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EDUCATIONAL LABORATORY SYSTEM BASED ON ELECTROCHEMICAL DEVICES

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Abstract. Fossil fuel crisis and issues of greenhouse gas emissions led to the development of renewable energy sources. To create a right mentality among young people for using renewable energy sources, it is important to understand how devices produce green energy. The most efficient device that converts chemical energy into electricity is the fuel cell. We have created a computerized educational laboratory system, consisting of three types of combustion cells: H_2/O_2, ethanol and magnesium with salt water. This system is monitored by an Arduino microprocessor. The proposed automatic educational laboratory is a simple and agreeable mode to learn fundamental physics concepts.

Key words: fuel cells, chemical energy, educational laboratory, renewable energy.

1. INTRODUCTION

Physics education is considered to be a challenging topic around the world and the success of every student is stricted related to the depth of his knowledge on fundamental concepts in physics [1–4]. New low-cost technology, such as the open-source Arduino [5–6], represents the path to simple implementation of physics student labs in order to encourage the sharing of ideas as well application to cover different learning objectives and to reinforce students' skills. In recent years, the low-cost Arduino microprocessor has become a popular prototyping platform, especially for educational purposes.

In the last decades, we are increasingly restrained to replace conventional energy sources with renewable, non-polluting sources. This is a priority in the education of pupils and students in high schools and faculties in Romania. In order to create an appropriate mentality among young people, from the perspective of using renewable energy sources, it is necessary to understand how devices that produce green energy work.

Many energy technologies have been investigated, such as solar, wind, hydro electrical power, geothermal, electrochemical and bioenergy. Each of these types of energy has advantages and disadvantages and is in various stages of research.

The conversion of chemical energy into electrical energy is done through devices called fuel cells [7]. Fuel cells have the capacity to satisfy the global power requirements, while they are very efficient and low polluting. We already know the use of fuel cells in the automotive industry. The reasons for developing the automotive fuel cell technology are efficiency, zero emission, and local fuel production rather than import. In addition to this application, cells are used to power houses where electricity is not available and commercial portable devices such as laptops, cell phones etc. Fuel cells may be integrated with solar and wind power devices, to create a hybrid energy system. An important and novel application of the fuel cell in the depollution water domain consists in the recovering of the hydrogen sulfide from sulfurous water [8, 9].

The new methodologies in energy storage and conversion have placed a demand on design and manufacturing customized materials, with enhanced physical properties. There had been investigated new low-cost materials that replace the expensive one [10–15].

Thus, the fuel cell technology is a perfect educational topic for teaching fundamental concepts of electrochemical devices, while keeping students up-to-date about current renewable energy technologies.

In this article we demonstrate that students can perform pertinent studies of physical phenomena at the level of high school or university curricula using the low-cost equipment as Arduino microprocesor.

We created a computer-controlled educational laboratory system consisting of three types of fuel cells, in order to show the modes to convert chemical energy into the electric power. The developed fuel cell educational system is an easy and pleasant way to learn fundamental concepts of physics. The educational activities based on this system intend to involve students in exploring scientific methods for formulating and verifying hypotheses, designing and conducting experiments. The data acquisition panel is based on the open source electronics prototyping platform Arduino that runs under Windows operating system. After the automatic acquisition of data, the students analyze experimental data, in order to draw useful conclusions.

The educational laboratory has been developed to be user-friendly, modular and easily handled, educationally reliable and inexpensive. The implementation of laboratories is the most comprehensive way of teaching physics at advanced level in universities, in combination with virtual instrumentation and computer simulations [16–19]. They are also used in combination with modern teaching tools and educational software at elementary school level [20–22].

2. THE LABORATORY SYSTEM DESIGN

2.1. FUEL CELL FUNCTIONING

Fuel cells are associated with irreversible kinetic processes residing in oxidation-reduction reactions. In the porous anode, the fuel is transported and absorbed on its surface, and then it is dissociated into ions and electrons through the oxidation process. Later, the electrons migrate from the anode, releasing the ionic gas at its surface. The transport of positive ions in the electrolyte must be ensured from the anode to the cathode. At the cathode, there are arriving ions coming through the electrolyte, electrons and the oxidant. The reduction reaction takes place at the cathode and thus the reaction product is obtained. During this operation, the electrodes do not suffer structural changes, their role being as support for reaction.

The classification of fuel cells depends on the type of electrolyte used, so it can be a solid polymer, liquid acid or base, molten ionic salt or ceramic. Also, the type of the fuel can be another criterion to classify the fuel cells. For the educational laboratory system, we have used a proton exchange membrane (PEM) fuel cell fed with hydrogen (H_2/O_2), direct ethanol fuel cell and magnesium with salt water fuel cell.

2.1.1. PEM Fuel Cell H_2/O_2

The proton exchange membrane fuel cells use a solid polymer containing a platinum or platinum alloy catalyst. It only requires hydrogen and oxygen to work. They are usually fed with pure hydrogen from storage tanks or hydrogen reformers. The oxygen used may be obtained from water electrolysis or from air. PEM combustion cells operate at relatively low temperatures, approximately 80°C. Low-temperature operation allows quickly start (low heating time) and the system components attrition is reduced, resulting a high durability. However, it requires a noble metal catalyst (usually platinum) to be used to separate electrons and hydrogen protons, thus increasing the cost of production [23].

Reactions that occur in hydrogen fuel cells are [24]:

$$\text{Anode: } H_2 \rightarrow 2H^+ + 2e^-$$

$$\text{Cathode: } O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

$$\text{Overall: } 2H_2 + O_2 \rightarrow 2H_2O$$

The proton exchange membrane allows only the positive ions to pass to the cathode, the electrons (negative charge) going through an external circuit. At the cathode, electrons combine with H^+ ions and form water (Fig. 1).

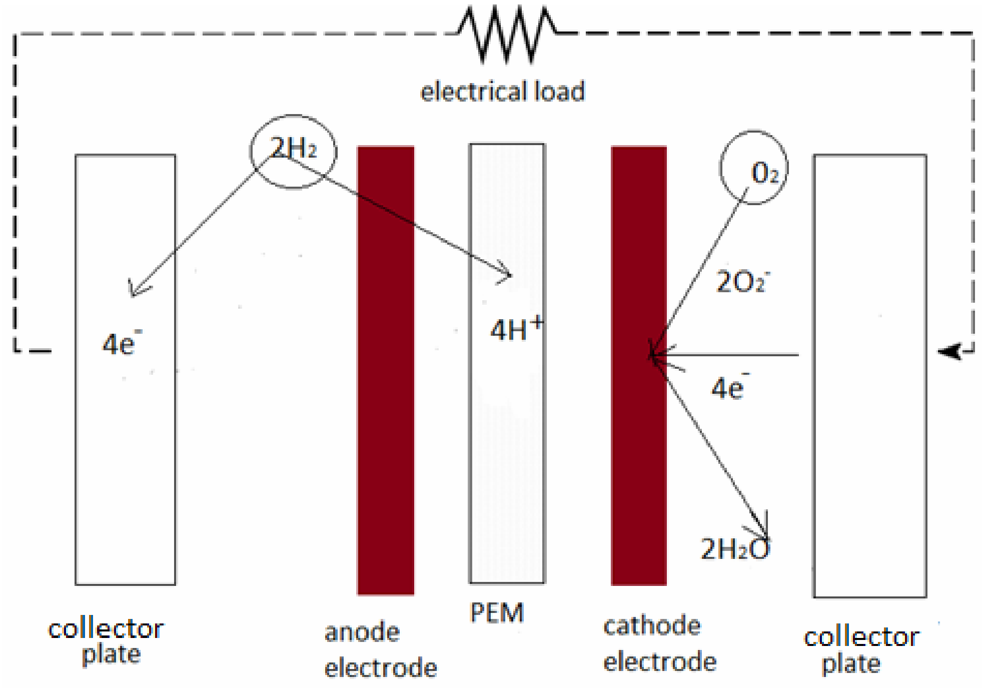

Fig. 1 – The working principle of PEM fuel cell H_2/O_2.
The colored versions can be accessed at http://www.infim.ro/rrp/.

2.1.2. Ethanol-direct fuel cell

Ethanol represents a main source of fuel used in the fuel cells, because of its advantages which consist in low toxicity and low prices. Recently, the ethanol-direct fuel cell (DEFC) was developed and platinum was found to be an excellent catalyst for the electrochemical reaction. Moreover, palladium will be tested as a potential substitute for the expensive platinum as the primary catalyst. Several studies have shown that palladium is superior to platinum, especially in alkaline media. The combustion chamber has two cell halves. The electrodes of platinum or ruthenium are placed in each of these two cell halves. These electrodes play the role of the catalysts, but they are not subject to any chemical reaction. The ethanol is supplied at the anode and the oxygen from the air at the cathode (Fig. 2). The ongoing reactions are [25]:

Anode: $CH_3CH_2OH + H_2O \rightarrow CH3COOH + 4H^+ + 4e^-$

Cathode: $O_2 + 4e^- + 4H^+ \rightarrow 2\ H_2O$

Overall: $CH_3CH_2OH + O_2 \rightarrow CH3COOH + H_2O$

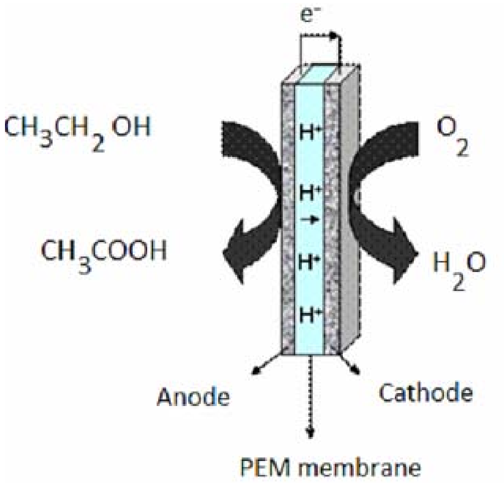

Fig. 2 – The working principle of the ethanol-direct fuel cell.
The colored versions can be accessed at http://www.infim.ro/rrp/.

2.1.3. Magnesium fuel cell

The environmentally friendly magnesium fuel cell system uses magnesium plate, salt water and atmospheric oxygen (Fig. 3). The salt water has the role of both catalyst and electrolyte. At the anode, the water reacts with magnesium and produces protons and magnesium hydroxide. Instead, at the cathode, hydroxyl ions are created due to the passing of the oxygen through the walls of the cell and reaction with water [26].

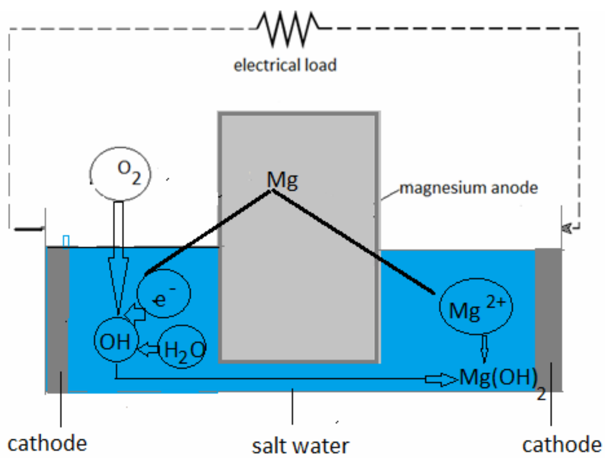

Fig. 3 – The working principle of the magnesium fuel cell with salt water.
The colored versions can be accessed at http://www.infim.ro/rrp/.

Anode: $Mg \rightarrow Mg^{2+} + 2e^{-}$

Cathode: $O_2 + 2\ H_2O + 4e^{-} \rightarrow 4OH^{-}$

Overall: $2Mg + O_2 + 2\ H_2O \rightarrow 2Mg(OH)_2$

2.2. MONITORING SYSTEM

Arduino microcontroller becomes an important and friendly device for monitoring a variety of physical parameters using a wide array of sensors [27–30].

Straight from the shelf, the Arduino comes equipped with a 6-channel analog to digital converter (ADC), measuring potential differences on a scale from 0 to 5 V with a resolution of 10 bits, forming the basis of the monitoring system. The collected data was read and process through GNU Octave's instrument control package over an USB emulated serial connection with the board.

The monitoring was developed around an Arduino UNO Revision 3 board powered by an ATMega328PU RISC-microcontroller clocked at 16 MHz. Between ground and the A0 channel of the ADC we have connected the output of various fuel cells, in order to measure the open circuit voltage produced (Fig. 4). The Arduino ADC input impedance is practically on the order of several tens of megaohms, minimizing the effect on the fuel-electrochemistry. The data was recorded at regular intervals of one second using the Arduino internal clock.

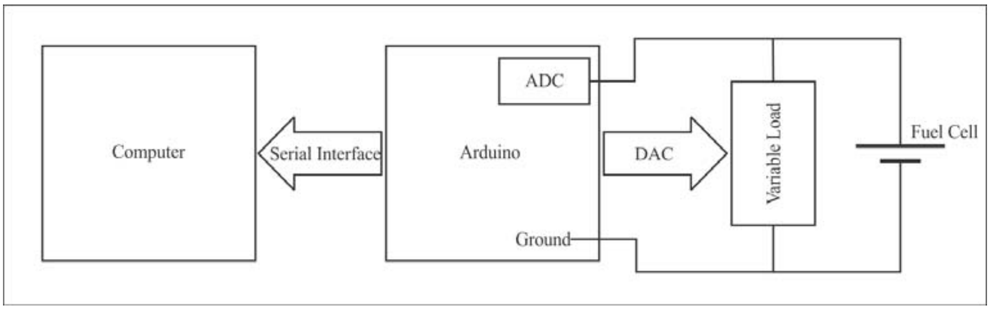

Fig. 4 – Developed monitoring system architecture.

Taking advantage of the three-state general-programmable input-output (GPIO) ports, we devised an exponentially variable load with the range from 54 Ω to 10^4 Ω. When configured as inputs, the GPIO port is in a high impedance state allowing only minute currents to pass. When configured as outputs, the GPIO ports are in a very low impedance state, passing relatively high currents either to ground or the positive lead of the power supply. To simulate a variable load, an array of 10 resistors with values chosen closest to a linear progression we connected to ports D3 to D12. We have skipped D0 and D1 as those ports have components connected for serial communication, while D13 has an LED connected to ground which will affect the impedance. We have chosen metallic film resistors with 1% precision with the following values 100 Ω, 220 Ω, 470 Ω, 1000 Ω, 2200 Ω, 4700 Ω, 10 kΩ, 22 kΩ, 47 kΩ respectively 100 kΩ (Fig. 5). The resistors connected to GPIO ports configured as inputs will virtually be disconnected from the circuit, while the resistors connected to GPIO ports configured as outputs set to LOW will close the fuel cell circuit. In this way we have build a low-cost digital to analog converter (DAC) with 1024 states, including the open circuit. This allowed the characterization of the internal processes governing the fuel cell behavior.

Because the output of the fuel cell can vary in a wide range, we have used in our experiments the ability of the Arduino to switch its internal ADC reference and thus the end of the measuring scale to 1.1 V by simply embedding the following statement in the setup part of the Arduino sketch:

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analogReference (INTERNAL);
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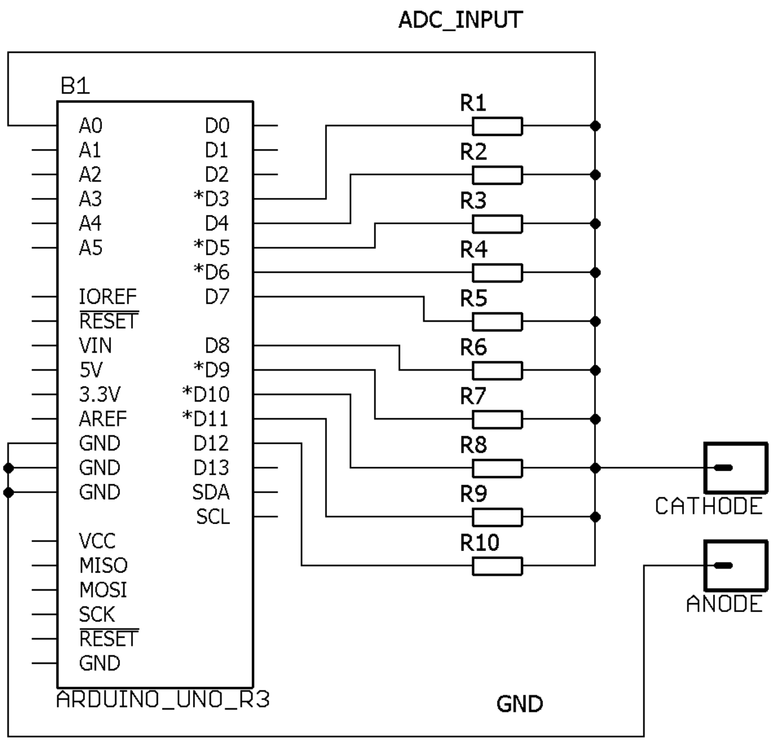

Fig. 5 – Monitoring system schematic diagram.

3. THE LABORATORY ACTIVITIES

The system of fuel cells is monitories in laboratory as in Fig. 6. We used fuel cells from Horizon laboratory set. The H_2/O_2 cell is fed with hydrogen from the metallic hydride stick and oxygen from the air. For testing, the ethanol fuel uses a solution ethanol-water with concentrations of 15%. In addition, there was monitored the magnesium fuel cell with concentrations of salt water of 20%.

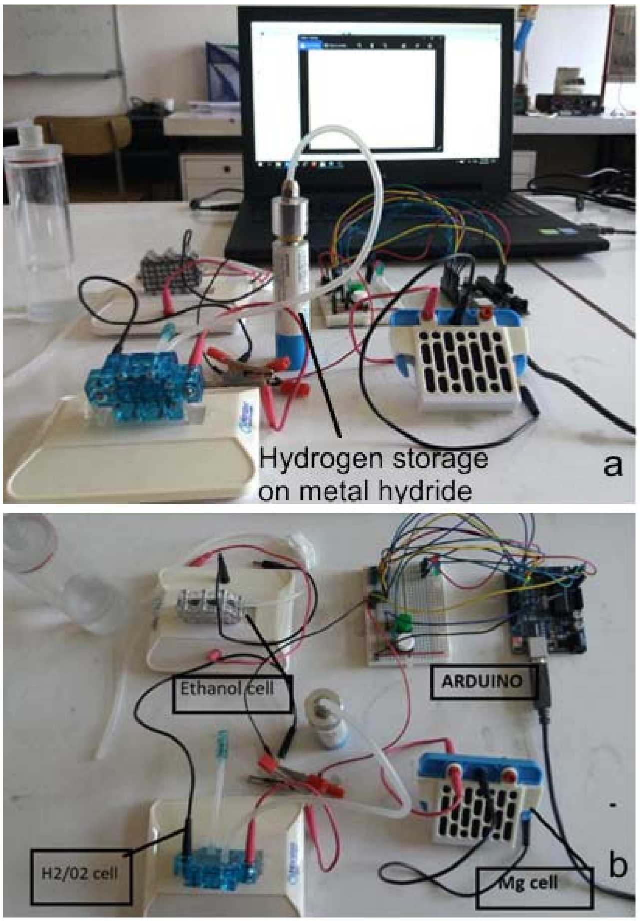

Fig. 6 – Laboratory setup for experimental tests: a) monitoring system; b) system of fuel cells and Arduino microcontroller. The colored versions can be accessed at http://www.infim.ro/rrp/.

The dependence of the open circuit voltage on time is recorded for all the three fuel cells (Fig. 7a).

The polarization curves of the fuel cells are presented in Figs. 7b and 7d and comparative curves power *versus* intensity in Fig. 7c.

The students can monitories these cells in different working conditions, as different temperatures for the fuel substances (hydrogen, ethanol solution, air), or at diverse temperatures for solution of salt water as catalyzer. In addition, they can vary the concentrations of the ethanol and salt, in order to improve the efficiency of the fuel cells. From the curves recorded by Arduino, the students can compare the power produced by various cells and establish their efficiency.

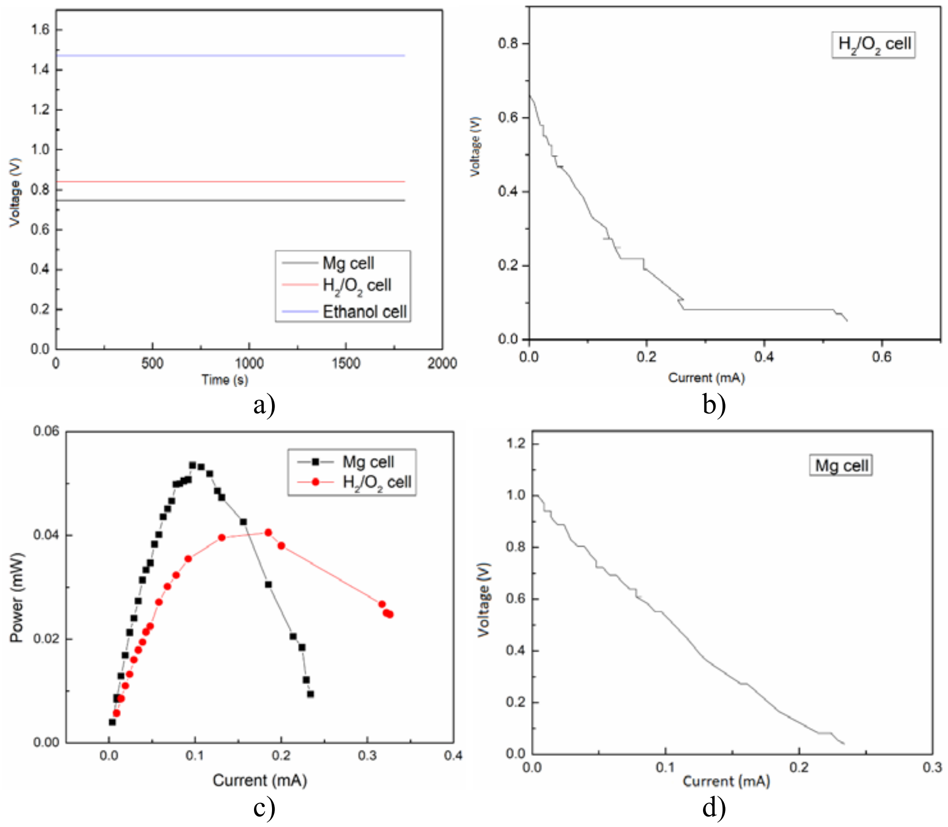

Fig. 7 – Examples of curves recorded by the monitoring system: a) open circuit voltage on time; b) polarization curve for H_2/O_2 cell; c) power curves; d) polarization curve for Mg cell. The colored versions can be accessed at http://www.infim.ro/rrp/.

4. CONCLUSIONS

This paper proposes an educational laboratory system and associated laboratory sessions for physics curriculum in high schools and faculties. This system and the training activities have been designed to support students by developing the skills of the scientific process by learning the basic aspects of the fuel cells. The implementation of the laboratory system is based on the electronic prototype platform (Arduino) for data acquisition and monitoring. The system currently supports laboratory sessions of increasing difficulties, as they maintain the interests they need, deeply studying the fundamentals of the chemical energy transformation into electricity and gain sufficient experience in designing and conducting experiments. A further extend of laboratory will be the introduction of other types of fuel cells into the system and their simultaneous monitoring. Developing a higher graphical presentation is a challenge for students studying the lab [31–33]. The system operation module, which allows an addition of the field of action, supports laboratory activities.

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