010, 195, 1454–1462.

[11] GCTool, version 2.4, ANL Argonne IL 2001.

[12] Kreith F. and Bohn M. S., Principles of Heat Transfer, Info Access & Distribution Pte Ltd, 1993.

Wen-Tang Hong is a senior engineer of Institute of Nuclear Energy Research. He has 19 years research experience, his research topics including: power plant, two phase flow, cold neutron source, and solid oxide fuel cell.
E-mail address: wthang@iner.gov.tw

Tzu-Hsiang Yen obtained a PhD in Mechanical engineering from National Cheng Kung University in Taiwan, 2006. He was a junior researcher at the Institute of Nuclear Energy Research. Now he is working at the Refining and Manufacturing Research Institute, CPC Corporation, Taiwan and responsible for the hydrogen energy planning and research. He has published 15 research papers in reputed International journals and conferences.
E-mail address: 078573@cpc.com.tw

Cheng-Nan Huang is an assistant engineer of Institute of Nuclear Energy Research.
E-mail address:ahnan@iner.gov.tw

Hsueh-I Tan is an assistant engineer of Institute of Nuclear Energy Research.
E-mail address:emily0216@iner.gov.tw

Yu Chao is an Associate Researcher of Institute of Nuclear Energy Research. He holds a PhD in environmental engineering, M.S and B.S. in chemical engineering. His research interests include biomass reforming, hydrogen generation and low level radwaste treatment.
E-mail address: ychao@iner.gov.tw

