Sensors and Materials, Vol. 34, No. # (2022) 3823–3855
MYU Tokyo

S & M 3079

Fabrication, Design, and Performance Investigation of Portable Proton Exchange Membrane Fuel Cell and Control System

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(Received May 22, 2022; accepted October 3, 2022)

Keywords: fuel cell, fuel cell controller, purge interval, purge duration

We constructed a controller for a 500 W proton exchange membrane fuel cell (PEMFC). The controller uses the Arduino Mega2560 control board for system construction and development. The controller can measure voltage, current, temperature, and power supply. The measurement data is stored in a computer via Bluetooth transmission technology. The system protection components are installed outside the control panel. The components are integrated using a printed circuit board (PCB) process. The self-built controller can avoid PEMFC overload and instantly transfer data to the user record. The PEMFC controller developed in this study can control the purge interval and duration of the valve according to the fuel cell stack under different load conditions, thus improving the stability and output performance of the fuel cell.

1. Introduction

A proton exchange membrane fuel cell (PEMFC) is a green power generator that uses hydrogen and oxygen as reactants, producing electricity and water without any pollution.(1) PEMFCs have high power density and efficiency.(2) The working voltage of a single fuel cell is 0.5–0.7 V; thus, to increase its application range, a PEMFC is connected as a stack to increase its working voltage. The fuel cell is usually stacked using a membrane electrode assembly (MEA) and graphite bipolar plates. There are two types of air-cooled PEMFC stacks: active and passive.(3) Passive air-cooled PEMFC stacks are cooled using air by natural convection and are usually equipped with a heat pipe or a heat spreader. Conversely, active air-cooled PEMFC stacks are cooled by force convection. The gas channel at the cathode has an open design, using oxygen in air as a reaction gas to supply the fuel cell stack. Fans are used in fuel cell stacks to increase the amount of cathode reaction gas and remove heat by forced convection.(4) A fuel cell stack power generation system typically includes a fuel cell stack, a controller, a fuel supply, and a purge valve. The controller is very important for the fuel cell stack and must control the fan speed and the opening and closing times for the intake and exhaust valves according to load

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https://doi.org/10.18494/SAM4099

ISSN 0914-4935

conditions. This permits the fuel cell stack to be controlled with stable output and high efficiency. Knobbe *et al.* stated that gas and water management systems are essential to achieve and maintain a high PEM fuel stack power output. During their experiments, they performed a purge valve control gas and moisture test. This method can ensure that the performance of the fuel cell anode channel is not limited or reduced by the accumulation of impurities under long-term operation. Their results show that the active gas management system can increase the PEM fuel cell stack power output by 30%. The battery can also maintain high-efficiency performance under long-term operation.(5) Cho *et al.* studied PEMFCs and conducted experiments on the dynamic characteristics and transient responses of PEM fuel cell stacks. They concluded that the air flow is overhumidified and that the temperature rises at high loads owing to an increased transport resistance. The surge phenomenon during transient changes is due to the oxygen supply, uneven oxygen distribution, and flooding in the cathode. During normal fuel cell operation, liquid water accumulates on the anode side of the fuel cell. Proper drainage helps improve water and gas management.(6) Choe *et al.* designed a proportional integral derivative (PID) controller for temperature regulation.(7) Fabian *et al.* conducted water management experiments on the cathode surface of PEM fuel cells. Under normal situations, liquid water is gradually generated on the cathode surface, meaning that the fuel gas is not uniformly distributed on the gas diffusion layer. If there is no effective drainage, a blocked flow channel causes insufficient fuel supply and damage to the MEA.(8) Lotfi *et al.* controlled the open-cathode fuel cell stack during voltage stabilization by temperature regulation. They experimentally showed that the fuel cell stack had good performance using this controller when the environment was unstable.(9) Controlling the fuel, electricity, temperature, and water management during the operation of the fuel cell power generation system is very important. The controller is used to manage the components around the fuel cell stack. The aim of our research is to improve fuel cell efficiency and increase hydrogen usage.

2. Fuel Cell Stack Controller

The main functions of the fuel cell controller are management, control, and protection. In terms of management, the water management of the by-products generated during fuel cell stack power generation can increase the utilization rate of hydrogen. The other type of management is thermal management. Fuel cell stacks generate high temperatures during operation. Effective heat dissipation is required to prevent the stacks from overheating and burning. Water and thermal management systems are very important for high-temperature, high-wattage fuel cell stacks. In terms of control, it is necessary to control external components such as the front magnetic valve, rear magnetic valve, and fan. The front magnetic valve controls the entry of the reaction gas, and the rear magnetic valve controls the discharge of the reaction gas and by-products.(10) The fan is controlled by the controller to adjust the air flow according to load and temperature changes. The protection includes voltage, load, temperature, and battery protection systems when the amount of reaction gas is insufficient. When the battery is abnormal, the protection function is activated to make a buzzer sound and generate a warning signal, and the power is turned off to protect the battery from damage. In this study, we mainly control the purge interval and duration of the magnetic valve. Figure 1 shows a commercially available fuel cell controller, whose purge time is set to 1 s every 10 s. In this study, we design a controller, compare it with the commercially available one, and improve the control strategy. The commercially available 500 W fuel cell stack is shown in Fig. 2, and the detailed specification sheet of this fuel cell stack is shown in Table 1.

When the fuel cell stack starts, the reactive gas is supplied. There are two important components in the control of the reactive gas on the anode side: the front magnetic valve, also called the gas supply valve, and the rear magnetic valve, also called the gas purge valve. These two magnetic valves were designed with reference to the valves in the commercially available fuel cell stack. When the gas is supplied to the fuel cell, the first control component is the supply valve, which is normally closed. When the fuel cell is not in use, it can isolate the entry of external air and prevent unnecessary dirty air from polluting the battery. When the fuel cell is under a low voltage, a large change in load, a high temperature, and a high load, the supply valve closes and stops supplying gas to the fuel cell stack, preventing damage to the fuel cell stack. The purge valve is normally closed. This valve is very important for the open-cathode fuel cell stack and controls the reaction gas discharge. When the fuel cell stack has been operating for a long time, impurities gradually accumulate in the flow channel, degrading the performance. Therefore, purging is required. The purge valve is opened regularly to remove the impurities inside. Purge valve control includes the control of the purge interval (valve closed) and purge duration (valve open). Too short an interval will lead to frequent valve action and unnecessary hydrogen consumption. Too long an interval will result in the excessive accumulation of impurities and reduce the hydrogen utilization rate of the fuel cell stack. Open-cathode fuel cell stacks use air as the cathode reactant. Forced convection is conducted using a fan. When the fuel cell stack has a high load, the fuel cell controller controls the fan speed to increase the flow rate. In addition, large amounts of water and heat are generated owing to the high load. Thus, the control of the fan is very important to prevent high temperatures from damaging the fuel cell

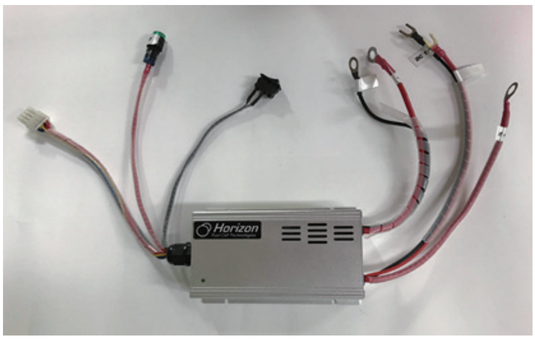

Fig. 1. (Color online) Commercially available fuel cell controller.

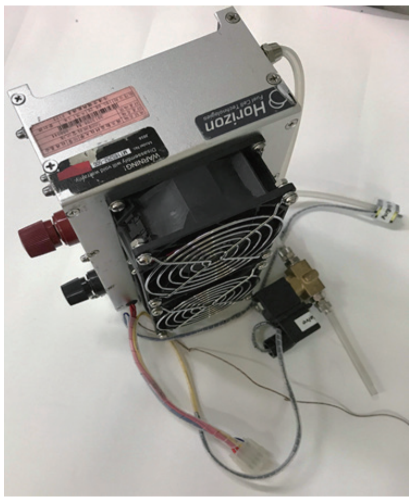

Fig. 2. (Color online) Commercially available fuel cell stack.

Table 1
Detailed specification sheet for 500 W fuel cell.

Type of fuel cell	PEM
Number of cells	36
Rated power	500 W
Performance	21.6 V @ 24 A
H_2 supply valve voltage	12 V
Purge valve voltage	12 V
Blower voltage	12 V
Reactants	Hydrogen and air
External temperature	5–30 °C
Maximum stack temperature	65 °C
H_2 pressure	0.45–0.55 bar
Hydrogen purity	≥99.995% dry H_2
Humidification	Self-humidified
Cooling	Air
Stack weight (with fan and casing)	2.8 kg
Controller weight	0.4 kg
Size	21.5 × 12.5 × 18 cm^3
Maximum flow rate of hydrogen	7 L/min
Start-up time	≤30 s at ambient temperature
Efficiency of stack	40% @ 21.6 V
Low-voltage shutdown	18 V
Overcurrent shutdown	30 A
Over-temperature shutdown	65 °C
External power supply	13 V (±1 V), <5 A

stack and to allow the reactant gas to enter the flow channel smoothly. Protection for fuel cell stacks is also indispensable. Commercially available fuel cell protection mechanisms include low-voltage, overcurrent, load transient, temperature, and foolproof protection mechanisms. When the above protection measures are activated, the LED above the controller flashes and the built-in buzzer starts and sounds. The load is turned off through the controller to stop any power output and to avoid reducing the lifetime of the fuel cell stack.

3. Controller Design and Experimental Method

3.1 Controller design

We use an Arduino Mega2560 control board in this study, which has a digital, analog or UART output (hardware serial ports). It can be modified to increase flexibility and convenience for the designer. Figure 3 shows the Arduino board and components. This self-built controller can control the supply valve, purge valve, and fan. It contains two types of sensors: a temperature sensor and a voltage sensor. If the fuel cell stack is at a high temperature or a high voltage, the sensor transmits a signal to the controller to shut it down and protect the fuel cell stack. Figure 4 shows the components of the self-built controller. The completed self-built controller is shown in Fig. 5.

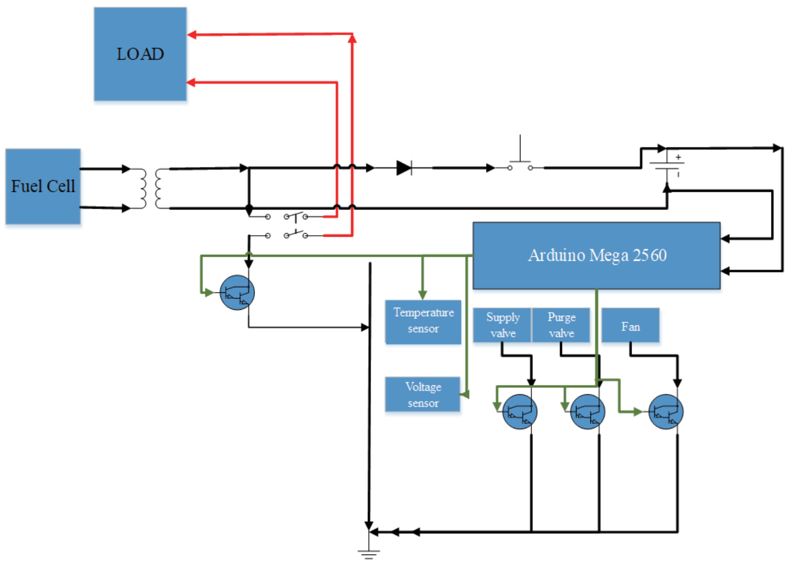

Fig. 3. (Color online) Self-built controller circuit.

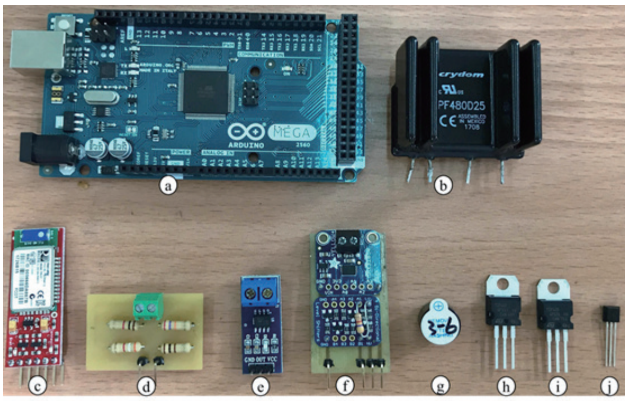

Fig. 4. (Color online) Components of self-built controller. (a) Arduino Mega2560 control board. (b) Relay. (c) Bluetooth transmitter. (d) Voltage sensor. (e) Current sensor. (f) Temperature sensor. (g) Buzzer. (h) T102 transistor. (i) T120 transistor. (j) 2n2222a transistor.

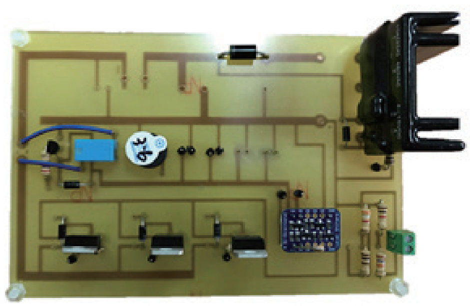

Fig. 5. (Color online) Controller circuit completion diagram.

3.2 Purge valve control strategy and experimental setup

The experimental setup is shown in Fig. 6 and the equipment used in the fuel cell stack experiment is shown in Fig. 7. In this experiment, we installed a pressure regulator at the anode inlet to supply hydrogen at a constant pressure. A magnetic valve that is normally closed blocks

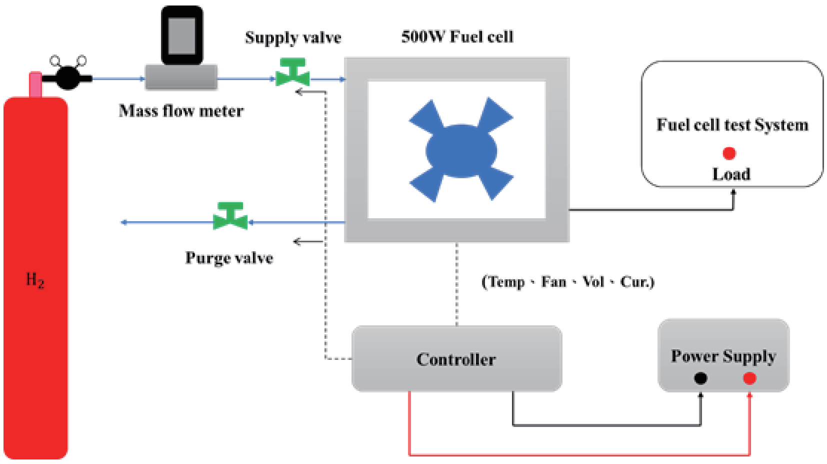

Fig. 6. (Color online) Schematic of experimental setup.

Fig. 7. (Color online) Experimental setup. (A) Power supply. (B) Pressure valve and hydrogen mass flow meter. (C) Fuel cell stack and self-built controller. (D) Loader. (E) Monitoring software. (F) Gas supply.

the anode inlet when the fuel cell stack is operating. During the operation, liquid water gradually penetrates from the cathode to the anode and accumulates in the anode channel, degrading the PEMFC performance. The proposed improvement method removes the accumulated impurities and water by opening the rear magnetic valve at the anode outlet.

The rear magnetic valve can also be called a purge valve. Its purge time parameters include the purge interval and duration. Experiments were carried out using different settings, and these two parameters were compared. We used a commercially available 500 W fuel cell stack. After writing the program with Arduino and uploading it to the Arduino Mega2560 control board, the fuel cell controller was fabricated with a PCB circuit board and set to different experimental conditions. The reaction gas at the anode was set as hydrogen at room temperature. The cathode uses a fan to induce the convection of air. The fan speed was changed according to the internal fuel cell temperature. A hydrogen mass flowmeter and a pressure regulator were installed at the anode gas inlet. The hydrogen mass flowmeter was mainly used to detect hydrogen consumption to set the subsequent hydrogen consumption. In the utilization rate experiment, the pressure regulator was fixed to set the fuel cell pressure. The load was manually set by the fuel cell test platform according to the experimental conditions.

3.3 Control purge time experiment under different load conditions and hydrogen consumption

After the experimental setup was completed, experiments with different purge times were carried out. A hydrogen pressure of 0.5 bar was used on the anode side. The load was supplied to the fuel cell stack by the fuel cell test platform in the constant voltage mode. The load setting range has three modes: low load (28 V), medium load (26 V), and high load (24 V). If the purge time exceeds 1.2 s, the gas purge time is very long and can easily damage the fuel cell stack. Therefore, the purge duration was set to 0.2, 0.4, 0.6, 0.8, and 1 s. The purge interval and duration were set in the experiment. The experimental time was 15 min and the optimal strategy setting was found. We compared the proposed controller with the commercially available controller.

4. Experimental Results

4.1 Low-load experiment (28 V)

In this experiment, Arduino was used to write a program and a PCB circuit board was used to build a controller. Different purge conditions were set, and the effect of increasing the hydrogen usage was examined. The low-load (28 V) purge intervals were 6, 8, 10, and 12 s. The purge duration was set to 0.2, 0.4, 0.6, 0.8, and 1 s. A 28 V constant voltage load was applied to investigate the fuel cell stack performance. From each purge interval experiment, the duration with the highest performance was selected, and its performance was compared with those of the other purge intervals. The power output, hydrogen consumption, and power produced per gram of hydrogen were used to make strategic choices of the controller at different loads.

Figure 8 shows that in the low-load experiment, the fuel cell stack had the lowest hydrogen consumption when the purge duration was 0.2 s. The hydrogen consumption decreased with increasing purge interval but increased with increasing purge duration, Figure 9 shows that the fuel cell stack with the purge duration set to 0.2 s every 12 s had the lowest hydrogen consumption and the highest power generation. The power generated was 25.22 W and the total hydrogen consumption was 1.83 g.

4.2 Medium-load experiment (26V)

In the medium-load experiment, the purge interval was set to 4, 6, 8, 10, and 12 s and the purge duration was set to 0.2, 0.4, 0.6, 0.8, and 1 s. The experimental time was 15 min. Figure 10 shows that the fuel cell stack had the lowest hydrogen consumption when the purge duration was 0.2 s. The total hydrogen consumption and power generation for different control strategies are shown in Fig. 11. The hydrogen consumption when the valve was purged for 0.2 s every 12 s was

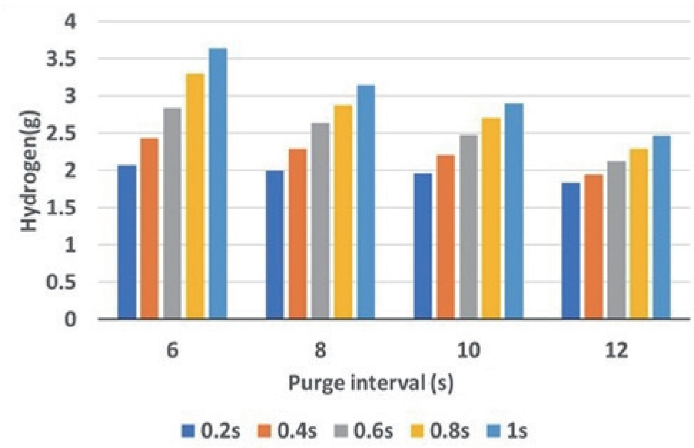

Fig. 8. (Color online) Comparison of hydrogen consumption at low load.

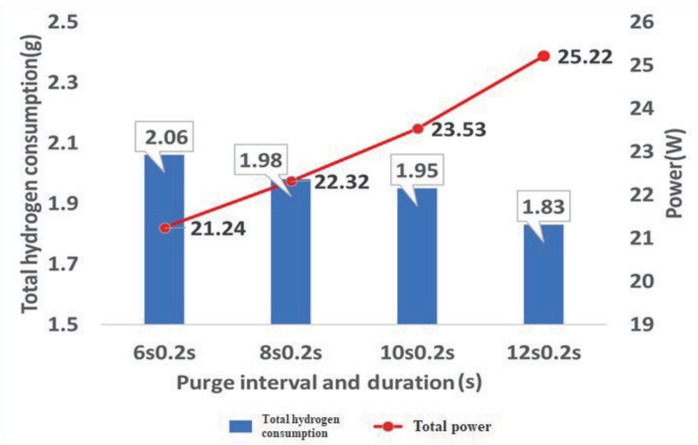

Fig. 9. (Color online) Comparison of total hydrogen consumption and total electricity at low load.

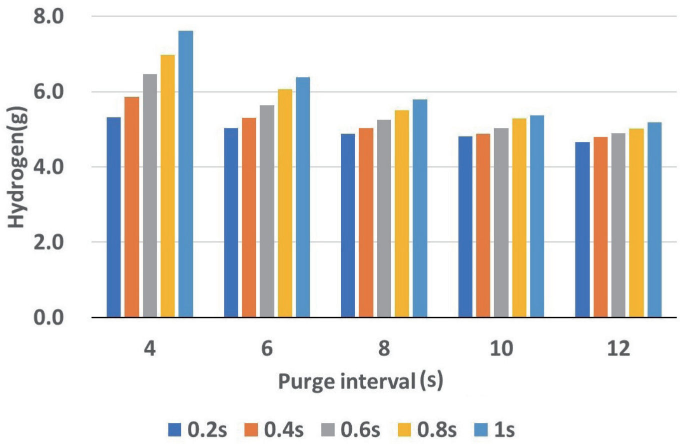

Fig. 10. (Color online) Comparison of hydrogen consumption at medium load.

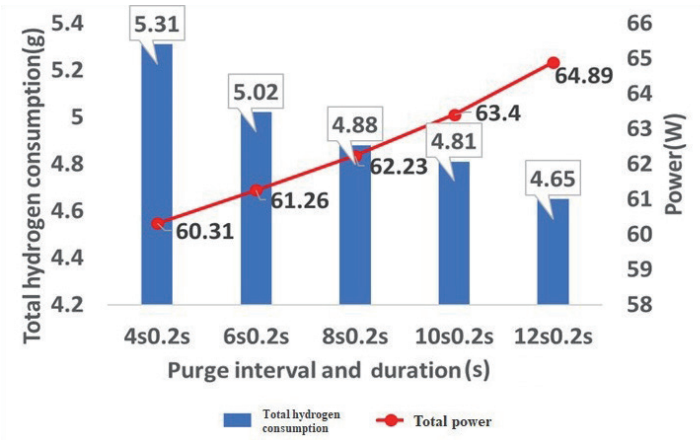

Fig. 11. (Color online) Comparison of total hydrogen consumption and total electricity at medium load.

4.65 g and the power generation was 64.89 W. This control strategy produced the lowest hydrogen consumption and the highest power generation and is the best strategy at a medium load.

4.3 High-load experiment (24 V)

In the high-load experiment, the purge interval was set to 2, 4, 6, 8, and 10 s and the purge duration was set to 0.2, 0.4, 0.6, 0.8, and 1 s. Figure 12 shows that the 0.2 s purge duration produced the lowest hydrogen consumption. Figure 13 shows the hydrogen consumption and power generation for different purge intervals and durations. The control strategy of 0.2 s purge duration for every 10 s operation produced the lowest hydrogen consumption in the high-load experiment.

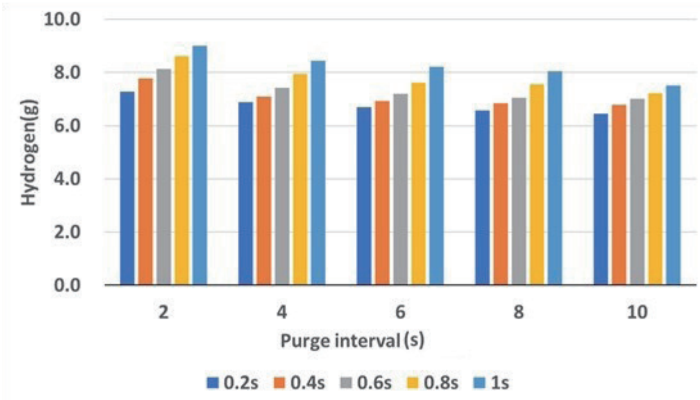

Fig. 12. (Color online) Comparison of hydrogen consumption at high load.

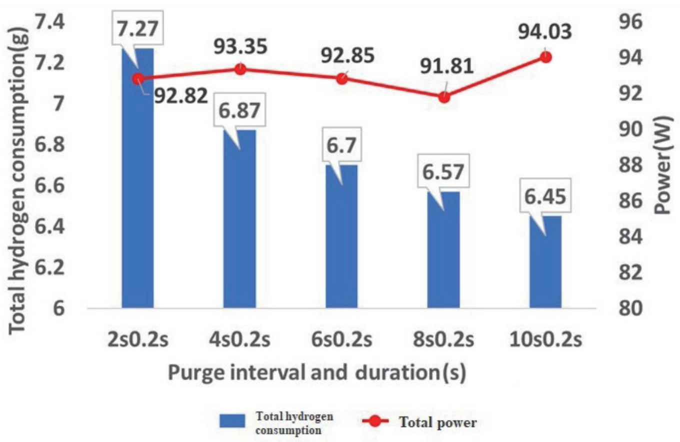

Fig. 13. (Color online) Comparison of total hydrogen consumption and total electricity at high load.

4.4 Comparison of self-built and commercially available fuel cell controllers

In the low-load experiment, the best self-built controller strategy was 0.2 s purge for every 10 s operation. We compared the self-built controller with a commercially available fuel cell controller. The self-built controller strategy was set in two modes: 0.2 s purge for every 12 s operation and 1 s purge for every 10 s operation. The average output, total power generation, total hydrogen consumption, and hydrogen usage for the self-built and commercially available controllers are shown in Table 2. The self-built controller with 0.2 s purge for every 12 s operation showed higher efficiency and performance than the commercially available controller under the same conditions.

In the medium-load experiment, the best self-built controller strategy was to purge every 0.2 s for every 12 s operation. Table 3 shows that the power generation and hydrogen usage using the self-built controller with the best control strategy were better than those using the commercially available controller under the same conditions.

Table 2
Low-load experiment.

Item	Controller type		
	Self-built controller (every 12 s purge 0.2 s)	Self-built controller (every 10 s purge 1 s)	Commercially available controller (every 10 s purge 0.2 s)
Average output (W)	100.87	82.39	90.85
Total power generation (Wh)	25.21	20.59	22.71
Total hydrogen consumption (g)	1.99	2.71	2.14
Hydrogen usage (Wh/g)	12.66	7.59	10.61

Table 3
Medium-load experiment.

Item	Controller type		
	Self-built controller (every 12 s purge 0.2 s)	Self-built controller (every 10 s purge 0.2 s)	Commercially available controller (every 10 s purge 0.2 s)
Average output (W)	259.57	208.44	240.79
Total power generation (Wh)	64.89	52.11	60.19
Total hydrogen consumption (g)	4.65	5.36	5.00
Hydrogen usage (Wh/g)	13.95	9.72	12.03

Table 4
High-load experiment.

Item	Controller type		
	Self-built controller (every 10 s purge 0.2 s)	Self-built controller (every 10 s purge 0.2 s)	Commercially available controller (every 10 s purge 0.2 s)
Average output (W)	375.01	358.04	326.43
Total power generation (Wh)	93.75	89.51	81.60
Total hydrogen consumption (g)	6.45	8.14	7.00
Hydrogen usage (Wh/g)	14.53	10.99	11.65

In the high-load experiment, the best control strategy for the self-built controller was to purge every 0.2 s for every 10 s operation. As shown in Table 4, the best performance was for the self-built controller with 0.2 s purge for 10 s operation, the worst performance was for the self-built controller with 1 s purge every 10 s operation, and the commercially available controller had a performance that falls between these two extremes. This experiment also shows that the self-built controller has better performance than the commercially available controller at a high load.

5. Conclusions

We analyzed the effect of different purge intervals and durations of the valve in the controller of a 500 W fuel cell stack. The load was set at three levels, namely, low (28 V), medium (26 V), and high (24 V), and the experimental time was 15 min. Experimental results show that a purge every 0.2 s for 12 s operation is the best power generation control strategy at both low and medium loads. At a high load, the best control strategy is to purge 0.2 s for every 10 s operation. In experiments, these control strategies resulted in higher performance than that of a commercially available controller at all three loads. The hydrogen consumption is partially controlled by the purge valve, which effectively reduces the consumption compared with that of a commercially available controller.

Acknowledgments

The experimental activities in this study were supported by the Air Conditioning and Energy Department of National Chin-Yi University of Technology (NCUT), Taiwan, and the Ministry of Science and Technology of Taiwan (MOST 105-2221-E-167 -027 and MOST 106-2221-E-167 -023).

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