

Performance Evaluation of a PEM Fuel Cell Stack with Coolant Operating Conditions

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ABSTRACT: A coolant operating condition in a fuel cell stack is an important factor to determine the temperature distribution which affects a fuel cell performance and relative humidity. In this study, the fuel cell performance were evaluated as a function of the coolant flow rate of 0.1~0.8 liter/min·cell and the coolant inlet temperature of 20~82°C when the anode inlet relative humidity was 0, 50 and 100%. In all cases, the cathode inlet relative humidity was fixed at 100% and the constant current mode of 0.7 A/cm². The coolant inlet temperature had the proper range to maintain the optimal cell voltage. The range of proper coolant inlet temperature moves to the higher temperature regime with increasing the coolant flow rate and the anode inlet relative humidity. The cell temperatures and the temperature differences between the coolant inlet and outlet increased with increasing the coolant inlet temperature and decreasing the coolant flow rate. The optimum voltage efficiency of the stack was observed at the anode inlet relative humidity 50% when the heat removal rate was 0.40~0.65 W/cm²·cell.

Keywords: Coolant, Flow rate, Heat removal, Humidity, Temperature, PEMFC

NOMENCLATURE

A_{react} Reaction area [cm²]

I Current [A]

m_c Coolant mass flow rate per a cell [kg/s]

n Number of cells in a fuel cell stack

q''_c Heat remove rate by a coolant from a fuel cell, $Q_c/A_{\text{react}} \cdot n$ [W/cm²·cell]

Q_c Total removed heat by a coolant from a fuel cell stack [W]

Q_{gen} Heat generated in a fuel cell stack [W]

Q_{in} Rate of energy transfer into a fuel cell stack [W]

Q_{out} Rate of energy transfer out of a fuel cell stack by unused reactants including heat of product water [W]

$T_{c,\text{in}}$ Coolant inlet temperature [°C]

$T_{c,\text{out}}$ Coolant outlet temperature [°C]

V_{cell} Cell voltage [V]

W_{el} Electricity generated in a fuel cell stack [W]

1. INTRODUCTION

The needs of alternative energy sources increase due to the shortage of fossil fuels. The hydrogen is one of the optimal energy to alternate the fossil fuels. The proton exchange membrane fuel cell (PEMFC) is the best method to use the hydrogen because of high efficiency, simplicity of its design and operation. Some attractive characteristics of the PEMFC system are lightweight, high energy density, no or low emissions and low temperature operation [1] [2] [3].

The PEMFC is generating reaction heat during a producing electric power through the electrochemical reactions. The generated heat elevates the temperature of the fuel cell stack to the proper reaction temperature, but over heating the cell causes the drying of the membrane and the decreasing of electric conductivity of membrane. To maintain the desired temperature, the generated heat by the electrochemical reactions has to be removed from the fuel cell stack [2], [3]. Many studies have examined the heat and water management to improve the performance in the fuel cell. For example, Dong et al. [4] experimentally investigated the current density and the mole fraction of H_2 along the flow channel of the anode in a unit cell as functions of air flow rate and the humidity of reactants by segmented current collectors and they explained to couple the current distribution with moisture contents and the mole fraction of H_2 in the fuel cell. Büch et al. [5] analyzed the current density distribution in a unit cell with electric control modes and the stoichiometry of reactants by semi-segmented plate. Hyun et al. [6] evaluated a performance of a fuel cell stack at a non-humidifying condition according to coolant types and cell temperatures which were determined coolant operating conditions.

In previous studies, the heat and water management in a fuel cell were one of the most important factors to maintain the performance of the fuel cell. The excess of water contents causes water flooding in a

cell and decreases the cell performance. Also, the lack of the water contents decreases the electric conductivity of the membrane and the cell performance.

In this study, the performance of a fuel cell stack is evaluated with the coolant inlet temperature and flow rate at the anode inlet relative humidity of 0, 50 and 100%. Additionally, a heat removal rate by the coolant from the fuel cell stack is compared with the performance. So the current study suggests the proper range of the heat removal rate and coolant operating conditions to maintain the optimal performance of the fuel cell stack.

2. EXPERIMENTAL SETUP

2.1 Test Apparatus

Figure 1 is the schematic diagram of the test apparatus to evaluate the performance of a fuel cell stack. In this study, H_2 and air flow through each supply tank are controlled by the mass flow meter and humidified by humidifiers which are the bubbler type. Line heaters heat the reactants to prevent condensation of vapour and control the temperature of reactants. The fuel cell stack is operated under constant current mode at 0.7 A/cm^2 by a load controller. Gore 57 Series MEAs are used to make the stack and the reaction areas of the cells are 200 cm^2 . The input power of a water pump is controlled in order to adjust the coolant flow rate. A line heater and a radiator control the coolant inlet temperature. Thermocouples, humidity sensors and pressure transducers are installed inside inlet and outlet of the reactants and the coolant for analyzing the heat balance of the fuel cell stack.

2.2 Experimental procedures

In this study, tests are conducted with a constant flow rate on the H_2 and air stoichiometry ratio of 1.5 and 2.5, respectively, and the inlet temperatures of reactants are fixed to 60°C . The fuel cell stack is operated with the constant current

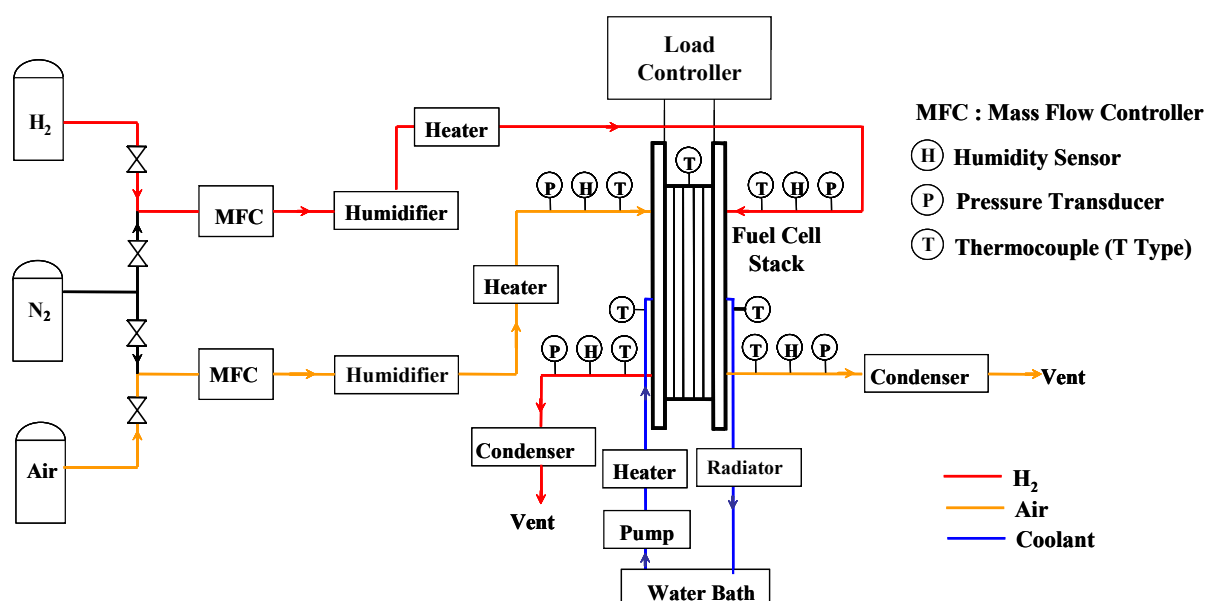


Figure 1: Schematic diagram of test apparatus to evaluate a fuel cell performance

mode at 0.7 A/cm^2 . The impact of the coolant operating condition on the performance of the fuel cell stack is investigated with anode inlet relative humidity at cathode inlet relative humidity of 100%. At anode inlet relative humidity of 0, 50 and 100%, the tests are conducted with the coolant flow rate of 0.1~0.8 liter/min·cell and the coolant inlet temperature of 20~82 °C.

The data collection is performed for 10 minutes after the fuel cell is allowed to reach a steady state for each operating conditions.

3. RESULTS AND DISCUSION

3.1 Performance of the fuel cell stack

Figure 2 shows the cell voltage according to the anode inlet relative humidity, the coolant inlet temperature and flow rate. The coolant inlet temperature has a proper range to maintain the optimal cell voltage. In case of the anode inlet relative humidity of 100% and the coolant flow rate of 0.1 liter/min·cell, the coolant inlet temperature range is 35~65 °C to maintain the satisfactory performance of the fuel cell stack. The cell voltage is reduced 5.9% and 17.6% at the coolant inlet temperature of 20 °C and 75 °C versus 45 °C, respectively. The range of proper

coolant inlet temperature moves to the high temperature regime with increasing the coolant flow rate. When the coolant flow rate is varied from 0.1 to 0.8 liter/min·cell at the anode inlet relative humidity of 100%, the range of the coolant inlet temperature to maintain the satisfactory performance of the stack is moved from 35~65 °C to 40~70 °C.

Also increasing the anode inlet relative humidity changes the range of the proper coolant inlet temperature to higher regime. When the anode inlet relative humidity is changed from 0 to 100% at the coolant flow rate of 0.8 liter/min·cell, the range of the proper coolant inlet temperature is moved from 40~60 °C to 50~70 °C. At the high coolant inlet temperature regime, the high relative humidity condition is more advantageous to obtain the high performance of the fuel cell stack. When the coolant flow rate of 0.2 liter/min·cell and the coolant inlet temperature of 70 °C, the cell voltage is decreased 12% at the anode inlet relative humidity of 0% versus 100%. When considering the maximum cell voltage, the anode inlet relative humidity of 50% is comparatively the optimum condition.

3.2 Analysis of heat removal rate

A fuel cell stack in operation has to be operated to avoid too much water and lack

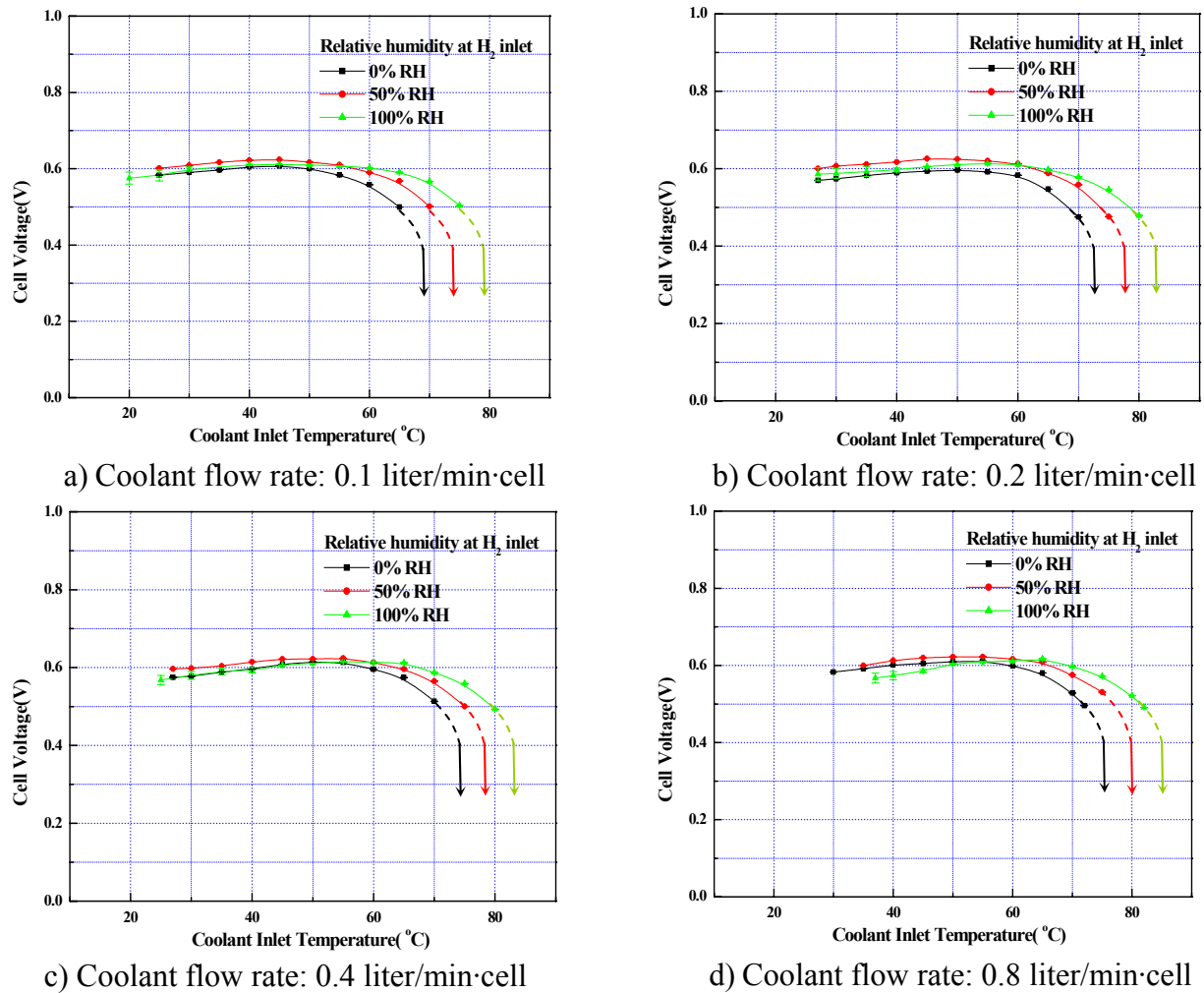


Figure 2: The cell voltage of the fuel cell stack according to the coolant inlet temperature, the coolant flow rate and the anode inlet relative humidity

of water. The excessive remaining of water in the fuel cell stack causes flooding in either the catalyst layer or the gas diffusion layer or in the gas channels. When water flooding is occurred, the cell voltage is decreased due to difficulty of one or both reactant gases reaching the catalyst sites. The lack of water causes drying of membranes, which increases the cell resistance and reduces the cell voltage [2].

The anode inlet relative humidity and coolant operating conditions affect the water contents and the temperature distribution in the fuel cell stack. The total water contents in the fuel cell stack are the sum of humidified water and generated water by electrochemical reaction. The generated water is fixed at the constant current mode,

so the humidified water determines the total water contents inside the fuel cell stack. Also the vaporization in the stack is varied as the temperature which is controlled by the heat removal with coolant operating conditions.

Accordingly, analysis of the heat removal rate, which means the total heat removed per reaction area in a cell by the coolant from the fuel cell stack, is needed for suggestion of the proper coolant operating conditions.

Figure 3 shows the cell temperature according to the coolant inlet temperature, the coolant flow rate and the anode inlet humidity. The cell temperature is directly proportional to the coolant inlet temperature and inversely proportional to the coolant flow rate. The anode inlet relative humidity

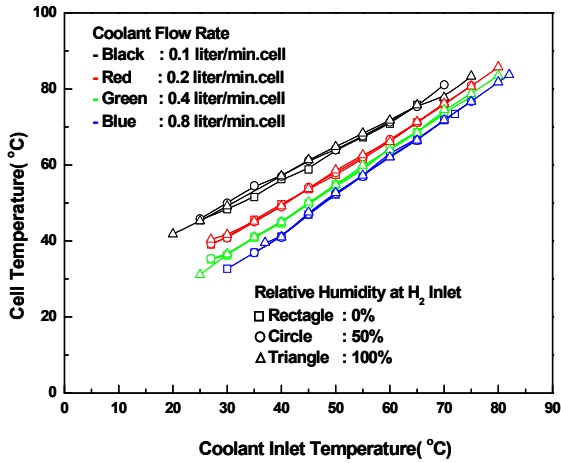


Figure 3: The cell temperature according to the coolant inlet temperature, the coolant flow rate and the anode inlet relative humidity.

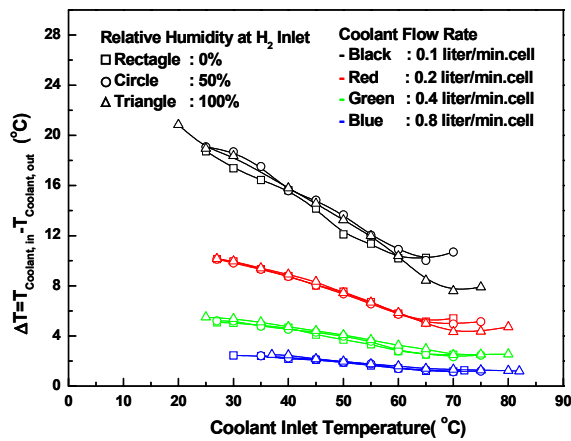


Figure 4: Temperature difference between coolant inlet and outlet according to the coolant inlet temperature, the coolant flow rate and the anode inlet relative humidity.

has no relation with the cell temperature. Figure 4 shows the temperature difference between coolant inlet and outlet with the coolant operating conditions and the anode inlet relative humidity. The temperature difference is increased with decreasing the coolant inlet temperature and flow rate and has no relation the anode inlet relative humidity. The effect of the coolant inlet temperature on temperature difference is decreased with increasing the coolant flow rate, because the maximum heat removal rate is limited from the fuel cell stack. The increasing of the temperature difference at

the high temperature regime is caused by the increasing of the heat generated in the fuel cell stack. The entire heat balance of the stack is expressed by equation (1). The enthalpy of reactants used the reaction into the fuel cell stack change the electric power and the generated heat. And the unused reactants are exhausted with a portion of the generated heat and the enthalpy of itself. The voltage losses determines the heat generation in a stack, most heat is generated in the cathode catalyst layers, then in the membrane due to ohmic losses, and also in the electrically conductive solid parts of the fuel cell stack. This heat generation is expressed approximately by the equation (2) at the higher heating value of H_2 . The equation (2) assumes that the product water leaves the stack as liquid at reactants inlet temperature. The heat generation is in inverse proportion to the cell voltage as the equation (2) [2].

The generated heat moves through porous media and bipolar plates by conduction. The majority of heat removal is by the coolant through convection and the conduction to the edge of the stack where it is transferred to the surrounding air through radiation and natural convection. Some heat is removed by the exhausting of the unused reactants and water. Using the coolant as water is the most effective and adjustable for the heat removal from the compact fuel cell stack. The heat removal rate by the coolant is expressed by the equation (3) [2].

$$\sum Q_{in} = W_{el} + Q_{gen} - \sum Q_{out} \quad (1)$$

$$Q_{gen} = (1.482 - V_{cell}) I n \quad (2)$$

$$q_c = \frac{m_c C_p (T_{c,out} - T_{c,in})}{A_{react}} \quad (3)$$

$$\eta_{volatge} = \frac{V_{cell}}{1.482} \quad (4)$$

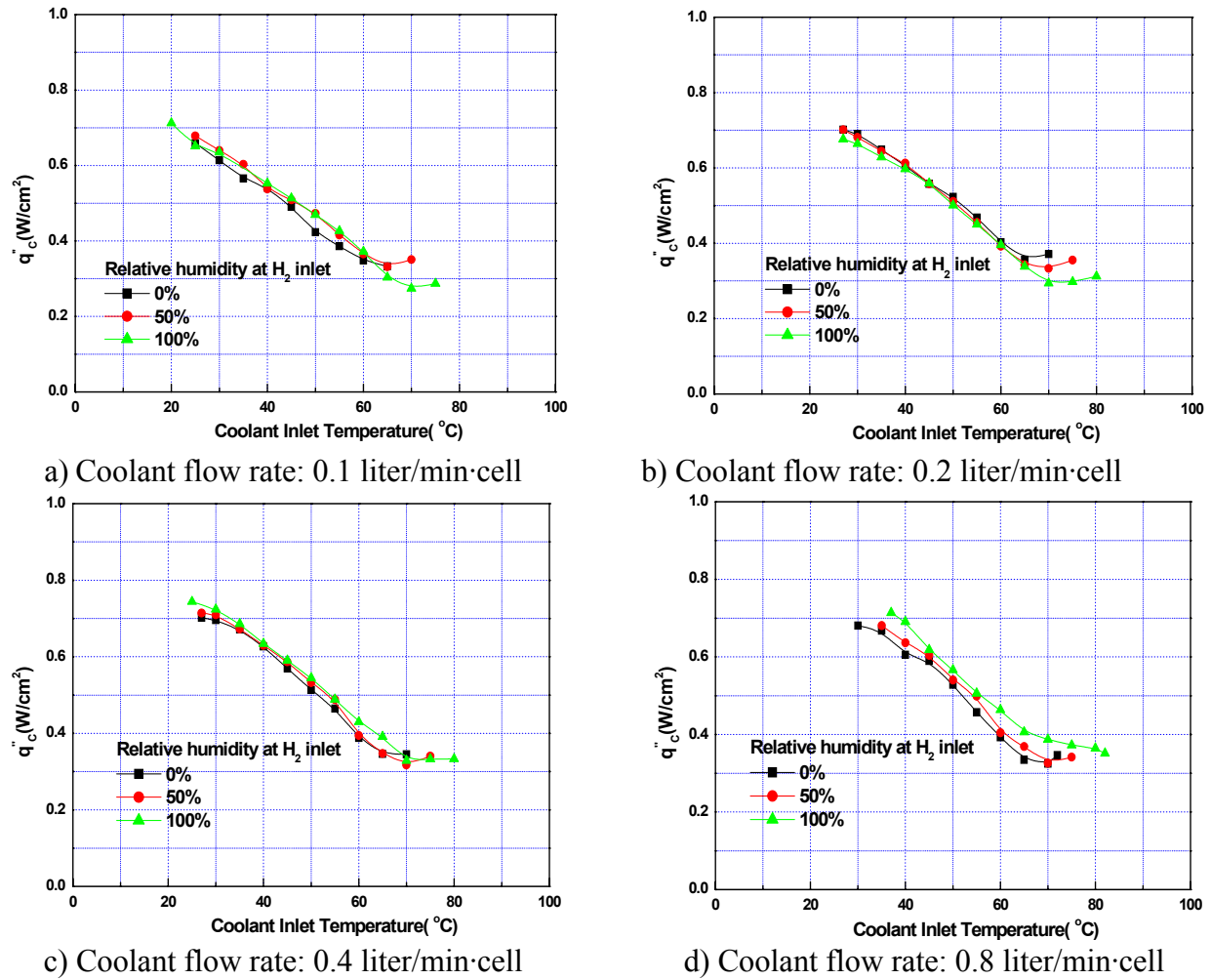


Figure 5: Heat removal rate by coolant from the fuel cell stack according to the coolant inlet temperatures, the coolant flow rate and the anode inlet relative humidity.

Figure 5 shows the heat removal rate according to the anode inlet humidity and the coolant operation conditions as the inlet temperature and flow rate. The heat removal rate is decreased with increasing the coolant inlet temperature and flow rate. As coolant inlet temperature increases, the temperature difference between the coolant and the heat transfer surface inside the fuel cell is reduced, which causes the reduction of the heat removal rate. At the high temperature regime in the coolant inlet, the heat removal rate is increased because heat generation is increased with increasing the voltage losses. Also the generated heat is transfer to surrounding air beside the fuel cell stack and unused reactants including water. When the heat removal rate by coolant is reduced with

increasing the coolant inlet temperature, the surface temperature of the fuel cell stack increases and the heat transfer to surrounding air is enhanced. Also when increasing the cell temperature enhances the vaporization of water in the fuel cell stack, the latent energy to be transferred out of the stack is increased.

The heat removal rate by coolant from the fuel cell stack is increased with increasing the coolant flow rate. Because increasing the coolant flow rate increases the convective heat transfer on the cooling channel. It seems that the anode inlet relative humidity is unrelated to the heat removal rate, because the added energy by the humidified water is insignificant in comparison with the heat removal rate by the coolant.

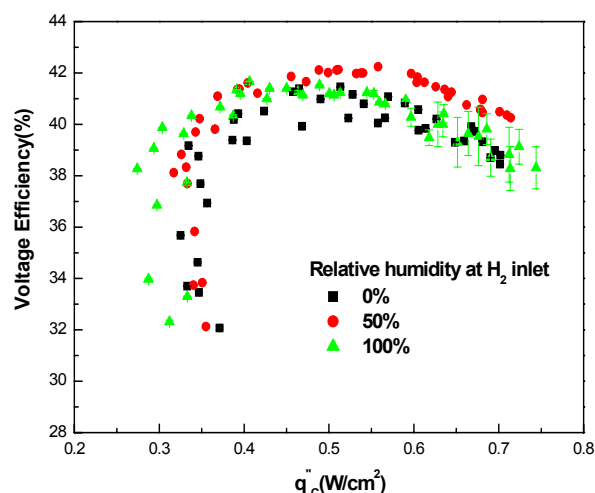


Figure 6: Voltage efficiency according to the heat removal rate by coolant from the fuel cell stack and the anode inlet relative humidity.

The equation (4) expresses the voltage efficiency based on the higher heating value of H_2 . The voltage efficiency represents the performance of the stack. Figure 6 shows the voltage efficiency according to the heat removal rate by coolant and the anode inlet relative humidity.

The range of heat removal rate is in existence to maintain the proper voltage efficiency. In case of the anode inlet relative humidity of 50%, the range of the heat removal rate is $0.40\sim 0.65\text{ W/cm}^2\cdot\text{cell}$ to maintain the adequate performance of the fuel cell stack. The decreasing voltage efficiency of the maximum 10.2% and 2.0% occur under $0.40\text{ W/cm}^2\cdot\text{cell}$ and over $0.65\text{ W/cm}^2\cdot\text{cell}$, respectively.

All cases of the anode inlet relative humidity, the tendency of the voltage efficiency is similar to 50% RH. At the anode inlet relative humidity of 100%, the proper range of the heat removal rate is $0.40\sim 0.60\text{ W/cm}^2\cdot\text{cell}$. In particular, the deviation of the voltage efficiency is increased to the maximum 2% at 0.7 W/cm^2 over the proper range. The increase of the deviation is probably caused by the water flooding at the high heat removal rate. And the rapid reduction of the voltage efficiency at the low heat removal rate is because of

decreasing of the electric conductivity by drying of MEAs. At the anode inlet relative humidity of 0%, the performance of the fuel cell stack is lower than the others and the distribution of the proper voltage efficiency is scattered.

The optimum voltage efficiency is denoted in case of the anode inlet relative humidity of 50%. The coolant operating condition is varied with the humidification. At the low humidification condition, the performance of the fuel cell stack is sensitive to drying of MEAs, therefore the stack is cooled enough. At the high humidification condition, water flooding has to be considered in order to operate the cooling system properly.

At the real system as automotive or building applications, the fuel cell system is operated to consider using the exhaust heat and the electric power consumption of the humidification system and the cooling system. If the high temperature of the exhaust coolant is needed for using the hot water, it is useful that the fuel cell system is operated with the high humidification condition. If the high efficiency is important as not using the exhaust heat, the fuel cell system is operated with proper humidification level to consider the humidification energy.

4. CONCLUSION

The performance of the stack was evaluated with the anode inlet relative humidity level and coolant operating conditions such as the coolant flow rate and the coolant inlet temperature. The range of the heat removal rate was suggested to maintain the proper performance of the fuel cell stack. The results of this paper are summarized as follows

The coolant inlet temperature had the proper range to maintain the optimal cell voltage and the proper coolant inlet temperature was changed into the higher temperature regime with increasing the

coolant flow rate and the anode inlet relative humidity.

The cell temperature increases with increasing the coolant inlet temperature and decreasing the coolant flow rate. The temperature difference between the coolant inlet and outlet is increased with decreasing the coolant inlet temperature. The anode inlet relative humidity is unrelated with both.

To obtain the optimum voltage efficiency of the fuel cell stack, the anode inlet relative humidity and the heat removal rate is 50%, 0.40~0.65 W/cm²·cell, respectively.

ACKNOWLEDGEMENT

This work is financially supported by the Ministry of Education and Human Resources Development (MOE), the Ministry of Commerce, Industry and Energy (MOCIE) and the Ministry of Labor (MOLAB) through the fostering project of the Lab of Excellency.

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