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Thermodynamic and exergoeconomic analysis of biogas fed solid oxide fuel cell power plants emphasizing on anode and cathode recycling: A comparative study

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ABSTRACT

Four different configurations of natural gas and biogas fed solid oxide fuel cell are proposed and analyzed thermoeconomically, focusing on the influence of anode and/or cathode gas recycling. It is observed that the net output power is maximized at an optimum current density the value of which is lowered as the methane concentration in the biogas is decreased. Results indicate that when the current density is low, there is an optimum anode recycling ratio at which the thermal efficiency is maximized. In addition, an increase in the anode recycling ratio increases the unit product cost of the system while an increase in the cathode recycling ratio has a revers effect. For the same working conditions, the solid oxide fuel cell with anode and cathode recycling is superior to the other configurations and its thermal efficiency is calculated as 46.09% being 6.81% higher than that of the simple solid oxide fuel cell fed by natural gas. The unit product cost of the solid oxide fuel cell-anode and cathode recycling system is calculated as 19.07$/GJ which is about 35% lower than the corresponding value for the simple natural gas fed solid oxide fuel cell system.

1. Introduction

Biogas is a byproduct of the decomposition of organic matter by anaerobic bacteria. It is a clean and renewable energy source that may be used instead of natural gas for cooking, producing hot water and steam or generating electricity. Biogas is normally produced in nature by the anaerobic degradation of organic waste in soil, marshes, ocean, etc. It is also produced in landfills where organic food waste degrades in anaerobic conditions. Meanwhile, it can be produced in anaerobic digesters. These are equipment (tanks) providing full control of the process and ensuring full biogas recovery [1]. Depending on the source of production, biogas composition will be different. The composition of biogas from different sources is summarized in Table 1. It is observed that, no matter what the source of production is, methane (CH_4) and carbon dioxide (CO_2) are the two main ingredients of biogas [2].

Several technologies are used to produce electricity from biogas three of which are the microturbines, fuel cells, and internal combustion engines. Among these systems, solid oxide fuel cell (SOFC) is an interesting choice because like most fuel cell technologies, have some advantages such as being modular, scalable, and efficient. In addition, they are not subjected to Carnot cycle limitations as they are not heat engines. In addition, relative to other fuel cells, the SOFCs are fuel-flexible and can reform methane internally, use carbon monoxide as a fuel, and tolerate some degree of common fossil fuel impurities, such as ammonia and chlorides. Furthermore, the SOFC is a high-temperature technology and can be combined with bottoming cycles such as gas turbines and steam turbines in cascade to have higher efficiency. Finally, the SOFCs are ideal for carbon capturing because the fuel and oxidant (air) streams can be separated facilitating high levels of carbon capture without substantial additional cost [3].

In recent years, feeding SOFC with biomass gas (syngas) and biogas has been practiced by researchers. However, relatively less research works have been published for biogas. The combination of biomass gasification with solid oxide fuel cells (SOFCs) is analyzed thermodynamically by Athanasioua et al. [4]. The results revealed that, under ideal conditions, the generated electricity by the SOFC unit could correspond to the 26.7% of the LHV of the biomass feed. It is also reported that the steam gasification is the most energy demanding process, but it facilitates the direct feed of the solid oxide fuel cell. Ozgur Colpan et al. [5] developed a model for direct internal reforming SOFC (DIR-SOFC) fed by syngas.

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Table 1
Main composition of biogas from different sources [2].

Components	Municipal waste	Wastewater	Agricultural/animal waste	Waste from agro-food industry	Landfill
CH_4 (vol.%)	50–60	61–65	60–75	68	45–70
CO_2 (vol.%)	34–38	36–38	19–33	26	35–40
N_2 (vol.%)	0–5	<1	<1	–	<3
O_2 (vol.%)	0–1	<0.5	<0.5	–	<0.2
H_2 (vol.%)	–	–	–	–	0–5
CO (vol.%)	–	–	–	–	0–3
H_2S (ppm)	70–650	700–2800	2100–7000	2800	10–200

The effect of recirculation ratio of the anode exit gas is taken into account and it is showed that for high current densities, as recirculation ratio increases the fuel mass flow rate, air utilization ratio, terminal voltage, output power, and cell electrical efficiency decrease. It is also declared that high recirculation ratios increase the system's complexity, in addition; its effect is not very significant at low current densities. Thermoeconomic optimization is performed for a wood-gasifier-SOFC system for small scale applications by Morandin et al. [6]. For the gasification process, two different biomass gasifiers (circulating fluidized bed and downdraft) are used. The study showed that very high system efficiencies can be obtained at the expense of really high system costs mainly because of the high costs of the fuel cell and the gasifier especially at the small scale level considered. The minimum specific plant costs of the most cost-effective configuration is found to be greater than 7000$/kW. Three types of biomass gasifiers integrated SOFC–GT systems are analyzed including both atmospheric and pressurized by Caliandro et al. [7]. The results showed the potential of the system converting woody biomass into electricity is greater than 70%. In addition, economic evaluations of systems revealed that for pressurized gasification options lower specific costs can be reached compared to atmospheric systems.

Using a biogas fed SOFC, a direct electricity production from wastewater treatment is proposed and analyzed by Yentekakis et al. [8]. Both the intermediate and high temperature solid oxide fuel cells based on 10 mol% Gd_2O_3 doped CeO_2 and 8 mol% Y_2O_3 stabilized ZrO_2 solid electrolytes, respectively, have been constructed and tested. Three biogas-fuelled SOFC heat and power cogeneration systems for application in residential dwellings are evaluated by Farhad et al. [9]. Different methods are used in the systems to prevent carbon deposition in the anode and an efficiency of up to 80.5% is obtained. For having minimum number of cells at a fuel utilization ratio of 80% different values of cell voltages are found. Borello et al. [10] modeled a SOFC based CHP system fed by biogas produced from anaerobic digestion of municipal waste integrated with solar collectors and storage unit. The results of transient model revealed that the heat supplied to the digester by the solar field would save 7.63 ton/y of biogas or the 4% of the total biogas production, equal to 131 GJ/y of electricity production by the SOFC. Using biogas from wastewater treatment facilities, Trendewicz and Braun [11] analyzed a biogas-fueled solid oxide fuel cell (SOFC) system for producing heat and power from the view point of techno-economic. They estimated that the baseline cost of electricity for the small, the medium, and the large plants is 0.079$/kW h, 0.058$/kW h and 0.05$/kW h, respectively. Gandiglio et al. [12] proposed a model to analyze the integration of waste water treatment biogas and solid oxide fuel cell considering both the internal and external reforming. The authors studied the influence of fuel utilization, internal reforming, biogas composition and steam-to-carbon ratio on both the SOFC and overall plant performance. Their results showed that an increase in the methane concentration of biogas would increase the electrical efficiency of the plant slightly. Siefert and Litster [13] investigated the performance of a biogas fed SOFC from the view point of economics. Their interesting result may be the one revealing that the anaerobic digestion-SOFC system is significantly more economic than the systems in which the biogas is sent to internal combustion engines or micro gas turbines. The evaluation of biogas fed SOFC power system considering three types of steam reforming, partial oxidation and autothermal reforming is investigated by Chiodo et al. [14]. It is found that the SOFC electrical efficiency is higher for the system using the steam reforming. Speidel et al. [15] combined fermentation, gasification and SOFC power system in a new process concept. Three configurations of considering the combinations are investigated. It is reported that the benefit of such a combination is that the waste heat can be used as a heat source in drying the fermentation waste. In addition, when steam from gasification gas is used for internal reforming of methane out of biogas at the anode of the SOFC, not only the complexity of the plant is reduced but also it has a great influence on the overall efficiency of the system.

As indicated above, the biogas fed SOFC power plants has been paid a lot of attention in recent years. Although, there are several publications concerned with the thermodynamic analysis of biogas fed SOFC systems, there is a lack of information on the economics of these systems and to the authors' knowledge, the exergoeconomic analysis of a biogas fed SOFC power system considering the recycling has not been investigated yet. The present work is an attempt to fulfill this gap. For the base case analysis, a 60% CH_4 and 40% CO_2 is assumed for the biogas composition. Considering the anode recycling (AR), cathode recycling (CR) and anode–cathode recycling (ACR) as well as the base case (without recycling) four different configurations are proposed and analyzed in detail. The exergetic cost theory is applied for each of the proposed cycles in order to pinpoint their optimum design conditions with respect to a given set of decision variables. A parametric study is performed for each system to identify the effects of decision variables on the energy and exergy efficiencies as well as on the specific cost of the systems' product. Finally, a comprehensively comparison is made between the performance of systems.

2. System configurations and description

Schematic diagrams of biogas fed simple SOFC system (without recycling) and the proposed SOFC systems are shown in Fig. 1. The simple SOFC system (Fig. 1a) consists of a SOFC stack, an after burner, an AC/DC invertor, a mixer, heat exchangers, blowers, and a water pump. The fuel (natural gas/biogas) and air are preheated through the fuel heat exchanger and air heat exchanger, respectively, after being pressurized with the help of fuel and air blowers. The heated air is sent to the cathode of the stack while the heated fuel is mixed with the water coming from the water heat exchanger before passing to the anode of the stack. The mixed stream experiences the reforming process which brings hydrogen-rich products to participate in the electrochemical reaction inside the fuel cell stack. An inverter is used to convert the DC power generated by the stack into grid quality electricity. The electrochemical reaction generates thermal energy a part of which is used to deliver the required heat for the internal reforming reaction, another part