Some aspects of gaseous hydrogen storage and the performance of a 10-kW Polymer Electrolyte Membrane Fuel Cells stack as part of a hybrid power source

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Abstract. A 10-kW polymer electrolyte membrane fuel cell (PEMFC) stack was designed and built as part of a hybrid power source to supply a motor glider. The power of the PEMFC stack reached ~10 kW for the electrical parameters I = 61 A, U = 153 V. The time of operation of the stack under an electrical load close to 10 kW was strongly dependent on the pressure of the hydrogen fuel stored composite tanks, which could be varied from 220 bar for 30 min to 700 bar for 80 min. It was found that the electrical efficiency of the constructed 10-kW PEMFC stack was greater than 50%.

1. Introduction

Hydrogen is a secondary energy carrier, i.e. it must be produced from primary energy sources such as fossil fuels, biomass, solar energy, wind, hydropower, or nuclear power. Potentially, the hydrogen economy will make it possible to take advantage of local sources of energy, reducing the dependence of the energy sector on imported fuels in accordance with sustainable development. Another advantage arising from the conversion of hydrogen to usable energy is its negligible effect on the environment [1-3]. The expected climate changes are forcing the aviation industry to reduce emissions. The application of hydrogen as an alternative fuel for combustion in engines is still being considered on a global basis. Another approach is the use of electric motors instead of internal combustion engines. In the design of energy systems for supplying electric motors, some electrochemical power sources, including batteries, supercapacitors, and hydrogen fuel cells, are being considered for use. Of these three sources, fuel cells will provide the greatest amount of available energy that can be produced by a relatively light power unit (fuel cell stack + hydrogen tank + small accessories to control system...
operation). Compared to fuel cells, electrochemical accumulators and, to an even greater extent, supercapacitors are characterised by unfavourable values of energy density (the amount of energy stored in a unit of mass). Their advantage is high power density (generated power ÷ mass of the device) [4].

Fuel cells are electrochemical devices which directly convert the chemical energy of fuel into electrical energy. The waste products of this conversion are heat and water/water vapour. Hydrogen is the main practical fuel that can be used in the present generation of fuel cells, mainly due to the electrochemical reactivity of hydrogen compared with that of the more common fuels from which it is derived, such as hydrocarbons, alcohol, or coal. Moreover, its reaction mechanisms are well understood and characterised by the relative simplicity of their reaction steps, which do not lead to by-products. As opposed to batteries, fuel cells can be operated as long as they can be continuously supplied with reagents. Polymer electrolyte membrane fuel cells (PEMFCs) appear to be the main type of fuel cells used for the construction of power sources forming part of hybrid sources to supply electric motors in Unmanned Aerial Vehicle, (UAV) small aircraft, motor gliders, and planes [5,6].

In recent years there has been a greater number of consumers of electricity, including specific consumers with extremely high electrical load profiles Environmental Control System (e.g. electric ECS), flight control system, landing gears), which equates to a much greater demand for electric power. An aircraft’s auxiliary power unit generates on-board electricity for air conditioning and other functions, particularly during the on-ground period and during preparation for take-off. It is believed that relatively small fuel cell units, such as auxiliary power units for on-board electricity supply, can be applied and can begin to play an important role in reducing energy consumption. Moreover, they can be used as energy sources for emission-free hydrogen-based taxis and regional airport infrastructure. They are needed as well for underground operations (not only for flights), especially those forming part of an airport’s infrastructure [7,8]. The idea of hydrogen fuelling stations has been developed in many countries, as hydrogen refuelling is much faster than charging batteries [9,10]. The main problem associated with the practical application of hydrogen for supplying power sources involving fuel cells is the amount which can be stored aboard an aircraft. Various hydrogen storage technologies have been developed around the world, but in the case of aircraft applications additional restrictive requirements concerning the construction dimensions and mass of the aircraft must also be taken into account when choosing an appropriate technology. Storage of compressed hydrogen in ultra-light composites was the technology most frequently applied in the first attempts to supply fuel cells in a small aircraft [11,12].

The aim of this paper is to present some results of an investigation of the electrical performance of a constructed 10-kW PEMFC stack under static and electrical load supplied with hydrogen stored in ultra-light composite tanks. Special attention was also paid to the utilisation of hydrogen for the production of electrical energy and the purification process (“purge”).

Figure 1a. Diagram of installation components of hybrid power sources in a motor glider

Figure 1b. Location for placement of a 10-kW PEMFC stack within the fuselage
2. Experimental

Analysis of the energy system requirements for ensuring the attainment of flight altitude in air by a motor glider with a speed of up to 0.5 m/s and a horizontal flight mission indicated that electrical energy of 10 kW is required. To meet these electrical energy requirements, a 10-kW PEMFC stack was designed and built. According to the construction dimensions and mass of the motor glider, the total weight of power sources, including the PEMFC stack, installed composite hydrogen fuel tanks, and all accessories, should not exceed 80 kg.

The dimensions of the PEMFC stack are limited by the space available in the fuselage of the motor glider. A diagram of the construction of the motor glider, including the space in which to place the PEMFC stack, is presented in Figure 1a, b.

The first part of the experiment required the calculation of the flow rate of hydrogen necessary to supply a 10-kW PEMFC stack. The stack required 130 dm³ H₂/min to operate at maximum electrical power. The hydrogen source chosen to supply the PEMFC stack was gaseous fuel, compressed to 220-300 bar in an ultra-light composite cylinder. In Poland the maximum legal compression of hydrogen is ~220 bar. In cases where higher compression pressure is needed, a special apparatus (hydrogen boosters) should be applied to increase the pressure of hydrogen in composite bottles. Two LC12.0-30A composite cylinders (Horizon, Fuel Cell Technologies Singapore) with a total capacity of 24 Ndm³ will be installed on board the motor glider (as shown in figure 1a). The volume of stored hydrogen in the composite tanks is calculated at 3,025 Ndm³ at a pressure of 300 bar, which makes it possible to power the electric motor mostly from fuel cells, enabling the glider to fly horizontally for 40 minutes.

The stationary setup for the investigation of a 10-kW PEMFC stack with a laboratory hydrogen fuel installation is presented in figures 2a- b. The setup consists of two LC12.0-30A composite tanks (1), each with a capacity of 12 Ndm³ and a permissible pressure of 300 bar, connected to a common shut-off valve (2) and high pressure regulator (300 to 10 bar) (3), which lowers the pressure to 5–10 bar. This pressure range is acceptable for a short-distance hydrogen supply line to a PEMFC fuel cell generator (6) with a single common pipe. Near the electrochemical devices, the supply line divides into two lines, supplying hydrogen to PEMFC stacks (A) and (B). Due to permissible pressure drops at high flow rates > 65 Ndm³/min, two LP (low-pressure) electronic regulators (10 bar to 0.5 bar) (4) are installed at a distance of < 30 cm to control the hydrogen gas inlet pressure (at a level of 0.5 bar +/- 0.05 bar). In addition, two solenoid inlet valves, monitored by a stack controller, are installed just before the location where hydrogen is supplied to the anode chamber of the PEMFC stack. These comprise a hydrogen supply electrovalve (5) and a hydrogen-out ‘purge’ solenoid valve (7). Also included are two hydrogen safety sensors (8) used to monitor the system to detect low levels of H₂ in the environment.

Figure 2a. Setup for investigation of a 10-kW PEMFC stack with a laboratory hydrogen fuel installation
Figure 2b. Photo of the experimental setup for a stationary test of the 10-kW PEMFC stack
3. Results

Figure 3 presents variations in voltage ($U$), current ($I$), and power ($P$) vs time for a 10-kW PEMFC stack, recorded under an applied dynamic load. The analysis of electric parameters recorded for the constructed PEMFC stack indicated that the power output of the stack achieved the expected power of 10 kW within the applied time period. This preliminary result enabled us to conduct further research focused on determining the electrical efficiency of the PEMFC stack.

**Figure 3.** Variation of voltage ($U$), current ($I$) and power ($P$) over time vs applied variable electrical load.

**Figure 4.** Voltage ($U$)-current ($I$) and power ($P$)-current ($I$) relationships recorded for the 10-kW PEMFC stack.
Figure 4 presents the voltage ($U$)-current ($I$) and power ($P$)-current ($I$) relationships recorded for the 10-kW PEMFC stack in the course of further investigations. It can be observed on the $U$-$I$ curve that the open-circuit voltage (OCV) of the stack is ~220 VDC. As the current increases, the voltage decreases linearly to approximately 153 V at 61 A. As the current increases, the power of the PEMFC stack increases linearly, but does not yet reach its maximum point. The power of the stack reaches ~10 kW for the electrical parameters $I = 61$ A, $U = 153$ V. The analysis of the recorded $U$-$I$ curve and calculated values of electrical power ($P$) vs variation in current ($I$) indicates that the electrochemical power source has not yet reached the so-called maximum power output $P_{\text{max}}$, after which the electrical load of the power source from the fuel cell should lead to a decrease in electrical power produced by the investigated electrochemical source. During PEMFC stack performance, the temperature did not exceed 65ºC. The stationary fan controlling the air flow was adjusted to maintain the temperature of the PEMFC stack under load within a safe operating temperature range for electrochemical devices, i.e. below 65ºC, and the average temperature was maintained at approximately 55ºC, ensuring optimal operation of the stack.

The gaseous hydrogen in the PEMFC stack is used as well to produce electrical energy for the purification (or ‘purge’) requirements of the PEMFC stack itself. The problem of utilisation of hydrogen stored in tanks at pressures under 220 bar was analysed for the 10-kW PEMFC and separately for 5-kW PEMFC stack (A) and (B). The most important task in the application of fuel cells is to find fuel storage methods which will enable operation of the PEMFC stack over a long period of time during flight. The amount of compressed hydrogen in composite tanks depends on the applied pressure. Figure 5 presents an analysis of the variation of volume of hydrogen vs applied hydrogen pressure as well as the expected time of operation of the 10-kW PEMFC stack.

As can be seen, the volume of compressed hydrogen increases gradually with applied compression pressure. The time of operation of the 10-kW PEMFC stack also increases with increasing hydrogen pressure and volume. The expected time of operation of the 10-kW PEMFC stack under different partial pressures was also experimentally verified. Data for hydrogen compressed under pressures of 200 (A), 120 (B) and 80 (C) bar is also shown in this graph. The expected time of operation of a PEMFC stack with electrical power of 10 kW for composite tanks of hydrogen compressed under 200 bar is 31.8 min; the actual time of operation was 30 min. However, in the case of fuel compressed under pressures of 120 or 80 bar, the ratio between expected and operating times was 19/18 min or
15/13 min, respectively. One of the important parameters determining the efficient operation of a PEMFC stack as a power source is the pressure of hydrogen at the time it is being supplied to the anode chamber in PEMFC stacks (A) and (B). In the case of the 10-kW PEMFC stack, which consists of two 5-kW PEMFC stacks, stabilisation of hydrogen partial pressure is required, to a level of 500 mbar for each module. Figure 6 presents variation in the inlet pressure of hydrogen supplied to the anode chambers vs time, recorded for a 10-kW PEMFC stack supplied by hydrogen from composite tanks. The hydrogen was compressed at 180 bar.

As can be seen in figure 6, the orange curve shows the mean value of the hydrogen stabilisation pressure via an automatic electronic pressure regulator at the fuel cell module hydrogen inlet. Hydrogen inlet pressure (the dark blue curve) changes as a result of the anode flushing system (the purge valve opens every 10 seconds). It can be observed that, throughout the tested load range of the PEMFC stack supplied by hydrogen from composite cylinders located next to the PEMFC fuel cells, a suitable hydrogen flow rate is provided, maintained by the pressure regulator at the level \( p = 500 \) mbar) required by the device. The PEMFC stack therefore must be powered by hydrogen from composite cylinders located nearby to avoid pressure losses on the excess supply line.

The gaseous hydrogen in the PEMFC stack is used to produce electrical energy as well as for the (purge) requirements of the stack itself. In order to define the efficiency of the 5-kW PEMFC stack during its operation under variable load, the flow rate of hydrogen fuel \( Q_{H_2} \) [dm\(^3\)H\(_2\)/min] was measured and recorded as shown in figure 7. Hydrogen pressure changes \( p_{H_2} \) [bar] at the inlet to the PEMFC stack were also measured and recorded during operation under load as shown in figure 8.

![Figure 7. Hydrogen fuel consumption \( Q_{H_2} \) [dm\(^3\)H\(_2\)/min] of the PEMFC stack during operation under electrical load.](image-url)
Figure 8. Hydrogen pressure $p_{\text{H}_2}$ [bar] at the inlet to the PEMFC stack (A) or (B) during operation under electrical load.

The red baseline curve (as seen in figure 7) corresponding to the minimum value of the recorded hydrogen flow rate shows the actual hydrogen consumption for the electrochemical reaction occurring in the PEMFC stack. The amount of hydrogen consumed by the PEMFC module during its operation increased as the electrical load of the stack surged. The black line, visible in figures 7 and 8 in the form of peaks, corresponds to the increased hydrogen flow caused by openings (which occur every 10 seconds, with a duration of approximately 100 ms) of the normally closed purge solenoid valve located at the hydrogen outlet of the 5-kW stack. The solenoid openings are triggered by the fuel cell stack controller, allowing the hydrogen to flow freely in order to purge it of the anodic humidity and gaseous hydrogen coming from the cathodic side, which accumulates in the normally closed enclosure and results in the dilution of hydrogen fuel, which in the long run can lead to diminished performance of the electrochemical device. Due to construction requirements, it is vital to maintain the constant pressure of the hydrogen supply at the value required by the cell, i.e. $p = 0.5$ bar (+/- 0.05 bar), in order for the correct amount of hydrogen to reach all of the cells in the stack. Figure 8 shows that the hydrogen pressure at the inlet to the PEMFC stack was maintained at the required level of 0.45–0.55 bar; the visible pressure increased at 750, 1,750, and 3,000 seconds, resulting from the manual adjustment of the pressure reducer valve situated on the hydrogen supply line to keep the pressure at the required level. This confirms the need for an automatic hydrogen pressure regulator which will maintain a steady hydrogen pressure at the inlet to the PEMFC stacks regardless of the pressure drop caused by the varying electrical load of the device.
Figure 9. $P_{ic}$ – internal power consumption of the PEMFC stack and $\eta_{H2} \%$ – utilisation of hydrogen fuel depending on the total power $P_T$ produced by the PEMFC stack (A) or (B).

Figure 10. Electrical diagram of fuel cell stack efficiency $\eta$ and hydrogen consumption $V_{H2}$ according to electrical power $P$ level at the terminals of the PEMFC stack (A) and (B).

The performance of the purge system (figure 8) improves the performance of the 5-kW PEMFC stack; however, it causes a loss of hydrogen fuel associated with periodic flushing of the anode, and prevents the hydrogen fuel being delivered to the PEMFC stack from being converted in full to usable energy. The degree of utilisation of hydrogen in the PEMFC stack equals $\eta_{H2} \%$, depending on the power taken from the investigated power source. Figure 9 was calculated as the ratio of hydrogen
consumed by the fuel cells for the electrochemical reaction (the area under the red curve in figure 7) to the total consumption of hydrogen by the PEMFC stack (the area under the black curve in figure 7). The degree of utilisation of hydrogen, i.e. $\eta_{H2} \%$, reaches more than 90% at a 1.5 kW load and is maintained at 90–95% for higher loads. The diagram in figure 9 shows $P_{IC}$ (internal power consumption), i.e. the power needed internally by the PEMFC stack for electrical loads up to 3.5 kW to maintain $P_{IC}=45$ W due to the minimum power consumed by the control system of the cooling fans, which rotate at a constant minimum speed. It is only after a power level of 3.5 kW is exceeded that we can see a clear increase in the demand for internal power as a result of the forced cooling of the PEMFC stack by the air fans.

On the basis of the measurements and analyses of hydrogen consumption (figure 10), it was determined that the hydrogen consumption of the 5-kW PEMFC stack increased linearly with PEMFC electrical output power and reached a value of approximately 65 dm$^3$/min for 5 kW of rated electrical power.

The energy efficiency of the fuel cell was calculated from the following formula (1):

$$\eta = \frac{E_{el}}{E_{H2}}$$

which is the ratio of the electricity $E_{el}$ generated at the terminals of the fuel cell stack to the chemical energy $E_{H2}$ of hydrogen consumed during operation of the fuel cell (assuming a calorific value of 1 m$^3$ of hydrogen at 20°C of $H_{H2} = 11.92$ [MJ/m$^3$]). Figure 10 presents an electrical diagram of PEMFC stack efficiency and hydrogen consumption according to the electrical power at the terminals of the stack. The high efficiency of the stack (over 50%) is achieved when the power is above 500 W and remains at this high level up to a maximum load of approximately 5kW. When the power exceeds a level of approximately 3 kW, we can observe a slight decrease in energy efficiency, which means the losses in the PEMFC stack increase as heat raises the temperature. This necessitates intensified cooling of the stack so as not to exceed the maximum permissible operating temperature.

4. Conclusions

A 10-kW PEMFC stack with an air cooling system was constructed. The power of the stack reached the desired electrical power of 10 kW; moreover, this value was below the peak limit of its performance, indicating that the investigated power source can supply surplus electrical power for a short period of time. The expected time of operation with a power of 10 kW was established at 30 min for a stack supplied by hydrogen compressed to 220 bar. The application of higher pressures to the hydrogen stored in composite tanks should lead to an increase in time of operation. Stable values of hydrogen pressure were observed at a location just before the inlet to the anode chambers of PEMFC stacks (A) and (B). The rate of utilisation of hydrogen for electrical energy production, as well as for purging, was also determined. The electrical efficiency of the stack was found to be more than 50%.

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References

[1] Ball M, Basile A and Veziroglu N T, 2016 Compendium of Hydrogen energy Vol 1-4 (Woodhead Publishing series in Energy, Elsevier)
[2] Ball M and Weeda M 2015 The hydrogen economy, Vission and reality? Int. J. Hydrog. Energy 25 7903-7919
[3] Brostow W and Hagg Lobland H E, 2017 Materials: Introduction and Applications (John Wiley & Sons)
[4] Garche J, 2014 Encyclopedia of electrochemical power sources Vol 1-4 (Elsevier)
[5] Guida D and Minutillo M, 2017 Design methodology for a PEM fuel cell power system in a more electrical aircraft Applied Energy 192 446-456

[6] Hartung I, Kirsch S, Zibrul P, Müller O and Unwerth T, 2016 Improved electrochemical in-situ characterization of polymer electrolyte membrane fuel cell stack J. Power Sources 307 280-288

[7] Elitzur S, Rosenband V and Gany A, 2017 On-board hydrogen production for auxiliary power in passenger aircraft Int. J. Hydrog. Energy 42 14003-14009

[8] Yilmaz I, İlbaş M, Taştan M and Tarhan C, 2012 Investigation of hydrogen usage in aviation industry Energy Convers. Manag. 63 63-69

[9] 2016 Idemitsu opens its first commercial hydrogen station at Narita airport Fuel Cells Bulletin 3 8

[10] 2015 Norway opens new hydrogen station at Oslo Airport Fuel Cell Bulletin 10 9-10

[11] Hua T Q, Roh H S and Ahluwalia R K, 2017 Performance assessment of 700-bar compressed hydrogen storage for light duty fuel cell vehicles Int. J. Hydrog. Energy 42 25121-25129

[12] Sinigaglia T, Lewiski F, Martins M E SandSiluk J C M, 2017 Production, storage, fuel stations of hydrogen and its utilization in automotive applications- a review Int. J. Hydrog. Energy 42 24597-24611