PEM Fuel Cell Investigation at Chiang Mai University, Thailand

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ABSTRACT

A Proton Exchange Membrane (PEM) fuel cell has been undergoing development in Thailand for five years. A fuel cell testing station has been set up to measure and control the mass flow rate of hydrogen (H_2) and oxygen (O_2), cell temperature, backing pressure and gas humidity. An interfacial unit and software have also been developed to provide significant data instantly. Membrane Electrode Assembly (MEA) was fabricated using solid electrolyte membrane, Nafion® 115, and platinum catalyst 20 wt% on carbon particle. The study is devoted to test PEM fuel cell performance, by analyzing the current density and voltage characteristics (I-V curve) and the current density and power density (I-P) curve, at various soaking conditions. It is found that the operating conditions which yield the best cell performance are the following: relative humidity of hydrogen at 80% to 90%, and relative humidity of oxygen at 50% to 60%; mass flow rate of hydrogen at 100 standard cubic centimeters per minute (sccm/min) and mass flow rate of oxygen at 140 sccm/min. These operating conditions yielded the maximum power density at about 150 milliwatts per square centimeters (mW/cm^2) in reaction area of 25 cm^2. The performance of aluminum alloy (94% Al and 6% Si) as the gas flow field in place of graphite was also investigated. It is found that the gas flow field made of aluminum alloy yielded lower performance than that of graphite because of the oxide film at the surface of the aluminum alloy.

1. INTRODUCTION

Energy is an essential resource and has become a growing concern worldwide because of the continued depletion of fossil energy resources. Consequently, energy prices continue to increase every year. In Thailand, the average price of gasoline from 1999 to 2000 increased to around 15%. Besides the rising cost, energy emissions from combustion also pollute the air and the efficiency of conventional engine has never exceeded 30%. Hence, proton exchange membrane (PEM) fuel cells have been explored and developed to investigate their performance as alternative energy source.

PEM fuel cell is a device for converting chemical energy directly to electrical energy. The fuel cell creates power by oxidizing hydrogen atom into a proton and an electron on the anode electrode and reduced oxygen atom with proton on cathode. PEM fuel cell operates at the lowest temperature among all kinds of fuel cells making the system operation easy to start up. Moreover, PEM fuel cell is compact, lightweight and uses synthesis fuel. Not only is hydrogen a typical fuel in PEM fuel cell engines, methanol can also be applied as an alternative fuel without reformer [1]. With reformer, PEM can be employed with variety of fuels such as methane, alcohol or gasoline. Because of these advantages, researchers around the world have become interested in materials, theory, performance and applications in many fields related to PEM [2-7]. Despite the relatively high cost of development, many companies and research institutes have invested and are aiming to reduce the price of commercially developed fuel cells. In Canada, the Ballard Power Systems Inc., a well-known PEM fuel cell company, has been

considerably prosperous and acquired clients from automotive companies which have currently demonstrated the use of PEM fuel cells in vehicles in Japan, Europe and the U.S.A.

Thailand, like many countries, does not have enough fossil fuel reserves. Therefore, most of fossil energy used in Thailand has been imported from the Organization of the Petroleum Exporting Countries (OPEC) to meet the energy demands of the country. With this, energy security in Thailand depends mainly on the world's energy situation.

Thailand is an agricultural country with abundant supply of various farm products. Rice, cassava and sugar cane, for example, can be fermented, distilled and converted into alcohol which can be used as a fuel in PEM fuel cell with reformer. In addition, wastes from agricultural crops can be transformed to methane which can also be used as a fuel in PEM fuel cell. Currently, PEM fuel cell has been utilized in many applications such as automobiles, home electric generators, batteries, and in nano-technology devices. With these advantages, there is therefore a big potential for the use of PEM fuel cell technology as an alternative energy source in Thailand.

This paper aims to present the investigation and development of PEM fuel cell at Chiang Mai University, Thailand. Initially, fuel cell test station was gradually constructed and single cell was tested later. Cell performances were measured in various soaking conditions as well as at different flow rates. Recently, aluminum alloy was chosen as gas flow field in place of graphite and the performance of aluminum alloy was compared to graphite's.

2. FUEL CELL TEST STATION

The fuel cell test station is composed of two main units: hardware components and software program.

2.1 Hardware Components

The PEM fuel cell test process is shown in Fig. 1. Both hydrogen and oxygen gases were regulated by pressure regulators and flowed through the flow control units, manipulated by a computer. Upon entering the humidifier, these dry gases were bubbled in cylinder water tank thus becoming moist gas streams. Principally, humidity was correlated with temperature, while pressure was kept constant. Relative humidity was measured at different temperatures. The measurements were then stored in the computer as correlative reference before testing the fuel cell performance.

Fig. 1 Diagram of the fuel cell test station comprising of flow control unit, humidifier, heater and back pressure unit

The heater functioned as a humidity controller according to the correlation. Pressure was kept constant by adjusting the needle valve after the gases passed through fuel cell called the "back pressure unit".

2.2 Software Program

The hardware components were controlled by a software program called LabVIEW, which is a graphical programming language that is different from other programming systems (for example, the C, BASIC, and FORTRAN). Rather than creating programs by writing lines of text-base statements, the program was created by selecting and properly patterning graphical icons. The software programmed by LabVIEW was designed to facilitate computer-controller data acquisition and analysis. All analog signals were converted to digital for processing in the computer. There were six subroutines used: mass flow controller, heater and humidifier control, electronic load control, performance monitoring, automatic control and main-control board. Figure 2 shows the software monitor which displays the significant information of the hardware and the performance of fuel cell instantly. The combination of hardware and software makes up the fuel cell test station as shown in Fig. 3. The station was fully equipped in order to test and analyze the fuel cell performance.

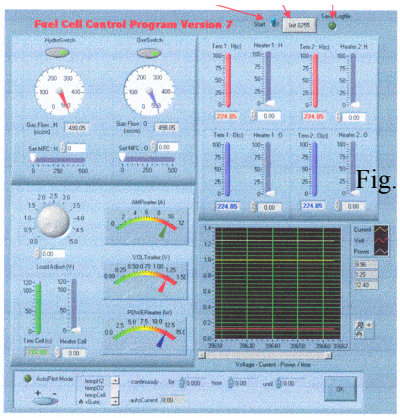

Fig. 2 The monitor of fuel cell test station at Chiang Mai University consisting of flow controller, temperature control, cell performance and electronic load control

Fig. 3 Fuel cell test station built by Chiang Mai University

3. EXPERIMENTAL PROCEDURE

3.1 Single Cell Assembly

Anode and cathode electrodes of 1 mg/cm^2 platinum used as catalyst (from ElectroChem. Inc.) were attached on both sides of electrolyte membrane, Nafion® 115 (DuPont), by using 5% Nafion solution as a binder. Membrane Electrode Assembly (MEA) was fabricated by hot-pressing method with 25 cm^2 of reactive area. MEA was assembled using a graphite gas flow field as shown in Fig. 4. As soon as humid hydrogen was supplied to the fuel cell, it was oxidized and yielded hydrogen ion and electron spontaneously. Hydrogen ions were allowed to transfer through membrane electrolyte (Nafion), while electron was repelled to the external electronic device. At the cathode, oxygen was reduced with hydrogen ions and electron producing water as the product.

3.2 Testing and Operating Conditions

A fuel cell was set up into the test station as shown in Figs. 1 and 3, and connected to the electronic resistor called "electronic load" which is controlled by computer. When the electronic resistor was gradually diminished from infinite to almost zero resistance by computer control, the current and output voltage could basically change. Usually, the current was divided by reactive area known as current density, mA/cm^2. All operating conditions including current and output voltage were measured and recorded into the computer.

Hydrogen and oxygen were utilized as fuel and oxidant, respectively. Firstly, the proper humidity was investigated by setting a trial flow rate of 100 sccm/min (standard cubic centimeter per minute) for both hydrogen and oxygen. The humidity was varied from 50% RH to 100% RH at the ambient pressure. Then the flow rate was tested by changing the mass flow rate of hydrogen from 50 to 200 sccm/min while the mass flow rate of oxygen was changed from 100 to 150 sccm/min.

During the experiment, the pressure was kept constant at atmospheric condition while the cell temperature was kept constant at 50^{o}C. The current density and voltage characteristics (I-V curve) as well as current density and power density characteristics (I-P curve) in each operating condition were analyzed. These graphs were compared in order to evaluate the best performance of the PEM fuel cell.

3.3 Aluminum Alloy as Gas Flow Field

Gas flow field allowed the reactant and fuel gas to flow into the electrode and, consequently, the reaction took place. Moreover, it also conducted electrons from the chemical reaction out of the anode to the outside circuit and took those electrons back to the cathode to complete the redox (reduction-

Fig. 4 A simple cross-section of single cell assembly comprising of MEA and gas flow field

oxidation) reaction, as shown in Fig. 4. Conventionally, graphite has been chosen as the gas flow field because of its high chemical resistance and low contact resistance. However, graphite is breakable and has a high volume that will make the fuel cell ponderous when cells are stacked for higher power output. Therefore, aluminum alloy was selected to replace graphite and machined to function as the gas flow field, with a 10 x 10 x 0.8 mm dimension. The performance and the possibility of aluminum alloy to be used as gas flow field was investigated.

4. RESULTS AND DISCUSSIONS

4.1 Effects of Humidity

Hydrogen (at anode) and oxygen (at cathode) were continuously fed to the single cell with 25 cm^2 reactive area, respectively. The effect of humidity to the fuel cell performance was determined by changing oxygen humidity from 50% to 100% RH; while all conditions were set constant and hydrogen humidity was initially set at 50% RH. The relative humidity of oxygen was measured at the following range: 50 to 60%, 60 to 70% until 90% to 100% RH as shown in Figs. 5(a) and (b). Figure 5(a), the I-V curve, shows that the curves did not yield significant difference. At these conditions, fuel cell produced electricity at 200 mA/cm^2 and at 0.3 to 0.4 volt. Figure 5(b), the current density and power density (I-P) curve, shows that the humidity of oxygen decreased at higher humidity range, and the highest power obtained was around 70 mW/cm^2 at 50% to 60% RH. Because oxygen was fed at cathode and spontaneously produced water to complete the reduction, humidity added into the oxygen stream was not quite important. In contrast, if there was too much water, it would obstruct the reduction unintentionally by reducing the reactive area of oxygen. Consequently, the humidity of oxygen was proper at around 50% to 60% RH.

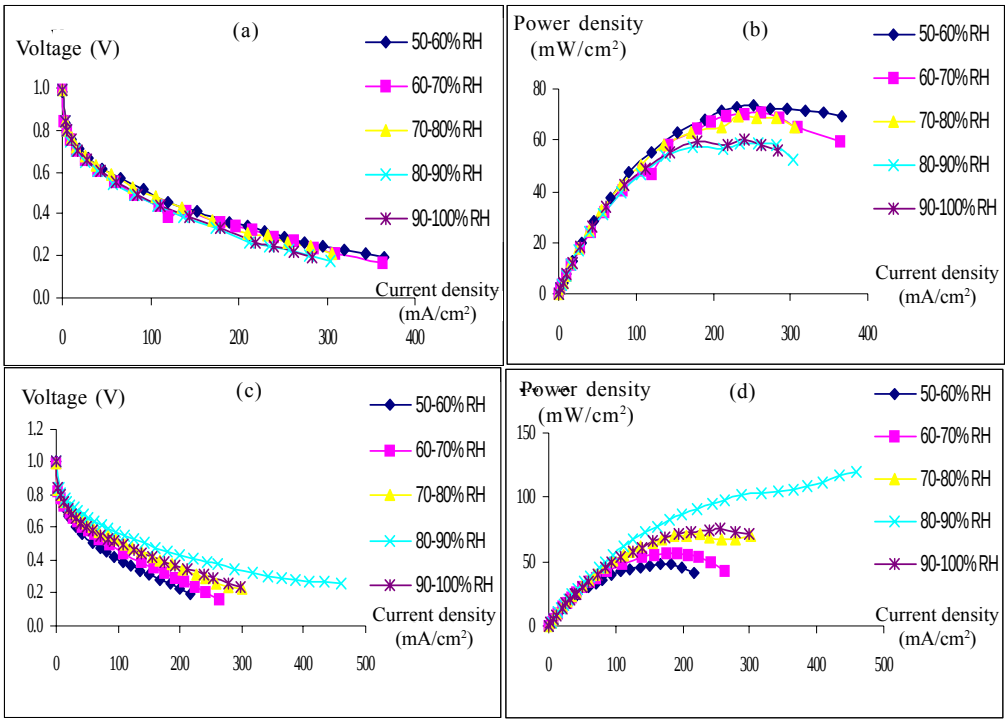

Fig. 5 Fuel cell performance at various humidity conditions at atmospheric pressure and 50°C cell temperature: (a) I-V curve and (b) I-P curve at various oxygen humidity, and (c) I-V curve and (d) I-P curve at various hydrogen humidity

The effect of hydrogen humidity to the cell performance was also investigated. The result was obviously more distinctive than that of oxygen; as shown in Figs. 5(c) and (d). In both I-V and I-P curves, Figs. 5(c) and (d), respectively, the results show that the higher the relative humidity, the higher is the voltage and power density except at 90% to 100% RH. It appeared that the hydrogen humidity of 80% to 90% RH achieved the highest performance producing power at around 100 mW/cm^2, while humidity at 90% to 100% RH gave almost similar profile as that at 70% to 80% RH. It could be inferred that hydrogen stream at the anode, needed water to enhance fuel cell performance. The water facilitated the membrane polymer, Nafion® 115, to become electrolyte so as to allow hydrogen ion transport through the membrane. However, if water was too much, it would hinder the reactive area of hydrogen and the catalyst, like in the case at 90% to 100% RH.

The results indicate that water contained within hydrogen and oxygen affects essentially the fuel cell performance. The optimum humidity to give the maximum performance is 50% to 60% RH for oxygen and 80% to 90% RH for hydrogen.

4.2 Effects of Flow Rate

Flow rate represents hydrogen and oxygen concentration if pressure and temperature are held constant and when the reaction takes place based on ideal gas law. Based from the results of humidity investigation, hydrogen and oxygen humidity were set at 80% to 90% RH and 50% to 60% RH respectively, considering the highest cell performance. The oxygen flow rate was studied first by maintaining the hydrogen flow rate at 100 sccm/min. The oxygen flow rate was varied from 100 to 150 sccm/min at 10 sccm/min interval. Figures 6(a) and (b) show that the oxygen flow rates are almost identical at different intervals on both I-V and I-P curves and the maximum power density is about 120 mW/cm^2 at 400 mA/cm^2. Then hydrogen flow rate was tested while oxygen flow rate was set at 140 sccm/min. Figures 6(c) and (d) show the I-V and I-P curves, respectively.

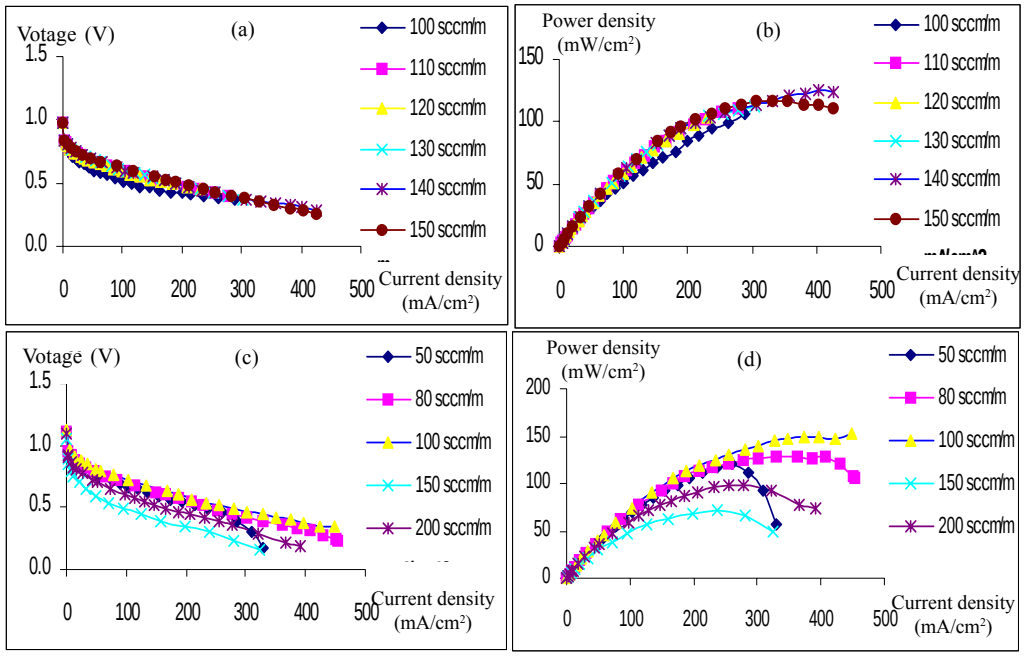

Fig. 6 Fuel cell performance at various flow rate conditions, at atmospheric pressure, and 50°C cell temperature: (a) I-V curve and (b) I-P curve at various oxygen flow rates, and (c) I-V curve and (d) I-P curve at various hydrogen flow rates.

By varying the hydrogen flow rate, both I-V and I-P curves show distinct profiles, probably because of the greater interval at 50 sccm/min. Higher flow rates, such as 150 and 200 sccm/min, did not quarantee that higher performance will be acquired. According to the graph, low flow rates 50 to 100 sccm/min, yielded higher performance than those of high flow rates, but flow rates at 50 and 80 sccm/min decreased their performance at higher current density because of hydrogen depletion. Therefore, the maximum power output was attained at hydrogen flow rate of 100 sccm/min.

Theoretically, two moles of hydrogen react with one mole of oxygen to produce two moles of water, this is generally the overall redox reaction in PEM fuel cell. It is clear that the ratio of hydrogen consumed is double that of oxygen by volume if those gases behave as ideal gas. Nevertheless, in the experiment, the hydrogen and oxygen ratio was 1:1.4 by volume. This might be due to the moisture in the gas stream which affected the reaction area. Furthermore, the overall reaction inevitably depended on platinum contents and MEA fabrications which were more essential and more complicated; the effects of these factors will be the focus of future studies.

As shown in Fig. 7, the best performance of the cell was obtained at maximum power output of approximately 150 mW/cm^2 in an area of 25 cm^2, with flow rate of oxygen and hydrogen at 140 and 100 sccm/min, respectively, and the gas humidity was 50% to 60% RH of oxygen and 80% to 90% RH of hydrogen.

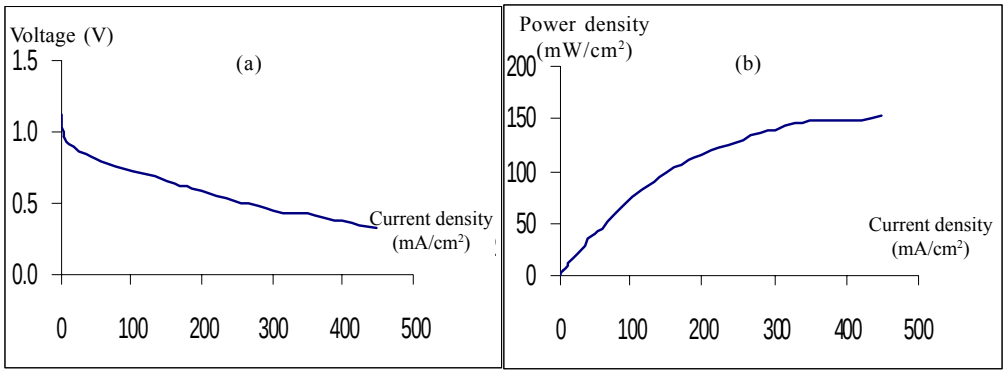

Fig. 7 (a) I-V curve and (b) I-P curve showing the best fuel cell performance with maximum power output of 150 mW/cm^2 at an oxygen flow rate of 140 sccm/min and relative humidity of 50% to 60%, and a hydrogen flow rate of 100 sccm/min and relative humidity of 80% to 90%

4.3 Aluminum Alloy Gas Flow Field

The serpentine gas flow field from aluminum alloy was machined and then assembled with MEA. Its cell performance was measured at the same condition as graphite, as shown in Fig. 8. The I-V curve of aluminum alloy was lower than that of graphite. During fuel cell operation, the reaction took place at both anode (oxidation) and cathode (reduction), and consequently acidic environment occurred at the electrode surface that contacted with the gas flow field. Hence, aluminum gas flow field in acidic condition could generate spontaneously oxide film, which is an electrical insulator, and caused a lower fuel cell performance. The aluminum alloy was modified by adding a gold coating at its surface. Figure 8 shows that the coated aluminum alloy yielded similar performance with that of graphite.

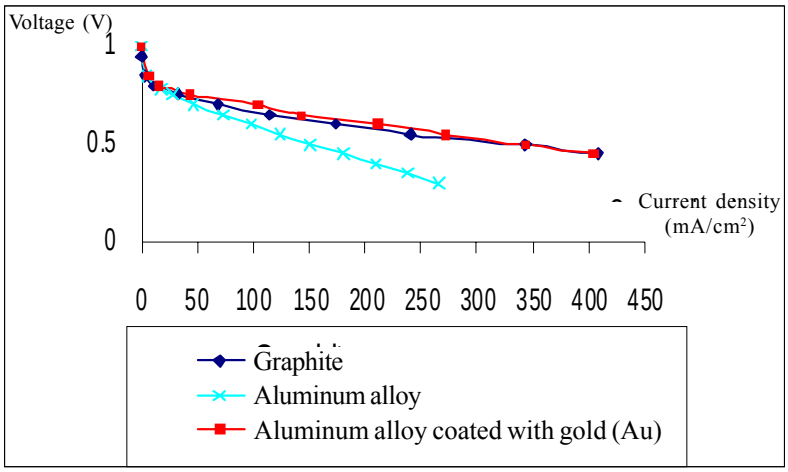

Figure 8 Comparison of fuel cell performance of graphite, aluminum alloy and aluminum alloy coated with gold as the gas flow fields

5. CONCLUSIONS

A test station was built to control flow rate, humidity of oxygen and hydrogen, cell temperature and electronic load. All data were collected and recorded into the computer in order to analyze fuel cell performance. The operating conditions were investigated, particularly gas humidity and flow rate. The fuel cell performance was analyzed by varying those conditions systematically. The best performance yielded a maximum power output of about 150 mW/cm^2, while humidity of oxygen and hydrogen were 50% to 60% RH and 80% to 90% RH respectively, and oxygen and hydrogen flow rates were 100 and 140 sccm/min, respectively. The gas flow field made of aluminum alloy yielded lower performance than that of graphite because of the oxide film at the surface. The aluminum surface was rectified by adding gold coating and this gave similar performance as graphite.

6. ACKNOWLEDGEMENTS

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