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INVESTIGATION OF THE ELECTROLYSIS PROCESS OF OBTAINING HYDROGEN AND OXYGEN WITH SERIAL AND PARALLEL CONNECTION OF ELECTRODES

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This paper presents theoretical and experimental studies of the process of electrochemical generation of hydrogen and oxygen with a parallel and serial connection of electrodes in one electrolyte volume. This study is based on the laws of conservation of mass, thermodynamics, electrical engineering, electrochemistry, using data obtained from the methods of mathematical and physical modeling. Data on the development and research of two designs of electrode assemblies, namely, with a parallel and series connection of electrodes, and with the subsequent placement of each assembly in one electrolyte volume. Experimental and calculated data revealed the regularities of the electrochemical reaction of decomposition of the liquid electrolyte into hydrogen and oxygen, the distribution of voltage when the electrodes are connected in parallel and in series in one electrolyte volume. A change in the electric potential between the internal electrodes was also found. Voltage measurement was performed from electrode 1 to electrode 4. The results of experimental studies were displayed graphically. The graphs show that the voltage at the terminals of the internal electrodes is lower than necessary for the electrochemical reaction of decomposition of the liquid electrolyte with the generation of gaseous hydrogen and oxygen. To implement the concept of placing a series (bipolar) connection of electrodes in one electrolyte volume, it is necessary to focus on the design of the electrolyzer that will be able to disconnect the electrodes electrically and provide galvanic isolation between them (separately isolated electrolyte volumes for each electrode pair). This will increase the operating pressure of the generated hydrogen and oxygen to 20.0 MPa, reducing the current load of the electrolysis process when using alternative energy sources.

Keywords: electrolyzer, series and parallel connection of electrodes, hydrogen, oxygen, high pressure.

Introduction

The growing number of energy installations using renewable energy sources, which are part of energy supply systems at the regional, national, and international levels of Ukraine [1], requires that attention to energy conversion and storage technologies be increased [2, 3] to compensate for energy fluctuations and balance energy surplus and deficit in accordance with the needs of the energy market [4, 5].

Compared with other methods of hydrogen generation [6, 7], electrolysis is characterized by the simplicity of technological scheme, possibility of efficient use of renewable energy sources [8–15], availability of raw materials, and relative ease of maintenance of power plants [16–18]. A significant disadvantage of the electrochemical method of hydrogen generation is the high power consumption of the water decomposition process [19, 20].

Generation of hydrogen and high-pressure oxygen with the help of a cyclic method using a gas-absorbing electrode is one of the technologies that can provide storage of large amounts of energy in the form of hydrogen under high pressure [21, 22] and use it as an environmentally friendly fuel for vehicles [23, 24].

The problems associated with the widespread use of water electrolyzers are their high power consumption and operating costs, which must be reduced by optimizing work processes [25]. Experimental results are presented differently, which complicates the conclusion about the ways to optimize the electrolysis process [26]. To ensure the comparison of process effectiveness evaluations, there is a need to unify test methods and protocols [27]. To do this, the methodology of the experiment was first developed, the main elements of the research equipment were designed, followed by the verification of the effectiveness of its application to ensure the specified accuracy of measuring the parameters of the working process of liquid alkaline electrolyte solution electrolysis. Subsequently, a minimum set of requirements for the equipment of

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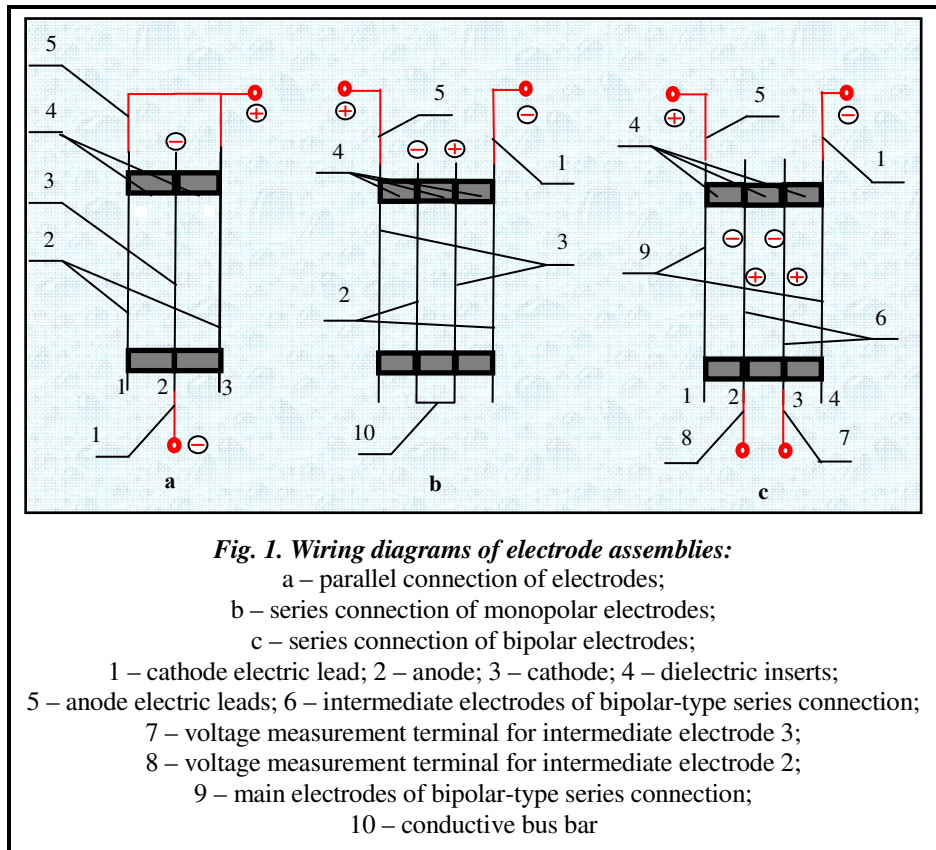
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the test complex was determined. This paper confirms the urgent need to determine one or more reference measurement parameters in addition to the methodology to conduct the experiment and structure of the equipment to ensure an accurate comparison of results. This approach creates the preconditions for the study and development of new gas-absorbing electrode structures [28] and, on their basis, conceptually new hydrogen and high-pressure oxygen generators [29].

Particular attention should be paid to the test conditions and electrolyser type (monopolar or bipolar) [30], the method of electrical connections (parallel or series) [31] to obtain reliable performance.

Analysis of the Existing Circuits for Connecting Electrodes in the Electrolyzer to Generate Hydrogen and Oxygen

Fig. 1 shows the connection options for electrode assemblies of different types. According to the type of electrode connection, there exist monopolar electrode assemblies (electrodes electrically connected in parallel) (Fig. 1, a) and bipolar electrode assemblies (electrodes connected in series) (Fig. 1, c). To reduce current loads and increase the productivity of monopolar electrolyzers, they are connected to the mains in series by means of conductive bus bars (Fig. 1, b). Today, filter-press bipolar electrolyzers are widely used due to the smaller overall dimensions of electrolysis systems and lack of multiple electrical connections. In addition, a battery with bipolar electrolyzers is



designed for high total voltage, while a battery with monopolar electrolyzers requires large current loads at low voltage.

The main disadvantages of filter-press electrolyzers include a large number of sealing materials, technological difficulties in ensuring the tightness of many multi-cellular batteries.

Theoretical Foundations of Calculating the Working Characteristics of the Electrolyzer with a Parallel and Series Connection of Electrodes

The value of current I in the power supply circuit of the electrolyzer is maintained within the inversely proportional dependence on the number of connected modules [32]:

$$I = \frac{m}{Nkt} \text{ or } I = \frac{VM}{22.4Nkt},$$

where m is the mass of the gas released at the electrode, kg; I is the amount of current in the electrical circuit of the electrolyzer, A; t is the time of electrolysis, s; M is the molar mass of gases generated; N is the number of the electrolyzer modules connected to the electrical circuit; V is the volume of gases generated, m^3 .

In relation to the scheme of operation of the electrolyzer, the dependence of the current in the power supply circuit of electrolyzer modules is determined by Faraday's law [32]

$$m = kQ = kIt, \tag{1}$$

where Q is the amount of electricity, C; k is the electrochemical equivalent due to the ratio

$$k = \frac{M}{Na \cdot e \cdot z},$$

where M is the molar mass of the gas generated at the electrode; e is the electron charge; z is the valence of the released substance ions that are present in the process; Na is the Avogadro number.

The number of moles of gas released [32]

$$n = \frac{m}{M},$$

taking into account the volume of moles of gaseous substance under normal conditions, is 22.4 l, and the volume of gas released is defined as

$$V = n \cdot 22.4 = \frac{m}{M} \cdot 22.4, \tag{2}$$

or, if we substitute in formula (2) the mass of gas from formula (1), then the volume of gas released will be defined as

$$V = \frac{kl}{M} \cdot 22.4.$$

For a series connection scheme, the mass of gas released will be [32]

$$m = Nklt,$$

where N is the number of modules.

In this case, the total voltage consumed by the electrolyzer increases due to an increase in voltage by a factor of [32]

$$U_{\Sigma} = NU_1,$$

where U_1 is the voltage on each electrolyzer module.

Conducting the Experiment and Discussing the Results of the Study

To perform an experimental study of the processes of hydrogen and oxygen generation, the department of hydrogen energy of A. Pidhornyi Institute of Mechanical Engineering Problems of the NAS of Ukraine has designed the main elements of the laboratory installation, developed a methodology for conducting an experiment with subsequent verification of the effectiveness of its application to ensure the specified accuracy of measuring the parameters of the working process of electrolysis. The department has also developed two designs of electrode assemblies with the parallel and series connection of electrodes (Fig. 2), which were alternately placed in a transparent sealed container with an electrolyte.

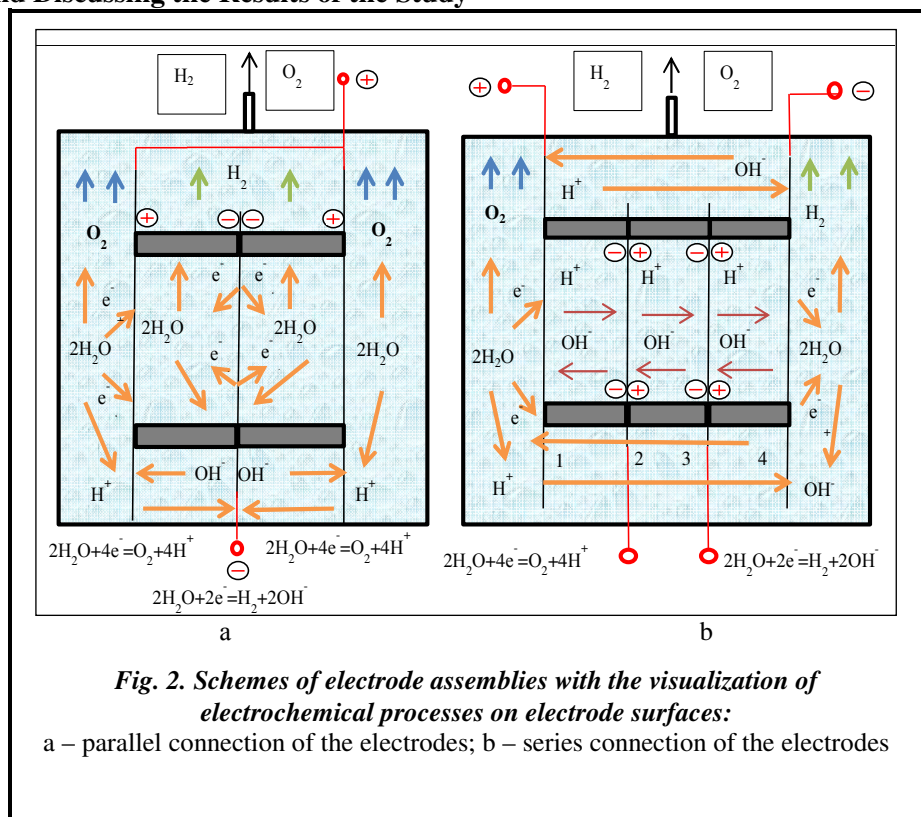


Fig. 2. Schemes of electrode assemblies with the visualization of electrochemical processes on electrode surfaces:
 a – parallel connection of the electrodes; b – series connection of the electrodes

In monopolar electrolyzers, the entire electrode surface has the same potential, and the requirements for the material and surface of the electrode are the same for all its parts. In bipolar electrolyzers, one side of

the electrode acts as a cathode and the other one as an anode [33, 34]. Bipolar electrodes are included in the electrical network as conductors of the second kind [35].

The basic data obtained experimentally during the study of the parallel and series connection of electrode assemblies are presented in the table. Electrodes are made of the 08Kh18N10T stainless steel.

Results of the study of the type of electrode assembly connection

Connection type	Electrode area, cm ²	Current, A	Voltage, V	Current density, A/cm ²	Volume of hydrogen released, m ³ /h	Volume of oxygen released, m ³ /h	Electricity consumption, kW·h/m ³
08Kh18N10T – 08Kh18N10T							
Parallel	29.75	0.44	2.2	0.007	0.56·10 ⁻³	0.28·10 ⁻³	5.2
Series	29.75	0.44	2.2	0.015	0.56·10 ⁻³	0.28·10 ⁻³	5.2

When the electrodes were connected in parallel, the electric potential was applied to the terminal of anodes 5 and the terminal of cathode 1 (Fig. 1, a), with the release of hydrogen at cathode 3 and oxygen at anodes 2. Voltage at terminals 1 and 5 of the electrode assembly was 2.2 V (Fig. 1, a) and did not increase during the experiment (10 min.).

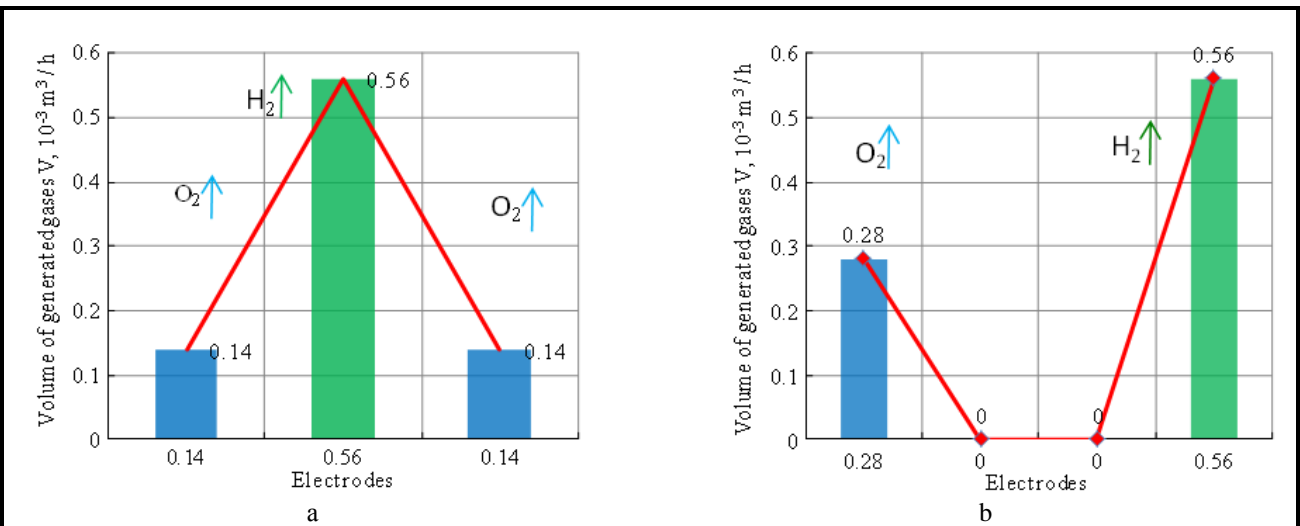


Fig. 3. Distribution of hydrogen and oxygen release at the electrodes and their volumes:
 a – parallel electrode connection; b – bipolar-type series connection of the electrodes

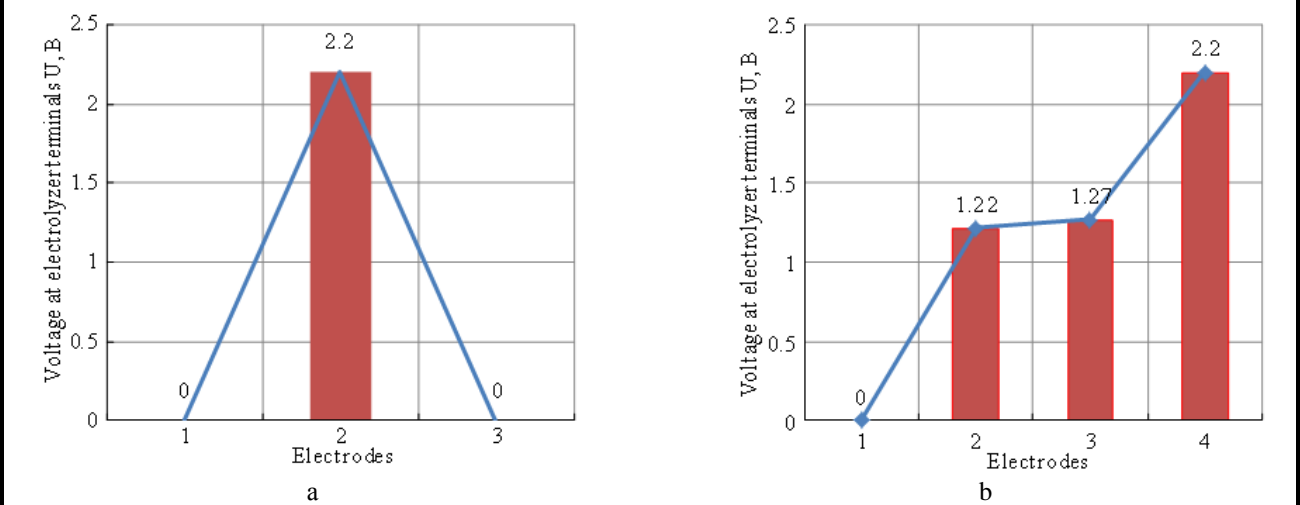


Fig. 4. Distribution and value of voltage between the electrodes:
 a – parallel electrode connection; b – bipolar-type series connection of the electrodes

Fig. 3 shows bar graphs of release of the generated hydrogen and oxygen when the electrodes are connected in parallel (monopolar-type connection, Fig. 3, a) and in series (bipolar-type connection, Fig. 3, b) and their volumes. When the electrodes were connected in series, the electric potential was applied to terminals 1 and 5 (Fig. 1, b) of the electrode assemblies, after which there was an active release of gases at electrodes 9, directly connected to the power supply (outer plates). The release of gas at internal electrodes 6 was absent (Fig. 3, b).

Distribution of voltage with parallel and series connections of the electrodes in one electrolyte volume is shown in Fig. 4. A change in the potential between the electrodes was also observed (Fig. 4, b). Voltage measurement was performed from electrode 1 to electrode 4 (Fig. 1, b). The graph shows that the voltage at the terminals of internal electrodes 7 and 8 is lower than necessary for the electrochemical reaction of liquid electrolyte decomposition – 1.48 V.

Fig. 5 shows graphs of the calculated voltage value for the electrochemical process and the corresponding experimental values of voltage at the series connection of the electrodes.

As can be seen from Fig. 5, the theoretical (calculated) voltage, when the electrodes are connected in series (08Kh18N10T – 08Kh18N10T), is 6.6 V in accordance with 3 electrode pairs. The value of the voltage obtained experimentally in one electrolyte volume of 25% NaOH solution is 2.2 V, corresponding to the parallel electrode connection scheme.

To implement the concept of placing a series (bipolar) connection of electrodes in one electrolyte volume, it is necessary to focus on the development of the electrolyzer that will be able to disconnect the electrodes electrically and provide galvanic isolation between them (separately isolated electrolyte volumes for each electrode pair).

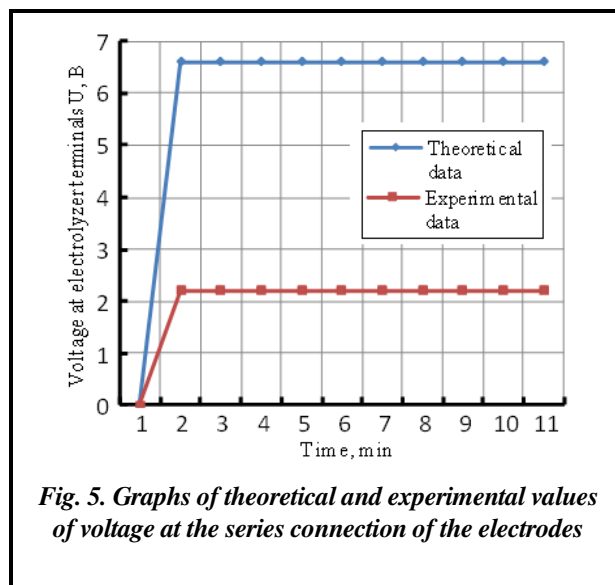


Fig. 5. Graphs of theoretical and experimental values of voltage at the series connection of the electrodes

Conclusions

Experimental data show that the voltage, when placing the electrode assembly with the series connection of the electrodes in one electrolyte volume, should be 6.6 V for three electrode pairs, but it is at the level of 2.2 V, which corresponds to the parallel electrode connection scheme.

Based on the studies of the electrochemical characteristics of electrode assemblies formed by different types of connections, it is determined that to implement the connection of electrodes to the power supply according to the series connection scheme, it is necessary to electrically insulate and divide the total electrolyte volume into elementary volumes, which makes it impossible for the current to leak past the working surfaces of the active working zone of the electrodes.

Particular attention should be paid to the development of a new design of the high-pressure hydrogen electrolyzer with the use of a gas-absorbing electrode that would meet the above requirements for serial electrode connection in one strong case.

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Дослідження електролізного процесу отримання водню і кисню при послідовному і паралельному підключенні електродів

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В статті наведено теоретичні та експериментальні дослідження процесу електрохімічного утворення водню і кисню при паралельному та послідовному підключенні електродів в одному електролітному об'ємі. Це дослідження ґрунтується на законах збереження маси, термодинаміки, електротехніки, електрохімії з використанням даних, отриманих на основі методів математичного та фізичного моделювання. Наведено дані з розробки та дослідження двох конструкцій електродних пакетів, а саме, з паралельним і послідовним з'єднанням електродів, з подальшим розміщенням кожного пакету в одному електролітному об'ємі. Експериментальні та розрахункові дані дозволили виявити закономірності протікання електрохімічної реакції розкладання рідкого електроліту на водень і кисень, розподілу напруги при паралельному та послідовному підключенні електродів в одному електролітному об'ємі. Також було встановлено зміну електричного потенціалу між внутрішніми електродами. Забір напруги проводився від електроду 1 до електроду 4. Результати експериментальних досліджень були відображені графічно. З наведених графіків видно, що напруга на клеммах внутрішніх електродів нижче, ніж необхідно для протікання електрохімічної реакції розкладання рідкого електроліту з генеруванням газоподібного водню і кисню. Для реалізації концепції розміщення послідовного (біполярного) з'єднання електродів в одному електролітному об'ємі необхідно акцентувати увагу на розробці конструкції електролізера, який дозволить роз'єднати електроди електрично і забезпечити гальванічну ізоляцію їх між собою (окремо ізольовані електролітні об'єми для кожної електродної пари). Це дасть змогу підвищити робочий тиск згенерованих водню і кисню до 20,0 МПа та знизити струмове навантаження електролізного процесу під час використання альтернативних джерел енергії.

Ключові слова: електролізер, послідовне і паралельне з'єднання електродів, водень, кисень, високий тиск.

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