AUTONOMOUS CYBERPHYSICAL SYSTEM OF CONTROLLED TREATMENT AND WATER COMPOSITION CONTROL

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Abstract: An autonomous cyberphysical adaptive system of controlled purification and control of water composition has been considered. Theoretical analysis and experimental studies of the functioning of the components of the proposed system of controlled purification and control of water composition has been performed. The proposed installation is designed to implement the technology of self-regulating system. When using intelligent digital means, it becomes an autonomous cyberphysical adaptive system of controlled purification and control of water composition.

Index Terms: cyber-physical systems, magnetohydrodynamic separation, admittance method of control.

I. INTRODUCTION

Among the global problems of today, the problem of providing many regions of our planet with fresh, suitable for human consumption water is one of the most important. Intensive development of agriculture and industry, population growth lead to a significant increase in fresh water consumption. On the other hand, global warming, obvious climate change and climate change have caused a sharp decrease in precipitation in Ukraine, which has caused a shortage of fresh water in natural reservoirs and in the upper aquifer in many places and in Ukraine. Thus, the problem of insufficient fresh water has become extremely relevant for Ukraine.

Along with this, it should be noted that due to intensive economic activities of people, huge volumes of water are polluted on our planet every year, and only a relatively small part of polluted water is completely purified naturally and returned to reuse.

Today, everyone knows that water is the most common inorganic compound on Earth. It is the basis of all processes of organic life forms. 90 % of plants, and representatives of the fauna on average 75 % consist of water, the loss of living organisms by 10–20 % leads to their death. Aqueous solutions are the most common substance on Earth, which is an integral part of living and inanimate nature. Many technical fluids in various industries are also aqueous solutions [1].

Modern rules of nature use require companies with intensive use of fresh water to install special water treatment systems, most of which require high consumption of electricity and other energy sources, as well as various consumable filter materials and components.

A separate task of the identified problem is the problem of seawater desalination. Modern methods of its solution are also energy and material consuming. However, the solution of this problem in the future will obviously be the main reserve for meeting the needs of fresh water for the population of the Earth.

In [1], the principle of functioning of water purification technology based on its separation into separate streams after passing in a strong transverse magnetic field (the principle of magnetohydrodynamic separation) was proposed for the first time. Later, this technology was used in the construction of a specialized system of automatic control and optimal control of water purification, which was described in [3]. Somewhat different in performance, but identical in principle of design solutions that certify the originality of the proposed system were simultaneously protected by patents of Ukraine and the United States [4, 5].

At the same time, along with the traditional directions of development of equipment and technologies, the rapid development of telecommunication, computer and cybernetic systems has led to the emergence of a new modern direction of development of technical systems, called cyberphysical systems. Within the paradigm of this direction of development of technical systems there is an opportunity to create advanced, adaptive cyberphysical systems of controlled purification and control of water composition. The article is devoted to consideration of all aspects of synthesis, modeling and experimental research of such kind of systems.

The purpose of the work is to analyze the technology of magnetohydrodynamic water purification in a specialized adaptive cyberphysical system, to create the necessary technical and mathematical support for the optimal functioning of such a system, as well as to conduct appropriate computer modeling and experimental research.

II. PRESENTING THE MAIN MATERIAL

The solution to the problem of water purification today is carried out with the help of many different technical means, systems, and complexes. However, they are all based on the use of a relatively small number of basic methods of cleaning liquids, which by mechanisms of action can be classified into the following:

– mechanical – used to treat wastewater from solid particles and oil contamination. The choice of water purification scheme from such substances depends on the type, number of contaminants and the required degree of purification;

– physical – are the basis of thermal treatment, which is used to neutralize mineralized wastewater;

– chemical – used independently before supplying wastewater to the circulating water supply system, before lowering them into reservoirs or municipal sewerage network;

– physico-chemical and physico-mechanical – are used for treatment of technical waters at the machine-building, woodworking, pulp and paper enterprises, and also at factories of a chipboard, woodworking plants where a large number of pollutants is observed;

– biological – used to treat wastewater discharged by the food, pulp and paper, furniture industries and others, by oxidation and mineralization of organic pollutants due to aerobic biochemical processes[1].

Protection of the hydrosphere includes both wastewater treatment and improvement of production technology, which reduces or eliminates the inflow of pollutants into water bodies. According to the current legislation of Ukraine, all wastewater of enterprises must be treated for toxic impurities before discharge into the reservoir.

The nature and nature of water pollution are very diverse, this is primarily because water is a universal natural solvent. For an adaptive cyberphysical system of controlled purification and control of water composition there is an important classification feature of pollution from the standpoint of the presence of an electric charge. Aqueous solutions are a mixture of solutes in the form of ions, complex compounds, and molecular substances of organic origin.[1]

In most cases, the ionic composition of natural waters is determined by cations Na^+, K^+, Ca^{2+}, Mg^{2+}, and anions HCO_3^-, SO_4^{2-}, Cl^-.

Cations H^+, NH^{4+}, Cu^{2+}, Fe^{2+}, Fe^{3+}, Mn^{2+}, Al^{3+}, and others anions OH^-, CO_3^{2-}, NO^{2-}, NO^{3-}, F^-, J^-, HPO_4^{2-}, HS^- etc. in natural water are contained in small quantities, but their impact on the properties and quality of water is sometimes also very large .[1].

Considering the degree of mineralization, natural waters are divided into fresh, mineralized, saline and brine – respectively, containing up to 1, from 1 to 25, from 25 to 50 and more than 50 g/dm^3 of salts.

Cations Ca^{2+} i Mg^{2+} are present in all mineralized waters. Their source is natural deposits of limestone, gypsum and dolomite. In low-mineralized waters most cations Ca^{2+}. With increasing degree of water mineralization, the ion Ca^{2+} content decreases rapidly and rarely exceeds 1g/dm^3. The content of cations Mg^{2+} in mineralized waters can reach several grams, and in salt lakes – several tens of grams per 1dm^3 of water.

The cations Fe^{2+}, Fe^{3+}, Mn^{2+} in the truly dissolved state are in very small concentrations. Most of the iron and manganese in natural waters are contained in the form of colloids and suspensions. In groundwater, iron and manganese compounds predominate in the form of bicarbonates, sulfates, and chlorides, in surface waters – in the form of organic complex compounds (eg, humic acids) or in the form of a finely dispersed suspension.

The content of anions Cl^- and SO_4^{2-} in natural waters varies widely (from fractions of a milligram to several grams per liter) and is due to leaching of salt-containing rocks or discharge into reservoirs of industrial and domestic wastewater. The presence of more than 500 mg/dm^3 of sulfates or 350 mg/dm^3 of chlorides in water gives it a salty taste and leads to disruption of the gastrointestinal tract of humans. Water with a high content of chloride and sulfate ions also has increased corrosion activity, higher non-carbonate hardness, destroys reinforced concrete structure. Nitrogen compounds are found in natural water in their ammonium cations NH_4^+, nitrite NO^{2-} and nitrate NO^{3-} anions. The appearance of these ions in natural waters is associated with the decomposition of complex organic substances of animal and plant origin, as well as protein substances that fall into reservoirs with domestic wastewater.

Natural waters contain very small amounts of ions F^-, Br^-, J^-, and others, but they have a significant effect on human health. Thus, a lack or excess of fluoride in drinking water causes tooth decay and changes in the skeleton, the absence or lack of iodine leads to endemic goiter, etc.

Natural waters may also contain ions of radioactive elements entering the water as a result of leaching of radioactive minerals or testing of nuclear weapons and discharge of waste water from nuclear reactors. Cations Pb^{2+}, Cu^{2+}, Sr^{2+}, Zn^{2+}, Se^{6+}, As^{3+}, As^{5+} and other toxic substances are found in natural waters, as a rule, in small quantities and enter them in large volumes as a result of the discharge of untreated wastewater .[1].

The functioning of the studied cyberphysical system is based on the effects of the interaction of water with strong magnetic fields. When water flows in a transverse magnetic field, both ionized impurities in the water with the magnetic field and the dipole water molecules themselves interact with this field. The latter type of interaction is known and actively used [2–7].

It is known as the method of magnetic water treatment. At certain values of magnetic induction and water velocity, the effect of magnetohydrodynamic resonance occurs. The coincidence of the frequency of Lorentz force pulsations and the natural oscillations of water initiates a phase transition of the second kind – a change in the structure of matter without changing its physical state. Structured water has unique physical, chemical and biological properties. For example, the use of structured water for the production of water vapor reduces energy consumption by 10–15 %, and in the production of concrete saves cement 15–20 %. In water that has undergone magnetic treatment, significantly increases the efficiency of processes widely used in various technological installations.

The use of magnetic treatment of drinking water was recommended by the problem commission of the

Ministry of Health of Ukraine. In thermal power engineering, the use of magnetic treatment in water treatment to soften water is promising (reducing the concentrations of Ca^{2+} and Mg^{2+} ions dissolved in water, which are responsible for the formation of scale).

In addition, the magnetic treatment of water helps not only to prevent the formation of salts that form scale from the water, but also significantly reduce the deposition of organic matter, such as paraffin. To remove fine substances from water that are difficult to remove chemically, the ability of the magnetized water to change the aggregate stability is used, which will accelerate the coagulation (sticking and deposition) of the suspended particles with the subsequent formation of fine sludge. This facilitates the removal of various suspensions from the water.

When the flow of water molecules in a magnetic field perpendicular to its lines of force, along the Y axis (see Vector V), as it is shown in Fig. 1, there will be a moment of forces F1, F2 (Lorentz forces), which try to deploy the molecule in the horizontal plane (Fig. 1).
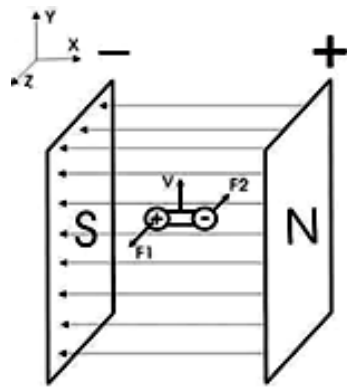

Fig. 1. Model of forces acting on a driver molecule during their motion in a transverse magnetic field

According to the laws of physics, if the motion of water molecules occurs in the horizontal plane along the Z axis, then in the vertical plane there will be a moment of force. But the Lorentz force will always prevent the rotation of the molecule, and therefore will inhibit the movement of molecules perpendicular to the lines of the magnetic field. This leads to the fact that in the water molecule placed between the two poles of the magnet, there is only one degree of freedom – oscillations along the X axis – the lines of force of the applied magnetic field. In all other coordinates, the motion of water molecules will be limited: the water molecule becomes "clamped" between the poles of the magnet, making only oscillating motions about the X axis. orderly.

The proposed cyberphysical system uses magnetohydrodynamic technology of water separation in which a much more effective effect is exerted by the transverse magnetic field on the ionized particles of contaminants moving in the water flow.

The image (Fig. 2) shows a fragment of a channel of rectangular cross-section with the appropriate size designations through which water flows with charged particles of pollution through the lines of force of the transverse magnetic field and the scheme of force interaction of moving positively and negatively charged particles in a magnetic field.
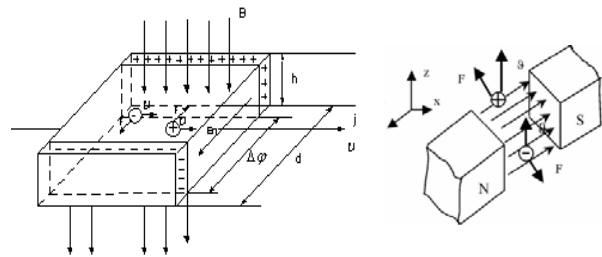

Fig. 2. Schematic representation of the channel through which water flows with contaminants and the scheme of force interaction of charged particles

Magnetohydrodynamic cleaning technology is based on the use of the interaction of particles of contaminants that have an uncompensated electric charge with a magnetic field. When moving with the flow of water in a transverse magnetic field, the Lorentz force acts on these particles. Its magnitude is proportional to the velocity of the particle, the magnitude of its charge and the induction of the magnetic field, and the direction of action is determined by the "rule of the left hand" and depends on the sign of the charge.

$$F_l = q \upsilon B \sin\alpha \qquad (1)$$

where, q – charge of the particles; B – magnetic field induction; υ is the velocity of the particles; α is the angle between the vectors B and υ.

The action of the Lorentz force causes a change in the trajectory of the particles of contaminants, and under the action of this force there is a redistribution of concentrations of contaminant ions. Zones of high concentrations of charges are formed near the opposite faces of the channel of the system, which leads to the appearance of a transverse electric field with voltage En, and in addition, allows to remove them due to the special design of the channels.

The stationary distribution of these charges will be achieved only when the field strength increases to such a value that its action on the charged particles balances the action of the Lorentz force, that is:

$$qE_n = q\Delta\varphi / d = q\upsilon B, \qquad (2)$$

where we get:

$$\Delta\varphi = \upsilon B d, \qquad (3)$$

Thus, the installation in the process of magnetohydrodynamic technology of water purification will itself generate a certain voltage $U = \Delta\varphi$, which can be used to power the microcontroller which will perform the function of control and management of the installation.

Qualitative picture of the distribution of concentrations of ionized particles of contaminants in the cross section of the flow is shown in (Fig. 3).
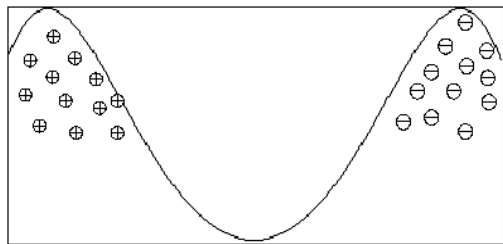
Fig. 3. Qualitative picture of the distribution of the concentration of ionized contaminant particles

After passing the active zone of interaction with the transverse magnetic field, there is a mechanical separation of a continuous stream of water with an already formed gradient of concentrations into three separate streams, two side of which will have a high concentration of ionized contaminants, and the middle, on the contrary, will have a total cross-sectional area – the case of adjustable ion composition.

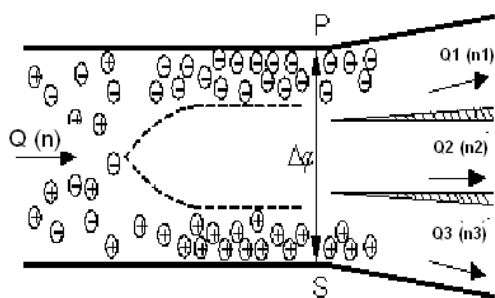Schematically, the separation process is shown in (Fig. 4).

Fig. 4. The initial part of the studied system with flow separation

III. EXPERIMENTAL STUDIES

Experimental studies were performed on the installation, the general view of which is shown in Fig. 5.

Fig. 5. General view of the installation for experimental studies

Along with the controlled parameters for the process is the task of quality control of output streams and input stream.

To solve this problem, it is proposed to use the admittance method of controlling the composition of liquid substances. [8,9]. Its essence is to measure the complex resistance of a substance at different frequencies. The immittance characteristics thus obtained allow to determine the concentrations of various contaminants quite accurately. The measurement scheme was used in the work, which is shown in (Fig. 6). Accuracy (up to 0.0001g) is proved by comparison with the results of standard chemical analysis.
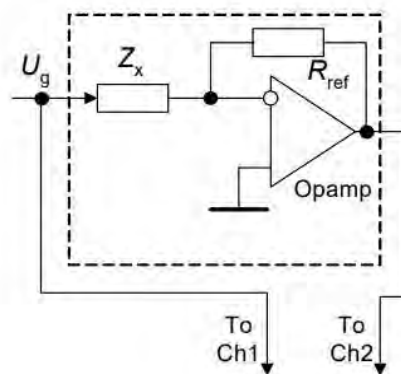

Fig. 6. Measuring scheme

Signals, which reduced the effect of noise, were used as testers.

$$U(t) = U_c \cos(2\pi ft) + U_s \sin(2\pi ft) + U_0, \qquad (4)$$

where Uc and Us are the amplitudes of quadrature component signals, U_0 is the constant component, and f is the frequency of the test signal.

The formation of components was carried out according to the formulas:

$$U_c = \frac{\sum_{m=1}^{M} \cos(2\pi ft_m) y_m}{\sum_{m=1}^{M} \cos(2\pi ft_m)^2},$$

$$U_s = \frac{\sum_{m=1}^{M} \sin(2\pi ft_m) y_m}{\sum_{m=1}^{M} \sin(2\pi ft_m)^2}, \qquad (5)$$

where the index m means the corresponding digital samples.

The values of the amplitude and phase of the generated signal are calculated by the formulas:

$$U = \sqrt{U_c^2 + U_s^2}, \quad \varphi = \operatorname{arctg}\left(\frac{U_s}{U_c}\right). \qquad (6)$$

Given the peculiarity of this measuring circuit, the current through Rref is balanced by the current through Zx, so measuring the output voltage at a known value of the input voltage and resistance Rref allows you to easily calculate the complex resistance Zx.

The general simplified block diagram of the autonomous cyberphysical adaptive system of controlled purification and control of water composition is shown in (Fig. 7).
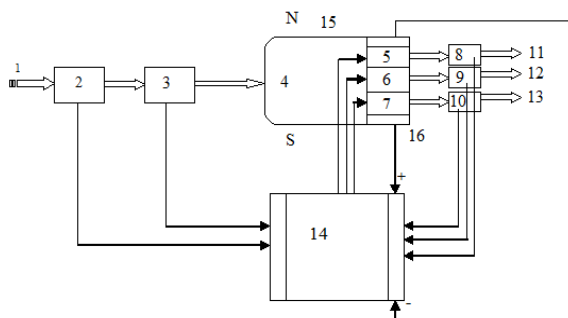
Fig. 7. Simplified block diagram of the cyberphysical system of controlled purification and control of water composition

In the scheme shown in the figure, the following notations are used: 1 – input stream; 2 – electric sensor of the composition of the input stream; 3 – sensor speed and temperature of the input stream; 4 – installation of magnetohydrodynamic technology of water purification; 5, 6, 7 – forming outputs with a controlled cross-sectional area of the corresponding output stream; 8, 9, 10 – sensors imitation control of the composition of the generated flows; 11, 12, 13 – output streams; 14 – microcontroller control and management; 15, 16 – electrode system for supplying the generated voltage to the microcontroller for its power supply.

According to the given scheme, model experiments were carried out. The magnetohydrodynamic technology of a solution of copper sulphate of known concentration of 1.077 g/l was carried out (m). 3 solutions with concentrations: 0,941g/l (m^2), 0,996g/l (m^3), 1.099g/l. (m1) were obtained. The method of determining concentrations is titrimetric. The temperature is fixed at 23 °C. The generated voltage was a maximum of 1.62 V. The use of the imitation method allowed to obtain the experimental dependences, which are shown in the (Fig. 8).
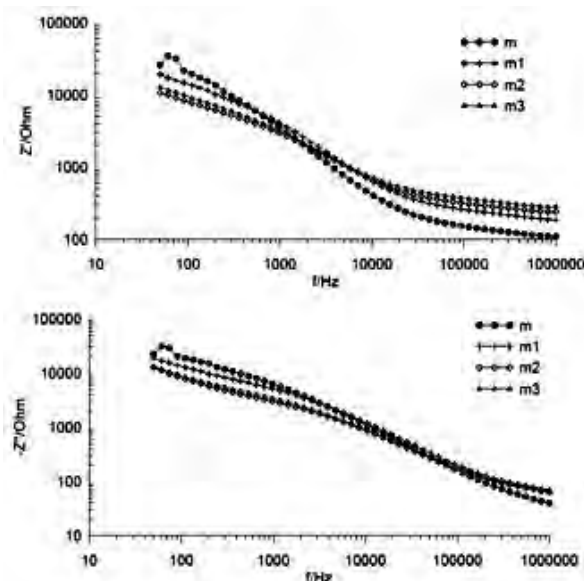

Fig. 8. Dependence of active Z "and reactive Z components of complex conductivity on the frequency of the test signal

The obtained experimental data show that the magnetohydrodynamic technology really leads to a change in the concentrations of solutes, and the immittance spectroscopy method shows high sensitivity in two bands of frequency of the test signal – around 100 Hz and about 1 MHz (Fig. 8).

The number of experimental studies has been conducted more than 100 times. The general picture (ratio of graphical dependences) described in Fig. 9 – was not changed, which made it possible to draw the following conclusions without statistical calculations.

IV. CONCLUSION

The theoretical research performed in the work creates a scientifically sound basis for the practical application of magnetohydrodynamic technology in solving the important problem of water purification from excess dissolved ions.

When performing experimental research, the following results were obtained.

1. Following the modern model solution with a magnetic field in the developed design, three initial solutions with a reliable content concentration of the controlled substance were obtained, which was confirmed in the presence of standard analytical laboratory questions.

2. The change in the concentrations of the controlled substances after separation, which were measured by standard analytical methods, with an accuracy of 0.001 g/l, led to a change in the values of the measured electrical parameters (complex conductivity). This confirms the possibility of using admixture spectroscopy to monitor their concentration [8--17].

The undeniable advantages of the developed technology are that its implementation requires neither consumables nor external energy sources. In further scientific research, the ability of installations designed to implement electricity generation technology makes it possible to create a closed self-regulating system, which when using intelligent digital means becomes an autonomous cyberphysical adaptive system of the controlled purification and control of water composition.

Experimental studies have provided conclusive evidence of the functioning of magnetohydrodynamic technology, high sensitivity of the imitation method to control the composition and concentrations of solutions, the presence of sufficient for the operation of low-power microcontrollers potential difference.

Thus, an experimental test of the functioning of all components of the proposed autonomous cyberphysical adaptive system of the controlled purification and control of water composition. In further researches it is planned to carry out theoretical and experimental searches of optimum modes of functioning of the developed system.

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