Journal of Electrochemical Science and Technology
Vol. 1, No. 2, 2010, 102-111
DOI:10.5229/JECST.2010.1.2.102

THE KOREAN ELECTROCHEMICAL SOCIETY **Journal of Electrochemical Science and Technology**

Economic Feasibility Study for Molten Carbonate Fuel Cells Fed with Biogas

Shin Ae Song, Jonghee Han†, Sung Pil Yoon, Suk Woo Nam, In-Hwan Oh and Dae Ki Choi
Fuel Cell Research Center, Korea Institute of Science and Technology, 39-1 Hawolgok-dong, Seongbuk-gu, Seoul 136-791, Republic of Korea

ABSTRACT

Molten carbonate fuel cell (MCFC) power plants are one of most attractive electricity generation systems for the use of biogas to generate high-efficiency ultra-clean power. However, MCFCs are considerably more expensive than comparable conventional electricity generation systems. The commercialization of MCFCs has been delayed more than expected. After being effective in the Kyoto protocol and considerably increasing the fossil price, the attention focused on CO_2 regression and renewable energy sources has increased dramatically. In particular, the commercialization and application of MCFC systems fed with biogas have been revived because of the characteristics of CO_2 collection and fuel variety of MCFCs. Better economic results of MCFC systems fed with biogas are expected because biogas is a relatively inexpensive fuel compared to liquefied natural gas (LNG). However, the pretreatment cost is added when using anaerobic digester gas (ADG), one of the biogases, as a fuel of MCFC systems because it contains high H_2S and other contaminants, which are harmful sources to the MCFC stack in ADG. Thus, an accurate economic analysis and comparison between MCFCs fed with biogas and LNG are very necessary before the installation of an MCFC system fed with biogas in a plant. In this paper, the economic analysis of an MCFC fed with ADG was carried out for various conditions of electricity and fuel price and compared with the case of an MCFC fed with LNG.

Keywords : Molten carbonate fuel cell, Economic feasibility, Biogas, Anaerobic digester gas

Received December 14, 2010 : Accepted December 23, 2010

1. Introduction

Fuel cells are considered a possible candidate for efficiently converting the chemical energy stored in hydrogen or fossil fuels (oil, natural gas, etc.) into electric energy with low pollutant and greenhouse gas emissions.[1,2] In fuel cells, molten carbonate fuel cells (MCFCs) have received much attention due to their high energy efficiency, usefulness for electrical power and heat energy, low emissions and variety of useful fuels.[3-5] For these reasons, MCFCs are very close to commercialization. MCFCs have received much more attention for CO_2 reduction after the Kyoto protocol went into effect in February 2005 because of the probability of the condensation and collection of CO_2.[6] The transportation of CO_2 across the electrolyte, from the cathode side to the anode side of the MCFC, is possible because CO_2 acts as a charge carrier in MCFCs. In a gas composition composed of unreacted H_2, steam and concentrated CO_2 from the cathode side at the anode exit, steam can be easily condensed, H_2 can be separated, and the residual CO_2 can be thereby be collected in a relatively pure stream for removal.[7,8]

With the growing concern about global warming, the potential of biogas has become a popular topic for the reduction of greenhouse gas (GHG) emissions.[9]

†Corresponding author. Tel.: +82-2-958-5277
E-mail address: jhan@kist.re.kr

Biogas is a more versatile renewable energy source due to declining fossil fuels, decreasing greenhouse effects, and ease of storage.[9,10] It is obtained after specific treatments from animal waste, human sewage or crop residues.[11] The waste disposal problem is currently a major issue in many cities.[6] If the use of biogas made from waste is possible, it could save fossil fuels. There are many different types of biogas,[11,12] including anaerobic digester gas (ADG), landfill gas (LFG), syngas from an entrained bed steam gasifier (EBG), and syngas from a dual interconnected fluidized bed steam gasifier (DBG). In biogases, ADG is produced at wastewater treatment plants during the process of treating sewage anaerobically to reduce solids.[11] ADG is composed of CH_4 (57-66% volume), CO_2 (33-39% volume), N_2 (1-4% volume), and a small amount of O_2 (< 0.5% volume).[11] LFG, one of the other biogases, is produced by chemical reactions and microbes acting upon the waste as the putrescible materials begin to break down in the landfill.[13] LFG is composed of CH_4 (40-60%), CO_2 (35-50%) and small amounts of O_2 (0-3%) and N_2.[13] It has a composition similar to that of ADG. At present, almost all ADG or LFG produced in South Korea is burned, and only small amounts are used for the production of electricity. If it is possible to utilize dumped ADG or LFG for fuel in MCFCs, the supply of fuel can become smoother, and electricity production can be economical.

However, it is not easy to utilize ADG and LFG without a purification process because ADG and LFG contain relatively high amounts of hydrogen sulfide (H_2S) and various volatile organic compounds (VOC), including organic-sulfur compounds (e.g., carbonyl sulfide, mercaptans), silicon-containing compounds (e.g., siloxanes), halogenatedcompounds, aromatics and aliphatic hydrocarbons.[11-13] To use ADG or LFG for fuel in MCFCs, a purification process is certainly necessary. Now many research results about the effects of contaminants have been published to understand the maximum allowable concentration of each contaminant.[12,14-16] Due to the lower tolerance to impurities, the usage of biogas in MCFCs with no purification process would result in poisoning the reformer catalyst in only a few hours of operation.[12] For this reason, the harmful contaminants have to be removed by a suitable purification process before biogas is fed into MCFCs. Among the several poisons studied, H_2S is one of the most harmful to MCFC stacks.[6,9,12] The H_2S concentration in biogas can vary from 0.1% to 2% in feedstock to higher than 3% from manure and protein-rich organic wastes.[12] The H_2S content in biogas is greatly above the tolerance of the MCFC. (It is known that MCFC can be accepted below 5 ppm of H_2S without cell damage[6]). Thus, the design of a biogas pretreatment system for use in a MCFC focuses on the removal of H_2S. Other contaminant materials in biogas can be removed through treatment processes such as cooling, adsorption or absorption with inorganic and organic solvents.

Many researchers working on the use of biogas for MCFCs have carried out system analyses, economic analyses and tests on small-scale fuel cells to validate the potentiality of biogas.[11-13,17-21] In 1999, Spiegel *et al.* developed and published a conceptual design of a 1.2 MW commercial MCFC power plant operating with ADG.[17] It was an initial investigation of the economic feasibility of an MCFC operation using ADG. In the results of the economic feasibility study, the fuel cell is economical, where plant electricity costs are 5 cent/kWh or higher, based on entry level fuel cell costs of 3,000 USD/kWh at that time. To support a larger 1.2 MW fuel cell power module, a wastewater treatment facility would need to provide approximately twelve million liters of ADG per day at 65% by volume and a heating value of 5,785 kcal/m^3. Kivisaasri *et al.* carried out the system analysis of a biomass powered IGCC (integrated gasification combined cycle)-MCFC (60 MW class) using the Aspen Plus program.[19] According to the results, the biomass could be converted into electricity via an IGCC-MCFC process with an efficiency of 30-43% depending on whether internal reforming is deployed. Donolo *et al.* carried out the steady state simulation of biomass gasification and its utilization in MCFCs.[20]

The efficiency obtained by coupling the biomass gasifier and the MCFC was approximately 36-40%, depending upon the biomass used. CRIEPI (Central Research Institute of Electric Power Industry) in Japan studied the effect of various impurities and the fuel gas composition on the performance or efficiency of MCFCs for the application of various fuels in MCFCs.[6] Krumbeck *et al.* reported the first installation of an MCFC fed with ADG in the city of Ahlen in Europe.[21] The wastewater treatment plant in Ahlen produced about 1,500-2,000 m^3 of ADG per day. Based on an average CH_4 content of about 60%, it contains enough energy to operate an MCFC unit of the 250 kW class near full load. In the operation results, the fuel cell fed with ADG showed good performance and long-time operation. Bove *et al*. carried out the experimental comparison of MCFC performance using three different biogas types (ADG, EBG, and DBG) and CH_4 at the lab scale.[11] The performances of all of the biogases were very similar to those of reformed natural gas. These results showed the possibility of biogas using as MCFC fuel.

In South Korea, the work on MCFCs fed with biogas has also increased. A 250 kW class MCFC fed with ADG was successfully operated at the Tanchon wastewater treatment plant in South Korea for two years from 2006. In the beginning of installation, the rate of total operation was 41.4%. It was very low, but the rate of total operation reached to over 90% after supplementation of the pretreatment technology with ADG. A 2.8 MW class MCFC system is planned to be launched in South Korea soon. A review of the economics and the technology of an MCFC fed with biogas are thus urgently necessary. In this study, the economic feasibility of MCFC system fed with natural gas and ADG was studied and compared to determine whether the MCFC system fed with ADG rather than LNG is an attractive economic choice.

2. The calculation for a 1.4 MW class MCFC

A 1.4 MW class MCFC system was considered for the economic analysis in this study. Most of the data required for the calculations, such as the installation cost, equipment span, amount of fuel consumption, LTSA (long-term service agreement) fee, amount of water consumption, water price, rate of performance drop, electrical efficiency, and heat efficiency, were received from a company prepared for the commercialization of MCFCs in Korea in 2009. The total installation cost of the MCFC system was 5,267.78 USD/kWh, including the stack and BOP installation costs. For the equipment, it was assumed that the stack span was 5 years, and the spans of the BOP and rest equipment were 20 years. For the operation and management costs, it was assumed that operation and management costs contained the water cost, fuel cost, labor fee, and LTSA fee. Here, the LTSA fee represents the contracted annual management cost in which the company selling the MCFC system makes a promise to the customer buying the MCFC system. This LTSA fee contains the operation costs and the cost of stack replacement every 5 years.

The assumed data for the performance of the MCFC system are as follows. The rate of performance drop was 1.1%/6 month, and the operation rate of the MCFC system was 90%. The electrical efficiency and heat efficiency were 47% and 27%, respectively. The income during the operation of the MCFC system was found through the sale of the electricity and heat produced. Thus, the income is very sensitive to the electricity price and heat price. In this study, it was assumed that the electricity price would change from 0.60 to 0.30 USD/kWh, and the heat price was fixed at 0.05 USD/kWh in the first year. It was assumed that the inflation rate and interest rate were 3% and 5%, respectively. The conditions for the MCFC system

Table 1. The basic conditions for the economic analysis of an MCFC system

Investment Cost	
Total installation cost of MCFC	5,267.78 USD/kWh
Stack cost	4,126.43 USD /kWh
Installation cost	1,141.35 USD /kWh
Equipment span	
Stack span	5 yr
BOP and attachment equipment	20 yr
Operation Cost	
Amount of fuel consumption(LNG)	298 Nm^3/hr
Fuel Price (LNG)	0.2~0.6 USD /Nm^3
CH_4 LHV	9.97 kWh/Nm^3
LTSA (long-term service agreement) Fee	272.80 USD /kWh yr
Amount of water consumption	1.35 m^3/hr
Water price	0.13 USD /m^3
One Labor	11,413.52 USD/person
Performance	
Performance	1,400 kW
Rate of performance drop	1.1% / 6 month
Operation rate	90%
Electrical efficiency	47%
Heat efficiency	27%
Income	
Electricity price	0.1~0.25 USD/kWh
Heat price	0.05 USD/kWh
Inflation rate	3%
Interest rate	5%

1 dollar = 1,132 KRW (Korea Republic Won, 2010. 09. 30)

for economic analysis are summarized in Table 1.

Table 2 shows the composition of ADG from Tan-chon in Korea before operating the MCFC system. In this paper, the methane in the ADG from Tan-chon was used for the calculation of the economic analysis of the MCFC system fed with biogas. The H_2S content in the ADG from Tan-chon, 1525 ppm, is high compared to those of other references.[11)] In this work, the economic study considered two cases of low (300 ppm) and high (1500 ppm) H_2S composition of the ADG. Although there are many contaminants in ADG before the purification process, as shown in Table 2, only the purification process for H_2S removal was considered in this study because it is known that H_2S is the most harmful contaminant to the performance and span of an MCFC stack and that the H_2S removal process is expensive.

Table 2. The composition of ADG from Tan-chon in South Korea (2005. 9)

Group	Component	Unit	Content (Before purification)
Alkane & Olefins	CH_4	%	68.2
	i-C_5H_{12}	ppm	0.67
	n-C_6H_{14}(hexane)	ppm	0.79
Siloxanes	Decamethylcyclopentasi-loxane	ppm	14.64
Sulfur	COS(carbonyl sulfide)	ppm	0.11
	H_2S	ppm	1525
	CS_2(carbon disulfide)	ppm	2.0
	C_2H_5SH(ethyl mercaptan)	ppm	0.6
	n-propyl mercaptan	ppm	3.3
Others	CO_2	%	28.6
	N_2	%	0.7
	H_2	%	0.002
	O_2	%	0.2
BTX	Toluene	ppm	4.98
Heavy Hydrocarbon	Nonane	ppm	0.33
	Decane	ppm	0.60
	Undecane	ppm	0.52

For use of ADG as fuel, the purification process has to be considered. Fig. 1 shows the strategy for the purification process of H_2S in ADG at two H_2S concentrations (300 ppm and 1500 ppm). It was assumed that the ADG flow only passed through a dry process for H_2S removal when the H_2S concentration in ADG was 300 ppm, and ADG flow passed through two steps, composed of a wet process and a dry process, for H_2S purification for a H_2S concentration of 1500 ppm. These two cases for purification the process of ADG were the results of the project "The Study of Pretreatment of fuel and operation technology for 250 kW class MCFC system" (UCM1886-8280-6) supported by the government of South Korea. The purification process was designed for H_2S concentrations up to 5 ppm after only a dry process for the purification of H_2S at a concentration of 300 ppm. It was assumed that the concentration of H_2S would decrease to 300 ppm via the wet process, and then the concentration of H_2S was finally reduced to 5 ppm via the dry process at high concentration (300~1500 ppm). The final concentration of H_2S in ADG after the purification process in the two cases was determined to be 5 ppm, which is the concentration of H_2S that is known not to damage the performance and span of MCFC stacks.

Table 3 shows the conditions for the economic analysis of an MCFC system fed with ADG as fuel. The specific installation costs for the H_2S wet purification

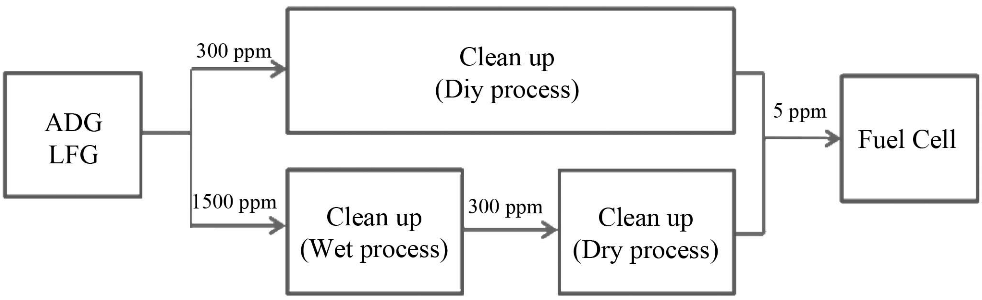


Fig. 1. The strategy for the purification process of H_2S in ADG.

Table 3. The basic conditions for the economic analysis of an MCFC system when using ADG for fuel

For Fuel		
ADG	Price	0.04 ~ 0.26 USD /Nm^3
	H_2S Concentration	1500 ppm, 300 ppm
	CH_4 content	68%
	CO_2 content	28.6%
Purification process for H_2S		
Wet Process	H_2S concentration in flowing ADG before purification process	300~1500 ppm
	H_2S concentration in flowing ADG after purification process	300 ppm
	Installation cost	41,855.25 USD /$(Nm^3/hr)^{0.5}$
	Operation cost	1.33 USD/g H_2S, yr
Drying Process	H_2S concentration in flowing ADG before purification process	Under 300 ppm
	H_2S concentration in flowing ADG after purification process	5 ppm
	Installation cost	29,298.68 USD/$(Nm^3/hr)^{0.5}$
	Operation cost	3.38 USD/g H_2S, yr

process and dry purification process were 41,855.25 USD/$(Nm^3/hr)^{0.5}$ and 29,298.68 USD/$(Nm^3/hr)^{0.5}$, respectively. The specific operation cost for the H_2S wet purification process and dry purification process were 1.33 USD/g of H_2S/yr and 3.38 USD/g of H_2S/yr, respectively. These cost values were calculated in the project "The Study of Pretreatment of fuel and operation technology for 250 kW class MCFC system" (UCM1886-8280-6) supported by the government of South Korea. It was assumed that the installation cost of the H_2S purification process was proportional to square root of the flow rate of the pretreatment fuel, and the operation cost of the H_2S purification process was proportional to the product of the flow rate of the pretreatment fuel and the H_2S concentration (amount of H_2S removed) when the pretreatment cost was calculated. The calculation process for economic analysis is given in the Appendix.

Table 4. The electricity prices in various countries

Country	Electricity Prices for Households (USD/kWh)	Electricity Prices for Industry (USD/kWh)
Austria	0.214	0.134
Taiwan	0.079	0.059
Finland	0.145	0.081
France	0.158	0.056
Hungary	0.188	0.134
Ireland	0.244	0.149
Italy	0.258	0.237
Korea, South	0.102	0.069
Singapore	0.143	0.112
Switzerland	0.136	0.084
United States	0.106	0.064

All data of electricity prices of various countries were obtained from the website of the U.S. Energy Information Administration(2008).

3. Results and Discussion

To understand the present economic situation of MCFCs, the economic analysis of an MCFC fed with LNG was carried out using the average electricity price and LNG price in various countries. The electricity prices and natural gas prices in various countries were examined before the economic calculation for MCFCs in various countries. In this study, $CDCF_{20}$ (cumulated discounted cash flow at 20^{th} year) was used as a representive value for economic analysis. Table 4 shows the average electricity prices for industry and households in various countries. In Italy and Ireland, electricity prices are relatively high, whereas the electricity prices are relatively low in Taiwan, Korea and the United States. The difference between the electricity prices in different countries is very large. Even the

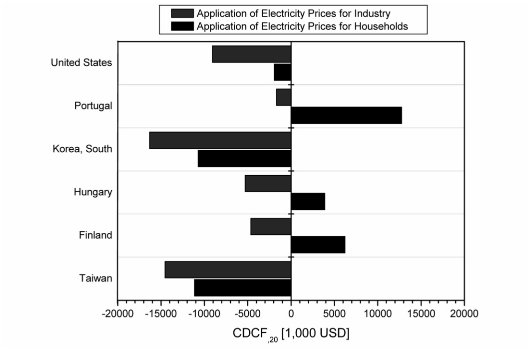
Table 5. The prices of natural gas in various countries

Country	Prices of natural gas (USD /Nm^3)
Taiwan	0.40
Finland	0.24
Hungary	0.49
Korea, South	0.49
Portugal	0.37
United States	0.28

All data of natural gas prices of various countries were obtained from the website of the U.S. Energy Information Administration (2008).

difference between inexpensive and expensive electricity prices is over a factor of three. Table 5 shows the average prices of natural gas used as fuel for the production of electricity in various countries. In addition, there are the price differences of natural gas among various countries (about a factor of two). In particular, the price of natural gas is relatively high in Taiwan and Korea because of the importation of all of the natural gas and fossil fuels used for the production of electricity. In Taiwan and Korea, however, the price of natural gas is not reflected in the electricity price, which is part of the production cost, because those countries make a profit by the exportation of industrial products. Thus, it was expected that the economic feasibility of MCFCs was not good in these countries.

Fig. 2 shows the $CDCF_{,20}$ calculated with the prices of electricity and natural gas in various countries in Tables 4 and 5 if a 1.4 MW class MCFC fed with natural gas is operated for 20 years. In the countries where the electrical price is relatively low and the price of natural gas is relatively high, such as South Korea and Taiwan, the deficit created by the operation of the 1.4 MWh class MCFC system for 20 years is very large for both cases in the application of electricity prices for industry and households, as expected. In South Korea and Taiwan, the main income of the country is earned through the export of industrial products using imported raw materials because there are no natural resources. These countries have to carry out the policy to supply electricity at low cost for price competitiveness of their own products. Thus, it is very difficult to make a profit through the operation of an MCFC system fed with LNG in these countries. There are countries such as Portugal and Finland that earn money through the operation of a 1.4 MWh class MCFC system fed with LNG due to the relatively high electricity price. However, it is not easy to make a profit through the operation of an MCFC system in many countries due to high natural gas prices and investment costs.



Country	$CDCF_{,20}$ at Electricity Prices for Households (1,000 USD)	$CDCF_{,20}$ at Electricity Prices for Industry (1,000 USD)
Taiwan	-11,151	-14,545
Finland	6,220	-4,641
Hungary	3,876	-5,288
South Korea	-10,718	-16,319
Portugal	12,747	-1,678
United States	-1,941	-9,068

Fig. 2. The comparison of 'cumulated discounted cash flow at 20^{th} year' of various countries calculated using the data in Table 4 and 5.

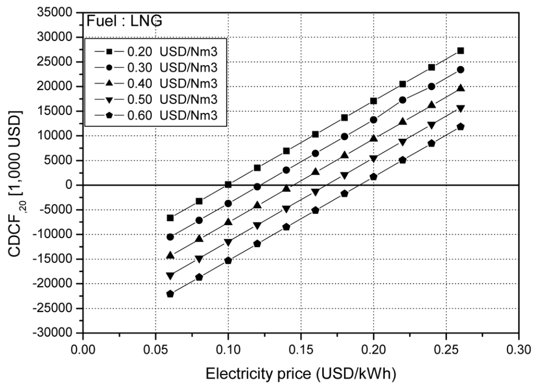
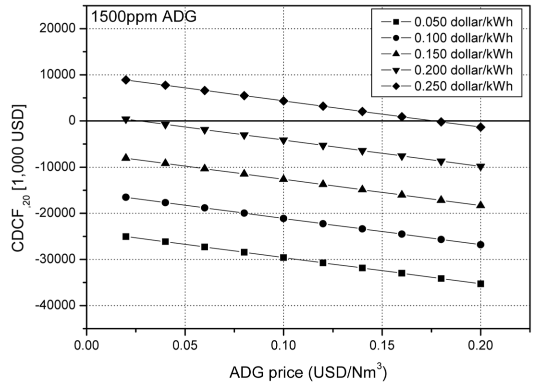


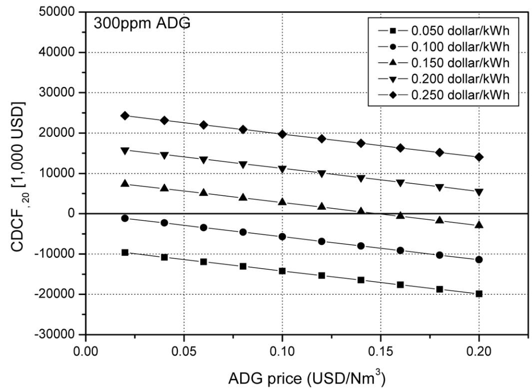
Fig. 3. The "cumulated discounted cash flow at 20^{th} year" with changing electricity prices and LNG prices using LNG as fuel for MCFCs.

Fig. 3 shows the $CDCF_{,20}$ when operating the MCFC system fed with LNG for various electricity and fuel prices. For a surplus of $CDCF_{,20}$, the electricity price has to be over 0.1 USD/kWh with an LNG price of 0.2 USD/Nm^3. At an LNG price of 0.5 USD/Nm^3 (LNG price, South Korea, 2009), the electricity price has to be over 0.18 USD/kWh to reach a surplus in the operation of an MCFC system fed with LNG. However, the average electricity price is below 0.1 USD/kWh in South Korea. There is a very large gap between the real electricity price and electricity price for the surplus. Practically, because the installation cost of the MCFC system including the MCFC stack cost is too high, it is not easy to make a profit through the operation of an MCFC system. To earn a profit through the operation of an MCFC system, the initial investment cost and the operation cost contained in the fuel price have to lower, or the electricity price has to increase. A sudden decrease of investment costs and an increase in the electricity price are impossible in reality. To find a more inexpensive fuel source is a better choice than reducing the investment cost for MCFCs due to the variety of fuel choices. Thus, the attention to the application of renewable fuel sources such as ADG, LFG, EDG for MCFC is increasing because of more inexpensive prices. At present, the ADG price is 0.07~0.08 USD/Nm^3 in South Korea (2009). Although ADG is more inexpensive than LNG, ADG contains a high concentration of H_2S, which damages the MCFC stack. Thus, when using ADG as the fuel for an MCFC system, the purification process for H_2S removal is certainly necessary. Therefore, an economic analysis and comparison of the two cases of LNG and ADG purified through H_2S removal for MCFCs are needed before the application of ADG as a fuel in MCFCs.

The economic analysis for ADG used as fuel for MCFC system was conducted, and it was compared with the results of the use of LNG in MCFCs. The H_2S concentration in ADG was assumed to have two possible levels: 300 and 1500 ppm. The results of the economic analysis using ADG as fuel are shown in Figs. 4 and 5. When using an H_2S concentration of 300 ppm in the ADG, if the ADG price is below 0.13 USD/Nm^3, a surplus operation of the MCFC is possible. It is a realistic result because the ADG price is presently about 0.07~0.08 USD/Nm^3 in South Korea. Compared with the usage of LNG for fuel (Fig. 3), it is a surprising result. In the case of 1500 ppm of H_2S concentration, the result is not good compared with LNG as the fuel. At an ADG price of 0.07 USD/Nm^3, the electricity price has to be over



(a)



(b)

Fig. 4. The "cumulated discounted cash flow at 20th year" for various electricity prices and ADG prices using purified ADG as fuel for an MCFC at (a) 1500 ppm and (b) 300 ppm of H_2S concentration in ADG before purification.

0.23 USD/kWh to create a surplus. Although the ADG price is inexpensive, if the H_2S concentration is high, earning a profit is not easy because of the large purification costs for H_2S removal.

The adoptable limited H_2S concentration in ADG at each electricity price and the ADG price are better than the economic situation when using LNG for fuel. Fig. 5 shows the results of $CDCF_{,20}$ with the change of H_2S concentration in ADG and the ADG price. When the electricity price is 0.1 USD/kWh, for the surplus operation of an MCFC fed with ADG, the H_2S concentration has to be very low, and the ADG has to be very inexpensive. In South Korea, the operation of an MCFC system fed with LNG or purified ADG cannot make a profit due to the policy concerning

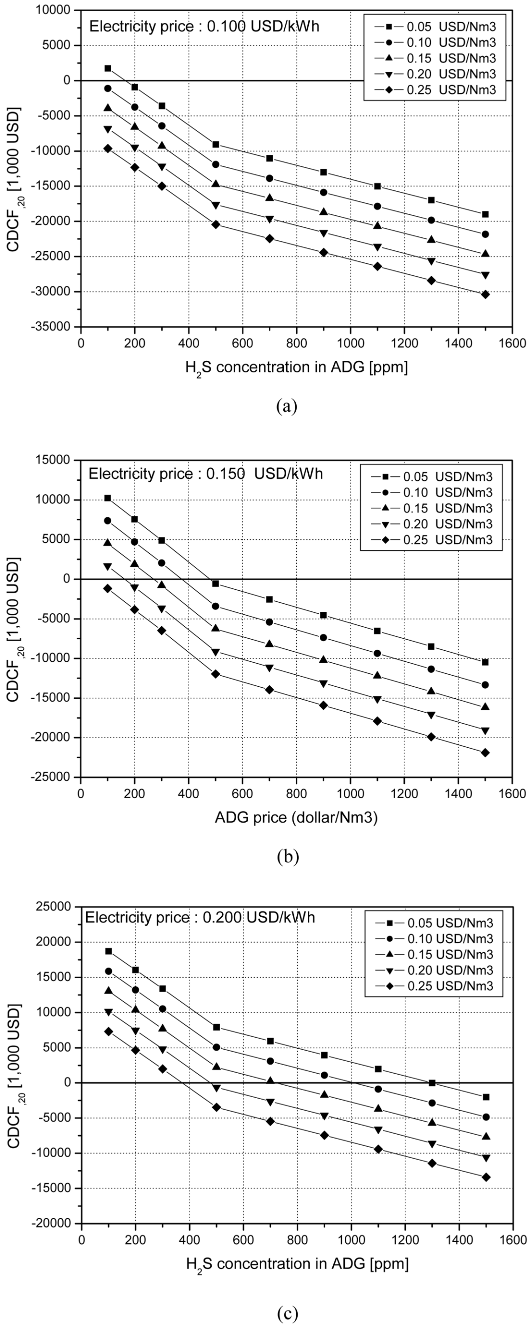


Fig. 5. The "cumulated discounted cash flow at 20th year" with changing H_2S concentrations and ADG prices using purified ADG as fuel for an MCFC at electricity prices of (a) 0.1, (b) 0.15 and (c) 0.2 USD/kWh.

low electricity price. When the ADG price is under 0.05 USD/Nm^3, the operation of an MCFC system fed with purified ADG can recover the investment money for an H_2S concentration of 150 ppm. Table 6 shows the more profitable limited H_2S concentrations for ADG than LNG for different LNG prices at an ADG price of 0.07 USD/Nm^3 of ADG and an electricity price of 0.1 USD/kWh. The more profitable limited H_2S concentrations with ADG than with LNG are 240, 300, 550, 1,000 ppm when LNG prices are 0.3, 0.4, 0.5 and 0.6 USD/Nm^3, respectively. The limited H_2S concentration in ADG also increases as the LNG price increases. The limited H_2S concentration in ADG increases because an increase of the LNG price is predicted in the future.

Table 6. The limited H_2S concentration in ADG showed a better profit compared with the use of LNG in the MCFC (ADG price: 0.07 USD/Nm^3, electricity price: 0.1 USD/Nm^3)

LNG price (USD/Nm^3)	0.30	0.40	0.50	0.60
H_2S concentration (ppm)	240	300	550	1,000

In South Korea, the policy of "Feed-In Tariffs of Electricity Generating from New-Renewable Energy Sources" has been in effect since 2002 to increase the usage of new-renewable energy sources. According to this policy, the South Korean government buys the generated electricity from new-renewable energy sources such as solar cells, wind energy, and fuel cells at a high electricity price (0.2 USD/kWh using biogas as fuel, 2009) because it is not easy to sell the electricity produced from renewable energy sources at real electricity prices and make a profit due to the inexpensive electricity in South Korea. Thus, the research on electricity generation from renewable energy sources concerns many companies and research institutes. They earn money on the sale of electricity produced from renewable energy sources in reality. However, this policy is scheduled to gradually begin disappearing in 2015. An economic feasibility study and the securing strategy of price competitiveness of MCFC systems are needed for the propagation and application of MCFC systems for electricity production in the next generation. In this view, the economic feasibility study of MCFC fed with ADG is very important.

4. Conclusion

MCFCs have gained much attention as prospective candidates for the next generation systems for electricity production due to their low emission and high efficiency over a long period. The technology is very close to commercialization, although some problems have to be solved. A 250 kW class MCFC fed with ADG was installed and operated in the city of Ahlen in Europe at 2005. A 250 kW class MCFC fed with ADG was successfully operated at the Tanchon water waste treatment plant in South Korea for two years from 2006. The launch of a 2.8 MW class MCFC system is in preparation in South Korea. At this time, there is an urgent need for the serious concerns about the application of MCFCs fed with biogas for electricity production systems in terms of economics.

In this study, an economic study of an MCFC system fed with ADG was carried out. According to the results of the economic calculation, the MCFC system fed with ADG had the possibility of making a profit at some zone of H_2S concentration and fuel price. However, the investment and operation cost of the MCFC fed with ADG was still higher than those of other conventional electricity generation systems. The results of this study indicate that future research on MCFCs fed with ADG should focus on the improvement of pretreatment technologies for biogas and the reduction of the investment cost and operation cost of MCFC systems and the purification process of biogas. In addition, the level control of the H_2S concentration in untreated ADG is expected to help to reduce the pretreatment cost of biogas.

Acknowledgements

This work was supported as the project "The feasibility study for the application of fuel cells for district heating system" by the Korea District Heating Corporation.

APPENDIX

The data needed for the economic analysis of MCFCs were divided into 3 blocks: investment costs, operation costs, and income. The overall cost was calculated as the sum of the investment costs and operation costs taking into account the operation rate, performance decreasing rate, and span of MCFC. The overall income may be produced from the sale of the total produced electricity and heat. It was assumed that the MCFC plant was operated for 20 years. The "cumulated discounted cash flow at the 20^{th} year" ($CDCF_{20}$) was used as a representative value of the economic results. Combining the yearly overall cost with the overall income, the yearly cash flow of the MCFC was determined, and the economic feasibility of the fuel cell was predicted.

Investment

$$I_1 = (I_{si} + I_{in}) \times P_p \quad \text{(for LNG)} \quad (1)$$

$$I_1 = (I_{si} + I_{in}) \times P_p + I_{pre} \times \sqrt{Q_{fuel,\,in}} \quad \text{(for ADG)} \quad (2)$$

where
I_1 = Total investment cost in the first year (USD)
I_{st} = Specific cost of a stack for the MCFC (USD/kW)
I_{in} = Specific investment cost of the installation for the MCFC (USD/kW)
P_p = Plant power (kW)
I_{pre} = Specific investment cost of the installation for the purification process of H_2S removal ($(USD/(Nm^3/hr))^{0.5}$)
$Q_{fuel,in}$ = Flow rate of ADG (Nm^3/hr)

Operation costs

$$C_{fuel,1} = \frac{E_{pry}}{Eff_{el} * LHV} \times G_{pr,\,1} \times 1000 \quad (3)$$

$$C_{OP\&Mtot,1} = C_{fuel,1} + C_{water,1} + C_{labor,1} + C_{LTSA,1} \quad \text{(for LNG)} \quad (4)$$

$$C_{pre,1} = C_{sp} \times Q_{fuel,in} \times C_{H2S} \quad (5)$$

$$C_{OP\&Mtot,1} = C_{fuel,1} + C_{water,1} + C_{labor,1} + C_{LTSA,1} + C_{pre,1} \quad \text{(for ADG)} \quad (6)$$

$$C_{OP\&Mtot,n} = C_{op\&Mtot,1} \times (1 + I_{inf})^n \quad (7)$$

where
$C_{fuel,1}$ = Fuel cost in the first year (USD)
E_{pry} = Electric energy produced per year (kWh/year)
Eff_{el} = Electric efficiency (%)
LHV = Low heating value (kWh/m^3)
$G_{pr,1}$ = Gas price in the first year (USD/m^3)
$C_{OP\&Mtot,1}$ = Total operation and management cost for the MCFC system in the first year (USD/year)
$C_{OP\&Mtot,n}$ = Total operation and management cost for the MCFC system in the n^{th} year (USD/year)
$C_{water,1}$ = Water price in the first year (USD/year)
C_{LTSA} = Long-term service agreement (USD/year)
$C_{labor,1}$ = Labor fee in the first year (USD/year)
$C_{pre,1}$ = Total operation and management cost for the purification process of H_2S removal (USD/year)
C_{sp} = Specific operation cost for the purification process of H_2S removal (USD/g H_2S, year)
$Q_{fuel,in}$ = Flow rate of ADG (Nm^3/hr)

C_{H2S} = H_2S concentration in ADG (ppm)
n = Year
I_{inf} = Inflation rate (%/year)

Income

$$IN_{ele,1} = E_{pry} \times V_{ele,1} \quad (8)$$
$$IN_{th,1} = E_{thy} \times V_{th,1} \quad (9)$$
$$IN_{tot,1} = IN_{ele,1} + IN_{th,1} \quad (10)$$
$$IN_{tot,n} = IN_{tot,1} \times (1 + I_{inf})^n \quad (11)$$

where
$IN_{ele,1}$ = Income from electric energy in the first year (USD)
E_{pry} = Electric energy produced per year (kWh/year)
V_{ele} = Value of electric energy (USD/kWh)
E_{thy} = Heat produced per year (kWh/year)
V_{th} = Value of heat (USD/kWh)
P_p = Plant total power (kW)
$IN_{tot,1}$ = Income in the first year (USD)
$IN_{tot,n}$ = Income in the n^{th} year (USD)
I_{inf} = Inflation rate (%/year)

Net income

$$NI_{,1} = IN_{tot,1} - C_{OP\&Mtot,1} \quad (12)$$
$$NI_{,n} = IN_{tot,n} - C_{OP\&Mtot,n} \quad (13)$$

where
$NI_{,1}$ = Net income in the first year (USD)
$NI_{,n}$ = Net income in the n^{th} year (USD)

Cash flow

$$CF,1 = NI,1 - I,1 \quad (14)$$
$$CF,n = NI,n - I,n \quad (15)$$

where
CF,1 = Cash flow in the first year (USD)
I,n = Investment in the n^{th} year (USD)

Discounted Cash Flow

$$DCF_{,n} = = \frac{CF_{,n}}{(1 + I_{int})^n} \quad (16)$$

where
$DCF_{,n}$ = Discounted cash flow in the n^{th} year (USD)
I_{int} = Interest rate (%/year)

Cumulated Discounted Cash Flow

$$CDCF,n = = \sum \frac{CF_{,n}}{(1 + I_{int})^n} \quad (17)$$

where
$CDCF_{,n}$ = Cumulated discounted cash flow in the n^{th} year (USD)

References

1. A. Kirubakaran, S. Jain and R.K. Nema, Renewable and Sustainable Energy Reviews, **13**, 2430-2440, (2009).
2. J. Brouwer, Current Applied Physics, **10**, S9-S17, (2010).
3. Y. Lee, I. Kim, G. Chung, C. Lee, H. Lim, T. Lim, S. Nam and S. Hong, *J. Power Source*, **137**, 9-16, (2004).
4. S. Kim, S. Hyun, T. Lim and S. Hong, *J. Power Source*, **137**, 24-29, (2004).
5. R. Rashidi, I. Dincer and P. Berg, *J. Power Sources*, **185**, 1107-1114, (2008).
6. T. Watanabe, Y. Izaki, Y. Mugikura, H. Morita, M. Yoshikawa, M. Kawase, F. Yoshiba and K. Asano, *J. Power Sources*, **160**, 868-871, (2006).
7. M. Lusardi, B. Bosio and E. Arato, *J. Power Sources*, **131**, 351-360, (2004).
8. S. Campanari, P. Chiesa and G. Manzolini, International Journal of Green House Gas Control, (2009).
9. M. Poschl, S. Ward and P. Owende, Applied Energy, (2010).
10. L. Zhang, C. Xu and P. Champagne, Energy Conversion and Management, **51**, 969-982, (2010).
11. R. Bove and P. Lunghi, *J. Power Source*, **145**, 588-593, (2005).
12. R. Ciccoli, V. Cigolotti, R. Lo Presti, E. Massi, S.J. McPhail, G. Monteleone, A. Moreno, V. Naticchioni, C. Paoletti, E. Simonetti and F. Zaza, Waste Management, **30**, 1018-1024, (2010).
13. W. Urban, H. Lohmann and J.I. Salazar Gomez, *J. Power Sources*, **193**, 359-366, (2009).
14. I. Uchida, S. Ohuchi and T. Nishina, *J. Electroanal. Chem.*, **369**, 161-168, (1994).
15. H. Devianto, S.P. Yoon, S.W. Nam, J. Han and T. Lim, *J. Power Sources*, **159**, 1147-1152, (2006).
16. M. Kawase, Y. Mugikura, T. Watanabe, Y. Hiraga and T. Ujihara, *J. Power Sources*, **104**, 265-271, (2002).
17. R.J. Spiegel, S.A. Thorneloe, J.C. Trocciola and J.L. Preston, Waste Management, **19**, 389-399, (1999).
18. K.V. Lobachyov and H.J. Richter, Energy Conversion and Management, **39**, 1931-1943, (1998).
19. T. Kivisaari, P. Bjornbom and C. Sylwan, *J. Power Sources*, **104**, 115-124, (2002).
20. G. Donolo, G. De simon and M. Femeglia, *J. Power Sources*, **158**, 1282-1289, (2006).
21. M. Krumbeck, T. Klinge and B. Doding, *J. Power Sources*, **157**, 902-905, (2006).