ARTICLE IN PRESS

Applied Thermal Engineering xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Examination of a high-efficiency solid oxide fuel cell system that reuses exhaust gas

Takaaki Somekawa *, Kazuo Nakamura, Takuto Kushi, Takao Kume, Kenjiro Fujita, Hisataka Yakabe

Fundamental Technology Dept., Tokyo Gas Co., Ltd., 1-7-7 Suehiro-cho, Tsurumi-ku, Yokohama City, Kanagawa 230-0045, Japan

HIGHLIGHTS

- 2-stage SOFC system with fuel regenerating techniques was designed and fabricated.
- Total fuel utilization ratio was successfully enhanced to 92.0% in hot module tests.
- The maximum power generation efficiency reached 77.8% (DC, LHV).
- The requirement of heat loss was clarified by the heat balance analysis.

ARTICLE INFO

Article history:
Received 4 April 2016
Revised 11 October 2016
Accepted 14 October 2016
Available online xxxx

Keywords:
Solid oxide fuel cell
Efficiency
Multi-stage
Regeneration
Hot module

ABSTRACT

Enhancing the power generation efficiency, which is the main advantage of solid oxide fuel cells (SOFCs), can have valuable benefits to introduce SOFC systems into business and industrial markets of Japan, where power demands are higher than thermal demands. In this study, we examined a high-efficiency SOFC system with an off-gas regenerating technique. A two-stage SOFC stack configuration was employed. For off-gas regeneration, we used a CO_2 absorber and a H_2O condenser. A total of 92.0% of the fuel was successfully used with an electrical efficiency of 77.8% (DC, LHV). However, there existed the heat loss from the fuel cell system due to the thermal insulation performance. To compensate the heat loss, additional electric heaters were used to keep temperatures high, therefore heat sustainability remained an issue.

1. Introduction

The most important feature of a fuel cell is that it can directly convert chemical energy from fuels into electricity and achieve a high energy-conversion efficiency compared to existing thermal power generation systems. Among all fuel cell types, solid oxide fuel cells (SOFCs) are expected to have the highest power generation efficiency, which is consistent with the results of various research and development projects from industrial, government, and academic research groups. A micro combined heat and power SOFC system with rated power output of 700 W [1] and power generation efficiency of 45.0% LHV [1] (lower heating value) for residential use was introduced to the Japanese market in 2011, and its cumulated total number of installed systems has been increasing steadily. In contrast, in business and industrial areas, main activities of SOFC development still remains in the experimental or empirical research stage. In June 2014, the Ministry of Economy, Trade and Industry of Japan formalized a "Strategic road map for hydrogen and fuel cells", laying out objectives for the large-scale introduction of SOFCs with comparatively high electric power generation efficiency to the market in 2017 [2].

In the industrial regions of Japan, nearly six tenths of the market is comprised of the markets where power demands exceed thermal demands such as office buildings, convenience stores, and schools [3]. Therefore, to accelerate the introduction of SOFCs to this market, the development of high-efficiency power generation technology is very important.

The power generation efficiency in a SOFC system, η, is generally given as follows:

$$\eta = -\frac{nF}{\Delta H} \times V \times \eta_{Fuel} \times \eta_{aux} \times \eta_{PC} \tag{1}$$

where n is the number of electrons that contribute to the reaction per mole of fuel, F is the Faraday constant, ΔH is the calorific power of the fuel, V is the operating voltage of the SOFC cell, η_{Fuel} is the fuel utilization ratio, η_{aux} is the efficiency of the auxiliary machines, and η_{PC} is the efficiency of the power conditioner. To improve the effi-

* Corresponding author.
E-mail address: somekawa@tokyo-gas.co.jp (T. Somekawa).

http://dx.doi.org/10.1016/j.applthermaleng.2016.10.096
1359-4311/

Please cite this article in press as: T. Somekawa et al., Examination of a high-efficiency solid oxide fuel cell system that reuses exhaust gas, Appl. Therm. Eng. (2016), http://dx.doi.org/10.1016/j.applthermaleng.2016.10.096

ciency of a SOFC system, at least one these elements must be improved. It has been reported that fuel utilization ratio can be significantly increased compared to that of conventional SOFC systems shown in Fig. 1 by devising a system structure [4–7]. To create high-efficiency power generation systems, developments not only for increasing efficiency but also for minimizing the heat radiation loss from the system are needed [8,9].

To study the feasibility of SOFC systems with higher power generation efficiencies, we analysed the heat balance of the SOFC system with regenerating devices of the anode off-gas. And we designed and manufactured the SOFC system.

In this paper we report the investigation results of the manufactured system such as fuel utilization ratio, the electrical performance, and generation stability at continuous operation tests.

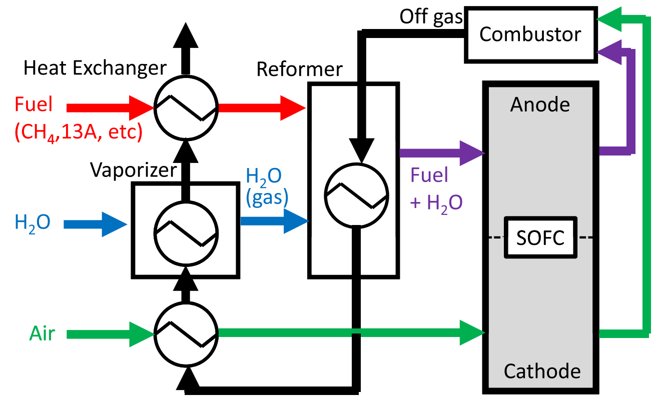

Fig. 1. Composition of a conventional SOFC system.

2. SOFC systems with regenerating off-gas techniques

2.1. Conventional SOFC system

At the anode of a SOFC, the following electrochemical reactions occur:

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

$$CO + O^{2-} \rightarrow CO_2 + 2e^- \quad (3)$$

These reactions produce H_2O and CO_2, the concentrations of which increase with the fuel utilization ratio during operation, which decrease the partial pressures of the fuels and prevent electrode reactions from progressing. When the fuel utilization ratio is high, the local partial pressure of oxygen at the anode can increase, which may cause a re-oxidation of the anode material, Ni, to NiO, which involves irreversible plastic deformation and causes a destruction of the cell. Therefore, in conventional SOFC systems, approximately 20–30% of the supplied fuel is generally not used for power generation but is burned for use as heat to maintain the cell temperature or the steam reforming reaction temperature. The remaining heat is emitted as exhaust gas.

More specifically, when the CO_2 and H_2O molecules that disturb the electrode reactions are removed and the fuel concentrations increase, the fuels in the off-gas that are not used to supply heat can be reused as a fuel for power generation. This recycling enhances the total fuel utilization ratio and consequently power generation efficiency. To realize these concepts, fuel recycling SOFC systems and multi-stage SOFCs have been reported [4,5].

2.2. Fuel recycling SOFC system

Fig. 2 shows a schematic of a fuel recycling SOFC system. In this figure, [1]red lines represent fuel arrows, blue arrows represent water flows, green arrows represent air flows, purple arrows represent the flows of mixtures containing both fuels and water vapor, and black arrows represent off-gas flows. These colors are applicable in the same way for subsequent figures. The H_2O and CO_2 gases in the anode off-gas are removed by regenerators, such as a separation membrane and a CO_2 absorption agent (the regenerator in Fig. 2), or H_2 and CO gasses are selectively extracted. These regenerated gases are recirculated into the anode by a gas blower and are reused. This reuse of fuel can increase the total fuel utilization ratio. When the H_2O needed for steam reformation is recirculated to the steam reformer, or a partial oxidation (POx) is employed to reform the fuel, as shown in Fig. 3, the system can be simplified by removing the water supply pumps. However, these fuel recycling systems need

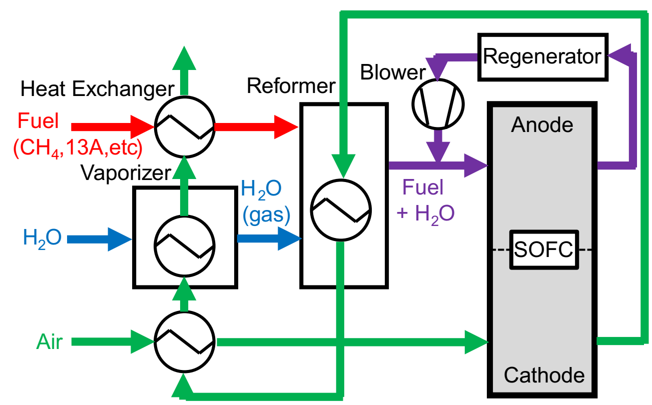

Fig. 2. Composition of a fuel recycling SOFC system.

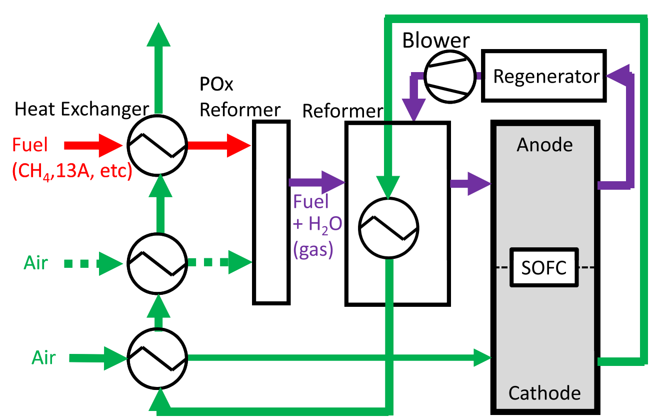

Fig. 3. Composition of a fuel recycling SOFC system with a POx starter.

gas blowers to circulate the combustible gas that is ejected from the anode of the SOFC cells at high temperatures. Extensive peripheral equipment is needed for blower installations intended for high-temperature usage due to safety reasons. Therefore, the issues related to the use of fuel recycling systems are the complications imposed by the system structure and the durability of the blowers.

2.3. Multi-stage SOFC system

Fig. 4 shows a two-stage stack configuration of a SOFC system. The SOFC stacks are arranged along the fuel flow, and the residual fuels that are not used at the 1st SOFC stack can be used at the 2nd

[1] For interpretation of color in Figs. 2 and 5, the reader is referred to the web version of this article.