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The hydrogen fuel cell system for mobile robotics solutions

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Abstract

This work discusses the fuel cell technology. In article systematization of those system has been presented. An exemplary fuel cell system was tested in field of robotics.

Keywords: hydrogen, fuel cell, mobile robots

Zastosowanie wodorowych ogniw paliwowych w robotyce

Streszczenie

Praca zawiera informacje na temat technologii ogniw paliwowych. W artykule dokonano systematyzacji ogniw paliwowych, przedstawiono także dzisiejszy stan wiedzy na temat ogniw i zastosowania ogniw paliwowych.

Słowa kluczowe: wodór, ogniwa paliwowe, mobilne roboty

1. Introduction

Together with growing popularity of mobile robots, an issue of drive used for their supply becomes more and more important. In the industry industrial manipulators are often used; their supply varies widely because of many requirements imposed for such machines. Sometimes pneumatic and hydraulic media are applied; in case of big loads and great accuracy, hydraulic drive is often the choice, whilst in case of colision-positioned system, which does not demand such a great accuracy – pneumatic drive is used.

In vehicular machines electric supply is mostly used, as – while concerning traffic planning, drive systems and control system – it is the easiest one. Mostly, with such a system a battery or accumulator is connected. However, sometimes – especially in solutions characterized by increased autonomy – it is necessary to install additional sources of supply, e.g. solar batteries, as in a case of “Sojourner” or “Pathfinder” devices, which were sent to Mars, and could have operated for a long time only with solar batteries. In this case, an important issue was to adjust the machine for its working environment, that is to say – outer space. Similar problems arouse while concerning robots that work at nuclear power plants, tanks used for petroleum storage, etc.

Placing supply system on the robot is more and more common while projecting modern systems. The problem is that, cable bunches may interfere with electronics, sensors or control systems. However, non-cable transmission of information, cannot be used everywhere, so despite this drawbacks, electric supply can be found in the majority of robots. Other drives are in minority, each one of them has its advantages and disadvantages. Pneumatics and hydraulics require separate systems of medium preparation. Durability of solar batteries is limited, they are not sufficient source of energy in some conditions; moreover they tend to be rather disappointing because of insulation. rising demands with which mobile robots must cope, as well as harder working conditions and greater accuracy, there is a continuous research of alternative sources of supply that can revolutionize today’s view at robot’s drive and supply.

Paper’s aim was to develop knowledge about fuel cells and their capabilities in order to construct a system that could replace other supplying sources, e.g. electric, or common accumulators, batteries. Many actions, among them market research, as well as contact with companies working at new technologies, careful analysis of the books and current press articles, have been taken.

Subsequently, different types of fuel cells were studied, along with their parameters, characteristics, and other features, so as to select appropriate cell type for our thesis. Very important thing in this thesis was to investigate construction and principle of operation of the individual cells.

2. Fuel cells

2.1. Historical background

The technology that can be traced back to the nineteenth century was invented by Sir William Robert Grove [1]. The discovery that hydrogen and oxygen could be combined to produce water and an electric current is now influencing every field of human activity. Fuel cell is being developed to power the cars, homes, mobile phones, laptop computers and everything in between. While the technology for these electrochemical power plants has existed since 1839, only recently have fuel cells gained popular recognition and come under serious consideration as an economically and technically viable power source. Step by step scientists have been building and improving on earlier research. From the William Grove’s invention, we had to wait almost one century for Francis Bacon to develop first successful fuel cell device, a hydrogen-oxygen cell using alkaline electrolytes and nickel electrodes [1]. It took next twenty years for NASA to demonstrate some of the fuel cell’s potential application in providing power during the space flights. Starting from early 60’s of the last century the commercial use of the technology has been growing significantly, but encountered technical barriers and high investment cost. The world turns to fuel cells, driven by technical, economic and social forces, such as high performance characteristics, reliability, durability, low cost and environmental benefits.

2.2. How do fuel cells compare to internal combustion engines and batteries

Before we present the construction schemes we would like to focus on the issue: how do fuel cells compare to internal combustion engines and batteries. Their purpose is common; they all are devices to convert energy from one form to another. As a starting point, let's consider the internal combustion engine which has a variety of application and happen to be very popular. We all know that they run on noisy, high temperature explosions resulting form of release of chemical energy by burning fuel with oxygen from the air. Internal combustion engines, as well as conventional utility power plants, change chemical energy of fuel to thermal energy to generate mechanical and, in the case of a power plant, electrical energy. Fuel cells and batteries are electrochemical devices, and by their very nature have a more efficient conversion process: chemical energy is converted directly to electrical energy. Internal combustion engines are less efficient because they include the conversion of thermal to mechanical energy, which is limited by the Carnot Cycle. If eg. Cars were powered by electricity generated from direct hydrogen fuel cells, there would be no combustion involved. In an automotive fuel cell, hydrogen and oxygen undergo a relatively cool, electrochemical reaction that directly produces electrical energy. The direct hydrogen fuel cell vehicle will have no emissions even during idling - this is especially important during city rush hours. There are some similarities to an internal combustion engine, however. There is still a need for a fuel tank and oxygen is still supplied from the air. Many people incorrectly assume that all electric vehicles are powered by batteries. Actually, this is a vehicle with an electric drive train powered by either an on-board battery or fuel cell. Batteries and fuel cells are similar in that they both convert chemical energy into electricity very efficiently and they both require minimal maintenance because neither has any moving parts. However, unlike a fuel cell, the reactants in a battery are stored internally and, when used up, the battery must be either recharged or replaced. In a battery-powered vehicles, rechargeable batteries are used. In vehicles equipt in fuel cell the fuel is stored externally in the vehicle's fuel tank and air is obtained from the atmosphere. As long as the vehicle's tank contains fuel, the fuel cell will produce energy in the form of electricity and heat. The choice of electrochemical device, battery or fuel cell, depends upon use. For larger scale applications, fuel cells have several advantages over batteries including smaller size, lighter weight, quick refueling, and longer range.

Fuel cells are electrochemical devices that convert a fuel's chemical energy directly to electrical energy with high efficiency. An important difference between fuel cells and batteries is that batteries store energy, while fuel cells can produce electricity continuously as long as fuel and air are supplied. Fuel cells electrochemically combine a fuel (typically hydrogen) and an oxidant without burning, thereby dispensing with the inefficiencies and pollution of traditional energy conversion systems. Fuel cells forego the traditional fuel-to-electricity production route common in modern power production, which consists of heat extraction from fuel, conversion of heat to mechanical energy and, finally, transformation of mechanical energy into electrical energy. In a sense, our bodies operate like fuel cells because we oxidize hydrocarbon compounds in our food and release chemical energy without combustion.

2.3. How fuel cells work

Fuel cells function on quite simple principal of electrolytic charge exchange between a positively charged anode plate and a negatively charged cathode plate. When hydrogen is used as the basic fuel, "reverse hydrolysis" occurs, yielding only water and heat as byproducts while converting chemical energy into electricity.

As one can see on the Fuel Cell Mode presented in Fig. 1, hydrogen flows directly into the fuel cell on the anode side, when the separation of the hydrogen gas into electrons and protons (hydrogen ions) in a proton exchange membrane or PEM fuel cell is safen by a platinum catalyst.

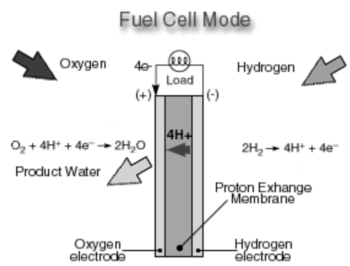

Fig. 1. The fuel cell mode
Rys. 1. Schemat ogniwa paliwowego

Platinum catalyst is also responsible for combining the hydrogen ion, which passes through the membrane, with oxygen and electrons on the cathode side producing water. The electrons, which cannot pass through the membrane, flow from the anode to the cathode through an external circuit containing an electric load which consumes the power generated by the cell. The overall electrochemical process of a fuel cell is called "reverse hydrolysis," or the opposite of hydrolyzing water to form hydrogen and oxygen. Hydrolysis can be accomplished by a reversible fuel cell through the supply of electricity to the cell. Moreover the supply of water on the cathode is also a must, what is shown by the Electrolyzer Cell Mode in Fig. 2. Not all fuel cell types are reversible, in a sense that they can accomplish the electrochemistry associated with the production of electricity from fuel as well as the production of fuel and oxidant from water when supplied with electricity.

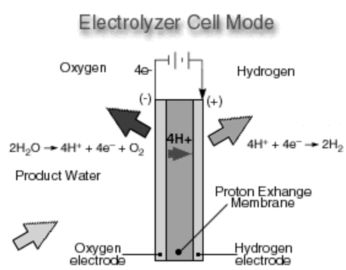

Fig. 2. The electrolyzer cell mode
Rys. 2. Schemat elektrolizera

The Reversible fuel cell concept is one that incorporates a reversible fuel cell that can accomplish both hydrolysis and reverse hydrolysis in the same cell. This allows one to consider the completely renewable production of electricity by using a renewable energy supply (e.g., solar, wind) to produce hydrogen and oxygen from water which can subsequently be used to produce electricity through the same fuel cell from the fuel and oxidant produced previously [2, 3].

2.4. Design of Fuel Cell Systems

The design of fuel cell systems is complex and can vary significantly depending upon fuel cell type and application. However, most of fuel cell system consists of four basic components: fuel cell stack, fuel processor, current converter, heat recovery system. Most fuel cell systems also include other components and subsystems to control fuel cell humidity, temperature, gas pressure, and wastewater.

2.4.1. Fuel Cell Stack

The fuel cell stack is the heart of a fuel cell power system. It generates electricity in the form of direct current (DC) from chemical reactions that take place in the fuel cell. A single fuel cell produces enough electricity for only the smallest applications. Therefore, individual fuel cells are typically combined in series into a fuel cell stack. A typical fuel cell stack may consist of hundreds of fuel cells. The amount of power produced by a fuel cell depends upon several factors, such as fuel cell type, cell size, the temperature at which it operates, and the pressure at which the gases are supplied to the cell. We also distinguish further fuel cell parts, which differ accordingly to various types of the devices. Although there are several types of fuel cells, only one has prospects as a power source for portable devices, the proton exchange membrane (PEM) fuel cell that can work at relatively low temperatures, lends itself to miniaturization and products more power than any other fuel cell. PEM fuel cells are made of several layers of different materials [4, 5].

2.4.2. Membrane Electrode Assembly

The electrodes (anode and cathode), catalyst, and polymer electrolyte membrane together form the membrane electrode assembly (MEA) of a PEM fuel cell [4].

- Anode. The anode, the negative side of the fuel cell, has several jobs. It conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. Channels etched into the anode disperse the hydrogen gas equally over the surface of the catalyst.
- Cathode. The cathode, the positive side of the fuel cell, also contains channels that distribute the oxygen to the surface of the catalyst. It conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water.
- Polymer electrolyte membrane. The polymer electrolyte membrane (PEM)—a specially treated material that looks like ordinary plastic wrap—conducts only positively charged ions and blocks the electrons. The PEM is the key to the fuel cell technology; it must permit only the necessary ions to pass between the anode and cathode. Other substances passing through the electrolyte would disrupt the chemical reaction.

2.4.3. Current Inverters and Conditioners

Current inverters and conditioners adapt the electrical current from the fuel cell to suit the electrical needs of the application, whether it is a simple electrical motor or a complex utility power grid. Fuel cells produce electricity in the form of direct current (DC). In a direct current circuit, electricity flows in only one direction. The electricity in your home and work place is in the form of alternating current (AC), which flows in both directions on alternating cycles. If the fuel cell is used to power equipment using AC, the direct current will have to be converted to alternating current. Both AC and DC power must be conditioned. Power conditioning includes controlling current flow (amperes), voltage, frequency, and other characteristics of the electrical current to meet the needs of the application. Conversion and conditioning reduce system efficiency only slightly, around 2 to 6 percent.

2.4.4. Heat Recovery System

Fuel cell systems are not primarily used to generate heat. However, since significant amounts of heat are generated by some fuel cell systems—especially those that operate at high temperatures such as solid oxide and molten carbonate systems—this excess energy can be used to produce steam or hot water or converted to electricity via a gas turbine or other technology. This increases the overall energy efficiency of the systems.

3. Fuel cell and accessories used to powered mobile robot

3.1. The Fuel cell

In our project we are used fuel cell made by E2-Economy Company, presented in Fig. 3. There is three-cell hydrogen/oxygen fuel cell stack. Expected power is about 10-12 W at 1.8 V. Recommended gas pressure is 1 bar for hydrogen and 1.2 bar for oxygen [6].

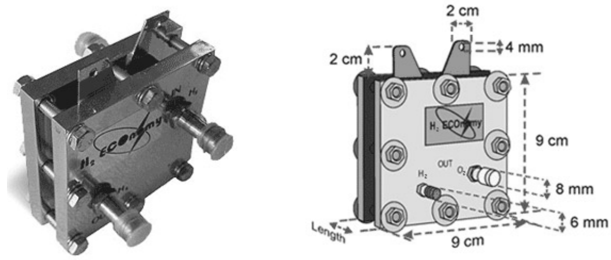

Fig. 3. The fuel cell made by E2-Economy Company
Rys. 3. Ogniwo paliwowe firmy E2-Economy

Very important thing is to use DC-DC converter with fuel cell, because they give low voltage and high current and normally we need the opposite. The DC-100 series low input voltage DC-DC converters enable the use of smaller fuel cell stacks to produce voltages suitable for portable power applications. With H_2 ECOnomy's DC-100 series converter you can have an energy source that lasts 4-5 times longer than batteries in portable applications, with the same size and characteristics.

3.2. Electrolizer

The Double-cell PEM electrolyzer, presented in Fig. 4, has been used for production of hydrogen from water [6].

Fig. 4. The double –cell PEM electrolyzer
Rys. 4. Dwu-ogniwowy elektrolizer PEM

This used electrolyzer produce above 65 cm3/min of hydrogen.

3.3. Metal Hydride Tank with refilling kit

This tank is used to store hydrogen and by using transparent plastics gives the opportunity to discover the latest technology for storage. The Plastic Metal Hydride Storage Tank, presented in Fig. 5, can easily demonstrate this technology [6].

Fig. 5. The plastic metal hydride storage tank
Rys. 5. Zbiornik plastikowo metalowy na wodór

Inside of the tank there are Metal Hydride Particles (alloy) which absorb molecule of hydrogen. In this tank we can store 10 liters of hydrogen at 1-3 bar. Regarding time of operation with 10 liter tank – it depends on the compression pressure.

3.4. Handling cylinder for pure hydrogen

The Cylinder which has been presented in Fig. 6 is design to store pure hydrogen [7].

Fig. 6. The especial tank for pure hydrogen
Rys. 6. Zbiornik metalowy na czysty wodór

This cylinder, presented in Fig. 6, is for Pure Hydrogen Source for Precision Testing Instruments. In our case it is very good solution because we can store about 50 liters of pure hydrogen, charged under pressure equal 1.5-2.5 MPa, and of course dimension, weight of the cylinder are acceptable for our application (32mm x 165mm; 0,75 kg).

3.5. Regulator

Regulator which is visible in Fig. 7 is essential to charge our handling cylinder from industrial storage tank which is operating under 200MPa pressure.

Fig. 7. The regulator used to charge handling cylinder tank
Rys. 7. Regulator wykorzystywany do napełniania zbiornika na wodór

On the left side we can see gauge which is responsible to check pressure in the industrial tank with hydrogen, the next one show us pressure in our handling cylinder.

4. Description and course of an examination concerning use of cell as a source of energy for a robot DC drives

The main task in this experiment was to examine fuel cells and to use them as a source of energy in a mobile robot systems. At first, we checked robot's parameters and chose suitable cell. However, we wanted cell to produce large amounts of power (about 10-12 W), and that is why we decided to use 'EcoFC-3' cell manufactured by a Swiss company E2-Economy. In this cell, hydrogen is a fuel, so we were able to acquire needed parameters from one fuel cell. However, production and storage of hydrogen was a problem. We were advised to buy an electrolyser that produces hydrogen from twice-distilled water, and a special container with a filter, through which, immediately after electrolyse, hydrogen is passed. Its aim is to hold moisture and pass only a pure gas. As we know, hydrogen-storing-container was necessary to acquire mobility of the whole system. On the Fig. 8 whole set of elements – electrolyser, filter and container – that was previously designed do produce and store hydrogen has been presented.

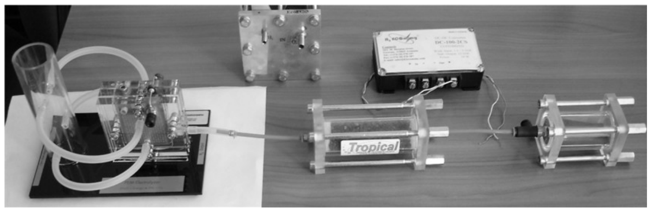

Fig. 8. The set of all elements necessary to produce hydrogen
Rys. 8. Elementy do wytwarzania wodoru

Through a filter with special granulate that held moisture, hydrogen from electrolyser was puted into the container in which it was absorbed. After charging the container with a cell and a converter was placed on a robot's construction. Unfortunately, robot didn't work at all. It was caused by a lack of pressure control of container's charging and by too small pressure of hydrogen distributed to the cell (manufacturer advises this pressure to be approximately 1-2 bar). That we have decided to buy very handy bottle that may consist of 50 litres of gas (Fig. 6).

Moreover, the Taiwan company that sold us a bottle offer us to deliver a special regulator, thanks to which both pressure of charging and pressure in a charged bottle can be controlled during charging (Fig. 7).

Because of very strict fire and industrial safety regulations, charging of such a bottle is possible in a specialized places. So after charging at appropriate pressure, it was necessary to use pressure regulator, presented in Fig. 9, in order to control flow of hydrogen that supplied a fuel cell from the bottle.

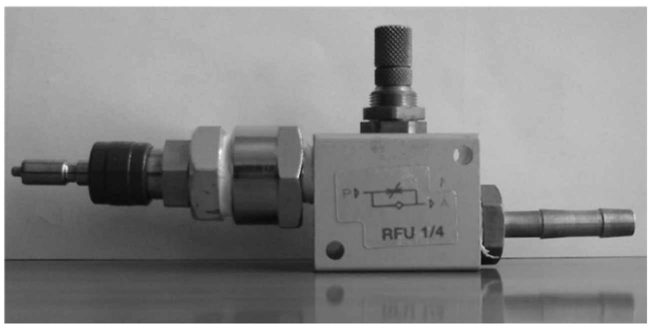

Fig. 9. The pressure regulator necessary to flow control
Rys. 9. Regulator ciśnienia

This flow control system based on pressure regulator (Fig. 9) has been constructed at Department of Robotics and Mechatronics AGH University of Science and Technology especially for this system. While using it together with a fuel cell and with a hydrogen-charged-bottle, next experiment has been carried (elements of this experiment have been presented in Fig. 10).

Fig. 10. The elements used in experiment connected with fuel cell testing
Rys. 10. Elementy wykorzystane w eksperymencie

Now, the system worked better than it had before. However, robot's main units as drives worked satisfactory, exemplary tested elements have been presented in Fig. 11.

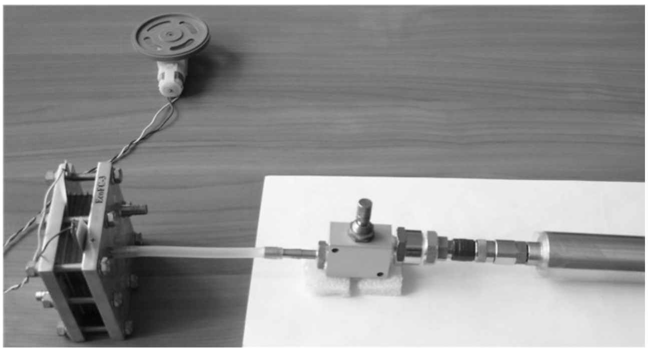

Fig. 11. The mobile drive unit used in experiment
Rys. 11. Zespół napędowy wykorzystany w eksperymencie

Conducted experiment aimed to check efficiency of such type of supply. Engine was working perfectly than we start to examine our system with 2 drives and also power supply was satisfactory but when we try to supply all robot systems connected with drives and robot's electronics it was insufficient power.

The overall remark was that the our cell was too weak to power all robot units it means was not capable to produce enough power. In order to verify it, we decided to use especially capacitors responsible for charges storage. Currently we are working on using super capacitors technology in mobile robots.

5. Conclusions

The most important conclusion is that, we were able to construct a system able to supply a mobile robot units. Knowledge not only about fuel cells, their types, principles of operation, possibilities of use, but also about production and storage of hydrogen was developed, which is very difficult in our conditions. Reason for too small efficiency of the system should be looked for in activity of some mechanisms influencing cell's operation. First of all, more professional regulator controlling hydrogen flow to the cell should be used. It should be equipped with a special gauge indicating pressure of the gas (approximately 1-2 bars). It is also vital to seal regulator's input and outputs – as we lost too much of the gas by them. Pure oxygen under appropriate pressure should be delivered to the cell. Of course it is not necessary (we were using air at atmospheric pressure), however pure oxygen significantly improves efficiency of the cell. There are also too large losses of power and small currents that were given to us by the cell. In order to eliminate this drawback, electronic systems able to neutralize mentioned losses should be used. I should also using special hydrogen-pump that could make charging of our bottle to the maximum possible. It would cause significant time elongation of the system's activity. And obviously we need to use super capacitors to store charges.

6. References

[1] LARMINIE J., DICKS A.: Fuel Cell Systems Explained, John Wiley & Sons, LTD, 2003.
[2] PISTOIA G., Batteries for Portable Devices, Springer Netherlands, 2006.
[3] MACARTHUR D.M., BLOMGREN G.E.: The Powers Review: Year 2002 Battery and Fuel Cell Industry Development, 2002
[4] BARBIR F.: PEM Fuel Cells: Theory and Practice, ELSEVIRE, 2005
[5] HOOGERS G.:Fuel Cell Technology Handbook, 2005
[6] www.h2economy.com
[7] www.hbank.com.tw

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