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CHEMICAL HYDROGEN PRODUCTION FROM ALUMINUM ALLOY AK7 USING NAF AND NACL ACTIVATORS FOR EMERGENCY POWER SUPPLY SYSTEMS

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Abstract. This study explores a method for hydrogen production via the chemical dissolution of aluminum alloy AK7 in alkaline solutions with NaF and NaCl activators. The optimized electrolyte composition and activator concentrations significantly enhance the aluminum dissolution rate, leading to efficient hydrogen evolution. The proposed method offers advantages in sustainability, economic efficiency, and minimal environmental impact. A comprehensive analysis of the kinetic parameters was conducted, establishing optimal process conditions. The developed technological scheme can be integrated into emergency power supply systems for water supply facilities, providing several hours of autonomous operation of water supply equipment under emergency and extreme conditions.

Keywords: hydrogen production, aluminum alloy AK7, alkaline solution, NaF activators, NaCl activators, critical infrastructure, energy supply.

1. Introduction

Nowadays, the problem of ensuring energy independence for critical infrastructure such as water supply, sewage, and heating systems is one of the key ones in the context of extreme conditions, including military conflicts and environmental disasters. These systems are critically important for the sustainable development of cities and people’s safe and comfortable lives.[1–6] Energy dependence makes them vulnerable in the absence of a stable electricity supply, which may occur due to damage to infrastructure, blockades, interruptions in the supply of energy resources, or the consequences of natural disasters, such as floods, earthquakes, or hurricanes. Especially the water supply system, where water should follow three criteria: to reach the consumer in the required quantity, the required quality, and under the required pressure. The phrase “required quality” is understood as the quality indicators of water should be adequate for the requirements established for drinking water and be safe for human consumption.[2] Thus, according to the report of the UN Human Rights Monitoring Mission in Ukraine,[3] due to attacks on energy infrastructure facilities, residents of some cities remained for a long time without access to safe drinking water. For example, in 2022, the drinking water supply system in the city of Mykolaiv was destroyed. As a result, people were forced to get water from pump rooms or temporary distribution points. In 2024, after attacks on energy facilities, the pumping stations at these points stopped working correctly due to a lack of electricity. This caused water shortages, which caused people to stand in long queues to collect the minimum amount of water for their drinking needs.[3]

The main challenges of water infrastructure energy supply include:

– vulnerability to power outages. In military conditions, power supply is often disrupted due to the destruction of power networks, targeted attacks on infrastructure facilities, or blocking access to energy resources. During environmental disasters, such as storms or floods, large-scale damage to power networks is possible, leading to long-term outages;

– risks of secondary disasters. Disruptions in the operation of pumping stations can cause flooding or a decrease in water quality, and malfunctions in treatment facilities threaten the spread of infectious diseases due to contamination of water bodies;

– high energy consumption of water treatment processes. Water treatment and supplying technologies require significant energy, which creates dependence on external suppliers, especially in increased loads during emergencies.

Effective and long-term backup power sources are needed to support the operation of water infrastructure facilities in emergencies. These can be:

1. Renewable energy sources:

– solar energy. Installing solar panels near water supply facilities provides part of their energy needs. The disadvantages of this solution are that effective operation depends on weather conditions, high initial equipment costs, and the need for large areas for installing panels;

– wind energy. The use of wind turbines is effective in places with strong, constant winds. Disadvantages include dependence on wind conditions, high maintenance costs, impact on the landscape, and possible environmental risks;

– hydropower. Small-scale hydroelectric power plants can power facilities near water flows, but geographical conditions and potential impact on the river ecosystem limit this solution.

2. Battery energy storage systems. They accumulate excess energy from renewable sources and work during peak load or power outages. The disadvantages include the limited service life of batteries, the high cost of installation and maintenance, and the regular disposal of used batteries.

3. Traditional backup generators. Backup generators running on diesel or gas fuel provide an operational power supply during outages. Although the use of such a solution is quite widespread, it cannot be attributed as the best option from an environmental point of view. High carbon dioxide emissions, dependence on fuel supply, noise pollution, and significant operating costs worsen the environmental situation in their locations.

Modern development in the energy sector necessitates using environmentally safe energy sources, among which hydrogen energy is significant.[7–10] Much scientific and technical research is currently dedicated to synthesizing hydrogen as an alternative and environmentally friendly fuel with high energy performance.[5] The main volumes of hydrogen are obtained through the high-temperature conversion of natural gas and coal. However, this method requires additional purification from impurities and has high industrial costs, exceeding natural gas's cost by 8–10 times.

Using traditional carbon fuel resources leads to negative environmental consequences, such as emissions of toxic substances into the atmosphere, which stimulates the search for new, safe, and economically advantageous energy sources.[6, 7] Among the alternative methods for hydrogen synthesis, chemical-thermal cycles stand out, allowing hydrogen production through the interaction of certain metals with aqueous solutions. However, modern methods of hydrogen synthesis are characterized by high production costs and unsatisfactory environmental consequences, limiting the development of hydrogen energy.[11]

To reduce energy and economic costs, new methods of hydrogen synthesis, such as biocatalytic systems, are proposed, but their implementation requires a long time. One promising direction is the dissolution of aluminum or its alloys in alkaline solutions with the subsequent release of hydrogen. Using aluminum alloys can reduce the cost of hydrogen and produce an environmentally friendly energy carrier.[12–15] Due to the large volumes of aluminum production and developed infrastructure, aluminum alloys and waste can significantly lower synthesized hydrogen costs.[9]

Particular attention should be paid to the aluminum-silicon alloy grade AK, widely used in various industries. The use of waste from this alloy for hydrogen synthesis can ensure the production of high-purity hydrogen. The chemical dissolution of aluminum alloys in alkaline solutions is a simple technological process that does not require complex equipment. This allows the creation of a technological scheme that includes a chemical reactor, a hydrogen purification system, and storage tanks.[5]

Aluminum-based hydrogen generation technologies belong to processes utilizing renewable materials within a closed-loop resource utilization system. This cycle includes the chemical interaction of aluminum with alkaline electrolyte, hydrogen production, and comprehensive processing of dissolution reaction products, returning them as aluminum oxide to aluminum production. The advantages of using aluminum alloys for hydrogen generation include their availability, safe transportation, and storage compared to liquid hydrogen.

Currently, the synthesis of hydrogen through the dissolution of aluminum-silicon alloys is insufficiently studied and requires additional research. It is necessary to investigate the kinetic characteristics of the chemical interaction of these alloys and determine the technological indicators for creating a new technological process for hydrogen synthesis using aluminum alloys of grade AK.[4]

2. Experimental

2.1. Materials

For hydrogen synthesis, the most readily available construction aluminum alloy AK7 was used, which consists of aluminum with a mass fraction of 87.6–93.6 %. Additionally, the alloy includes the following impurities: 6–8 % Si, up to 1.3 % Fe, up to 1.5 % Cu, 0.2–0.6 % Mn, 0.2–0.5 % Mg, up to 0.5 % Zn, and up to 0.3 % Ni.[16–19]

In addition to the AK7 alloy, the following materials were used in this study: sodium hydroxide (NaOH), which served as the base component for preparing the alkaline medium at a concentration of 2.5 mol/dm^3, and sodium fluoride (NaF) and sodium chloride (NaCl), which acted as halide activators to accelerate the aluminum dissolution process, in concentrations ranging from 0.02 to 0.2 mol/dm^3. All reagents were of analytical grade and used as received, without additional purification. Electrolyte solutions were freshly prepared before each experiment to ensure reproducibility of results and to minimize the risk of contamination.

2.2. Methods

The weight indicators of the samples were determined using the gravimetric method with VLR-200 analytical scales. The average rate of hydrogen release was experimentally determined using a gas meter and by recording the specific values of the change in the weight indicator of the sample, and adjusted to normal conditions. The rate of hydrogen release was calculated based on the balance of reaction (1)

$$2Al+4H_2O \rightarrow 2AlOOH+3H_2\uparrow \qquad (1)$$

The experimentally measured average hydrogen release rate showed good agreement with the theoretical calculations, confirming that hydrogen is released in a 3:2 molar ratio relative to aluminum, as defined by the overall reaction. The dissolution rates of the studied samples and the hydrogen release rates were calculated based on the dependencies of the specific weight loss ΔP (g/m$^2\cdot$hour) and the average hydrogen release rate (cm^3/m$^2\cdot$hour).

Previously, we established and substantiated that, as a result of studies on the effect of concentration on interaction with an aluminum alloy for hydrogen production, the use of sodium hydroxide with a concentration of 2.5 mol/dm^3 was employed. However, the data obtained from the studies indicate that the values are insignificant for hydrogen synthesis on an industrial scale and require further increase to obtain it in larger quantities.[8]

The duration of each experiment was limited to 1 h to investigate the initial stage of the reaction and obtain clear kinetic data. This time frame was sufficient to observe stable and reproducible trends in the dissolution rate of aluminum and the rate of hydrogen evolution. Extending the duration beyond this point could introduce additional variables such as significant oxide layer buildup, changes in electrolyte composition, or sediment accumulation, which would complicate the interpretation of the primary kinetic behavior.

2.3. Calculations

Based on the approximation of the obtained data regarding the study of the interaction of the aluminum alloy with the alkaline-halide solution, curves corresponding to polynomial functions were constructed in the form of equations (Eqs. 2 and 3):

$$\Delta P = 1964.3\cdot x^2 + 405.3\cdot x - 46.855 \qquad (2)$$

$$V_{H_2} = 948.4\cdot x^2 + 201.74\cdot x - 22.275 \qquad (3)$$

where X is the duration of the study, hours.

The empirical Eqs. (2) and (3) were obtained by approximating the experimental data derived from more than 16 measurements conducted under varying time intervals and electrolyte compositions. Standard polynomial regression was used to fit the experimental values of the aluminum dissolution rate and hydrogen evolution rate. The resulting equations showed a high level of accuracy, with a maximum deviation not exceeding 3.5 % and a coefficient of determination (R^2) greater than 0.98.

The material balance calculation for hydrogen production from the AK7 alloy was performed using specific chemical reaction equations. However, the determination of the amount of hydrogen released was calculated using reaction (1) and the theoretical values of the necessary coefficients, based on the stoichiometric ratios by which the conversion of raw materials into the target product occurs according to formula (Eq. 4):[18]

$$m(C)=\frac{m(A)\cdot n_c\cdot A(C)}{AA\cdot nA}, \qquad (4)$$

where $m(C)$ is the weight of the product, g; $m(A)$ is the weight of the initial substance, g; n_c is the number of molecules of product C; $A(C)$ is the molecular weight of product C, g/mol; AA is the atomic mass of the initial metal, g/mol; nA is the number of molecules of product A.

It should be noted that the calculations for hydrogen release based on reaction (Eq.1) and formula (Eq. 5) should fully coincide.

$$N=\beta\cdot\left(\frac{\Delta G_f^0}{Q}\right)\cdot 100\%, \qquad (5)$$

Eq. (5) is used to evaluate the thermodynamic efficiency of the hydrogen generation process. It calculates the percentage ratio between the standard Gibbs free energy of formation (ΔG^0_f) and the actual heat (Q) consumed during the reaction. The coefficient β accounts for process-specific parameters, including system losses and operational factors. This approach allows for the assessment of the energy performance of the aluminum dissolution process and provides a basis for optimizing energy consumption in the system.

The amount of working electrolyte was determined using formula (Eq. 6):[19, 20]

$$\rho=\frac{m}{V}, \qquad (6)$$

where ρ is the density of the alkaline solution, g/cm^3; V is the volume of the chemical reactor, cm^3; and m is the amount of working electrolyte, g.

The weight of the AK7 alloy was calculated using formula (Eq. 7):

$$\omega_{substance} = \frac{m_{substance}}{m_{alloys}} \cdot 100\%, \qquad (7)$$

where $\omega_{substance}$ is the aluminum content in the alloy, %; $m_{substance}$ is the weight of aluminum in the alloy, g; m_{alloys} is the weight of the alloy, g.

The material balance is calculated either solely based on the main overall reaction equation or by taking into account all parallel, side reactions and products. The material balance is calculated according to the general law of mass conservation as follows:

$$\sum m_{input} = \sum m_{output}, \; \sum m_{input} - \sum m_{output} = 0 \qquad (8)$$

where $\sum m_{input}$ is the total weight of the substances required for the cycle process, g; $\sum m_{output}$ is the total weight of the final products of the process, g.

Calculations of material balances and the quantity of starting materials are carried out depending on the specified hydrogen productivity (1–10 m^3/day), taking into account the use of impurities and reaction products. In this technological process, the material balance calculation is based on a nominal productivity of 1 m^3 of hydrogen per day.

On the surface of aluminum or its alloy, the dissolution reaction of the protective oxide layer occurs. After its dissolution, the main reaction (Eq. 1) proceeds, according to which the weight of synthesized hydrogen, as per formula (Eq. 2), released in 1 hour is 89.3 g. To obtain 89.3 g of hydrogen, it is necessary to calculate the required weight of aluminum based on its reaction with the alkaline solution, which proceeds according to scheme (Eq. 9). According to the calculations, based on reaction (Eq. 9), the required amount of aluminum is 804 g.

$$2Al + 2NaOH + 6H_2O \rightarrow 3H_2 + 2Na[Al(OH)_4]_4 \qquad (9)$$

To obtain 89.3 g of hydrogen, the required amount of aluminum is 804 g. However, the AK7 alloy contains impurities, the total amount of which is 11.4 %. Thus, the weight of pure aluminum in the AK7 alloy is 88.6 %. According to formula (Eq. 7), we calculate the total weight of the AK7 alloy, taking into account the impurities present in the alloy:

$$m_{alloys} = \frac{804}{0.886} = 907.4 \text{ g} \qquad (10)$$

The total amount of impurities in 907.4 g (according to formula (10)) of the alloy is 103.3 g, specifically:
Si = 63.5 g; Fe = 11.8 g; Mn = 3.6 g; Ni = 2.7 g; Cu = 13.6 g; Mg = 3.6 g; Zn = 4.5 g. Therefore, it is necessary to perform calculations separately for each impurity according to the equations of their reactions.

Similarly to the data provided for the dissolution of pure aluminum, we use the same data for the calculation. Therefore, to obtain 1 m^3 of hydrogen (89.3 g), according to reaction (Eq. 1), the required amount of aluminum is 804 g, of alkali is 1191 g, and of water is 1608 g.

3. Results and Discussion

In recent years, significant attention has been paid to the study of the influence of various additives in solutions on chemical[10] and electrochemical processes,[11,12,20,21] as well as on material properties.[13, 22] These studies play an important role in the development of new materials and technologies for various industries. The effectiveness of metal dissolution processes can be significantly enhanced by the use of activators. These activators, depending on their quantity and method of introduction into the reaction medium, can result in a synergistic interaction that improves chemical process productivity.[23, 24] The addition of sodium chloride and sodium fluoride to chemical processes enhances solubilization, reaction efficiency, and environmental safety. Each compound contributes uniquely, optimizing the overall productivity and effectiveness of industrial chemical reactions. Currently, there is almost no information in the literature about the mechanism of interaction between the aluminum surface and an alkaline solution containing an activator.

Within the concentration range of 0.02–0.17 mol/dm^3, the dissolution rate of the alloy increases ninefold over 1 hour. Another indicator of the increased dissolution rate of AK7 is the adsorption of certain ions on the surface of the alloy, which react with the alkaline-halide solution. The addition of halide salts such as NaF and NaCl to the alkaline electrolyte significantly enhances the efficiency of hydrogen generation. This effect is associated with the ability of halide ions (F^- and Cl^-) to locally disrupt or dissolve the passive aluminum oxide film that naturally forms on the alloy surface. Fluoride ions, in particular, are known to be highly effective in penetrating and destabilizing oxide layers, which promotes direct contact between the metallic aluminum and the electrolyte. As a result, the surface becomes more reactive, increasing the rate of aluminum dissolution and consequently accelerating hydrogen release. Moreover, the presence of halide ions may facilitate the formation of soluble aluminum complexes, further supporting the reaction process.[25–28]

The kinetic regularities of the chemical behavior of the AK7 aluminum alloy in alkaline solutions with the addition of chlorides and fluorides have been established, specifically the dissolution rate of the AK7 alloy and the hydrogen evolution rate.

Fig. 1 shows the change in the dissolution rate of the AK7 alloy in an alkaline solution with a concentration of 2.5 mol/dm^3, containing NaCl impurities within the concentration range of 0.02–0.17 mol/dm^3, at a temperature of 293–298 K over a period of 1 hour compared to a pure 2.5 mol/dm^3 solution. However, when comparing the effect of chloride ions in the alkaline solution, we choose a concentration of 0.1 mol/dm^3, as increasing this concentration is impractical due to the supersaturation of the working electrolyte, which leads to a decrease in the specific dissolution rate of the alloy.

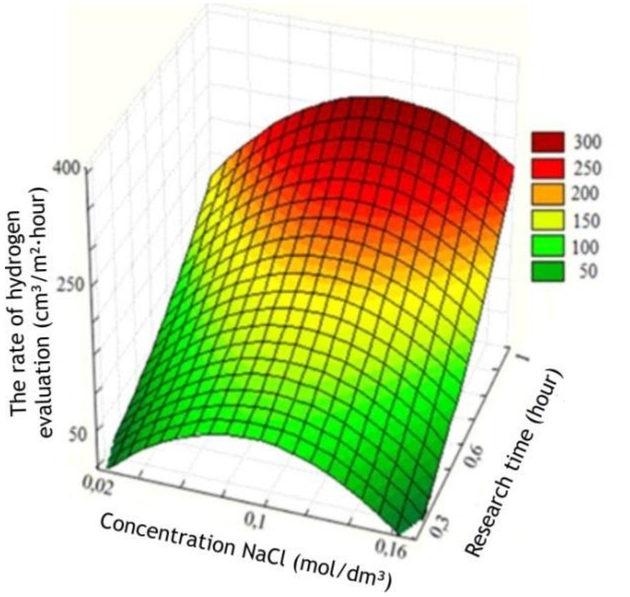

Fig. 1. The dependence of the hydrogen evolution rate as a result of the dissolution of AK7 in alkaline solutions on the NaCl concentration and the duration of the study

Data analysis indicates that the introduction of sodium fluoride into the alkaline solution significantly increases the interaction rate of the aluminum alloy. At a concentration of 0.1 mol/dm^3 over 1 hour, the dissolution rate is 1.05 times higher compared to the presence of chloride ions at a concentration of 0.1 mol/dm^3 in the presence of hydroxyl ions, and 9.4 times higher compared to a pure solution with a concentration of 2.5 mol/dm^3. Accordingly, the hydrogen evolution rate also increases (Fig. 2).

This study also investigated the simultaneous action of the activators NaF and NaCl, which were introduced into a technologically optimized alkaline electrolyte (2.5 mol/dm^3 NaOH). The chemical dissolution of the aluminum alloy AK7 was studied in an alkaline solution with a concentration of 2.5 mol/dm^3, enhanced by the addition of two activators: NaF and NaCl, at concentrations of 0.2 mol/dm^3 and 0.1 mol/dm^3, respectively. The experiments were conducted using aluminum alloy samples with a geometrical surface area of $5.6 \cdot 10^{-4}$ m^2 under conditions of 293–298 K for 1 hour.

The experimental results demonstrated a significant correlation between the research duration and the mass loss of the AK7 aluminum alloy during its interaction with the alkaline-halide solution. Throughout the study, the specific mass loss of the alloy increased from an initial 600 g/m^2·hour at 0.15 hours to approximately 2400 g/m^2·hour after 1.05 hours. This progressive increase in dissolution rate indicates the catalytic effects of halide ions present in the electrolyte.

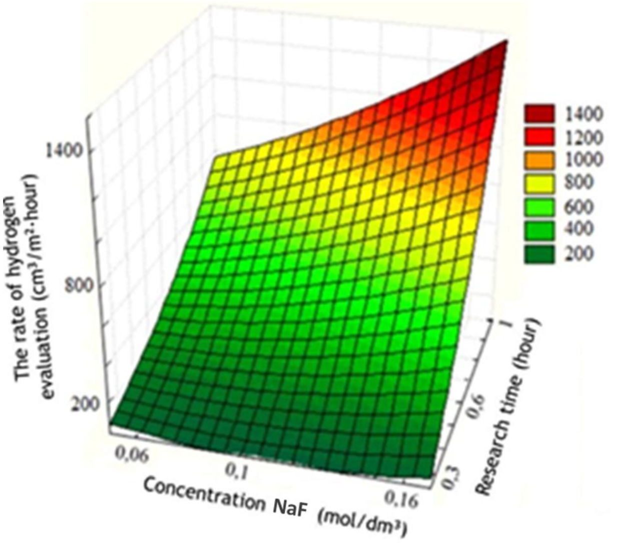

Fig. 2. The dependence of the hydrogen evolution rate as a result of the dissolution of AK7 in alkaline solutions on the NaF concentration and the duration of the study

The data also confirm a nonlinear dependency of dissolution rate on time, characterized by an initial gradual increase followed by a more rapid acceleration. This behavior is attributed to the combined actions of sodium fluoride and sodium chloride, which enhance the dissolution of the protective oxide layer on the aluminum surface and subsequently facilitate the reaction with the alkaline medium. These findings underscore the technological viability of the proposed electrolyte composition for industrial hydrogen production, as it ensures a substantial dissolution rate of the aluminum alloy and corresponding hydrogen evolution within relatively short timeframes. The obtained results provide a solid basis for optimizing reaction conditions to further enhance process efficiency. Analyzing the data, it is possible to conclude the promising use of this solution on an industrial scale, as the rate of hydrogen release in the use of this electrolyte also increases, reaching significant values when using halide activators in the alkaline solution.

Fig. 3 shows the dependence of the hydrogen release rate on the influence of NaF and NaCl impurities at concentrations of 0.2 mol/dm^3 and 0.1 mol/dm^3, respectively, in a 2.5 mol/dm^3 NaOH solution at temperatures of 293–298 K over 1 hour.

Analyzing the obtained data on the interaction of the AK7 alloy with the alkaline-halide electrolyte, it is evident that with an increase in the duration of the study, there is a rapid increase in the dissolution rate of the aluminum alloy (Fig. 1), which also leads to an increase in the hydrogen release rate (Fig. 3).

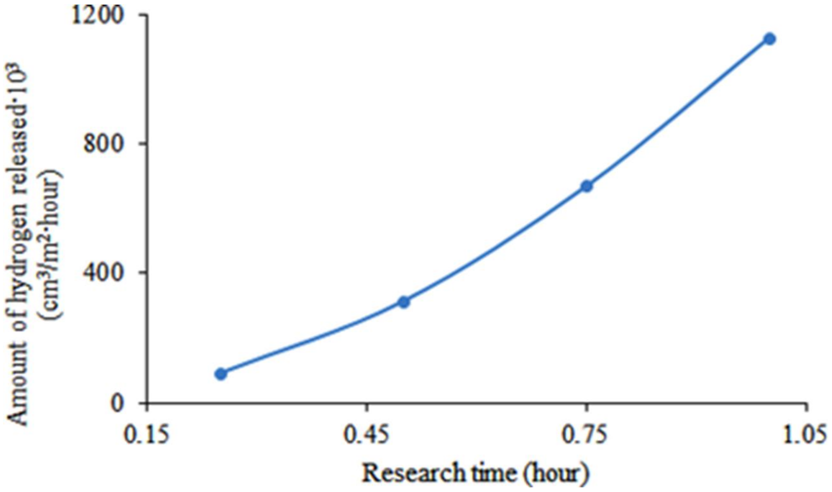

Fig. 3. Rate of hydrogen release due to the combined effect of two activators in an alkaline solution

The presented research results (Figs. 1 and 2) correspond to the empirical equations (Eqs. 2 and 3), which fully determine the most technological patterns of the influence of electrolyte components and the duration of the study on the dissolution rate of the AK7 alloy and the amount of hydrogen released over 1 hour. Based on the experimental data, it has been established that NaF and NaCl are technologically promising activators in an alkaline solution, with concentrations that can vary between 0.19–0.21 mol/dm³ and 0.09–0.11 mol/dm³, respectively.

It should be noted that the simultaneous action of accelerators NaF and NaCl at concentrations of 0.19–0.21 mol/dm³ and 0.09–0.11 mol/dm³, respectively, in an electrolyte of 2.4–2.6 mol/dm³ NaOH, provides promising prospects for hydrogen production. The obtained data show that the dissolution rate of the AK7 alloy is 10 times higher compared to the absence of activator impurities and is characterized by the following values: ΔP = 2321.43 g and V_{H_2}=1126.4·103 cm³ per 1 m² within 1 hour.

The rate of hydrogen release depends strongly on the concentration of halide activators in the alkaline electrolyte. At lower concentrations (0.02–0.05 mol/dm³), both NaCl and NaF significantly increase the reaction rate by facilitating the destruction of the passive aluminum oxide layer and enhancing the accessibility of the aluminum surface to the electrolyte. As the concentration of NaCl or NaF increases up to 0.2 mol/dm³, the rate of hydrogen evolution also increases, but the effect tends to plateau beyond certain concentrations, indicating saturation of the activation mechanism. This behavior suggests that there is an optimal range of halide concentration for maximizing hydrogen yield, beyond which further increases in concentration do not provide significant kinetic benefits and may even lead to secondary effects such as complexation or ionic strength interference.

The noticeably higher effectiveness of NaF as an activator compared to NaCl is primarily attributed to the unique chemical properties of fluoride ions (F^-). Fluoride has a smaller ionic radius and higher electronegativity than chloride, which enables it to more effectively penetrate and destabilize the passive oxide film on the aluminum surface. This leads to a more active dissolution process and a correspondingly higher rate of hydrogen evolution. In contrast, chloride ions (Cl^-), although also capable of disrupting oxide films, exhibit a weaker effect due to their lower reactivity with aluminum oxide and their tendency to form less stable surface complexes.

The production of hydrogen through the interaction of aluminum alloys with alkaline solutions (destructive depolarization cycle – DDC) involves the use of the working surface of aluminum in the form of rolled plates and a wide range of powders with sodium hydroxide solutions containing activator impurities. Based on the conducted research and analysis of literature data, it is possible to create a technological process for the chemical production of hydrogen using widely used materials. To implement this process, material balance calculations of the materials entering the reactor and the output of reaction products are carried out.

Table presents the calculation results of the components of the material balance that affect hydrogen production through the chemical interaction of the AK7 alloy with alkaline solutions containing halide impurities at a temperature of T = 293–298 K.

Table. Components of the material balance for hydrogen production from the AK7 alloy

Required Materials			Expenditures		
No.	Materials	Weight, g	No.	Materials	Weight, g
1	AK7 alloy:	907.4:	1	Hydrogen	99.4
	aluminum	804	2	Na[Al(OH)$_4$]	3514
	silicon	63.5	3	Na_2SiO_3	276.7
	iron	11.8	4	FeO	15.17
	manganese	3.6	5	MnO	4.65
	nickel	2.7	6	Ni+Cu	16.3
	copper	13.6	7	(sludge)	
	magnesium	3.6	8	MgO	6
	zinc	4.5		ZnO	5.6
2	Electrolyte:	13860:	9	Electrolyte:	10829.9
	NaOH	1386		NaOH	13.6
	NaCl	69.3		NaCl	69.3
	NaF	116.4		NaF	116.4
	water	12288.3		water	10630.59
	Total	14767		Total	14767

Based on the calculations summarized in Table 1, the material balance equation (Eq. 8) is satisfied. According to this equation, $\sum m_{intake} - \sum m_{expenditures} = 0$, which indicates the feasibility of calculating the necessary practical expenditure coefficients for producing 1 m^3 of hydrogen.

The results obtained in this study are in agreement with published data on the enhancement of hydrogen generation from aluminum in alkaline media. According to Feng *et al.*,[21] the addition of salts such as NaCl to aluminum powder increases the hydrogen yield significantly by facilitating the breakdown of the passive oxide layer. Although Wang *et al.*[17] focused on NaOH and KOH, their findings confirm that preventing passivation and optimizing reaction conditions, such as temperature and base volume, are key to improving hydrogen evolution rates. In our study, the use of halide salts (NaF and NaCl) at optimized concentrations allowed for comparable or better hydrogen release under milder conditions, emphasizing their potential as effective activators in aluminum-based hydrogen generation systems.

The principal process scheme for hydrogen synthesis is illustrated in Fig. 4. The technological scheme demonstrates the process of hydrogen production through the chemical dissolution of aluminum alloy AK7 in an alkaline solution with activators.

The technological process involves preparatory operations, which include:

- sorting the AK7 alloy raw material by size and degree of contamination with mineral oils;
- chemically degreasing the surface to remove mineral oils;
- preparing the solution for interaction with the aluminum alloy;
- preparing the chemical reactor for operation;
- supplying components to the reactor.

The reactor system is purged with an inert gas (argon or nitrogen) before each experiment and subsequently sealed to prevent the ingress of atmospheric oxygen. This step is critical for two reasons: first, oxygen can react with the aluminum surface to form a passive oxide layer, which inhibits further dissolution and reduces hydrogen generation efficiency; second, the simultaneous presence of hydrogen and oxygen in a closed system poses a significant explosion hazard. Therefore, maintaining an oxygen-free environment ensures both the safety and effectiveness of the process.

The hydrogen production process is carried out in batch mode, where the reactor is loaded with a fixed quantity of aluminum alloy and electrolyte, allowed to react for a defined time, and then cleaned and reloaded for subsequent cycles. This operational mode allows precise control over reaction conditions and facilitates the collection of experimental data.

The sorted and degreased raw material is fed into the hopper. From the raw material hopper (1) to the chemical reactor (2), AK7 alloy or aluminum powder is supplied through the pipeline (11). Through pipeline (3), the working electrolyte is supplied to the reaction device. Before bringing the reactor parts into working condition, the technological line is purged with inert gas. After this operation, the chemical reactor is started, followed by its sealing to prevent oxygen from entering the reaction space. After the chemical reactor operates, the synthesized hydrogen is transported through its pipeline into the hydrogen purification system (6), where it is brought to working condition and then fed into the storage unit (7) using a compressor (9). In the storage unit (7), hydrogen fills the storage containers, undergoes quality checks by sampling gas according and then enters the combustion system to generate heat through the pipeline (10). The operational state of the hydrogen synthesis technological scheme is controlled by the process control unit (5).

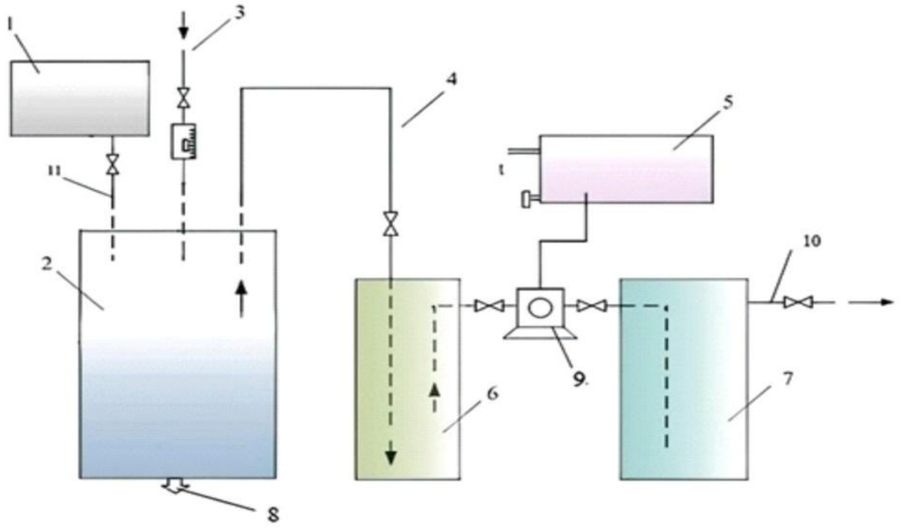

Fig. 4. Technological scheme for hydrogen synthesis: 1 – raw material hopper; 2 – reactor; 3 – electrolyte supply; 4 – hydrogen transport pipeline; 5 – process control unit; 6 – hydrogen purification system; 7 – hydrogen storage; 8 – sludge discharge pipeline; 9 – compressor; 10 – hydrogen output pipeline as needed; 11 – raw material supply pipeline

The reaction products in the form of sludge and supersaturated solutions enter the lower zone of the reactor, where they are transferred to the disposal chamber for obtaining the final product Al_2O_3 using the sludge removal pipeline (8).

The technological scheme for producing hydrogen from aluminum alloys additionally includes systems for raw material preparation and processing of reaction products, which comprise crystallization concentrators for aluminates, oxides, and aluminum oxides. The line features a heat reactor where these compounds are converted into Al_2O_3, dried, and then directed to regeneration or aluminum adsorption filter systems.

After preparing the raw material to the required quality, it is loaded into the reactor. The design of the reactor, its productivity, and operational reliability are of great importance. It must meet the following requirements[17] and be resistant to the action of reagents:

– have a high level of sealing of the reaction chamber;

– exclude the possibility of oxygen entering the reaction zone and the occurrence of an explosion;

– be equipped with devices for supplying aluminum alloy and working electrolyte;

– ensure the removal of hydrogen from the reaction zone and its purification;

– have a system for removing reaction products (sludge) and their processing.

A simplified diagram of the chemical reactor shown in Fig. 5 represents a batch ideal mixing reactor (BIMR) with a mechanical stirrer.

Operation of the chemical reactor: aluminum alloy AK7 plates or aluminum powder are fed to the surface of the reaction device through the pipeline (8). The reactor is filled to 75 % of its volume, after which the electrolyte is pumped into it via pipeline (4) based on the productivity and reaction balances of AK7 interacting with sodium hydroxide. Before bringing the reactor parts into working condition, the technological line is purged with inert gas. The reactor is then sealed, and the mechanical stirrer (Eq. 6) is activated. As a result, hydrogen is released and fills the volume of the reactor. After the BIMR operation, the synthesized hydrogen is transferred through pipeline (7) to the system for separation from the electrolyte for drying and storage in special containers. The purified gas is collected in containers, sealed, or burned as fuel if necessary. The reaction products in the form of sludge and supersaturated solutions enter the lower zone of the reactor and are then discharged through the sludge removal pipeline (3) into steel containers and processed into the final product, aluminum oxide. After the hydrogen synthesis is completed, the reactor is cleaned of residues and prepared for further cycles.

Thus, the calculations of materials, reagents, and energy carriers for the specified productivity fully correspond to the experimental results. The dissolution products of the alloy, primarily aluminates, formed as sludge or supersaturated solutions, are processed at high temperatures to obtain aluminum oxide as the final product, which is subsequently reused as intended.

The research demonstrates the possibility of producing hydrogen via a low-temperature chemical interaction of AK7 aluminum alloy with alkaline-halide electrolytes, without the use of membrane electrolyzers. Hydrogen is generated in the reactor, then purified and directed to storage units for further use.

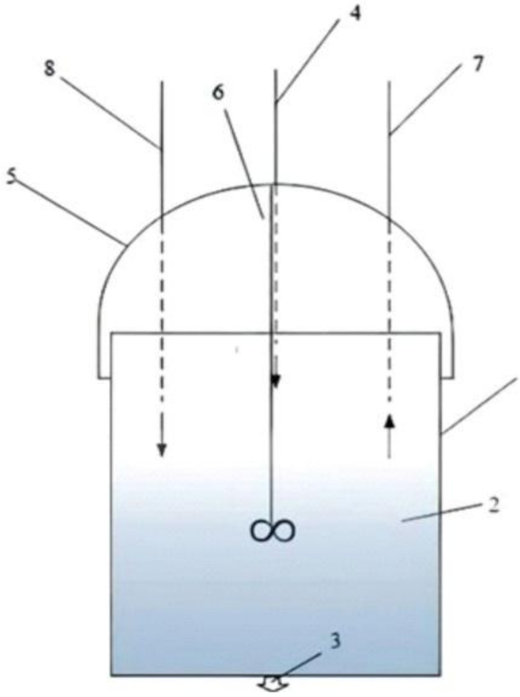

Fig. 5. Simplified diagram of the hydrogen production reactor: 1 – reactor body; 2 – reaction device; 3 – sludge removal pipeline; 4 – electrolyte supply; 5 – reactor cover; 6 – mechanical stirrer; 7 – hydrogen outlet; 8 – raw material supply pipeline

One of the key areas of practical implementation of the proposed technology is its use to ensure a backup power supply for infrastructure. For example, the technological equipment of the first and second lift pumping stations, which carry out water intake and supply to consumers, is powered. They are critically important objects, especially in emergencies,[29] when the centralized power supply is disrupted.

Fig. 6 presents a conceptual diagram of the implementation of a hydrogen backup power supply system for a pumping station. The main elements of the system are:

- a chemical hydrogen generator based on aluminum alloy AK7 and alkaline electrolyte with NaF/NaCl activators;
- a hydrogen purification, drying, and storage unit;
- a fuel cell or hydrogen generator;
- an inverter and voltage stabilizer for powering electrical equipment;
- a system for disposing of reaction by-products.

Preliminary calculations of the implementation of such scheme for backup power supply of the second lift pumping station show that using 24.3 kg of AK7, 36 kg of alkali and 30–35 l of water will provide 3 hours of autonomous operation of a medium-power pumping station (up to 15 kW) without the use of diesel generators or external power. After the cycle is completed, the system can be quickly prepared for restart if raw materials are available.

The results open up several directions for further research in the energy supply of critical infrastructure based on hydrogen technologies. First, a deeper study is required to optimize hydrogen power systems for infrastructure facilities (pumping stations, water treatment plants, *etc.*). It is important to determine the most effective schemes for scaling such systems, considering typical energy consumption and operating modes.

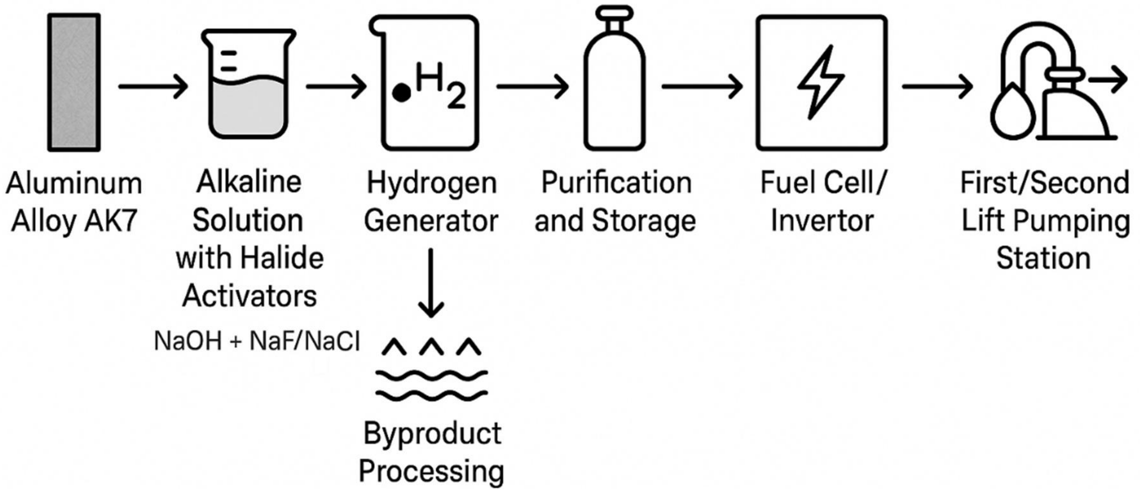

Fig. 6. Conceptual diagram of the implementation of the hydrogen backup power system at the first/second lift pumping stations

Our further research will compare hydrogen power sources' efficiency and economic feasibility with traditional backup systems, such as diesel generators, batteries, or solar panels. This will allow us to assess the payback of implementing hydrogen installations for water supply and sewage enterprises. Special attention will be paid to such systems' safety and reliability issues in conditions of temperature fluctuations, humidity, and other external factors. It is important to ensure a stable hydrogen supply, a controlled generation process, and safe operation of fuel cells.

4. Conclusions

Based on experimental data, it has been established that the technologically promising activators in an alkaline solution are NaF and NaCl, with concentrations of 0.19–0.21 mol/dm^3 and 0.09–0.11 mol/dm^3, respectively. It has been found that the simultaneous use of NaF and NaCl at concentrations of 0.19–0.21 mol/dm^3 and 0.09–0.11 mol/dm^3 in an electrolyte of 2.4–2.6 mol/dm^3 NaOH is promising for hydrogen production.

A technological scheme for hydrogen synthesis has been developed. Its feature lies in its simplicity and accessibility, as its implementation requires readily available chemical reagents and widely used domestic materials. Material balance calculations for production have been carried out using pure aluminum and the AK7 casting alloy. It should be noted that the material balance calculations and the quantity of initial products are determined based on the specified hydrogen productivity.

The study demonstrates an effective approach for hydrogen production through chemical dissolution of AK7 aluminum alloy in an alkaline solution with NaF and NaCl activators. The proposed electrolyte composition significantly increases the dissolution rate and hydrogen yield. Experimental analysis revealed the key role of halide activators in enhancing reaction kinetics, enabling process optimization. The developed method is simple, based on accessible materials, and applicable under emergency conditions.

The practical significance lies in developing a chemical hydrogen-generation method using AK7 aluminum alloy in an alkaline solution to provide backup power for critical infrastructure, particularly first- and second-stage pumping stations in centralized water-supply systems. The resulting modular hydrogen units operate without external electricity or fuel and can be activated immediately during outages to sustain pumping and potable water delivery. Moreover, this technology applies to decentralized hydrogen-energy frameworks, offering emergency power to utilities, healthcare facilities, communication systems, and other essential services. Overall, it contributes to a resilient, environmentally sustainable energy infrastructure.

References

[1] Epoyan, S.; Airapetian, T.; Haiduchok, O.; Blahodarna, H.; Kravchuk, O. Experimental Research of Combined Horizontal Settling Tank for Drinking Water Supply. *IOP Conf. Ser.: Earth Environ. Sci.* **2024**, *1376*, 012029. https://doi.org/10.1088/1755-1315/1376/1/012029

[2] Haiduchok, O.; Kanunnikova, N.; Sakun, A.; Tomashevskyi, R.; Vorobiov, B. Prospective Technologies of Water Purification and Disinfection for Safe Human Consumption. In *The Development of Technical, Agricultural and Applied Sciences as the Main Factor in Improving Life.* Collective Monograph; Primedia eLaunch: Boston, 2024; pp. 230–252. https://doi.org/10.46299/ISG.2024.MONO.TECH.2

[3] Attacks on Ukraine's Energy Infrastructure: Harm to the Civilian Population. *Bulletin of UN Human Rights Monitoring Mission in Ukraine*. United Nations Human Rights, 2024. https://ukraine.ohchr.org/sites/default/files/2024-09/Population.pdf (accessed 2024-11-28).

[4] Kwon, H.; Park, H.; Jun, S.; Choi, S.; Jang, H. High Performance Transition Metal-Based Electrocatalysts for Green Hydrogen Production. *Chem. Commun.* **2022**, *58*, 7874–7889. https://doi.org/10.1039/d2cc02423c

[5] Dincer, I.; Acar, C. Review and Evaluation of Hydrogen Production Methods for Better Sustainability. *Int. J. Hydrog. Energy* **2015**, *40*, 11094–11111. https://doi.org/10.1016/J.IJHYDENE.2014.12.035

[6] Li, Z.; Xu, Q. Metal-Nanoparticle-Catalyzed Hydrogen Generation from Formic Acid. *Acc. Chem. Res.* **2017**, *50*, 1449–1458. https://doi.org/10.1021/acs.accounts.7b00132

[7] Pyshyev, S.; Lypko, Yu.; Demchuk, Yu.; Kukhar, O.; Korchak, B.; Pochapska, I.; Zhytnetskyi, I. Characteristics and Applications of Waste Tire Pyrolysis Products: A Review. *Chem. Chem. Technol.* **2024**, *18*, 244–257. https://doi.org/10.23939/chcht18.02.244

[8] Abdelhafiz, A.; Li, J. High Entropy Oxides Synthesis by Rapid Plasma Generation with Applications Towards Electrocatalytic Hydrogen Generation. *ECS Meet. Abstr.* **2023**, *MA2023-01*, 1500. https://doi.org/10.1149/ma2023-01201500mtgabs

[9] Nishiyama, H.; Yamada, T.; Nakabayashi, M.; Maehara, Y.; Yamaguchi, M.; Kuromiya, Y.; Domen, K. Photocatalytic Solar Hydrogen Production from Water on a 100-m² Scale. *Nature* **2021**, *598*, 304–307. https://doi.org/10.1038/s41586-021-03907-3

[10] Lavrova, I. O.; Demidov, I. M.; Cherkashina, G. M. Comparative Analysis of the Impact of Synthetic Additives and Phosphatide Concentrate on the Adhesive Properties of Road Petroleum Bitumen. *Vopr. Khimii Khimicheskoi Tekhnologii.* **2023**, *146*, 18–25. https://doi.org/10.32434/0321-4095-2023-146-1-18-25

[11] Shtefan, V. V.; Smyrnov, O. O.; Bezhenko, A. O.; Epifanova, A. S.; Kanunnikova, N. O.; Metenkanych, M. M.; Knyazev, S. A. Corrosion of Cobalt-Molybdenum Alloys in Chloride Solutions. *Mater. Sci.* **2019**, *54*, 512–518. https://doi.org/10.1007/s11003-019-00225-y

[12] Shtefan, V. V.; Bulhakova, A. S.; Kanunnikova, N. A. Electrochemical Behavior of Co-Mo Alloy. *Funct. Mater.* **2022**, *29*, 215–220. https://doi.org/10.15407/fm29.02.215

[13] Shtefan, V. V.; Kanunnikova, N. A. Oxidation of AISI 304 Steel in Al- and Ti-Containing Solutions. *Prot. Met. Phys. Chem. Surf.* **2020**, *56*, 379–384. https://doi.org/10.1134/S2070205120020239

[14] Alacid, E.; Nájera, C. Aqueous Sodium Hydroxide Promoted Cross-Coupling Reactions of Alkenyltrialkoxysilanes under Ligand-Free Conditions. *J. Org. Chem.* **2008**, *73*, 2315–2322. https://doi.org/10.1021/jo702570q

[15] Shtefan, V.; Kanunnikova, N.; Pilipenko, A.; Pancheva, H. Corrosion Behavior of AISI 304 Steel in Acid Solutions. *Mater. Today: Proc.* **2019**, *6*, 149–156. https://doi.org/10.1016/j.matpr.2018.10.088

[16] Shtefan, V. V.; Kanunnikova, N. O.; Goncharenko, T. Y. Analysis of the Structure and Anticorrosion Properties of Oxide Coatings on AISI 304 Steel. *Mater. Sci.* **2021**, *57*, 248–255. https://doi.org/10.1007/s11003-021-00539-w

[17] Wang, C.; Chou, Y.; Yen, C. Hydrogen Generation from Aluminum and Aluminum Alloys Powder. *Procedia Eng.* **2012**, *36*, 105–113. https://doi.org/10.1016/J.PROENG.2012.03.017

[18] Katsoufis, P.; Doukas, E.; Politis, C.; Avgouropoulos, G.; Lianos, P. Enhanced Rate of Hydrogen Production by Corrosion of Commercial Aluminum. *Int. J. Hydrog. Energy* **2020**, *45*, 10729–10734. https://doi.org/10.1016/j.ijhydene.2020.01.215.

[19] Das, B.; Robi, P. S.; Mahanta, P. Experimental Investigation and Modelling by Machine Learning Techniques for Hydrogen Generation by Reacting Aluminium with Aqueous NaOH Solution. *Fuel* **2023**, *351*, 128924. https://doi.org/10.1016/j.fuel.2023.128924

[20] Nur, A.; Budiman, A. W.; Jumari, A.; Nazriati, N.; Fajaroh, F. Electrosynthesis of Ni-Co/Hydroxyapatite as a Catalyst for Hydrogen Generation *via* the Hydrolysis of Aqueous Sodium Borohydride ($NaBH_4$) Solutions. *Chem. Chem. Technol.* **2021**, *15*, 389–394. https://doi.org/10.23939/chcht15.03.389

[21] Feng, J.; Du, H.; Li, K. Current Status of Aluminium-Water Reaction for Hydrogen Production and Cogeneration Research. *Adv. Comput. Eng. Technol. Res.* **2024**, *1*, 273–279. https://doi.org/10.61935/acetr.2.1.2024.P273

[22] Lu, J.; Yu, W.; Tan, S.; Wang, L.; Yang, X.; Liu, J. Controlled Hydrogen Generation Using Interaction of Artificial Seawater with Aluminum Plates Activated by Liquid Ga–In Alloy. *RSC Adv.* **2017**, *7*, 30839–30844. https://doi.org/10.1039/C7RA01839H

[23] Dai, H.; Ma, G.; Xia, H.; Wang, P. Reaction of Aluminium with Alkaline Sodium Stannate Solution as a Controlled Source of Hydrogen. *Energy Environ. Sci.* **2011**, *4*, 2206–2212. https://doi.org/10.1039/C1EE00014D

[24] Mahmoodi, K.; Alinejad, B. Enhancement of Hydrogen Generation Rate in Reaction of Aluminum with Water. *Int. J. Hydrog. Energy* **2010**, *35*, 5227–5232. https://doi.org/10.1016/J.IJHYDENE.2010.03.016

[25] Soler, L.; Candela, A.; Macanás, J.; Muñoz, M.; Casado, J. In Situ Generation of Hydrogen from Water by Aluminum Corrosion in Solutions of Sodium Aluminate. *J. Power Sources* **2009**, *192*, 21–26. https://doi.org/10.1016/J.JPOWSOUR.2008.11.009

[26] Fadhilah, N.; Maulana, F.; Wahyuono, R.; Raditya, M.; Risanti, D. Hydrogen Generation from Waste Aluminum Foil AA 1235 Promoted by Sodium Aluminate in Sodium Hydroxide Solutions. *Key Eng. Mater.* **2023**, *965*, 113–118. https://doi.org/10.4028/p-UR11a3

[27] Hiraki, T.; Takeuchi, M.; Hisa, M.; Akiyama, T. Hydrogen Production from Waste Aluminum at Different Temperatures, with LCA. *Mater. Trans.* **2005**, *46*, 1052–1057. https://doi.org/10.2320/MATERTRANS.46.1052

[28] Noland, B.; Erickson, P. Apparent Kinetics of Hydrogen Production with Water-Slurried Aluminum Delivery in Aqueous Sodium Hydroxide Solutions. *Int. J. Hydrog. Energy* **2020**, *45*, 24285–24299. https://doi.org/10.1016/j.ijhydene.2020.06.165

[29] Tomashevskyi, R.; Vorobiov, B.; Kanunnikova, N.; Shestopalov, O.; Haiduchok, O.; Kniazieva, H. Portable Device for Purifying and Disinfecting Water in Extreme Conditions. *2024 IEEE 5th KhPI Week on Advanced Technology (KhPIWeek)* **2024**, 1–5. https://doi.org/10.1109/khpiweek61434.2024.10877947

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ХІМІЧНЕ ВИРОБНИЦТВО ВОДНЮ З АЛЮМІНІЄВОГО СПЛАВУ АК7 З ВИКОРИСТАННЯМ АКТИВАТОРІВ NAF ТА NACL ДЛЯ СИСТЕМ АВАРІЙНОГО ЕНЕРГОЗАБЕЗПЕЧЕННЯ

Анотація. *Розглянуто метод отримання водню хімічним розчиненням алюмінієвого сплаву АК7 в лужних розчинах з додаванням активаторів NaF і NaCl. Оптимізований склад електроліту та концентрації активаторів істотно підвищують швидкість розчинення алюмінію, що сприяє ефективному виділенню водню. Запропонований метод має переваги щодо стійкості, економічної ефективності та мінімального впливу на довкілля. Виконано всебічний аналіз кінетичних параметрів, що дало змогу визначити оптимальні умови процесу. Розроблену технологічну схему генерації водню можна інтегрувати в системи аварійного електропостачання об'єктів водопостачання, забезпечуючи декілька годин автономної роботи водопровідного обладнання в аварійних та екстремальних умовах.*

Ключові слова: *виробництво водню, алюмінієвий сплав АК7, лужний розчин, активатори NaF, активатори NaCl, критична інфраструктура, енергозабезпечення.*