Removal of Contaminants from an Aqueous Solution by a Magnetic Field Using the Effect of Focusing Ionic Impurities

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1 Introduction

The relevance of the problem of water purification is noted in the UN materials "Management of water resources in conditions of uncertainty and risk". As a result, the High Level Panel on Water (HLPW) was convened in April 2016 to ensure availability and sustainable water consumption for all countries. In relation to Ukraine, the relevance is confirmed by the Law of Ukraine "On the Nationwide Program" "Drinking Water of Ukraine for 2016–2030" dated March 3, 2015 No. 2455-IV. Water shortage is associated with population growth and rapid urbanization of human activities. Therefore, water purification and processing was, is and will be an urgent problem all over the world.

The use of traditional chemical and mechanical methods is associated with the use of expensive reagents and complex equipment, moreover, they are not always effective and safe. Therefore, more and more emphasis is placed on physical cleaning methods.

Physical methods of water purification are more effective and cheaper. Water purification by physical methods is carried out by external force fields, without

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adding chemicals to the working volume. Therefore, such studies should be considered relevant, aimed at further improvement and development of water reuse technology. However, in this direction of research, the conditions for the influence of the electromagnetic field on the impurities contaminating the liquid are insufficiently substantiated.

2 Analysis of Literary Studies and Statement of the Problem

In work [1], a review and analysis of wastewater disinfection was carried out. Known methods of wastewater disinfection, such as combining with domestic wastewater, recycling, aerobic and anaerobic processes have both advantages and disadvantages. Disadvantages include frequent cleaning of the filters themselves, and the need to have a reserve of special reagents for their restoration, coagulation, formation of lumps, chemical precipitation, adsorption, dismantling of ammonium, chemical oxidation, ion exchange. The advantages include the simplicity of the design, the availability of replaceable filters that can be quickly replaced, and the formation of sediment on the filter elements, and not on the working surfaces of the device. Modern technologies: membrane filtration, microfiltration, ultrafiltration, nanofiltration and reverse osmosis are science-intensive and expensive.

Research has established that the mentioned possibilities of increasing the efficiency of membrane methods by electromagnetic influences on impurities are becoming more and more widespread. In works [2–10], the effect of electromagnetic field (EMF) on the control of membrane fouling and scale formation is studied. Due to the installation of reverse osmosis (RO reverse osmosis), desalination of brackish groundwater was achieved. EMF reduced membrane scaling and improved RO performance by 38.3%. Despite all the advantages of reverse osmosis installations, they also have disadvantages—the structural complexity of manufacturing filter elements with nano-sized cells, high cost, etc.

Scale and biofouling are two main problems in the operation of reverse osmosis (RO) membranes [11]. This is a fairly new technology. From literature it is clear that the scientific basis of its supposed effectiveness has not yet been established. Systematic scientific research is needed to confirm the application and commercialization of EMF technologies. The application of EMF is a pretreatment for fouling control in RO membrane systems.

The investigated [11] determined the quantitative value of the electrical properties of RO membranes during the processes of pollution and cleaning using electrical impedance spectroscopy. “Process condition” monitoring is particularly useful for pollution control in the RO industry. Monitoring of the fouling process of single and binary pollutants on the RO membrane was carried out. Different forms of the Nyquist graph were obtained for different types of pollution. However, it should be noted that this paper does not provide quantitative values of the electrical properties of RO membranes. The growth of a layer of pollution on the surface of the membrane is also considered a disadvantage.

Ultrasonic treatment was introduced into the membrane distillation process [12, 13] and the effect of ultrasonic irradiation on the control of silica fouling was investigated. A hollow fiber membrane can retain its mechanical properties and initial pore size distribution in the presence of ultrasonic irradiation. The disadvantage is that increasing the concentration factor had almost no effect on the liquid flow. A large amount of silica settled on the surface of the membrane. To overcome this problem in operation, the surface of the membrane should be kept clean. Under ultrasonic irradiation, the permeate flow remained stable and increased by approximately 43%. Ultrasonic irradiation can effectively control silica fouling during membrane distillation.

Good results were achieved when using water purification with direct and reverse osmosis [14]. Engineers of the University of California in Riverside (USA) have developed a new method of restoring drinking water from highly concentrated salt solutions with almost 100% yield. In the work, considerable attention is paid to the modes of recovery of drinking water from highly concentrated salt solutions. It is not entirely clear how and under what conditions almost 100% yield was achieved. In our opinion, additional research in this direction is necessary.

Modern studies [3] are focused on a review of the rapid growth in the use of magnetized water in various fields of science. The work illuminates the circulation of water for 24 h. in electromagnetic fields of intensity 500, 1000, 1500 and 2000 G. The advantages of magnetization and the use of magnetized water are the improvement of the geotechnical properties of the soil due to the precipitation of calcite. It increases the bond between soil particles and subsequently the strength of the soil. But improving the geotechnical properties of the soil due to the precipitation of calcite is not always beneficial for the natural environment.

The operation of vacuum-plasma and power electronics devices is based on the use of electromagnetic control of the shape and direction of the electron flow of charges [4]. The magnetic field in induction devices is created using HF inductors. This technology improves the vaporization of materials with subsequent ionization.

In the study [5], the efficiency of $CaCO_3$ crystallization caused by a different combination of treatment with an alternating electromagnetic field (AEMF alternating electromagnetic field) and ultrasonic (ultrasonic (US) treatment).

The disadvantage is that the results improve only with the correct addition of Mg^{2+} ions. A combination with AEMF+US or US+AEMF can significantly improve the physical effectiveness of anti-scaling. But the work does not define the concept of correct addition of Mg^{2+} ions. This can cause difficulties associated with the choice of modes of operation of the alternating electromagnetic field and processing of the flow with ultrasound.

Experiments conducted in order to assess the impact of sediment before and after treatment of the working surfaces of the equipment with an electromagnetic field were conducted in work [6]. The scale of the brine consisted mainly of calcium bicarbonate ions. The reported results were obtained using a Dynamic Scale Loop system with brine exposed to a magnetic field generated by a 6480 Gauss class N45SH magnet in a diametrical orientation for 2.5 s. The disadvantage of such a solution is the complexity of managing the magnetic treatment of the working surface. This circumstance is related to the fact that the scale of brine is not placed evenly on the work surface. This significantly changes the stability and uniformity of the treatment of the working surfaces of the equipment by the electromagnetic field.

Various methods are used for water purification, such as ultraviolet irradiation, heat treatment, addition of disinfectants, such as chlorine, etc. Using these methods of water purification reduces turbidity, improves taste and removes microbes. Studies [7] evaluated water purification using Phyllanthus embolic wood. As a result, color, aroma, turbidity, conductivity, solids, alkalinity, calcium, iron, chloride and nitrate levels are increased in the test container. The following were reduced: pH, total hardness, sulfate and magnesium levels. The level of Escherichia coli, total coliforms and fecal coliforms was reduced. Despite the practical significance of such results, water purification using Phyllanthus embolic wood is not sufficiently considered in the paper.

The study [8] provides information on the positive aspects of magnetism and magnetic materials for water purification. These cleaning methods can ensure that the water complies with the standards. Magnetic separation is one of these cleaning methods. It is used in the mining and oil industry. It provides not only water purification, but also cleaning of pipes from the sticking of impurities on the inner wall. Under the influence of a magnetic field, the energy of the ion state of impurities in the liquid increases. This leads to the ionization of impurities, which increases the efficiency of the electromagnetic system. Due to the difference in the concentration of cations and anions in the liquid, electric fields arise, caused by the electric charge of the total volume of ions. The effect of the magnetic field on the liquid affects the trajectory of the charged particle. Overcoming the problem of managing the trajectory of particle movement is associated with the difficulty of determining the necessary factors for optimal indicators of the cleaning process. In [9], a new membrane electrocoagulation reactor (electrocoagulation membrane reactor ECMR) is given, in which ultrafiltration (UF) membrane modules are placed between the electrodes. Its use improves the quality of wastewater and reduces membrane fouling. Higher current density and slightly acidic pH in EMCR promoted faster formation of large follicles. The disadvantage is structural complexity, contamination and blocking of membrane pores, the formation of a polarized cake layer was controlled by current density and voltage.

The influence of the electromagnetic field during salt and water transport and carbonate recovery was investigated [13, 14]. The deposition of salts during reverse osmosis desalination is interesting. The electromagnetic field was created by an alternating current. Current flows through a solenoid wound around the membrane separation module. Current strength and frequency were 25 A and 50 Hz, respectively. Experiments were carried out using $CaCO_3$ solution at a concentration of 5.5 mmol/l. For comparison, membrane desalination was carried out in the presence and absence of an electromagnetic field. Powder-like elements were formed under the influence of an electromagnetic field. They had a lower density than precipitation formed in the case of non-use of an electromagnetic field. Powder-like elements almost did not react to the electromagnetic field. This is due to the difficulty of determining the operating parameters for choosing their cleaning modes.

Mathematical models of ocean eddies (whirlpool) are presented in [15]. Attention is drawn to the mathematical model of oceanic eddies [16]—the complexity of the processes operating in eddies requires complex mathematical apparatus for their description [17]. The given models do not allow to describe complex processes in eddies.

The studies analyzed definitely have positive results. Therefore, such research should be considered relevant, aimed at further improvement and development of water purification technology for its reuse [18, 19].

However, in the considered studies, the conditions and results of the influence of the electromagnetic field on the trajectory of impurities contaminating the liquid are insufficiently substantiated. Also, there are undiscovered possibilities of accumulation of impurities due to the action of Lorentz forces in the paraboloid of rotation, and the possibility of separating purified water from impurities that contaminate it during the creation of a vortex in the working focusing chamber [20, 21].

Thus, there are reasons to assert:

- about the possibility of controlling the trajectory of the movement of impurities;
- and the Lorentz forces contribute to the focusing of the paraboloid of rotation;
- directional regulation of the processes of focusing of impurities by the magnetic influence unit in the working focusing chamber.

This determines the need for more in-depth research in this direction. The analysis of water purification methods made it possible to formulate the following research idea.

In the flow of water contaminated with ionic impurities, it is necessary to form a magnetic field with a structure that should ensure focusing in the cross section of the liquid flow the maximum concentration of ionic impurities, which will lead to the distribution in space and time of the total contamination of the flow into two flows:

- purified main flow by volume with a low concentration of impurities;
- the second axial flow with a much smaller volume and with a high concentration of ionic impurities, which makes it quite easy to remove it from the volume of the purified flow.

3 The Purpose of the Study

To develop a method and a means of removing ionic impurities from an aqueous solution by a magnetic field using the effect of focusing ions into a paraboloid of rotation with a small flow volume and a high concentration of ionic impurities, which greatly facilitates the spatial distribution of purified and contaminated flows and the effective removal of the flow with impurities from the environment to the tank of purified water.

To achieve the set goal, the following tasks were solved:

1. Investigate on a physical and mathematical model the process of focusing ionic impurities into a paraboloid of rotation under the action of a magnetic field during the purification of a flow of a contaminated aqueous solution.
2. To develop and investigate the principle scheme of the research stand in accordance with the physical–mathematical model of focusing the flow of ionic impurities into a paraboloid of rotation.
3. To justify the mathematical model of the formation of the necessary structure of the magnetic field for focusing the flow of ionic impurities into the paraboloid of rotation and to simulate the process on the created virtual device using the Lab VIEW software environment.
4. To conduct a comprehensive study of the operating parameters of the process of cleaning an aqueous solution from ionic impurities by a structured magnetic field with the combined use of:

   – a physical-mathematical model of the process of focusing ionic impurities into a paraboloid of rotation under the action of a magnetic field;
   – a virtual device using the Lab VIEW software environment;
   – an experimental laboratory stand for researching the possibilities of controlling real trajectories of ion movement under the influence of a magnetic field.

4 Physico-Mathematical Model of Focusing of Ionic Impurities by an Electromagnetic Field in a Liquid Flow

Many substances that get into water are ionized. Therefore, in water we have a mixture of metal ions, acid residues and other substances that for one reason or another must be removed from the solution. A number of technologies using an electromagnetic field have been developed to purify water from ionic impurities.

The Lorentz force acts on a particle of mass m and charge q in a contaminated aqueous solution from the side of the electromagnetic field.

$$\overrightarrow{F} = q\overrightarrow{E} + q(\overrightarrow{V} \times \overrightarrow{B}), \tag{1}$$

where: $\overrightarrow{E}$—electric field strength, $\overrightarrow{B}$—magnetic field induction, $\overrightarrow{V}$—velocity of a particle with a charge q.

The force $\overrightarrow{F} = q \cdot \overrightarrow{E}$ is the force acting on the charge from the side of the electric component of the field, and can have an arbitrary direction relative to the speed of the particle of matter. The work of this electric force can be positive, negative and zero depending on the angle between the direction of velocity $\overrightarrow{V}$ and the intensity of the electric field $\overrightarrow{E}$.

The second force acting on the charged particle is the magnetic force and is directed perpendicular to the velocity of the particle $\overrightarrow{F}m = q(\overrightarrow{V} \times \overrightarrow{\mathrm{B}})$, this force does no work. The magnetic force does not change the kinetic energy of a particle with a charge (q), does not change the velocity module $\left|\overrightarrow{V}\right|$ and only changes the direction of the velocity.

When considering the motion of a particle with mass m and charge q in a magnetic field, the velocity of the particle can be written as the sum of the velocity parallel to the magnetic field $\overrightarrow{V}_{\parallel}$ and perpendicular to it $\overrightarrow{V}_{\perp}$:

$$\overrightarrow{V} = (\overrightarrow{V}_{\parallel} + \overrightarrow{V}_{\perp}). \tag{2}$$

In this case, the Lorentz force acting on the charge of the particle will be equal to:

$$\overrightarrow{F} = e\overrightarrow{V}_{\perp} \cdot \overrightarrow{B}, \tag{3}$$

where e—electron charge.

The component of the Lorentz forces along the magnetic field is zero. Then the equations of motion for the parallel and perpendicular components of velocity have the form:

$$m(d\overrightarrow{V}_{\parallel}/dt) = 0; \tag{4}$$

$$m(d\overrightarrow{V}_{\perp}/dt) = e\overrightarrow{V}_{\perp} \times \overrightarrow{B}. \tag{5}$$

The modules of the vectors $\overrightarrow{V}_{\perp}$ and $\overrightarrow{B}$ do not change. The force in the right-hand side of expression (5) is perpendicular to the velocity and is constant in magnitude. This equation describes the motion of a particle with a constant acceleration directed all the time perpendicular to the velocity, i.e., we have motion in a circle. The left part of Eq. (5) is the product of the mass by the centripetal acceleration $\overrightarrow{V}_{\perp}/$ r, so it can be written:

$$mv^2/r = |q|/(v_{\perp} \cdot B), \tag{6}$$

where r—radius of the circle.

This equation fully characterizes the movement of a charged particle in a circle in a plane that is perpendicular to a uniform magnetic field. The direction of rotation depends on the sign of the charge q and is set by the rules of left or right screws.

From Eq. (6), we can find expressions for the angular frequency of rotation in a circle

$$\omega = v_{\perp}/r = \left|\overrightarrow{q}\right|B/m, \tag{7}$$

as well as for the radius of the orbit

$$r = v_{\perp}/\omega = mv_{\perp}/|q|B. \tag{8}$$

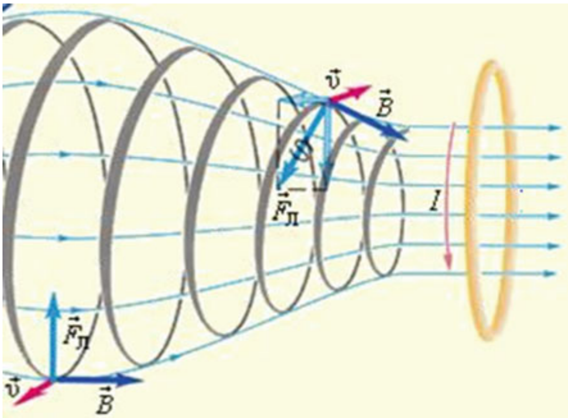

Fig. 1 Lorentz force generation by a current-carrying coil

The complete movement of a charged particle of a contaminated substance in a homogeneous, constant magnetic field consists of uniform movement along the field and rotation in a plane perpendicular to the field. That is, the particle moves in a spiral with a step:

$$l = v_{\parallel} \cdot 2\pi/\omega. \tag{9}$$

Consider a magnetic field whose induction lines are parallel to each other, and the magnitude of the field varies in the direction perpendicular to the field (Fig. 1). If the field is uniform, then the charged particle moves in a circle [17]. However, taking into account the heterogeneity of the field, the radius of curvature of the trajectory changes during movement: where the field is larger, the radius is smaller and vice versa. That is, in fact, the particle behaves as in a transverse electromagnetic field, but the radius of curvature of the trajectory changes not due to energy, but due to the magnitude of the magnetic field in different points of space.

In this case, particle drift occurs due to the inhomogeneity of the magnetic field in a direction that is perpendicular both to the magnetic field itself and to the direction in which the magnetic field is inhomogeneous.

The system of equations in this case has the form:

$$m\left(\frac{d^2x}{dt^2}\right) = 0; \tag{10}$$

$$m\left(\frac{d^2y}{dt^2}\right) = qv_zB; \tag{11}$$

$$m\left(\frac{d^2z}{dt^2}\right) = -qv_yB. \tag{12}$$

The analysis and solution of this system of equations, taking into account the fact that v_y is much smaller than v_z under appropriate initial conditions, showed that Eq. (11) for the y coordinate can be written in the form:

$$\frac{d^2y}{dz^2} = \frac{q}{mv}B(\text{z}), \tag{13}$$

that is, taking into account the change in magnetic induction in the direction of the (Z) coordinate, the solution of Eq. (13) has the form:

$$y = \left[\frac{q}{mv}\right]b, \tag{14}$$

where $b = \int_0^{z_0}(Z_0 - \eta)\text{B}(\eta)d_\eta$ is a constant that depends on the configuration of the electromagnetic field and is found by calculation or experimentally (η) is the integration variable.

The exact analytical solution of this problem is rather complicated, so the drift speed can be set with some approximation [2] in the form:

$$v_d = \left(\frac{mv^2}{qB^2}\right)\cdot\frac{dB}{dy}. \tag{15}$$

In this case, the drift is perpendicular to the magnetic induction vector $\overrightarrow{B}$ and to the direction of maximum change of the magnetic induction module. In vector form, Eq. (15) has the form:

$$v_d = mv^2/2qB^2[[\overrightarrow{b} \times grad\left|\overrightarrow{B}\right|] \tag{16}$$

where $\overrightarrow{b} = \overrightarrow{B}/\text{B}$—unit vector along the magnetic field; grad $\left|\overrightarrow{B}\right|$—vector which is directed to the maximum growth of the modulus of the vector $\overrightarrow{B}$

In nature, in general, the induction lines of a non-uniform magnetic field are not straight. They are curved lines, at each point of which it is possible to indicate their curvature. At the same time, the charged particle rotates around the conducting center, which is located on the line and moves along it. The trajectory of the particle. There is a spiral that winds up on the line of magnetic induction. In the coordinate system associated with the conducting center, the particle is acted upon by the centrifugal force of inertia $\overrightarrow{F}_{cf}$, equivalent to the action of the electric field with the intensity $\overrightarrow{E}_{cf} = \overrightarrow{F}_{cf}/q$. Thus, the particle moves under conditions equivalent to a transverse electromagnetic field. The particle will drift in a direction perpendicular to both the magnetic induction $\overrightarrow{B}$ of the field and the force $\overrightarrow{F}_{cf}$ perpendicular to the plane. In this case, the movement in a circle relative to the center is carried out with the drift speed $\overrightarrow{V}_d$. To find it, you need to write down the equation of motion:

$$m\left(\frac{d\overrightarrow{V}}{dt}\right) = q\overrightarrow{E} + q\overrightarrow{V} \times \overrightarrow{B}, \tag{17}$$

and find its solution in the form [1],

$$v_d = B^{-2}(\overrightarrow{E}_{cf} \times \overrightarrow{B}) = E_{cf}/B, \tag{18}$$

or the expression for the drift speed caused by the curvature of the magnetic force line in the form:

$$v_d = mv_{\|}^2/qBR, \tag{19}$$

where $v_{\|}$—projection of the particle velocity onto the direction of the magnetic field.

For the general picture, this drift is added to the drift associated with the inhomogeneity of the magnetic field (16).

The conducted analysis showed that the movement of a charged particle with mass m and charge q has three components:

- rotation of the particle around the line of force of the magnetic field;
- movement of the conducting center along the magnetic line of force;
- the drift of the conducting center in the direction perpendicular to the vector $\overrightarrow{B}$ of the magnetic field and the gradient of the magnetic induction module.

To further clarify the geometric, kinematic, force and energy parameters of the focusing volume of ionic impurities, it is necessary to introduce the concept of magnetic moment into the analysis. In many practical cases, the magnetic field changes little over a distance of the order of the radius of the trajectory of the charged particle. By analogy with the magnetic orbital moment of elementary particles, we can talk about the magnetic moment of a macro particle moving in a magnetic field. The feasibility of introducing such a concept makes sense in the fact that in slowly changing magnetic fields this magnetic moment retains its value and its use greatly simplifies the analysis of the movement of a charged particle under the action of a magnetic field. In this case, the magnetic moment of the charged particle during circular motion along the trajectory will be written in the form:

$$p_m = SI, \tag{20}$$

where S—the area covered by the electric current; I $=\frac{\overrightarrow{q}}{T}$—electric circuit current; T is the period of rotation along a circular path.

Taking into account the size and shape of the movement trajectory, we obtain:

$$p_m = \left(\frac{\overrightarrow{q}}{\mathrm{T}}\right)\pi R^2 = \frac{1}{2}mv^2/B. \tag{21}$$

When introducing the concept of magnetic moment during the movement of a charged particle under the action of an electromagnetic field, it is also appropriate to introduce the concept of an adiabatic invariant of magnetic moment. Adiabatic invariance of the magnetic moment means its conservation in electromagnetic fields that change slowly in space or time. It is shown [3] that when the magnetic field changes in time $dp_m/dt = 0$, then the magnetic moment also does not change, $p_m = const$ [3].

Thus, we assume that the magnetic moment p_m (19) does not change during the movement of a charged particle in the case of slow changes in the electromagnetic field in space and time.

And this, in turn, means that charged particles move along the surface of a magnetic tube, that is, a tube whose surface is created by lines of force of magnetic induction. This statement follows from the fact that the magnetic flux through the cross-section of the tube does not change along it. Then the magnetic flux through the cross section of the tube can be written as:

$$\phi = \pi R^2 B = \frac{2\overrightarrow{V} m}{q^e} \cdot p_m = const \cdot p_m. \quad (22)$$

It can be seen from this expression that the preservation of the magnetic flux along the magnetic tube is equivalent to the preservation of the magnetic moment of a particle that moves along a trajectory located on the surface of the tube, that is, it is really seen that the particle moves along the surface of the power tube.

To fully characterize the movement of a particle, it is necessary to take into account its drift (16) and (19). As a result of its drift, the particle moves from one power tube to another in such a way that the magnetic flux contained in these tubes is the same.

5 Mathematical Model of the Formation of the Structure of the Electromagnetic Field to Control the Trajectory of the Movement of Ionic Impurities in the Volume of the Working Chamber

Given that charged particles move in a hydraulic flow under the action of a non-uniform magnetic field along the surface of a magnetic tube, which is created in three-dimensional space by the lines of force of magnetic induction $\overrightarrow{B}$, for the mathematical description of this surface a conical helical surface is chosen, which, in accordance with the physics of the process, allows to simulate the movement charge q with mass m in the three-dimensional space of the working magnetic chamber.

In this regard, the Ulysses Dini equation [17] was used to describe the ion focusing process.

$$x = a \cdot \cos(u) \cdot \sin(v);$$

$$y = a \cdot \sin(\mathrm{u}) \cdot \sin(\mathrm{v}); \quad (23)$$

$$z = b \cdot u + a \cdot \left(\cos(v) + \log\left(\tan\left(\frac{v}{2}\right)\right)\right).$$

The range of changing the parameters of the equation: $0 < = \mathrm{u} < = 4\pi$; $0.01 < = \mathrm{v} < = 1$; $\mathrm{a} = 1, \mathrm{b} = 0.2$

In the general conical form, this equation has the form:

$$\frac{(x - x_0)^2}{a^2} + \frac{(y - y_0)^2}{b^2} - \frac{(z - z_0)^2}{c^2} = 0, \quad (24)$$

where the constants *a* and *c* are determined by the ratios *c*/*a*.

Thus, the lateral surface of a right circular cone (conical surface) is a second-order surface. The transition of the particle trajectory due to drift from one surface of the magnetic field to another is taken into account. In parametric notation, it has the form of a conical helix:

$$X = C \cdot e^{mt} \cos t;$$

$$Y = C \cdot e^{mt} \sin t; \quad (25)$$

$$Z = C \cdot e^{mt} \mathrm{ctg}\alpha,$$

where t—arc length of the curved trajectory; α—angle between the axis of the cone and its origin; φ—angle between the tangent to the helical line and the generating cone; *m*—sin α/tg φ.

A virtual device has been developed to simulate the focusing modes of impurities polluting the fluid flow. The simulation results confirm the shape and dimensions of the conical helix of the charged particle trajectory in an inhomogeneous magnetic field of the corresponding configuration. The projection of a conical helix on a plane perpendicular to the axis of the cone is a logarithmic spiral with a pole in the projection of the cone apex (Fig. 2) [17].

The simulation results confirm the shape and dimensions of the conical helical line of the trajectory of the charged particle in a non-uniform magnetic field of the corresponding configuration.

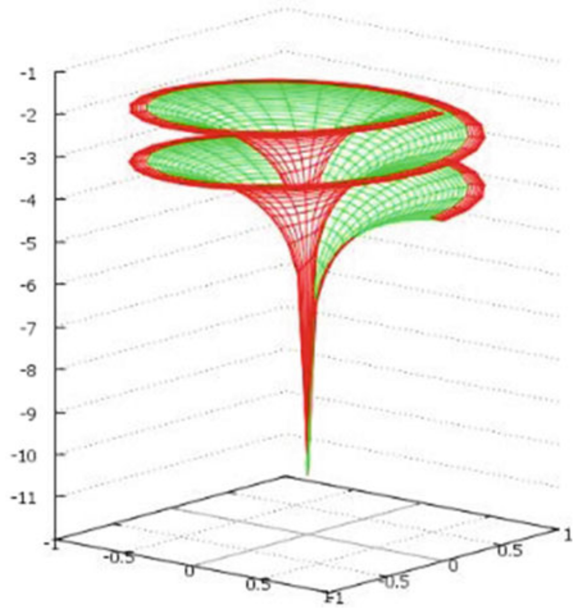

Fig. 2 Ulysses Dini cone surface model

6 Laboratory Stand for Cleaning an Aqueous Solution with a Non-uniform Magnetic Field Using the Effect of Focusing Ionic Impurities

The hydraulic scheme of the stand for electromagnetic focusing of liquid contamination (Fig. 3) has a tank 1 of contaminated liquid, an initial pipeline with a coarse filter 2. The filter used is an Irritec disc filter with a connection diameter of 1 inch.

Pump 3 JEX500 has electrical power from a two-phase motor with a voltage of 220 V and a frequency of 50 Hz. The working fluid through the hydraulic line through the tee is directed into the line with the safety valve 4. In the event of excess pressure in the hydraulic system of the stand, thanks to the safety valve 4, there will be no emergency pressure increase in the system due to the pumping of part of the working fluid back to the tank 1.

Further, the working fluid through the working condition regulator 5 is directed to the focus input of the working chamber 6 of impurities (WCF). Several (from 2 to 4) "snail" inlet channels are placed at the entrance of the WCF for the initial mechanical spiral twisting of the contaminated liquid. On the outer wall of the WCF, several coils are placed in series with an interval of 7. Moreover, each subsequent coil has a larger number of turns of wire (n1….n5), which provides a Larmor which ensures the Larmor precession of the movement of impurity particles, an increase in electromagnetic induction and a decrease in the radius of rotation of pollution particles.

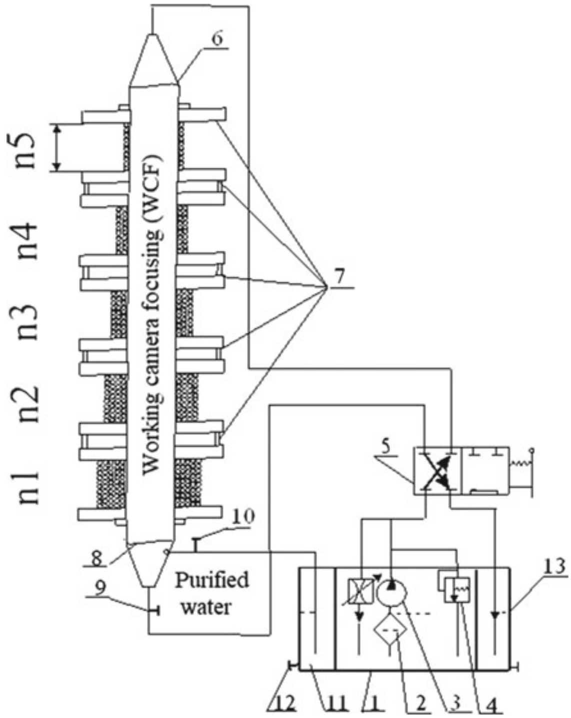

Fig. 3 Scheme of the stand for electromagnetic focusing of liquid contaminants

Thus, in the WCF, under the action of the Lorentz force in a magnetic field, impurities are focused around the WCF axis into a paraboloid of spiral rotation. Its top is directed to the central hole of the insert. To remove impurities from the WCF, a special insert is installed in its final part (Fig. 4).

Insert 8 (Fig. 4) in the end part of the WCF for separating the liquid flow has one central hole 1 to remove impurities from the contamination of the liquid flow, through the sampling valve 9, into the tank 13 of the liquid with impurities and, for

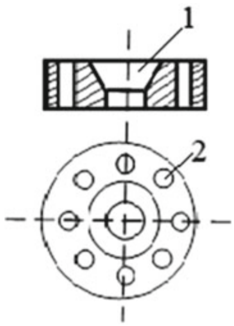

Fig. 4 Insert 8 at the end of the WCF to remove focused impurities from the fluid flow: 1—central hole for removing contaminants; 2—holes for removing the purified liquid

example, 8 peripheral holes 2 to remove the purified liquids. liquid, through the valve 12 sampling, into the tank 11—purified liquid.

7 Research Program and Results

For planning and conducting the research, the ranges of changes of the main factors are established, by changing which it is possible to regulate the process of ion focusing both in space and in time (Table 1).

The main parameter of the focusing magnetic system, as well as the entire installation as a whole, is the value of the magnetic induction $\vec{B}$ and the structure of the magnetic field. From a constructive point of view, the main geometric parameter is the Larmor parameter the radius of the particle trajectory in the magnetic field:

$$R = mU_{\perp}l/(|q|\mu_0\mu In), \tag{26}$$

where m—mass of the charged particle; q—particle charge; $U_{\perp}$—velocity of the particle perpendicular to the magnetic field lines; l—length of the focusing coil; μ_0—magnetic constant; μ—magnetic permeability; I—current of the magnetization loop; n—number of coil turns.

It is possible to regulate the cleaning process by changing three parameters: the rate of the fraction $V_{\perp}$; magnetizing circuit current I; the total length of the focus coils l. This is done by regulating the current I (Fig. 5), while changing the magnetic induction B, within the established limits (Table 2).

The magnetic field can be changed due to the total length of the magnetization coils l (Fig. 6), as well as by changing the number of turns n of the wire on the WCF coils.

Checking the results of modeling the trajectories of charged particles in an aqueous solution on a laboratory bench confirmed the possibility of using a method for cleaning a polluted water flow from ionic impurities magnetic field using the focusing effect (Table 2).

Such a dual approach in modeling the process of focusing of ionic impurities in a stream of polluted water under the action of a non-uniform magnetic field, as well as experiments conducted on a laboratory bench, allow:

Table 1 Factor regulation ranges

Factor	Levels			Variation interval
	Lower	Average	Upper	
Q—fluid flow, × 10^{-2}, м^3/sec	1.40	2.75	4.10	1.35
$\vec{B}$—magnetic field induction, × 10^{-5}, Tl	2.244	4.488	6.732	2.244
Number of coils	1	2	3	1

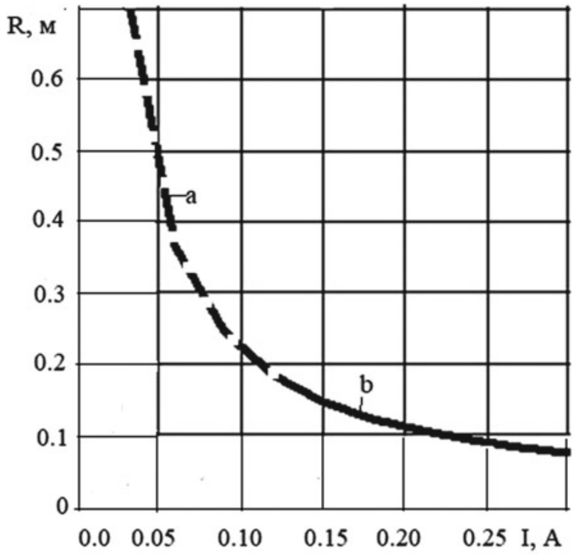

Fig. 5 Influence of the magnetization current on the Larmor radius: **a**—idle mode; **b**—mode of operation

Table 2 Maximum and minimum focusing radii of ions at a current in the focusing coils of 1.0 A and 8.0 A, respectively

Pollutants ion impurities	Coil current, I_{min}, A	Radius larmor, R_{max}, m	Coil current, I_{max}, A	Radius larmor, R_{min}, m
Anions				
Sulfate, SO_4^2	1	0.0978	8	0.0123
Hydrocarbonate, HCO_3	1	0.0318	8	0.0048
Chloride, Cl	1	0.0221	8	0.0028
Cations				
Iron, Fe^{3+}	1	0.0348	8	0.0044
Calcium, Ca^{2+}	1	0.0255	8	0.0032
Potassium, K^+	1	0.0224	8	0.0030
Magnesium, Mg^{2+}	1	0.0152	8	0.0019
Sodium, Na^+	1	0.0143	8	0.0018
Ammonium, NH_4^+	1	0.0109	8	0.0014

- to confirm the shape of the trajectory of ion movement in a magnetic field, which is adequately modeled by a curvilinear conical surface using the equation Ulissa Dani;
- to establish a connection between the parameters of the trajectory of the ions during focusing with the working dimensions of the magnetic chamber and the experimental laboratory stand;

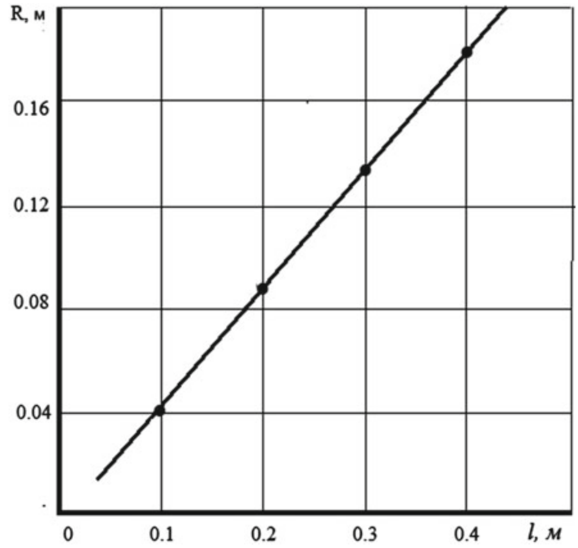

Fig. 6 Dependence of the radius (R) of impurities on the length of the focusing coils

– to set the parameters of the focusing process, which allow you to control its course both in the three-dimensional space of the working magnetic camera and in time.

8 Discussion of the Results of the Study of the Effect of a Non-uniform Magnetic Field on the Purification of an Aqueous Solution Using the Effect of Focusing by Ionic Impurities

The study of the process of interaction of pollution ions with a magnetic field using a physical and mathematical model basically confirmed the idea of the possibility of focusing ionic impurities in a water stream under the influence of a non-uniform magnetic field. The relationship between the intensity of the magnetic field and the geometric and kinematic constructive ones is established parameters of the magnetic camera.

Model laboratory stand using a virtual environment allowed us to choose a conical spiral line according to the Ulysses Dini equation as the trajectory of the movement of a charged particle in a water stream under the influence of a non-uniform magnetic field, as a three-dimensional geographical image of the particle's movement in space. When modeling the process of cleaning the water flow using the LabVIEW package, the mass of particles, their charges, speed, as well as the hydrodynamic resistance of the liquid and the design features of the magnetic coils, which are associated with giving the field the necessary structure, are taken into account.

This approach greatly simplified both the development of the hydraulic scheme of the stand (Fig. 3) and the design and manufacture of the research laboratory stand.

In accordance with the developed methodology and research program, the laws of the effect on charged impurities in the water flow of a non-uniform magnetic field were established on the laboratory bench, which led to the focusing of ions in the volume of the paraboloid of rotation. and the formation of an internal flow with a high concentration of impurities and reduced to a given cross section of the Larmor radius.

It was established that the process of formation of an internal axial flow with a high concentration of impurities should be regulated by changing three parameters:

- total length l of magnetic coils (due to the length of each coil l_i and the number of turns of wire on each coil ni);
- velocity of charged particles $V_{\perp}$ in the flow of polluted water (due to regulation of the total flow of liquid through the working focusing chamber);
- the magnitude of the magnetic induction $\overrightarrow{B}$ along the trajectory of the particle in space (due to the change in the current I in the working focusing coils).

It was established that the size of the Larmor radius R at the beginning of the trajectory is mainly influenced by the value of the current I (and through it the value of the initial magnetic induction $\overrightarrow{B}1$ and the size of the internal flux R_2 at the exit from the magnetic coils is significantly influenced by the value of the magnetic field itself $\overrightarrow{B}2$ so and its gradient $\frac{\partial B2}{\partial y}$.

The obtained dependence of the Larmor radius on the current of the magnetic coils R = f(I), (Fig. 5). It was found that for current values $I < 0.125$ A, the focusing mode is not set. The operating mode starts at a current of $I \geq 0.25$ A, which corresponds to a trajectory with a radius of curvature $R \leq 0.075$ m.

Thus, it is confirmed that the effective influence on the trajectory of the movement of impurities is possible not only due to an increase in the magnitude of the magnetic induction field $\overrightarrow{B}$, but also due to the gradient of the field in the axial direction in accordance with expression (16) when changing the number of turns n and the total length of the magnetic coils l (Fig. 6).

In general, at a given maximum concentration of impurities in the purified stream, the most effective purification mode is established with simultaneous adjustment of at least three parameters (I, $U_{\perp}$, l) both with manual and automated control.

9 Conclusions

1. The proven idea of using the effect of focusing by an inhomogeneous magnetic field of ionic impurities in a stream of polluted water is based on the fundamental laws of Ampere, Lorentz, and Larmor. The essence of the idea is the ability to realize the trajectory of the movement of ionic impurities in the liquid flow with a non-uniform magnetic field due to a purposeful dynamic change in its structure.

2. The process of focusing charged particles by a non-uniform magnetic field using an analytical physical–mathematical model of the field, the constructive shape and dimensions of the magnetic chamber is substantiated dimensions and working focusing camera.
3. Simulation modeling of the magnetic field using a working impurity focusing camera and a trajectory model in virtual space confirmed the previous results of analytical modeling and made it possible to specify the shape and parameters of the impurity trajectory using the Ulysses Dini equation, as a three-dimensional geometric representation of the trajectory in the form of a conical spiral line. Based on the simulation results, a hydraulic scheme of the cleaning system and a schematic diagram of the experimental laboratory stand were developed.
4. The development and use of an experimental laboratory stand made it possible to confirm in practice the possibility of regulating the real trajectory of the movement of charged particles in a water stream under the action of a non-uniform magnetic field and to make the necessary corrections in the mathematical models of the liquid purification process.
5. The conducted set of theoretical and experimental studies showed the reality and effectiveness of the method of cleaning a polluted water flow with a non-uniform magnetic field using the effect of focusing ionic impurities with their subsequent removal from the cleaned flow.

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