01 Sep 2013

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Recommended Citation
T. A. Hamad et al., "Study of a Molten Carbonate Fuel Cell Combined Heat, Hydrogen and Power System: End-Use Application," *Case Studies in Thermal Engineering*, vol. 1, pp. 45-50, Elsevier, Sep 2013.
The definitive version is available at https://doi.org/10.1016/j.csite.2013.09.001

Case Studies in Thermal Engineering 1 (2013) 45–50

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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

Study of a molten carbonate fuel cell combined heat, hydrogen and power system: End-use application

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ARTICLE INFO

Article history:
Received 22 August 2013
Received in revised form
5 September 2013
Accepted 5 September 2013
Available online 13 September 2013

Keywords:
CHHP system
A molten carbonate
Anaerobic digestion
Renewable energy

ABSTRACT

To address the problem of fossil fuel usage and high greenhouse gas emissions at the Missouri University of Science and Technology campus, using of alternative fuels and renewable energy sources can lower energy consumption and greenhouse gas emissions. Biogas, produced by anaerobic digestion of wastewater, organic waste, agricultural waste, industrial waste, and animal by-products is a potential source of renewable energy. In this work, we have discussed the design of CHHP system for the campus using local resources. An energy flow and resource availability study is performed to identify the type and source of feedstock required to continuously run the fuel cell system at peak capacity. Following the resource assessment study, the team selects FuelCell Energy DFC1500™ unit as a molten carbonate fuel cell. The CHHP system provides electricity to power the university campus, thermal energy for heating the anaerobic digester, and hydrogen for transportation, back-up power and other needs. In conclusion, the CHHP system will be able to reduce fossil fuel usage, and greenhouse gas emissions at the university campus.

1. Introduction

The Missouri University of Science and Technology (Missouri S&T) campus in Rolla, Missouri, USA is a relatively small campus with 1.15 km^2 and approximately 6500 students on campus. The university is one of the City of Rolla's largest electric power consumers with a peak demand of 6.36 MW_e and annual electric energy consumption of 2.55×10^6 kWh/yr. Currently, electrical power for the university campus is purchased from RMU and distributed from the substation and switchgear located at the campus power plant. In addition, the university thermal power plant generates electricity with a back pressure steam turbine, accounting for an additional 10% of electricity. Biogas produced by anaerobic digestion of wastewater, organic waste, agricultural waste, and industrial waste is a potential source of renewable energy. Treated biogas can be used to generate CHHP using a molten carbonate fuel cell. The power generated by the CHHP system is used at various locations on the campus to reduce the total electric power purchased and minimize air pollution [1–3]. In addition, the CHHP system has higher efficiency than other distributed generation plants of similar size [4,5]. The hydrogen generated is used to power different applications on the university campus including personal transportation [6,7]. The research

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2214-157X
http://dx.doi.org/10.1016/j.csite.2013.09.001

Nomenclature

CHHP	combined heat, hydrogen and power system
DFC	direct fuel cell
MSW	municipal solid waste
RMU	Rolla municipal utilities
MTNF	mark twain national forest
AOG	anode outlet gas
HEX.W.G	heat exchanger water and gas
AGO	anode gas oxidizer
E-BOP	electrical balance of the plant
MBOP	mechanical balance of the plant
CHP	combined heat and power
UPS	uninterruptable power supply
VS	volatile solids

presented in this paper was performed as part of the 2012 Hydrogen Student Design Contest. The contest rules specified the use of FuelCell Energy fuel cell and biogas with 60% methane and 40% carbon dioxide concentration. An energy flow and resource availability study was performed to identify the type and source of feedstock required to continuously run the CHHP system to produce maximum capacity of electricity, heat recovery and hydrogen [8].

2. Resource assessment

2.1. Feedstock source identification

During the assessment, "locally available feedstock" was defined as one which is within 20 km of Rolla. The largest source of locally available feedstock is MSW averaging 60 t/day. Of this, approximately 33% is organic waste including 17% food waste. The campus plans to partner with the City of Rolla and will start an "Organic Waste Collection Program" to collect organic waste. Food waste collected daily is mixed with the trash and the sanitary sewer and is connected to the city's main sewer lines.

3. Experimental procedure

3.1. CHHP system technical design

The design discussed in this paper has three major systems: (i) anaerobic digestion system, (ii) CHHP system consisting of a DFC1500™ fuel cell unit, and (iii) hydrogen compression, storage, and dispensing system [8]. These systems were designed based on the results from the feedstock assessment and the biogas production from local resources. It was found that the anticipated methane production after biogas treatment is 260 m^3/h with a heat content of 156 MJ/m^3.

The anaerobic digestion system and the CHHP system are sized based on the amount of locally available feedstock and the amount of methane gas generated respectively [9]. The hydrogen recovery, purification, compression, storage, and distribution system are designed based on the hydrogen demand on the university campus and the 65% fuel utilization rate [10,11].

3.2. Anaerobic digestion, gas treatment system and fuel storage

Digester and biogas production are shown in Fig. 1 [9]. The feedstock from the cement storage bin is transported via a screw feeder to a hygienisation unit where it is heated to 70 °C for 1 h to remove all the pathogens [12]. After heating, the feedstock is transported to a 45.4 m^3 equalization tank where the biomass is mixed to form a homogenous mixture before being fed into the digester [13]. Biogas from the anaerobic digestion is stored in a buffer tank which supplies biogas to the gas treatment system. The treatment system uses pressure swing adsorption (PSA) technology to separate methane present in the biogas [14–18].

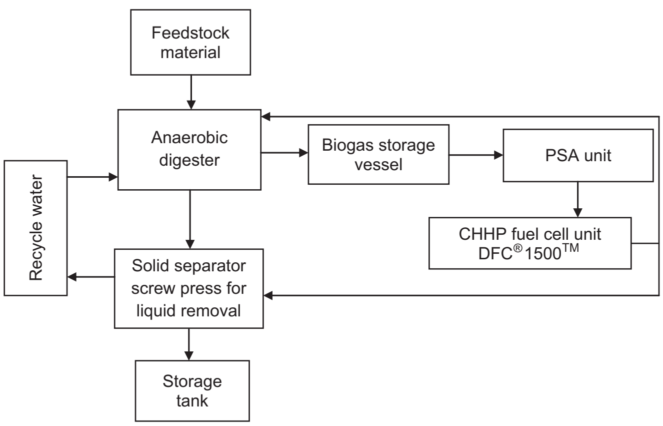

Fig. 1. Flow diagram for digester and biogas production.

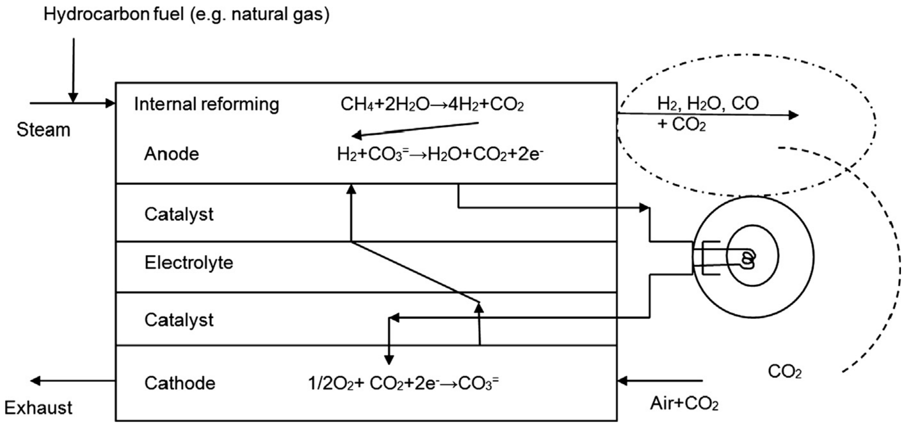

Fig. 2. Internal reforming DFC® technology.

3.3. DFC1500™ FuelCell power plant

The anaerobic digester system will be able to supply 90% of fuel for the DFC1500™ unit from locally available feedstock. The remaining 10% fuel required will be purchased from the utility company. In order to accommodate the fluctuations in gas quality, the natural gas used in the design contains 98% methane and 2% carbon dioxide (with an average heating value of 156 MJ/m^3). Fig. 2 shows the reactions taking place inside the fuel cell.

3.3.1. AOG calculations

The anode outlet gas calculations are made based on the following AOG composition calculation document provided by FuelCell Energy [19].

$$CH_4+2H_2O \rightarrow 4H_2+CO_2 \quad (1)$$

Assuming 1 mol of CH_4 is fed to the DFC® system; only 65% of the hydrogen (i.e. 2.6 mol) reacts at the anode and will result in the following equation. Corresponding reaction at anode:

$$2.6H_2+2.6CO_3{}^{2-} \rightarrow 2.6H_2O+2.6CO_2+2e^- \quad (2)$$

The remaining 35% of the H_2 (1.4 mol) and the entire CO_2 (1 mol) from Eq. (1) goes directly to the AOG. Combining the products from (2) and 1.4 mol of H_2 and 1 mol of CO_2 from (1) results in the following AOG composition.

$$1.4H_2+2.6H_2O+3.6CO_2 \quad (3)$$

But in reality, another internal reaction takes place in the DFC® fuel cell. One third of the H_2 in Eq. (3) (i.e. 0.47 mol) needs to back-shifted to H_2O and CO resulting in Eq. (4).

$$0.47H_2+0.47CO_2 \rightarrow 0.47H_2O+0.47CO \quad (4)$$

Combining Eqs. (3) and (4) yields the following products:

$$0.93H_2+3.07H_2O+0.47CO+3.13CO_2 \quad (5)$$

Hence for every 1 mol of CH_4 the following AOG composition is obtained as on a molar percentage basis H_2O, CO_2, CO, and H_2 are 40.4, 41.2, 6.2, and 12.2 respectively with assuming 100% CH_4. The inlet fuel requirement of the DFC1500™ unit based on 156 MJ/m^3 input fuel is calculated and found to be 286 m^3/h consists of 198 mol of CH_4 and 4 mol of CO_2. The actual AOG flowrate of methane (mol/min) for H_2, H_2O, CO, and CO_2 is calculated using Eq. (5) are 156.5, 516.8, 79.1 and 526.9 respectively.

3.3.2. Hydrogen recovery and cleaning system

In order to achieve a CHHP system, hydrogen from the AOG must be recovered, cleaned and distributed. The details of the hydrogen recovery and purification process are shown in Fig. 3. The AOG outlet pressure is 1.08 bar and outlet temperature to be 600 °C.

$$H_2O+CO \rightarrow H_2+CO_2 \quad (6)$$

The entire CO present in the AOG reacts with H_2O to produce an additional 242 kg of H_2 and of 4×10^3 kg of CO_2 per day. The water vapor is condensed and recycled to the anode side of the fuel cell for the internal reforming of methane. The amount of water produced during condensation is greater than the fuel cell requirement with the excess water is sent into the sewer. The CO_2 and H_2 coming out of the water–gas shift reactor is cooled and separated using a PSA unit. The hydrogen coming out of the PSA unit is compressed and used for different applications on the university campus. Outside air is preheated using the heat exchanger and is mixed with the CO_2 coming out the PSA unit in AGO. The mixture is then transferred to the cathode to complete the cathode reaction as shown in the following equation.

$$CO_2+0.5O_2+2e^- \rightarrow CO_3 \quad (7)$$

The flow rates of gases at different stages were tabulated in Table 1. These flow rates are necessary to calculate the amount of hydrogen generated, amount of outside air needed, and amount of exhaust gas. The amount of hydrogen generated per day is 650 kg.

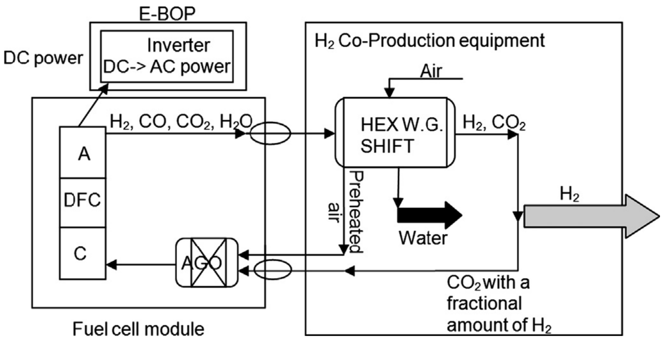

Fig. 3. Hydrogen recovery and purification.

Table 1
Flow of gases at different sections of the system.

Gas	HEX W.G. shift inlet (mol/min)	HEX W.G. shift outlet (mol/min)	PSA product outlet (mol/min)	PSA tail gas (mol/min)	AGO inlet (mol/min)	Cathode exhaust (mol/min)
H_2	156.5	235.6	212	23.6	23.6	23.6
CO_2	526.9	606	–	606	606	181.8
H_2O	516.8	437.7	–	–	–	–
CO	79.1	–	–	–	–	–
O_2	–	–	–	–	303	90.9
N_2	–	–	–	–	1140	1140

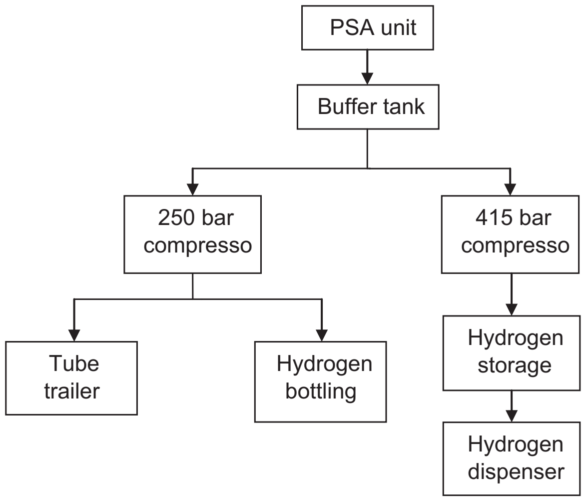

Fig. 4. Hydrogen compression, storage, and dispensing.

3.4. Hydrogen compression, storage, dispensing/distribution system

The system will be incorporated into the existing hydrogen infrastructure on the university campus. The existing hydrogen station was designed such that it could handle higher volume of hydrogen in the future. The product hydrogen from the PSA unit will be transferred into the buffer tank located in the adjacent hydrogen station via pipeline. The buffer tank feds two compressors; (i) the existing Hydro-Pac C06-10-70/140LX compressor (415 bar) and (ii) the PDC machines (PDC-13-1000-3000) compressor (250 bar). The compressed hydrogen from the Hydro-Pac compressor will be stored in existing storage tanks. Hydrogen from the PDC machine compressor will be used to fill a hydrogen tube trailer and K-cylinder manifold. The entire process of hydrogen compression, storage, dispensing and distribution is shown in Fig. 4.

4. Results and discussion

4.1. Electricity use

The electric power output of the DFC1500™ unit operating in the simple cycle CHP mode is 1.4 MW_e. This corresponds to the net power after providing the parasitic loads for its MBOP and energy loss in the E-BOP. However, there are additional

Table 2
Power demand and energy consumption.

Equipment	Max. power rating (kW_e)	Daily operation time (h)	Daily energy consumption (kWh)
Feedstock storage facility	5	12	60
Macerator	15	4	60
Screw feeder	5	4	20
Pump	75	4	300
Hygienization unit	2	4	8
Anaerobic digester	5	24	120
Storage tank	5	24	120
Biogas PSA unit	40	24	960
Hydrogen compressor Comp1	7.5	24	180
Hydrogen compressor Comp2	100	24	2.4×10^3
Auxiliary loads	20	16	320
Total	279.5	164	4548

Table 3
Thermal energy available for heat recovery from the DFC1500™ CHHP system.

Gas	Cathode exhaust (kmol/min)	Mass flow rate (kg/h)	C_P (kJ/kg K)	ΔT (K)	Q flow rate (MJ/h)
H_2	0.024	2.85	14.32	322	13.1
CO_2	0.18	196.5	0.84	322	53.4
O_2	0.91	152.79	0.92	322	45.2
N_2	1.14	2188.28	1.04	322	732.8
Total		2540			844.6

components that require electric power for the DFC1500™ unit operating in CHHP mode. These components, including the heat exchanger for anode outlet gas cooling, the water–gas shift reactor, and the PSA unit for hydrogen purification and operate collectively with the fuel cell unit to form the CHHP system. Based on the power requirements of these components, the net power output from the CHHP system was 1.1 MW_e. The total electric power requirement of different equipment used in the design is tabulated in Table 2.

The total net energy production from the CHHP system is 26.4×10^3 kWh per day and the energy demand for on-site use is 4548 kWh per day. Hence, the CHHP system will be able to provide 22×10^3 kWh per day to the university campus. This corresponds to 27% of the whole campus electricity requirement.

4.2. Thermal and hydrogen use

The DFC1500™ unit has 4 GJ/h at 322 K available for heat recovery while operating in CHP mode. The thermal energy available for heat recovery was calculated based on the cathode exhaust gas composition in Table 3 and Eq. (8) and is shown in Table 3. The temperature difference of the input and output temperature of the heat recovery system is 320 K [20].

$$Q = mC_P(\Delta T) \tag{8}$$

where m, C_P and ΔT are the mass flow rate of the gas (kg/h), the specific heat of the gas (kJ/kg K) and the change in temperature of the gas (K) respectively.

The hydrogen usage (kg/day) on the university campus including personal transportation applications, backup power applications, portable power applications, and other mobility applications are 56, 16, 29, 17, and 5 respectively. The different applications, potential users, and total hydrogen usage per day (123 kg/day) are shown in Fig. 5.

5. Conclusion

In this paper, we have discussed the design of a CHHP system for the Missouri S&T campus using local resources. Following the resource assessment study, the team selects FuelCell Energy DFC1500™ unit for its fuel cell. The CHHP system provides electricity to power the university campus, thermal energy for heating the anaerobic digester, and hydrogen for transportation, back-up power and other needs. The CHHP system will be able to provide approximately 22,000 kWh and 650 kg of hydrogen to the university campus per day. In conclusion, the CHHP system will reduce energy consumption, fossil fuel usage, and greenhouse gas (GHG) emissions at the Missouri S&T campus. It will be able to provide approximately 27% of the university campus' electricity need.

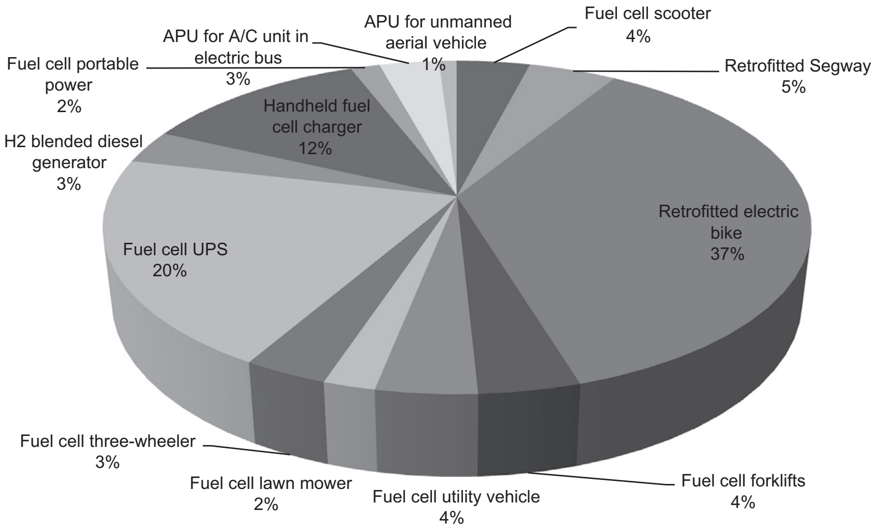

Fig. 5. Hydrogen application and usage on the university campus.

Acknowledgments

The authors wish to acknowledge the Hydrogen Education Foundation for their support of the Annual Hydrogen Student Design Contest which challenges university students to design hydrogen energy applications for real-world use.

References

[1] Abbasi T, Tauseef SM, Abbasi SA. Anaerobic digestion for global warming control and energy generation – an overview. Renewable & Sustainable Energy Reviews 2012;16:3228–42.
[2] Nasir IM, Mohd Ghazi TI, Omar R. Anaerobic digestion technology in livestock manure treatment for biogas production: a review. Engineering in Life Sciences 2012;12:258–69.
[3] Shoko E, McLellan B, Dicks AL, da Costa JCD. Hydrogen from coal: production and utilisation technologies. International Journal of Coal Geology 2006;65:213–22.
[4] Braun RJ. Techno-economic optimal design of solid oxide fuel cell systems for micro-combined heat and Power applications in the U.S. Journal of Fuel Cell Science and Technology 2010;7:0310181–15.
[5] Vera D, Jurado F, de Mena B, Schories G. Comparison between externally fired gas turbine and gasifier-gas turbine system for the olive oil industry. Energy 2011;36:6720–30.
[6] Oller I, Malato S, Sánchez-Pérez JA. Combination of advanced oxidation processes and biological treatments for wastewater decontamination. Science of Total Environment 2011;409:4141–66.
[7] Pronto JL, Gooch CA. Greenhouse gas emission reductions for seven on-farm dairy manure-based anaerobic digestion systems – final results. American Society of Agricultural and Biological Engineers 2010;7:35–42.
[8] Yu M, Muy S, Quader F, Bonifacio A, Varghese R, Clerigo E, et al. Combined Hydrogen, Heat and Power (CHHP) pilot plant design. International Journal of Hydrogen Energy 2013;3812:4881–8.
[9] Weiland P. Biogas production: current state and perspectives. Applied Microbiology and Biotechnology 2010;85(4):849–60.
[10] Ward AJ, Hobbs PJ, Holliman PJ, Jones DL. Optimisation of the anaerobic digestion of agricultural resources. Bioresource Technology 2008;99:7928–40.
[11] Huang W, Zhang Y. Energy efficiency analysis: biomass-to-wheel efficiency related with biofuels production, fuel distribution, and powertrain systems. PLoS One 2011;6:7.
[12] Karellas S, Boukis I, Kontopoulos G. Development of an investment decision tool for biogas production from agricultural waste. Renewable and Sustainable Energy Reviews 2010;14:1273–82.
[13] Zingoni A. Shell forms for egg-shaped concrete sludge digesters: a comparative study on structural efficiency. Structural Engineering & Mechanics 2005;19:321–36.
[14] Krishna R. Adsorptive separation of $CO_2/CH_4/CO$ gas mixtures at high pressures. Microporous and Mesoporous Materials 2012;156:217–23.
[15] Rittmann BE, Mayer B, Westerhoff P, Edwards M. Capturing the lost phosphorus. Chemosphere 2011;84:846–53.
[16] Locher C, Meyer C, Steinmetz H. Operating experiences with a molten carbonate fuel cell at Stuttgart-Möhringen wastewater treatment plant. Water Science and Technology 2012;65:789–94.
[17] Köppel W. Biogas treatment for SNG production. International Gas Research Conference: Proceedings 2008;2:1327–45.
[18] Kamarudin SK, Daud WRW, Som AM, Mohammad AW, Takriff S, Masdar MS. The conceptual design of a PEMFC system via simulation. Chemical Engineering Journal 2004;103:99–113.
[19] Anode outlet gas composition calculation example: ⟨http://hydrogencontest.org/pdf/AOG%20Composition%20Example.pdf⟩; 2012.
[20] AglI AA, Hamad YM, Hamad TA, Thomas M, Bapat S, Martin KB, et al. Study of a molten carbonate fuel cell combined heat, hydrogen and power system: energy analysis. Applied Thermal Engineering 2013;59:634–8.