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CONCEPTUAL DESIGN OF ANAEROBIC DIGESTION GAS-FUELLED SOFC SYSTEMS TO GENERATE ELECTRICITY AND HEAT IN WASTEWATER TREATMENT PLANTS

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ABSTRACT

In this work, three solid oxide fuel cell (SOFC) systems to generate electricity and heat required for anaerobic digestion (AD) process in wastewater treatment plants (WWTPs) were studied. In each system, a different method was used to utilize the AD gas in SOFC to prevent carbon deposition over anode catalyst. The methods include anode gas recirculation, steam reforming, and partial oxidation. To evaluate the systems, a computer code has been developed for the simulation of planar SOFCs in cell, stack and system levels and applied for the calculation of system efficiencies. Accordingly, the key parameters affecting system performance were identified at steady state operating conditions. The results presented are based on the data obtained from the Robert O. Pickard Environmental Centre's WWTP in the city of Ottawa. The results showed that these SOFC systems are capable to supply the required electricity and heat for the plant and generate additional electricity for the electrical grid. Among the three SOFC systems, it was shown that the anode gas recirculation and steam reforming fuel processor-based systems are more suitable for WWTPs. The anode gas recirculation-based system can generate about 13.1% more electricity than the conventional system that is currently in operation in the Pickard Centre.

KEYWORDS: SOFC system, combined heat and power, anaerobic digestion process, wastewater treatment plant, fuel processor, performance evaluation.

INTRODUCTION

There is increasing pressure on developing nations to utilize fossil fuels because of a variety of economic and social reasons. It has long been recognized that this excessive fossil fuel consumption not only leads to diminishing the fossil fuel reserve, but also has a significant adverse impact on the environment. Fundamental changes are necessary in the energy sector in terms of global resource limitation, sustainable development and reduction of greenhouse gases to address some of these concerns.

The biogas produced in the wastewater treatment plants (WWTPs) is a renewable and alternative fuel that can help to reduce the consumption of fossil fuel. Anaerobic digestion (AD) process is widely used to treat wastewater sludge and organic wastes. In this process, micro-organisms break down biodegradable materials in the absence of oxygen. The by-product of the process is a biogas containing mainly methane and carbon dioxide that is suitable for heat and electricity generation. Utilizing the biogas produced in AD process also helps reducing the green house gases.

The AD facilities have been recognized by the United Nations Development Program as one of the most useful decentralized sources of energy supply [1]. In developing countries, simple home and farm-based anaerobic digestion systems offer a potential for low-cost energy for cooking and lighting. Pressure from environmental legislations on solid waste disposal methods in developed countries has increased the application of AD as a process for reducing waste volumes and generating useful by-products. In the United States, if fuel cells are used to convert AD gas to electricity, there is potential to provide on the order of 2 GW of electricity from WWTPs; the world-wide potential is approximately 13 GW [2]. At present, a significant number of WWTPs in the province of Ontario in Canada employ the AD process and about 314,000m^3 biogas is produced per day. The majority of the AD-generated biogas in Ontario is simply flared off to the atmosphere and, in some cases, a portion of the biogas is used to supply the required heat for the AD process [3].

The potential of using the produced biogas in WWTPs has long been widely recognized and current techniques are being developed to upgrade quality and to enhance energy use. Fuel cells that convert the chemical energy of fuel to electricity directly are promising power generation devices with high efficiency. The first project of this nature in California was undertaken with two 200 kW phosphoric acid fuel cells in 1999 to convert about 3400 m^3 of methane gas produced daily into hydrogen, which is used in the fuel cell to produce electricity and heat. The fuel cell provides 75 to 90% of the facility's electricity and the required heat for the digester with the CHP (combined heat and power) efficiency between 80 and 90 % [4]. The first European fuel cell-based system was developed in Germany in 2005. In this project, a 250 kW molten carbonate fuel cell provides the required power and heat for the WWTPs using about 1500-2000 m^3 biogas produced per day [5].

Because the solid oxide fuel cell (SOFC) has significant advantages of fuel flexibility and high electrical and CHP efficiencies [6], three biogas-fuelled SOFC CHP systems are evaluated in this study to operate in WWTPs to supply heat and electricity required for the plant and also to generate extra electricity for the electrical grid.

ANAEROBIC DIGESTION PROCESS

As shown in Fig. 1, the AD process begins with bacterial hydrolysis of the input materials to break down insoluble organic polymers such as carbohydrates and make them available for other bacteria. Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids. Acetogenic bacteria then convert these resulting organic acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide. Methanogens, finally are able to convert these products to methane and carbon dioxide [7-9]. A simplified generic chemical equation for the overall AD processes is as follows:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

Table 1 lists the key chemical species in the AD gas produced in WWTPs in Ontario. Other compounds such as toluene, benzene, methyl chloride, and CFC's are present at levels below 10 ppm. The relative percentage of these gases in biogas depends on the feed material and management of the process. The outlet temperature of the biogas is typically 30°C and at, or near, atmospheric pressure [3].

Table 1. Biogas composition from WWTPs in Ontario [3]

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

MODEL DEVELOPMENT

Three configurations related to fuel processing in biogas-fuelled SOFC CHP systems were evaluated for operation in WWTPs. Their process flow diagrams are shown in Figs. 2 to 4. These systems are comprised of an SOFC stack to generate electricity and heat; an air preheater to increase the air temperature before entering the stack; an air blower to overcome the pressure drop in the system; an after-burner to convert the chemical energy of the unutilized fuel to heat; a boiler to supply the required thermal energy for the AD process and space heating in a building; an inverter to convert the generated DC electric current to AC; and a fuel processor. The effects of the water pump and biogas blower were assumed to be negligible.

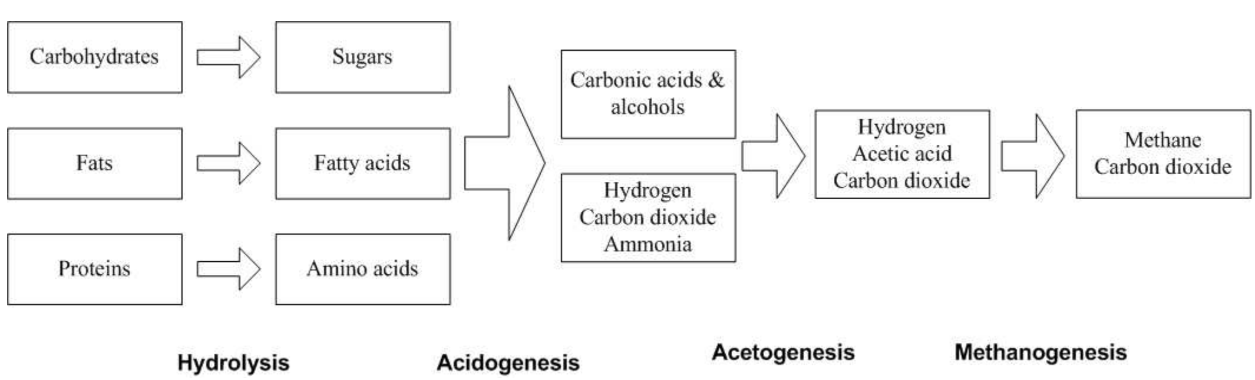

Fig. 1. The four basic biological and chemical stages of the AD process.

The fuel processor control volume is comprised of a biogas clean up system, heat exchanger(s) and an equipment required for mixing anode exit gas (system I), water (system II) or air (system III) with the fuel stream. In the biogas clean up system, the contaminants in the biogas are reduced to acceptable levels to avoid damaging the anode and/or reformer catalysts. The most attractive method to remove H_2S from the biogas is through the use of an activated carbon bed at 20-25 °C under atmospheric pressure. This method has been proven to be very effective (98% removal) at relatively low loadings of H_2S (<200 ppm) [3, 10-12]. In the case of high H_2S content, additional H_2S removal technologies are required to reduce the H_2S content to below 200 ppm prior to the use of an activated carbon bed. A similar absorption bed can also be used to remove silicon compounds [3].

Once biogas is cleaned, it must be processed or reformed to prevent carbon deposition over the anode catalyst. Carbon deposition deactivates the anode catalyst for the electrochemical and chemical reactions and reduces the performance of the SOFC stack gradually. The steam reforming (SR) [13-15], partial oxidation (POX) [16,17], auto-thermal reforming [18,19], and anode gas recirculation (AGR) [20,21] are typical fuel processing methods in SOFC systems.

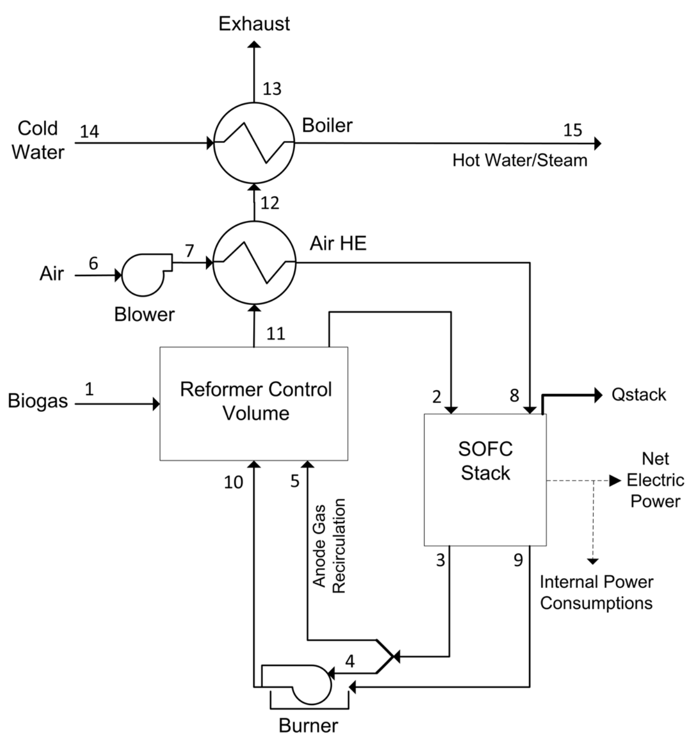

Fig. 2. Process flow diagram of system I with anode gas recirculation (AGR).

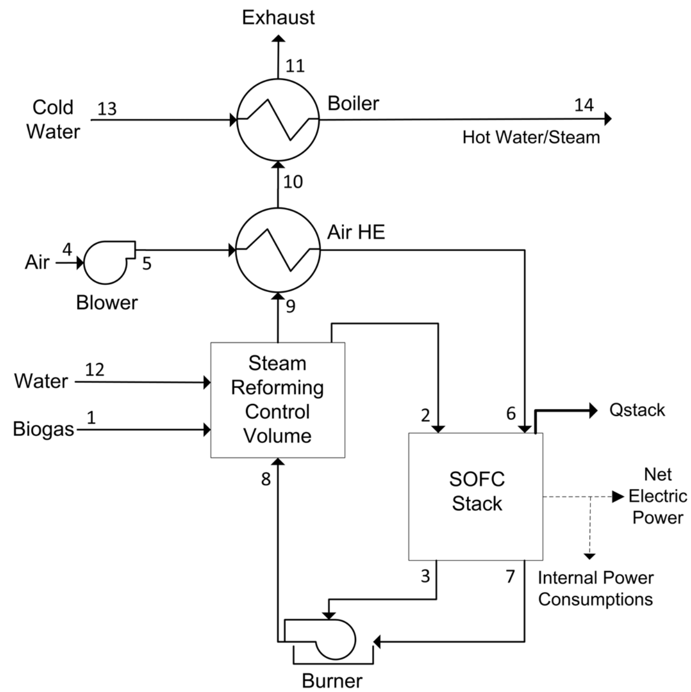

Fig. 3. Process flow diagram of system II with steam reforming (SR).

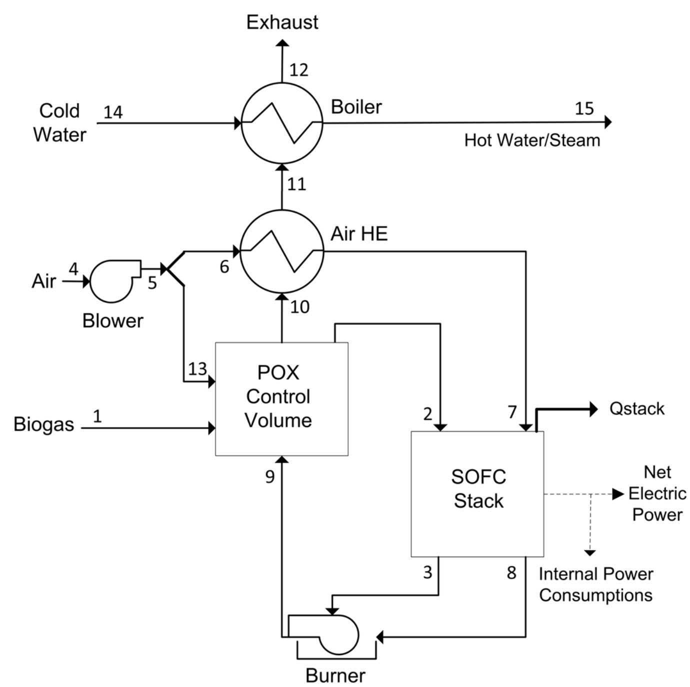

Fig. 4. Process flow diagram of system III with partial oxidation (POX) reformer.

To evaluate the systems, a computer code developed for the simulation of planar SOFCs at cell, stack and system levels was applied to calculate system efficiencies. At a cell level, a detailed model based on the combination of chemical and electrochemical reactions, thermodynamics and mass transfer was considered. At a stack level, heat transfer from the stack and its effect on the cell performance were taken into account. The balance of the plant such as heat exchanger, blower, and after-burner was thermodynamically modeled at steady state operating conditions. To prevent coke formation on anode, the required flow rate of anode exit gas recirculation for system I, water for system II and air for system III was determined from simulation based on thermodynamic equilibrium (the exit streams from the fuel processor control volume and the SOFC stack are assumed to be in thermodynamic equilibrium). After finding the properties, composition and flow rate of all streams of a system, the net electric power, heat, electric and CHP efficiencies are determined from Eqs. (1) to (4), respectively.

$$\dot{W}_{electric} = \dot{W}_{SOFC\,Stack} - \dot{W}_{blower} \quad (1)$$

$$\dot{Q} = \dot{m}_{water}\left(h_{hot\,water} - h_{cold\,water}\right) \quad (2)$$

$$\eta_{electric} = \frac{\dot{W}_{el}}{\dot{m}_{AD\,gas}\,LHV_{AD\,gas}} \quad (3)$$

$$\eta_{CHP} = \frac{\dot{W}_{el} + \dot{Q}}{\dot{m}_{AD\,gas}\,LHV_{AD\,gas}} \quad (4)$$

Where, $\dot{W}$, $\dot{Q}$, $\dot{m}$, h, LHV, and η represent the generated power, generated heat, mass flow rate, specific enthalpy, lower heating value, and efficiency, respectively.

RESULTS AND DISCUSSION

The evaluation of the SOFC systems was performed with the fixed parameters for anode supported SOFC cell, stack, and integrated SOFC/AD system as presented in Tables 2 to 4.

Table 2. Fixed parameters in an anode-supported SOFC cell for the simulation

Parameter		Value
Voltage		0.7V
Average temperature		800°C
Operating pressure		1 atm
Fuel inlet temperature		700°C
Air inlet temperature		700°C
Fuel utilization ratio		80%
Anode	thickness	518 μm
	porosity	0.33 (-)
	tortuosity	4 (-)
Cathode	thickness	45 μm
	porosity	0.33 (-)
	tortuosity	4 (-)
Electrolyte thickness		5 μm
Interconnect thickness		3000 μm
Cell active length		4 cm
Cell active width		4 cm

The anode supported cell used in the simulation was comprised of Ni/YSZ (Yttrium Stabilized Zirconia) anode, dense YSZ electrolyte and YSZ/LSM (Lanthanum Strontium Manganese Oxide) cathode.

Table 3. Fixed parameters in an anode supported SOFC stack for the simulation

Parameter		Value
Insulation	thickness	50 mm
	conductivity	0.025 $Wm^{-1}K^{-1}$
Emissivity of the outer surface		0.8 (-)

The characteristics of the biogas produced in the Robert O. Pickard Centre's WWTP presented in Table 4 are used for the simulation of the integrated SOFC/AD system. The Pickard Centre treats averagely 450,000 m^3/day domestic, commercial and industrial wastewater in the city of Ottawa. Prior to 1992, the biogas produced in the plant was burned and flared off to the atmosphere. From 1992 through 1997, the biogas was burned in boilers to produce hot water capable of delivering heat for space heating in the plant and the temperature control for the process. During low heat demand periods, the hot water was discharged to the sewer and the beneficial energy was wasted. In 1998, a CHP system converting 32% of the available energy in the biogas into electricity and 48% into heat was installed in the plant. In the CHP system, the biogas is burned by three combustion engines that drive generators to produce the electricity required for aeration blowers and centrifuges in the AD process. The generated heat has been more than enough to fulfill the heat demand in summer for the wastewater treatment plant, but has been fully used to heat the building space in the cold weather season.

Table 4. Fixed parameters in an integrated SOFC/AD system for the simulation

Parameter	Value
Biogas volumetric flow rate	27,000 m^3day^{-1}
Biogas composition	CH_4=61% CO_2=37.4% N_2=1.2% H_2S= 6.5 ppm
Pressure drop	0.3 bar
Air blower efficiency	62.5%
Inlet cold water temperature	35°C
Outlet hot water temperature	95°C
Inverter Efficiency	92%
Flue gas exhaust temperature	$T_{dewPoint}$+50°C
Pinch temperature in boiler	>20°C

Based on the cell, stack and system related input parameters given in Tables 2 to 4, the computer simulation results were obtained as shown in Table 5.

Table 5. The results obtained from the computer simulation

Parameter	System I	System II	System III
Generated electricity (MW)	2.92	2.78	2.14
Generated heat (MW)	2.33	2.14	3.21
Electrical efficiency (%)	45.1	43.0	33.0
CHP efficiency (%)	84.1	78.6	86.8
Exergy destruction (MW)	3.61	3.78	4.28
Number of cells in stack (-)	642892	547587	585785
Hot water flow rate (kg/s)	10.10	9.23	13.89
Heat transfer from stack (kW)	43.3	39.0	40.1
Ratio of the anode exit gas recirculation to the input fuel mass flow rate (-)	0.93	-	-
Ratio of the water to the input fuel mass flow rate (-)	-	0.38	-
Ratio of the air to the input fuel mass flow rate (-)	-	-	1.38

The electrical efficiencies of the SOFC-based systems were higher than that of the CHP system being operated in the Pickard Centre.

Among the studied SOFC systems, system I with the anode gas recirculation exhibited the maximum electrical efficiency of 45.1% that was 13.1% higher than that of the conventional CHP system in the Pickard Centre. The electrical efficiency of system II with a steam reforming fuel processor was also 11% higher than that of the conventional CHP system. The computer simulation with the average composition of the biogases produced from WWTPs in Ontario provided similar results.

Therefore, in case of operating system I or system II at any WWTP in Ontario, it is expected that the co-generation system can provide amount of electricity greater than the amount required to operate the plant. The extra amount of electricity can be sold to the electrical grid. The computer simulation for system III with the partial oxidation process provided the maximum CHP efficiency among the three suggested systems. Since the heat generated from systems I and II was enough for the WWTP, the CHP efficiency of the system III may not be as significantly important as the electrical efficiency, but can be considered meaningful for high heat demand periods. System II required the minimum number of cells in SOFC stack. The number of cells for system II was 17.4% less than that for system I.

Overall, it seems system I and system II were more suitable for the WWTPs. However, a detailed economic analysis would be required for selecting the best system applicable to co-generation in WWTPs.

To study the effect of the cell operating parameters on the performance of the SOFC systems, a sensitivity analysis was performed. The effects of the fuel utilization ratio, temperature of the inlet fuel and air to the stack, and the cell operating voltage on the electrical and CHP efficiencies and the electricity and heat generated in the SOFC systems were investigated in detail.

As shown in Fig. 5, the electrical and CHP efficiencies of the studied systems increased and decreased, respectively with increasing the fuel utilization ratio. The electrical efficiency of system II approached the value of system I as the fuel utilization increased.

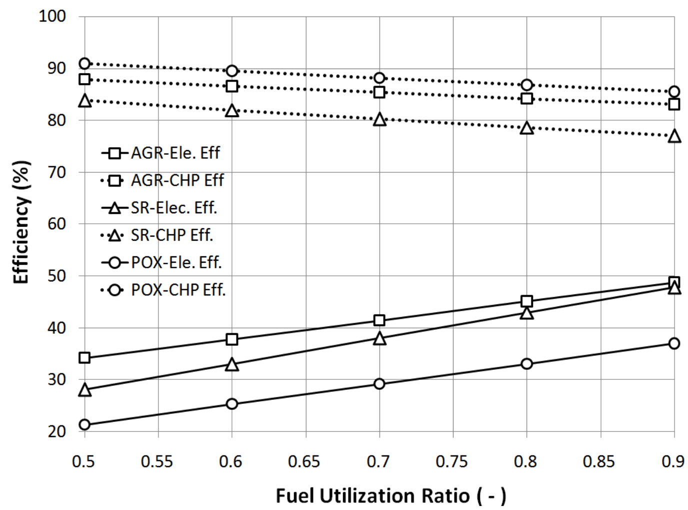

Fig. 5. Effect of fuel utilization ratio on the electrical and CHP efficiencies of the three studied SOFC systems.

Fig. 6 shows the electrical power generated from system I and system II are higher than the generated heat in the range of high fuel utilization ratio over 75%.

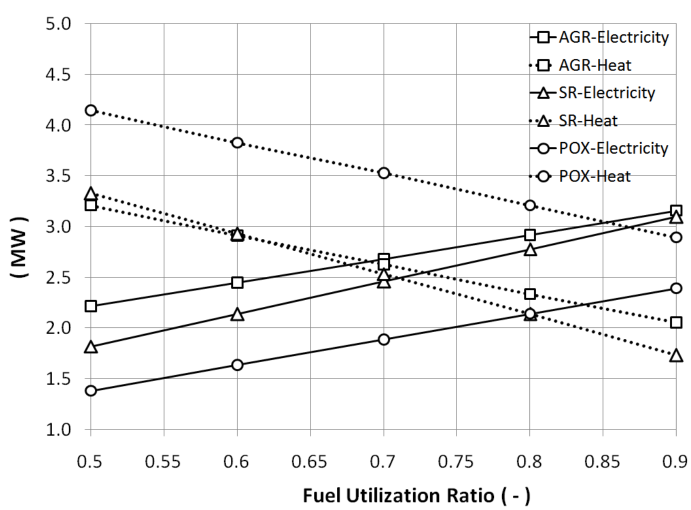

Fig. 6. Effect of fuel utilization ratio on electricity and heat generated in the three studied SOFC systems.

The electrical efficiency and the electricity generated in the systems I and II decreased with increasing the fuel temperature at the inlet of stack, as shown in Figs. 7 and 8.

Figs. 9 and 10 show that the electrical efficiency and the electricity generated in all of the systems decreased with increasing the air temperature at the inlet of stack.

As shown in Figs. 11 and 12, the electrical efficiency and the electricity generated in all the three systems significantly increased with increasing the cell operating voltage. However, the heat generated from the three systems decreased with increasing the cell operating voltage and the CHP efficiencies of the systems were relatively constant at the investigated cell operating voltage range.

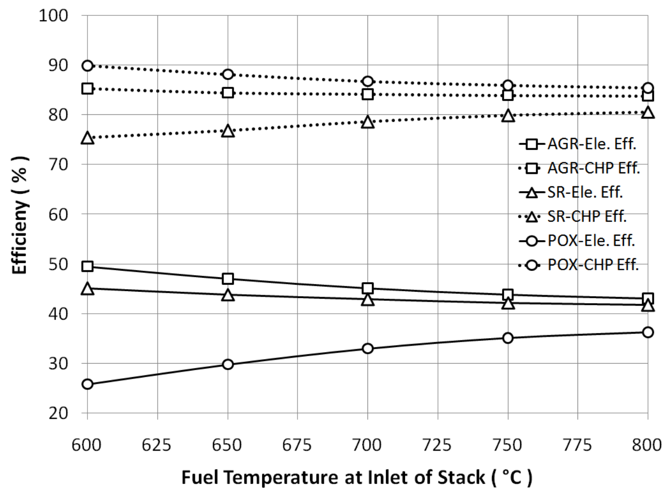

Fig. 7. Effect of fuel temperature at the inlet of stack on the electrical and CHP efficiencies of the three studied SOFC systems.

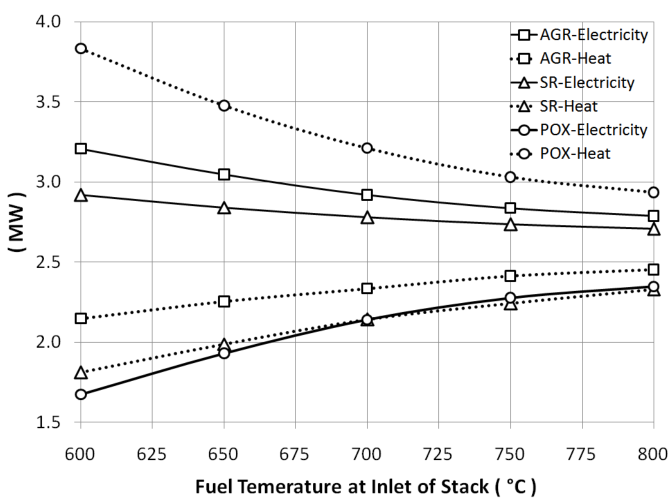

Fig. 8. Effect of fuel temperature at the inlet of stack on electricity and heat generated in the three studied SOFC systems.

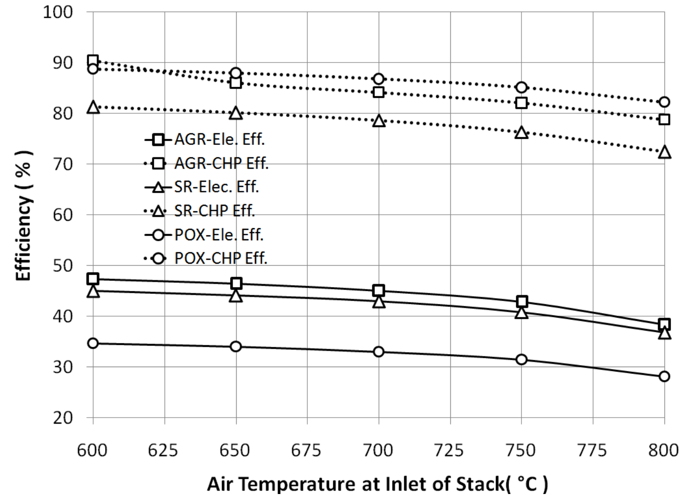

Fig. 9. Effect of air temperature at the inlet of stack on the electrical and CHP efficiencies of the three studied SOFC systems.

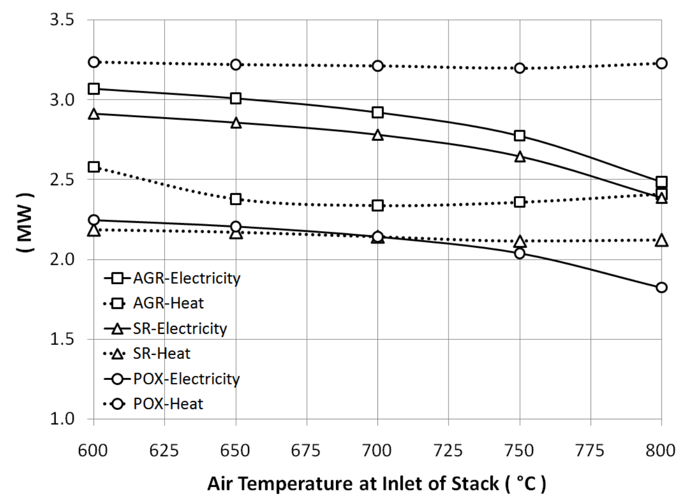

Fig. 10. Effect of air temperature at the inlet of stack on electricity and heat generated in the three studied SOFC systems.

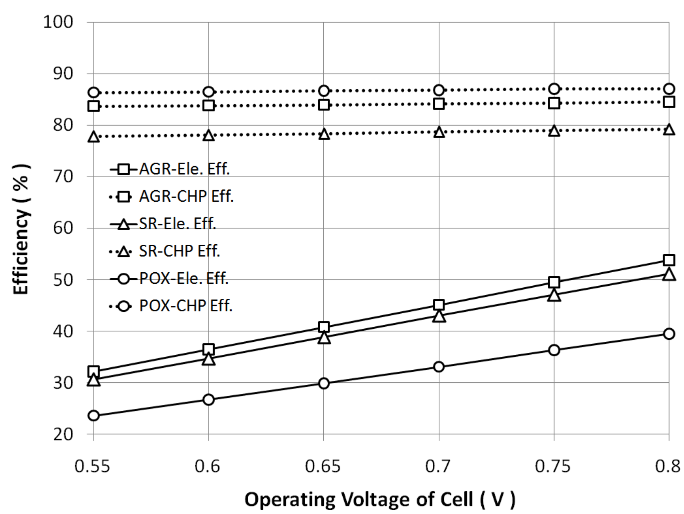

Fig. 11. Effect of operating cell voltage on the electrical and CHP efficiencies of the three studied SOFC systems.

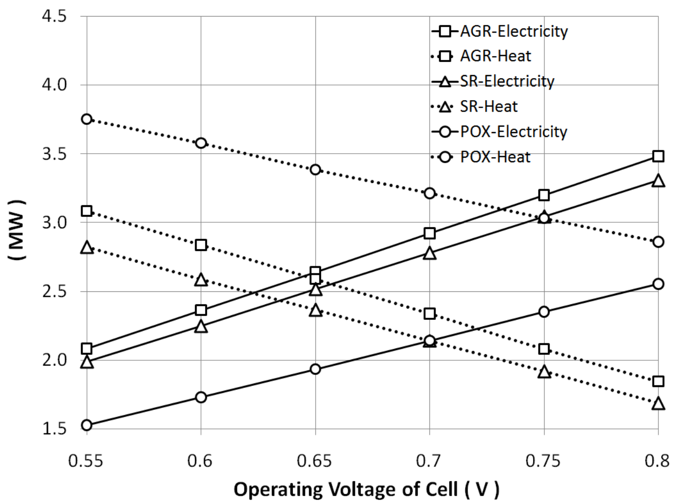

Fig. 12. Effect of cell operating voltage on electricity and heat generated in the three studied SOFC systems.

CONCLUSIONS

Biogas represents a significant source of alternative energy that remains largely undeveloped. It is possible to supply the electricity and heat required to operate WWTPs and sell the extra electricity if the AD gas produced from WWTPs can be utilized in the SOFC systems I or II. The SOFC systems are suitable to use the AD gas because the high amount of carbon dioxide in the AD gas can reduce the required amount of the anode exit gas recirculation (for system I), water (for system II), and air (for system III). The sensitivity analysis showed that the increase of the fuel utilization ratio and the cell operating voltage and the decrease of the air temperature at the inlet of SOFC stack increased the amount of electricity generated in the studied systems. The electricity generated from systems I and II decreased with increasing the fuel temperature at the inlet of SOFC stack, but increased from system III. Overall, system I and system II were more suitable for the WWTPs considered. However, a detailed economic analysis would be required for selecting the best system applicable to co-generation in WWTPs.

ACKNOWLEDGMENTS

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