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Effects of system configuration and operating condition on MCFC system efficiency

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Abstract

A process simulation model of an externally reformed molten carbonate fuel cell (MCFC) system is used to analyze quantitatively parametric effects on system efficiency. In order to verify the MCFC process simulation model, a 25 kW system is analyzed on the basis of experimental data and its calculated efficiency is found to be reasonable. The overall system efficiency of a high-temperature fuel cell system, especially a MCFC, cannot be increased without proper thermal integration between the heat recovery units and without additional power from auxiliary power generation units such as turbines. The results of the simulation show that the configuration of the unit operators in a given system has a great effect on system efficiency, while system size and operating conditions have slightly less effects. Based on the system configuration, the optimal operating conditions (including fuel, oxidant utilization, and recycle ratio) can be specified to maximize the system efficiency.

Keywords: Fuel cell; Molten carbonate; Efficiency; Process simulation

1. Introduction

The main advantage of the molten carbonate fuel cell (MCFC) power generating system is high efficiency and co-generation capability compared with low-temperature fuel cells. This is because of the high operating temperature (650 °C) of the MCFC [1]. MCFC power-generating systems of MW size are expected to become one of the major electric power plants in the future and their gross system efficiency has been reported as 45–50% [2]. The high temperature waste heat provides an overall system efficiency of 70% or higher by using additional turbine-based power generation systems and thermal integration.

In future markets, MCFC power-generation systems can also be used for dispersed power, alternative thermal power generation or industrial combined heat and power plants (CHPs) for decentralized applications such as hospitals and greenhouse gardening [3]. MCFCs of several hundred kW size are especially promising as dispersed power sources and until now a variety of capacities have been installed (100–1000 kW). To be at the stage of commercialization, the limit of overall system efficiency of kW MCFC power generating systems of a few hundred kW should be quantitatively explained.

Several past studies have demonstrated parametric models to calculate various effects on fuel-cell system efficiency. Thermal integration including the heat transfer losses between the subsystems in terms of exergy loss for a 1 MW solid oxide fuel cell (SOFC) system has been analyzed by comparing the internal with the external reforming approach [4]. Recently, parametric studies on fuel cell system efficiency were reported on the basis of thermodynamic calculations for direct methanol fuel cells or SOFCs [5–7]. These quantitative analyses have been done to show the high electrical efficiencies compared with those of conventional thermal systems prior to entering the commercial market. The combined system of SOFC with gas turbine (G/T) has been analyzed in terms of parametric analysis to demonstrate the relation between the fuel cell and additional power generation units in detail [8,9].

In this paper, a rigorous simulation model is developed for a MCFC system of 100 kW to analyze the various parametric effects on system efficiency. The process simulation model is verified on the basis of experimental data from a 25 kW system. The efficiency analysis of a 100 kW MCFC system relating to the system configuration and operating condition has a critical role in developing commercial plants for decentralized applications. The results can be easily applied to MW-scale systems by just increasing the number of 100 kW-scale stack units in the system.

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2. MCFC system

The MCFC stack produces electricity by the electrochemical reaction of fuel and oxidant in molten alkali electrolyte at 650 °C. The following half-reactions take place in porous electrodes under external current load.

$$H_2 + CO_3{}^{2-} \rightarrow H_2O + CO_2 + 2e^- \quad \text{(anode)} \tag{1}$$

$$CO_2 + \tfrac{1}{2}O_2 + 2e^- \rightarrow CO_3{}^{2-} \quad \text{(cathode)} \tag{2}$$

The overall reaction is exothermic because of the negative enthalpy change and the incomplete conversion of fuel to electricity in the stack, i.e.

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O + \text{electricity} + \text{heat (stack)} \tag{3}$$

In case of an external-reforming MCFC system, fuel processing of natural gas (CH_4) consists of steam reforming followed by a shift reaction in the reformer, i.e.

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \quad \text{(reformer)} \tag{4}$$

The sum of Eq. (3) multiplied by Eq. (4) yields:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 + \text{electricity} + \text{heat} \quad \text{(overall)} \tag{5}$$

The overall reaction taking place in the MCFC process is easily expressed by the oxidation of 1 mol of methane with 2 mol of oxygen, producing 2 mol of water, 1 mol of carbon dioxide, and electricity with heat (Eq. (5)). The MCFC system can be simply represented as a unit process which is composed of two reactants (natural gas, air), a product (alternating current), and two by-products (water, carbon dioxide), as shown in Fig. 1. The maximum possible efficiency of this process is more than 50%, that is, the ratio of power produced to the higher heating value (HHV) of fuel inlet, based on 80% of fuel utilization.

The main characteristic of the MCFC system in practical operation is that carbon dioxide produced at the anode side should be supplied to the cathode. This makes the unit more compact and also more complex compared with other fuel cell systems. The simplified MCFC process system can be divided into four major units, namely, the fuel processor, the fuel cell stack, the auxiliary power generation unit, and the heat recovery unit (see Fig. 2). In the MCFC system, the power generation part is composed of the MCFC stack which produces direct current (dc) and the auxiliary power generator (e.g. a turbine which produces ac).

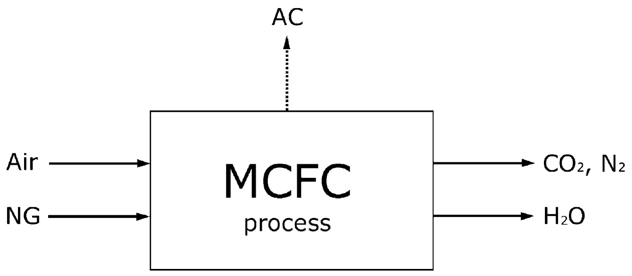

Fig. 1. Simplified MCFC process (AC: alternating current).

The fuel processor in the MCFC system is of paramount importance in designing efficiently the overall system. The effects of fuel type, reforming method, operating temperature, pressure, and steam to carbon ratio on performance of the fuel-processing unit are not explained here in detail, but have been reported elsewhere [10]. Three fuel processing methods frequently used in the fuel cell system are steam reforming, autothermal reforming, and partial oxidation. A natural gas steam reformer is used in this study because it produces the highest hydrogen concentration in the product [11]. The main purpose of the reformer is to produce hydrogen-rich gas for use as a fuel at the anode of the stack), and to burn the remaining (exit) anode gas to make carbon dioxide for supply to the cathode. Thermal integration between the reformer and fuel cell stack makes other parasitic power unnecessary, such as that for an electric preheater or auxiliary burner, and thus, it helps to increase system efficiency.

The high temperature waste heat produced in the stack should be used in an auxiliary power generator, such as a turbo-charger (T/C) or a gas turbine (G/T) as this makes the efficiency of MCFC system 70% or higher. In the heat-recovery unit, steam used in the reformer is produced using a

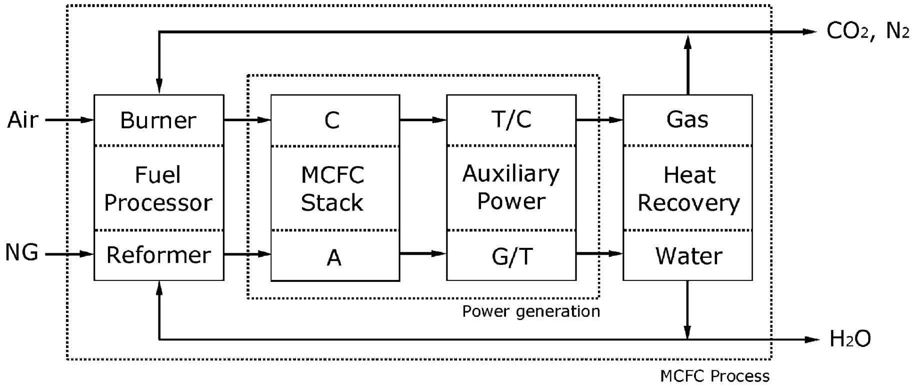

Fig. 2. Detailed process flow diagram of MCFC system (T/C: turbo-charger, G/T: gas turbine).

heat-exchanger network and water gas separation takes place for recycle operation.

The gross system efficiency is defined as the ratio of ac power produced in the system to the HHV of the total fuels supplied to the system, i.e.

$$\eta_{\mathrm{gross}} = \frac{\text{ac power produced}}{\text{HHV of total fuels to system}} \tag{6}$$

The net system efficiency is defined as the ratio of ac power produced less the parasitic power to the HHV of the total fuels supplied to the system, i.e.

$$\eta_{\mathrm{net}} = \frac{\text{ac power produced} - \text{parasitic power}}{\text{HHV of total fuels to system}} \tag{7}$$

The net electric efficiency of a fuel cell system integrated with turbine-based power generators is more than 65% as a result of increasing the electric power produced in the system and decreasing the parasitic power by using a turbo charger instead of an air compressor.

3. Process analysis and simulation of MCFC systems

3.1. 25 kW MCFC system

The process flow diagram of a 25 kW MCFC system is shown in Fig. 3. To set up a process model for the MCFC system, CYCLE-TEMPO (version 4.02) is used. This was developed at Delft University to calculate the power efficiency in a thermal power cycle [4]. The commercial software takes the fuel cell stack as a standard unit model, which can be modeled with several different model blocks and user-defined functions by means of commercial chemical software [12].

Water and natural gas are supplied to the steam reformer at which natural gas can be converted to a gas mixture that contains H_2 and CO for use in the fuel cell. The reformed gas passes to the fuel pre-heater, where it is heated to 550 °C. In the fuel cell stack, 60% of the fuel is converted to produce electricity proportional to current load. The outlet gas from the stack is cooled to 40 °C in the anode cooler, which also functions as a water–gas separator. The remaining anode gas from the anode cooler is recycled either to the catalytic burner to make CO_2 gas for the cathode or to the anode inlet to increase the fuel utilization rate.

The burned gas from catalytic burner is supplied to the cathode pre-heater, where it is heated to 550 °C, and then enters into the cathode side in the stack. A large amount of the outlet gas from the stack is recycled to maintain the temperature difference between the inlet and the outlet of the stack within 100° because the oxidant recycle is mainly used as stack coolant in pressurized operation. The overall oxidant utilization rate, taking into account of the anode recycle stream, is less than 30% in normal operation.

The net system efficiency with a MCFC stack larger than 25 kW has been reported to be than 50% with natural-gas fueled and oxygen-enrichment operation [1]. The low system efficiency based on the experimental values of the 25 kW MCFC system studied here can be explained in terms of heat transfer losses in the fuel-cell system. The power input and output of the 25 kW MCFC system are summarized in Table 1. There is a gross efficiency of 12.3% which is much lower than reported elsewhere. The main reason for the lower gross efficiency is that there is no thermal integration between the fuel processor and the heat-recovery system. The electric power consumed in the pre-heater is twice that produced in the stack. Another reason for the lower efficiency is that the efficiency of the unit operators used in the system is lower than 60% on account of the smaller size. The effect of unit operators on system efficiency will be explained later in detail.

3.2. 100 kW MCFC system

The MCFC system studied here is composed of a MCFC stack and external steam reformer as a fuel processor, and

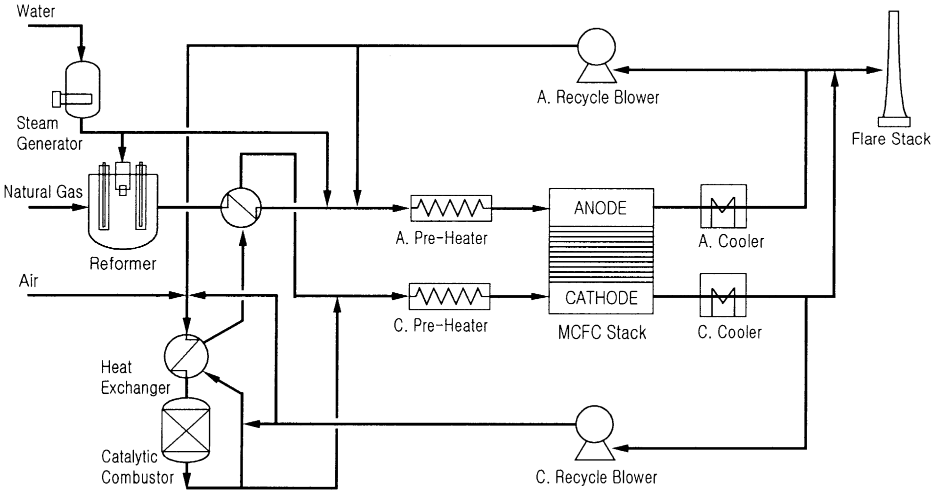

Fig. 3. Schematic diagram of externally reformed 25 kW MCFC system.

Table 1
System efficiencies, power (kW) input and output of 25 kW MCFC power generating system[a]

Power	Apparatus	Energy	Total
Absorbed power	NG source	119.96	203.23
	Steam generator	7.0	
	Pre-heater	54.76	
Delivered power	MCFC stack		25.00
Auxiliary power consumption	Anode blower	2.12	14.50
	Cathode blower	17.61	
	Cooling pump	17.48	
	Air compressor	5.78	
Delivered net power			10.50
Efficiency (%)			
Gross		12.301	
Net		5.167	

[a] $U_f = 60\%$, $U_{ox} = 400\%$, $I = 150\ \text{mA cm}^{-2}$, operating pressure = 3 kg cm^{-2}.

other balance of plant (BOP) such as a heat exchanger, an inverter, a turbo-charger, a blower, a flash, and a pump as shown in Fig. 4.

The fuel cell stack consists of 170 unit cells, which comprise two electrodes and an electrolyte in a matrix. The area of each electrode is about 6000 cm^2. The anode and cathode gases flow in a co-flow direction. The pressure drop in the stack is 500 mmH$_2$O at the cathode and 200 mmH$_2$O at the anode. The normal operating condition for this stack is 80% fuel utilization, 30% oxidant utilization, and 125 mA cm^{-2} current density. The efficiency of the inverter converting dc to ac is assumed to be 95%.

The steam reformer (S/R produces hydrogen-rich gas by an endothermic reaction (Eq. (4)) at 800 °C with the aid of burning the anode exit gas recycled from the stack. Additional natural gas is used to increase the temperature of the reformer burner with a fuel utilization of more than 60%. The steam-to-carbon ratio of this reaction is maintained at 3 to prevent carbon formation. In this system, the anode exit gas is used as fuel for burning in the reformer.

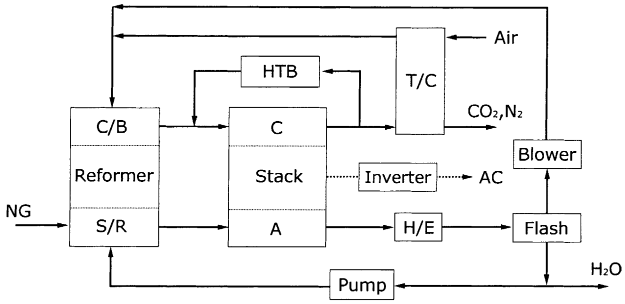

Fig. 4. Process flow diagram of externally-reformed 100 kW MCFC system (C/B: catalytic burner; S/R: steam reformer; HTB: high temperature blower; H/E: heat exchanger; T/C: turbo-charger; AC: alternating current).

The anode exit gas which containing a large portion of water from the stack, passes the heat exchanger (H/E). The H/E is used for thermal integration between the anode exit gas and the recycled water supplied to the steam reformer The anode exit gas is separated into water and remaining combustible gas in the flash operated at 80 °C. The drained water from the flash is supplied to the steam-reformer to compensate for the steam in reforming reaction. The remaining combustible gas is used as the fuel gas in the catalytic burner (C/B) using an anode gas blower. The compressed air from the turbo charger (T/C) is mixed with recycled anode exit gas in the catalytic the resulting mixture is burner and supplied to the cathode inlet at 580 °C including CO$_2$, which is necessary for the cathode reaction. Due to the low oxidant utilization, a large amount of high-temperature cathode exit gas is used to generate electricity in the turbo charger. The overall system efficiency is markedly increased by using a turbo charger because it reduces the auxiliary power consumed by the air compressor and generates electric power. The recycle ratio at the cathode is determined by the ratio of the vent to the recycled gas.

Heat exchangers are constructed between the fuel processor and the heat-recovery system. The latter is composed of several heat exchangers so as to reduce heat losses in the system. The pinch temperature of each heat exchanger used is set to 10 °C and the configuration of the exchangers is based on cross flow.

4. Results and discussion

4.1. System configuration

The gross system efficiency with a 25 kW MCFC system is about 12.5%, which is lower than expected. The overall system efficiency is greatly affected by the configuration of the unit operators, as shown in Fig. 5. The net system efficiency increases from 9.86 to 38.4% by integrating thermal energy or producing auxiliary electric power.

The power input and output used in the four cases shown in Fig. 5, together with system efficiency are summarized in Table 2. Case 1 uses simple thermal integration by means of a heat-exchanger network, which has a pinch point of atleast 10 °C. The heat exchanger between the anode and cathode streams should be avoided at high temperature to prevent the burning which can cause cracks in the heat exchanger. A large amount of cathode exit gas is generally used as heat source to produce steam in the heat recovery steam generator. The gross system efficiency increases from 12.5 to 30.2% when using a heat exchanger between the inlet and outlet gases. The efficiency of the fuel cell stack can be determined from the fuel utilization, which is always lower than 100% because of various overpotentials in converting fuels to electricity. The fuel utilization in the stack is 80% under normal operating conditions and 20% of fuel remains in the anode outlet stream.

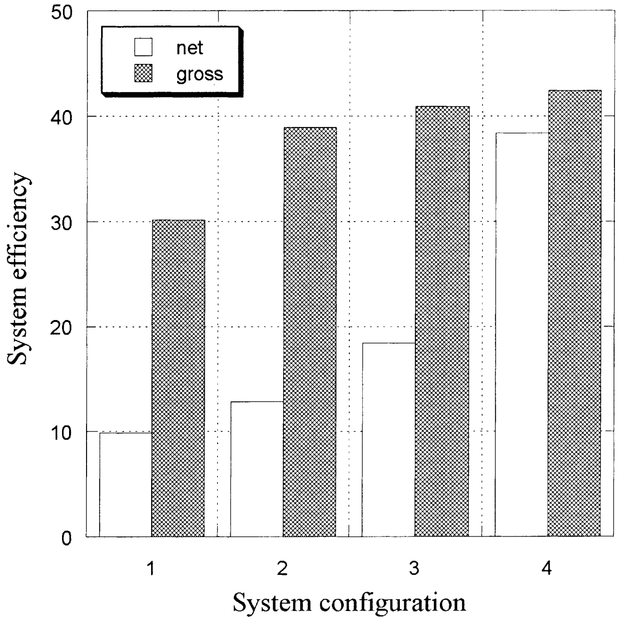

Fig. 5. Effect of system configuration on externally-reformed MCFC system efficiency (case 1: system with heat exchanger network; case 2: system using anode exit gas; case 3: system with high temperature blower; case 4: system with turbo-charger; net: net efficiency; gross: gross efficiency).

Case 2 shows the effect of using exit fuel gas on the system efficiency. The anode exit gas can be used as fuel for the cathode reformer or at the anode inlet to increase the overall fuel utilization, which raises the gross system efficiency from 30.19 to 38.96%. To analyze the effects of having a high-temperature blower (HTB) at the cathode, case 3 contains a HTB at the cathode side, which should be specially designed to increase the system efficiency with direct recycling exit stream into the cathode inlet. The advantage of using a HTB at the cathode is to reduce the heat-transfer loss in the gas cooling and re-heating, and she increase the system gross efficiency from 40.91 to 38.96%. The large increase of net efficiency from 18.42 to 38.4% in case 4 is due to the turbo charger, which reduces the parasitic electric power required in air compressor. This case is used as the standard configuration to calculate other effects on system efficiency in later simulations of the system.

Table 2
System efficiencies and power (kW) input and output of four configurations of 100 kW MCFC system[a]

Power	Apparatus	Case			
		1	2	3	4
Absorbed power	NG source	171.13	171.13	171.13	171.13
	NG burn	160.12	85.56	73.34	58.67
	Sub-total	331.25	256.69	244.47	229.80
Delivered power	MCFC stack	100.0	100.0	100.0	100.0
Auxiliary power consumption	NG compressor	4.30	3.42	3.25	3.04
	Air compressor	63.04	59.16	45.49	3.40
	Cooling pump	0.02	0.02	0.02	0.02
	Anode blower	17.48	4.51	4.39	4.40
	Cathode blower	0.0	0.0	2.14	2.17
	Sub-total	67.36	67.11	55.29	13.03
Delivered net power		32.65	32.89	44.71	86.97
Efficiency (%)					
Gross		30.193	38.958	40.904	42.032
Net		9.858	12.815	18.289	37.844

[a] $U_f = 80\%$, $U_{ox} = 30\%$, $I = 125\ \mathrm{mA\ cm^{-2}}$, operating pressure $= 5\ \mathrm{kg\ cm^{-2}}$.

4.2. System size

The optimal system configuration listed above can be possible when the system size is larger than a few hundred kW. Auxiliary power such as a turbo charger or a gas turbine increases the system efficiency by reducing the parasitic power required by the air compressor. There is much interest in MCFC applications in the range 250–400 kW for commercial application and the choice of system size is a more important factor to attain the target for a commercial MCFC plant [9]. The effect of system size from 100 kW to 1 MW on the system efficiency of a fixed system configuration, (i.e. case 4, Fig. 5) is shown in Fig. 6. It should be noted that the system efficiency is determined not by the system size but by the system configuration, which can be variously set up according to the system size.

The slightly higher system efficiency (about 5%) resulting from increase in the system size is due to the increased electric power produced in the turbo charger which is proportional to the greater oxidant exit flow. The increase in electric power from 4.43 to 45.8 kW, the required power consumed by the air compressor, equally affects the increase

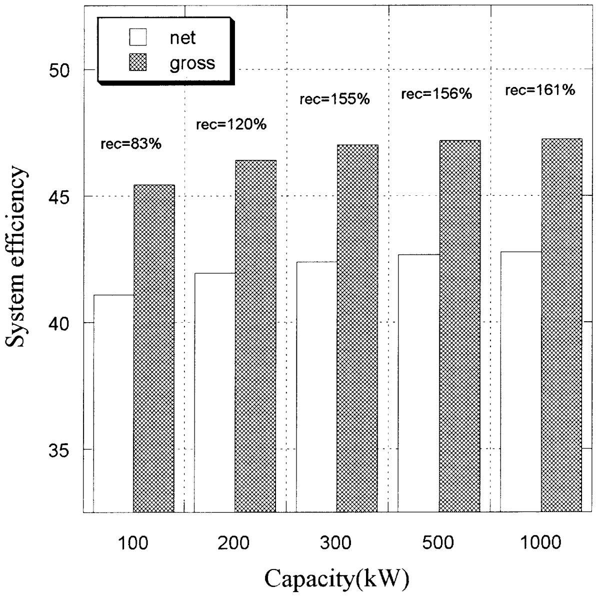

Fig. 6. Effect of system size on externally-reformed MCFC system efficiency (net: net efficiency; gross: gross efficiency; rec: cathode recycle ratio).

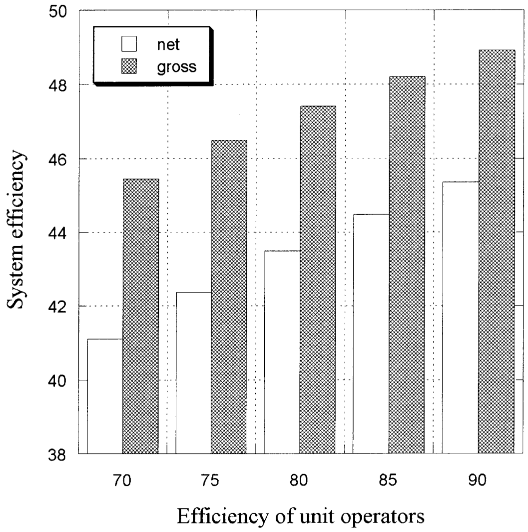

Fig. 7. Effect of efficiency of unit operators on 100 kW externally-reformed MCFC system efficiency (net: net efficiency; gross: gross efficiency).

of gross and net efficiency, as shown in Fig. 6. The recycle ratio is increased from 83 to 161% as the system size increases to maintain the temperature difference in the stack within the set limit.

4.3. *Efficiency of unit operators*

The efficiency of each of the unit processors used in the system e.g. as blower, compressor, turbine, pump) is assumed to 70%. The effect of the efficiency of the unit operators used in the system on the system efficiency is shown in Fig. 7. The gross efficiency increases monotonically from 45.45 to 48.92% with increase in the mechanical efficiency of the unit operators, while the net efficiency increases from 41.09 to 45.36%. The noticeable influence of the unit operators on the system efficiency can be also explained in terms of system size because the efficiency of the unit operators is highly related to their size.

4.4. *Fuel utilization*

For a stack outlet temperature below 680 °C, a constant oxidant utilization (30%) and a constant cathode gas recycle ratio (83%), the effect of fuel flow rate or fuel utilization rate on the system efficiency is shown in Fig. 8. The stack outlet temperature decreases when fuel flow increases due to the convective cooling effect but is smaller than that of oxidant flow. Fig. 8 show a greater decrease in system efficiency when the fuel utilization is less than 60%. The required amount of fuel used in the reformer burner is about 40% of fuel into the fuel processor on the basis of a fuel utilization of 80%. The slight increase in system efficiency when the fuel utilization is higher than 60% is due to the use of natural gas to make up for the fuel required in the reformer burner. From these findings, the optimal operating condition required for fuel utilization is more than 60%.

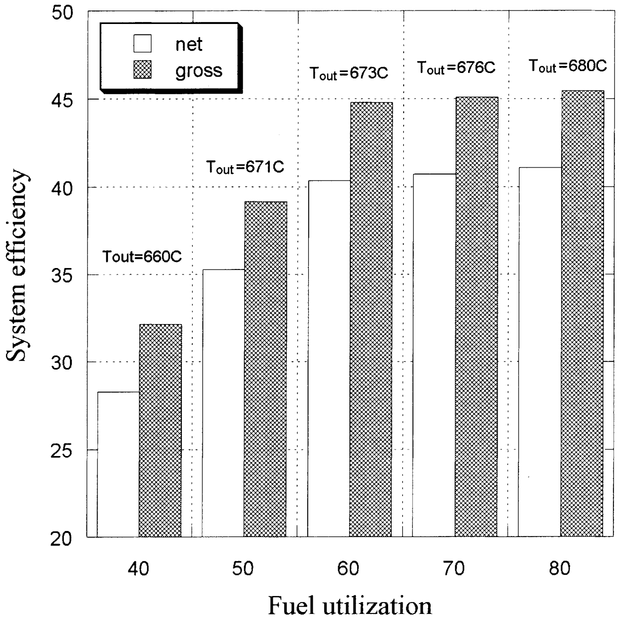

Fig. 8. Effect of fuel utilization on 100 kW externally-reformed MCFC system efficiency (net: net efficiency; gross: gross efficiency; T_{out}: stack outlet temperature; recycle ratio: 83%; oxidant utilization rate: 30%).

4.5. *Oxidant utilization*

The oxidant flow rate greatly influences the system efficiency because it is usually supplied by means of a compressor, which consumes more power than any of the other unit operators. Cathode gas flow is used as a primary coolant for the stack, so more is required than reacts in the stack. The effect of oxidant utilization rate on system efficiency is shown in Fig. 9. The optimal operating condition for oxidant utilization is about 30%. The recycle ratio increases as the oxidant flow rate decreases to control the temperature of stack outlet gas within the allowable limit. The overall system efficiency drops sharply at less than 30% oxidant utilization due mainly to the parasitic power consumed in the air compressor. Although these trends can vary with the efficiency of the unit operators and the system configuration, 30% oxidant utilization is the optimal operating condition for the given system.

4.6. *Recycle ratio*

In pressurized operation, recycled cathode gas recycle is needed to increase the amount of oxidant flow rate used as stack coolant. The recycle ratio is defined as the ratio of recycled flow to exit flow. In other words, the recycle ratio is 100% when the recycled stream is equal to the exit stream. The effect of the cathode gas recycle ratio on system efficiency, with all other variables fixed, is shown in

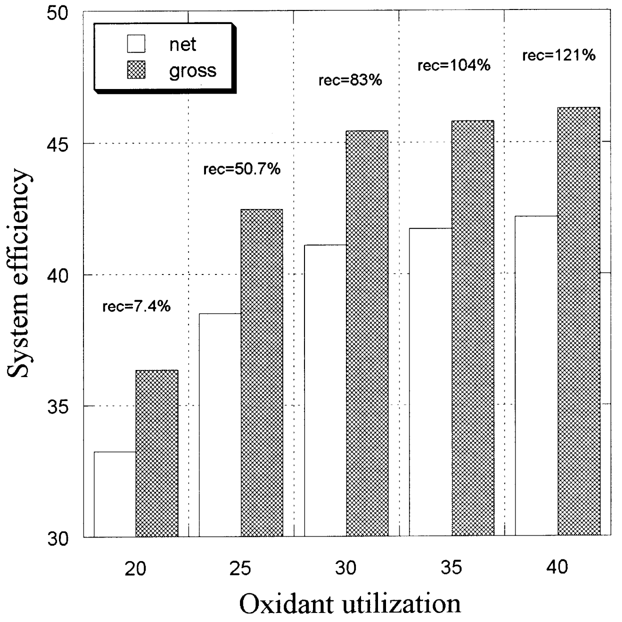

Fig. 9. Effect of oxidant utilization on 100 kW externally reformed MCFC system efficiency (net: net efficiency; gross: gross efficiency; fuel utilization rate: 80%; stack outlet temperature: 680 °C).

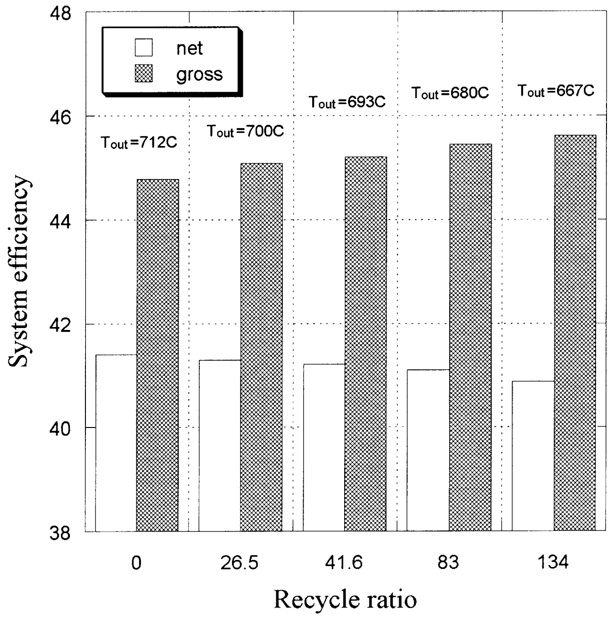

Fig. 10. Effect of cathode recycle ratio on 100 kW externally reformed MCFC system efficiency (net: net efficiency; gross: gross efficiency; T_{out}: stack outlet temperature; fuel utilization rate: 80%; oxidant utilization rate: 30%).

Fig. 10. At a given operating condition, the cathode gas should be recycled to more than 83% to maintain the stack outlet temperature with the allowable limit. The increase in gross efficiency with recycle ratio as shown in Fig. 10 can be explained by the fact that the increased recycle ratio diminishes the electric power produced in the turbo-charger. The net efficiency decreases with increasing recycle ratio because more electric power is needed for the cathode blower, which increases the parasitic power. The net efficiency and outlet temperature of the stack should both be considered in order to operate the overall system optimally.

5. Conclusion

The effects of system configuration and operating conditions on the system efficiency of a 100 kW MCFC system has been analyzed. A process model based on experimental data obtained from a 25 kW MCFC system is used to calculate quantitatively the various effects on the overall system efficiency. The efficiency is highly affected by the system configuration rather than system size and the efficiency of the unit operators. Four systems with different unit operators have been selected to analyze the effect of system configuration on system efficiency. The highest net efficiency is obtained from a system which uses a turbo-charger to produce the power required for air compressing. This shows that the fuel cell system should be used as a combined power cycle. Operating conditions, fuel, oxidant utilization and cathode recycle ratio also affect system efficiency. Nevertheless, the efficiency can be adjusted to a limited optimal range, which is practical in normal operation. By analyzing these effects, the optimal operating conditions for a given MCFC system can be determined to maximize the overall system efficiency.

Acknowledgements

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