Effects of Key Operating Parameters on the Efficiency of Two Types of PEM Fuel Cell Systems (High-Pressure and Low-Pressure Operating) for Automotive Applications

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The proton exchange membrane (PEM) fuel cell system consisting of stack and balance of plant (BOP) was modeled in a MATLAB/Simulink environment. High-pressure operating (compressor type) and low-pressure operating (air blower type) fuel cell systems were considered. The effects of two main operating parameters (humidity and the pressure of the supplied gas) on the power distribution characteristics of BOP and the net system efficiency of the two systems mentioned above were compared and discussed. The simulation determines an optimum condition regarding parameters such as the cathode air pressure and the relative humidity for maximum net system efficiency for the operating fuel cell systems. This study contributes to get a basic insight into the fuel cell stack and BOP component sizing. Further research using multi-object variable optimization packages and the approach developed by this study can effectively contribute to an operating strategy for the practical use of fuel cell systems for vehicles.

Key Words: PEM Fuel Cell, Fuel Cell System, BOP, High-Pressure Operating, Low-Pressure Operating, Net System Efficiency, Component Sizing

Nomenclature

A : Surface area of the stack (cm^2)
a : Modeling constant
C_p : Specific heat (J/kgK)
c_1 : Modeling constant
c_2 : Modeling constant
c_3 : Modeling constant
E : Open circuit voltage (V)
h : Heat transfer coefficient (W/cm^2 K)
i : Current density (A/cm^2)
i_{max} : Current density that cause precipitous voltage drop (A/cm^2)
i_0 : Exchange current density (A/cm^2)
LHV_{H_2} : Lower heating value of hydrogen (J/kg)
$\dot{m}_{cw}$: Mass flow rate of stack coolant (kg/s)
$\dot{m}_{H_2}$: Mass flow rate of hydrogen gas (kg/s)
P_{BOP} : Parasitic load of BOP (W)
P_{net} : Net system power (W)
P_{stack} : Stack gross electric power (W)
R_{ohm} : Internal electrical resistance (Ω cm^2)
$T_{cw,m}$: Mean temperature of coolant (℃)
$T_{s,m}$: Mean temperature of stack (℃)
V_{act} : Activation overpotential (V)
V_{conc} : Concentration overpotential (V)
V_{fc} : Fuel cell voltage (V)
V_{ohm} : Ohmic overpotential (V)
v_a : Constant (V)
v_0 : Voltage drop at zero current density (V)
W_s : Stack power (W)
ΔT_{cw} : Coolant temperature difference between stack inlet and stack outlet (℃)

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η_{net} : Net system efficiency

1. Introduction

With the increasing concern for the environment, automakers worldwide in recent years, have been engaged in different research and development activities aiming at reducing exhaust emissions. However, current internal combustion engine can hardly meet the more stringent emission standards and CO_2 regulations. Consequently, nowadays, many car manufactures are engaged in active researches on fuel cell powered vehicles basically to reduce CO_2 emission and to improve power-train efficiency. Fuel cell is an electro-chemical device that can directly convert the chemical energy of a reactant into electrical energy (Pukrushpan et al., 2003 ; Jung and Koo, 2003). It is recognized as a promising future energy source because it is environmentally friendly, and it can achieve efficiency higher than the conventional combustion cycle. Among various types of fuel cells, proton exchange membrane (PEM) fuel cell is considered to be practical for the automotive applications because of its high efficiency, low-operating temperature, high power density, quick response to load change, low emissions, low noise operation, and modular design. Previous researches on PEM fuel cell have been mainly focused on the development of high performance membrane electrode assembly (MEA) by electro-chemical approaches (Larminie and Dicks, 2000 ; Cunningham et al., 2001).

However, for the PEM fuel cell to be commercialized as automotive power source it is necessary to conduct a system based analysis and research that will optimize its elements such as the auxiliary components (blower, compressor, humidifier, and pump etc.) as well as the fuel cell stacks. The auxiliary components to drive the fuel cell stack are generally called as balance of plant (BOP). Main components of BOP include gas supplying system (such as compressor and blower), water management system (humidifier and pump), and heat management system (stack cooler, condenser, and heat exchanger). The goal of research on BOP components in fuel cell system is to enhance the performance and efficiency of fuel cell system by optimizing the fuel cell stack power with changing power demands (Friedman et al., 2001 ; Nelson et al., 2000 ; Ronald, 2003).

Recently, of particular concern in research on fuel cell for automotive applications is whether the air to the stacks should be applied at a compressed state or at a low pressure (nearly ambient) state. The device structure is relatively compact and easy to control in the case of low-pressure operating systems. However, with that system it is difficult to control the relative humidity of the supplied gas. On the other hand, the high-pressure operating system makes easy the control of the humidity but increases the system weight. Furthermore, it renders the control of the system difficult due to the complicated nature of its configuration.

This paper consists of three main parts : The first part presents the modeling of the BOP components for both low and high pressure operating fuel cell systems, then, follows a comparison of the net system efficiency of the two operating systems working with the same number of stacked unit cells. The final section of the paper discusses the characteristics of the two types of fuel cell systems having the same net system power level.

2. Fuel Cell System Model

In this study, the fuel cell stack and the BOP system components for the low-pressure and high-pressure operating systems were described. The main criteria dividing a fuel cell system (low vs. high-pressure operating system) is operating system pressure. In this study, low-pressure operating system is driven by blower and the operating system pressure is less than 1.5 bar. On the other hand, high-pressure operating system is usually driven by compressor and its operating pressure is over 1.5 bar.

The models were implemented in MATLAB/Simulink environment.

The main modeling assumptions employed for this study were presented in this section.

2.1 Assumptions

A fuel cell system was assumed to operate in steady state. The complex nature of the detailed transport processes related to chemical species, water, and heat inside the PEM fuel cell was neglected :

(1) The thermal properties of working fluid are constant. (The temperature change in fuel cell is relative small.)

(2) Gas streams in the flow channel are humidified, fully developed flow and show ideal gas behavior.

(3) The efficiency of motor used to drive the air blower was assumed to be 85% and constant.

(4) The efficiency of cooling water pump is set equal to 70%. (For the maximum stack power condition (over 75 kW), it was found that the required power for the cooling water pump was relatively small compared to the maximum stack power.)

(5) The relative humidity (ϕ_{self}) of the supplied gas after the self humidifying system is assumed. (This is for the investigating the effect of membrane type humidifier on the performance of fuel cell system in this study.)

(6) The heat generated by the cooling circuit was assumed to be totally absorbed by the cooling water.

2.2 Low-pressure operating fuel cell system model

In this section, the fuel cell stack and the BOP system components of the low-pressure operating

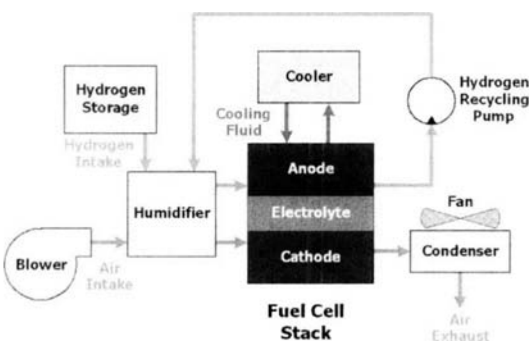

Fig. 1 Schematic diagram of the low-pressure operating fuel cell system

system were modeled as described in Fig. 1.

2.2.1 Stack modeling

The stack used in this study, was constructed by piling up unit cells. The modeling of the unit cell was based on the fuel cell model developed by Pukrushpan (Pukrushpan et al., 2003).

In the Pukrushpan's fuel cell model, the voltage of fuel cell can be obtained by subtracting the fuel cell losses from the open circuit voltage E. The fuel cell losses include activation overvoltage (V_{act}), ohmic overvoltage (V_{ohm}), and concentration overvoltage (V_{conc}). Each is defined as follows (Pukrushpan et al., 2003);

$$V_{fc}=E-V_{act}-V_{ohm}-V_{conc} \tag{1}$$

$$V_{act}=a\ln\left(\frac{i}{i_0}\right)v_0+v_a(1-e^{-c_1 i}) \tag{2}$$

$$V_{ohm}=iR_{ohm} \tag{3}$$

$$V_{conc}=i\left(c_2\frac{i}{i_{\max}}\right)^{c_3} \tag{4}$$

The coefficients in the equations (2) and (4) are functions of temperature, pressure, and partial pressure of oxygen. In the stack model, the current, voltage, and power of the fuel cell stack were calculated using specified stack temperature, the pressure and humidity of supplied gas as input conditions.

The active area of the unit cell used for the construction of the stack was 400 cm^2 (20×20 cm^2). The unit cells were stacked to achieve the required net system peak power of 80 kW.

Air was provided to the cathode side with a stoichiometry of 2.0. Hydrogen gas was supplied to the anode side with a stoichiometry of 1.2.

2.2.2 Modeling of air blower

For low-pressure operating system, air blower is used to supply air to the fuel cell stack with nearly ambient state. Since the centrifugal-type air blower is commonly used for PEM fuel cell system, the centrifugal-type air blower was chosen to supply air to the cathode side in order to simulate the low-pressure operating fuel cell system. The pressure of the supplied air and the efficiency of the blower were obtained from the lookup table of performance map using MATLAB/Simulink environment.

2.2.3 Humidifier modeling

Since the conductivity of the polymer depends on the relative humidity of the gas, the performance of the PEM fuel cell is strongly related to the relative humidity of the supplied gas that the stack is in contact with (Ronald, 2003). Therefore, proton exchange membrane must be fully hydrated to main a good ionic conductivity and performance with proper water management. Various types of humidifiers are being applied for humidifying inlet gas stream. Among those, the self humidifying system and injection type humidifying system are adopted because of their common use for PEM fuel cell system.

As shown in Fig. 2, the supplied gas was humidified using the air stream on the cathode side. The air was provided with high humidity and temperature using a membrane type humidifying system. The relative humidity of the gas was controlled through the injection type humidifying system represented in Fig. 3. The system controls the humidity of the supplied gas by evaporating the water by the injector into the air stream using a heater and a humidifier combined into one component (Nelson et al., 2000).

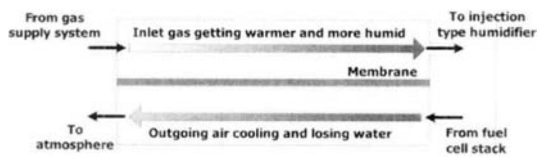

Fig. 2 Membrane type humidifying system for PEM fuel cell

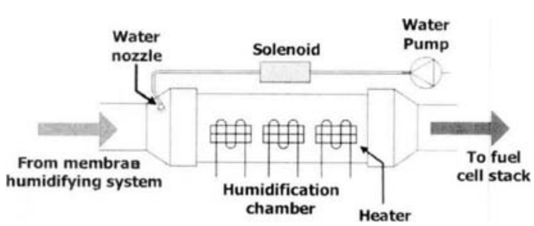

Fig. 3 Injection type humidifying system for PEM fuel cell

Hereafter, the relative humidity of the supplied gas after the self humidifying system shown in Figure 2, and at the entrance of stack will be denoted as ϕ_{self}, and ϕ_i respectively.

The power required for the humidifier was obtained based upon the phase-change energy required for evaporating the necessary water vapor to control the relative humidity of supplied gas.

2.2.4 Modeling of coolant module

The stack was cooled with some cooling water. A cooling plate was installed for every three cells in a repetitive sequence, and served to cool them down. The flow rate of the cooling water and the pressure loss across the cooling plate were calculated to determine the stack temperature and the power of the water pump.

For considering the energy balance of stack coolant module, the equation 5 was used.

$$W_s\left(\frac{E}{V_{fc}}\right)=\dot{m}_{cw}C_p\Delta T_{cw}=hA(T_{s,m}-T_{cw,m}) \quad (5)$$

Using above equation, the coolant temperature at the outlet of stack can be calculated.

2.3 High-pressure operating fuel cell system model

The BOP system components for the high-pressure operating system were modeled as shown in Fig. 4. The models for the stack, cooling and

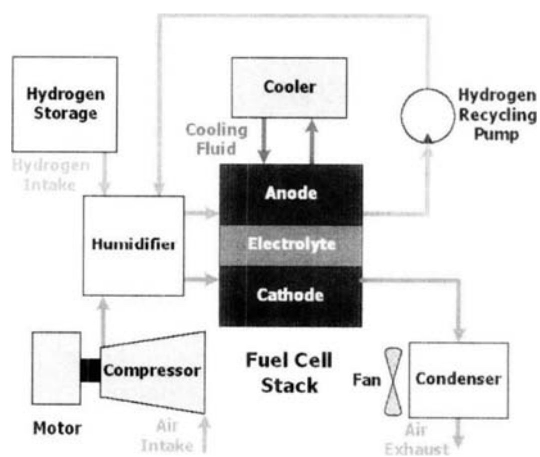

Fig. 4 Schematic diagram of the high-pressure operating fuel cell system

humidifier modules were the same as those used for the low-pressure operating system. However, instead of an air blower, a compressor was adopted to provide air to the cathode side.

2.3.1 Compressor model

Since the screw type compressor is commonly used for PEM fuel cell systems because of merits in performance and noise characteristics, the compressor component was modeled according to a screw type compressor. Its efficiency was obtained through a performance map which can use linear interpolations and extrapolations to get the desired values (Larminie and Dicks, 2000).

3. Simulation Results

3.1 Simulation conditions

In this study, comparison and discussion between a low-pressure operating system and a high-pressure operating system based on two aspects of their working conditions were made. Initially, two types of operating systems with the same number of stacked unit cells were investigated. Then, the characteristics of two operating systems working at the same net system power level were presented. The conditions of the stacks for the two types of operating systems are summarized in Table 1.

The net system power is simply defined as the stack gross electric power (P_{stack}) minus the parasitic load of BOP (P_{BOP}). This relationship is represented in equation 6 (Friedman et al., 2001).

$$P_{net}=P_{stack}-P_{BOP} \tag{6}$$

Table 1 Simulated stack conditions

Same Stack Size Condition		
	Compressor	Blower
Max. Net Power	115 kW	80 kW
# of Cells	650	650
Area of the Cell	400 cm^2	400 cm^2
Same Max. Net Power Condition		
Max. Net Power	80 kW	80 kW
# of Cells	450	650
Area of the Cell	400 cm^2	400 cm^2

Table 2 System input conditions

Stack Temperature	65℃
ϕ_{self}	50%
ϕ_i	70%

The performance of the stack highly depends on its temperature and pressure as well as the relative humidity of the supplied gas. Therefore, the stack conditions were evaluated based on the inlet parameters in Table 2.

The input conditions illustrated in Table 2 were selected for two reasons. The first one is that for vehicle applications, the stable fuel cell operating temperature is around 65℃. The other is that when the relative humidity of the supplied air stream approaches 70%, then the relative humidity of air stream exiting the stack can reach 100% by liquid water produced in the cathode side. If the cathode inlet air is supplied with fully humidified, the liquid water flooding can occur at the outlet of cathode channel.

3.2 Unit cell performance with cell temperature and inlet air pressure

As mentioned in a previous section, generally the performance of a fuel cell is strongly dependent on its temperature and the pressure of the supplied gas. As shown in Figes. 5 and 6, the performance of fuel cell increases as its temperature and the supplied air pressure increase. In order to take advantage of the high cathode air

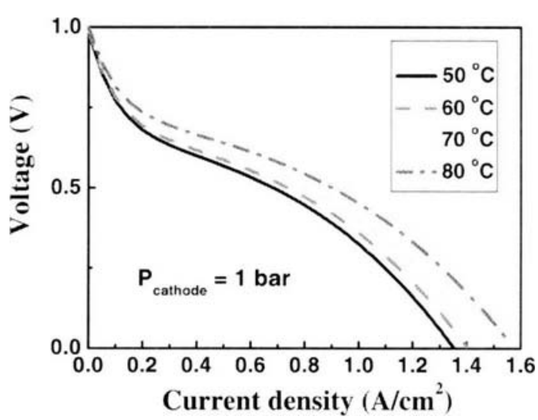

Fig. 5 Polarization curves for different fuel cell temperatures

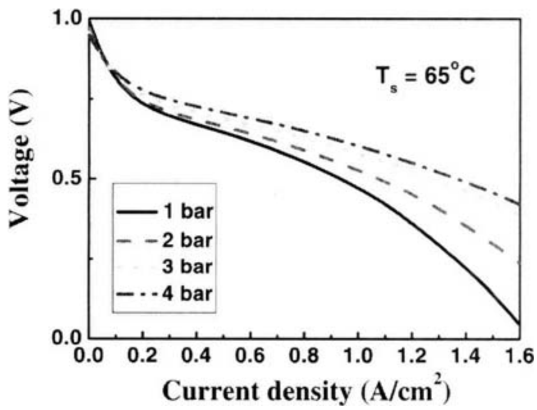

Fig. 6 Polarization curves with different cathode inlet air pressures

pressure, the compressor type of fuel cell system, which operates at high-pressure is usually a good alternative for fuel cell powered vehicles.

3.3 Simulation results under the same stack size condition

When the stack with the same number (650) of unit cells was used for low-pressure and high-pressure operating systems respectively, it was found that the net system peak power for the high-pressure operating system increases from 80 kW to 115 kW by 35 kW as shown in Table 3.

Figure 7 shows the net system peak power and net system efficiency with varying cathode air pressure for the high-pressure operating system. In that figure, with the increase of cathode air pressure, the net system peak power gradually increases to reach the maximum of 115 kW at 3 bar. When the cathode air pressure exceeds the 3 bar, the net system peak power decreases drastically. This was due to the fact that the efficiency of the compressor drops suddenly when the cathode air pressure was over 3 bar and hence the ratio of the compressor power to system net power increases abruptly. The fluctuation of the net system efficiency with the cathode air pressure was due to changes in the efficiency of the compressor as well as the system operating conditions. The net system efficiency of the fuel cell system is defined in equation 7 (Cunningham et al., 2001).

Table 3 Comparison of system net efficiency and power distribution at maximum net power (# of cells : 650)

	Blower	Compressor
Max. Net Power (kW)	80(78.9%)	115(75.6%)
Stack Power (kW)	101.4	152.1
Cooling Pump Power (kW)	0.8(0.8%)	2.0(1.34%)
Compressor (Blower) Power(kW)	4.5(4.4%)	34.7(22.8%)
Humidifier Power (kW)	16.1(15.9%)	5.5(3.6%)
Efficiency(%)	32.5	30.8

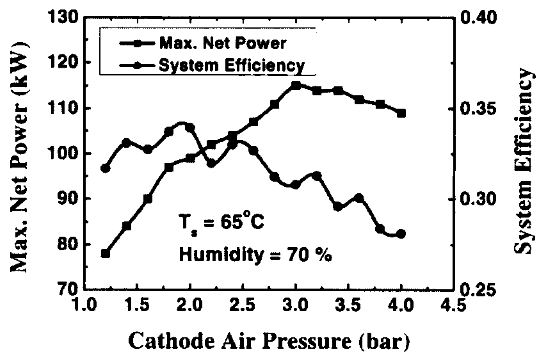

Fig. 7 Effect of the cathode pressure on the maximum net system power and the net system efficiency

$$\eta_{net} = \frac{P_{net}}{\dot{m}_{H_2} \cdot LHV_{H_2}} \quad (7)$$

The required parasitic load of the BOP under the net system peak power condition is listed in Table 3. The value in parenthesis represents the percentage over the stack power for each BOP component. For the low-pressure operating system, the power of the humidifier was 16.1 kW, which was the largest portion (15.9%) among all BOP components. Therefore, it is thought that the control of humidity is a key element in improving the net system efficiency of the low-pressure operating system.

As for the high-pressure operating system, the required power for the compressor was 34.7 kW, which was the largest portion (22.8%) of all BOP components. Hence, improving the performance of the compressor is a main factor for improving the efficiency of the high-pressure operating system. For that operating system, the required power for the humidifier was 5.5 kW, a relatively small portion (3.6 %) compared with that of the low-pressure operating system. It can be explained by the fact that the heat resulting from the increased temperature with the compressed air effectively evaporates the injected liquid water.

3.4 Simulation results under the same maximum net power condition

As shown in Table 1, for the high-pressure operating system, the maximum net system power (80 kW) applied to the low-pressure operating system can be achieved with smaller number of cells. This was because the stack power could be improved by increasing the cathode air pressure.

The efficiencies and performances of the two operating systems were compared through simulation by varying the pressure and the humidity of supplied gas. The details of the stack temperature, ϕ_{self}, and ϕ_i are summarized in Table 4.

Figure 8 represents the variation of the net system efficiency as a function of cathode inlet air pressure for four different net system power values. An optimum cathode inlet air pressure for the maximum net system efficiency was obtained for each net system power.

Table 4 Stack temperature and relative humidities

Stack Temperature	ϕ_i	ϕ_{self}
65℃	70%	40%
		50%
		60%

For three values of the relative humidity, the optimum cathode air pressures with the maximum net system power were calculated using the same simulation procedure and were presented in Figure 9. This confirms that the optimum cathode air pressure tends to increase as ϕ_{self} decreases. As ϕ_{self} decreases, the amount of water needed to be evaporated increases. Hence, the required power for humidifier increases. The gain resulting from increasing cathode air pressure also increases. An explanation for this may be that as the cathode air pressure increases, the increased temperature at the outlet of the compressor facilitates the evaporation of the injected water without the need of additional heating power.

Using the cathode air pressure obtained in Fig. 9, the efficiencies of the two operating systems for the case of $\phi_{self}=40\%$ were compared and illustrated in Fig. 10. As presented in that figure, the net system efficiency for the high-pressure operating system was higher than that of the low-pressure operating system by 2~10%. This can be explained by the fact that the amount of water vapor supplied by injection type humidifier increases much and the required power for humidifier gets much larger for low-pressure operating system.

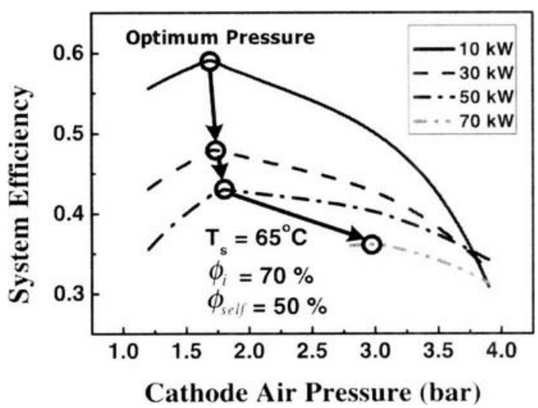

Fig. 8 Net system efficiency as a function of the cathode air pressure at different net system power conditions

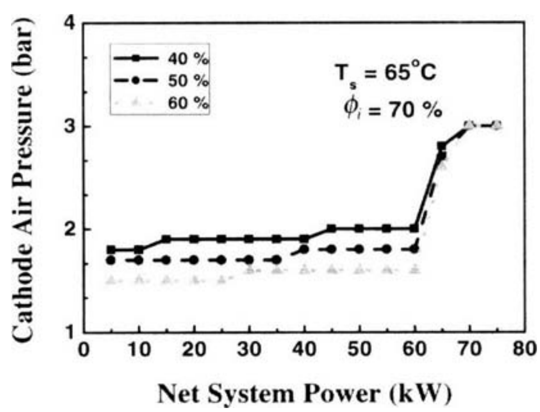

Fig. 9 Optimum cathode air pressure at different ϕ_{self}

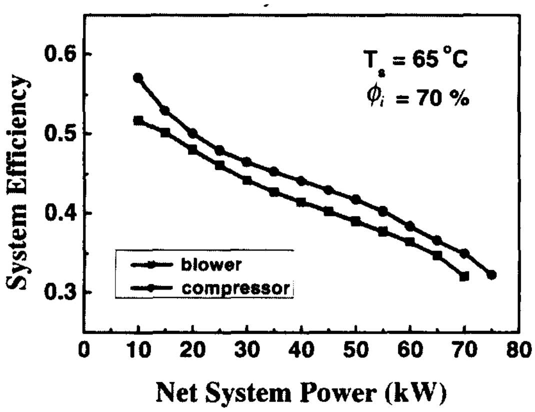

Fig. 10 Comparison of the low-pressure and the high-pressure operating fuel cell system efficiencies at $\phi_{setf}=40\%$

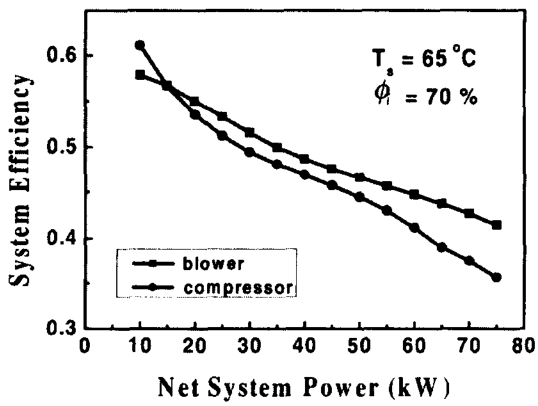

Fig. 12 Comparison of the low-pressure and the high-pressure operating fuel cell system efficiencies at $\phi_{setf}=60\%$

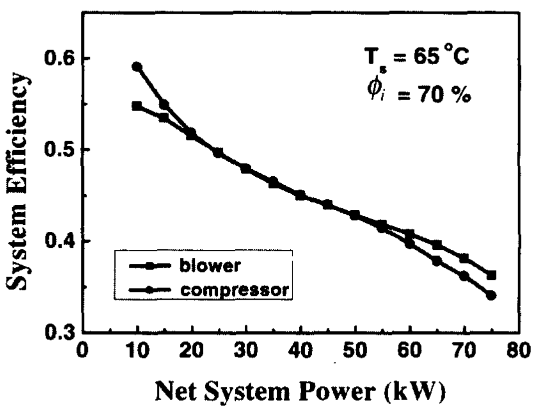

Fig. 11 Comparison of the low-pressure and the high-pressure operating fuel cell system efficiencies at $\phi_{setf}=50\%$

In Fig. 11, for $\phi_{setf}=50\%$, the net system efficiency of the high-pressure operating system was higher in the net system power range of 5 to 20 kW. The net system efficiency of the low-pressure was higher when the net system power was between 50 and 75 kW.

The data presented in Fig. 12 illustrates that for the case of $\phi_{setf}=60\%$, when the net system power exceeds 15 kW, the net system efficiency of the low-pressure operating system is higher than that of the high-pressure operating system by 2~6%. Consequently, through this, it can be concluded that the low-pressure operating system will be more advantageous if ϕ_{setf} can be kept high. This is due to the fact that in case of the low-pressure operating system the humidifier takes up the largest part of the necessary power for the BOP.

It is also seen that the net system efficiency of the high-pressure operating system is lower than that of the low-pressure operation system for elevated net system power condition. This can be explained by the fact that for the high-pressure operating system, the required compressor power gets much larger as the net system power increases.

4. Conclusions

In this study, the PEM fuel cell system consisting of a stack and a BOP was modeled and when operating at low-pressure and high-pressure its characteristics (net system peak power and net system efficiency) were compared. First, the two types of operating fuel cell systems with the same number of stacked unit cells were compared. Then, their characteristics for the same net system power level were presented. The major findings of this study can be summarized as follows ;

(1) For the two operating fuel cell systems piled up with 650 unit cells, the net system peak power for the high-pressure operating system was 114 kW, which is 41% higher than that of

the low-pressure operating system.

(2) The individual component which takes up the largest portion of the parasitic load of the BOP was the humidifier module for the low-pressure operating system, and the compressor component for the high-pressure operating system.

(3) The optimum cathode air pressures for the maximum net system efficiency power were presented according to different net system power conditions. The optimum cathode air pressure tends to increase as ϕ_{self} decreases.

(4) As ϕ_{self} increases, the required power for the humidifier module becomes smaller. Therefore, the low-pressure operating system with air blower is considered more advantageous in terms of net system efficiency than the high-pressure operating system.

(5) Through this study, basic insight into the fuel cell stack and the BOP component sizing was presented. Along with optimization packages, the approach adopted in this study can be effectively used for establishing an operating strategy for the practical use of fuel cell systems for vehicles.

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