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The use of fuel cells to store energy from renewable sources

Abstract. *The paper characterizes the design, operation, classification and application of fuel cells and presents a proposal of an analysis of the cooperation of a laboratory hydrogen fuel cell with photovoltaic modules that constitute the power source for an electrolyser. The results of the tests conducted can constitute a substantive teaching basis.*

Streszczenie. *W pracy scharakteryzowano budowę, zasadę działania, klasyfikację i zastosowania ogniw paliwowych oraz przedstawiono propozycję analizy współpracy laboratoryjnego ogniwa wodorowego z modułami fotowoltaicznymi, stanowiącymi źródło zasilania dla elektrolizera. Wyniki przeprowadzonych doświadczeń mogą stanowić merytoryczną bazę w dydaktyce.(**Wykorzystanie ogniw paliwowych do magazynowania energii ze źródeł odnawialnych**)*

Keywords: types of fuel cells, electrolyser, hydrogen fuel cell, photovoltaic conversion, efficiency
Słowa kluczowe: rodzaje ogniw paliwowych, elektrolizer, ogniwo paliwowe wodorowe, konwersja fotowoltaiczna, sprawność

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Introduction

Fuel cells were used as early as during the Apollo space program, where they were used to generate electric energy and warm water on board of a space ship. The growing demand for highly efficient and clean energy sources at the time when fossil fuel sources are quickly depleting led to the rapid development of fuel cells. Nowadays, fuel cells are used to construct the batteries for mobile devices, low and high power generators, stationary power plants, vehicles, etc. [1],[3].

Fuel cells

A fuel cell is an electro-chemical device which produces usable energy (electricity, heat) as a result of a chemical reaction of hydrogen and oxygen. The by-product of the reaction is water. Figure 1 presents the schematic structure and the principle of operation of a hydrogen fuel cell.

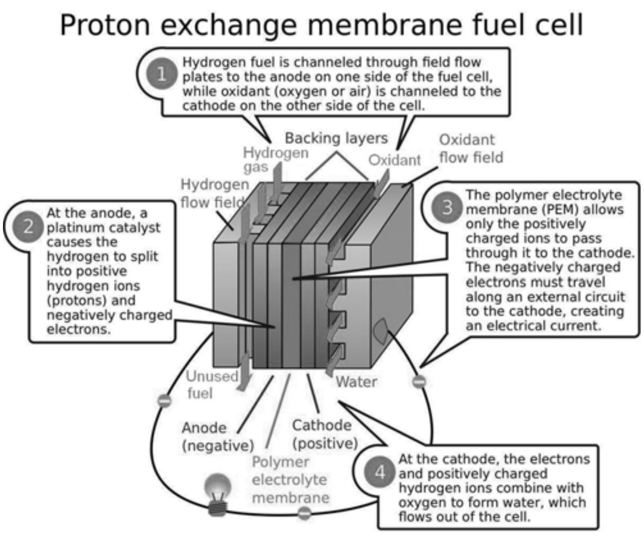

Fig. 1. The structure and the principle of operation of a hydrogen fuel cell [4],[7]

The hydrogen necessary for the fuel cell can be obtained from water in the process of electrolysis, using alternative energy sources, e.g. solar radiation. Hydrogen can also be obtained from methane in the process of steam reforming whose efficiency reaches about 80 %. The by-product of this process is carbon dioxide. The most common and the most frequently used way to store hydrogen is storing it in containers under the pressure of up to 1000 bar.

A review of fuel cell types

The division of fuel cells is based on the type of fuel powering the cell and on the electrolyte used which determines the temperature of the reaction occurring in the system.

PEM (Proton Exchange Membrane) fuel cells are powered with pure hydrogen or with reformate. The membrane of a PEM cell is made of a polymer material (e.g. nafion). A characteristic feature of PEM cells is the high efficiency (35÷65 %) of the conversion of chemical energy into electric energy and the low amount of heat generated. An advantage of a PEM cell is its good tracking performance in systems exposed to varying loads and short start-up time (up to 60 s.); the reaction in the cell takes place in low temperature (60-100°C). The efficiency of fuel cells in terms of the amount of electric energy generated reaches up to 50 %. In the process of co-generation, generation of both electric energy and heat, fuel cells reach the efficiency of up to 85 %.

DMFC cells (Direct Methanol Fuel Cell) have a polymer membrane the same as in PEM cells. The difference between a DMFC cell and a PEM cell lies in the construction of the anode which makes it possible to perform internal reforming of methanol and obtain hydrogen to power the cell. DMFC cells eliminate the problem of fuel storage, they are attractive for mobile applications thanks to the low temperature of the reaction occurring in them (about 80 degrees Celsius). A DMFC cell is characterized by lower efficiency (40%) in comparison to a PEM cell. Such cells are used to construct batteries for mobile devices and they offer efficiency rates that are not achievable for standard batteries. Powering a notebook by means of a methanol tank with the capacity of 250 ml which makes it possible for the device to operate for 12 hours can serve as an example. The result cannot be achieved for a standard battery of comparable mass / capacity.

AFC (Alkaline Fuel Cell) are fuel cells which were used for the first time in cosmonautics. KOH solution is used as the electrolyte. The reaction occurs at the temperatures of 100 to 250 °C. The temperature of the reaction depends on the concentration of the KOH solution; higher reaction temperatures make it possible to obtain higher cell efficiency for electric energy and heat generation. AFC cells were used on the Apollo space shuttle for cogeneration of electric energy and heat. AFC cells are sensitive to any pollution and they require fuel of high purity levels which constitutes an obstacle to their commercialization.

PAFC cells (Phosphoric Acid) are used for the construction of electric energy and heat cogeneration systems. The efficiency electric energy generation is 40 %, additionally water vapor generated by the cell can be converted into heat. The electrolyte in the PAFC cell is the phosphoric acid (H_3PO_4). The advantage of those cells is their high tolerance to carbon oxides which makes it possible to use many types of fuel (it is important, however, for the fuel to be desulphurized).

MCFC cells (Molten Carbonate Fuel Cell) operate at high temperatures and they are used to generate power in low and medium capacity power plants. The electrolyte in MCFC cells is melted Li/K carbonate. The high temperature of the reaction occurring in the cell makes it possible to use a wide range of fuels (natural gas, petrol, hydrogen, propane).

SOFC cells (Solid Oxide) are equipped with a membrane made of oxide ceramics. They operate at the temperatures from 650 to 1000 degrees Celsius. The result of the high temperature of the reaction occurring in the SOFC cell is high efficiency in electric energy and heat cogeneration systems – even 85 %. The features mentioned above and the long time to full efficiency make SOFC suitable for stationary CHP (heat and power cogeneration) systems. SOFC cells are characterized by high tolerance for fuel pollution (carbon oxides and sulphur) which makes it possible to use a wide range of fuels [5].

Fuel cells of the PEM/DMFC and SOFC types are the most frequently used fuel cells in industry. The popularity of those cells results from their high efficiency and the membrane constructed of solid materials – the lack of moving parts in the cell is a great advantage in industrial applications.

Cells of the SOFC type are characterized by high reaction temperature and slow follow-up to load changes. For this reason, SOFC cells are used in the construction of stationary electric energy and heat generators operating in a continuous manner under the same load.

PEM and DMFC cells are characterized by low reaction temperature and they are used in the construction of both small and large energy sources. The difference between a PEM cell and a DMFC cell lies in the type of fuel used. A DMFC cell is powered with methanol. Methanol is a type of fuel that is easy to store which, in connection with the low reaction temperature, makes DMFC cells ideal as low power batteries.

A cell of the PEM type is characterized by higher efficiency (40 % - DMFC, 65 % - PEM). The fuel powering a PEM cell is hydrogen or fuel reformat. If fuel reformat is used, the system should be equipped with the so-called fuel processor which produces hydrogen from the fuel used. This increases the cost of the system but proves economical in many cases, e.g. in stationary energy generation units with easy access to natural gas.

PEM/DMFC and SOFC cells are already present on the consumer market; they can be purchased both as independent equipment (fuel cell stack), as well as in ready-made complete power systems. Table 1 presents the characteristic usage parameters and applications of popular fuel cells.

Table 1. Summary of fuel cell features [4],[6]

Cell type	Electrolyte	Operation temperature [°C]	Efficiency (electric energy generation / cogeneration)	Applications	Fuel
PEM (Proton Exchange Membrane)	Solid polymer	75	35 - 60 %	- UPS devices - mobile batteries - low capacity power plants and energy and heat generators - automotive industry, mobile applications	Hydrogen
AFC (Alkaline Fuel Cell)	KOH solution	Below 80	50 - 70 %	- military - cosmonautics	Hydrogen
DMFC (Direct Methanol Fuel Cell)	Solid polymer	75	35 - 40 %	- mobile devices - batteries	Methanol Methanol and water solution
PAFC (Phosphoric Acid Fuel Cell)	Phosphoric acid	210	35 - 50 %	- stationary generators	Hydrogen
MCFC (Molten Carbonate Fuel Cell)	Melted Li/K carbonate	650	40 - 50 %	- large power plants and generators - CHP devices (Combined Heat & Power)	Hydrogen, methanol, methane, biogas, LPG gas, and others Hydrocarbon gases Internal reforming
SOFC (Solid Oxide Fuel Cell)	Oxide ceramics	650 - 1000	45 - 60 % / 85%	- large power plants and generators - CHP devices (Combined Heat & Power)	Hydrogen, methanol, methane, biogas, LPG gas, and others Hydrocarbon gases Internal reforming

Advantages of fuel cells

The energy provided by fuel cells is resistant to disturbances, thanks to which they constitute an ideal source of power for medical equipment, measurement devices, computers, etc.

Fuel cells are characterized by high power density, thanks to which they are always smaller and lighter than other energy sources of comparable power capacity. What is more, a fuel cell generates energy directly through a chemical reaction, so there is no fuel burning process. In mobile applications, fuel cells generate energy that is used directly for powering the drive unit, in contrast to combustion engines in which mechanical energy is generated and transformed into drive energy by mechanical transmission. The efficiency of fuel cells in electric energy generation reaches as much as 50 %. In the process of cogeneration, that is – generation of both electric energy and heat, fuel cells can reach the efficiency of as much as 85 %.

Fuel cells can be powered with any hydrogen-rich fuel. Obtaining hydrogen from the fuel can take place inside the fuel cell, the so-called internal reforming, or outside of the cell in an external device called the fuel reformer. Thanks to the phenomenon of the electrolysis, hydrogen for the fuel cell can be produced with the use of renewable energy sources – as it is the case in the present study.

A fuel cell produces 25 times less pollution in comparison to combustion generators. When the fuel cell is powered with hydrogen, the amount of pollution generated is negligible.

Single fuel cells can be connected in order to achieve the desired capacity level. Fuel cell systems are used both to power a single light bulb as well as industrial machinery.

Applications of fuel cells

Low-power batteries

Fuel cells are more and more often viewed as substitute for conventional batteries and storage cells used in the industry for powering small electrical devices (laptops, cameras, mobile phones, MP3 players, etc.). PEMFC and DMFC cells are used for such applications thanks to their low operation temperature properties.

Stationary systems

Stationary systems are both small household units that generate power or heat or auxiliary power sources with the power capacity at the level of kilowatts, as well as large power plants with the capacity of a few megawatts. Such devices are used in the locations where access to electric energy is critical, that is – in hospitals, military bases, office buildings, or in the industry. Stationary fuel cell systems are used as secondary installations that generate power which is sent back to the distribution grid, as emergency systems in hospital and other buildings. Generators equipped with a fuel cell system are powered with hydrogen or with hydrocarbon compounds.

Means of transport

The advantages of fuel cells for powering means of transport include: high efficiency (65% for a fuel cell in comparison to 35% for a combustion engine), lack of vibrations and noise accompanying energy generation, generation of energy that directly powers electric engines, no fuel burning during stops, constant torque. Currently, the cost efficiency of an FCV vehicle (Fuel Cell Vehicle) is comparable to the current hybrid vehicles. According to the announcements of the manufacturers, the first FCV will go into production as early as before 2015. Now, the main problem in the commercialization of FCV vehicles is their high price. Fuel cells are also (although rarely) in other areas connected with the means of transport. Drones or even wheelchairs or submarines powered with fuel cells are worth noting here. In automotive applications, be sure to changing operating temperatures and the effects of electromagnetic interference on the working components of the fuel cell system. In order to optimize the design of the target [2].

Robots

Parameters such as the weight/volume, efficiency, the quality of the energy produced have considerable influence on the construction of robots and the operational parameters of a robot. Fuel cells assure a reliable energy source which is capable of powering electric systems used in robotics. At the same time, the weight of such a power system is relatively small in relation to the amount of energy generated [5],[6].

Experimental research

The primary goal of the research is to experimentally verify the knowledge about the functioning of the electrolyser system with a fuel cell powered with energy obtained from photovoltaic modules (PV). What is more, special attention was put on the obtained efficiency levels of the whole system as well as of its individual elements. Measurements were performed on the stand presented on figure 2.

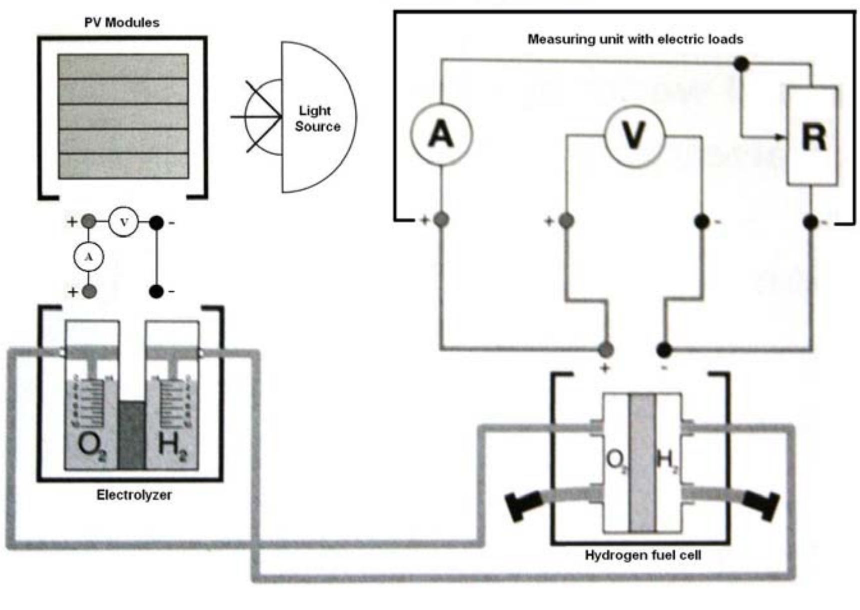

Fig. 2. A diagram of a measurement stand used to determine the operation and efficiency characteristics of a hydrogen cell system cooperating with photovoltaic modules

Apart from the start-up and determining the operational characteristics (*U=f(I)* and *P=f(I)*) of the hydrogen cell examined (Fig. 3, Fig. 4), the experiment was also focused on determining the efficiency.

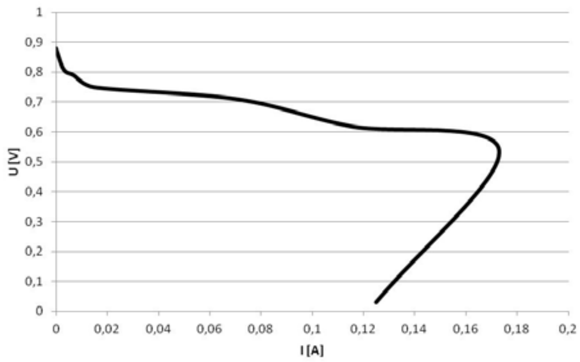

Fig. 3. *U=f(I)* characteristics of a loaded hydrogen cell

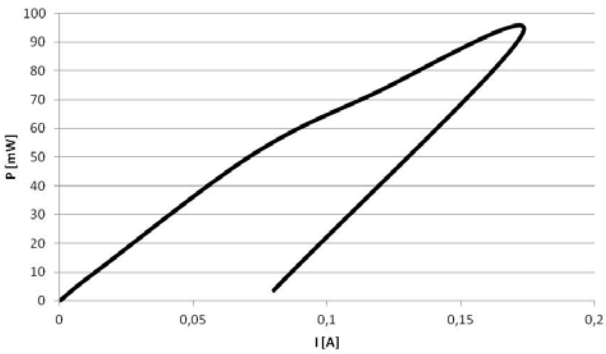

Fig. 4. *P=f(I)* characteristics of a loaded hydrogen cell

The efficiency η_1 means the efficiency of photovoltaic conversion of PV modules, η_2 – the efficiency of the process of electrolysis and of the hydrogen cell, and η_3 – the efficiency of the whole process including photovoltaic conversion, according to the following formulas:

(1) $$\eta_1 = \frac{U_{PV} I_{PV}}{ES} 100 \ [\%]$$

(2) $$\eta_2 = \frac{UI}{U_{PV} I_{PV}} 100 \ [\%]$$

(3) $$\eta_3 = \frac{UI}{ES} 100 \ [\%]$$

where: *U, I [V, A]* – voltage and current of the loaded hydrogen cell, U_{PV}, I_{PV} *[V, A]* – voltage and current of the system of PV modules powering the electrolyser, *E* $[W/m^2]$ – irradiance on the surface of PV modules, *S* $[m^2]$ – the area of PV modules.

As a result of the measurements and calculations performed, the results summarized in table 2 were obtained. Maximum efficiency of the hydrogen cell η_2 as well as of the whole system η_3 were obtained for the maximum power point whose value was 95 mW.

Table 2. Maximal efficiency levels obtained in the experiment

η_1 [%]	η_2 [%]	η_3 [%]
4,11	32,40	1,33

It is known from the literature that the efficiency levels of hydrogen cells are usually considerably higher than the values obtained in lab tests (tab. 2), which could result, among others, from non-optimal selection of the PV modules powering the electrolyser. What is more, the anode of the electrolyser was polluted, which had an influence on lower (about 30%) oxygen production in comparison to hydrogen production.

Conclusion

Increasing interest in the applications of fuel cells in different fields has been noted over the last few years. High hopes for the future are placed in the use of fuel cells for energy storage (mainly energy surplus), especially energy generated from uncontrollable renewable sources. The results of the experiments make it possible to obtain practical knowledge on the nature of the process of electrolysis, the functioning of a hydrogen cell and the efficiency of the whole system as well as its individual components in the form of: photovoltaic modules, the electrolyser and the hydrogen cell working under load.

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