

# Efficiency of a solid polymer fuel cell operating on ethanol

Theophilos Ioannides<sup>\*</sup>, Stylianos Neophytides

*Foundation for Research and Technology-Hellas (FORTH), Institute of Chemical Engineering and High Temperature Chemical Processes (ICE / HT),  
P.O. Box 1414, GR-265 00 Patras, Greece*

Received 30 September 1999; received in revised form 29 February 2000; accepted 29 February 2000

## Abstract

The efficiency of a solid polymer fuel cell (SPFC) system operating on ethanol fuel has been analyzed as a function of operating parameters focusing on vehicle and stationary applications. Two types of ethanol processors — employing either steam reforming or partial oxidation (POX) steps — have been considered and their performance has been investigated by thermodynamic analysis. SPFC operation has been analyzed by an available parametric model. It has been found that dilute ethanol–water mixtures (~ 55% v/v EtOH) are the most suitable for stationary applications with a steam reformer (SR)–SPFC system. Regarding vehicle applications, pure ethanol (~ 95% v/v EtOH) appears to be the best fuel with a POX–SPFC system. Efficiencies in the case of an ideal ethanol processor can be of the order of 60% under low load conditions and 30–35% at peak power, while efficiencies with an actual processor are 80–85% of the above values. © 2000 Elsevier Science S.A. All rights reserved.

*Keywords:* Ethanol; Solid polymer fuel cell; Reforming; Partial oxidation; Thermodynamic analysis

## 1. Introduction

Environmental concerns and the need for improvement of efficiency of vehicles has spurred development efforts in fuel cell technology. Fuel cells operate on hydrogen fuel and have higher energy conversion efficiency compared to conventional engines accompanied by practically zero emissions of pollutants. Solid polymer fuel cells (SPFC) are considered to be the most suitable for vehicle applications [1–3]. A major issue in the advancement of fuel cell vehicles is that of on-board hydrogen storage. Various methods are being investigated, e.g. as a pressurized gas, a cryogenic liquid, in adsorbed form as metal hydrides, in adsorbed form in microporous solids or chemical storage in the form of a liquid fuel [4]. Chemical storage in liquid fuels has the advantage of utilization of already available infrastructure for fuel distribution to end-users [5]. On the other hand, an on-board fuel processor is necessary to convert liquid fuel to hydrogen [6]. In principle, any type of liquid fuel may be employed as a hydrogen source, e.g. gasoline and other oil derivatives, methanol, ethanol, etc. Among candidate liquid fuels, ethanol is a particular case, because it can be readily produced from renewable sources

(biomass) available throughout the world. As a consequence, use of ethanol as a hydrogen source can contribute towards the goal of reduction of CO<sub>2</sub> emissions in the transportation sector.

The performance of a fuel cell system powered by ethanol is determined by the efficiency of the ethanol-to-hydrogen step in the fuel processor along with the efficiency of the hydrogen-to-electricity step in the SPFC unit. In the present work, the overall efficiency of a SPFC system operating on ethanol fuel has been analyzed as a function of operating parameters. Two types of ethanol processors have been considered and their performance has been investigated by thermodynamic analysis. SPFC operation has been analyzed by the parametric model developed by Amphlett et al. [7,8]. The goal of this work is to identify optimal operating conditions of the system, for which efficiency can be maximized.

## 2. Description of the system

A schematic diagram of a SPFC operating on ethanol is presented in Fig. 1. Hydrogen required for SPFC operation is produced from ethanol in a processor unit consisting of either a steam reformer (SR) (Fig. 1A) or a partial oxidation (POX) reactor (Fig. 1B) in series with a water–gas

<sup>\*</sup> Corresponding author. Fax: +30-61-965-223.  
E-mail address: theo@iceht.forth.gr (T. Ioannides).

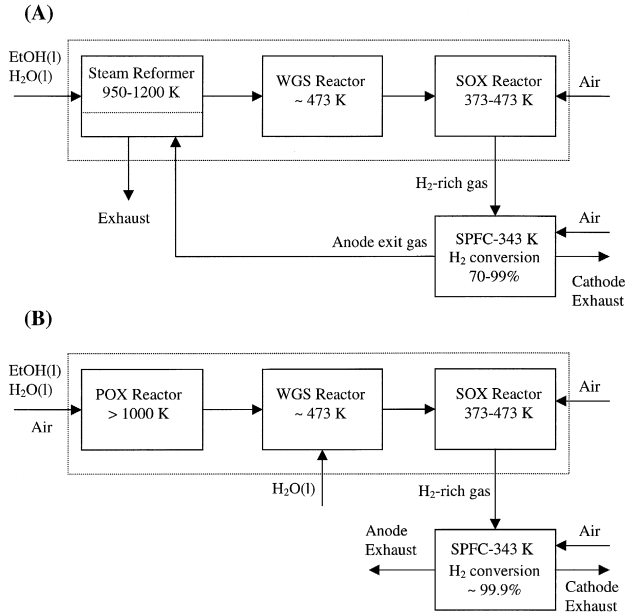


Fig. 1. Schematic diagram of SPFC system with (A) SR-processor and (B) POX-processor.

shift (WGS) reactor and a reactor for selective oxidation (SOX) of CO. When the ethanol processor incorporates a SR (SR-processor), it is assumed that the SPFC operates at hydrogen conversions less than unity and the anode exit gas is combusted in the reformer to supply the required heat for the reforming reaction. When the ethanol processor incorporates a POX reactor (POX processor), on the other hand, the required heat is produced by combustion of a fraction of incoming ethanol in an autothermal mode of operation. In this case, hydrogen conversion in the SPFC should be close to unity to maximize efficiency.

Product gas from the reformer or the POX reactor, which operate at exit temperatures higher than 950 K, contains a mixture of H<sub>2</sub>, CO, CO<sub>2</sub>, CH<sub>4</sub> and H<sub>2</sub>O. After cooling, this stream enters the WGS reactor, where a large fraction of CO reacts with H<sub>2</sub>O towards CO<sub>2</sub> and H<sub>2</sub> at a temperature of ~ 473 K. The product gas of the WGS reactor contains ~ 0.1–1.5% of residual CO and enters the SOX reactor, where CO is totally oxidized with the addition of small amounts of air to CO<sub>2</sub> (residual CO less than 10 ppm) at temperatures in the range of 373–473 K. The CO-free, hydrogen-rich stream is then fed to the fuel cell, where hydrogen is electrochemically oxidized to H<sub>2</sub>O with simultaneous production of electrical energy.

The parameters influencing the performance of the ethanol processor are: the H<sub>2</sub>O/EtOH molar ratio of the feed,  $R$ ; the temperatures of the reformer,  $T_{REF}$ ; POX reactor,  $T_{POX}$ ; WGS reactor,  $T_{WGS}$ ; the pressure,  $P$ ; and the oxidation selectivity of CO in the SOX reactor,  $S_{OX}$ . In the case of the POX reactor, an additional parameter is the fuel equivalence ratio,  $\Phi$ , defined as:  $\Phi = (\text{EtOH}/\text{O}_2)_{\text{feed}}/(\text{EtOH}/\text{O}_2)_{\text{stoich}}$ . The feed to the system is assumed to be at 298 K with H<sub>2</sub>O and EtOH in the

liquid state. Product gas of the processor is assumed to exit the processor at 343 K, i.e. at the operating temperature of the SPFC. The processor is also assumed to operate with no heat losses to the surroundings. The equilibrium composition of the processor product gas, as well as the hydrogen yield, has been obtained as a function of operating parameters of the system by thermodynamic analysis. Details of the procedure are given elsewhere [9].

### 3. SPFC model

The mechanistic model employed in this work has been proposed by Amphlett et al. [7,8] and describes the performance of a single cell of the MkIV design produced by Ballard Power Systems. The cell uses a DuPont Nafion 117 polymeric membrane with a geometric surface area of 50.56 cm<sup>2</sup>. It is assumed that the cell operates at 343 K with a water-saturated cathode inlet stream and a half-saturated anode inlet stream. Based on these assumptions, the following relationships can be derived from Refs. [7,8]:

Equilibrium potential:  $E_{th}$

$$= 1.19088 + 0.01478 \left[ \ln(p_{H_2}^*) + 1/2 \ln(p_{O_2}^*) \right] \quad (1)$$

Activation overpotential:  $\eta_{act}$

$$= -0.11876 + 0.06414 \ln(i) - 0.02538 \ln(c_{O_2}^*) \quad (2)$$

Internal resistance:  $R_{int} = 0.004045 + 8.0 \times 10^{-5} i$  (3)

Operating potential:  $E_{op} = E_{th} - \eta_{act} - iR_{int}$ . (4)

The effective concentration of oxygen,  $c_{O_2}^*$ , is given by the following expression:

$$c_{O_2}^* = 8.408 \times 10^{-7} p_{O_2}^*. \quad (5)$$

And  $p_{O_2}^*$  is:

$$p_{O_2}^* = P \left[ 1 - x_{H_2O}^{sat} - x_{N_2}^{channel} \exp(0.0023I) \right] \quad (6)$$

while the effective hydrogen pressure,  $p_{H_2}^*$ , is:

$$p_{H_2}^* = P \left[ 1 - 0.5 x_{H_2O}^{sat} - x_{inert}^{channel} \exp(0.0014I) \right] \quad (7)$$

and  $P$  denotes operating pressure,  $x_{H_2O}^{sat}$  is the molar fraction of water under saturation conditions at 343 K,  $x_{N_2}^{channel}$  is the log mean average mole fraction of nitrogen in the humidified gas at the interface of the cathode and  $x_{inert}^{channel}$  is the arithmetic mean average mole fraction of inert species (N<sub>2</sub> + CO<sub>2</sub> + CH<sub>4</sub>) at the interface of the anode.  $x_{N_2}^{channel}$  and  $x_{inert}^{channel}$  are calculated by the following expressions:

$$x_{N_2}^{channel} = 0.8427 \left( 1 - \frac{0.3075}{P} \right) \quad (8)$$

$$x_{\text{inert}}^{\text{channel}} = \frac{x_{\text{out}}^{\text{hum}} + x_{\text{in}}^{\text{hum}}}{2} \quad (9)$$

$$x_{\text{in}}^{\text{hum}} = x_{\text{in}}^{\text{dry}} \left( 1 - \frac{0.1538 - x_{\text{H}_2\text{O}}^{\text{dry}} P}{P} \right) \quad (10)$$

$$x_{\text{out}}^{\text{hum}} = \frac{x_{\text{in}}^{\text{dry}}}{(1 - X_{\text{FC}}) x_{\text{H}_2}^{\text{dry}} + x_{\text{in}}^{\text{dry}}} \times \left( 1 - \frac{0.1538 - x_{\text{H}_2\text{O}}^{\text{dry}} P}{P} \right) \quad (11)$$

where  $X_{\text{FC}}$  is the hydrogen conversion in the SPFC,  $x_{\text{in}}^{\text{dry}}$ ,  $x_{\text{H}_2}^{\text{dry}}$  and  $x_{\text{H}_2\text{O}}^{\text{dry}}$  are the molar fractions of inert species, hydrogen and water, respectively, in the product gas stream of the ethanol processor. Superscripts denoted as “hum” indicate molar fractions after humidification of the gas stream. It has to be noted that, depending on operating conditions of the ethanol processor, the product gas contains varying amounts of water. In any case, water molar fraction at the anode inlet is set to half its saturation value at the temperature of 343 K.

Electric power produced by the SPFC,  $P_{\text{el}}$ , is given by:

$$P_{\text{el}} = E_{\text{op}} i \quad (12)$$

and the corresponding molar flow of hydrogen,  $G_{\text{H}_2}$ , is:

$$G_{\text{H}_2} = \frac{i}{2FX_{\text{FC}}} \quad (13)$$

where  $F$  is the Faraday constant. Molar flow of ethanol,  $G_{\text{EtOH}}$ , is related to  $G_{\text{H}_2}$  by the following expression:

$$G_{\text{EtOH}} = \frac{G_{\text{H}_2}}{Y_{\text{H}_2}} \quad (14)$$

where  $Y_{\text{H}_2}$  is the hydrogen yield obtained in the ethanol processor expressed in moles of  $\text{H}_2$  produced per mol of EtOH fed to the system. Finally, the LHV efficiency,  $a$ , of the system is defined as:

$$a = \frac{P_{\text{el}}}{G_{\text{EtOH}}(\text{LHV})_{\text{EtOH}}} \quad (15)$$

where  $(\text{LHV})_{\text{EtOH}} = 1235.57 \text{ kJ/mol EtOH}$ .

## 4. Results

A typical example of the SPFC performance according to the aforementioned model is depicted in Fig. 2, where the operating voltage,  $E_{\text{op}}$ , and the power density are plotted as a function of current density for operating pressures of 1 and 3 atm. The anode feed used to obtain the behavior of Fig. 2 has a composition typical of a SR-processor ( $\sim 70\% \text{ H}_2$ ), while the cathode feed was assumed to be water-saturated air. Operation at 3 atm has a positive effect on SPFC performance compared to atmospheric operation. Maximum power density, which is ob-

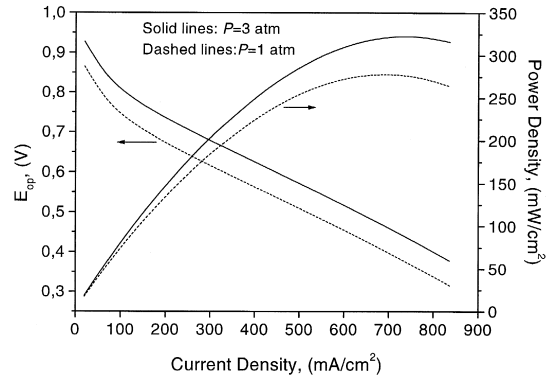


Fig. 2. Performance of SPFC with reformat gas (70%  $\text{H}_2$ ) at 343 K according to the model of Amphlett et al. [7,8].

tained at a current density of  $\sim 700 \text{ mA/cm}^2$ , increases by  $\sim 12\%$  with increase of pressure from 1 to 3 atm. The beneficial effect of pressure on SPFC performance more than compensates the minor negative effect of pressure on the performance of the processor (increase of pressure to 3 atm results in a decrease in hydrogen yield of less than 0.5%). For this reason, results presented in this work have been obtained assuming an operating pressure of 3 atm, both for the SPFC and the ethanol processor.

### 4.1. Ideal processors

The term “ideal processor” signifies a processor operating under conditions of overall thermoneutrality, in which case hydrogen yield is maximized. In addition, it is assumed that oxidation of CO in the SOX reactor takes place with a very high selectivity of 0.90, so that hydrogen losses due to oxidation are minimal. It has to be noted that typical catalysts, which are developed for this reaction, oxidize CO with a selectivity of  $\sim 0.5$  in the presence of hydrogen [10,11].

In the case of a SR-processor, the basic parameter influencing performance is the  $R$ -value of the feed. The efficiency of the system is presented in Fig. 3 as a function of power density for various  $R$ -values of the feed. Operating temperatures for the reformer and the WGS reactor were taken to be 1200 and 473 K, respectively. It can be observed that the efficiency of the system decreases considerably with increase of water content of the feed. A maximum in efficiency appears at  $R = 2.8$ . As it was mentioned in Section 2, it is assumed that heat, required in the SR, is supplied by combustion of the anode exit gas. This mode of operation does away with the problem of formation of  $\text{CH}_4$  byproduct in the processor, because  $\text{CH}_4$  is recycled and used as a fuel in the reformer. It has been found that there exists a specific  $R$ -value for which the efficiency of the system is maximized at each reformer temperature.

Results of this optimization are presented in Table 1, where the maximum efficiency of the system at power

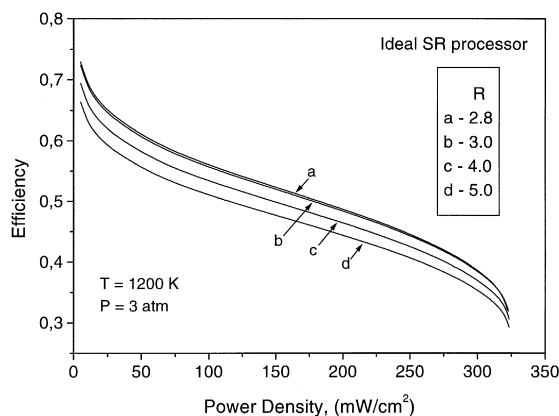


Fig. 3. Efficiency of the SPFC system as a function of power density in the case of an ideal SR-processor.

densities of 75 and 300  $\text{mW}/\text{cm}^2$  is presented as a function of the reformer temperature of the SR-processor. It can be observed that the optimal  $\text{H}_2\text{O}/\text{EtOH}$  molar ratio in the feed,  $R_{\text{opt}}$ , decreases from 2.8 to 2.5 when reformer temperature is reduced from 1200 to 1000 K. This is a consequence of the equilibrium shift towards methane and water formation ( $\text{CO} + 3\text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}$ ) with decrease in temperature. When reformer temperature is further reduced to 950 K,  $R_{\text{opt}}$  increases to 2.7. Under these conditions, the amount of methane formed is sufficient to provide on its own the heat required in the reformer. If  $R$ -values lower than 2.7 are used, the amount of methane produced is higher than the one needed by the reformer, leading to reduced efficiencies. The corresponding hydrogen conversion in the SPFC,  $X_{\text{FC}}$ , is 0.805 for  $T_{\text{REF}} = 1200$  K and increases with decreasing reformer temperature down to 950 K, where  $X_{\text{FC}}$  is close to unity. This can be explained as follows: formation of  $\text{CH}_4$  is minimal at high reformer temperatures (it is  $3.4 \times 10^{-4}$  mol  $\text{CH}_4/\text{mol H}_2$  at 1200 K), so that heat required in the reformer is essentially supplied by hydrogen not converted in the SPFC. As the reformer temperature decreases, methane formation increases and at 950 K methane formation is so significant (0.075 mol  $\text{CH}_4/\text{mol H}_2$  produced) that the heat required in the reformer is essentially supplied by methane combustion and hydrogen conversion in the SPFC should be close to unity. It can also be seen that the efficiency of the system for electricity production is not practically influenced by the operating conditions of the

Table 1  
Effect of reformer temperature,  $T_{\text{REF}}$ , on optimal system efficiency,  $a$  ( $P = 3$  atm)

$T_{\text{REF}}$ (K)	$R_{\text{opt}}$	$X_{\text{FC}}$	$a$ (75 $\text{mW}/\text{cm}^2$ )	$a$ (300 $\text{mW}/\text{cm}^2$ )
1200	2.8	0.805	0.581	0.387
1100	2.75	0.816	0.581	0.387
1000	2.5	0.913	0.584	0.386
950	2.7	0.998	0.576	0.376

reformer as long as the optimal feed is used in each case. Predicted efficiencies are in the range of 0.576–0.584 for a power density of 75  $\text{mW}/\text{cm}^2$  (corresponding to  $\sim 23\%$  load) and 0.376–0.387 for a power density of 300  $\text{mW}/\text{cm}^2$  (corresponding to  $\sim 93\%$  load). This result implies that there is large flexibility in the selection of the reformer temperature in this mode of operation, the only constraint being that it should be higher than 950 K.

The efficiency of the system in the case of an ideal POX-processor is presented in Fig. 4 as a function of power density. Similarly to what was found in the case of the SR-processor, the efficiency decreases with increase of water content in the feed. This happens because the required amount of oxygen in the POX reactor (and the fraction of ethanol consumed) increases with increase of the water content. Therefore, the value of the required fuel equivalence ratio,  $\Phi$ , is dependent on the  $R$ -value of the feed. More oxygen is needed (thus lower equivalence ratios) for feeds with high  $R$ -values. Corresponding values of  $\Phi$  for each  $R$ -value are also shown in Fig. 4. It can be seen that  $\Phi$  is equal to 5.34 or 3.59 for feeds with  $R = 1$  or 4, respectively. The maximum efficiency is obtained for  $R$ -values lower or equal to 1.0. The fact that the maximum appears at a lower  $R$ -value compared to the SR-processor is not surprising, because additional water is produced inside the POX reactor from combustion of ethanol and, as a consequence, the effective water concentration is larger than what the  $R$ -value implies. Maximum power density also decreases with increase in  $R$ . For example, maximum power density is 314.7  $\text{mW}/\text{cm}^2$  for  $R = 1$  and 307.1  $\text{mW}/\text{cm}^2$  for  $R = 4$ .

#### 4.2. Comparison of ideal POX- and SR-processors

The performance of an ideal POX-processor system is compared to the one of a SR-processor system in Fig. 5. Identical values of operating parameters have been assumed in both cases, i.e.  $T_{\text{REF}} = T_{\text{POX}} = 1200$  K,  $T_{\text{WGS}} = 473$  K and  $S_{\text{OX}} = 0.9$ . The  $R$ -value of the feed was taken

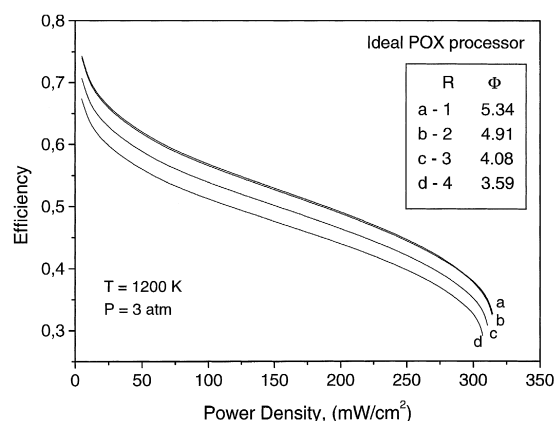


Fig. 4. Efficiency of the SPFC system as a function of power density in the case of an ideal POX-processor.

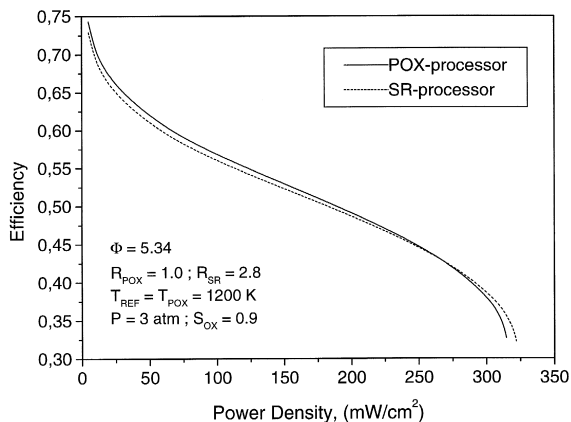


Fig. 5. Comparison of the performance of SPFC systems with ideal POX- and SR-processors.

to be 2.8 in the case of the SR-processor and 1.0 in the case of the POX-processor, based on the results presented in Figs. 3 and 4. It can be observed that the efficiency of the POX-processor is higher than the one of the SR-processor at power densities lower than  $\sim 260$   $\text{mW}/\text{cm}^2$ , while the reverse is true at power densities larger than  $260$   $\text{mW}/\text{cm}^2$ . For example, at a power density of  $113$   $\text{mW}/\text{cm}^2$  the efficiency of the POX-system is  $0.557$  and that of the SR-system  $0.548$ , i.e. a difference of  $1.6\%$ . In addition, maximum power density is larger in the case of the SR-system ( $322$  vs.  $315$   $\text{mW}/\text{cm}^2$ ). The observed behavior can be attributed to the following factors.

- Hydrogen yield in the POX-processor is  $3\%$  higher than hydrogen yield in the SR-processor. This is due to the fact that the feed to the SR-processor contains a larger proportion of water and, as a consequence, has increased enthalpy requirements for evaporation.

- The average concentration of  $\text{H}_2$  in the SPFC is larger in the case of the SR-system because: (i) molar fraction of  $\text{H}_2$  in the SR-processor product gas is larger ( $0.68$  vs.  $0.51$  for the POX-processor) and (ii) hydrogen conversion in the SPFC of the SR-system is  $\sim 0.8$ , while it is  $\sim 1.0$  in the POX-system.

Due to the influence of the latter factor, the difference in efficiencies of the two systems is less than  $3\%$ , a value which would be expected, based solely on the difference in hydrogen yield between the two processor types.

#### 4.3. Comparison of ideal and real systems

It is of interest to compare the efficiency of an ideal system to the one expected in the case of a current real system. Mitchell et al. [12] have reported on the performance of a catalytic POX reactor operating on ethanol. Based on their results, a typical exit temperature of the POX reactor is  $\sim 1300$  K. Preheating of the feed was found to increase the efficiency of the reactor. A preheat temperature of  $650$  K is assumed here, taking into account

that the autoignition temperature of ethanol is  $696$  K [13]. A typical temperature for the operation of the WGS reactor is  $473$  K, while the oxidation selectivity of CO in the SOX reactor with catalysts currently used and appropriate design of the reactor is  $S_{\text{OX}} = 0.50$ . The efficiency of a real system has been calculated based on the aforementioned values of operating parameters. It has also been assumed that thermodynamic equilibrium is attained in the POX-processor and that the POX reactor is adiabatic (no heat losses to the surroundings). Two different types of feed have been examined:

- Pure ethanol feed ( $\sim 95\%$  v/v EtOH). In this case, addition of extra water is assumed in the WGS reactor to a final  $\text{H}_2\text{O}/\text{EtOH}$  molar ratio of  $5.0$ , because the initial feed water content is less than the stoichiometric amount.
- Diluted ethanol feed ( $\sim 52\%$  v/v EtOH) corresponding to  $R = 3.0$ .

The efficiency of a real POX-system operating on pure and diluted ethanol feeds is compared to the efficiency of the ideal POX-system in Fig. 6. Efficiencies predicted in the real system are approximately  $81$ – $86\%$  of ideal efficiencies depending on SPFC load. Operation with diluted feed results in a decrease of efficiency of  $8$ – $10\%$  compared to operation with pure ethanol. Maximum power density is also lower by  $\sim 1.7\%$  in the real system. These results represent the upper limits of the efficiency of a real system, because, in practice, adiabatic operation of the POX reactor will not be attained, especially in a small-scale unit and, in addition, deviations from equilibrium will be present.

The sources of power losses in an ideal and a real POX-system are presented in Table 2 in the case of a  $95\%$  ethanol feed and power densities of  $75$  and  $300$   $\text{mW}/\text{cm}^2$ , which correspond to  $\sim 24\%$  and  $\sim 95\%$  SPFC load, respectively. It can be seen that in the case of the ideal POX-system the main source of power loss is the activa-

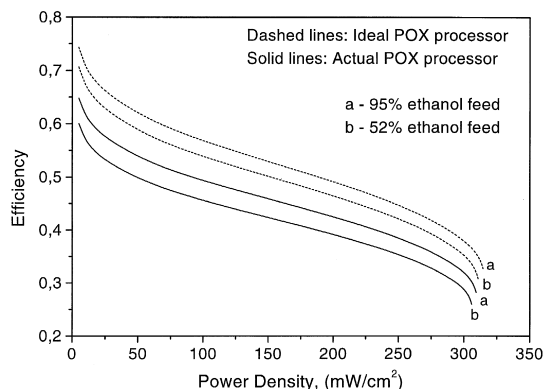


Fig. 6. Comparison of the performance of SPFC systems with ideal and actual POX-processors.

Table 2  
Distribution of incoming power in an ideal and a real POX-system

% Distribution of incoming power	Ideal POX-system		Real POX-system	
	75 mW/cm <sup>2</sup>	300 mW/cm <sup>2</sup>	75 mW/cm <sup>2</sup>	300 mW/cm <sup>2</sup>
Electric power	59.0	38.1	51.3	32.1
Overpotential activation losses	26.4	35.0	23.2	30.9
Ohmic losses	1.5	13.8	1.4	12.9
Processor losses	13.1	13.1	24.1	24.1

tion overpotential in the SPFC. More than one third of power entering the system in the form of ethanol is consumed in activation overpotential losses under high load conditions. Ohmic losses are negligible under low load conditions, but they increase substantially when the system operates at peak power. Overall, SPFC inefficiencies comprise 68% of total losses under low load conditions and 79% of losses under high load conditions. Losses in the POX-processor are due to: (i) thermodynamic constraints in the WGS reactor, (ii) hydrogen loss due to oxidation in the SOX reactor, as the SOX selectivity was assumed to be 0.90. In the case of the real POX-system, losses in the POX-processor are dominant under low load conditions, while activation overpotential losses become the most important factor under high load conditions. SPFC inefficiencies comprise 50% of total losses under low load conditions and 64% of losses under high load conditions.

## 5. Discussion

The results of this work have shown that the efficiency of a SPFC system operating on ethanol can be higher than 0.5 (50%) under low load conditions and 0.30–0.35 under high load conditions. Power requirements for the air compressor and other accessories, as well as losses in the electric motor will bring down the above figures, but, in any case, the efficiency of a SPFC system easily exceeds the one obtainable with conventional systems, i.e. internal combustion engines. Fabrication cost of the SPFC appears to be the critical factor for market penetration. Improvement in system efficiency should target activation overpotential losses, which are the main source of inefficiency [14]. Losses in the POX-processor are also significant. The main source of losses in the POX-processor appears to be the POX reactor itself. Fuel equivalence ratios, higher than those thermodynamically required, are used to avoid soot formation and to achieve high operating temperatures, where catalytic activity is high [12]. This results in consumption of a larger proportion of ethanol and a corresponding decrease in hydrogen yield. Improvements in POX performance can, therefore, be realized by development of catalysts exhibiting high activity at lower operating temperatures and by improvement of reactor design to control the problem of soot formation.

The issue of the purity of ethanol feed (pure or diluted) bears some interesting implications related to the processor type and the application (mobile or stationary). Ethanol is produced by fermentation as a dilute aqueous solution of ~ 10% v/v concentration. A distillation step is required to purify ethanol and it is understandable that a dilute ethanol mixture (~ 50–60% v/v) will have a lower production cost on a per mol of ethanol basis than the one of pure ethanol (~ 95% v/v). The question is whether dilute ethanol fuel may have an advantage over pure ethanol. This is examined below in terms of the processor type employed.

(a) SR-processor. The envisaged application of SR-systems is for small-scale, stationary electricity production. Regarding vehicle applications, POX-systems are considered to be superior, because they exhibit faster transient response characteristics [12]. As it was shown in the Results section, optimal performance of the SR-processor is obtained with feeds of  $R$  in the range of 2.5–2.8. Such  $R$ -values correspond to ethanol mixtures of 54–57% v/v. Therefore, SR-processors are perfectly suited to operate with lower-cost, dilute ethanol feeds. Of course, the SR-processor may also operate on pure ethanol with required water being recycled from the SPFC exhaust. Dilute feeds have a lower energy content per volume and tanks of larger volume are needed for fuel storage. This, however, is not an important issue in stationary applications.

(b) POX-processor. The efficiency of a real POX-processor is maximized with a pure ethanol feed. In a vehicle application, use of pure ethanol has also the advantage of a smaller reservoir tank required for a specific mileage. The drop in system efficiency resulting from the use of a 52% ethanol feed ( $R = 3$ , Fig. 6) compared to a pure ethanol feed is approximately 8%. Therefore, employment of the specific dilute feed may be economically advantageous, if its cost is at least 8% lower than the cost of pure ethanol on a per mol of EtOH basis.

## 6. Conclusions

Operation of a SPFC system on ethanol fuel offers the advantage of electricity production with high efficiency and minimal emission of air pollutants and CO<sub>2</sub> greenhouse gas. Lower-cost, dilute ethanol–water mixtures (~ 55% v/v EtOH) are perfectly suited for stationary applica-

tions employing a SR-SPFC system. On the other hand, pure ethanol ( $\sim 95\%$  v/v EtOH) appears to be the best fuel in vehicle applications employing a POX-SPFC system. Efficiencies with an ideal processor and the assumed SPFC unit can be on the order of 60% under low load conditions and 30–35% at peak power, while efficiencies with an actual processor are 80–85% of the aforementioned values. The major source of inefficiencies in the system is the SPFC itself and, particularly, the activation overpotential losses. There is also room for improvement in the performance of the POX reactor through the development of more active catalysts and appropriate design in order to achieve efficient operation at lower temperatures and higher fuel equivalence ratios.

### Nomenclature

$c_{O_2}^*$	Effective oxygen concentration on cathode side, mol/cm <sup>3</sup>
$E_{th}$	Thermodynamic equilibrium potential, V
$E_{op}$	Operating potential (output voltage), V
$F$	Faraday constant
$G_{EtOH}$	Molar flow rate of ethanol, mol/s
$G_{H_2}$	Molar flow rate of hydrogen, mol/s
$I$	Current density, A/cm <sup>2</sup>
$i$	Current, A
$P$	Pressure, atm
$P_{el}$	Electric power, W
$p_{H_2}^*$	Effective partial pressure of hydrogen on anode side, atm
$p_{O_2}^*$	Effective partial pressure of oxygen on cathode side, atm
$R$	Water/ethanol molar ratio in the feed
$R_{int}$	Internal electrical resistance, $\Omega$
$R_{opt}$	Optimal water/ethanol ratio for SR-processor
$S_{OX}$	Oxidation selectivity of CO in the SOX reactor
$T_{REF}$	Temperature of SR, K
$T_{POX}$	Temperature of POX reactor, K
$T_{WGS}$	Temperature of WGS reactor, K
$X_{FC}$	Hydrogen conversion in the SPFC
$x_{H_2O}^{sat}$	Molar fraction of water at saturation
$x_{N_2}^{channel}$	Molar fraction of nitrogen at the cathode interface

$x_{inert}^{channel}$	Molar fraction of inert species ( $N_2 + CO_2 + CH_4$ ) at the anode interface
$x_{in}^{dry}$	Molar fraction of inert species at the product gas of ethanol processor
$x_{H_2}^{dry}$	Molar fraction of hydrogen at the product gas of ethanol processor
$x_{H_2O}^{dry}$	Molar fraction of water at the product gas of ethanol processor
$x_{in}^{hum}$	Molar fraction of inert species after humidification of the product gas of ethanol processor
$x_{out}^{hum}$	Molar fraction of inert species at the exit gas of the anode

### Greek

$a$	LHV efficiency of the system
$\eta_{act}$	Activation overpotential, V
$\Phi$	Fuel equivalence ratio of feed in the POX-processor

### References

- [1] K.B. Prater, J. Power Sources 61 (1996) 105.
- [2] T.F. Fuller, The Electrochemical Society Interface (1997) 26–32, Fall.
- [3] F. Panik, J. Power Sources 71 (1998) 36.
- [4] A.J. Appleby, Int. J. Hydrogen Energy 19 (1994) 175.
- [5] J.M. Ogden, M.M. Steinbugler, T.G. Kreutz, J. Power Sources 79 (1999) 143.
- [6] K. Ledjeff-Hey, V. Formanski, T. Kalk, J. Roes, J. Power Sources 71 (1998) 199.
- [7] J.C. Amphlett, R.M. Baumert, R.F. Mann, B.A. Peppley, P.R. Roberge, T.J. Harris, J. Electrochem. Soc. 142 (1995) 1.
- [8] J.C. Amphlett, R.M. Baumert, R.F. Mann, B.A. Peppley, P.R. Roberge, T.J. Harris, J. Electrochem. Soc. 142 (1995) 9.
- [9] T. Ioannides, J. Power Sources, in press.
- [10] H. Igarashi, H. Uchida, M. Suzuki, Y. Sasaki, M. Watanabe, Appl. Catal., A: General 159 (1997) 159.
- [11] M.J. Kahlich, H.A. Gasteiger, R.J. Behm, J. Catal. 182 (1999) 430.
- [12] W.L. Mitchell, J.H.J. Thijssen, J.M. Bentley, N.J. Marek, Proceedings of the 1995 SAE Alternative Fuels Conference, SAE Technical Paper Series, Paper #952761.
- [13] J.A. Dean, Lange's Handbook of Chemistry, 14th edn., McGraw-Hill, 1992.
- [14] G.J.K. Acres, J.C. Frost, G.A. Hards, R.J. Potter, T.R. Ralph, D. Thompsett, G.T. Burstein, G.J. Hutchings, Catal. Today 38 (1997) 393.