Experimental analysis of the performance characteristics of the regenerative fuel cell system based on serpentine flow-field design

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Abstract. The energy demand has recently been increasing dramatically; thus, it is evident that scientists worldwide need to find out the solution to solve the above problem. Among these technologies, solar and wind power energy are the most potential source as alternatives to fossil fuels. However, these energy sources are not continuous and are therefore considered as additional sources. A regenerative fuel cell (RFC) is a type of fuel cell that can function as an electrolyzer and fuel cell; therefore, this system is an independent power source and overcome the drawbacks of the original fuel cell system. This research has built a system to control the entire regenerative fuel cell system's flow, temperature, and energy. The system uses electricity to produce hydrogen and oxygen for storage; when the electrical power is insufficient, the system can automatically reverse the operation using hydrogen and oxygen to create electrical energy. The result showed that the power density in fuel cell mode ranges from 0.1 to 0.69 W/cm² in the fuel cell mode, and the flow rate of hydrogen and oxygen reaches a stable value of 1100 and 2200 ml/min after 10 minutes, respectively.

1. Introduction

Exhaust emissions from internal combustion engines are the primary polluted source and responsible for over 65 percent of global GHG emissions worldwide [1]. As global energy demand is expected to continue to increase in the future, there are many comments that fundamental measures are urgently needed to meet growing energy demand. The UN Framework Convention on Climate Change was adopted by the United Nations Conference on Environment and Development in 1992 to prevent global warming. As the Kyoto Protocol, including concrete action plans, has entered into force, international environmental regulations to curb greenhouse gas emissions have been strengthened [2]. Generally, the energy forms to be transferred to the final users, the always convenient, clean, safe, efficient, and flexible energy carriers are necessary. Electricity is a traditional form of energy, created by various energy sources, easy to transport, and comfortable to transfer to the final users. And thus, automobile electricity has been developed worldwide due to its advantage in energy consumption prices and exhaust emission, as mentioned in [3]. However, the drawback of the automobile electricity related to the short driving range and long recharge time has limited its applications.
Hydrogen is also a clean, efficient, and flexible energy carrier and easily compensates the electricity. The two energy carriers, electricity and the hydrogen, can satisfy all energy demands in the future and build individual first energy sources and an independent permanent energy system [4]. Indeed, hydrogen generated from renewable resources can be used for various applications such as transportation, electrical production, and heat for industry, buildings, and primary industry. Related to this point, proton exchange membrane fuel cell (PEMFC) using hydrogen has been used to cope with the energy crisis and air pollution because of its fewer emissions and high efficiency compared [5-6]. It works as a battery transferring the chemical energy into electricity; if hydrogen is fed continually, it will prevail battery in low energy storage. However, hydrogen production is expensive and not widely available, and its riskiness in the storage process. An RFC system can solve this problem due to its capability to function either as an electrolyzer or a fuel cell [7]. As a result, the reversible reaction most commonly used in an RFC is as follows:

\[ \text{H}_2\text{O} + \text{energy} \leftrightarrow \text{H}_2 + \frac{1}{2}\text{O}_2 \] (1)

In the electrolyzer mode, electricity is supplied to dissociate H\(_2\text{O}\) into H\(_2\) and O\(_2\). These storage gases are fed back into the RFC in the fuel cell mode to create electricity. Thus, RFC has potential development in areas of transportation [8]. This research conducted an experimental procedure to test the UFC system based on the serpentine flow-field design. Accordingly, the flow-field of the bipolar plate was manufactured and assembled with a membrane exchange assembly (MEA) for the experiment.

2. Experimental procedure for the regenerative fuel cell system based on serpentine flow-field design

In this research, the simulation work has been conducted to optimize the flow-field design based on a 3-D mass transfer model, including heat transfer aspects of PEMFCs, as mentioned in [1]. Consequently, the optimized flow-field is a 5-passes 40turns serpentine channel flow field fabricated by the steel material. The 3D drawing was performed in 3-D drawing software, and all the flow-fields using for the fuel cell assembly were manufactured by a highly accurate CNC machine to ensure high precision, as shown in Fig. 1.

![Figure. 1 Flow-field design with 5-pass 4-turn serpentine type](image-url)
The fabricated flow-fields are assembled with the MEA to form a single fuel cell. MEA composes of the solid polymer membrane playing a role as the electrolyte. The electrodes are in contact with the membrane and must be porous to allow the flow of gases and liquid water to and from reaction sites. In an RFC, fuel cell and electrolyzer device are both integrated into a single system. This system includes a water control system and a gas storage system to function as a standalone energy storage unit. One key advantage of an RFC compared with a separate electrolyzer and fuel cell is integrating all functions in a single compact system; thus, it can conduct the energy storage mission and compete directly with batteries.

Additionally, an RFC allows the closing of the water cycle, whereby product water in the fuel cell mode can be returned to the electrolyzer's water storage. It may become advantageous in stationary power supply applications where the supply of H₂O is challenging. The different design of the electrolyzer and fuel cell allows these two components to be optimized their performance and cost-effectiveness. It permits the cell's capacities in the fuel cell and electrolyzer mode to be conducted separately, and thus it can operate in both ways simultaneously. In electrolyzer mode, an RFC converts water into gaseous hydrogen and oxygen; otherwise, hydrogen and oxygen gases electrochemically combine to form water, with the generation of heat and electricity in the fuel cell mode as mentioned in Fig. 2.

Figure. 2 Fundamental work of the RFC system

In the experiment, the system was designed with the ability to automatically switch between electricity storage mode and electricity generation mode composing of the following parts: main water tank, an automatic water pumping system that is controlled by relays, water supply pipes for supplying water when the procedure operates in electrolytic mode, air pipes for providing air when the system works in power generation mode, 1-way solenoid valves and solenoid control system, flow meters for accurately measuring water and airflow supplied to the system. The full system test is described in Fig. 2.

Figure. 3 Schematic diagram of the RFC system
Where (2) is cartridge heater with the thermocouple, (3) is electronic load and DC power, (4) is a one-way valve, (5) is liquid mass flow controller, (6) is a relief valve, (7) is the water pump, (8) is the water tank, (9) is water and gas separation tank, (10) is water separator, (11) is pressure regulator, (12) and (13) are high-pressure gas pump, 14 is a gas check valve, (15) is the gas cooling chamber, (16) is heating tape

3. Results and Discussion

The experimental RFC's performance data with both electrolyzer and fuel cell modes are given in Fig. 4 and Fig. 5. Consequently, the power density in fuel cell mode changes according to the current density and reaches the maximum value of 0.69 W/cm$^2$ at the current density of 1.4 W/cm$^2$.

![Figure 4](image1.png)

**Figure. 4** Polarization and power density curve of URFC at fuel cell mode

The hydrogen and oxygen production rates by the URFCs trialed in electrolyzer mode are presented in Fig. 5. It can be observed that they are small in the first period and rapidly increase after 5 minutes. After 10 minutes, the flow rate of hydrogen and oxygen reach a stable value of 1100 and 2200 ml/min, respectively.

![Figure 5](image2.png)

**Figure. 5** Hydrogen and oxygen flow rate of URFC at electrolyzer mode

These results are expected a priori since a given electrode's electrochemical performance would be expected to stay the same if its composition remained constant, even though changes are
made on the other electrode. The system is well-operated during the longtime of the experiment. However, RFC's power density at the fuel cell mode is a little smaller than that of previous research studies with the same fuel cell design configuration. It can be resulted by the restriction of the membrane protection parts added in the anode side and the cathode side. These parts help protect the membrane under electrochemical corrosion; however, they hinder the flow channel and reduce the fuel cell performance. And thus, future research will be conducted to solve this problem to apply worldwide applications.

4. Conclusions

This research shows the experimental result of the RFC system. It can be observed that the system worked smoothly, corresponding to both the fuel cell and electrolyzer mode. The maximum value of the power density is about 0.69 W/cm² at the fuel cell mode; meanwhile, the hydrogen flow production can be reached to 2.2 l/min at the electrolyzer mode corresponding to 25 cm² active area MEA. This work's findings provide a foundation for optimizing the flow-field design for efficient PEMFCs and applying the RFC system worldwide.

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