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Influence of stack arrangement on performance of multiple-stack solid oxide fuel cells with non-uniform potential operation

S. Assabumrungrat [a,*], N. Ruangrassamee [a], S. Vivanpatarakij [a], N. Laosiripojana [b], A. Arpornwichanop [c]

[a] Center of Excellence in Catalysis and Catalytic Reaction Engineering, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand
[b] The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand
[c] Control and Systems Engineering, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand

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ABSTRACT

The performance of multiple-stack solid oxide fuel cells (SOFCs) with different stack arrangements is compared with respect to the presence of an in-stack pressure drop. It was demonstrated in our previous work that when a multiple-stack SOFC is arranged in series and the operating voltages are allowed to vary among the different stacks, an improved performance over a conventional SOFC (stacks arranged in parallel and operated under the same operating voltage) can be realized. Nevertheless, the differences in pressure drop and the required power for compression among the different operations were not taken into account. In the study reported here, it is demonstrated that the pressure drop in the stack depends not only on the feed rate and operating voltage, but also on the stack arrangement. The pressure drop in the anode channels is about half that in the cathode channels. The configuration of stacks in series with compressors installed only at the inlets of the first stack is the best option as it shows the highest electrical power generation. The pressure drops in the anode and cathode channels are about 4.7 and 3.75 times those in the corresponding channels of the conventional case with the stacks arranged in parallel. In addition, when considering the net obtained electrical power, it appears that multiple-stack SOFCs with stacks arranged in series are not as attractive as the conventional SOFC because they require much higher compression power. Therefore, it is suggested that a new stack design with a low pressure drop is required for the concept of multiple-stack SOFC with non-uniform potential operation to become practical.

1. Introduction

Fuel cells are considered to be an attractive technology for energy conversion because of their better environmental friendliness, practically noise-free operation, and higher efficiency. Nevertheless, the use of fuel cell is still limited due to the high cost of cell stacks. Consequently, much effort has been made to improve the performance fuel cells and their systems. For example, stack cell components with better characteristics have been explored [1–3]. Some researchers have focused on integrating a fuel cell with other units such as a gas turbine (GT) [4]. Among the several procedures aimed at improving fuel cell performance, non-uniform potential operation (NUP) or multiple-stack operation, whose concept is based on arranging stacks in series and allowing operating voltages to be varied stack-by-stack, is an interesting approach. Under such operation, the cell is run close to its theoretical potential, and therefore results in lower overpotential losses and thus higher efficiency.

The concept of multiple-stack operation has been studied by some researchers. George and Lames [5] stated that the United States Department of Energy (DOE) proposed a multiple-stack fuel cell system with five serial stages of cells in order to reduce the regenerative heat for fuel and air, and to extend the operating temperature range. Moreover, Senn and Poulikakos [6] investigated the performance of polymer electrolyte membrane fuel cells (PEMFCs) that were divided into many stages of equal stage size. It was found that the non-uniform potential operation offers enhanced maximum electrical power densities compared with the traditional concept involving uniform potential operation. An improvement in maximum power density of 6.5% was reported. For a molten carbonate fuel cell (MCFC), it was reported that an improvement in electrical efficiency of about 1% could be achieved by splitting the cell area into two segments [7]. This conclusion was based on both analytical mathematical modelling and simplified flowsheet calculations. Multiple-stack operations of a MCFC with a different flow arrangement have been studied [8]. When both

* Corresponding author. Fax: +66 2 218 6877.
E-mail address: Suttichai.A@chula.ac.th (S. Assabumrungrat).

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Nomenclature

a	first ohmic resistance constant as shown in Eq. (12) (Ω m)
b	second ohmic resistant constant as shown in Eq. (12) (K)
C_p	specific heat capacity at constant pressure ($J\,mol^{-1}\,K^{-1}$)
C_V	specific heat capacity at constant volume ($J\,mol^{-1}\,K^{-1}$)
D	hydraulic diameter (m)
E_0	open-circuit voltage (V)
f	friction factor
F	Faraday constant (96485.34 $C\,mol^{-1}$)
g_c	proportionality factor ($kg\,m\,N^{-1}\,s^{-2}$)
i	current density ($A\,m^{-2}$)
L	cell length (m)
m	constant polarization parameters
$\dot{m}$	molar flow rate of gas ($mol\,s^{-1}$)
p	partial pressure (atm)
P	power (kW)
R	universal gas constant (8.31447×10^{-3}) ($kJ\,mol^{-1}\,K^{-1}$)
T	absolute temperature (K)
T_1	feed temperature to compressor (K)
T_2	isentropic temperature (K)
u	gas velocity ($m\,s^{-1}$)
U_f	fuel utilization (%)
V	operating voltage (V)

Greeks letters

η	overpotential ($\Omega\,m^2$)
η_c	isentropic efficiency
γ	ratio of specific heat capacities of a gas, C_p/C_V
δ	thickness (m)
ρ	specific ohmic resistance (Ω m)
φ	potential (V)

Subscripts

A	anode
Act	activation
C	cathode
Conc	concentration
Ohm	ohmic

the anode and cathode streams were passed in series along the stacks, the improvement in performance was about 0.6%. Additionally, when the anode stream flowed in series while the cathode streams were flowed in parallel, an improved performance up to 0.3% was achieved. Liebhafsky and Cairns [9] and Selimovic and Palsson [10] applied the concept of multiple-stack operation to a solid oxide fuel cell (SOFC). It was found that an improvement in power output of about 5% could be obtained from their systems. Our previous work [11] determined suitable operating voltages and the number of cell sections for an SOFC system. The cell was divided into equal sections in term of fuel utilization (U_f) and no pressure drop was assumed. It was reported that no significant improvement was obtained when the cell was divided into more than two sections and the increase in electrical efficiency was within 10%.

The concept of non-uniform potential operation is not practically implemented for single stack operation because the design of current-collectors becomes very complicated. It is generally carried out by arranging the multiple stacks in series and operating the voltages at different values among the stacks. Under this operation, as each stack is operated under a small value of fuel utilization, higher flow rates of fuel and air in each stack and thus a higher pressure drop and a higher power consumption for operating compressors are inevitable. Therefore, it is the aim of this work to determine whether the gained electrical power from such operation can compensate the attendant higher demands in energy. Two configurations of multiple-stack SOFCs arranged in series with non-uniform potential operation (one with compressors installed only at the inlets of the first stack and the other with compressors installed at the inlets of each stack) are considered. The performances in terms of pressure drop, power consumption at compressors, generated electrical power and net electrical power are calculated and compared with those of a conventional SOFC with multiple stacks arranged in parallel and operated at the same operating voltage.

2. Theory

2.1. Mathematical model

A planar-type SOFC with co-flow configuration is considered as it has been reported to offer a higher power density than a tubular-type SOFC [12]. The higher power density of the planar-type SOFC is due to the shorter current paths that result in low ohmic overpotential. Moreover, the planar-type SOFC is simple to fabricate and can be manufactured in various configurations [13]. A schematic diagram of the planar-type SOFC stack is given in Fig. 1. Typical information on the system has been given by Iwata et al. [14] and Pasaogullari and Wang [15]. The typical SOFC dimensions [16,17] adopted for this study are given in Fig. 2. In a single cell, the interconnects are in the form of ribs with twenty air channels for the air-side interconnect and 20 fuel channels for the fuel-side interconnect corresponding to the location of the rib roots, and the gas channel locations to the rib tips. The stack module is a column of 100 cells (30 cm × 30 cm × 60 cm) joined with interconnects. Thus, one standard stack in this work has a total cell area of 1.2 m^2. The multiple stacks are connected in different configurations, as will be described in the next section. It should be noted that as the cell channels of the planar-type SOFC usually have slimmer cross-sectional area than those of the tubular-type SOFC, the planar-type SOFC is likely to encounter greater influence of generated pressure drop in the cell channels. This effect is taken into account in this work. The pressure drop and required compression power can be calculated using the following equations (refer to list of

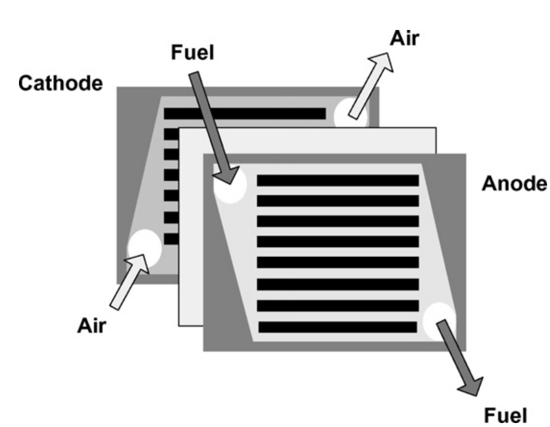

Fig. 1. Schematic diagram of planar-type SOFC stack.

nomenclature):

$$\Delta P = fp\frac{L}{D}\frac{u^2}{2g_c} \quad (1)$$

$$\text{Power} = \dot{m}C_p\frac{T_1}{\eta_c}\left(\left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} - 1\right) \quad (2)$$

$$\eta_c = \frac{T_1}{T_2 - T_1}\left(\left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} - 1\right) \quad (3)$$

$$\frac{T_2'}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} \quad (4)$$

The SOFC can be operated with a non-hydrogen fuel such as methane, which is the fuel used in this work. A reformer is generally required to process the fuel with a reforming agent (e.g., steam) to a hydrogen-rich stream before feeding to the SOFC stack. Methane steam reforming is followed by the water–gas shift reaction. It is assumed that the equilibrium reactions take place at 973 K, to yield an outlet gas composition of 1.50% CH_4, 12.77% CO, 5.93% CO_2, 62.01% H_2 and 17.79% H_2O. In the SOFC stack, it is assumed that only hydrogen reacts electrochemically with oxygen. The equilibrium water–gas shift reaction takes place along the stack channel to convert CO to hydrogen in the anode stream.

2.2. Electrochemical model

The electrochemical reactions of hydrogen and oxygen taking place in the cell are as follows:

$$\text{anode}: H_2 + O^{2-} = H_2O + 2e^- \quad (5)$$

$$\text{cathode}: O_2 + 4e^- = 2O^{2-} \quad (6)$$

The cell is divided into small cell elements in calculations of the electrochemical performance. The actual SOFC voltage is always lower than its open-circuit value because of the presence of various irreversible losses, i.e., activation overpotential (η_{Act}), ohmic overpotential (η_{Ohm}) and concentration overpotential (η_{Conc}). The activation overpotential Eqs. (7)–(10) can be determined from the Butler–Volmer equation [18]. The ohmic overpotential (Eqs. (11) and (12)) is calculated from the resistivity and an equivalent area corresponding to the thickness of the electrodes or electrolyte. The resistivity for the SOFC materials (Table 1) is based on the values reported by Bessette et al. [19].

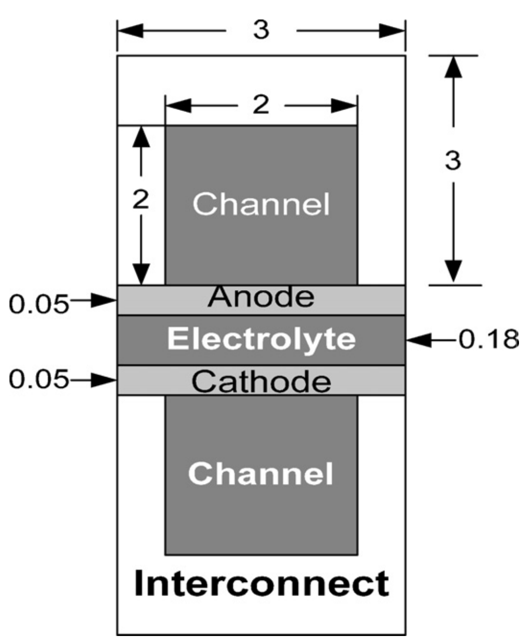

Fig. 2. Dimensions of fuel/air channels in SOFC stack (units in mm).

Table 1
Summary of cell components and their resistivities.

Materials (anode/electrolyte/cathode)	Ni–YSZ/YSZ/LSM–YSZ
Anode ohmic resistance constant	a = 0.0000298, b = −1392
Cathode ohmic resistance constant	a = 0.0000811, b = 600
Electrolyte ohmic resistance constant	a = 0.0000294, b = 10350
Interconnect ohmic resistance constant	a = 0.0001256, b = 4690

Activation overpotential:

$$i = i_0\left[\exp\left(\frac{\alpha n_e F\eta_{Act}}{RT}\right) - \exp\left(-\frac{(1-\alpha)n_e F\eta_{Act}}{RT}\right)\right] \quad (7)$$

$$\eta_{Act} = \frac{2RT}{n_e F}\sinh^{-1}\left(\frac{i}{i_0}\right); \quad \text{where } \alpha = 0.5 \quad (8)$$

$$i_{0,A} = 5.5 \times 10^8\left(\frac{p_{H_2}}{p}\right)\left(\frac{p_{H_2O}}{p}\right)\exp\left(\frac{-100 \times 10^3}{RT}\right) \quad (9)$$

$$i_{0,C} = 7.0 \times 10^8\left(\frac{p_{O_2}}{p}\right)^m\exp\left(\frac{-120 \times 10^3}{RT}\right) \quad (10)$$

Ohmic overpotential:

$$\eta_{Ohm} = \sum \rho_j\delta_j \quad (11)$$

$$\rho_j = a_j\exp(b_jT) \quad (12)$$

It is assumed that the SOFC stacks are operated under steady-state and isothermal conditions. In this case, the operating temperature is maintained at 1173 K. To simplify calculations of the SOFC performance, the concentration overpotential due to the mass transport effect is neglected. Such overpotential becomes important at low concentration of the reactant gases and high values of current density. Therefore, the calculations in this study are performed only within moderate ranges of current density (<8000 A m^{-2}).

2.3. System configurations

The following three configurations of multiple-stack SOFC are considered:

(1) *Configuration A*: Multiple-stack SOFC with stacks arranged in parallel. There is only one set of compressors installed at the feed inlets (Fig. 3a). The outlet pressure of each stack is at atmospheric pressure. This configuration is a conventional SOFC system.
(2) *Configuration B*: Multiple-stack SOFC with stacks arranged in series with only one set of compressors installed at the inlets of the first stack (Fig. 3b). The outlet pressure of the last stack is at atmospheric pressure.
(3) *Configuration C*: Multiple-stack SOFC with stacks arranged in series with compressors installed at the inlets of each stack. The outlet pressure of each stack is at atmospheric pressure (Fig. 3c).

In this study, only two stacks are considered according to the previous report [11] indicating that the performance improvement of the multiple stacks arranged in series with non-uniform potential operation becomes less significant when the number of stacks is more than two.

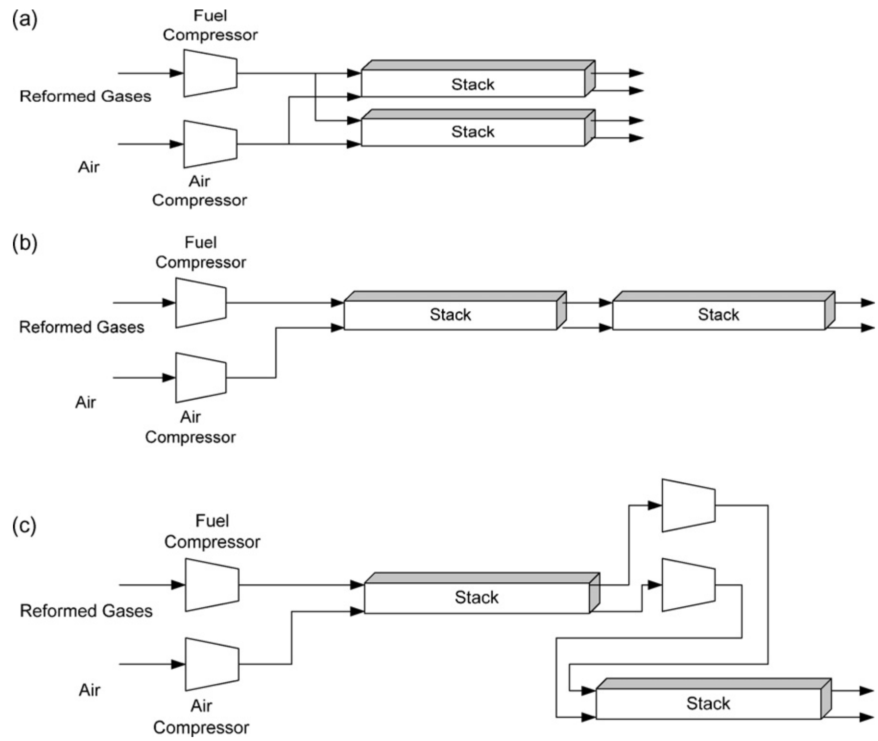

Fig. 3. Different configurations of multiple-stack SOFC: (a) parallel stacks with one set of compressors inlets of SOFC stack; (b) stacks in series with compressors at inlets of first SOFC stack; (c) stack in series with compressors at inlets of each stack.

3. Results and discussion

3.1. Model validation

The developed model was validated with results from the previous literature [20]. Fig. 4 shows the characteristic *I–P* and *I–V* curves for the system fed by pure hydrogen as the fuel and air as the oxidant. The cell was operated at 1173 K and a fuel utilization (U_f) of 80%. The continuous lines show the simulation results from this study while symbols show those from the previous work. Based on the same operating condition, the comparison shows good agreement between those data with small deviation within 4.6%, indicating that our model is capable of predicting the performance of a planar SOFC. It should be noted that the discrepancy may be arisen from our assumption that neglects the effect of concentration overpotential due to the mass transport effect, unlike the reference work. It was reported that concentration overpotential becomes an important loss when the system is operated at low concentrations of the reactant gases and high values of current density [21]. Therefore, to ensure the reliability of our model, the simulations in this study are performed within the range of moderate current density (<8000 A m^{-2}).

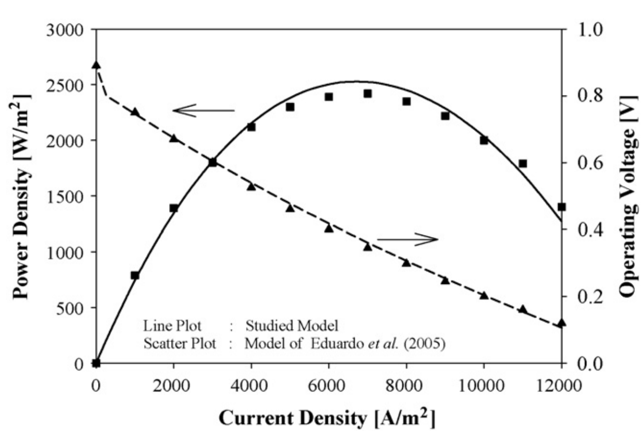

Fig. 4. Characteristic curves of SOFC (anode feed = pure H_2, cathode feed = air, U_f = 80% and T = 1173 K).

3.2. Generated pressure drop in single-stack SOFC

In practical operation, as the stack is divided into many small cell channels, particularly for a planar-type stack, compressors are required to feed the fuel and air into the anode and cathode channels, respectively. Fig. 5 shows the pressure drop at the anode and cathode channels at different methane feed rates and operating voltages. In all calculations, the pressures at the channel exits are always maintained at atmospheric pressure. It is obvious that both methane feed rate and operating voltage influence the pressure drop. In addition, the anode pressure drop is much lower than the cathode pressure drop, i.e., by about a half. The observed results agree well with numerical simulation results of Koh et al. [22] who calculated the generated pressure drop in both anode and cathode channels by varying the channel depth [19]. It was found that the anode pressure drop is approximately 45–60% of the cathode pressure drop. In this work, it was found that the maximum calculated pressure drops in the anode and cathode channels are not higher than 4% and 6% of inlet pressure, respectively. Moreover, it is clear that when the methane feed rate increases, a higher pressure drop is observed. In addition, the pressure drop also varies with operating voltage. When the stack is run at a higher operating voltage and the methane feed rate is kept constant, less oxygen is transferred to the anode according to the characteristic *I–V* curve (Fig. 4) and thus the pressure drop in the cathode increases. The pressure drop in the anode channel also varies due to the difference in the anode gas compositions (especially H_2 and H_2O) that arises from the change of operating voltage. It should be noted that the operat-

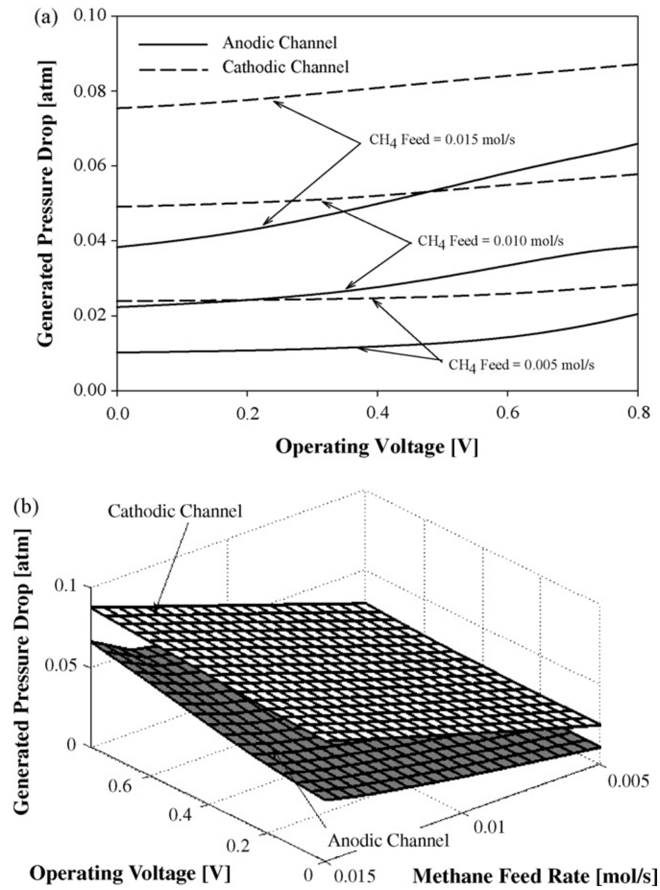

Fig. 5. Effects of operating voltage and methane feed rate on pressure drop in anode and cathode channels of single-stack SOFC.

ing voltage is closely related to the current density according to the *I–V* characteristic curve, whereas the methane feed rate is closely related to fuel utilization (U_f) (Fig. 5).

In SOFC operation, part of the electrical power obtained from the SOFC is consumed by the compressors that elevate the pressures of both fuel and air to the desired values. The effects of operating voltage and methane feed rate on the power generated from the SOFC and the power consumption by the compressors in a single-stack SOFC are shown in Fig. 6. Considering the solid lines, it is found that the generated power follows the form of an upturned curve. By contrast, the percentage of power consumption at the compressor shows an inverse tendency to the generated power, that is, percentage of power consumption increases rapidly at the lowest and highest operating voltages. This obviously shows that the presence of a pressure drop influences the performance of SOFC, depending on the levels of the operating voltage and methane feed rate. In particular, the fraction of energy required for the compressor depends significantly on these two parameters. At maximum generated power, the compression power is within the range of 10% of the generated power. This shows that the power consumption by the compressor is not pronounced as long as the power obtained from the SOFC is high. It should be noted that when the multiple-stack SOFC is arranged in series, the flow rates in each stack become much higher and thus the pressure drop and power consumption for operating the compressors should become more significant.

3.3. Performance of multiple-stack SOFCs with different stack arrangements

The performance of three configurations of multiple-stack SOFCs have been compared with respect to the effect of the generated pressure drop. The influence of operating voltage in the first stack on the generated electrical power is demonstrated in Fig. 7. Three values of the operating voltage of the second stack (0.55, 0.65 and 0.75 V) are considered. The solid line represents the results for the conventional SOFC whose stacks are arranged in parallel and operated at the same operating voltage. It is clear that there are some ranges of operating voltages in which the arrangement in series offers higher generated electrical power than that in parallel. For the series arrangement with two different configurations of stacks and compressors, however, the configuration with one set of compressors installed at the inlets of the first stack always offers slightly higher power than that with compressors at the inlets of each SOFC stack. For the former system, it is necessary to compress the fuel and air at higher inlet pressures at the first stack in order to guarantee that the outlet pressure at the last stack is at atmospheric pressure. Due to this pressurized condition, the electrochemical performance becomes better. Thus the configuration in series with one set of compressors installed at the inlets of the first stack is a preferable choice in terms of generated power (Fig. 7). Nevertheless, due to high inlet pressure, it is essential to consider the additional power consumption by the compressors so as to calculate the net electrical power generation, which is an important

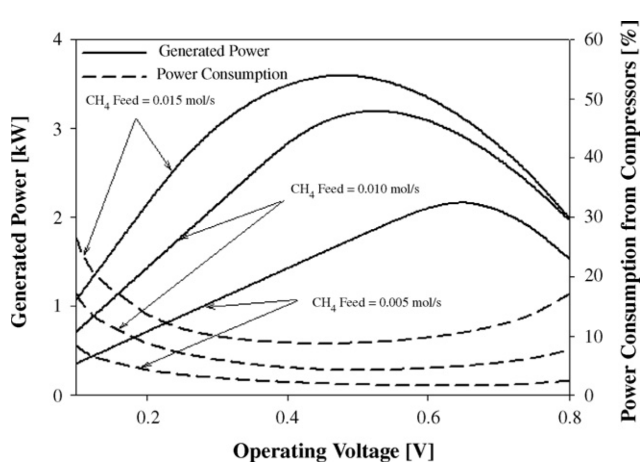

Fig. 6. Effects of operating voltage and methane feed rate on electrical power generation and power requirement for compressors in single-stack SOFC.

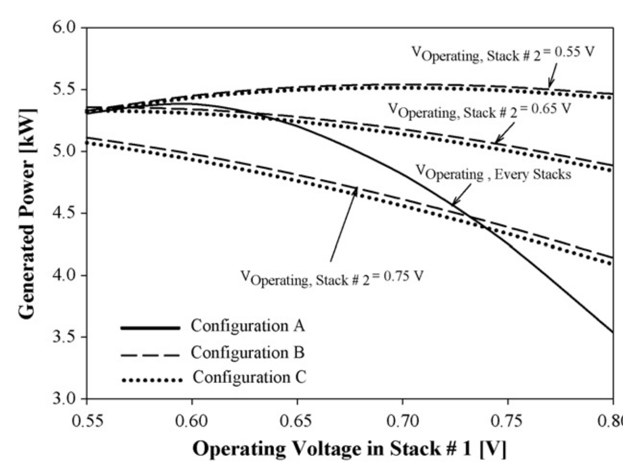

Fig. 7. Effects of operating voltages and configuration of multiple-stack SOFC on electrical power generation.

indicator of the practical feasibility of the use of the best configuration of multiple-stack SOFC.

Among the three configurations, it is important to understand that the flow rates of the fuel and air streams through stacks networked in series are much larger than those through stacks connected in parallel even though the same initial feed streams are used. For the SOFC configuration in parallel, the initial feed streams are divided into many streams corresponding to the number of stacks arranged in parallel. For stacks arranged in series, however, the initial feed streams are not divided but fed directly into the first stack and others in the series of many stacks. From the results discussed in Section 3.2, it is obvious that an increased flow rate creates larger pressure drops. Thus, it is certain that both configurations in series should encounter larger generated pressure drop than the configuration in parallel. As shown in Fig. 8, pressure drops in series configurations are higher by about 4.7 and 3.75 times in the anode and cathode channels, respectively, compared with the parallel configuration. The pressure drop also depends on the operating voltage as mentioned earlier in Section 3.2. Considering the power consumption by the compressors, Fig. 9 shows that multiple stacks arranged in series with one set of compressors installed at the inlets of the first stack consume less power for operating the compressors than the arrangement in which the staged compressors are installed at the inlets of each SOFC stack. Compared with the conventional SOFC with stacks arranged in parallel, it is clear that the power consumption by series multiple-stack SOFCs are about 5–6 times higher.

As reduced from the above results there are some contrasts between the results for generated power from a SOFC and power consumption of the compressors. To propose the best configuration among the different stack arrangements, it is necessary to examine the net obtained electrical power. The data given in Fig. 10, indicate that the maximum net electrical power from the series multiple-stack SOFC is still less than that of the conventional parallel multiple-stack SOFC although the generated electrical power could be higher, as shown in Fig. 7. This is due to the presence of a higher pressure drop when the stacks are arranged in series. Thus, for the conventional planar-type stack, the use of non-uniform potential operation is not attractive in items of practical operation. It is necessary to develop a new stack design with a low pressure drop in order to make the concept of a multiple-stack SOFC with non-uniform potential operation become practical. A tubular-type stack could be a possible choice; but, various aspects such as cell performance and stack power density need to be taken into account. It should again noted that the electrical performance and stack pressure drop are also dependent on operating temperature. In general, increasing the operating temperature improves the electrical performance; but choices of materials and seal problem then become critical issues. A higher operating temperature also increases the pressure drop in the stack. This selection of cell components could also influence the performance of multiple-stack SOFCs. A number of efforts have addressed the search for better cell components, that would allow stack size, and consequently stack pressure drop, to become smaller. The influence works on the effects of cell components and operating temperature should be further investigated.

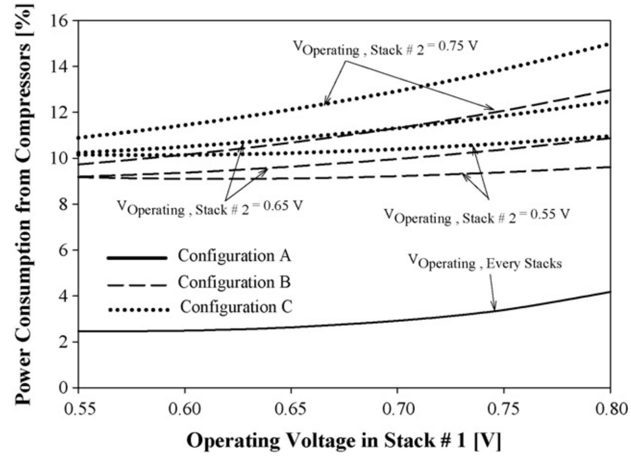

Fig. 9. Effects of operating voltages and configuration of multiple-stack SOFC on power requirement for compressors.

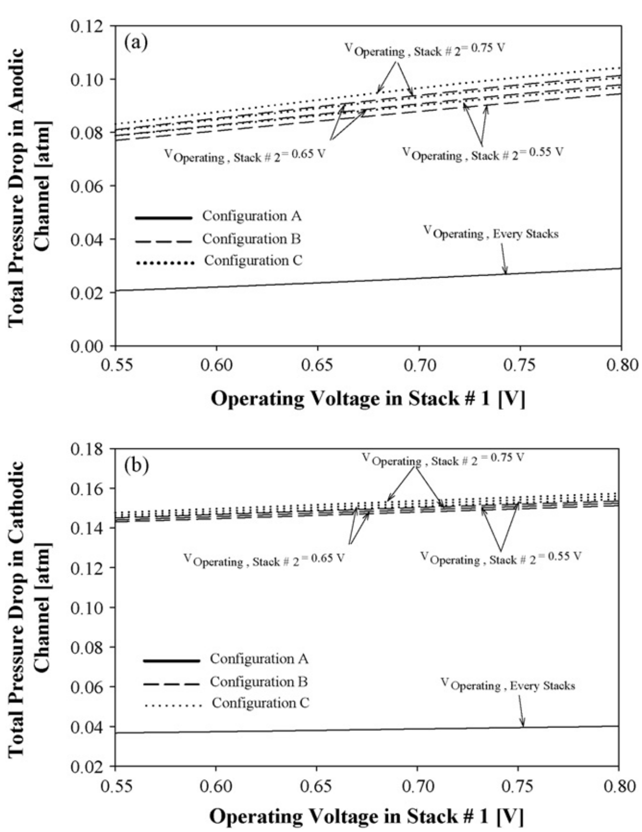

Fig. 8. Effects of operating voltages and configuration of multiple-stack SOFC on total pressure drop in anode and cathode channels.

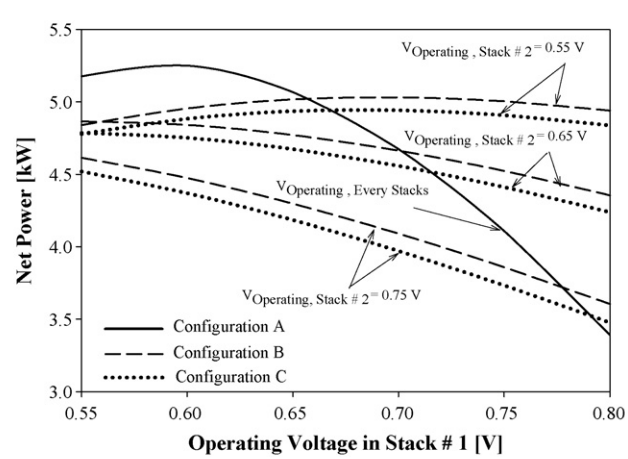

Fig. 10. Effects of operating voltages and configuration of multiple-stack SOFC on net electrical power generation.

4. Conclusions

The performance of multiple-stack SOFCs with different stack arrangements has been evaluated. Both configurations of series multiple-stack SOFCs can offer higher generated electrical power than conventional parallel multi-stack counterparts when operating voltages of the stacks are carefully selected. Nevertheless, due to the higher in-stack pressure drop, and thus higher power consumption on compressors, it appears that the conventional SOFC is the best configuration in terms of net power generation. It is therefore suggested that a new stack design with a low pressure drop is required for a multiple-stack SOFC with non-uniform potential operation to prove practical.

Acknowledgement

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