Energy Conversion and Management 148 (2017) 701–707

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Biogas-fueled flame fuel cell for micro-combined heat and power system

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ARTICLE INFO

Article history:
Received 27 April 2017
Received in revised form 12 June 2017
Accepted 13 June 2017

Keywords:
Flame fuel cell
Biogas
Porous media combustion
Carbon deposition
Combined heat and power

ABSTRACT

A biogas-fueled flame fuel cell (FFC) unit is proposed for the micro-combined heat and power (CHP) system using indigenous energy source. With fuel-rich flame as both heater and reformer, FFC is advantageous for quick start-up, no sealing, and simple thermal management. In this study, a porous media burner with non-catalytic fuel-rich combustion was utilized to provide both stable high temperature environment and reformed syngas for the solid oxide fuel cell (SOFC). The porous media burner and a micro-tubular SOFC were integrated directly in the biogas FFC reactor. The performance of fuel-rich combustion and electrochemical characteristic was studied for various equivalence ratios from 1.2 to 1.4. Experimental results showed that the reforming efficiency reached 42.3% with the porous media burner, using model biogas of 60% CH_4 and 40% CO_2 as fuel. The maximum power for a single tubular fuel cell reached 1.4 W when fed with model biogas at an equivalence ratio of 1.4. Furthermore, performance degradation caused by carbon deposition at the anode was investigated.

1. Introduction

Biogas is an abundant renewable energy source that converts waste into energy, which has attracted great attention for its application. Since biogas is extensively produced by local anaerobic biological waste treatment [1,2], like farm residues, sewage sludge, landfill, etc., it is typically used in heating equipment or small power houses with a range of 5–100 kW_{el} [3,4]. Especially for those distributed sources, there is great potential for micro-combined heat and power (CHP) system fed with biogas. For the conversion of biogas to electricity in small scale, compared with engines or micro-turbines, fuel cells have significant advantages due to higher efficiency, no noise, and no rotary machine.

Solid oxide fuel cell (SOFC) is a kind of high temperature fuel cell working at 700–1000 °C, which is most attractive for micro-CHP application of biogas [5]. A number of studies related to SOFC fueled with biogas have been reported so far [2,3,6–9]. For typical decentralized micro-CHP system, catalytic partial oxidation (CPOx) is usually adopted as a practical and economical reforming process to convert biogas into H_2 and CO [10–12], which are favorable fuels for SOFC. However, the catalyst deactivation due to coking, hot-spots and sintering is a serious issue for the reforming process [13,14]. Besides, CPOx and SOFC are two separate parts in classical biogas fueled micro-CHP with SOFC technology [4,15], when implementing real SOFC systems, many problems are required to be solved, such as sealing, slow start-up and complex thermal management [16].

Flame fuel cell (FFC) is a novel kind of SOFC that integrates fuel-rich flame and SOFC together, with great potential for distributed micro-CHP unit [17]. Utilizing non-catalytic fuel-rich flame as both reformer and heater, FFC can avoid high requirement of catalyst and extra thermal management, comparing with conventional SOFC system with CPOx. The oxygen at the anode of SOFC is consumed by the fuel-rich flame in FFC, which can be operated without the sealing challenge in traditional dual-chamber SOFC [18]. When utilized for biogas-fueled micro-CHP application, FFCs also have advantages including rapid start-up, simple setup [19,20]. Some researches on the FFC performance using methane as fuel have been carried out [19–26], but for biogas as fuel, there is little research concerning the feasibility of biogas FFC. Only a FFC setup with model biofuels, including a planar SOFC and a quartz tube acting as a burner, was tested by Falkenstein-Smith et al. [27].

Combustor is one of the most important components of FFC that affects the operating temperature and the fuel composition of SOFC. In current studies of FFC, many combustors such as Bunsen burner [28], Quartz tube [29], Alcohol burner [30], Mckenna burner [31], Hencken burner [23] have been used. Nevertheless, compared with traditional natural gas, high content of carbon dioxide in biogas (about 40%) makes it more difficult to burn [32], requiring more efficient combustion and larger flammability limits of the combustor. Wang et al. [19,21] proposed to use porous media combustor to expand the flame stability limit of methane, recovering heat from the combustion zone to the upstream layer and

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http://dx.doi.org/10.1016/j.enconman.2017.06.039
0196-8904/

preheating the fresh unburned gases. The experimental results showed that the maximum equivalence ratio reached 1.8 when using methane as fuel. In this work, a porous media introduced to enhance the fuel-rich combustion and expand the biogas flammability, thus a stable fuel-rich combustion of biogas can be achieved.

Biogas is usually free of non-methane hydrocarbons (NMHC) [3,4], containing large fractions of CH_4 and CO_2, and trace amounts of sulfur. Table 1 shows the composition of biogas from various biological wastes and the sulfur content before and after desulfurization [2,7]. A typical mixture, composed of 60% of methane and 40% of carbon dioxide [12], can be seen as a model biogas in primary study. In addition, although the high sulfur content in biogas might be a serious problem for SOFC, after desulfurization, the content of H_2S or organic sulfur could be reduced to below 10 ppm, which is comparable with that of natural gas or petroleum-based fuels and even lower [7]. That is to say, a simple desulfurization process can alleviate the performance attenuation problem poisoning with sulfur in biogas [15].

With biogas as fuel, a novel compact FFC configuration for micro-CHP application based on the porous media combustion technology is shown in this study. In order to obtain a stationary combustion in the porous media, two layers of porous media with different pore diameters are adopted [33]. The concept map of a biogas-fueled FFC micro-CHP system is shown in Fig. 1. On the front-end of SOFC, a two-layer porous media burner is utilized in fuel-rich condition, as a partial oxidation reformer from biogas into syngas. At this step, the inlet biogas is partial oxidized by air through the non-catalytic fuel-rich combustion:

$$(CH_4 + 0.67CO_2) + \frac{2}{\Phi}(O_2 + 3.76N_2) \rightarrow aH_2 + bCO + cCO_2 + dH_2O + \frac{2 \times 3.76}{\Phi}N_2 \quad (1)$$

Where the equivalence ratio is defined as

$$\Phi = \frac{n_{fuel}/n_{air}}{n^s_{fuel}/n^s_{air}} \quad (2)$$

where n_{fuel} and n_{air} are the molar flow rates of the fuel (model biogas, i.e., the mixture of CO_2 and CH_4) and air, respectively, n^s_{fuel} and n^s_{air} are the molar flow rates in stoichiometric conditions. The obtained H_2 and CO in the fuel-rich combustion products are the effective fuels for the SOFC. Hence, at the anode of SOFC, the H_2 and CO in the combustion products are oxidized by the oxygen ions at the three phase boundary:

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \quad (3)$$

$$CO + O^{2-} \rightarrow CO_2 + 2e^- \quad (4)$$

At the cathode of SOFC, the oxygen is reduced by the electrons to the oxygen ions:

$$O_2 + 4e^- \rightarrow 2O^{2-} \quad (5)$$

On the back-end of SOFC, the residual fuel gases from anode and unreacted air from cathode meet together and completely burn in another porous media burner. The total combustion of H_2 and CO takes place at this stage:

$$2H_2 + O_2 \rightarrow 2H_2O \quad (6)$$

$$2CO + O_2 \rightarrow 2CO_2 \quad (7)$$

As a primary work to confirm the feasibility of this novel configuration, the complete combustion of the exhaust gas from SOFC is not considered in this study. Rather than planar SOFCs, micro-tubular SOFCs are designed to be used in the new configuration, due to their robustness, fast start-up and good thermal resistance.

2. Experimental

2.1. Experimental setup and measurement techniques

Fig. 2 shows the schematic diagram of the experimental setup, mainly consisting of the gas supply system, the FFC reactor and the performance testing system.

In the gas supply system, a gas mixture consisting of a mole fraction of 60% CH_4 and a mole fraction of 40% CO_2 was set as a model biogas. The flow rates of model biogas and air at a desired equivalence ratio were controlled by mass flow controllers. Then the model biogas and air mixed in the premix chamber, went through the anti-backfire chamber and reacted in the FFC reactor. The anti-backfire chamber was filled with 1–2 mm quartz sands, which prevented the flame from propagating to the premix chamber. One way of air was fed into the cathode of SOFC through a stainless steel coil.

A two-layer porous media and a micro-tubular SOFC were integrated in the FFC reactor. The incoming model biogas was partial oxidized through the non-catalytic fuel-rich combustion in the porous media, and then directly fed to the SOFC. The FFC reactor was about 30 mm in diameter and 200 mm in height. A stainless steel tube of 54 mm in inner diameter and 60 mm in outer diameter and 200 mm in height served as the framework, which was inserted by an insulation cylinder of aluminum silicate and surrounded with an outer ceramic insulation. The outer insulation was 80 mm in thickness, with room temperature at outside of insulation. The porous media consisted of an upstream layer of 2–3 mm Al_2O_3 beads in 20 mm height and a downstream layer of 7.5 mm Al_2O_3 beads in 60 mm height. A 60 PPI SiC foam, with a length of 100 mm, an inner diameter of 10 mm and an outer diameter of 30 mm, was placed on top of the downstream porous media layer. A micro-tubular SOFC, with a length of 95 mm and an inner diameter of 5 mm, was inserted into the hollow SiC foam. The micro-tubular SOFC consisted of a Ni/YSZ anode-support layer, a Ni/ScSZ anode-active layer, a ScSZ electrolyte layer and a LSM/ScSZ

Table 1
Composition of biogas and sulfur content before and after desulfurization (from various biological wastes) [7].

Samples	Cow manure		Pig manure		Sludge and wet refuse	
Composition (%)						
CH_4	60.2		66.9		61.4	
CO_2	39.8		33.1		38.5	
H_2	Not detected		Not detected		0.14	
Sulfur content (ppm)	Before	After	Before	After	Before	After
Inorganic H_2S	1531	24.6	4011	5.4	99.6	3.5
Organic						
CH_3SH	11.66	0.50	0.92	Not detected	0.70	0.01
C_2H_5SH	0.99	0.36	0.40	0.07	0.33	0.17
Others	0.35	0.33	1.28	0.40	2.61	0.18