

# Some issues on performance analysis of fuel cells in thermodynamic point of view

Sung Tack Ro, Jeong L. Sohn\*

*School of Mechanical and Aerospace Engineering, Seoul National University, San 56-1, Shilim-Dong, Gwanak-Gu, Seoul 151-742, Republic of Korea*

Received 31 January 2007; received in revised form 27 February 2007; accepted 27 February 2007  
Available online 7 March 2007

## Abstract

In order to develop a new fuel cell and/or to enhance fuel cell performance, it is very important to understand clearly what the real performance of a fuel cell is. However, some important issues for the assessment of a fuel cell performance still require additional considerations. For example, the performance of a fuel cell is generally described based on an isothermal condition in spite of the non-uniform cell temperature distributions under real operating conditions. For this purpose, a formulation for the performance of a fuel cell operating at an isentropic condition (*e.g.*, non-uniform cell temperature) is introduced in this study and compared with a reversible isothermal case (*e.g.*, uniform cell temperature). Also, it is necessary to reveal the real difference in the performance of a fuel cell and a heat engine. Understanding of the purpose of the hybridization of a fuel cell with a heat engine is another important issue. In the present study, issues related to the performance of a fuel cell are considered from a thermodynamic point of view.

© 2007 Elsevier B.V. All rights reserved.

**Keywords:** Fuel cell; Performance; Efficiency; Carnot heat engine; Hybrid system

## 1. Introduction

Fuel cell is a thermodynamic system that generates power by a direct conversion of the chemical energy in fuel into electrical power through electrochemical reactions [1]. Long after the invention of the fuel cell by Sir William Grove in 1839, its first commercial use was in space program applications in 1965 [2]. Recent advancement of fuel cell technologies has been driven by the demand for highly efficient power generation devices. Current fuel cell investments are mainly made by the automotive industries to increase fuel efficiency and/or to use hydrogen as an alternative fuel. It is also expected that application will be expanded to other sectors such as power and electronic industries.

In spite of the expected growth of the market potential of fuel cells, it is still necessary to elucidate whether the generally accepted thermodynamic descriptions so far for the fuel cell performance are accurate. For example, the fuel cell performance

is normally calculated based on an assumption of a constant cell temperature condition [3]. Nevertheless, in real operation situations of the fuel cell, the cell temperature is not uniform, but the exhaust (products) temperature is generally higher than entrance (reactants). Also, it is commonly accepted that the performance of the fuel cell is superior to heat engines. The main difference between a fuel cell and a heat engine is related to the basic thermodynamic characteristics. From a view of the second law of thermodynamics, the efficiency of a heat engine, which is a thermodynamic cycle, is smaller than that of a Carnot heat engine. However, since the fuel cell is not a thermodynamic cycle but a thermodynamic process, its performance is not related to a Carnot cycle. This is the reason why it is widely described that the efficiency of the fuel cell is higher than the heat engine. This description was negated by several authors such as Wright [4] and Lutz et al. [5] and they showed that the performance of two systems is the same if they operate at reversible processes with the same operating temperature. However, it should be recognized that, in any types of heat engines including reversible one, there exist internal irreversibilities such as combustion processes in the high temperature heat source, which does not exist in the electrochemical reaction in fuel cells, and they may

\* Corresponding author. Tel.: +82 2 880 7434; fax: +82 2 889 6205.  
E-mail address: [jlsohn@snu.ac.kr](mailto:jlsohn@snu.ac.kr) (J.L. Sohn).

### Nomenclature

$C_p$	specific heat at constant pressure ( $\text{kJ kmol}^{-1} \text{K}^{-1}$ )
$H$	enthalpy (kJ)
$Q$	heat (kJ)
$W$	work (kJ)

### Greek letters

$\eta$	efficiency (%)
$\Theta$	entropy production ( $\text{kJ K}^{-1}$ )

### subscripts

ad	adiabatic
c	cell temperature
C	Carnot cycle
ex	exhaust gas
FC	fuel cell
hybrid	hybrid
H	high temperature
is	isentropic
lm	log-mean
pr	preheating
P	products
rev	reversible
R	reactants
total	total
T	reversible isothermal
0	ambient

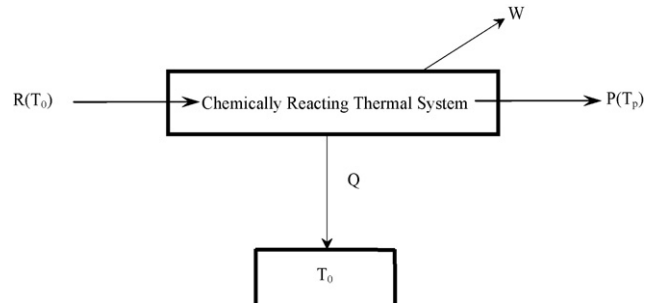


Fig. 1. A chemically reacting thermodynamic system.

the surrounding. It is assumed that all substances are ideal gases and this system operates at a constant pressure,  $P_0$ . Complete chemical reactions are considered in this study and there are no reactants remained after a reaction. Based upon the first and second thermodynamic laws, the conservation of energy and entropy for this system can be expressed as

$$H_R(T_0) = H_P(T_P) + Q + W \quad (1a)$$

$$S_R(T_0) + \int \left( -\frac{\delta Q}{T} \right) + \Theta = S_P(T_P) \quad (1b)$$

Since the thermodynamic characteristics of this system depend upon the conditions of a chemical reaction, three different cases are considered as follows.

#### 2.1. Adiabatic combustion

If the chemical reaction occurs under an adiabatic condition without work production, *e.g.*, *adiabatic combustion*, the above equations become

$$H_R(T_0) = H_P(T_{ad}) \quad (2a)$$

$$S_R(T_0) + \Theta = S_P(T_{ad}) \quad (2b)$$

Here,  $T_{ad}$  is called as the “adiabatic flame temperature,” which is the highest possible temperature of the products due to the combustion heat of the fuel. It should be noted that, in spite of the adiabatic conditions, *i.e.*,  $Q = 0$ , there exists irreversibilities with an entropy generation ( $\Theta$ ), which is produced by the combustion process within the thermodynamic system.

#### 2.2. Isentropic reaction

If the chemical reaction occurs at an isentropic (*e.g.*, reversible adiabatic) condition, Eqs. (1a) and (1b) are simplified as

$$H_R(T_0) = H_P(T_{is}) + W \quad (3a)$$

$$S_R(T_0) = S_P(T_{is}) \quad (3b)$$

The temperature of the products,  $T_{is}$ , is defined as the “isentropic temperature” which is higher than the temperature of the reactants. The produced work can be calculated by noting the enthalpy difference in Eq. (3a).

cause the difference in performance between fuel cells and heat engines.

In spite of the reduced work production from a reversible fuel cell with the increase of the operating temperature, the high temperature fuel cell (*e.g.*, solid oxide fuel cell (SOFC)) is more beneficial due to higher cell voltage than low temperature one (*e.g.*, proton exchange membrane fuel cell (PEMFC)) due to smaller internal irreversibilities. Another advantage of the high temperature fuel cell is the potential use of the high temperature exhaust gas. Hybridization of a high temperature fuel cell with a heat engine such as a gas turbine is a valuable concept to convert heat wasted from a fuel cell to a useful work [6].

In the present study, performance characteristics of the fuel cell are considered by a thermodynamic point of view based on a reversible fuel cell and compared with a Carnot heat engine. Also, the benefit of the construction of the fuel cell–heat engine hybrid system and its performance characteristics are described.

## 2. Thermodynamic fundamentals

Prior to discussing the performance characteristics of fuel cells, we should consider thermodynamic principles of a chemically reacting thermodynamic system, as shown in Fig. 1, with reactants entering at a reference (*e.g.*, ambient) temperature  $T_0$  and products exhausted at a temperature  $T_P$ . Here, the reference temperature represents the ambient temperature in this study. This system possibly produces work and/or exchange heat with

### 2.3. Reversible isothermal reaction

If the chemical reaction occurs at a reversible isothermal condition, Eqs. (1a) and (1b) can be written as

$$H_R(T_0) = H_P(T_0) + Q + W \quad (4a)$$

$$S_R(T_0) - \frac{Q}{T_0} = S_P(T_0) \quad (4b)$$

Then, the produced work can be expressed as the difference of Gibbs energy as follows:

$$W = -(\Delta_f H(T_0) - T_0 \Delta_f S(T_0)) = -\Delta_f G(T_0) \quad (5)$$

Here,  $\Delta_f$  is an operator representing the difference of thermodynamic property between products and reactants in a chemically reacting system. It should be noted that, in this case, the temperature of the products is the same as that of the reactants which is much lower than both the adiabatic flame temperature  $T_{ad}$  and isentropic temperature  $T_{is}$ .

To compare the thermodynamic characteristics of the above three different cases, a chemical reaction for the oxidization of 1 mol of hydrogen with 1/2 mol of oxygen is considered:



Fig. 2 clearly shows the differences of three cases described above, i.e., A  $\rightarrow$  B: adiabatic combustion, A  $\rightarrow$  C: isentropic case and A  $\rightarrow$  D: reversible isothermal case, for the oxidization process of the hydrogen. Here, the enthalpy of the product is calculated based on high heating value (HHV) and this is applicable to other computations in this study. As in Table 1, the highest possible temperature of the product (e.g., water) is the adiabatic flame temperature. It should be denoted that this is the highest possible adiabatic flame temperature due to an assumption of the complete chemical reaction. If dissociations are considered, the chemical reaction comes to equilibrium at about 64% conversion of the hydrogen with a decreased adiabatic flame temperature as 3500 K. The isentropic temperature is much lower than the adiabatic flame temperature. To maintain a constant system temperature as in a reversible isothermal case, it is necessary to release a certain amount of heat to the surroundings, which is the value of  $-T_0 \Delta S$ .

### 3. Reversible fuel cell

A reversible fuel cell is defined as the fuel cell operating without any internal irreversibilities such as activation losses, ohmic losses, etc. In case of a reversible fuel cell operating at an isothermal condition, its performance is generally expressed

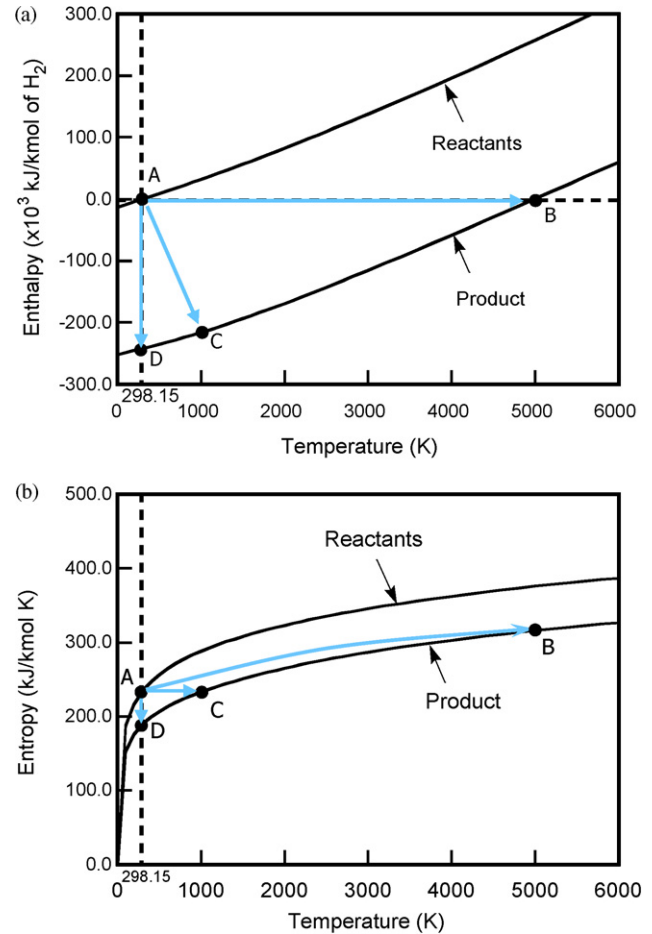


Fig. 2. Enthalpy (a) and entropy (b) of reactants and products in case of the oxidation of the hydrogen with oxygen as an oxidizer (A  $\rightarrow$  B: adiabatic combustion, A  $\rightarrow$  C: isentropic reaction, A  $\rightarrow$  D: reversible isothermal reaction).

as follows:

$$W_{FC}(T_c) = -(\Delta_f H(T_c) - T_c \Delta_f S(T_c)) = -\Delta_f G(T_c) \quad (7a)$$

$$\eta_{FC}(T_c) = \frac{W_{FC}(T_c)}{-\Delta_f H(T_0)} = \frac{-\Delta_f G(T_c)}{-\Delta_f H(T_0)} \quad (7b)$$

In the above expression, the fuel cell efficiency is a function of a cell temperature and defined as the ratio of the produced work at a “cell” temperature,  $-\Delta_f G(T_c)$ , to the heating value of the fuel at a “reference” temperature ( $-\Delta_f H(T_0)$ ). In contrary to previous definitions of the fuel cell efficiency [7] in which the heating value of the fuel at a “cell” temperature,  $-\Delta_f H(T_c)$ , is generally used in the denominator, Eq. (7b) stands for the efficiency based on the fixed amount of energy supplied to the fuel cell at a reference temperature regardless of the cell temperature. Another definition for the fuel cell efficiency based on the exergy pro-

Table 1  
Results of thermodynamic analysis of a chemical reaction of the hydrogen with the oxygen ( $T_0 = 298.15$  K)

Case	$T_P$ (K)	$W$ (kJ kmol <sup>-1</sup> )	$Q$ (kJ kmol <sup>-1</sup> )	$\Delta_f S$ (kJ kmol <sup>-1</sup> K <sup>-1</sup> )
Adiabatic combustion	4991.9	0	0	82.62
Isentropic reaction	1012.9	215,286	0	0
Reversible isothermal reaction	298.15	228,582	13,243	-44.42

posed by Wright [4] is also acceptable as the new expression for the fuel cell performance.

To maintain a uniform cell temperature as described above, the heat ( $-T_c \Delta_f S$ ) must be released from the fuel cell into the surrounding. This is impractical unless equipped with a special heat sink device. As an alternative for the expression of the fuel cell performance, it is possible to assume that a fuel cell operates in an isentropic (*e.g.*, reversible adiabatic) condition instead of an isothermal one. In this case, the fuel cell performance can be described as

$$W_{FC, is} = -(H_P(T_{is}) - H_R(T_0)) \quad (8a)$$

$$\eta_{FC} = \frac{W_{FC, is}}{-\Delta_f H(T_0)} \quad (8b)$$

Because the cell temperature changes from reactants ( $T_0$ ) to products ( $T_{is}$ ), the work produced by a fuel cell cannot be expressed as the formation Gibbs energy at a constant temperature, but as the enthalpy difference between the entrance and exit of the fuel cell as in Eq. (8a). If a “representative” cell temperature is required, it may be defined from

$$W_{FC, is}(\bar{T}) = -\Delta_f G(\bar{T}) \quad (9)$$

In case of a fuel cell operating with 1 mol of hydrogen and 1/2 mol of oxygen (*i.e.*, reactants) supplied at ambient temperature (298.15 K), the isentropic temperature is 1012.9 K as in Table 1 and the “representative” cell temperature is calculated as 573.83 K, which is different from the arithmetic mean of  $T_0$  and  $T_{is}$ . Fig. 3 shows comparisons of three different fuel cell temperatures. The representative cell temperature is between isothermal cell temperature and isentropic temperature, but it is different from a simple arithmetic average of those values.

Fig. 4 shows efficiencies of fuel cells operating at reversible isothermal and isentropic conditions. The difference is caused by a higher enthalpy of the product at an isentropic condition than the other one. This means that the energy released by products through the exhaust of the isentropic fuel cell is larger than the heat released to the surrounding by the entropy change of the reversible one. This figure also shows that the work produced by a fuel cell decreases with high operating temperature

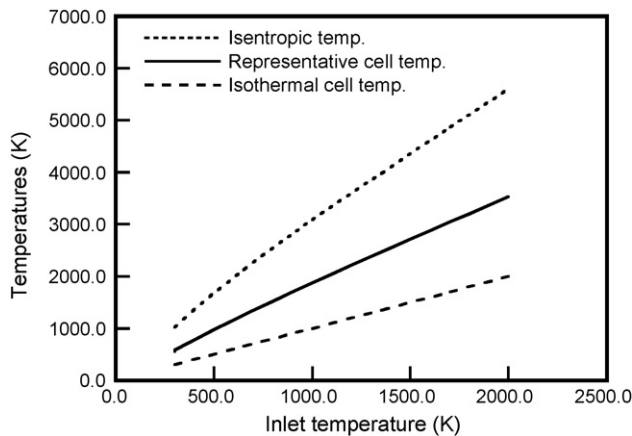


Fig. 3. Comparisons of various cell temperatures of a fuel cell operating with hydrogen as a fuel.

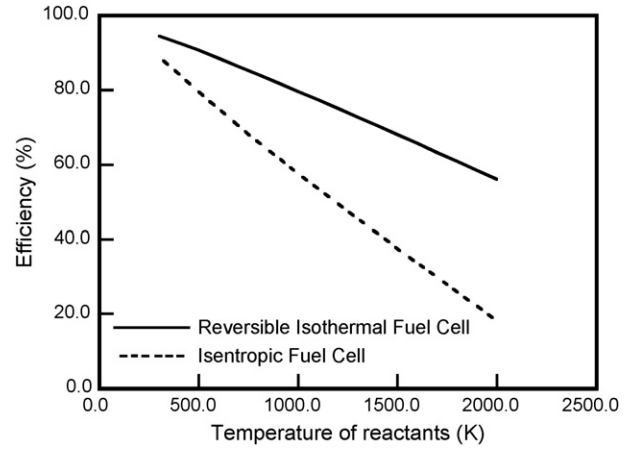


Fig. 4. Efficiencies of reversible isothermal and isentropic fuel cells with hydrogen as a fuel.

in both cases. The maximum work is produced from a reversible isothermal fuel cell operating at the ambient temperature as follows:

$$W_{FC, max} = -(\Delta_f H(T_0) - T_0 \Delta_f S(T_0)) = -\Delta_f G(T_0) \quad (10)$$

This expression can be used as a criterion to estimate the maximum fuel cell performances. For reversible fuel cells operating at higher cell temperature than  $T_0$  and/or at different conditions such as an isentropic one, their produced work is always smaller than this value. In cases of irreversible fuel cells, the produced work is also smaller than this value because of various losses inside fuel cells.

#### 4. Comparisons with a Carnot heat engine

To compare the performance of a reversible fuel cell with a heat engine, it is necessary to consider the performance characteristics of a Carnot heat engine. The basic Carnot heat engine is a reversible thermodynamic cycle operating with two constant temperature heat sources as in Fig. 5 with its performance as follows:

$$W_C = Q \left( 1 - \frac{T_0}{T_H} \right) \quad (11a)$$

$$\eta_C = 1 - \frac{T_0}{T_H} \quad (11b)$$

If the high temperature heat source is a reversible thermodynamic open system, then, the heat supplied to a Carnot heat engine can be calculated either from the enthalpy difference or the entropy difference of the high temperature heat source:

$$Q = -\Delta H = -T \Delta S \quad (12)$$

Here, contrary to  $\Delta_f$ ,  $\Delta$  is an operator representing difference of a thermodynamic property of a substance (or a mixture of substances) in a chemically non-reacting system. From the above relation, the temperature of the high temperature heat source is

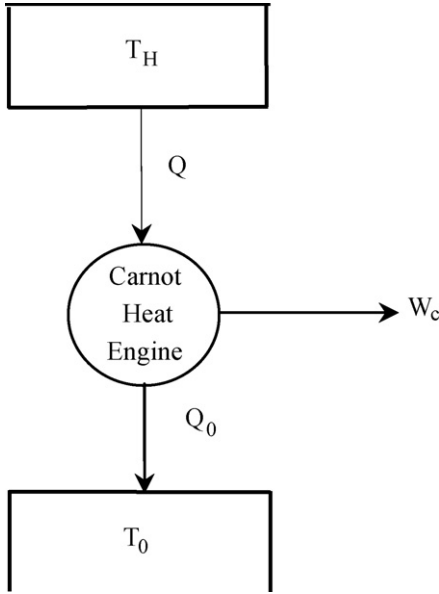


Fig. 5. Carnot heat engines operating between two heat sources.

obtained as

$$T_H = \frac{-\Delta H}{-\Delta S} \quad (13)$$

Therefore, from the above expression, the work produced by a Carnot heat engine can be expressed as follows:

$$W_C = -\Delta H - T_0 \Delta S \quad (14)$$

In general, the high temperature heat sources in heat engines are normally combustors, which are not reversible but include internal irreversibilities. To compare the performance of the fuel cell with the heat engine more carefully, a heat engine operating with the heat supplied by products from the exhaust of an adiabatic combustor as shown in Fig. 6 can be considered. In this case, the adiabatic combustor chemically converts reactants to products with an increase of the temperature from  $T_0$  to  $T_{ad}$  and the exhaust heat in products is used to operate a Carnot heat

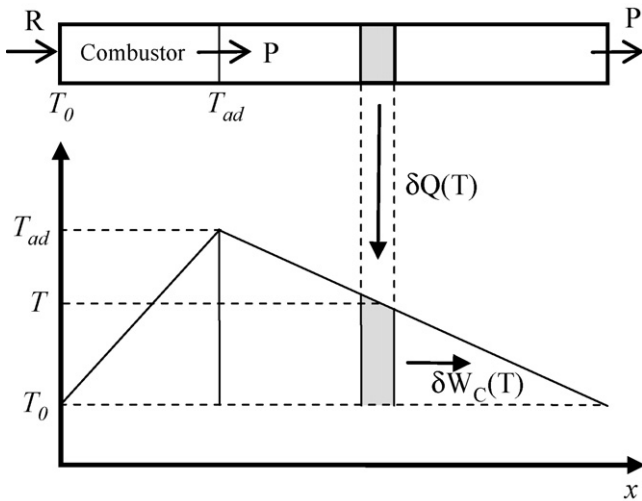


Fig. 6. Carnot heat engine operating with products of an adiabatic combustor.

engine until the temperature of the products is cooled from  $T_{ad}$  to  $T_0$ . The infinitesimal work produced by a Carnot heat engine operating between  $T$  and  $T_0$  is

$$\delta W_C = \delta Q \left( 1 - \frac{T_0}{T} \right) \quad (15)$$

Since the heat transferred to a Carnot heat engine within an infinitesimal length is equivalent to the decrease of enthalpy of the products and proportional to their corresponding entropy change, the above equation can be converted to

$$\delta W_C(T) = -(dH_P(T) - T_0 dS_P(T)) \quad (16)$$

and, therefore, the total work produced by a Carnot heat engine becomes

$$\begin{aligned} W_C &= - \int_{T_{ad}}^{T_0} (dH_P - T_0 dS_P) \\ &= -[(H_P(T_0) - H_P(T_{ad})) - T_0(S_P(T_0) - S_P(T_{ad}))] \quad (17) \end{aligned}$$

Based on the thermodynamic characteristics of the adiabatic combustor described in Section 2, the above equation can be re-arranged as follows:

$$\begin{aligned} W_C &= -(\Delta_f H(T_0) - T_0 \Delta_f S(T_0)) - T_0 \Theta \\ &= W_{FC,max} - T_0 \Theta \quad (18) \end{aligned}$$

where  $W_{FC,max}$  has the same form as Eq. (10). Therefore, in this case, the work produced by a Carnot heat engine is always smaller than maximum work produced by a fuel cell and their difference originates from the irreversibility in the combustion process.

If the product of adiabatic combustion in Fig. 6 is an ideal gas with a constant specific heat, then, Eq. (17) can be converted to

$$W_C = C_p(T_{ad} - T_0) \left( 1 - \frac{T_0}{(T_{ad} - T_0) / \ln(T_{ad}/T_0)} \right) \quad (19)$$

This equation is simplified as

$$W_C = Q \left( 1 - \frac{T_0}{T_{lm}} \right) \quad (20)$$

with

$$Q = C_p(T_{ad} - T_0) \quad (21)$$

and

$$T_{lm} \equiv \frac{T_{ad} - T_0}{\ln(T_{ad} - T_0)} \quad (22)$$

This is a log-mean average temperature of  $T_{ad}$  and  $T_0$ . From Eq. (20), the efficiency of a Carnot heat engine operating with the exhaust gas of an adiabatic combustor can be expressed as

$$\eta_C = 1 - \frac{T_0}{T_{lm}} \quad (23)$$

This efficiency is much smaller than the efficiency of Carnot heat engine with adiabatic flame temperature.

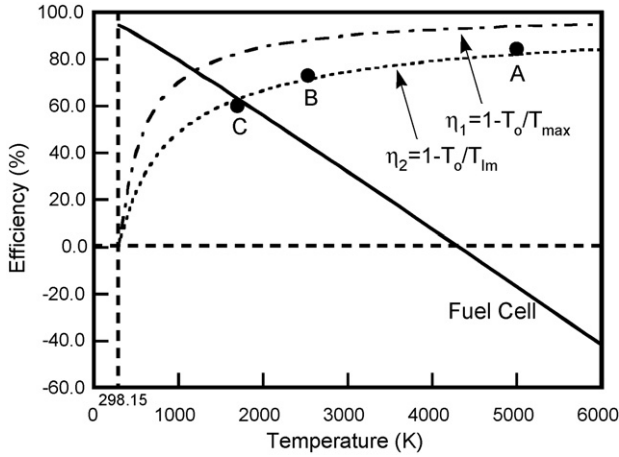


Fig. 7. Comparisons of efficiencies of a reversible fuel cell and a Carnot heat engine operating with the exhaust heat of an adiabatic combustor [A(4991.3, 84.3), B(2524.1, 73.1), C(1700, 60)].

Fig. 7 shows efficiencies of a reversible isothermal fuel cell and a Carnot heat engine operating with an adiabatic combustor using the same fuel (hydrogen). The decrease of the fuel cell efficiency with very high cell temperature tells that the operation of fuel cells must be limited to relatively low temperatures. In this figure, two different forms of efficiencies for the Carnot heat engine are provided, *i.e.*, (1) based on an adiabatic flame temperature ( $\eta_{C1}$ ) and (2) based on a log-mean average temperature ( $\eta_{C2}$ ), respectively. In case of the use of the pure oxygen as an oxidizer (point A),  $\eta_{C2}$  is calculated as 84.3%. On the other hand, if the air, instead of the pure oxygen, is used as an oxidizer (point B), this value is decreased to 73.1%. These two values lie on  $\eta_{C2}$  curve, not on  $\eta_{C1}$  curve. As the currently utmost performance of the heat engine, the efficiency of a combined cycle power plant operating with a turbine inlet temperature near 1700 K is almost 60% [8], which is also on  $\eta_{C2}$ -curve as point C in this figure. Therefore, the log-mean temperature can be a meaningful value for the qualitative assessment of the performance of heat engines.

As described above, the superior performance of fuel cells to heat engines is originated from the irreversibility in heat engines that cannot be eliminated as long as the use of combustors as high temperature heat sources in heat engines. However, in spite of their excellent theoretical performance, the efficiencies of the currently available fuel cells are lower than heat engines in their best performance. This is related to the relatively pre-mature technologies in fuel cells, which is related irreversibilities in fuel cells such as activation and ohmic losses, etc. Therefore, numerous research opportunities exist in fuel cell development to maximize the fuel cell performance.

## 5. Hybridization

As described above, the work produced by a fuel cell has the maximum value operating at the reference (*i.e.*, ambient) temperature with a reversible isothermal condition and it will

be reduced with the increase of the cell temperature. The work produced by a reversible isothermal fuel cell operating at a cell temperature  $T_c$  is represented as in Eq. (7a). However, in real situation, additional work is required to preheat reactants supplied from  $T_0$  to  $T_c$ . This work can be supplied by installing a reversed engine, *i.e.*, Carnot heat pump, operating with the work as below:

$$W_{pr}(T_c) = (H_R(T_c) - T_0 S_R(T_c)) - (H_R(T_0) - T_0 S_R(T_0)) \quad (24)$$

Also, because the temperature of the products is higher than  $T_0$ , additional work can be extracted by operating a Carnot heat engine using the exhaust heat of the fuel cell:

$$W_{ex}(T_c) = (H_P(T_c) - T_0 S_P(T_c)) - (H_P(T_0) - T_0 S_P(T_0)) \quad (25)$$

Above two equations represent exergies of reactants and products at a cell temperature, respectively. Therefore, the total work produced by a reversible isothermal fuel cell operating as a constant cell temperature  $T_c$  can be obtained as follows:

$$\begin{aligned} W_{FC, total}(T_c) &= W_{FC}(T_c) - W_{pr}(T_c) + W_{ex}(T_c) \\ &= -\Delta_f G(T_0) - (-T_c \Delta_f S(T_c)) \left(1 - \frac{T_0}{T_c}\right) \end{aligned} \quad (26)$$

If there is a Carnot heat engine operating with the heat ( $-T_c \Delta_f S(T_c)$ ) received from a high temperature heat source at  $T_c$  and extracting heat to the ambient, then, the last term in the above equation can be converted to the work produce by a Carnot heat engine:

$$W_C(T_c) = Q \left(1 - \frac{T_0}{T_c}\right) \quad (27a)$$

with

$$Q = -T_c \Delta_f S(T_c) \quad (27b)$$

Therefore, if a reversible fuel cell is operated with a cell temperature higher than the ambient temperature, the wasted heat to the surrounding by the temperature difference ( $T_c - T_0$ ) can be recovered by operating a Carnot heat engine and produces work  $W_C(T_c)$ . This means that, if a hybrid system is constructed as shown in Fig. 8, the work produced by this system is exactly the same as the maximum fuel cell work:

$$W_{hybrid} = W_{FC, total}(T_c) + W_C(T_c) = -\Delta G(T_0) = W_{FC, max} \quad (28)$$

If a reversible isothermal fuel cell of the hybrid system in Fig. 8 is replaced by an isentropic fuel cell, which is also reversible, operating with reactants supplied at  $T_0$ , producing the same work as denoted in Eq. (8a), the heat source to operate a Carnot heat engine is the products exhausted from the fuel cell at temperature  $T_{is}$  which is much higher than the ambient temperature  $T_0$ . In this case, the work produced by a Carnot heat

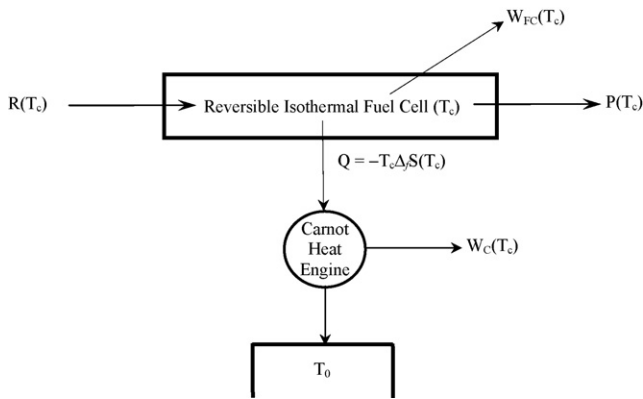


Fig. 8. Fuel cell–Carnot heat engine hybrid system.

engine can be obtained as follows:

$$W_C = (H_P(T_{is}) - T_0 S_P(T_{is})) - T_0 (H_P(T_0) - T_0 S_P(T_0)) \quad (29)$$

This also represents the exergy of the products of an isentropic fuel cell. Combining with Eq. (8a), the work produced by the hybrid system constructed by an isentropic fuel cell and Carnot heat engine can also be calculated as

$$W_{\text{hybrid}} = W_{\text{FC, is}} + W_C(T_{is}) = -\Delta G(T_0) = W_{\text{FC, max}} \quad (30)$$

If the exhaust temperature of a fuel cell is higher than the isentropic temperature, the work produced by the fuel cell will be reduced. However, the additional heat exhausted from the fuel cell due to higher exhaust temperature contributes to increase the high temperature heat for a Carnot heat engine and, as a result, the work produced by a hybrid system will be the same as in Eq. (30).

Therefore, the above description provides an important conclusion that the work produced by a hybrid system of a reversible fuel cell operating at a temperature higher than  $T_0$  and a Carnot heat engine operating with the exhaust heat of a fuel cell is the same as the maximum work produced by a reversible fuel cell at an ambient temperature regardless of the fuel cell types. This means that, in case of the high temperature reversible fuel cell, its performance can be recovered to that of the low temperature one by constructing the hybrid system with a Carnot heat engine.

## 6. Conclusions

Some important conclusions may be drawn from the results of thermodynamic considerations regarding some issues in the fuel cell performance, and are summarized as follows:

- (1) In real operating conditions of fuel cells, it is very difficult to maintain an isothermal condition which is required for the description of the fuel cell performance in general. To account for the performance of the fuel cell operating at the non-uniform cell temperature, a new formulation based on the concept of an isentropic fuel cell is proposed in this study.
- (2) The maximum produced work by a reversible fuel cell is the formation Gibbs energy at a reference (*e.g.*, ambient) temperature. With the same chemical reaction, the difference in performance between a reversible fuel cell and a Carnot heat engine is caused by the irreversibility in the combustion process in high temperature heat source of the Carnot heat engine.
- (3) Lower performance of high temperature fuel cells than low temperature ones can be overcome by constructing a fuel cell–heat engine hybrid system. In case of a hybrid system with a reversible fuel cell and a Carnot heat engine, the produced work is exactly the same as the work of a fuel cell operating at the ambient temperature. This is true in both reversible isothermal and isentropic fuel cells.

## References

- [1] J. Larminie, A. Dicks, *Fuel Cell Systems Explained*, Wiley, 2000.
- [2] G. Hoogers, *Fuel Cell Technology Handbook*, CRC Press, 2003.
- [3] X. Li, *Principles of Fuel Cells*, Taylor & Francis, 2006.
- [4] S.E. Wright, *Renew. Energy* 29 (2004) 179–195.
- [5] A.E. Lutz, R.S. Larson, J.O. Keller, *Int. J. Hydrogen Energy* 27 (2002) 1103–1111.
- [6] S.E. Veyo, L.A. Shockling, J.T. Dederer, J.E. Gillett, W.L. Lundberg, *Trans. ASME: J. Eng. Gas Turbines Power* 124 (2002) 845–849.
- [7] A.J. Appleby, in: L.J.M.J. Blomen, M.N. Mugerwa (Eds.), *Fuel Cell Systems*, 1993, pp. 157–199.
- [8] M.P. Boyce, *Gas Turbine Engineering Handbook*, Gulf Professional Publishing, 2002.