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Short communication

Optimization of a combined heat and power PEFC by exergy analysis

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Abstract

In this paper, design and exergy method optimization of a 5 kW power output polymer electrolyte fuel cell (PEFC) fuel cell with cogeneration application has been investigated. It is assumed that cooling water is passed through the fuel cell cooling channel, warmed up and supplied for space heating applications. The performance of the proposed system has been optimized by the second law based on exergy analysis. Results show that for maximum system efficiency and minimum entropy generation, fuel cell temperature and voltage should be as high as possible in the range of application. Also, the fuel cell pressure and stoichiometric air:fuel ratio should be as low as possible in the range of application.

Keywords: Cogeneration; Efficiency; Exergy; Optimization; PEFC; Fuel cell

1. Introduction

Fuel cells are electrochemical devices that directly convert the chemical energy of a reaction into electrical energy. The basic structure or building block of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on each side. One of the most popular types of fuel cells is the polymer electrolyte fuel cell (PEFC). The electrolyte in this fuel cell is an ion exchange membrane in which corrosion problems are minimal. A schematic representation of a PEFC with the reactant/product gases and the ion conduction flow directions through the cell is shown in Fig. 1.

From point of view of thermodynamic design, there are several methods to increase the efficiency of a fuel cell. The most popular way using power and heat is combined cycles (CHP) [1,2]. The polymer electrolyte fuel cell which has a low power and heat generation capacity may be used in buildings for local power distribution. For CHP application of this fuel cell, water, which is a cooling media in the fuel cell, is used for space heating or water heating [3]. In these fuel cells, water is passed through the fuel cell cooling channel, warmed up and is used for the CHP application. There are previous publications about energy and exergy analyses of PEFC fuel cell systems. These analyses have been published with varying degrees of cogeneration in order to seek and develop fuel cells with better economic and energy saving characteristics than conventional power generating plants [4,5]. Several hybrid system configurations have been suggested for efficiency improvement. In addition, performance predictions under part-load conditions have been made for the systems, for which power output is over 200 kW [6–8]. Magistri et al. [9] proposed a very small 5 kW gas turbine plant combined with a SOFC 31 kW, and evaluated its part-load performance. However, none of the previous works have done a complete exergy analysis of a CHP system, which considers the heat transfer and pressure drop in the reactant, product and cooling channel.

2. Mathematical model

The proposed system under consideration is shown in Fig. 1. The model consists of a PEFC fuel cell having 5 kW power output with cogeneration application. In this system,

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Nomenclature

a	air:fuel stoichiometric ratio
C_P	average specific heat (kJ (kg K)$^{-1}$
D_h	hydraulic diameter (m)
e	exergy (kJ kg^{-1})
f	friction coefficient
F	Faraday constant
h	convection heat transfer coefficient (W (m^2 °C)$^{-1}$)
$\dot{h}_f$	enthalpy of formation (kJ kg^{-1})
k	heat conduction coefficient (W (m °C)$^{-1}$)
K	correction factor (Eq. (16))
L	length of passage (m)
$\dot{m}$	mass flow rate (kg s^{-1})
M	atomic number
n	number of cells
Nu	Nusselt number
P	pressure (kPa)
ΔP	pressure loss (kPa)
P_c	perimeter of cooling channel (m)
Q	heat production (kW)
R	universal gas constant (kJ (kmol K)$^{-1}$)
Re	Reynolds number
T	temperature (K)
v	velocity of fluid in channel (m s^{-1})
V	fuel cell voltage (V)
W	power (kW)
x	mole fraction

Subscripts

ch	chemical
f	fuel cell
f_i	inlet water temperature
f_o	outlet water temperature
in	inlet
K	local
l	friction
o	standard condition
out	outlet
ph	physical
s	diffusion layer
tot	total
w	water

Greek symbols

μ	viscosity coefficient (Pa s)
ρ	density (kg m^{-3})
φ	correction factor
η	system efficiency

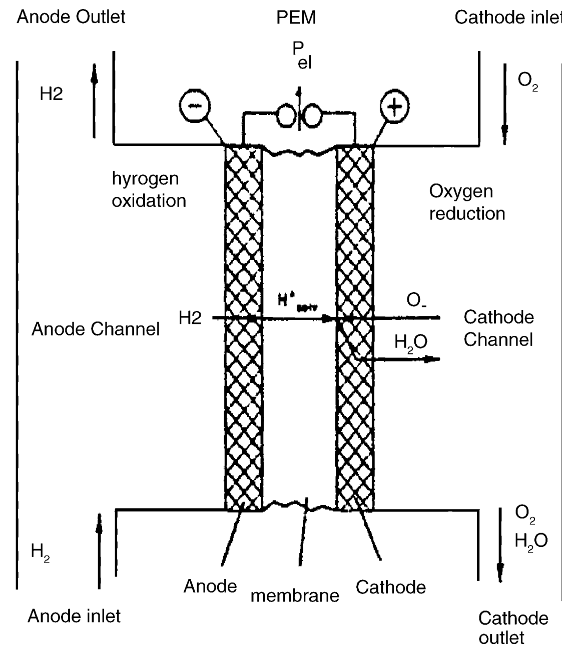

Fig. 1. Schematic of a PEFC fuel cell with proton exchange membranes.

cooling water is passed through a cooling channel, warmed up and supplied for space heating. The following reactions take place in the anode and cathode of the proposed fuel cell:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

$$2H^+ + 2e^- + \tfrac{1}{2}O_2 \rightarrow H_2O \quad (2)$$

Based on the control volume, which is shown in Fig. 2, and the mass flow rates of inlet hydrogen, the inlet and outlet air and steam can be calculated as follows:

$$\dot{m}_{H_2,in} = \frac{W}{2FV} M_{H_2} \quad (3)$$

$$\dot{m}_{air,in} = \frac{W}{4FV}\frac{1}{x_{O_2}} a M_{air} \quad (4)$$

$$\dot{m}_{air,out} = \frac{W}{4FV}\frac{1}{x_{O_2}} (a-1) M_{air} \quad (5)$$

$$\dot{m}_{steam,out} = \frac{W}{2FV} M_{H_2O} \quad (6)$$

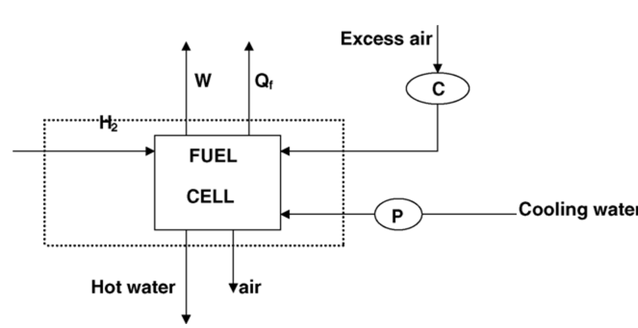

Fig. 2. Proposed control volume.

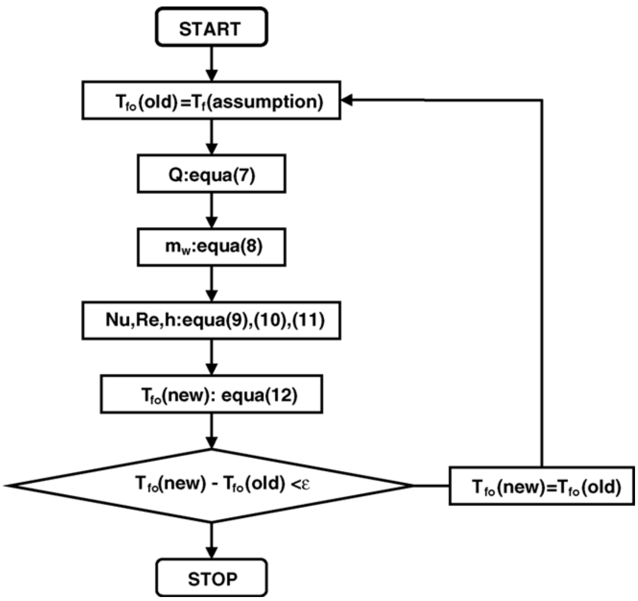

Fig. 3. Flowchart to calculate outlet temperature of the cooling water.

Also, the heat generation can be calculated by the following equations:

$$Q - W = \sum \dot{m}_{\mathrm{air,out}}(\dot{h}_{\mathrm{f}} + C_{\mathrm{P}}(T_{\mathrm{f}} - T_{\mathrm{o}}))_{\mathrm{air,out}} + \sum \dot{m}_{\mathrm{steam,out}}(\dot{h}_{\mathrm{f}} + C_{\mathrm{P}}(T_{\mathrm{f}} - T_{\mathrm{o}}))_{\mathrm{steam,out}} - \sum \dot{m}_{\mathrm{air,in}}(\dot{h}_{\mathrm{f}})_{\mathrm{air,in}} - \sum \dot{m}_{\mathrm{H_2,in}}(\dot{h}_{\mathrm{f}})_{\mathrm{H_2,in}} \quad (7)$$

It should be noted that Eq. (7) is based on the two assumptions, which are given as follows:

1. inlet air and hydrogen are at standard condition ($T_{\mathrm{o}} = 298$ K, $P_{\mathrm{o}} = 1$ atm);
2. outlet air and steam are at fuel cell temperature.

Mass flow rate of cooling water is calculated as follows:

$$\dot{m}_{\mathrm{w}} = \frac{Q}{C_{\mathrm{P}}(T_{\mathrm{f_o}} - T_{\mathrm{f_i}})} \quad (8)$$

The unknown outlet temperature of the cooling water can be calculated based on the flowchart, which is shown in Fig. 3. The specification of the system is summarized in Table 1. The configuration of cooling channel is shown in Fig. 4. Also, the Reynolds and Nusselt numbers are calculated as follows [10,11]:

$$Re = \frac{4\dot{m}_{\mathrm{w}}}{\pi D_{\mathrm{h}} \mu n}, \qquad Re \leq 2300 \quad (9)$$

$$Nu = 7.53 \quad (10)$$

The convection heat transfer coefficient h and outlet temperature of the cooling water $T_{\mathrm{f_o}}$ are calculated [12], respectively:

$$h = \frac{k}{D_{\mathrm{h}}} Nu \quad (11)$$

$$T_{\mathrm{f_o}} = T_{\mathrm{f}} - (T_{\mathrm{f}} - T_{\mathrm{f_i}}) \exp\left(\frac{-p_{\mathrm{c}} n L}{\dot{m}_{\mathrm{w}} C\mathrm{p_w}} h\right) \quad (12)$$

Frictional pressure loss in the cooling, reactant and product channel of the fuel cell is calculated as follows [10,11]:

$$\Delta P_{\mathrm{l}} = f \frac{L}{D_{\mathrm{h}}} \rho \frac{v^2}{2} \quad (13)$$

Also, friction coefficient in the cooling channel is [10,11]:

$$f = \frac{82}{Re} \quad (14)$$

where this coefficient in reactant and product channel is [10,11]:

$$f = \varphi \frac{64}{Re} \quad (15)$$

The value of correction factor φ is equal to 0.85 [10,11].

Local pressure loss in the cooling, reactant and product channel of the fuel cell is as follows [10,11]:

$$\Delta P_{\mathrm{k}} = K \rho \frac{v^2}{2} \quad (16)$$

The value of the multiplier K depends on the channel geometry and the range of its variation is $1 < K < 2$ [10,11].

Table 1
Specification of the system

W (w)	5000
V (V)	220
A (cm^2)	250
λ	2
n	440
P (kPa)	300

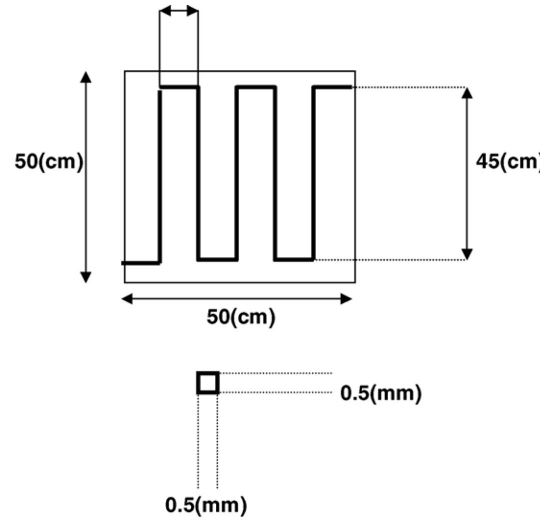

Fig. 4. The configuration of the cooling, reactant and product channels.

The total pressure loss in the cooling channel can be calculated by the following equation [10,11]:

$$\Delta P_t = \Delta P_l + \Delta P_k + \Delta P_s \tag{17}$$

Also, pressure loss in the diffusion layer can be calculated as follows [13]:

$$\Delta P_s = \frac{384000}{n}\dot{m} \tag{18}$$

Finally, the total pressure loss in the fuel cell is as follows [13]:

$$\Delta P_t = f\frac{L}{D_h}\rho\frac{v^2}{2} + K\rho\frac{v^2}{2} + \frac{384000}{n}\dot{m} \tag{19}$$

2.1. Exergy analysis

Physical exergy is associated with the temperature and pressure of the reactants and the products in the fuel cell system. The physical exergy is expressed in terms of the of enthalpy and entropy difference from those standard conditions of temperature and pressure $T_o = 298$ K and $P_o = 1$ atm, respectively. The physical exergy of an ideal gas with constant specific heat C_P can be written as follows:

$$e_{ph} = C_P T_o\left[\frac{T}{T_o} - 1 - \ln\left(\frac{T}{T_o}\right)\right] + RT_o \ln\left(\frac{P}{P_o}\right) \tag{20}$$

The chemical exergy is associated with the departure of the chemical composition of a system from that of the environment can be calculated by equation below:

$$e_{ch} = \sum x_n e_{ch} + RT_o \sum x_n \ln x_n \tag{21}$$

The total exergy flow can be calculated:

$$e_{tot} = e_{ph} + e_{ch} \tag{22}$$

As a result, the entropy generation of the system can be calculated as follows:

$$\dot{S}_{gen} = \frac{1}{T_o}\left\{\sum \dot{m}_{in} e_{tot,in} - \sum \dot{m}_{out} e_{tot,out} - W\right\} \tag{23}$$

The second law efficiency of the system is as follows:

$$\eta = \frac{\dot{m}_w C_{P,w}(T_{f_o} - T_{f_i}) + W}{\sum_{in}\dot{m}_{in} e_{tot,in} - \sum_{out}\dot{m}_{out} e_{tot,out}} \tag{24}$$

Considering Eqs. (3)–(23), the functional relationship of the entropy generation of the system can be written as follows:

$$\dot{S}_{gen} = f(W, V, a, T_f, \eta, L, p_c, P) \tag{25}$$

Noting that the cooling and reactant and product channels have a constant geometry which is shown in Fig. 4, the function of the entropy generation can be simplified as below:

$$\dot{S}_{gen} = f(W, V, a, T_f, P, \eta) \tag{26}$$

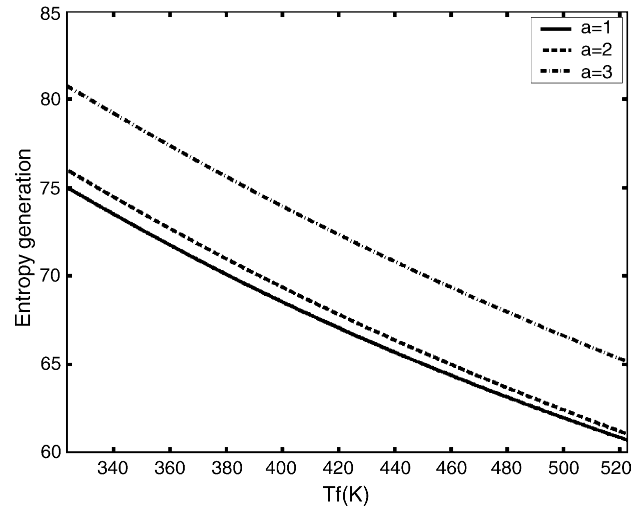

Fig. 5. Variation of entropy generation with fuel cell temperature at different stoichiometric fuel air ratios.

Assuming a constant number of cells be equal to 440 and output power of 5 kW. The entropy generation function can be more simplified such as:

$$\dot{S}_{gen} = f(V, a, T_f, P) \tag{27}$$

3. Results and discussions

Effect of the fuel cell temperature and stoichiometric ratio of fuel air on the entropy generation and system efficiency are shown in Figs. 5 and 6.

It is obvious from the above-mentioned figures that the increase in fuel cell temperature causes the increase in outlet temperature of the cooling water, which is supplied for co-generation in this system (Eqs. (11) and (12)), so that based on this effect the system efficiency increases and entropy generation decreases.

The increase in stoichiometric air:fuel ratio causes the increase in outlet air mass flow rate, which is warmed up

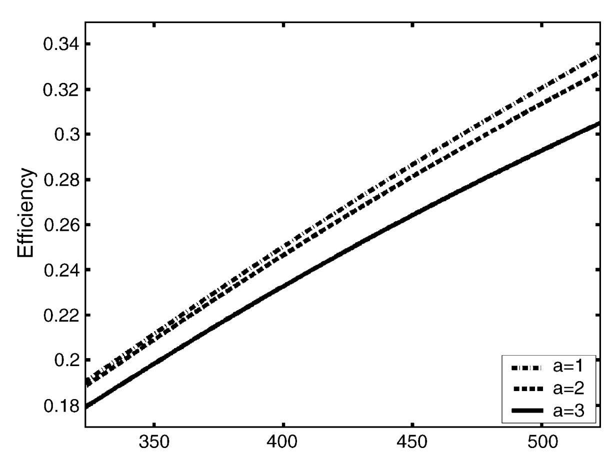

Fig. 6. Variation of system efficiency with fuel cell temperature at different stoichiometric fuel air ratios.

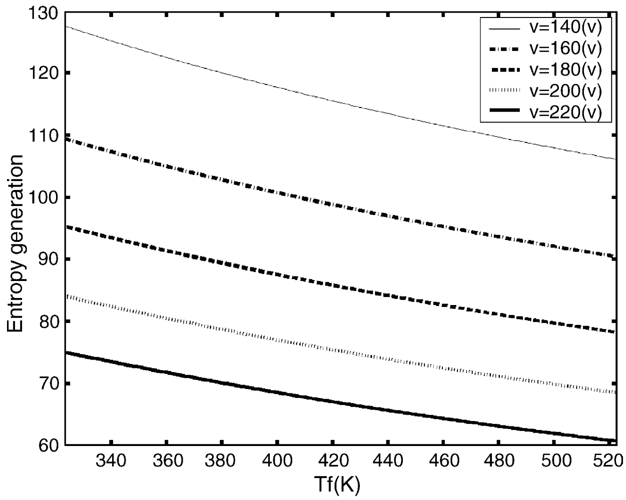

Fig. 7. Variation of entropy generation with fuel cell temperature at different voltage.

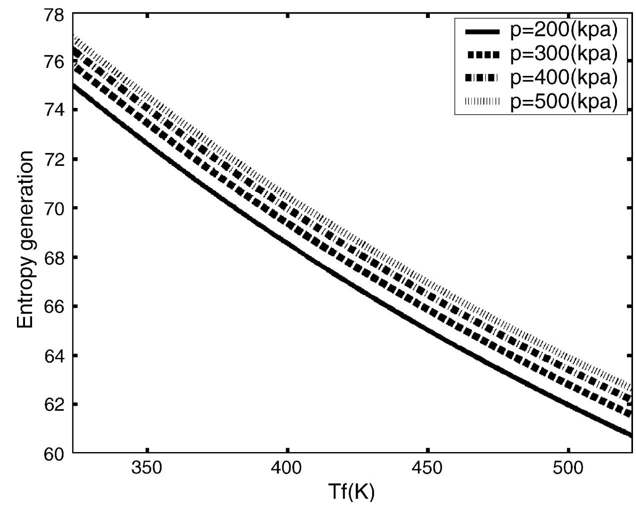

Fig. 9. Variation of entropy generation with fuel cell temperature at different pressure.

in the fuel cell and is rejected to environment. Due to this rejection of heat, entropy generation increases and system efficiency decreases.

As seen in Figs. 5 and 6, fuel cell temperature has a greater effect on the system efficiency than entropy generation. Now, consider air:fuel ratio $a = 1$; the increase in fuel cell temperature from 330 K to 550 K decreases entropy generation about 21% but increases system efficiency about 79%. Variation of entropy generation and efficiency of the system with fuel cell voltage and temperature are shown in Figs. 7 and 8, respectively. The increase in fuel cell voltage from 140 V to 220 V at constant temperature decreases entropy generation about 71% and increases efficiency about 44%. This variation shows the vital influence of fuel cell voltage on the system entropy generation and efficiency. Considering Eqs. (3)–(6), it is obvious that the increase in voltage, decreases mass flow rate. This reduction decreases pressure loss according to Eqs. (13)–(19), whereas this variation decreases entropy generation and increases system efficiency.

Figs. 9 and 10 show the effect of fuel cell pressure and temperature on the entropy generation of the system and efficiency, respectively. As shown, the increase in fuel cell pressure increases entropy generation and decreases system efficiency. Focussing on Eq. (20), it is understandable that the increase in pressure increases physical exergy at the inlet and outlet of the fuel cell, but this effect is greater at the fuel cell inlet than the outlet, which causes increasing net physical exergy in the fuel cell. According to Eqs. (23) and (24) entropy generation increases and system efficiency decreases.

The most effective parameter affecting entropy generation and system efficiency according to Figs. 5–10 is voltage and the pressure has a lesser effect on system performance, so for the maximum efficiency and minimum entropy generation, the fuel cell temperature and voltage should be as high as

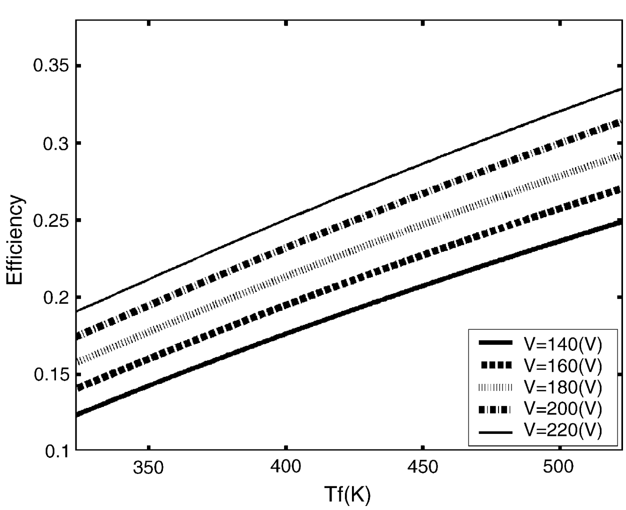

Fig. 8. Variation of system efficiency generation with fuel cell temperature at different voltage.

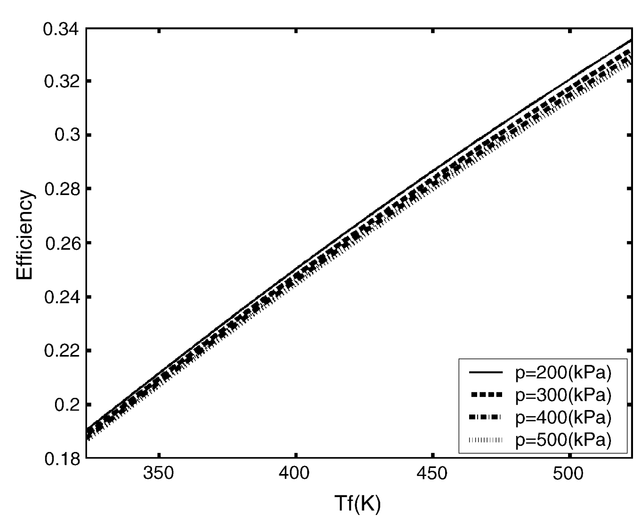

Fig. 10. Variation of system efficiency with fuel cell temperature at different pressure.

possible; meanwhile, the pressure and stoichiometric air:fuel ratio should be as low as possible.

4. Conclusions

A PEFC fuel cell with a 5 kW power output and a cogeneration application has been thermodynamically designed and its optimized performance has been considered by exergy analysis. The effect of variation in fuel cell temperature, stoichiometric air:fuel ratio, voltage and pressure on the system has been investigated. The following conclusions are obtained:

1. Exergy analysis is a suitable tool for system optimization.
2. Increase in fuel cell temperature and voltage, decrease entropy generation, and as a result the fuel cell efficiency increases, whereas an increase in the stoichiometric air:fuel ratio and fuel cell pressure, increase entropy generation, and as a result, the system efficiency decreases.
3. The fuel cell voltage has the most influence on entropy generation and system efficiency, whereas, fuel cell pressure has the weakest effect on entropy generation and system efficiency. So, fuel cell temperature and voltage should be as high as possible. Also, the fuel cell pressure and stoichiometric air:fuel ratio should be as low as possible.

References

[1] M. Burner, K. Tana ksa, D. Favrat, K. Yamada, Multi-criteria optimization of a district cogeneration plant integrating a solid oxide fuel cell–gas turbine combined cycle, heat pumps and chiller, Energy 28 (2003) 497–518.
[2] A. Selimovic, J. Palsson, Networked solid oxide fuel cell stacks combined with a gas turbine cycle, J. Power Sources 106 (2003) 76–82.
[3] M.A. Rosen, D.S. Scott, A thermodynamic investigation of the potential for cogeneration for fuel cells, Int. J. Hydrogen Energy 13 (1988) 775–782.
[4] M.A. Rosen, Comparsion based on energy and exergy analyses of the potential cogeneration efficiencies for fuel cells and other electricity generation devices, Int. J. Hydrogen Energy 15 (1990) 267–274.
[5] Y. Matsumoto, R. Yokoyama, K. Ito, Engineering–economic optimization of fuel cell cogeneration plant, J. Eng. Gas Turbines Power Trans. ASME 116 (1994) 8–14.
[6] P. Costamagna, L. Magistri, A.F. Massardo, Design and partload performance of a hybrid system based on a solid oxide fuel cell reactor and a micro gas turbine, J. Power Sources 96 (2001) 352–368.
[7] S. Campanari, Full load and part-load performance prediction for integrated SOFC and microturbine systems, Trans. ASME J. Eng. Gas Turbine Power 122 (2000) 239–246.
[8] J. Palsson, A. Selimovic, Design and off-design predictions of a combined SOFC and gas turbine system, ASME Paper, 2001-GT-379, 2001.
[9] L. Magistri, A. Massardo, C. Rodgers, C.F. McDonald, A hybrid system based on a personal turbine(5 kW) and a SOFC stack: a flexible and high efficiency concept for the distributed power market, ASME Paper, 2001-GT-92, 2001.
[10] Q. Weilin, I. Mudawar, Experimental and numerical study of pressure drop and heat transfer in a single phase micro-channel heat sink, Int. J. Heat Mass Transfer 45 (2002) 2549–2565.
[11] Q. Weilin, I. Mudawar, Analysis of three-dimensional heat transfer in micro-channel heat sinks, Int. J. Heat Mass Transfer 45 (2002) 3973–3985.
[12] F.P. Incropera, D.P. Dewitt, Introduction to Heat Transfer, second ed., Mc Graw-Hill, 1995.
[13] H. Dohle, R. Jung, N. Kimiaie, J. Mergel, M. Muller, Interaction between the diffusion layer and the flow field of polymer electrolyte fuel cells—experiments and simulation studies, J. Power Sources 124 (2003) 371–384.