Methane-fuelled SOFC CHP systems for brewery applications

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Abstract

The brewing process is characterized by a large consumption of water and energy. The great volume of wastewater containing high content of organic matter requires a suitable treatment. In this way, anaerobic digestion can be used for brewery wastewater treatment. This research examines the possibility of generating electrical and thermal energy using a SOFC CHP system running on biogas. If the system is fueled only by biogas produced from the brewery wastewater, 20-35% of the brewery total electrical energy demand can be provided by the proposed plant. In order to supply a substantial portion (~ 80%) of the facility's baseload power, natural gas should be purchased. Waste heat collected as steam provides only ~ 9% (natural gas + biogas) or 2.5% (biogas only) of the heat demanded by the brewery.

Key words: Fuel Cells. Methane. Wastewater

Theme area: Energy and Renewable Energy

Sistemas de geração combinada de calor e eletricidade com base em células a combustível do tipo óxido sólido abastecidas com metano para aplicação em cervejarias

Cervejarias são caracterizadas por um elevado consumo de água e energia no processo de fabricação. O grande volume de água residual que contém alto teor de matéria orgânica requer um tratamento adequado. Desse modo, a digestão anaeróbia pode ser empregada para o tratamento de águas residuais da cervejaria. Esta pesquisa explora a possibilidade de geração de energia elétrica e térmica por meio de um sistema SOFC CHP abastecido por biogás. Se o sistema for abastecido somente com o biogás oriundo do tratamento da água residual da cervejaria, 20-35% da demanda total de energia elétrica podem ser supridos pela planta proposta. A fim de se obter uma porção substancial (~ 80%) da demanda elétrica, gás natural deve ser utilizado conjuntamente com o biogás. O calor produzido na planta, que é transferido através de vapor d'água, fornece apenas ~ 9 (gás natural+biogás) ou 2,5% (somente biogás) da demanda de calor da cervejaria.

Palavras-chave: Células a combustível. Metano. Águas residuais

Área Temática: Energia e energias renováveis

1 Introduction

The brewing sector holds a strategic economic position with an annual world beer production exceeding 1.34 billion hL in 2002 (FAO, 2013). The brewing process is known as being energy intensive and by a large water volume consumption. Brewery wastewater, like many food and drink related wastewaters, can be treated very efficiently using a high rate anaerobic biological process. The anaerobic process can typically remove up to 85% of the total Chemical Oxygen Demand (COD) load from the wastewater and convert it into biogas, which can be used as a renewable energy source to replace fossil fuel in the brewery boilers, or as fuel to generate heat and electricity in a CHP (Combined Heat and Power) plant (VEOLIA WATER SOLUTIONS & TECHNOLOGIES, 2011). In this context, it is worth mentioning Sierra Nevada Brewery, located in Chico, California, as an example of a well-designed brewery that employs methane produced from its wastewater anaerobic digester in a fuel cell CHP system (the brewery has installed four molten carbonate 250 kW direct fuel cells from Fuel Cell Energy Inc. that run on a combination of natural gas and methane captured from biogas). The fuel cell CHP system of 1 MW_{el} provides a substantial portion of the facility's baseload power while the waste heat collected as steam is used for the brewing process as well as other heating needs onsite. The biogas was integrated into the project in 2006, displacing 25-40% of natural gas use (DOE, 2011).

In this way, the present research work will closely examine the potential use of biogas from breweries' wastewaters digester in a SOFC (Solid Oxide Fuel Cells) CHP system for electricity and heat generation. The three following cases are under analysis:

- Large brewery, with SOFC CHP system running on natural gas + methane from biogas;
- Medium brewery, with SOFC CHP system running on natural gas + methane from biogas;
- Medium brewery, with SOFC CHP system running totally on biogas generated from wastewater.

The work is aimed at providing meaningful values for the CHP system, for each of the operation cases, considering the respective beer production, and verifying what portion of the electricity and heat demanded by the facility can be provided by the SOFC CHP system.

2 Methodology

2.1. Estimating biogas production from breweries' wastewater

The quantity of brewery wastewater will depend on the production and the specific water consumption. Brewery wastewater has high organic matter content; the concentration of which is usually measured as Chemical Oxygen Demand (COD) or Biological Oxygen Demand (BOD). The COD consists mainly of easily biodegradable organic compounds such as sugars, ethanol and soluble starch. Because of the high biodegradability, biological treatment (anaerobic and aerobic) is the most widely used treatment process for brewery wastewater (VEOLIA WATER SOLUTIONS & TECHNOLOGIES, 2011).

The following assumptions were considered for estimating biogas production from brewery wastewater:

- Breweries produce typically 2-6 hL of wastewater per hL of beer produced;
- The wastewater has a COD concentration in the range of 2000-6000 mg/L;
- A typical anaerobic treatment of brewery wastewater generates about 0.4-0.5 m^3 of biogas per kg of COD removed;

Based on these data, in the present work it will be taken into consideration an average COD concentration of 4kg per cubic meter of wastewater, and 0.4 m^3 of biogas per kg of COD removed. From this, the rule-of-thumb values adopted in the research were determined:

- 1.6 m^3 of biogas per cubic meter of treated wastewater; this corresponds to 0.96 m^3 of methane per cubic meter of treated wastewater (for biogas composed of 60% CH_4 + 40% CO_2);

2.2. Simulation of SOFC CHP plant

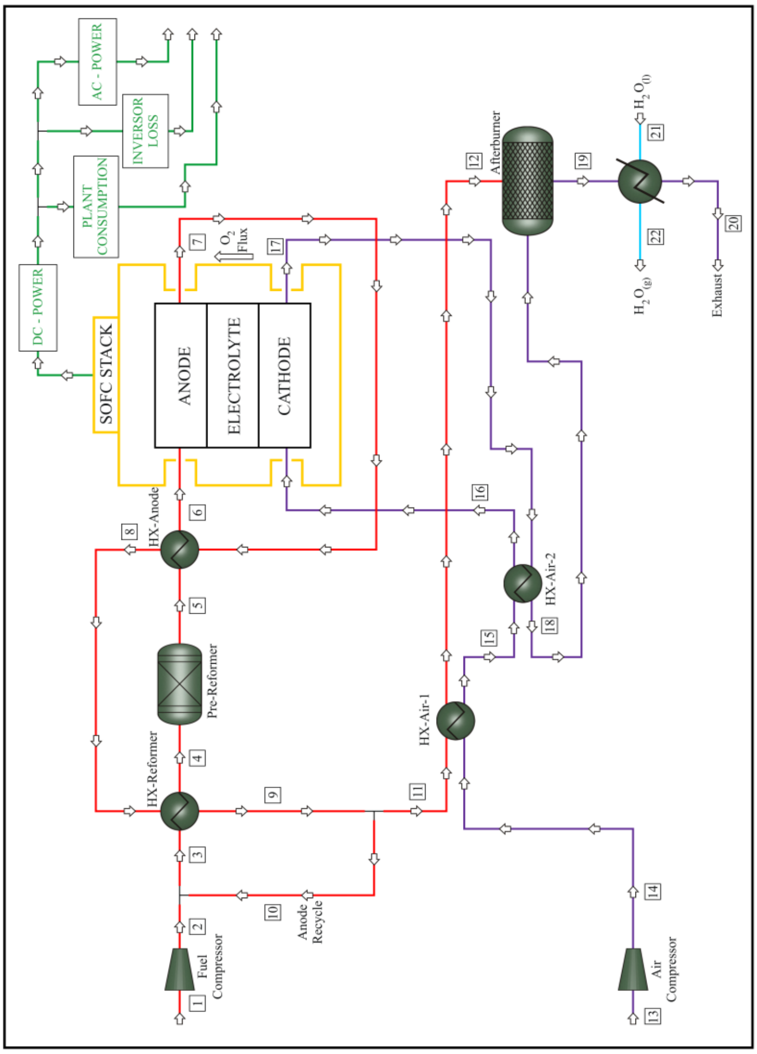
The simulation of the SOFC CHP system with anode exhaust gas recycling is based on an iterative approach that considers the composition of the anode exhaust gas as a variable, and the SOFC system model is solved until the assumed variables are recalculated. The procedure is repeated until the difference in the values of the assumed and calculated variables satisfies the accuracy of 10^{-6}. The gas reformer and afterburner are modeled as Gibbs reactors, and the planar SOFC is modeled according to the steady-state 1D model described by Kang et al. (2009). The electrochemical model and the heat balance applied to each control volume are described by Saebea *et al.* (2012). The model employed in the present study was coded and solved using MATLAB and FactSage software and databases.

For estimating the total electrical and heat demand of a brewery, it was considered that well-run breweries use 10kWh/hL electricity and 150MJ thermal energy per hectoliter (OLAJIRE, 2012).

Table 1 - Input data for computer simulation of the CH_4-fueled 1 $MW_{el.}$ SOFC CHP system

Parameter	Value
Cell operating temperature	1073 K
Fuel inlet temperature to the SOFC stack	923 K
Fuel utilization ratio	62-63%
Anode and Cathode thickness	30µm
Electrolyte thickness	150µm
Excess air ratio	3.0
% External Reforming	≈ 20
Inlet cold water to steam generator	293K
Heat loss reformer	0.5% LHV methane
Heat loss stack	2.5% LHV methane
Heat loss afterburner	1% LHVmethane
Single cell active area	552cm^2 (1 MW and 10kW) and 100cm^2 (2.4kW)
Number of cells	8140 (1MW), 81 (10 kW),113(2.4kW)
Pressure drop in the system	0.24 atm
Air compressor efficiency	62%
Fuel compressor efficiency	71.3%
DC to AC inversor efficiency	93%
Flue gas exhaust temperature	$T_{dew\ point}$+50K
Inlet methane (LHV) (kW)	1817(1MW), 18.17 (10kW), 4.54 (2.4kW)

Figure 1 – Configuration of natural gas - or biogas-fuelled SOFC CHP systems

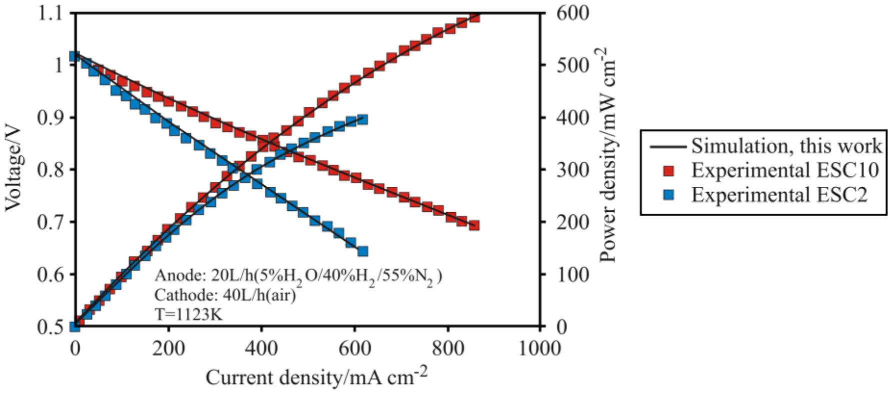


3 Results

3.1. Verification of the prepared computer code

The performances of commercially available electrolyte supported cells (ESC2) and (ESC10) produced by H.C. Starck Company were simulated in order to validate the developed computer code at the cell level. The ESC10 cell is composed of Ni/GDC (Gadolinia-doped Ceria) anode, dense ScSZ electrolyte and YSZ/LSM (lanthanum strontium manganese oxide) cathode. The ESC2 cell is composed of Ni/GDC anode, YSZ/LSM cathode and dense YSZ electrolyte. Figure 2 shows the voltage and power density of the ESC cells obtained by the computer simulations carried out in the present work along with experimental data reported by the manufacturer. From these results, one can see that theoretical results are in excellent agreement with the experimental ones. ESC10 was chosen as the fuel cell for the CHP plant due to its superior performance when compared to ESC2.

Figure 2 – Validation of the computational simulation results with the experimental data for commercially available electrolyte supported cells (ESC2) and (ESC10)



3.2. Simulation of 1MW SOFC CHP system operating on natural gas + digester gas for a large brewery

Figure 3 shows the molar fraction of the species along the SOFC anode and cathode channel, for the 1MW SOFC CHP system. At the channel inlet, methane is reformed by CO_2 and H_2O, producing H_2 and CO. Note that only after CH_4 has been completely reformed that H_2 and CO can be electrochemically oxidized to H_2O and CO_2. Therefore, at the anode channel outlet, the gas is composed mainly of H_2O and CO_2.

Figure 3 – Profile of the molar fractions of the species along the anode and cathode channel

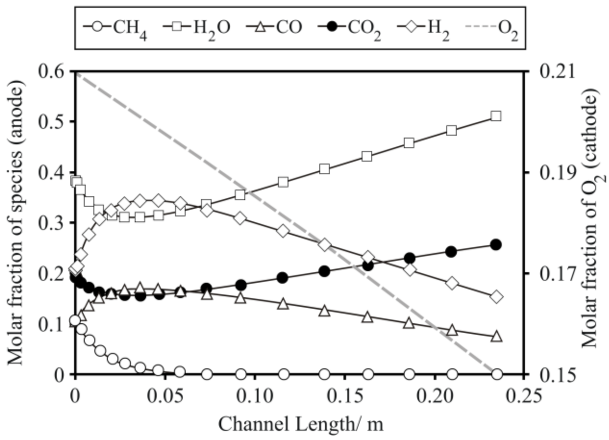


Table 2 shows the total volume of methane needed for running the SOFC CHP $1MW_{el.}$, as well as the computed values for DC and AC power, electrical and thermal efficiencies and the amount of steam generated. As mentioned before, Sierra Nevada Brewery adopted a $1MW_{el.}$ fuel cell CHP system, and according to the data reported by the technical staff of that brewery, it is possible to displace 25-40% of natural gas use with digester gas. In this way, 1178 m^3 of CH_4 per day could come from biogas. Based on the data of the section 2.1, one can see that a daily production of beer of nearly 3070 hL is required. Therefore, the annual production should be of ~ 1.100.000 hectoliters. In fact, according to different sources (BREWBOUND, 2013), the annual production of Sierra Nevada brewery is around 1.000.000 barrels (~1.170.000 hL), which is in agreement with our simulation. The SOFC CHP $1MW_{el.}$

can provide ~ 80 and 9% of the electrical and thermal energy demand of the brewery, respectively.

Table 2 - Simulation results for 1 MW_{el} SOFC CHP plant

Total CH_4 m^3 per day	4712.2
CH_4 from natural gas m^3 per day	3534.0
CH_4 from biogas m^3 per day	1178.0
DC Power/kW	1134.3
Total consumption in compressors /kW	21.8
Inversor Loss/ kW	79.4
AC Power (kW)	1054.9
Plant consumption (~ 6% of AC Power, kW)	61.6
Net AC Power (kW)	993.3
DC electrical efficiency (%)	62.4
AC electrical efficiency (%)	54.7
Heat recovered (kW)	476.6
Thermal efficiency (%)	26.2
CHP efficiency (%)	80.9
steam generation mol/day	876873.6

3.3. Simulation of 10kW SOFC CHP system operating on natural gas + biogas for a medium brewery

Using the same approach adopted by the Sierra Nevada Brewery, considering 25% of methane coming from biogas, one can see that 11.78 m^3 of CH_4 should be produced daily, which requires a daily production of beer of 30.7 hL, corresponding to an annual production of 11050 hectoliters, which is typical for a medium brewery. It is worth pointing out that the net electrical efficiency and the CHP efficiency are essentially the same for all the system sizes, as can be seen by comparing Tables 2 and 3, which is a remarkable characteristic of the SOFC CHP systems.

Table 3 - Simulation results for 10 kW_{el} SOFC CHP plant

Total CH_4 m^3 per day	47.1
CH_4 from natural gas m^3 per day	35.4
CH_4 from biogas m^3 per day	11.8
DC Power/ kW	11.3
Total consumption in compressors /kW	0.2
Inversor Loss/ kW	0.8
AC Power (kW)	10.5
Plant consumption (~6% of AC Power, kW)	0.6
Net AC Power (kW)	9.9
DC electrical efficiency (%)	62.2
AC electrical efficiency (%)	54.5
Heat recovered (kW)	4.9
Thermal efficiency (%)	27.1
CHP efficiency (%)	81.6
steam generation mol/day	9072

The SOFC CHP 10kW$_{el.}$ can provide ~ 80 and 9% of the brewery electrical and thermal energy demand, respectively.

3.3. Simulation of a SOFC CHP system operating totally on biogas produced from wastewater, assuming a medium brewery

The same medium brewery, with an annual production of 11050 hectoliters of beer, is able to produce 19.64125 m^3 per day of biogas. Table 4 shows the results for the SOFC CHP system operating exclusively on this volume of biogas. As can be seen, with a net AC power of 2.4 kW, a daily electrical and thermal energy of 58.56 kWh and 112 MJ, respectively, can be provided by the stack. These values correspond to 20 and 2.5% of the electrical and thermal demands of the brewery, respectively.

Table 4 - Simulation results for 2.4 kW$_{el}$ SOFC CHP plant

DC Power/kW	2.8
Total consumption in compressors /kW	0.05
Inversor Loss/ kW	0.2
AC Power (kW)	2.6
Plant consumption (~6% of AC Power)	0.15
Net AC Power (kW)	2.4
DC electrical efficiency (%)	61.6
AC electrical efficiency (%)	53.9
Heat recovered (kW)	1.3
Thermal efficiency (%)	28.5
CHP efficiency (%)	82.4
steam generation mol/day	2376

4 Conclusions

The results from the present research show the possibility of obtaining electrical and thermal energy from SOFC CHP systems running on natural gas plus biogas or exclusively on biogas. In order to provide a substantial portion (~ 80%) of the facility's baseload power, natural gas should be purchased. If the SOFC CHP system is fueled only by biogas produced from the treatment of the brewery wastewater, ~ 20% of the electrical energy demand of the brewery can be provided by the proposed plant. The economy in the electrical energy could reach 35% if the upper limits for COD (6000 mg/L) and biogas production (0.5 m^3 per kg of COD removed) were considered. The waste heat that is collected as steam provides ~ 9% (natural gas + biogas case) and 2.5% (case of biogas only) of the heat demand of the brewery.

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