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Short communication

Medium-term stability testing of proton exchange membrane fuel cell stacks as independent power units ☆

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Abstract

A fuel cell stack needs to be stable and high-performing for optimum commercial viability. A program was undertaken to evaluate stability of a number of proton exchange membrane (PEM) fuel cell stacks and systems by operating them as independent power units at the rated maximum power outputs. Eight convection/forced-convection stacks and systems ranging in power outputs from 3 W to 150 W were evaluated for periods ranging from 170 h to 700 h. One 300 W forced-flow stack was evaluated for an 8-h period. All stacks and systems were operated self-humidified. The flow of hydrogen was kept dead-ended with periodic release to maximize its utilization. In general, the stability was observed to be excellent except of the smallest convection stack, which showed some variations from point to point. The documented stability behaviors indicate that stack and system designs were appropriate, the level of self-humidification was adequate, and that the tested products are ready for commercialization.
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1. Introduction

For practical application of a fuel cell as a power unit, and for the success of commercialization, a fuel cell system has to exhibit excellent stability and performance characteristics. The stability signifies the appropriateness of the design and operating conditions of the fuel cell. In addition to the fuel cell being stable, the percentage of utilization of reactants has to be high, and the power consumption for running the accessories, low. This article will deal with measurements of stability of proton exchange membrane (PEM) fuel cells fabricated at the BCS Fuel Cells, Inc. facility. The power consumption for running accessories will be kept at a minimum, and the control unit comprising the accessories will be operated as efficiently as possible. The primary focus of this article will be on convection-type fuel cells. Some data will be also presented for the forced-flow type fuel cells.

BCS Fuel Cells, Inc. develops and markets PEM fuel cells that operate in a simplified manner, requiring no humidification of reactants [1–4]. Fuel cells of two different modes of operation are manufactured: convection-type (or air-breathing) fuel cells and the regular (or forced-flow-type) fuel cells. A convection-type fuel cell requires the forced input of hydrogen only; the fuel cell picks up air from the atmosphere under natural or forced convection. A regular, forced-flow-type fuel cell, as its name implies, requires the forced input of reactants, air, and hydrogen.

The convection-type fuel cells evaluated for this article ranged in power output from 3 W to 150 W. A single forced-flow-type fuel cell of rated power output of 300 W was evaluated for the stability tests. A fuel cell stack combined with a control unit powered by that same fuel cell constituted a fuel cell system. A control unit comprising the accessories may contain components that do not consume power. Thus,

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the fuel cell stack along with the control unit becomes an independent power unit. Fuel cell stacks and systems using convection stacks were operated for periods ranging from 170 h to 700 h for evaluation of their stability characteristics near their rated maximum power outputs. One forced-flow stack system was operated for 8-h period to demonstrate that the observed stability characteristics are not restricted to the type of PEM fuel cells examined.

2. Experimental

2.1. Convection/forced-convection stacks

All fuel cell stacks were fabricated in-house using membrane-electrode assemblies also made in-house. The membrane was the commercially available Nafion® 112 proton exchange membrane. The control unit, inclusion of which makes a fuel cell stack an independent power unit (or a system), was made in-house with the help of a local company specializing in building electronic parts and components. It operated at 80% efficiency, consuming power of about 1–10 W, depending on the size of the fuel cell system examined. The control unit performed two functions: keeping the flow of hydrogen dead-ended by periodic release and regulating the speed of cooling fans, which also supplied the reactant air for the fuel cell operation.

The power unit for a convection stack requires only the input of hydrogen for its operation. The required accessories to operate under dead-ended conditions and the cooling fans were powered by the fuel cell stack whenever the stack voltage was at 6 V or higher. Thus, all stacks, except the 3 W 2.5 V and 10 W 2.5 V stacks, were operated as independent power units during stability tests. For the 3 W 2.5 V and 10 W 2.5 V stacks, the control unit was powered by a DC power supply.

The fuel cells exhibited utilization of hydrogen of about 98%. Such high utilization was achieved by keeping the systems dead-ended with periodic release during operations. As well, airflow by convection achieves maximum utilization of air in convection stacks. The air utilization percentage in a convection stack, however, is not calculable since the actual airflow cannot be measured easily. In the forced-flow stack, the air stoichiometry was kept 1.5–1.75, corresponding to air utilization in the range 57–67%.

With the hydrogen valve completely open, the required power can be withdrawn instantaneously. Thus, the stacks and systems had load-following capability with respect to hydrogen flow. A pushbutton valve for the startup of one power unit was introduced. This valve would start the flow of hydrogen, and the unit could produce the power required. No startup battery was needed for any of the convection/forced-convection fuel cell systems.

The fuel cell stack was conditioned for stability tests by operating it for a few hours before the start of the test. Data collection began when the stack attained steady-state temperature at the maximum rated power output of the stack or the system. Only when an empty hydrogen cylinder had to be replaced was the unit stopped for about 3–5 min, then started up again.

The pure convection method provided the reactant air for operating the 3 W 2.5 V, 10 W 2.5 V, and 10 W 6 V stacks. For the first two of these three power units, the control unit was powered by a DC power supply, as the control unit required a minimum of 6 V dc for its operation. Fuel cell stacks above 10 W-rated were operated under forced convection conditions. For the 10 W 6 V unit, the control unit was powered by the fuel cell stack as for other larger units, except that the cooling function of the control unit was not utilized.

All fuel cell stacks were operated self-humidified, requiring no additional outside humidification of reactants. The self-humidification developed by BCS Fuel Cells, Inc. allows operation of fuel cell systems under much wider temperature ranges, extending it up to 343 K.

Stacks were cooled either by radiation or by radiation combined with air cooling. Three stacks as identified above—3 W 2.5 V, 10 W 2.5 V, and 10 W 6 V stacks—were cooled by radiation alone. All other stacks were cooled by radiation and air cooling combined.

Hydrogen pressure for all stacks was kept at 6.9–20.7 kPa (1–3 psig) for dead-ended operations with periodic releases of about 0.3 s duration every 15 seconds for the length of the test. Air pressure was atmospheric under free convection and slightly above atmospheric under forced convection. It was important to insure adequate water removal from both air and hydrogen channels for stable performance. Free water flow was particularly important at the air channels, since air pressure was atmospheric.

The voltage data were recorded periodically at a constant current, and plots made of the power outputs versus time of operations.

2.2. Forced-flow stack

One forced-flow stack, 300 W 12 V, was tested for stability for 8 h. This stack required the forced inputs of both air and hydrogen for its operation. The air pressure was about 41 kPa and the hydrogen pressure, 20 kPa. The stack temperature was controlled in the range 333–338 K. The control unit and other accessories used were similar to those used with convection/forced-convection stacks. This stack also required a cooling unit for its operation. The cooling unit was powered by an AC power supply.

3. Results

3.1. Convection/forced-convection stacks

The stability data were recorded for the following eight convection/forced convection fuel cell stacks designated by

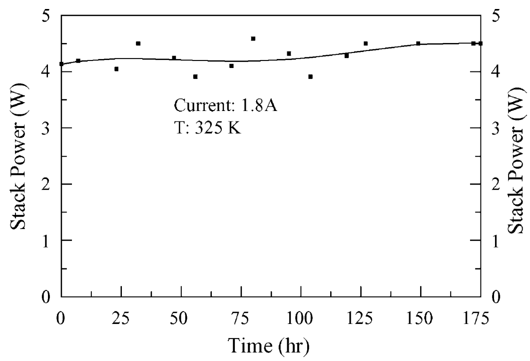

Fig. 1. Stability data of 3 W 2.5 V rated fuel cell stack at the constant current of 1.8 A and at the temperature of 325 K.

their nominal power and voltage ratings: 3 W 2.5 V, 10 W 2.5 V, 10 W 6 V, 25 W 13 V, 35 W 13 V, 30 W 6 V, 60 W 13 V, and 150 W 15 V. Duration of stability tests ranged from 1 week to 4 weeks (about 170–700 h).

The convection/forced-convection fuel cell stacks mentioned above can be further classified into two groups: pure convection and forced convection. The first three stacks—3 W 2.5 V, 10 W 2.5 V, and 10 W 6 V—are pure convection stacks. The remaining five stacks—25 W 13 V, 35 W 13 V, 30 W 6 V, 60 W 13 V, and150 W 15 V—are forced-convection stacks.

Figs. 1 and 2 show stability data of 3 W 2.5 V and 10 W 2.5 V convection stacks, respectively. Each stack was operated for about 170 h. Since the voltage of each cell was below 6 V, the control unit, which required a minimum of 6 V for operating these stacks, was powered by a DC power supply. Thus, these two stacks do not quite come under the category of an independent power unit for purposes of assessing stability data. Both stacks had four cells, differing only in the size of the electrode area. The 3 W-rated stack had an electrode area of 10 cm^2 per cell and operated at 180 mA cm^{-2}. The 10 W-rated stack had the electrode area of 25 cm^2 per cell, and operated at a current density of 160 mA cm^{-2}.

Fig. 3 shows the stability data of 10 W 6 V system. The electrode area per cell was 10 cm^2. This system is the smallest purely convection stack with adequate voltage (6 V) to power the control unit. Thus, this is the smallest system tested as a completely independent power unit. The system was operated for about 350 h under natural convection at a current density of 130 mA cm^{-2}.

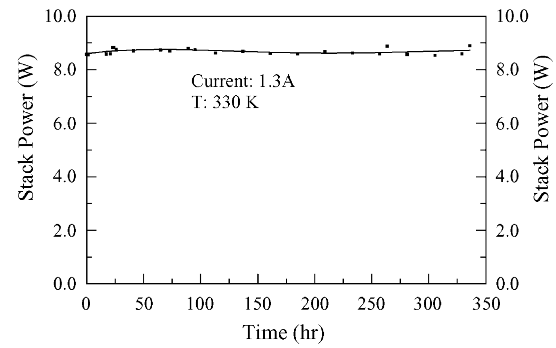

Fig. 3. Stability data of 10 W 6 V rated fuel cell system at the constant current of 1.3 A and at the temperature of 330 K.

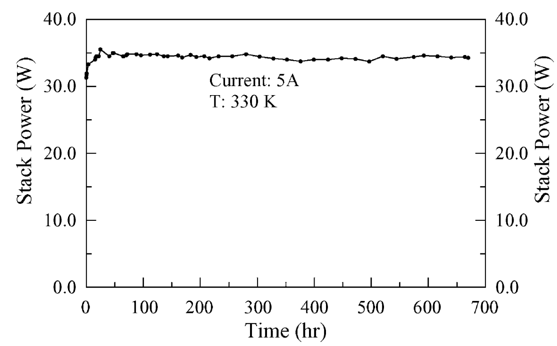

Fig. 4. Stability data of 30 W 6 V rated fuel cell system at the constant current of 5 A and at the temperature of 328 K.

Fig. 4 shows the stability data of 30 W 6 V system as an independent power unit. The electrode area per cell was 25 cm^2. This is the smallest stack operated under forced convection of air. The system was operated for about 700 h at a current density of 200 mA cm^{-2}.

Fig. 5 shows stability data of 25 W 13 V system operating at 1.8 A, corresponding to current density of 180 mA cm^{-2}.

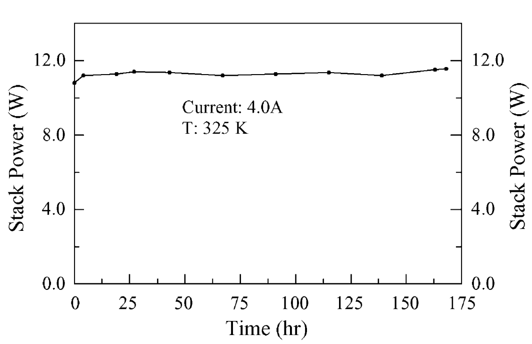

Fig. 2. Stability data of 10 W 2.5 V rated fuel cell stack at the constant current of 4 A and at the temperature of 325 K.

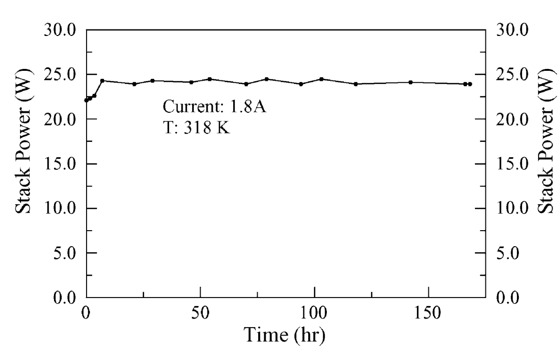

Fig. 5. Stability data of 25 W 13 V rated fuel cell system at the constant current of 1.8 A and at the temperature of 318 K.

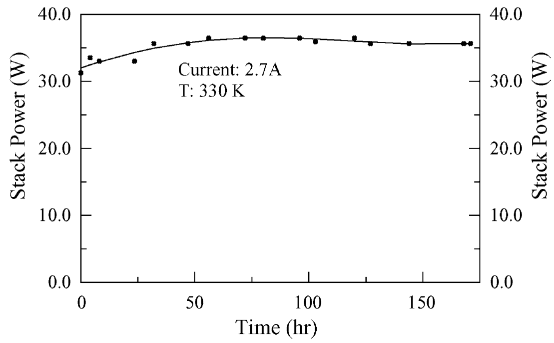

Fig. 6. Stability data of 35 W 13 V rated fuel cell system at the constant current of 2.7 A and at the temperature of 330 K.

The system was operated for about 175 h. Fig. 6 shows stability data of 35 W 13 V system operating at 2.7 A, corresponding to current density of 270 mA cm^{-2}. This system also operated for about 175 h. These two systems were built for two different commercial applications. One provided up to 25 W of power and the other up to 35 W of power. The latter system operated at higher power output (2.7 A versus 1.8 A). The difference in power was a function of the amount of reactants passed into the stacks and also the extent of cooling provided: the stack of Fig. 6 required more cooling than that of the stack in Fig. 5.

Fig. 7 shows stability data of 60 W 13 V system, operated for about 175 h. The electrode area was 25 cm^2 per cell. The current density was about 180 mA cm^{-2}.

Fig. 8 shows stability data of 150 W 15 V system operating for about 250 h. The electrode area was 50 cm^2 per cell. The current density was about 180 mA cm^{-2}.

3.2. Forced-flow stack

Fig. 9 shows stability data of 300 W 12 V forced-flow stack for a period of 8 h. Prior to starting data collection, the stack was conditioned by operating 4–6 h during two-day period. The current density was 400 mA cm^{-2} at 0.625 V at the nominal power output of the system.

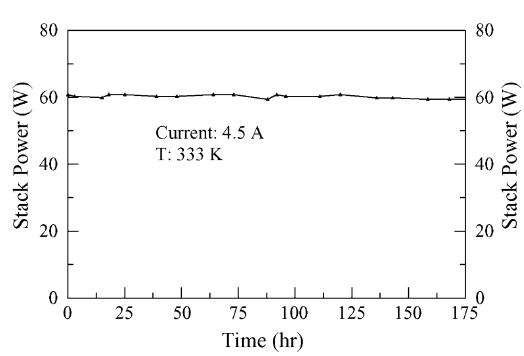

Fig. 7. Stability data of 60 W 13 V rated fuel cell system at the constant current of 4.5 A and at the temperature of 333 K.

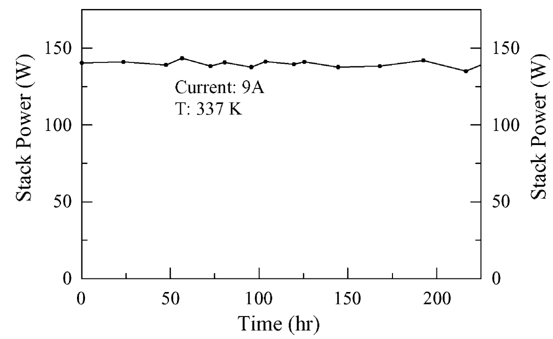

Fig. 8. Stability data of 150 W 15 V rated fuel cell system at the constant current of 9 A and at the temperature of 337 K.

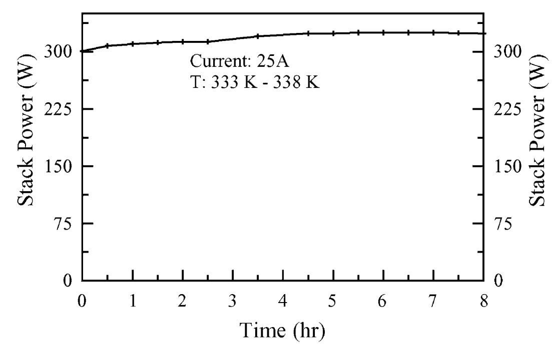

Fig. 9. Stability data of 300 W 12 V rated fuel cell system at the constant current of 25 A and at the temperature range of 333–338 K.

4. Discussion

4.1. Temperature rise in fuel cell stacks

Because of some inherent inefficiency of a fuel cell, not all of the available power is obtained as electricity; some power is dissipated as heat energy. The heat energy, however, can be recovered in larger system and put to good use. The fuel cells mentioned above were all operated at steady-state temperatures obtained under a particular set of operating conditions. This steady-state temperature is, of course, dependent on the power output and the amount of cooling provided. The operating temperature was in the range of 313–338 K.

4.2. Stability of stacks and systems

In general, the collected data exhibited excellent stability. Even though noticeable variations from point to point were observed in some fuel cells, the overall stability during the test periods was excellent. The overall drop in performance during the test periods was generally not significant. The most variation from point to point was observed in the smallest convection stack. Of all the stacks tested, the 3 W 2.5 V stack operating under free convection showed the most variation in the stability data (Fig. 1). Because of the relatively low power output of this stack, the stack temperature rises very slowly.

During the slow rise in temperature, water accumulates in the air channels and causes the drop in performance. Also, the small stack thickness and comparatively larger end plates may also be responsible for hindering the free convection to some extent. On the other hand, the 10 W 2.5 V stack, which had a larger electrode area, showed excellent stability over the period of the test. The relatively quick rise in temperature may have contributed to water removal from the air channels in this stack.

All other stability data shown in Figs. 3–8 of the convection/forced convection class refer to multi-cell stacks containing 10 cells and more. There, the relatively rapid rise in temperature and proprietary features of water removal combined helped to keep the channels clear of any accumulated water.

Fig. 9 showing data of the forced-flow stack, does not have the limitation of water removal from the flow channels, as the reactants pass through the channels under forced flow conditions.

4.3. Self-humidification

Figs. 1–3 represent pure convection stacks. Excellent stability observed in these stacks indicates that the level of self-humidification achieved was sufficient at the temperatures of operation and power output levels.

With reference to Figs. 4–8, it is noted that under forced convection conditions, air is blown into fuel cell stack. There was no additional humidification of either air or hydrogen. The excellent stability observed indicates that self-humidification of the fuel cell was sufficient also under forced convection conditions. This, in turn, indicates that during the forced convection of air, the airflow into the fuel cell stack is just sufficient to maintain the humidity level in the fuel cell. Although the air stoichiometry in a convection and forced-convection stack is not calculable, it is inferred that the flow cannot be very high, as airflow does not degrade the performance by drying the electrodes.

The forced-flow 300 W 12 V stack, with stability data shown in Fig. 9, was also operated under self-humidified conditions. Excellent stability of this system indicates that the self-humidification was sufficient to maintain continuous operation.

4.4. Advantages and disadvantages of convection/forced convection fuel cell stacks

In this class of fuel cells, air flows by passive means with the minimum expenditure of power into the fuel cell. Usually, free convection or forced convection with the help of one or few fans is sufficient to provide the air needed for the fuel cell operation.

Since the convection fuel cell operates under free air flow conditions without encountering any resistance to its flow, the current density is usually lower than that obtained under forced-flow conditions.

Low power density makes the volume of the fuel cell comparatively large. However, convection fuel cell stacks are easy to assemble, start, and operate without an elaborate arrangement for the airflow and stack cooling.

4.5. Comments on current density of convection/forced-convection stack

In general, the current densities obtained in a convection stack are less than that obtained in a regular forced-flow stack. In the results presented, the range of current densities obtained is 130–270 mA cm^{-2}. The comparatively lower values are due to the fact that convection/forced convection stacks operate at near atmospheric pressures of air, the parameter most influencing the current density. Also, elaborate cooling methods, such as passing water or any liquid through the stack, are not practical. Only air cooling is a practical and simple means of cooling a convection stack. When the stack is operated at a higher current density, air cooling would be insufficient and liquid cooling would be needed to adequately cool the stack. Another reason for low current density is that the open vertical channels for air flows needed for convection stacks cannot accept very high flows of air without making the stack dryer. A dry cell, of course, would lead to a much lower current density. Thus, a balanced flow of air that will maintain a reasonable power output from the fuel cell is required. The operations of various systems in the above range of current densities maintain continuous operations of the fuel cell systems under the conditions evaluated.

Convection stacks are operated under a slight excess pressure of hydrogen. The hydrogen pressure does not have much effect on current densities. A way to increase the current density is, of course, to use a very high catalyst loading on the cathode side or to use highly active catalysts. This area of study is undergoing continuous changes. The author has tested various catalysts of different activities. With a highly active catalyst, a very low loading can be used. The activity of the platinum catalyst is dependent on the method of production of the catalyst, type and treatment of carbon support material, and subsequent mixing of the catalyst with the carbon support material.

4.6. Comments on current density achieved in the forced-flow system

The current density achieved in 300 W 12 V stack was about 400 mA cm^{-2} at 0.625 V at the nominal power output of the system. This is reasonable for a forced-flow fuel cell system.

4.7. System efficiency

System efficiency depends on a number of factors: fuel efficiency (extent of fuel utilization), power consumption by accessories to operate as an independent power unit, and voltage efficiency. To illustrate these factors in the case of the 60 W system above, following are the parameters:

- Net power output: 60 W.
- Fuel efficiency: 98%.
- Power consumption by the control unit: 2.5 W (2 W at 80% efficiency).
- Voltage efficiency: 57%.

One first calculates the total power output taking into account the total hydrogen consumption: net power output is divided by fuel efficiency, and adding to it the power lost for operating the accessories. Next, the net power output is divided by the total power, and multiplied by the voltage efficiency. So, the overall system efficiency of the 60 W system is about 53.7%, arrived according to the following steps:

$$\left(\frac{60}{(60/0.98)+2.5}\right)\times 0.57 = 53.7\%.$$

5. Conclusions

A program of study was undertaken to test stability of BCS-produced fuel cell stacks. These were mostly convection/forced convection stacks, and one forced-flow stack. Most of the tests were conducted as systems to constitute independent power units. The presented data show that the fuel cell stacks and systems in general demonstrated excellent stability during these tests. The results validate the following:

- Proper design, assembly, and operation of the power units.
- Adequate self-humidification.
- Instantaneous startup.
- Adequate water removal from the anode and cathode chambers.
- Operation under maximum hydrogen utilization.
- High air utilization.
- No parasitic loss due to avoidance of humidification and associated required water purification.

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