

Molten carbonate fuel cell with indirect internal reforming

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Received 3 July 1993, in revised form 18 April 1994; accepted 23 April 1994

Abstract

Researchers in the field of internal reforming molten carbonate fuel cells (MCFC) propose two different configurations: (i) direct internal reforming, and (ii) indirect internal reforming. This paper reports the results of a study on the influence of the operating parameters on the energy balances of a MCFC fuelled with indirect internal reforming (IIR-MCFC). This analysis, carried out by using a mathematical model, identifies the temperature, the steam/carbon ratio, the current density, the useful heat fraction and the fuel-utilization coefficient as relevant parameters to determine the overall energy efficiency of the system. The results emphasize the influence of the working temperature (893 to 973 K) and the steam/carbon ratio (1.5 to 2.5) on the electrical efficiency and on the methane conversion. A detailed balance of the thermal power contributions has been determined, as well as the compositions of exhaust gases for various conditions. The most meaningful conclusion confirms the reliability of this system for the production of electricity with an efficiency in the order of 35 to 40%

Keywords: Molten carbonate fuel cell; Indirect internal reforming

1. Introduction

Research and development on molten carbonate fuel cell (MCFC) technology confirms the applicability of the system for high electrical efficiency power plants [1]. One of the most interesting features of the system is the high operating temperature (923 K) [2], that makes it possible to integrate the fuel reformer with the MCFC [3]. Furthermore, the internal reforming configuration offers some attractive advantages, such as higher plant efficiency. The internal reforming system is divided into direct (DIR-MCFC) and indirect (IIR-MCFC) [4]. The most important features of the IIR-MCFC configuration are given by the opportunity to use the exothermic heat of the cell reaction for the endothermic steam-reforming reaction and the cell geometry which separates the cell-reacting area from the reforming catalyst [5]. Thus, the cooling required by the cell is significantly reduced and the catalyst is sheltered against the poisoning effect of the electrolyte vapours.

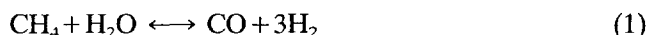
To verify the performance of the IIR-MCFC system, a wide investigation of the influence of the operating parameters on the mass and energy balance has been carried out. This analysis, developed by using a mathematical model, explored the influence of the temperature, the steam/carbon ratio, the current density,

the useful heat fraction and the fuel-utilization coefficient.

The results give important indications about the feasibility of the the advantages offered by the IIR-MCFC configuration in their application for an electrical power plant with bottoming cycle, in order to recover the thermal energy rejected by the cell.

2. Derivation of the model

Hydrogen is a very promising fuel because of its clean oxidation reaction (i.e., only H₂O is formed) and high energy density [6]. It can be produced easily by catalytic steam reforming of natural gas, as represented by the reactions [7]:



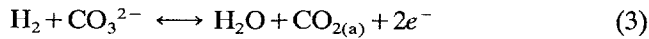
The mass balances of these reactions are:

$$(F_{\text{CH}_4}^0 - x) + (F_{\text{H}_2\text{O}}^0 - x - y) = (x - y) + (3x + y) \quad (1a)$$

$$(x - y) + (F_{\text{H}_2\text{O}}^0 - x - y) = y + (3x + y) \quad (2a)$$

In a MCFC with indirect internal reforming geometry (IIR-MCFC), this process takes place in a separate chamber being in contact with the anode compartment.

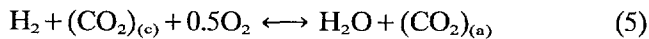
This configuration (IIR-MCFC) does not require an external fuel processor and, therefore, allows direct heat transfer from the cell to the reformer, resulting in an improvement of the performance. Thus, in this system, the first step is based on the steam-reforming production of hydrogen, then the produced synthesis gas is fed to the anode compartment where hydrogen is oxidized by the following reaction:



At the cathode the reaction is:



and the overall reaction can be written as:



The voltage that can be measured at the electrodes is given by the Nernst equation:

$$V = E_0 + \frac{RT}{nF} \ln \frac{(p_{\text{H}_2} p_{\text{O}_2}^{1/2} p_{\text{CO}_2(c)})}{(p_{\text{H}_2\text{O}} p_{\text{CO}_2(a)})} \quad (6)$$

where V is the open-circuit voltage. If the losses due to the electrode overpotentials and cell resistance are included, the cell voltage must be computed by the following equation:

$$V_0 = V - (\mu_a + \mu_c) - IR_i S_0 \quad (6a)$$

The cathodic (μ_c) and anodic (μ_a) overpotentials and the specific internal resistance (R_i) values considered in this analysis are typical for this system as reported in Ref. [8].

The unknown terms of the above equation have been calculated by solving the two equilibrium expressions of Eqs. (1) and (2), written as:

$$K_1 = \frac{(x-y)(3x+y)^3 P^2}{[(F_{\text{CH}_4}^0 - x)(F_{\text{H}_2\text{O}}^0 - x - y)(F_{\text{CH}_4}^0 + F_{\text{H}_2\text{O}}^0 + 2x)^2]} \quad (7)$$

$$K_2 = \frac{y(3x+y)}{(x-y)(F_{\text{H}_2\text{O}}^0 - x - y)} \quad (8)$$

These equations have been used to calculate the outlet-gas compositions and the cell voltage (V_0) (accounting for the losses due to the overpotentials and the internal resistance) when the current density was known. Consequently, the output electric power, the thermal power produced by the cell and by the combustion of exhaust gases (CH_4 , CO and H_2) can be computed. Thus, both electrical and thermal powers, which contribute to the overall cell efficiency can be determined.

For such a system, at steady-state condition and with negligible kinetic and potential energies, the energy balance can be written as:

$$m_f h_f + m_o h_o = W + Q_u + \sum Q_w + \sum m_w h_w \quad (9)$$

Eq. (9) shows the relationship between the total inlet energy (fuel + oxidant) and the total output electrical and thermal energy (useful + waste). For a MCFC plant that is integrated with a cogeneration device, the thermal energy is generated by the cell electrochemical reaction, ohmic resistance and combustion of the unreacted fuel ($\text{CH}_4 + \text{CO} + \text{H}_2$), but in practice only a fraction (f) of it can be used. In practice, f is the fraction of heat that is available to supply external users. In our calculations, an f of 0.5 has been computed by considering that the remaining heat should be used to generate the necessary steam, to heat the gases at operational temperatures and for other technical requirements. Thus, the theoretical efficiency can be calculated as:

$$\eta = \frac{W + Q}{m_f h_f} = \frac{W + f Q_p}{m_f h_f} \quad (10)$$

The exergy efficiency can be expressed by the Eq. (11):

$$\phi = \frac{W + Q_u(1 - T_0/T_p)}{m_f \epsilon_f} = \frac{W + f Q_p(1 - T_0/T_p)}{\alpha_E m_f h_f} \quad (11)$$

In Eq. (11), the reference temperature (T_0) is conventionally fixed at 298 K [9].

3. Standard base-line condition and evaluation parameters

The model has been developed to analyse the performance of a MCFC operating under indirect internal steam reforming. The calculations are related to an internal reforming MCFC operating at base-line conditions as reported in Refs. [2] and [10] and summarized in Table 1. Starting from these, a sensitivity analysis has been carried out taking into consideration the influence of the operating parameters on the behaviour of the system. Thus, calculations have been carried out considering the following parameters:

- steam/carbon ratio: which represents the ratio of the amount of inlet water vapour to methane

Table 1
Standard operating condition (base line)

Cell temperature (K)	923
Pressure (Ata)	1
Electrical power (kW)	0.566
Current density (mA/cm ²)	150
Effective cell area (cm ²)	5016
Fuel utilization (%)	60
Molar steam/carbon ratio	2.0
Oxidant utilization (%)	36.2
O ₂ /CO ₂ molar fraction	0.1672/0.2
Specific internal resistance (Ω cm ²)	0.6

- temperature: includes the working cell and reformer temperature
- current density: is the released current referred to the unit of electrode surface
- useful heat fraction: is the recovered portion of the total available heat
- unreacted fuel flow: evaluated as the sum of the single flows of unreacted fuels (CO, H₂ and CH₄)
- energy efficiency: defined as the ratio between the energy output and the energy input
- exergy efficiency: defined as the energy efficiency multiplied by a factor that takes into account the temperature of the system

4. Results

The calculations concern a system consisting of an IIR-MCFC for which the possibility to recover a fraction, *f*, (from 0 to 100%) of the available heat is hypothesized. This heat includes the thermal energy available from the combustion of the anode exhaust gases in the outlet and that is produced by the electrochemical cell reaction. A scheme of the proposed system is shown in Fig. 1. For the cell operating with a current density of 150 mA/cm², the results obtained indicate a methane conversion of 81.6% and a CO₂ selectivity of 84.8%, being in accordance with the thermodynamic values for the considered conditions. The unreacted fuel content in the exhaust-gas composition is 5.4% for the H₂, 7.0% for CO and 2.6% for CH₄. Under this condition, the cell gives an electrical efficiency of 37.0% and the overall efficiency corresponds to 68.4%, if a useful heat fraction, *f*, of 0.5 is adopted. Starting from these results, further calculations have shown the influence of the operating parameters on the sensitivity of the system.

The first parameter examined was the composition of the exhaust anodic gas determined as a function of the current density, for a steam/carbon ratio of 2.0 and a temperature of 923 K. The results, reported in Fig. 2, show some important aspects of this configuration. As example, the CH₄ content does not show significant

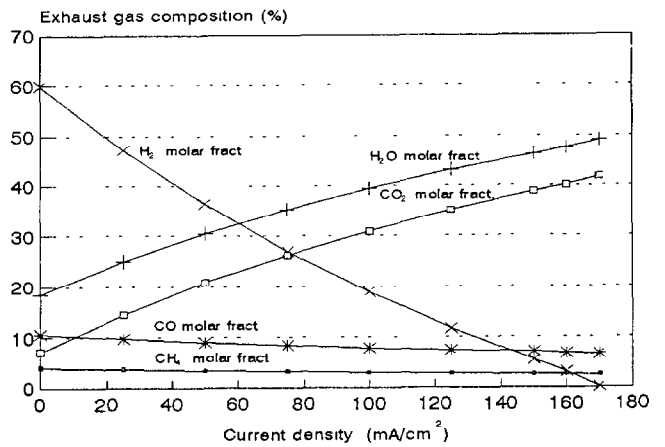


Fig. 2. Exhaust fuel compositions vs current density calculated at T=923 K and steam/carbon ratio of 2.0

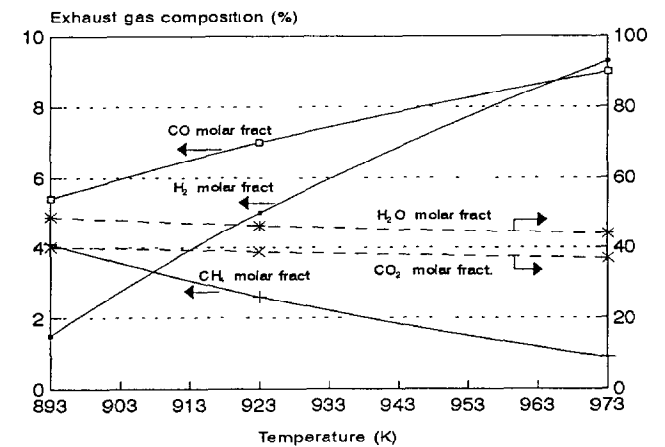


Fig. 3. Exhaust fuel composition vs working temperature, calculated at 150 mA/cm² and steam/carbon ratio of 2.0.

variations when the current density changes. In fact, the percentage of the CH₄ output (4.0%), when the cell is without electrical load, decreases to 2.5% at 170 mA/cm². This difference is a consequence of the increase of the total outlet flow with the current density, while the absolute amount of unconverted methane is constant for any value of the current. The H₂ content rapidly decreases with the electrical load because further conversion of the unconverted methane cannot be transferred to the anodic compartment. The CO content depends on the equilibrium of the steam-reforming reaction and for this reason it would be independent of the current density. Instead, the water/steam content depends strictly on the current density and reaches values in the order of 50%, when the current is higher than 170 mA/cm², with an enhancement of the hardware corrosion. Fig. 3 shows the curves of the anode exhaust-gas composition calculated as a function of the temperature, with constant current and steam/carbon ratio (150 mA/cm² and 2.0, respectively). It is evident that the temperature positively influences the steam-reforming reaction enhancing the conversion degree. For

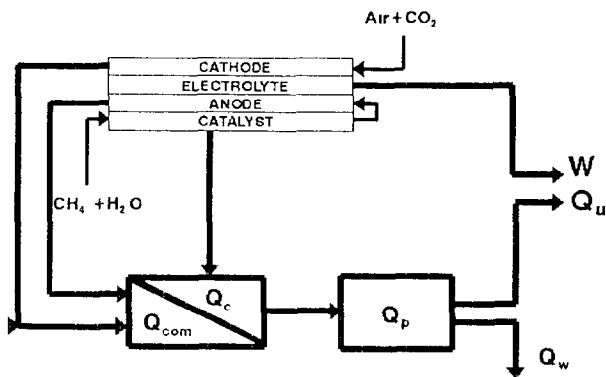


Fig. 1. Indirect internal reforming molten carbonate fuel cell scheme.

temperatures ranging from 893 to 973 K, the percentage of unconverted CH₄ decreases from 4.1 to 0.9%, the CO changes from 5.4 to 9.0% and the H₂ increases from 1.5 to 9.3%. In this case there are no appreciable variations in the H₂O and CO₂ contents because they depend on the current density and steam/carbon ratio. Fig. 4(a) reports the contributions of the different thermal power sources available for this system. Curve (a) in Fig. 4(a) represents the difference between the electrochemical power released by the cell and the thermal power required to sustain the steam-reforming reaction. This curve is an important parameter to evaluate when the electrochemical cell heat is the main thermal source to supply heat directly to the reformer reactor. The positive trend of this curve is evident because the heat required for the reforming is constant (66.8 mW/cm²) while the heat released by the cell increases directly with the current density (from 0 at open-circuit voltage (OCV) to 137.0 mW/cm² at 170 mA/cm²). Curve (b) in Fig. 4(a) represents the total heat available from the combustion of the outlet unconverted fuel. For the cell operating without electrical

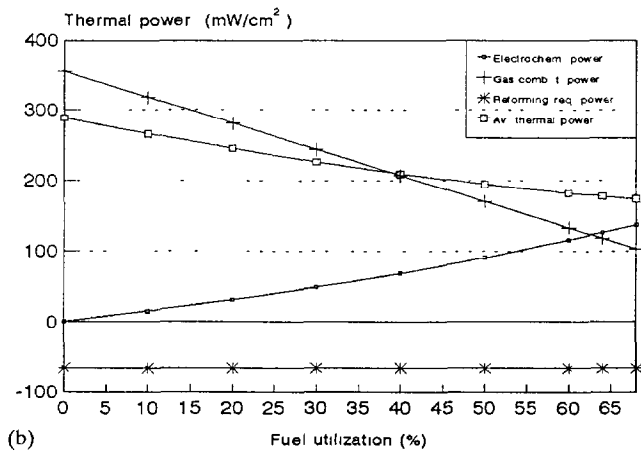
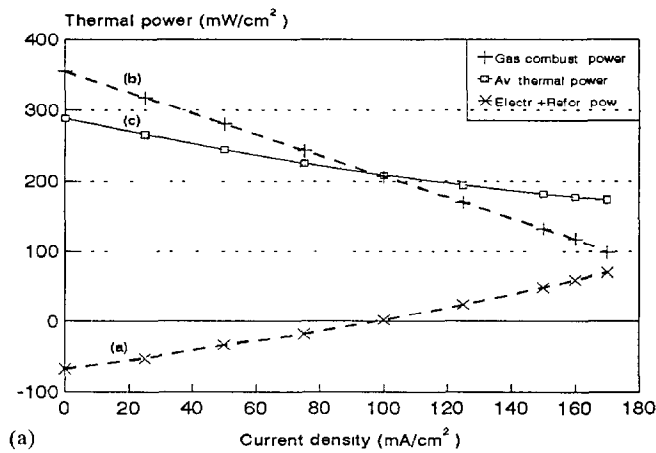


Fig. 4. (a) thermal power output vs current density, calculated at $T=923$ K and steam/carbon ratio of 2.0, (b) thermal power output vs. fuel utilization, calculated at $T=923$ K and steam/carbon ratio of 2.0

load (OCV conditions) this contribution is about 354 mW/cm² but it decreases to 132.7 mW/cm² when a current of 150 mA/cm² is produced. The overall amount of heat is represented by curve (c) in Fig. 4(a). A detailed variation of the different kinds of the thermal contribution, as a function of fuel utilization, is reported in Fig. 4(b).

Fig. 5 shows the correlation between the available power of the system (electrical plus thermal) and the useful heat fraction ($f=Q_u/Q_p$). The value for $f=0$ corresponds to an IIR-MCFC system devoted to produce electrical energy only (116.8 mW/cm²). In this case, the heat available in the system is not recovered, except for the heat required to sustain the internal reforming reaction. The condition in which the total available heat in the system is used corresponds to $f=1$. Most of the heat generated by the electrochemical reaction will be utilized for the steam-reforming reaction (66.8 mW/cm²), thus only the excess of heat will represent recoverable heat (48.6 mW/cm²). More heat can be recovered by the combustion of the outlet H₂/CO (79.7 mW/cm²) and CH₄ (53.0 mW/cm²). In practice, when the system operates at $f=0.5$ it will produce 116.8 mW/cm² of electricity and 88.6 mW/cm² of heat. This last term increases to 177.2 mW/cm² for $f=1$.

Interesting results have been obtained by calculating the system efficiencies as a function of the current density (Fig. 6). The electrical efficiency increases with the cell current density, and it shows a maximum (39.39%) in correspondence with $I=170$ mA/cm². Higher current densities produce an enhancement of the ohmic and overpotential losses which cause a reduction in the efficiency. The overall efficiency of the system will vary from 50 at OCV conditions to 69.2% at standard condition (150 mA/cm², 923 K) for $f=0.5$.

The final CH₄ conversion obtainable with the system examined changes with the variation of the steam/carbon ratio as reported in Fig. 7(a). The influence of

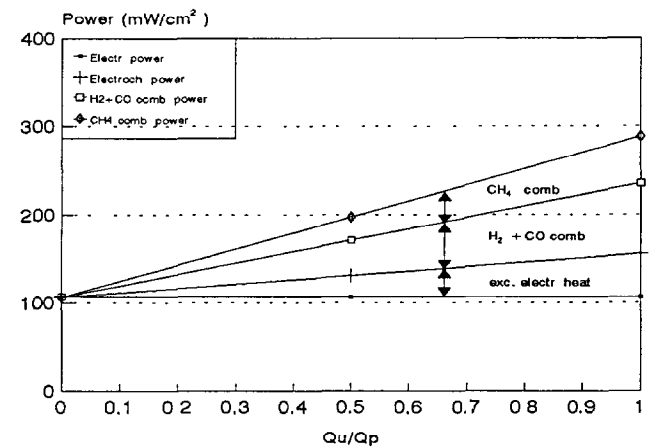


Fig 5 Electric and thermal power contributions vs. useful heat fraction (f) calculated at 150 mA/cm², $T=923$ K and steam/carbon ratio of 2.0.

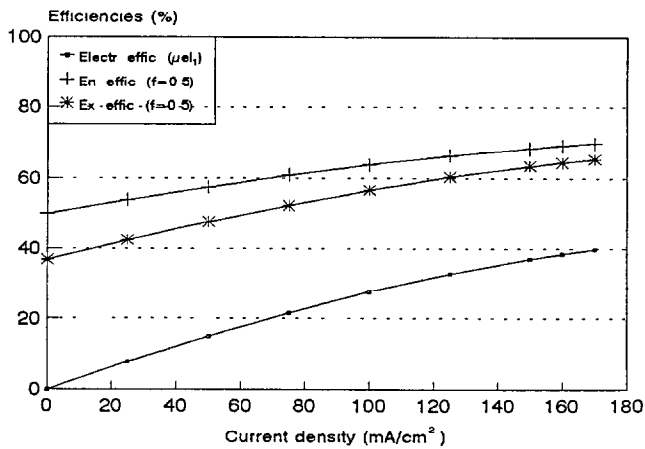


Fig. 6. Electrical and overall efficiencies vs. current density at $T=923$ K and steam/carbon ratio of 2.0.

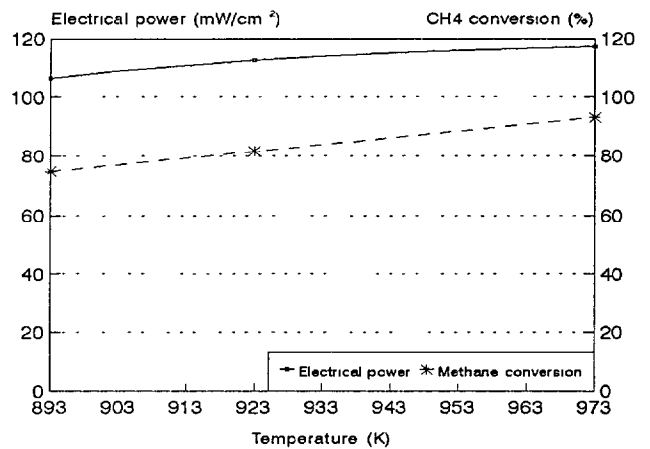


Fig. 8. Electrical power and methane conversion vs working temperature at 150 mA/cm² and steam/carbon ratio of 2.0.

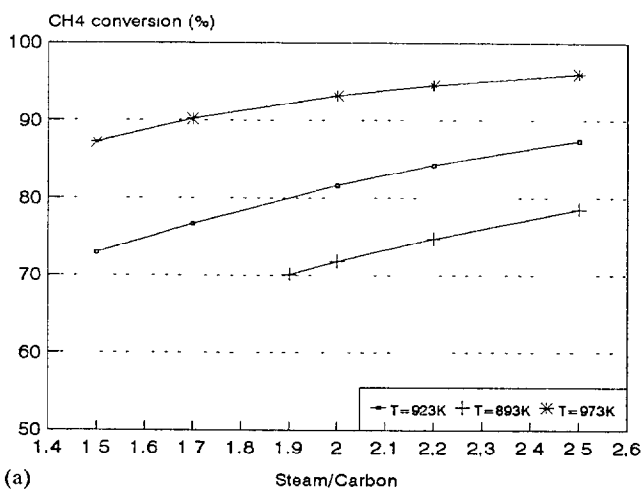
methane conversion. Otherwise, the increasing of the steam/carbon ratio from 2.0 to 2.5 gives an improvement in the highest electrical current released in the order of 14.5, 11.2 and 5.5%, at 893, 923 and 973 K, respectively. From the analysis of these curves, it is remarkable that at low temperature (893 K) the steam/carbon ratio is a determining parameter for an efficient system.

Finally, the effect of the temperature on the CH₄ conversion and the electrical power released has been investigated, see Fig. 8. This parameter influences the thermodynamic equilibrium of the steam-reforming reaction. The results of the calculations indicate that the CH₄ conversion changes from 71.8% at 893 K to 93.2% at 973 K, in the meantime the electrical power ranges from 106.7 to 117.4 mW/cm² (at 150 mA/cm²).

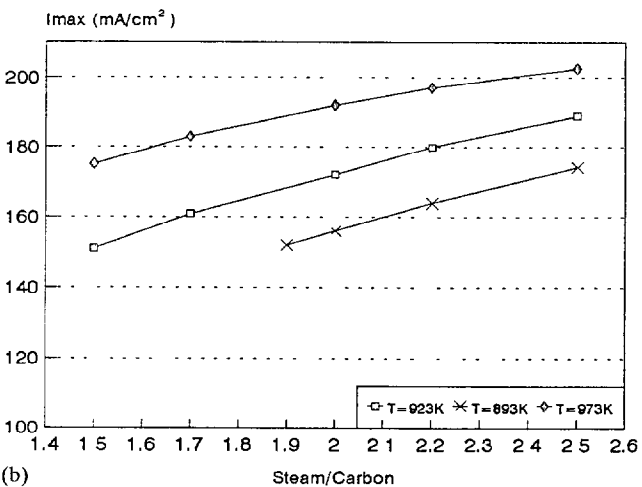
5. Discussion

Some preliminary conclusions are drawn from the analysis of the results reported in Fig. 2. A MCFC operating under indirect internal reforming conditions, as specified in Table 1, is able to produce a current density up to 171 mA/cm², due to the limited conversion of methane. In fact, the degree of conversion of the CH₄ steam reforming is dependent on the temperature and the steam/carbon ratio and independent of the current. Moreover, a negligible decrease of the percentage of CH₄ in the outlet is observed. This depends on the increasing of the total outlet flow of the anode gas when the current increases. In fact, each mole of H₂ converted in the anode produces one mole of H₂O and one of CO₂, with a consequent increase of the anode gases volume.

These conclusions are confirmed by the results shown in Fig. 3, where the influence of the temperature on the anode exhaust gas composition is verified, Table 2. This influence concerns both the thermodynamic



(a) CH₄ conversion vs. steam/carbon ratio, calculated at 893, 923 and 973 K;



(b) I_{max} vs. steam/carbon ratio, calculated at $T=893$, 923 and 973 K.

the steam/carbon ratio is more evident for lower working temperatures; in fact, at $T=893$ K the cell is unable to produce current higher than 150 mA/cm² for steam/carbon ratio lower than 1.9 because of the very low

Table 2
Exhaust fuel composition at $U_f=60\%$

Temperature (K)	Steam/carbon ratio (ad.)	R_1 ($\Omega \text{ cm}^2$)	W (mW/cm ²)	CH ₄ (%)	CO (%)	H ₂ (%)	H ₂ O (%)	CO ₂ (%)
893	1.9	0.6	106.4	4.5	5.5	0.6	0.6	40.8
893	2.0	0.6	106.7	4.1	5.4	1.5	48.7	40.2
893	2.2	0.6	107.2	3.6	5.2	3.2	48.9	39.2
893	2.5	0.6	107.7	2.9	4.8	5.2	49.3	37.8
923	1.5	0.6	111.4	4.3	7.7	0.4	46.2	41.5
923	1.7	0.6	112.1	3.5	7.4	2.7	46.1	40.3
923	2.0	0.6	112.8	2.6	7.0	5.4	46.3	38.8
923	2.2	0.6	113.2	2.2	6.6	6.7	46.6	37.9
923	2.5	0.6	113.6	1.6	6.1	8.2	47.3	36.7
973	1.5	0.6	116.5	1.9	10.4	6.0	42.8	38.9
973	1.7	0.6	117.0	1.4	9.8	7.7	43.1	38.0
973	2.0	0.6	117.4	0.9	9.0	9.3	43.9	36.9
973	2.2	0.6	117.5	0.7	8.4	10.1	44.6	36.3
973	2.5	0.6	117.6	0.5	7.6	10.8	45.7	35.3

equilibrium of the steam reforming and the kinetics of the cell electrochemical reactions causing a decrease in the percentage of CH₄ in the outlet and an increase in the unconverted CO. The combined effect keeps constant the percentage of the total outlet uncombusted fuels (9 to 10%). The opportunity to use this supplementary source of energy then arises.

The percentage of unconverted H₂, that ranges from 1.5 to 9.3% for temperatures of 893 and 973 K, respectively, indicates that the current density considered in the calculations (150 mA/cm²) is the highest obtainable at the lowest temperature, while for the advantage given by the elevated temperature, further electricity can be produced at 973 K.

In an IIR-MCFC it is of interest to observe the role that the cell electrochemical heat contributes to the energy balance of the fuel reformer (Fig. 4(a)). In fact, when the cell works at 100 mA/cm² the electrochemical heat produced by the cell is equal to that required from the methane reforming. As a consequence, the cell operates under thermal equilibrium and the system is thermally balanced. For the cell operating at standard conditions (150 mA/cm²), there is an excess in production of heat of 48.6 mW/cm², which must be removed from the cell through a cooling device. This excess of heat is lower than that rejected by an MCFC with external reforming, operating in the same conditions, because in this case the system is not able to utilize the electrochemical heat to supply the final reformer reaction. It will be an advantage in the sizing of the cell cooling system. Similar evidence comes out of the results reported in Fig. 4(b), where the thermal power contributions are calculated for several fuel utilization values. Moreover, it is also evident that the heat required to supply the methane steam reformer is almost constant as the fuel utilization is varied.

In standard conditions, the recovery of the available thermal energy can significantly enhance the overall energy efficiency of the system. In fact, if an $f=0.5$ is realized, the system will produce 112.8 mW/cm² of electric power and 90.7 mW/cm² of thermal power with a ratio $W_1/W_e=0.804$ (Fig. 5); this ratio increases with f and reaches the value of 1.608 when f is equal 1. This boundary condition is verified when the overall available heat is recovered.

The highest obtainable electrical efficiency for an IIR-MCFC system at standard conditions is 37.0% (Fig. 6), comparable with that of an external reforming fuelled MCFC. The amount of H₂ produced by the indirect reforming allows the cell to supply no more than 172 mA/cm² of current. Beyond this value the electrical efficiency drastically reduces. To overcome this, the CH₄ conversion should be increased by changing the temperature or the steam/carbon ratio. The reliability of this system for combined production of heat and electricity stands out from the consideration that the overall energy efficiency can reach 68.4% for $f=0.5$ which is a reasonable target for a commercial system.

As described above, the production of electrical energy depends on the effective content of H₂ in the anode compartment and consequently the parameters affecting the reforming equilibrium, such as T and steam/carbon ratio, assume a considerable importance (Fig. 7). Moreover, the steam/carbon ratio mostly influences the electrical efficiency of the system operating at low temperature (893 K), in fact, the high temperatures (923 and 973 K) favour the steam-reforming reaction thus balancing the detrimental effect of the steam/carbon ratio lower. Thus, the temperature is the important parameter affecting the cell performance, because it influences the methane-reforming equilibrium as well as the cell kinetics, reducing the electrodes

overpotentials. This assumption has been verified by the calculations that involved increasing the temperature by 80 K (from 893 to 973 K), which significantly enhanced the highest electrical power of the cell from 108.6 to 133.2 mW/cm² and the CH₄ conversion from 71.8 to 93.2%.

6. Conclusions

The application of the mathematical model to study the behaviour of an IIR-MCFC cell showed some important features of this system.

In the standard working conditions of the cell, the degree of CH₄ conversion, which is determined by the thermodynamic equilibrium of the steam-reforming reaction and independent of the cell current density, changes strongly with the temperature of the system. However, this limit does not affect the effectiveness of the system if the current density does not exceed 150 mA/cm².

The main advantage of this mode of operation is the capability to utilize the electrochemical heat of the cell to sustain the steam-reforming reaction in the anode compartment. In fact, the thermal equilibrium of the cell is already obtained at 100 mA/cm² and no heat is required or rejected.

The electrical efficiency obtainable is comparable with that of other kinds of fuel cells, but it is influenced by the steam/carbon ratio, the temperature, and the current density.

Finally, the high overall efficiency of the system makes the IIR-MCFC of interest for projected power plants with a recovery cycle for the combined production of electricity and thermal heat.

7. List of symbols

E^0	standard electromotive force or potential when all the species involved are at unit activity, V
f	useful heat fraction = Q_u/Q_p
F	Faraday constant, 23.06 kcal/V = 96 490 C/equivalent
$F_{\text{CH}_4}^0$	methane feed rate, mol/h
$F_{\text{H}_2\text{O}}^0 = F_{\text{CH}_4}^0 \times S/C$	water feed rate, mol/h
$F_{\text{H}_2} F_{\text{H}_2}$	hydrogen flow rate = $[3600(I/S_0)S_0]/(2 \times 96 490)$, mol/h
h	enthalpy, J/kg
I	current density, mA/cm ²
m	mass flow, kg/s
n	number of transferred electrons = 2

P	total pressure, Ata
p_{H_2}	hydrogen partial pressure, Ata
p_{CO_2}	carbon dioxide partial pressure, Ata
$p_{\text{H}_2\text{O}}$	water partial pressure, Ata
p_{O_2}	oxygen partial pressure, Ata
Q_p	total output thermal power = $Q_u + \sum_w Q_w$, W
R	universal gas constant, 1.987 cal/(K mol)
R_i	specific internal resistance, Ω cm ²
S_0	effective electrodes surface, cm ²
T	temperature, K
U_f	fuel utilization = $100(F_{\text{H}_2}/4F_{\text{CH}_4}^0)$, adim.
W	shaft work rate, W

Greek letters

α_E	exergy ratio for methane combustion = 0.92, see Ref. [11]
η	energy efficiency, adim.
ϕ	exergy efficiency, adim.
μ	electrode overpotential, V
ϵ	specific exergy, J/kg

Subscripts

x, y	rate of conversion CH ₄ and CO in Eqs. (1) and (2), respectively, mol/h
a, c	indices referred to the anode and cathode compartment
$f, o, u,$	indices referred to the fuel, oxidant, useful
w, p	indices referred to waste and produced

References

- [1] M.A. Rosen, *Int J. Hydrogen Energy*, 15 (1990) 267–274
- [2] S Freni, N. Giordano and S. Cavallaro, *J. Appl Electrochem*, 20 (1990) 804–810.
- [3] K. Sato, T. Tanaka and T. Murahashi, *Proc 1990 Fuel Cell Seminar, Phoenix AZ, USA, Nov 25–28, 1990*, pp. 40–43
- [4] J. Ohtsuki, A. Kusunoki, T. Murahashi, T. Tanaka and E. Nishiyama, *Proc Int. Fuel Cell Conf, Makiuhari, Japan, Feb 3–6, 1992*, pp. 251–254
- [5] T. Okada, H. Ide, M. Miyazaki and T. Tanaka, *Proc 25th Intersociety Energy Conversion Engineering Conf., Reno, NV, USA, Aug 12–17, 1990*, Vol 3, pp. 207–212.
- [6] D.L. Curtis, *Proc 8th World Hydrogen Energy Conf.*, Honolulu, HI, USA, July 22–27, 1990, pp. 49–58
- [7] J.R. Rostrup-Nielsen, *Steam Reforming Catalyst*, Danish Technical Press, Copenhagen, 1975.
- [8] G. Wilemski, J. Mitteldorf and J. Simons, Diagnostic fuel cell model, *PSI contract DE-AC05-79ET-15403*, 1982
- [9] R.A. Gaggioli and P.J. Petit, *Chemtech*, 7 (1977) 496–506.
- [10] K. Kinoshita, F.R. McLarsen and E.J. Cains, *Fuel Cells – A Handbook*, US Department of Energy–Office of Fossil Energy, 1988
- [11] H.B. Vakil and J.W. Flock, Closed loop chemical systems for energy storage and transmission, Prep by G.E. under ERDA contract no. EY-76-C-02-2676, 1978