HEFAT2008
6th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
30 June to 2 July 2008
Pretoria, South Africa
Paper number: MA3

PERFORMANCE ANALYSIS OF INTERNALLY REFORMED MCFC/IT-SOFC COMBINED CYCLE

Musa A.*, Huisseune H. and De Paepe M.
*Author for correspondence
Department of Flow, Heat and Combustion Mechanics,
University of Ghent,
Sint-Pietersnieuwstraat, 41,9000
Gent Belgium,
E-mail: Musa.Abdullatif@ugent.be, Michel.DePaepa@ugent.be.

ABSTRACT

High temperature fuel cells such as the solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) are considered extremely suitable for electrical power plant application. The intermediate temperature (IT) SOFC and MCFC performances are calculated using numerical models which are built in Aspen customer modeler for the internally reformed (IR) fuel cells. These models are integrated in Aspen Plus^{TM}. In this article, a new combined cycle is proposed: this combined cycle consisting of two-staged of MCFC and IT-SOFC. The MCFC&IT-SOFC combined cycle and single-staged cycle with MCFC only are simulated in order to evaluate and compare their performances. The simulations results indicate that the net efficiency of MCFC&IT-SOFC combined cycle is 64.6 % under standard operation conditions. On the other hand, the net efficiency of single-staged MCC cycle is 51.6%. In other words, the cycle with two-staged MCFC and IT-SOFC gives much better net efficiency than the cycle with single-staged MCFC.

INTRODUCTION

The development of energy system with readily available fuels, high efficiency and minimal impact are required in order to meet increasing energy demands and to respond to environmental concerns. Increasingly, fuel cell systems are being considered as promising solutions. Fuel cells convert chemical energy into electrical energy and have the advantage of continuous supply of reactant gases. The fuel cells used for stationary energy production are typically high temperature fuel cells (HTFCs) such as solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC).

In combination with gas turbine (GT) systems the MCFC or SOFC are now under study as part of new highly efficient power plants. The most typical hybrid configuration suggested in the literature is a recuperated gas turbine process with a MCFC as core unit of the system. This type of the system has been investigated in [3-7]. MCFCs can achieve an electrical efficiency of 60%.

A new approach is using serially connect fuel cells. The fuel cells have a higher efficiency than gas turbine and by raising the part of the cycle power they supply, cycle efficiency can be raised. The United State Department of Energy (DOE) has investigated ways to achieve high power generation efficiency of 80% and has proposed a multi-staged fuel cell system with five serial stages of fuel cells in order to reduce the regenerative heat for fuel and air, and to extend the operating temperature range of fuel cells. In [1] Araki and co-authors analysed a power generation system consisting of two- stages externally reformed SOFCs with serial connection of low and high temperature SOFCs. They showed that the power generation efficiency of the two-staged SOFCs is 50.3% and the total efficiency of power generation with gas turbine is 56.1% under standard operating conditions.

In this paper newly a combined cycle is proposed and investigated. Thermodynamic models for internally reformed IT-SOFC and MCFC are developed. These fuel cells are combined in different ways in order construct single-staged and two-staged fuel cell system combining different cell types. The aim of the paper is to find the best configuration for a single-staged or a two-staged combined system. Therefore, the performance of two types of cycles is analysed: combined cycle consisting of two-staged of MCFC and IT-SOFC and single-staged cycle with MCFC.

NOMENCLATURE

F	[kC/kmol]	Faraday's constant , 96487
i	[A/cm^2]	Current density
$\dot{Q}$	[kW]	Heat
p	[Pa]	Partial pressure
K	[-]	Equilibrium constant
h	[kJ/kmol]	Enthalpy

n	[mol s^{-1}]	Mole flow rate
s	[kJ/kmolK]	Entropy
P_{SOFC}	[kW]	SOFC stack electrical power
R_t	[Ω m^2]	Total resistance
$\dot{W}_{cv}$	[kW]	Work in a control volume
σ_{cv}	[kW/K]	Entropy production in a control volume
P_{Comp}	[kW]	Compressor Power
P_{turb}	[kW]	Turbine power
A_{cell}	[m^2]	Active cell area
T_{cell}	[°C]	Cell temperature
u_f	[-]	Total fuel utilization
V_{cell}	[V]	Cell voltage
S/C	[-]	Steam-carbon ratio

Subscripts and Superscripts

0	[-]	At standard temperature and pressure
i	[-]	Initial
p	[-]	Product
R	[-]	Reaction or reactants

Greek symbols

η	[-]	Efficiency
r_{ohm}	[Ω m^2]	Ohmic cell resistance
$r_{pol,an}$	[Ω m^2]	Anodic reaction resistance
$r_{pol,ca}$	[Ω m^2]	Cathodic reaction resistration
V_{loss}	[V]	Overpotential

CYCLES DESCRIPTION

The SOFC and MCFC cells currently in operation are fuelled with natural gas. The high temperature inside the cells stack allows for reforming the methane directly inside the cell if the steam is provided at the inlet. The heat necessary for this reforming reaction is delivered by the electrochemical reaction in the cell. Fuel is provided at atmospheric conditions. The fuel is pure methane (CH_4). In the cycles part of the anode gasses is recycled, as the anode gasses contain steam needed in the reforming reaction. This is a way of avoiding a steam generator in the cycles.

MCFC/IT-SOFC Combined Cycle Configuration

Fig.1 shows a cycle diagram of the combined cycle consisting of an MCFCC and IT-SOF. In this cycle the anode flow of the MCFC and IT-SOFC is in parallel connected. Methane is admitted into the heat exchanger H/E2 to preheat the methane. The preheated methane is split into two parts. Part of the preheated methane is mixed with the recycling anode gases; the mixture is supplied to the anode side of MCFC stack. The remaining part of the preheated methane is mixed with the part of recycling anode gases and then enters into the anode side in the IT-SOFC stack. In both stacks the remaining part of anode gases is recycled to the combustor. The combustor exit gas which contains a major part of air, and CO_2 is split into two parts. The first part is the cathode inlet gas of the MCFC stack. The remaining part of the combustor exit gas and cathode outlet gas of MCFC are mixed, the mixture is sent to a gas turbine and heat exchanger (H/E2) respectively. The cathode gases of the IT-SOFC stack is recycled to the combustor.

The compressed air from the compressor (AC) is supplied to the heat exchanger (H/E1) and then enters into the cathode side of the IT-SOFC stack.

Single-staged MCFC Cycle Configuration

The single-staged MCFC cycle is similar to the combined cycle (Fig. 1), except that there is no IT-SOFC stack. The combustor exit gas is split into two parts. The first part of the combustor exit gas and the compressed air from the compressor (AC) are mixed. This mixture is sent to the heat exchanger (H/E1) and then enters into the cathode side of the MCFC stack. The remaining part of the combustor exit gas is mixed with part of the cathode outlet gas, the mixture is sent to a gas turbine and heat exchanger (H/E2) for recovering energy. The remaining part of the cathode outlet gas is recycled to the combustor. In this cycle part of the preheated methane is bypassed to the combustor.

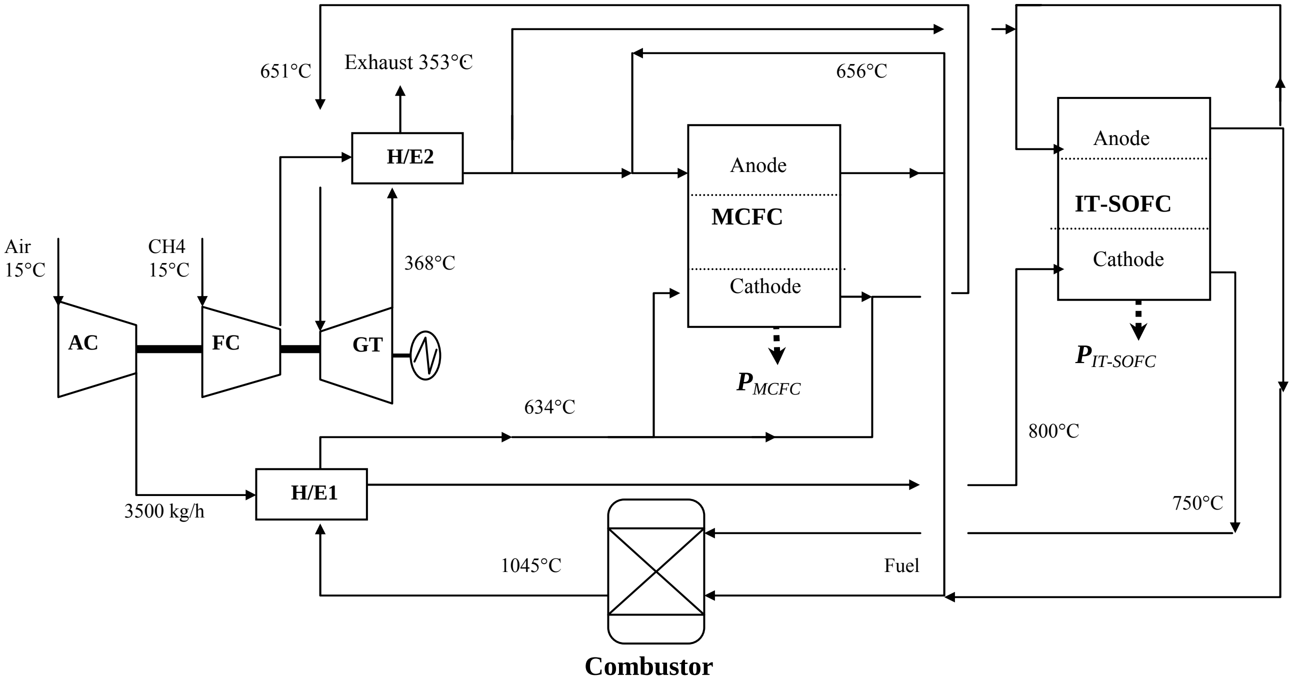

Figure 1 Schematic diagram of MCFC&IT-SOFC combined cycle (AC: air compressor; FC: fuel compressor; GT: gas turbine; H/E: heat exchanger)

CYCLES ANALYSIS METHODE

Assumptions and calculation conditions of the models

The assumptions and conditions of the models used in the simulation program are as follows:

- Steady state conditions with negligible frictional losses
- Negligible changes of potential and kinetic energies in any process
- Changes in the composition of the anode and cathode gases are only significant in the flow direction.
- Oxidant and fuel are considered to be ideal gases.
- Nernst potential is independent of hydrostatic pressure gradient.
- The operating temperature of the cell is equal the outlet cathode and anode temperature.

Thermochemical aspects: water gas shift and methane reforming reactions

In the models the chemical reactions are assumed to be in equilibrium. This means that the reactions occur instantaneously and reach the equilibrium condition spontaneously at each position.

For SOFC models the electrochemical reaction is implemented:

$$\tfrac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \quad \text{cathode} \tag{1}$$

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \quad \text{anode} \tag{2}$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \quad \text{overall reaction} \tag{3}$$

For MCFC model the electrochemical reaction is implemented:

$$CO_2 + \tfrac{1}{2}O_2 + 2e^- \rightarrow CO_3^{2-} \ \text{cathode} \tag{4}$$

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \ \text{anode} \tag{5}$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \ \text{overall reaction} \tag{6}$$

The IT-SOFC and MCFC operate at a temperature high enough to reform the steam reforming inside the anode. The chemical reactions in the steam reforming and shifting of methane are shown below:

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 \tag{7}$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \tag{8}$$

The electrochemical and water gas shift reactions are exothermic and, on the other hand, fuel reforming is a strongly endothermic reaction.

SOFC AND MCFC MODELS DESCRIPTION

The fuel cell is treated as a single control volume on which the steady state flow energy equation is applied with the assumption of negligible change of kinetic energy and potential energy. To determine actual cell performance, the overpotential must be deducted from the Nernst potential (E) which represents the ideal performance.

$$V_{cell} = E - V_{loss} \tag{9}$$

Evaluation of voltage drops in IT-SOFC

The model of the IT-SOFC stack used in this paper is based on an existing IT-SOFC model [2]. In the model the cell will utilize an electrolyte with the thickness of 25μm, a 50 μm thick cathode and 250 μm thick anode. The cells are assumed to be stacked between bipolar interconnect plates. Differently from the high temperature (HT) SOFC, which utilizes ceramic interconnect, the lower operating temperature of the IT-SOFC renders possible application of metal alloys.

It is difficult to break down reported cell characteristics in these individual contributions, and in the present context where the aim is stack and system modelling all cell losses is simply lumped together in one equivalent resistance. The cell resistance is assumed to have the following temperature dependence [2].

$$R_{tot} = \mathrm{A}\exp\left(\frac{\Delta \mathrm{E}}{\mathrm{K} \times T}\right) \tag{10}$$

Where T represents the cell operating temperature and K is the Boltzmann constant. The activation energy ($\Delta\mathrm{E} = 1.01 \times 10^{-19}$ J) and the pre-exponential factor ($\mathrm{A} = 2.98 \times 10^{-4}$) are chosen to fit the experimental data reported by [8].

The cell voltage of the IT-SOFC can be calculated by

$$V_{cell} = \frac{RT}{2F}\ln K + \frac{RT}{2F}\ln\left(\frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}}\right) - \left(iR_{tot}\right) \tag{11}$$

Evaluation of voltage drops in MCFC

In this article, the internal resistances of the MCFC stack can be calculated as in [3]. The ohmic cell resistance (r_{ohm}), anodic reaction resistance ($r_{pol,an}$) and cathodic reaction resistance ($r_{pol,ca}$) are reflected in the functions of the reaction temperatures and partial pressure of gas constituents. The ohmic cell resistance included the ionic and electric resistance; it is calculated using an Arrhenius equation as function of the operating temperature (eq 12).

$$r_{ohm} = 0.5\exp\left[3016 \times \left(\frac{1}{T_{cell}} - \frac{1}{923}\right)\right] \tag{12}$$

$$r_{pol,an} = 2.27 \times 10^{-5}\exp\left(\frac{6435}{T_{cell}}\right) P_{H_2}^{-0.42} P_{CO_2}^{-0.17} P_{H_2O}^{-1} \tag{13}$$

$$r_{pol,ca} = 7.505 \times 10^{-6}\exp\left(\frac{9298}{T_{cell}}\right) P_{O_2}^{-0.34} P_{CO2}^{-0.09} \tag{14}$$

The cell voltage of the MCFC can be calculated by

$$V_{cell} = \frac{RT}{2F}\ln K - \frac{RT}{2F}\ln\left(\frac{p_{H_2O}\,p_{CO_2an}}{p_{H_2}\,p_{CO_2ca}\sqrt{p_{O_2}}}\right) - i\times\left(r_{ohm} + r_{pol,an} + r_{pol,ca}\right) \tag{15}$$

Electrical power of the fuel cells

The electrical power produced by the fuel cell is calculated by:

$$\dot{W} = V_{cell} I \tag{16}$$

Similarly, the heat lost to the environment at an equilibrium state can be determined readily by evaluating the entropy rate balance for a control volume.

$$\dot{Q}_{cv} = T\left(\Delta S - \sigma_{cv}\right) \tag{17}$$

Where:

$$\Delta S = \left(S^{\circ}_{H_2O} - S^{\circ}_{H_2} - \tfrac{1}{2}S^{\circ}_{O_2}\right) + \frac{R}{2}\ln\left(\frac{(p_{H_2})^2\,p_{O_2}}{(p_{H_2O})^2}\right)$$

The ‘thermodynamic’ entropy production, which is actually the irreversibility, is related to the electrochemical overpotential as [4]:

$$\sigma_{cv} = \frac{2F}{T}V_{loss} \tag{18}$$

CYCLE PERFORMANCE VARIABLES

The steam carbon ratio is defined as the ratio between the mole flow rate of steam and the CH4 mole flow rate to the anode.

$$S/C = \frac{\dot{n}_{H_2O}}{\dot{n}_{CH_4}} \tag{19}$$

The fuel utilisation factor is defined by:

$$u_f = \frac{\dot{n}_{H_2consumed}}{\dot{n}_{H_2in} + \dot{n}_{COin} + 4\dot{n}_{CH_4in}} \tag{20}$$

The fuel cell efficiency (η_{FC}) is defined as the ratio of power produced by the fuel cell (IT-SOFC or MCFC) to the lower heating value (LHV) of the total amount of fuel ($Q_{tot} = m_{tot} * LHV$) supplied to the system.

$$\eta_{FC} = \frac{P_{FC}}{Q_{tot}} \tag{21}$$

The net cycle efficiency (η_{net}) is defined as the ratio of the power produced by the fuel cells (P_{FCs}) and the turbine, minus the total compressor power, to the (LHV) of the total amount of fuel (Q_{tot})

$$\eta_{net} = \frac{P_{FCs} + P_{turb} - P_{comp}}{Q_{tot}} \tag{22}$$

Table 1: Setting parameters of the cycles

A_{cell}	250m²	T_{cell} of IT-SOFC	750°C
P	6 bar	i of MCFC	0.15Acm^{-2}
u_f	0.75	Fuel recirculation rate	0.55
S/C ratio	2	η for compressor	0.8
T_{cell} of MCFC	650 °C	η for turbine	0.85

RESULTS AND DISCUSSION

The cycle’s layout under investigation is simulated under the standard operating conditions shown in table 1. The aim of this analysis is to evaluate and compared the performance of the cycles.

Performance of the MCFC/IT-SOFC combined cycle

In these simulations each one of the standard operating conditions was changed to see its effect on the MCFC&IT-SOFC combined cycle performance. The total fuel utilisation rate of the combined cycle is 85% (42.5% in the MCFC, 42.5% in the IT-SOFC). In the following analyses, the triangles (Δ) indicate the net efficiency of the MCFC&IT-SOFC combined cycle and the solid squares (■) indicate the efficiency added by both MCFC and IT-SOFC.

Current density

Fig. 2 shows the changes in the net efficiency of the combined cycle with mean current density and gives an idea about the contribution of the cells and the gas turbine to the net efficiency in the combined cycle. Increasing the current density increases the overpotential of stacks, resulting in decrease of the efficiency of MCFC and IT-SOFC. When the current density increases the MCFC outlet temperature and the exhaust fuel, which is sent to the gas turbine increase together with the increasing turbine output. Since the decrease in the efficiency of both MCFC and IT-SOFC is larger than the increase in the efficiency of gas turbine, the net efficiency of the combined cycle goes down

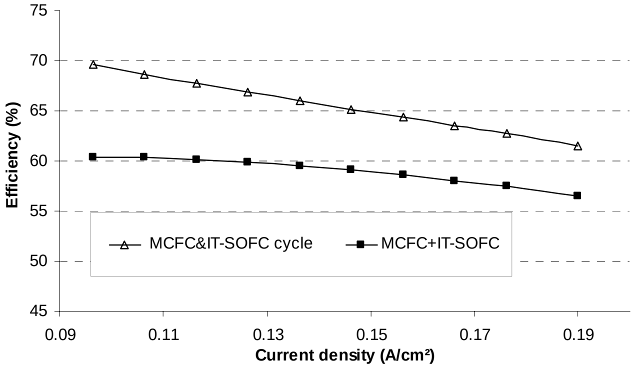

Figure 2 Change of net efficiency of combined cycle with current density

Operating temperature of MCFC

Fig. 3 shows the changes in the net efficiency of the combined cycle with the operating temperature of the MCFC. Increasing the operating temperature of the MCFC decreases the electrolyte resistance in MCFC stack, the efficiency of MCFC increase. In the bottoming gas turbine cycle, increase the operating temperature of the MCFC causes an increase in the outlet temperature of the MCFC. This means that the turbine inlet temperature increases with increasing turbine output. Since the increase in the MCFC and gas turbine efficiencies are larger than the decrease in the IT-SOFC efficiency, the net efficiency of the combined cycle goes up.

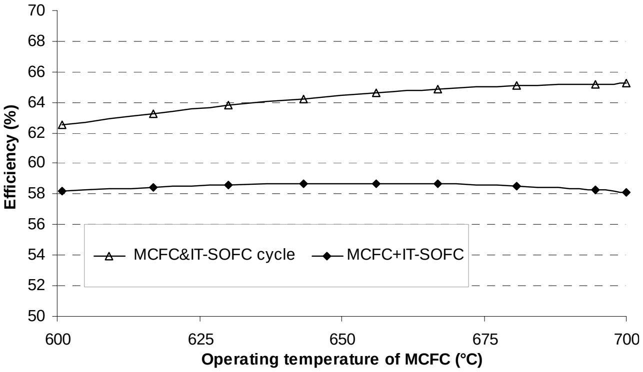

Figure 3 Change of net efficiency of combined cycle with operating temperature of MCFC

Operating pressure

Fig. 4 shows the changes in the net efficiency of the combined cycle with cell pressure. Raising the cell pressure causes an increase in the Nernst potential. Also increasing the operating pressure leads to some decrease in the overpotential, resulting in an increase in the net efficiency in the combined cycle. An increase in the compressors outlet temperature due to the increase of the operating pressure causes an increase in the turbine inlet temperature, resulting in an increase of gas turbine output. In particular, the higher the operating pressure, the higher the cell voltage determining a remarkable improvement of the electrical of the system. It is also obvious that when the value of the operating pressure is increased, higher compressors and turbine costs must be considered [5]

Fuel recirculation

Fig. 5 shows the changes in the net efficiency of the cycle with fuel recirculation rate. By increasing the fuel recirculation rate the CH_4 concentration in the outlet of the stacks anode goes down. This means an increase in the mass flow rate of steam results in moving the reforming and gas shift reaction equilibrium to the H_2 side. Increases in the fuel recirculation rate leads to increase the electrical output of the stacks, resulting in a slight increase in net efficiency of the cycle.

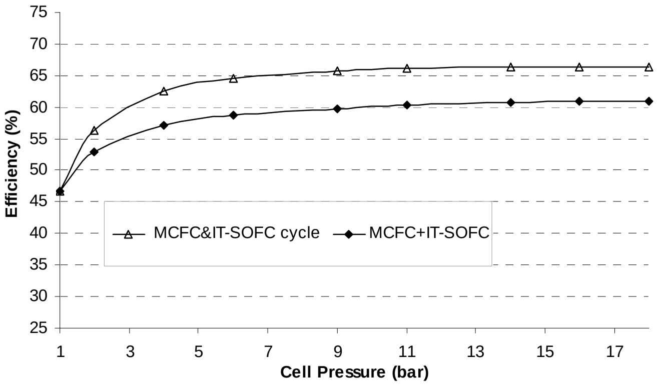

Figure 4 Change of net efficiency of combined cycle with operating pressure

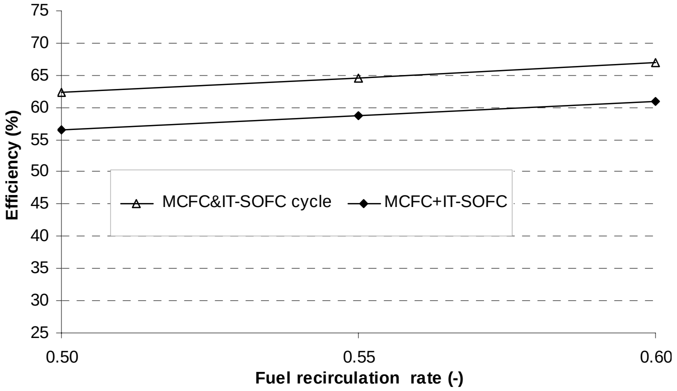

Figure 5 Change of net efficiency of combined cycle with fuel recirculation rate

Comparison of performances between the single-staged MCFC cycle and MCFC/IT-SOFC combined cycle

In this paragraph, the performance of the single-staged MCFC cycle is evaluated. In the combined cycle the performance is analysed with varying current density of MCFC and corresponding of different current density of IT-SOFC stack setting from 0.1 to 0.34 Acm^{-2}.

Fig. 6 shows the changes in the total power of the cycles with mean current density of MCFC. The total power of the cycle is the power produced by the fuel cells and turbine, minus the compressors power. Increasing the current density increases the fuel cell stacks overpotential, resulting a decrease of the cell voltage. Since the increase in the current density is larger than the decrease in the cell voltage, the electrical outputs of the fuel cell stacks (Fig. 7) goes up.

The increase in the total fuel consumption in the fuel cell stacks and the combustor in the cycles with mean current density (Fig. 8) causes an increase in the amount of inlet gas to the gas turbine; this means the electrical output of gas turbine also goes up.

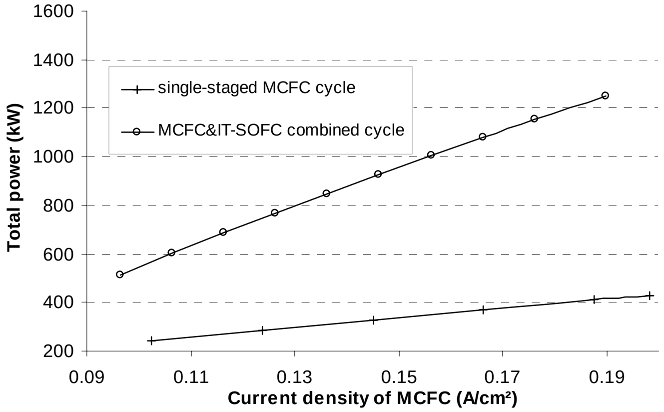

Figure 6 Total powers of the cycles as a function of current density of MCFC

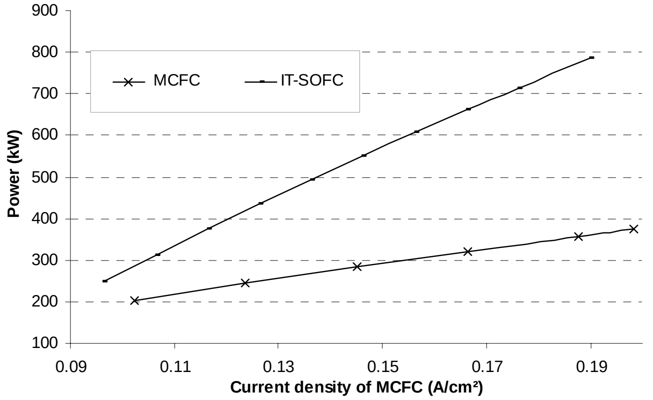

Figure 7 Fuel cell stacks power of the cycles as a function of current density of MCFC

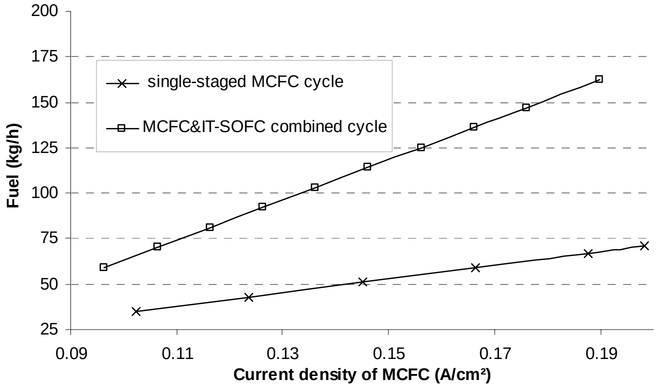

Figure 8 Total fuel consumption on the cycles as a function of current density of MCFC

Fig. 9 shows the changes in the net efficiency of the cycles with mean current density. As the total power of the cycles goes up (Fig. 6) and total fuel consumption in the fuel cell stacks and the combustor in the cycles changes greatly, net efficiency of the cycles goes down. Though the fuel consumption is lower in the single-staged MCFC cycle, the total power is also lower, causing the reduction in efficiency.

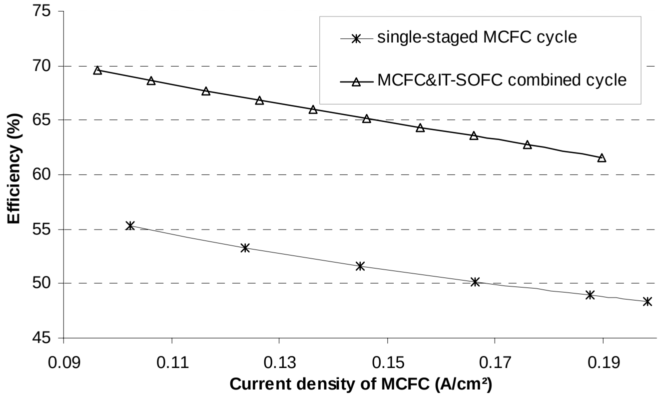

Figure 9 Change of the net efficiency with mean current density of MCFC

CONCLUSION

In this article, a new combined cycle was proposed: combined cycle consisting of two-staged of MCFC and IT-SOFC. The MCFC&IT-SOFC combined cycle and single-staged cycle with MCFC only were simulated in order to evaluate and compare their performances.

By changing the operating parameters, current density operating temperature of MCFC, cell pressure, and fuel recirculation rate, the effects of these operating parameters on combined cycle efficiency was investigated. The simulations results indicate that the net efficiency of MCFC&IT-SOFC combined cycle and single-staged MCFC cycle are 64.6% and 51.6% respectively under standard operating conditions of the cycles were mean current density of 0.150 Acm^{-2} for MCFC, operating temperature of 650°C for the MCFC, cell pressure of 6 bar, operating temperature of 750°C for the IT-SOFC, and fuel recirculation rate of 55%. In other words, the cycle with two-staged MCFC and IT-SOFC gives much better net efficiency than the cycle with single-staged MCFC.

REFERENCES

[1] Araki T, Ohba T, Takezawa S, Onda K, Sakaki Y. Cycle analysis of planar SOFC power generation with serial connection of low and high temperature SOFCs. J. Power Sources 2006; 158: 52-59.

[2] Plasson J, Selimovic A, Hendriksen P. Intermediate temperature SOFC in gas turbine cycles. J. ASME 2001; GT: 0091.

[3] Kimijima S, Kasagi N. Cycle analysis of micro gas turbine-molten carbonate fuel cell hybrid system. J. JSME 2005; series B: 48-1.

[4] Chan SH, Low CF, Ding OL. Energy and exergy analysis of simple solid-oxide fuel cell power systems J. Power Sources 2002; 103: 188-200.

[5] Bocci E, Orecchini F, Di Carlo A, MCFC and microturbine power plant simulation. J. Power source 2006; 160: 835-841.

[6] Musa A, Steeman H, De Paepe M. Performance of internal and external reforming molten carbonate fuel cell systems. J. ASME 2007; 4: 65-71.

[7] Baranak M, Atakül H, A basic model for analysis of molten carbonate fuel cell behavior. J. Power Sources 2007; 172: 831-839.

[8] Mogensen M, Solid oxide technology: Status, challenges and visions. Proceeding, Hydrogen Electrochemistry and Energetics, Norway, 1999; 69-80

[9] Calise F, Dentice d'Accadia M, Palombo A, Vanoli L. Simulation and exergy analysis of a hybrid Solid oxide fuel cell (SOFC)-Gas Turbine system J. Energy 2006; 31: 3278-3299.