The test-bed research of a low power low-temperature PEM fuel cell

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Abstract. The article presents the results of testbed research of Horizon H-300 PEM Fuel Cell. It is a Polymer Electrolyte Membrane Fuel Cell (PEMFC) which reaches 300 Watt output power. It is a power source for hyper-light prototype vehicles taking part in the Shell Eco-Marathon competition. The aim of the research was to develop the load characteristics of a PEM type cell. The tests were carried out in a steady state of operation and included developing the characteristics of the output voltage concerning the load current. The current load was carried out by a programmable electronic load with the ability to accurately determine the load current. It also allows for measuring the output voltage. The tests were carried out in the load current range 0.2 - 7A, which is a significant range of the cell’s operating parameters which is used in the vehicle. During the tests, hydrogen consumption was also measured at individual points of the cell’s operation using a flow meter. This has also allowed the development of the characteristics of fuel consumption and power generated by the cell. The developed characteristics are presented in this article. A linear characteristic of power and fuel consumption in the function of the current loading on the cell was obtained for practically the whole range of the tested loads. Also, the specific fuel consumption is linearly dependent on the load power, and the lowest values (in the example the highest efficiency) were obtained at the lowest value of load power.

1. Introduction

Today’s automotive technology is mainly based on internal combustion engines using fossil fuels as an energy source. Such a solution, dating back to the early twentieth century, causes high air pollution, emitting both toxic compounds and large amounts of greenhouse gases. Currently, methods are being searched to reduce these emissions or eliminate them completely [1-3].

One of the methods is to use hydrogen as a fuel. It is used both in conventional internal combustion engines and in new technologies based on flameless oxidation, which is the separation of an electron from an element without an accompanying flame [4-7]. This second approach is particularly interesting. It uses the phenomenon of reverse electrolysis, which consists in the release of the electron from the hydrogen molecule, and then merging of hydrogen with oxygen contained in the air. For this purpose special devices called fuel cells are used. It can therefore be said that fuel cells are converters of chemical energy contained in hydrogen into electricity. Their unquestionable advantages in the automotive industry are zero emissions, noiselessness, no moving or rotating parts, low operating temperature (about 65 – 85°C), high power density, omitting the combustion process during energy conversion, and the ability to start at low temperatures [5-8].
Fuel cells consist of three main components: anode, cathode, and electrolyte. In fuel cells with polymer electrolyte on the anode, a fuel (hydrogen) oxidation reaction occurs, followed by electron separation. On the cathode, however, the oxidant is reduced and electrons from the anode are attached. The purpose of the electrolyte is to physically separate the electrodes to block the flow of electrons between the electrodes and to conduct fuel-hydrogen ions very well. Electrons – electrical energy is dissipated through an external electrical circuit connected to the load. Due to the slow oxidation and reduction reactions, thin layers of catalysts are used on the electrodes – in this case, platinum. This construction is repeated several dozen times in series with auxiliary elements (bipolar plates, end plates, current collectors, seals) and is called a stack of fuel cells [10-12].

For the operation of fuel cells, auxiliary equipment is needed, among other things, for supplying gases, discharging reaction products, controlling temperature, and electrical parameters (controllers). In the further development of fuel cells with polymer electrolytes, solutions are being sought to produce cheaper and more durable materials for solid electrolytes. Research is also being conducted on new catalysts to replace expensive platinum or to reduce the amount of catalyst required. A philosophy of controlling gas flows and temperatures is also being developed based on the parameters of its operation [11-13].

In today’s automotive industry, more and more large car corporations are trying to develop their designs of hydrogen-powered cars. Mass production includes Toyota Mirai, Honda Clarity, Hyundai ix35, but brands such as BMW, Mercedes, and Volkswagen also research this subject. In addition, many bus models carry passengers in larger cities, as well as emission-free tractor models. According to data from h2stations.org, the number of hydrogen stations in Europe has more than doubled from 82 to 177 between 2016 and January 2019 (the largest number of hydrogen filling stations is in Germany) [14]. It can therefore be said for sure that interest in hydrogen as a fuel is growing year on year and this may be the cause of the next industrial revolution [13-15].

In current PEM fuel cells, the value of the output voltage generated depends on the amount of electricity drawn from the cell. The higher the current drawn from the cell, the lower the voltage generated by the cell, with this characteristic not being linear [6-9, 15, 17-21]. This characteristic is very important when designing drive systems based on cells. This is due to the limitations of actuator systems (electric motors) and, above all, control systems. Too high voltage can lead to damage to the circuit, and too low voltage can lead to a significant drop in efficiency or, in extreme cases, to switching off the powered system. In addition, the load value also changes the efficiency of the cell.

When building a propulsion system aimed at maximising the energy conversion efficiency of the entire system – as is the case with the Hydros prototype vehicle designed by the Student’s Scientific Association for Aircraft Propulsion – accurate knowledge of the cell’s characteristics is essential. This article presents the method of testing the fuel cell and the results of testing the selected cell.

2. Research description

2.1. Research object
The research was carried out on PEM type hydrogen cell (with polymer electrolyte), low power model – Horizon H – 300 PEM Fuel Cell (Figure 1.) was chosen. This cell is used in the prototype vehicle “Hydros” created within the scope of the work of the Students’ Scientific Association for Aircraft Propulsion, where it is one of the main elements of the propulsion system. Its task is to convert the chemical energy contained in hydrogen into electrical energy supplying the brushless electric motor. Selected technical parameters of the cell are shown in Table 1. The original controller of the cell was used during the research.

2.2. Test stand
The diagram of the test stand is shown in Figure 2. It included elements such as hydrogen cylinder, Swagelok pressure regulator, electro valve, Vogtlin Instruments Red-y GCM flow meter, programmable electronic load AXEL300W AXIOMET, UNI-T UTP3305 DC power supply. The
tests were carried out in a well-ventilated room, for observation of hydrogen concentration in the air. A digital hydrogen (H2) gas leakage detector was used.

Figure 1. Horizon H – 300 PEM Fuel Cell used in test-bed research as research object [16] A-H2 inlet connector; B – H2 outlet connector; C – Fuel cell air inlet side.

Figure 3 shows the test stand during the experiment. A 0.4-liter gas cylinder (compressed to a maximum pressure of 200 bar) was used as a fuel tank. The pressure from the cylinder was reduced through a single-stage Swagelock pressure regulator. This regulator is equipped with pressure gauges allowing for measuring the pressure in the cylinder and the pressure at the outlet of the regulator. The output pressure was manually set at 0.5 bar of relative pressure.

To measure hydrogen consumption, a Red GCM flow meter (a flowmeter calibrated by Shell for the Shell Eco-Marathon) was used. The figure also shows a programmable load which is a receiver of energy produced by the cell.

Table 1. Technical specifications Horizon H - 300 PEM Fuel Cell.

| Parameter                      | Value                        |
|-------------------------------|------------------------------|
| Number of cells               | 60                           |
| Rated Power                   | 300 W                        |
| Performance                   | 36V at 8.3 A                 |
| H2 supply valve voltage       | 12V                          |
| Purging valve voltage         |                              |
| Blower voltage                |                              |
| Reactants                     | Hydrogen and Air             |
| External temperature          | 5 – 30 ºC                    |
| Max. Stack temperature        | 65 ºC                        |
| H2 Pressure                   | 0.45 – 0.55 bar              |
| Hydrogen purity               | ≥99.995% dry H2              |
| Humidification                | Self – humidified            |
| Cooling                       | Air (integrated fans)        |
| Flow rate at max output       | 3.9 l/min                    |
| Efficiency of stack           | 40% at 36V                   |
| Low voltage shut down         | 30 V                         |
| Over-current shut down        | 12 A                         |
| Over-temperature shut down    | 65 ºC                        |

*Source: Own study using data provided by the manufacturer [16].
2.3. Scope and method of research
The tests were conducted in a wide range of operating parameters of a fuel cell. The system was loaded through the programmable electronic load as a load current in the range of 0.2 – 7A every 0.2A. The electronic load was also used to read the hydrogen cell voltage. Hydrogen consumption was monitored using a flow meter located on the hydrogen supply side of the fuel cell. All measurements were recorded in the steady-state of operation.

Hydrogen from the cylinder was supplied at a pressure of 0.5 bar relative pressure (1.5 bar absolute pressure). To ensure safety, the original cell controller was used during testing and potential hydrogen leaks from the fasteners were monitored. The ambient conditions were 31°C (304K) and 1014hPa.

This article aimed to develop and verify the method of measuring cell characteristics. A comparison of the results with the manufacturer’s data will allow assessing the correctness of the developed method and will provide a basis for the evaluation of cell aging during its use. As noted in the works [20, 21], the cell characteristics change (deteriorate) during its life. In this research, data on the new cell will be collected before its use during the competition. They will be the basis for the assessment of the degree of changes in the characteristics during further use.

3. The results of the tests
The results are presented in Table 2. During the tests, the values of voltage, current flow rate, and fuel consumption were measured and the power and specific fuel consumption were calculated on their base. This made it possible to develop the characteristics of the cell – Figures 4 and 5.
Table 2. The results of the tests.

| Current I [A] | Voltage U [V] | Hydrogen flow Q [l/min] | Power P [W] | Specific fuel consumption Ge [l/Wh] |
|---------------|---------------|--------------------------|-------------|-------------------------------------|
| 0.2           | 53.419        | 0.00                     | 10.684      | 0.000                               |
| 0.4           | 52.900        | 0.18                     | 21.160      | 0.510                               |
| 0.6           | 50.250        | 0.26                     | 30.150      | 0.517                               |
| 0.8           | 50.400        | 0.34                     | 40.320      | 0.506                               |
| 1.0           | 49.200        | 0.42                     | 49.200      | 0.512                               |
| 1.2           | 49.184        | 0.50                     | 59.021      | 0.508                               |
| 1.4           | 48.319        | 0.58                     | 67.647      | 0.514                               |
| 1.6           | 48.011        | 0.66                     | 76.818      | 0.516                               |
| 1.8           | 47.830        | 0.75                     | 86.094      | 0.523                               |
| 2.0           | 46.700        | 0.82                     | 93.400      | 0.527                               |
| 2.2           | 46.858        | 0.92                     | 103.088     | 0.535                               |
| 2.4           | 47.115        | 1.00                     | 113.076     | 0.531                               |
| 2.6           | 46.065        | 1.07                     | 119.769     | 0.536                               |
| 2.8           | 46.483        | 1.17                     | 130.152     | 0.539                               |
| 3.0           | 45.787        | 1.25                     | 137.361     | 0.546                               |
| 3.2           | 45.624        | 1.34                     | 145.997     | 0.551                               |
| 3.4           | 44.100        | 1.40                     | 149.940     | 0.560                               |
| 3.6           | 45.501        | 1.47                     | 163.804     | 0.538                               |
| 3.8           | 44.451        | 1.60                     | 168.914     | 0.568                               |
| 4.0           | 44.073        | 1.66                     | 176.292     | 0.565                               |
| 4.2           | 44.622        | 1.76                     | 187.412     | 0.563                               |
| 4.4           | 44.363        | 1.85                     | 195.197     | 0.569                               |
| 4.6           | 43.375        | 1.92                     | 199.525     | 0.577                               |
| 4.8           | 43.387        | 2.01                     | 208.258     | 0.579                               |
| 5.0           | 41.800        | 2.06                     | 209.000     | 0.591                               |
| 5.2           | 43.126        | 2.19                     | 224.255     | 0.586                               |
| 5.4           | 42.895        | 2.26                     | 231.633     | 0.585                               |
| 5.6           | 42.206        | 2.32                     | 236.354     | 0.589                               |
| 5.8           | 42.536        | 2.44                     | 246.709     | 0.593                               |
| 6.0           | 41.560        | 2.51                     | 249.360     | 0.604                               |
| 6.2           | 40.977        | 2.60                     | 254.057     | 0.614                               |
| 6.4           | 41.031        | 2.70                     | 262.598     | 0.617                               |
| 6.6           | 41.519        | 2.77                     | 274.025     | 0.607                               |
| 6.8           | 41.493        | 2.84                     | 282.152     | 0.604                               |
| 7.0           | 40.763        | 2.96                     | 285.341     | 0.622                               |

Measurement errors were also analysed. The error value of the load current of the cell was determined as:
\[ \Delta I = \pm(0.1\% \cdot I + 0.15\%FS) \]  

(1)

Where:

FS – measuring range  
FS = 30A  
I – the value of current at a specified measuring point

The error value was therefore determined for each measuring point. For example for the 16th measurement point:

\[ \Delta I_{16} = \pm(0.1\%3.2A + 0.15\%30A) = \pm 0.048A \approx \pm 0.05A \]  

(2)

Similarly, the error of measuring the cell voltage was determined:

\[ \Delta U = \pm(0.05\% \cdot U + 0.15\%FS) \]  

(3)

Where:

FS – measuring range  
FS = 150 V  
U – the value of the voltage at a specified measuring point

The error value was therefore determined for each measuring point. For example:

\[ \Delta U_{16} = \pm(0.05\% \cdot 45.624V + 0.15\%150V) = \pm 0.0603V \approx \pm 0.06V \]  

(4)

The value of the power determination error was calculated from the formulas:

\[ P = U \cdot I \]  

(5)

\[ \Delta P = \pm \left( \frac{\delta P}{\delta U} \cdot \Delta U + \frac{\delta P}{\delta I} \cdot \Delta I \right) = \pm \left( I \cdot \Delta U + U \cdot \Delta I \right) \]  

(6)

For example:

\[ \Delta P_{16} = \pm(3.2A \cdot 0.06V + 45.624V \cdot 0.05A) = \pm 2.39207W \approx \pm 2.4W \]  

(7)

\[ P_{16} = 3.2A \cdot 45.624V = 145.997W \approx 146W \]  

(8)

\[ \Delta Q = \pm(1\%FS) \]  

(9)

\[ \Delta Q = \pm(1\% \cdot 5000 \text{ ml/min}) = \pm 50 \text{ ml/min} = 0.05 \text{ ln/min} \]  

(10)

Where:

FS = 5000 ml/min

The error value for determining the specific fuel consumption was calculated from the formulas:

\[ \frac{Q \cdot 60}{P} \]  

(11)

For point 16. the error is:

\[ Ge_{16} = \frac{1.34\%}{145.99W} \cdot \frac{l}{Wh} = 0.55 \frac{l}{Wh} \]  

(12)

\[ \Delta \geq \pm \left( \frac{\delta Ge}{\delta P} \cdot \Delta P + \frac{\delta Ge}{\delta Q} \cdot \Delta Q \right) = \pm \left( \frac{60}{P} \cdot \Delta Q + \frac{60 \cdot Q}{p^2} \cdot \Delta P \right) \]  

(13)

\[ \Delta Ge_{16} = \pm \left( \frac{60}{145.99W} \cdot \frac{l}{145.99W} + \frac{60 \cdot 1.34\%}{145.99^2W^2} \cdot 2.4W \right) = 0.0164 \frac{l}{Wh} \]  

(14)
Figure 4. The voltage dependence on the current affecting the PEM fuel cell (in steady-state of operation) created during testing (measurements) compared with characteristic developed by the manufacturer.

In Figure 4, the results of the research on the dependence of the voltage generated by the cell on the value of the current drawn from it are presented. The measurement points and the data from the manufacturer have been plotted [16]. The tests captured an incomplete range of voltage and current characteristics. At low current consumption of 0-0.8A, a large voltage drop caused by activation losses (related to the slow course of electrochemical reactions) is visible. With increasing current consumption, losses caused by the cell’s internal resistance have a greater impact. During the tests, the rated current of 8.3A above which, according to the manufacturer’s characteristics, there is another sharp voltage drop caused by diffusion losses (lack of appropriate amount of fuel) was not exceeded. It is also visible that the characteristics practically coinciding with the manufacturer’s data were obtained.

Figure 5 shows the power characteristics obtained during the tests and those obtained from the manufacturer's data [16]. The power curve determined experimentally to 5A shows an almost linear course. Above this current consumption, it starts to gradually decrease its slope. Within this range, the power curve practically coincides with the power curve presented by the manufacturer.

Figure 5. The power dependence on the current affecting the PEM fuel cell (in steady-state of operation) created during testing (measurements) compared with characteristic developed by the manufacturer.
Figure 6. The hydrogen consumption dependence on the power affecting the PEM fuel cell (in steady-state of operation) created during testing (measurements) compared with characteristic developed by the manufacturer.

Figure 6 shows the nature of fuel consumption during the tests in comparison with the manufacturer’s data [16]. The hydrogen consumption increases linearly until it reaches about 250W when both characteristics show a clear increase in hydrogen consumption. During the experiment, however, higher fuel consumption was obtained than declared by the manufacturer. These differences are particularly noticeable in the central part of the characteristics, where actual consumption is even 15% higher than declared by the manufacturer.

Figure 7. The unit power dependence on the power affecting the PEM fuel cell (in steady-state of operation) created during testing (measurements).
The hydrogen specific consumption by volume (Figure 7) in the range 20W to 280W increases linearly from 0.5 l/Wh to 0.62l/Wh. The slight gradient of the graph's lines reflects the almost linear characteristic of hydrogen consumption as a function of power. Thus, a decrease in hydrogen conversion efficiency is visible as the cell load increases. This change is significant and amounts to about 25% between the lower and highest constant load of the cell.

4. Conclusions
As mentioned earlier, knowledge of the exact characteristics of the cell is key to maximising the efficiency of the Hydros propulsion system. After analysis of the characteristics created, it can be concluded that:

- the determined voltage-current characteristic shows a decrease in voltage as the cell load increases and largely coincides with the manufacturer’s characteristics throughout its range. only at the end of the test phase (from 6.6A) did better results than the standard ones were obtained;
- the power characteristics of the cell show high linearity of the power pattern when increasing the load. In the range 0.2-6.4A it coincides with the characteristics given by the manufacturer, in the range 6.6 to 7A better performance of the cell than expected by the manufacturer was recorded (the reference characteristic starts to fall. while the experimentally determined one keeps the linear characteristic);
- Fuel consumption also depends virtually linearly on the cell load. However, a difference can be seen between the power-dependent hydrogen consumption characteristics determined experimentally and those provided by the manufacturer, especially in the middle of the characteristics;
- the volumetric hydrogen unit consumption in the range from 20W to 280W increases linearly from 0.5l/Wh to 0.62l/Wh. This means that the cell is the most efficient at low loads and as the load increases, the efficiency decreases (unit consumption increases).

When designing a drive system based on this hydrogen cell, it would therefore be necessary to keep the constant load on the cell as low as possible. This will allow the system to be more efficient. The voltage values generated by the cell should also be taken into account. At low loads, this voltage is high, which can be problematic for receiving systems. Thus, a compromise approach to the selection of the cell's operating point is necessary and must be based on optimising the entire drive system. where the efficiency of the receiving systems (motor and supercondenser) will also be taken into account. However, the above studies have made it possible to collect the required data for the work on the powertrain. Differences between the data provided by the manufacturer and the test results shown in the characteristics may be caused by different ambient conditions between the tests carried out by Horizon Fuel Cells Technologies and the bench tests carried out by the students of the Scientific Association. The manufacturer states that the tests were carried out at sea level and an ambient temperature equal to room temperature (15 to 25°C). while students were testing the object at 31°C in a building situated approximately 183 metres above sea level.

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