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Problems and Ways of Creating Efficient Electric Power Installations for Unmanned Underwater Vehicles Based on Chemical Current Sources

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Abstract—The scheme of an electric installation of an unmanned underwater vehicle based on a chemical current source of aluminum–water type with an alkaline electrolyte is considered. The mass–volume and energy characteristics of energy sources based on the aluminum–water system with an alkaline electrolyte and the characteristics of the main and auxiliary batteries of energy sources are given. It is shown that, in terms of stored energy, installations with chemical current sources of the aluminum–oxygen system are equivalent to installations with aluminum–water current sources in an alkaline electrolyte and have about six times more energy than an SP-200 battery and twice as much as installations with magnesium–seawater current sources. The given characteristics of power plants show that hydronic chemical current sources based on aluminum are promising and have competitive indicators, but require the development of the production of appropriate materials for electrodes.

Keywords: unmanned underwater vehicle, electrical power plant, chemical current source, hydronic batteries

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Hydronic chemical current sources (CCSs), which employ alkaline-earth metals, in particular, aluminum or magnesium, as a fuel and an oxidizing agent represented by salt or sea water as an electrolyte, hold a specific place among chemical current sources [1, 2].

In the case of a magnesium–water CCS system, MA-2 and MA-8 magnesium alloys are used as anode fuel. In the case of an aluminum-based CCS, pure metal is inert due to the oxide film; therefore, various additives to the main metal are also used.

The alloys that are applicable for hydronic CCSs using a neutral electrolyte (seawater) are not industrially produced in Russia; therefore, it is of interest to study aluminum-based hydronic CCSs and compare them to magnesium-based batteries. For example, the theoretical values of emf and thermodynamic efficiency of reaction in magnesium–water CCSs are 1.86 and 1.02 V, respectively. The theoretical specific energy of a CCS per 1 kg of magnesium corresponds to 4.1 kWh. The theoretical specific energy of such widespread power sources as lead accumulators corresponds to 0.17 kWh/kg, which is around 20 times as low. However, the advantages of CCSs over accumulators are not totally realized due to the low rate of reaction and high polarization of electrodes, mainly the cathode. These advantages are obvious during high rate discharges, at which the fraction of construction materials is much less than the fraction of consumed fuel. In practice, the following characteristics can be obtained at a water electrolyte temperature of 42–45°C: the optimal mode is a voltage of 0.43 V and current density of 125 A/m^2, and the maximum power mode is a voltage of 0.33 V and a current density of 250 A/m^2. The output of hydrogen corresponds to 1.7–1.9 m^3/kWh.

The problem of a low specific power of a magnesium-based current source could be solved to some extent in a CCS of the aluminum–water system with an alkaline electrolyte, which in principle represents a combination of a hydronic CCS and current source with a strong electrolyte based on alkali. Their common feature is an inert cathode, on which water is reduced to hydrogen during operation of the current source.

The theoretical values of emf and thermodynamic efficiency of the reaction of aluminum with an aqueous solution of sodium hydroxide correspond to 1.43 and 1.01 V. Studies show that the theoretical specific energy of a CCS per 1 kg of aluminum is 4.544 kWh, and experiments show that a cell voltage of 0.5–0.55 V is achieved at a discharge current density of 700 A/m^2 at an electrolyte temperature of 45–50°C with a con-

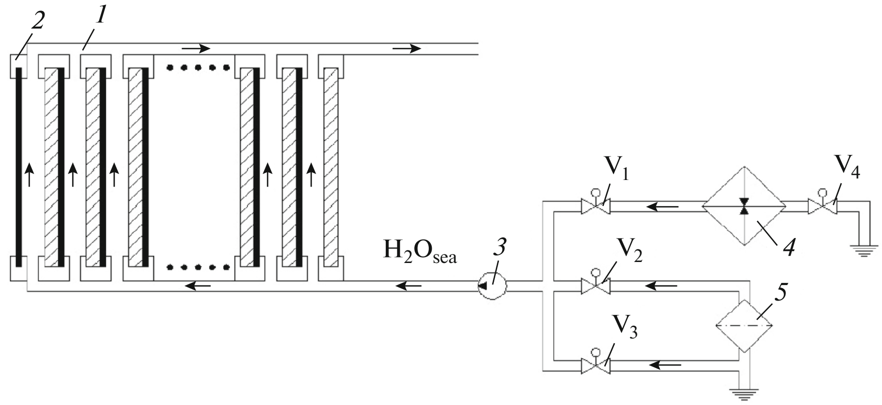

Fig. 1. Flow diagram of the CCS based on the aluminum–seawater system with alkaline electrolyte and natural circulation: (*1*) tank, (*2*) CCS, (*3*) seawater supply pump, (*4*) alkali concentrator, and (*5*) filter. V_1–V_4 are shutoff valves.

centration of potassium hydroxide of 2.0 mol/L. The output of hydrogen is 1.6–1.7 m^3/kWh upon operation of the CCS.

Inert surface-skeletal catalysts (SSCs) are used in aluminum–water CCSs. Manned and unmanned underwater vehicles (UUVs) are the most suitable field of application of such CCSs, because they can provide optimal values of the following characteristics as compared to other types of accumulators: the mass-to-volume ratio (kg/L), which governs the required buoyancy (in the case of lithium-ion accumulators, this value corresponds to around 2.0 kg/L, whereas it is higher than 3.0 kg/L in the case of lead accumulators, and density, which represents the ratio of power to energy (W/Wh), which governs the maintenance of required sustainability. In this case, thick short electrodes are used to provide high energy and thin long electrodes are used for high power.

Due to the fact that hydrogen is emitted into the environment during the discharge of CCSs, such current sources cannot be used in UUVs for reasons of stealth. This problem can be solved using the aluminum–oxygen system in CSSs of UUVs in main electric installations (EIs), in which hydrogen is generated at significantly lower quantities and could be neutralized in the presence of oxygen in the catalytic afterburning furnace on underwater vehicle (UV) if necessary [3].

Theoretical values of emf and thermodynamic efficiency of the reaction of aluminum–oxygen CCS correspond to 2.89 and 0.98 V; theoretical specific energy of CCS per 1 kg of aluminum is 4.56 kWh. Experiments showed that the cell voltage of 1.3–1.35 V is achieved at a discharge current density of 2500 A/m^2 at an electrolyte temperature of 45–50°C with the concentration of potassium hydroxide corresponding to 2.0 mol/L. The yield of hydrogen corresponds to 0.3–0.4 m^3/kWh upon operation of the CCS. In such a type of CCS, a porous oxygen electrode analogous to a cathode from an electrochemical generator (ECG) of hydrogen–oxygen type with liquid alkaline electrolyte is employed. UUVs are the most suitable field of application of such CCSs.

EFFECTIVE SCHEME OF AN ELECTRIC INSTALLATION BASED ON AN ALUMINUM–WATER CHEMICAL CURRENT SOURCE WITH AN ALKALINE ELECTROLYTE

The basic flow diagram and composition of EI equipment based on the aluminum–water system with natural circulation of alkaline electrolyte are given in Fig. 1.

Figure 2 shows the flow diagram of an EI based on the CCS of the aluminum–water system with an alkaline electrolyte and forced circulation of the electrolyte using a pump. The design of the electrodes also involves protection of an anode made from an alloy based on aluminum, indium, and tin, which is in the form of an aluminum foil and provides storage of the CCS when filled with fresh water [4, 5].

A concentrator containing solid potassium hydroxide and a saturated 50% solution of alkali, which are used upon initiation for preparation along with heating of the supplied electrolyte during dissolution of the solid alkali and maintenance of a constant electrolyte concentration upon operation of the CCS, was added to the setups (Figs. 1, 2). To avoid dissolution of alkali in the concentrator upon filling of the circulation circuit of the CCS with fresh water, the concentrator is cut off using shut-off valves V_3 and V_4. The electric drives of the circulation pump of the electrolyte, as well as the drives of shut-off and control valves are made in the outboard design, discharged from ambient pressure and possess the voids in the casings of electric motors filled with light oil or kerosene.

A low-capacity lithium-ion storage battery is suggested for the initialization of an electric power source based on both types of CCSs. Table 1 shows the results

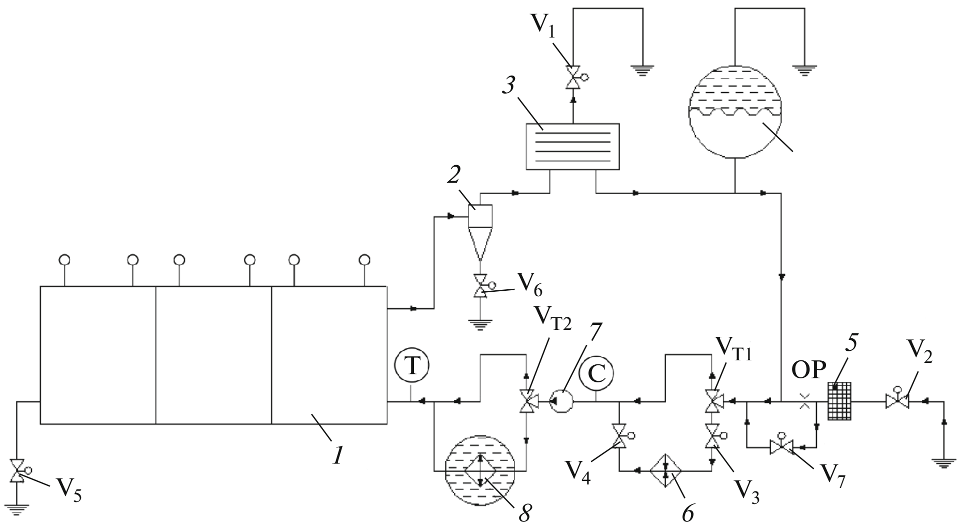

Fig. 2. Flow diagram of an EI based on a CCS of the aluminum–seawater system with an alkaline electrolyte and forced circulation: (*1*) CCS battery, (*2*) hydrocyclone, (*3*) gas separator, (*4*) volume equalizer, (*5*) filter, (*6*) concentrator with a reserve of molten sodium hydroxide, (*7*) circulation pump, and (*8*) heat exchanger represented by an outer condenser; T is the temperature sensor of the electrolyte, V_1–V_5 are the shutoff valves with an electric drive, V_{T1}–V_{T2} are triple valves with an electric drive, C is the concentration sensor of the electrolyte, and OP is the orifice plate.

of calculation of the EI parameters for UUVs with a sustainability period of 48 h at a velocity from 2 to 5 knots.

The suggested setup includes two batteries, main and auxiliary, each possessing autonomous recirculation circuit with the set of auxiliary equipment. The circuits are identical according to the composition of auxiliary equipment and contain pumping unit, heat exchanger, separator, crystallizer, hydrocyclones of coarse and fine purification, and salt-water filters. An alkali storage tank (KOH) is common for both batteries.

The main battery is designed for the electric propulsion of the UV, and the auxiliary battery is for maintenance of auxiliary equipment of the electrical power plant.

The main characteristics of the assemblies and batteries for the suggested scheme are given in Table 1, and the main characteristics of the energy source are given in Table 2. The main and auxiliary batteries are designed for the identical energy capacity and possess an identical number of assemblies (16); however, they differ in commutation. The voltage of the main battery is 54 V (eight parallel groups each having two parallel-connected assemblies). The assemblies of auxiliary battery are connected in parallel to the voltage of 27 V. The voltages of the main and auxiliary batteries are maintained constant in the entire loading range through the variation of the concentration of alkali.

EFFECTIVE SCHEME OF AN ELECTRIC INSTALLATION BASED ON ALUMINUM–OXYGEN CHEMICAL CURRENT SOURCE FOR A UUV

CCSs of the aluminum–hydrogen peroxide and aluminum–oxygen systems were investigated in underwater vehicles for several years by the Alupower Co. [6].

Table 1. Characteristics of main and auxiliary batteries of power sources based on the aluminum–water system with an alkaline electrolyte

Characteristics of UV	Battery type	Characteristics of assembly							Characteristics of battery				
		dimensions L × B × H, mm	number of electrodes	mass of assembly, kg	mass of aluminum, kg	voltage (at maximum current), V	maximum current, A	average energy capacity, kWh	number of assemblies	voltage (at maximum current), V	maximum current, A	maximum power, kW	average energy capacity, kWh
Diameter of 1-m case	Main	187 ×300 × 400	54	30.37	12.6	27	30.10	11.45	16	54	241	13.0	183
	Auxiliary	187 ×300 × 400	54	30.37	12.6	27	8.34	11.45	16	27	133	3.6	183

Table 2. Mass–volume and energy characteristics of power sources based on the aluminum–water system with alkaline electrolyte

Characteristics of UV	Characteristics of mean (energy) section			Mass of power source in the working state, kg	Energy capacity		Maximum power, kW	Specific energy capacity		Specific maximum power		Note
	diameter, m	length, m	volume, m^3		required for run, kWh	provided, kWh		mass, Wh/kg	volume, Wh/dm^3	mass, W/kg	volume, W/dm^3	
Diameter of 1-m case	1.0	2.25	1.767	1545	338	366	16.6	236	207	10.7	9.4	The run is of medium duration

These studies are related to current sources with an exchangeable disposable anode. The technology of the use of hydrogen peroxide in this EI is different from the scheme investigated in the Central Research Institute Named after Acad. A.N. Krylov and involves the following: hydrogen peroxide is first decomposed in a catalytic reactor into oxygen and water, with oxygen further arriving at the battery of semifuel cells to porous oxygen cathodes possessing a hydrophobic layer, which provides gas inlet to the reaction zone. An advantage of this scheme is that it has almost complete consumption of hydrogen peroxide as compared to that in the scheme suggested at Central Research Institute Named after Acad. A.N. Krylov (75–80%). Its drawback is that it has a more complex design and serious restrictions in the arrangement of the EI outside of the strong case of the UV, where it is necessary to maintain a precise pressure drop in the liquid and gas cavities of the battery of semifuel cells with a change of the submergence depth of the vehicle. Experiments showed that such a variant of design of the EI is unsuitable due to the complexity of the control of mutual operation of the CCS and the oxygen-generation system.

For the same reason, Alupower Co. supplied the CCS of the aluminum–oxygen system with oxidizing agent stored in compressed form in gas tanks.

To evaluate the energy and mass–volume characteristics of the CCS setup of the aluminum–oxygen system in the EI of the UUV, the Bester UUV was chosen as a prototype, which allows one to compare these parameters to the characteristics of the basic variant with an accumulator, as well as installations of other types.

Table 3. Characteristics of semifuel cells of the aluminum–oxygen system when using the alloy of aluminum and gallium

Parameter	Magnitude of parameter
Voltage of cell in rated mode, V	1.6
Density of discharge current, A/m^2	600
Specific consumption of aluminum, kg/kWh	0.2
Specific consumption of oxygen, kg/kWh	0.215

The suggested flow diagram of the EI with the CCS of the aluminum–oxygen system is given in Fig. 3. An alloy of aluminum (95%) and gallium (5%) is used as an anode material in such schemes abroad. In our country, an aluminum–indium alloy was developed that is not inferior to the foreign alloy; therefore, the scheme was designed for this alloy. The principal characteristics of the basic semifuel cell are given in Table 3.

The installation is considered in two variants: with a tank or cryogenic storage of oxygen.

The operation of the EI with the CCS of the aluminum–oxygen system differs marginally from the operation of the EI with the CCS of the aluminum–water system with an alkaline electrolyte according to the electrolyte line. The difference is the isolation from the environment by gas and liquid flows, the presence of a hydrogen igniter (5) in the EI scheme (Fig. 3), arrangement of main and auxiliary equipment in a separate strong energy container, and the addition of another strong container with reserves of the electrolyte and the possibility of return of liquid and solid products of the reaction with the consumption of the electrolyte to the EI scheme. In addition, the system of storage and supply of oxygen in tank and cryogenic versions was introduced to the EI scheme.

The results of the design and study of the EI with the CCS of the aluminum–oxygen system are given in Tables 4 and 5.

As follows from the comparison of the characteristics of the EI as concerns the Bester UV based on an ECG of hydrogen–oxygen type with various reagent storage conditions, hydrazine–hydrogen peroxide, CCS of the magnesium–saltwater system, aluminum–hydrogen peroxide, and the aforementioned aluminum–oxygen systems in two variants of oxygen storage, the EI with the CCS of the aluminum–oxygen system (oxygen is cryogenic) is identical to the EI with the CCS of the aluminum–water system in alkaline electrolyte according to the stored energy and possesses about six times as much energy as the SP-200 accumulator and twice as much energy as the EI

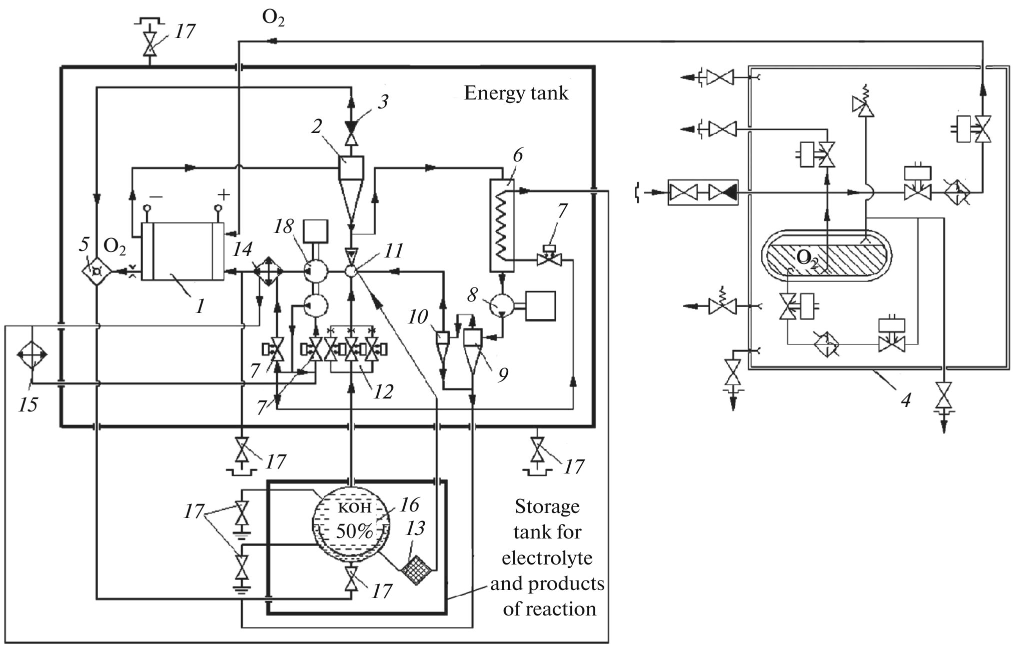

Fig. 3. Flow diagram of the EI with the CCS of the aluminum–oxygen system: (*1*) CCS battery, (*2*) gas separator, (*3*) nonreturn valve, (*4*) cryogenic oxygen-supply system, (*5*) hydrogen igniter, (*6*) crystallizer, (*7*) valve with electric drive, (*8*) electric pump, (*9*) hydrocyclone of coarse purification, (*10*) hydrocyclone of fine purification, (*11*) injector, (*12*) assembly of valves with an electric drive, (*13*) filter, (*14*) heat exchanger, (*15*) outboard heat exchanger, (*16*) tank with KOH, (*17*) shutoff valve, and (*18*) electric pump unit.

with the CCS of the magnesium–saltwater system, other conditions being equal.

As alternative oxygen storage systems, the variant with oxygen storage in solid oxygen sources based on sodium perchlorate can be considered instead of gas tank and cryogenic variants. It is widely used in individual emergency oxygen sources in airliner cabins. The variant of the oxygen storage system and its preparation through hydrolysis of sodium superoxide is also possible. In this variant, additional preparation of sodium hydroxide, which can also be used in the EI with the CCS of the aluminum–oxygen system, is a positive feature.

The aforementioned characteristics of the EI of the UUV show that hydronic CCSs based on aluminum are promising and possess competitive indicators;

Table 4. Weight loading of the electric installation of the CCS of the aluminum–oxygen system with oxygen storage in the gas state in the tanks under a pressure of 400 kg/cm^2

Parameter	Magnitude of parameter
Number of oxygen tanks	2
Total mass of the electric installation, kg	2738
Volume of equipment outside the energy tank, m^3	0.015
Volume of water displaced by the electric installation, m^3	1.833
Buoyancy, kg	−860
Full energy capacity, kWh	500
Efficient energy capacity, kWh	440
Efficient specific mass energy capacity, Wh/kg	160
Efficient specific volume energy capacity, Wh/dm^3	239

Table 5. Weight loading of the electric installation of the CCS of the aluminum–oxygen system with oxygen storage in the liquid state in a cryogenic tank

Parameter	Magnitude of parameter
Number of oxygen cryogenic tanks	1
Number of energy tanks	2
Mass of equipment arranged in the energy tank, kg	308
Mass of equipment arranged out of the energy tank, kg	68
Total mass of electric installation, kg	2348
Buoyancy, kg	−462
Full energy capacity, kWh	630
Efficient energy capacity	560
Efficient specific mass energy capacity, Wh/kg	238
Efficient specific volume energy capacity, Wh/dm^3	304

however, they require development of production of appropriate materials for electrodes.

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