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Effects of fuel processing methods on industrial scale biogas-fuelled solid oxide fuel cell system for operating in wastewater treatment plants

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ABSTRACT

The performance of three solid oxide fuel cell (SOFC) systems, fuelled by biogas produced through anaerobic digestion (AD) process, for heat and electricity generation in wastewater treatment plants (WWTPs) is studied. Each system has a different fuel processing method to prevent carbon deposition over the anode catalyst under biogas fuelling. Anode gas recirculation (AGR), steam reforming (SR), and partial oxidation (POX) are the methods employed in systems I–III, respectively. A planar SOFC stack used in these systems is based on the anode-supported cells with Ni–YSZ anode, YSZ electrolyte and YSZ–LSM cathode, operated at 800 °C. A computer code has been developed for the simulation of the planar SOFC in cell, stack and system levels and applied for the performance prediction of the SOFC systems. The key operational parameters affecting the performance of the SOFC systems are identified. The effect of these parameters on the electrical and CHP efficiencies, the generated electricity and heat, the total exergy destruction, and the number of cells in SOFC stack of the systems are studied. The results show that among the SOFC systems investigated in this study, the AGR and SR fuel processor-based systems with electrical efficiency of 45.1% and 43%, respectively, are suitable to be applied in WWTPs. If the entire biogas produced in a WWTP is used in the AGR or SR fuel processor-based SOFC system, the electricity and heat required to operate the WWTP can be completely self-supplied and the extra electricity generated can be sold to the electrical grid.

1. Introduction

Biogas gas is a renewable and alternative fuel that can assist to reduce the consumption of fossil fuel and emission of greenhouse gases. Pressure from environmental legislations on solid waste disposal methods in developed countries has increased the application of the anaerobic digestion (AD) process in wastewater treatment plants (WWTPs) for reducing waste volumes and generating useful by-products. One of the important by-products of this process is a biogas containing mainly methane and carbon dioxide, suitable for on-site heat and electricity generation required for the AD process.

Fuel cells convert the chemical energy of a fuel to electricity with high efficiency and they are promising power generation devices to use biogas as a fuel [1–5]. In the United States, if fuel cells are applied to convert biogas, generated in WWTPs, to electricity, there is potential to provide around 2 GW of electricity; the world-wide potential is approximately 13 GW [6]. The first project of this type was undertaken in California in 1999. The plant converted around 3400 m^3 of methane gas produced daily into hydrogen, fuelling two 200 kW phosphoric acid fuel cells to generate electricity and heat. The fuel cells provided 75–90% of the facility's electricity and the heat required for the digester, resulting in combined heat and power (CHP) efficiency between 80% and 90% [7]. The first European fuel cell-based system was developed in Germany in 2005. In this project, a 250 kW molten carbonate fuel cell provided the power and heat required for the WWTP using around 1500–2000 m^3 biogas produced per day [8].

Solid oxide fuel cell (SOFC) has significant advantages of fuel flexibility and high electrical and overall efficiencies. It can achieve a satisfactory performance even using biogas directly without the need for external hydrogen conversion [9–13]. Yi et al. showed that the electrical efficiency of an integrated SOFC system drops only around 1.1% once biogas with 60% methane and 40% carbon dioxide is used instead of natural [14]. In this paper, the performance of SOFC systems fuelled with biogas produced through AD process, with anode gas recirculation, external steam reforming, and partial oxidation, to supply electricity and heat required for WWTPs is studied.

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2. Biogas produced in WWTPs

In AD process, micro-organisms break down biodegradable materials in the absence of oxygen. Typically, this process begins with hydrolysis of the inlet materials to break down insoluble organic polymers to make them available to other bacteria. Acidogenic bacteria then convert the amino acids and sugars into hydrogen, carbon dioxide, ammonia, and organic acids. Furthermore, acetogenic bacteria convert the organic acids into acetic acid, along with additional hydrogen, carbon dioxide and ammonia. Methanogens finally convert these products to carbon dioxide and methane, which are the main constituent compounds of the biogas [15–17]. The AD process takes place over a wide range of temperatures from 10 to over 100 °C [18].

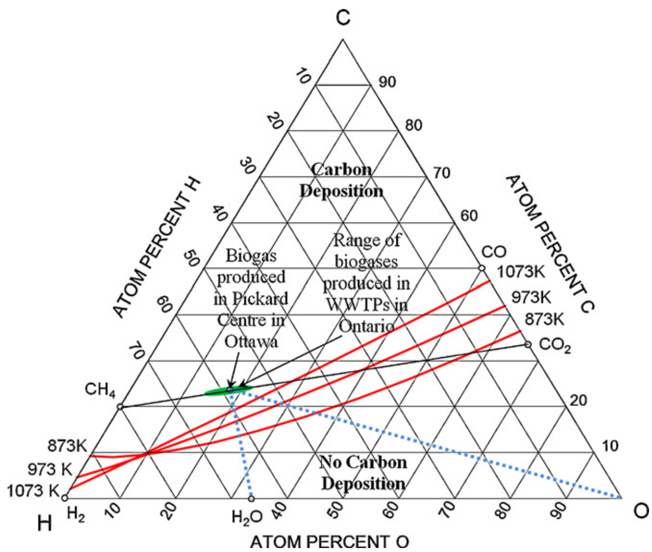

Fig. 1. The location of biogases produced in WWTPs in Ontario and carbon deposition boundary curves in the C–H–O ternary diagram.

Table 1
Biogas composition from WWTPs in Ontario [14].

Compound	Average	Range
CH_4 (%)	60.8	58–70
CO_2 (%)	34.8	30–43
O_2 (%)	1.5	0.1–2
N_2 (%)	2.4	1.2–7.1
H_2O (%)	0.01	0.01
H_2S (ppm)	570	2.5–3450
CO (ppm)	<100	0–100
H_2 (ppm)	<100	0–100
Silicon compounds (ppm)	n/a	0–2500

At present, a significant number of WWTPs in the province of Ontario in Canada employ the AD process and approximately 314,000 m^3 of biogas is produced per day. A majority of the AD-generated biogas in Ontario is simply flared off into the atmosphere [19]. Table 1 lists the key chemical species in the biogas produced from WWTPs in Ontario. Other compounds such as toluene, benzene, methyl chloride, and CFCs are present at levels below 10 ppm. The relative percentage of these gases in the biogas depends on the feed material and control of the process. The outlet temperature and pressure of the biogas are typically 30 °C and near atmospheric pressure, respectively [19].

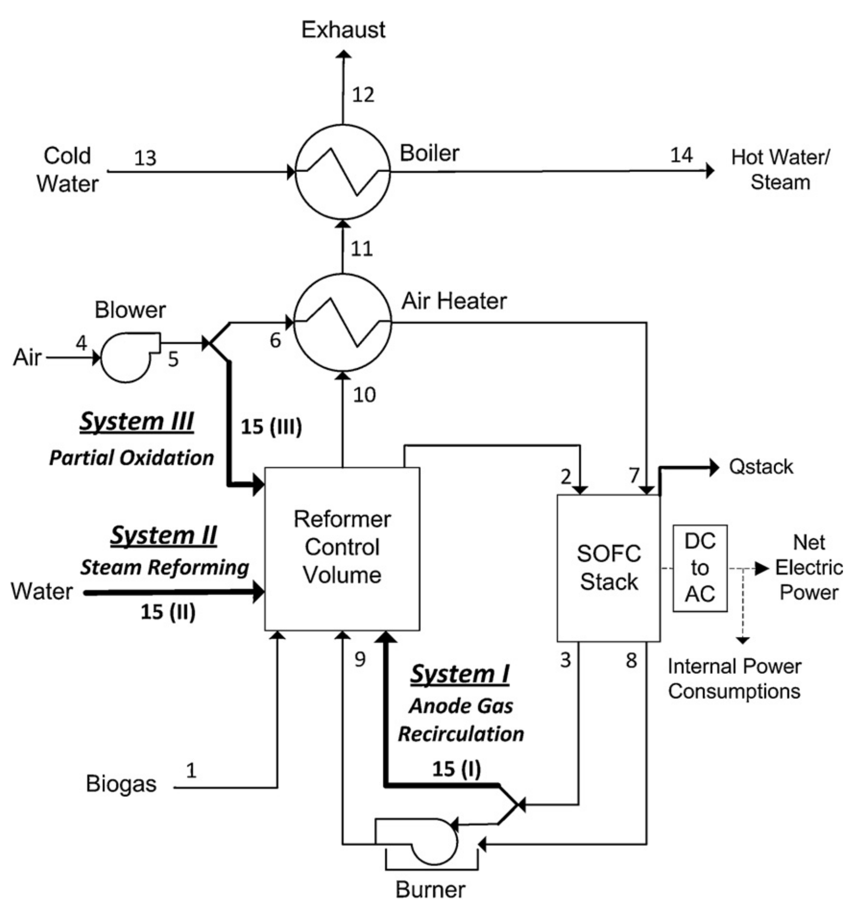

Fig. 2. Configuration of the biogas-fuelled SOFC systems (system I with anode gas recirculation, system II with steam reforming, and system III with partial oxidation reformer).