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# Study on the traveling magnetic field water purifier

A S Berdyshev<sup>1\*</sup>, Z Z Djumabayeva<sup>1</sup>, A A Abdullaev<sup>1</sup>, and A Mussabekov<sup>2</sup>

<sup>1</sup>Department of Electrotechnologies and Operation of Electrical Equipment, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, 100000 Tashkent, Uzbekistan

<sup>2</sup>Faculty of Natural Sciences, NJSC South Kazakhstan state pedagogical university, 160012 Shymkent, Kazakhstan

Email: berdyshev66@mail.bk

**Abstract.** The article discusses a new technology for Uzbekistan of purifying drinking water from mechanical particles. This is achieved due to the generated traveling magnetic field of the electric winding wound on the metal cylinder. An analysis of the resulting mechanical attraction forces in the space of a cylindrical purifier is given. Mathematical expressions are given to calculate these forces. The analysis of the obtained graphs of temporal and spatial characteristics is presented. The values of currents allow effectively implementing the process of water purification from mechanical impurities is determined.

## 1. Introduction

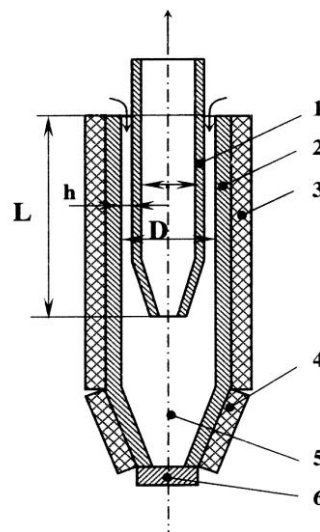
As the world's population grows, the amount of water available per capita decreases [1, 2]. So, while the scarcity of freshwater and its dwindling per capita availability is a problem [3], another big issue is water pollution, which has not only an environmental impact but also a significant impact on quality of life [4]. According to statistics of the World Health Organization (WHO), 783 million people around the world do not have access to clean and safe water. One out of every nine people on the planet does not have access to safe, clean drinking water. Each year, 443 million school days are missed owing to water-related illnesses. Poor water and sanitation conditions are linked to up to 80% of illnesses in impoverished countries.



Magnetic materials have been proposed for the removal of water pollutants in recent years, particularly organic contaminants (dyes, chlorinated hydrocarbons, aromatics), pesticides, and heavy metals [5, 6]. Adsorption, precipitation, solvent extraction, ion exchange, reverse osmosis, membrane separation, evaporation, and photocatalysis are just a few of the water treatment techniques available for safe drinking water [7]. Nanoscience and nanotechnology are shown their potential in removing hazardous substances from water bodies through improved water treatment processes [8, 9].

This paper provides the design of the developed purifier with traveling magnetic field. This purifier decreases power consumption and solve problems with purifier regeneration. Also, compared to the previously developed filters with a complex magnetic field configuration, the new purifiers reduce the consumption of electrical steel due to the lack of a trapping system [10].

## 2. Materials and Methods



**Figure 1.** Traveling wave electromagnetic purifier. 1 - outlet tube; 2 - filter case; 3 - electromagnetic system; 4 - permanent electromagnet; 5 - collecting hopper; 6 – shutter

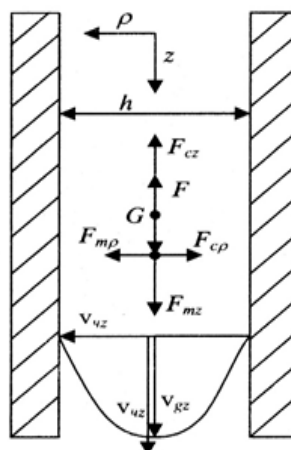
The Figure 1 shows the design of the purifier. On the outer surface of the case 2 is located the electromagnetic system 3, which creates the traveling magnetic field. The magnetic field, on the one hand, attracts ferromagnetic particles, located in the gap between the case 2 and the liquid discharge pipe 1, to the outer wall of the filter, and on the other hand, it moves the attracted ferromagnetic particles towards the hopper 5, where they are held by the direct current electromagnet 4. The traveling magnetic field is created by short-term voltage supply to individual coils

of the electromagnetic system. The law of change of the electromagnetic field inside the purifier depends on the viscosity of the liquid, the parameters of the contamination particle, etc. If it is necessary to remove the ferromagnetic particles separated from the liquid from the purifier, electromagnet 4 is disconnected from the network and the shutter 6 opens. The purified liquid flows through the outlet pipe to the consumer.

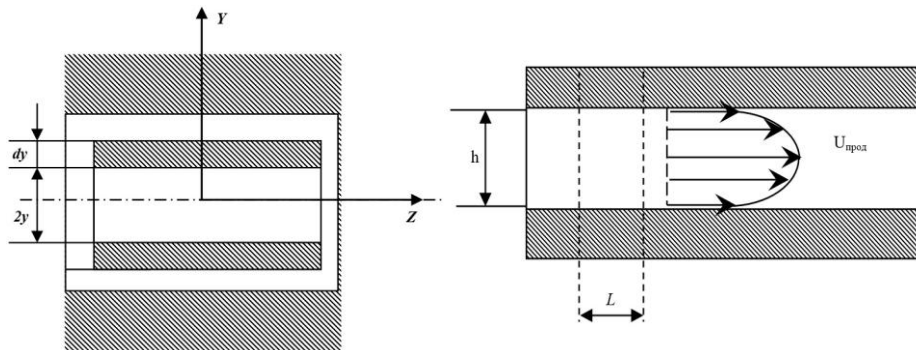
Consider the forces acting on a particle that is in the gap between the pipes. To do this, use Figure 2. The particle is affected by gravity  $G$ , the Archimedean force  $F_a$ , the drag force of the particle in the longitudinal direction  $F_{cz}$ , and the drag forces of the particle  $F_{cp}$  in the transverse direction after applying the ponderomotive force. It also shows the directions of forces and coordinates - along the axis of the purifier - cylindrical coordinates, denoted by  $z$ , and in the radial direction by  $\rho$ . The parameters of the particle motion between the pipes can be calculated by solving joint systems of hydrodynamic and electromagnetic equations.

Consider the operation of the purifier. In this case, we take into account the ponderomotive force, the Stokes drag force and the inertia force.

The inertia of the particle will determine the maximum switching frequency of the purifier electromagnetic system windings. Taking into account the inertia allows setting the maximum speed of movement of pollution particles into the hooper. In the ideal case, in the absence of environment resistance and the coil with one unit thickness, the speed of movement of the ferromagnetic particle coincides with the speed of the magnetic field and is determined only by the frequency of switching the voltage to each next turn of the winding. In reality, the particle will move with a delay, the value of which is determined by the law of motion of the pollution particle in a magnetic field, the speed of the liquid and the diameter of the wire coil [11].



**Figure 2.** Diagram of forces and velocities acting on the particle in the annular gap



**Figure 3.** To the calculation of the velocity field

To determine the law of motion of a particle, we calculate the forces acting on it. To determine the Stokes drag force, it is necessary to calculate the velocity field of the liquid in the working channel of the filter. The calculation is performed in the following order, using Figure 3. Place the origin of coordinates in the middle of the gap, directing the  $OZ$  axis along the flow of the liquid, and the  $OY$  axis along the normal to the walls of the purifier. Take two normal flow cross-sections at a distance  $L$  from one another and consider the width of the flow equal to one unity. To do this, we select the volume of liquid in the form of a rectangular parallelepiped, located symmetrically about the  $OZ$  axis between the selected flow cross sections and having the dimensions of the sides  $L \times 2y \times 1$ . Then the condition for the uniform movement of the selected volume along the  $OZ$  axis will be written by the following expression:

$$2yp_{mp} = -\mu \frac{dV_{g\rho}}{dy} 2L \quad (1)$$

$p_{mp} = p_1 - p_2$  - the pressure drop in the considered sections (the "-" sign is due to the fact that the derivative of the velocity is negative).

To determine the velocity increment  $dV_{g\rho}$  corresponding to the increment in the  $dy$  coordinate, integrate the expression:

$$V_{g\rho} = -\frac{p_{mp}}{2\mu L} y^2 + C \quad (2)$$

Taking into account that at the value of  $y = h/2$  the increment of the speed  $V_{нроч} = 0$ :

$$C = \frac{p_{mp}}{2\mu L} \frac{h^2}{4} \quad (3)$$

Then:

$$V_{g\rho} = \frac{p_{mp}}{2\mu L} \left( \frac{h^2}{4} - y^2 \right) \quad (4)$$

Calculate the flow rate per unit width of the flow, for which take two elementary platforms of size  $1 \times dy$  symmetrically relative to the OZ axis and express the elementary flow rate of the liquid using the following expression:

$$dQ = V_{g\rho} dS = \frac{p_{mp}}{2\mu L} \left( \frac{h^2}{4} - y^2 \right) 2dy \quad (5)$$

$$dQ = V_{g\rho} dS = \frac{p_{mp}}{2\mu L} \left( \frac{h^2}{4} - y^2 \right) 2dy \quad (6)$$

Write the flow rate in the form:

$$Q = \frac{p_{mp} h^3}{12\mu L} \quad (7)$$

The pressure loss in the purifier is expressed in terms of the average longitudinal velocity  $V_{g\rho} = Q/h$ . Then the expression for the pressure drop in the considered sections

$$p_{mp} = \frac{12\mu L V_{g\rho}}{h^2} \quad (8)$$

Rewrite the obtained equations to the case of an annular gap. The width of this gap will not be considered equal a one unit, but as a value equal to  $\pi(D-h)$ . Since  $D \gg h$  and  $p_{mp} = \Delta p$ , then the fluid flow rate has the form

$$Q_{\text{an}} = \frac{\Delta p h^3}{12\mu L} \pi D. \quad (9)$$

The value  $y$  can be expressed by  $x$ :

$$\begin{cases} x > \frac{h}{2} & y = x - \frac{h}{2} \\ x < \frac{h}{2} & y = \frac{h}{2} - x \end{cases} \quad (10)$$

The velocity distribution as a function of  $x$  can be written as:

$$V_{g\rho} = \frac{\Delta p}{2\mu L} (xh^2 - x) \quad (11)$$

The Reynolds number for the annular gap is defined by:

$$\text{Re} = \frac{hV_{g\rho}}{\nu}. \quad (12)$$

For this case, the critical Reynolds number is taken to be  $\text{Re}_{\text{cp}} = 600 \div 1000$ , and the drag law, through the hydraulic radius  $\lambda = \frac{24}{\text{Re}}$  [12].

### 3. Results and Discussion

Consider the ponderomotive force acting on a particle of pollution, which is in the magnetic field of the purifier.

At each separate moment in time, the magnetic field is created by a single turn of the winding, to which a short-term constant voltage is applied. The magnetic field strength in this case on the axis of a single loop is determined by the expression from [13]:

$$H_o = \frac{IR^2}{2(R^2 + z^2)^{1.5}} \quad (13)$$

Using the previously described method, when considering the electromagnetic purifier with a complex magnetic field configuration, we obtain the expression for determining the field strength in an arbitrary place in space in the form:

$$H = \frac{IR^4}{2(R^2 + z^2)^{1.5} (R^2 - \rho^2)} \quad (14)$$

Then, take the derivatives of (14) of the expression defining the field strength from the coordinates  $\rho$  and  $z$ :

$$\begin{cases} \frac{\partial H}{\partial \rho} = \frac{IR^4 \rho}{(R^2 + z^2)^{1.5} (R^2 - \rho^2)^2} \\ \frac{\partial H}{\partial z} = \frac{1.5IR^4 z}{(R^2 + z^2)^{2.5} (R^2 - \rho^2)} \end{cases} \quad (15)$$

Then the transverse and longitudinal components of the ponderomotive force are written in the form:

$$\begin{cases} F_{m_\rho} = \mu_o V \chi \frac{I^2 R^8 \rho}{2(R^2 + z^2)^3 (R^2 - \rho^2)^3} \\ F_{m_z} = 0.75 \mu_o V \chi \frac{I^2 R^8 z}{(R^2 + z^2)^4 (R^2 - \rho^2)^2} \end{cases} \quad (16)$$

For theoretical research, the authors developed the mathematical model of the purifier. The system includes five equations: two equations of motion for the projections  $\rho$  and  $z$ , equations for the ponderomotive force, and one equation for the longitudinal component of the fluid. The system of differential equations of the model:

$$\begin{cases} m \frac{dV_{p_z}}{dt} = F_{m_z} - 6\pi\mu r (V_{p_z} - V_{g_z}) \\ m \frac{dV_{p_\rho}}{dt} = F_{m_\rho} - 6\pi\mu r V_{p_\rho} \end{cases} \quad (17)$$

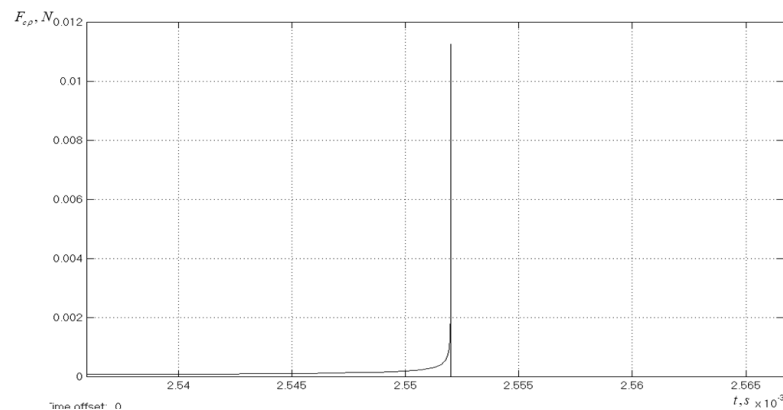
$$V_{g_z} = \frac{\Delta p}{2\mu L} \rho (h^2 - 1), \quad (18)$$

This model makes it possible to take into account the initial and boundary conditions in the system of equations describing the purifier with traveling magnetic wave:

$$\rho_{\text{nav}} = D/2 - h; \quad Z_{\text{nav}} = 0; \quad (19)$$

at  $\rho = D/2 - r$  and  $V_{\rho\rho} = 0$ .

The boundary conditions stipulate the following: when a particle of contamination is attracted to the side wall of the purifier, the transverse component of its velocity  $V_{\rho\rho}$  will be equal to 0. As the initial coordinate  $\rho$ , the most unfavorable variant of the particle location in terms of the impact of the ponderomotive force on it is taken – at the surface of the inner pipe of the purifier. Under these conditions, the dependences of the coordinates of the particle, the ponderomotive force acting on it, and the Stokes drag force opposing its motion on time were obtained. The graphs were calculated under the following conditions: the diameter of ferromagnetic particles during cleaning  $(20 \div 100) \times 10^{-6}$  m, amperage - (2.5-20) A, liquid temperature (10-60) °C, liquid flow - (0-15) l/s, slot height  $(2-5) \times 10^{-3}$  m, distance between loops  $(1-10) \times 10^{-3}$  m.



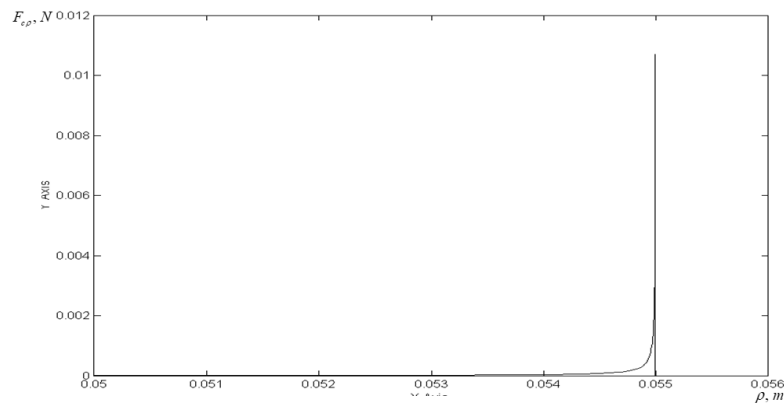
**Figure 4.** Time dependence of the transverse component of the Stokes force

The particle reaches the filter wall in 0.0258 s and then continues to move along it, never breaking away from the surface. This happens because the ponderomotive force is maximum when the particle reaches the filter surface, and this, in turn, is explained by the nature of the distribution of the magnetic field strength in the solenoid. As was shown by Landau and Lifshitz [14], the intensity is inversely proportional to the difference between the squares of the solenoid radius and the  $\rho$  coordinate, and as it approaches the solenoid surface (in our case, the purifier), it increases [15]. Taking into account that the maximum approach to the wall of the purifier is determined by the particle radius, which in our case is  $10 \times 10^{-6}$  m  $\div$   $100 \times 10^{-6}$  m (with a filter radius of  $5.5 \times 10^{-2}$  m), then it can be determined that when



moving from the inner pipe to the surface of the purifier (to the height of the slot  $5 \times 10^{-3}\text{m}$ ), the magnetic field intensity increases 4772 times.

Accordingly, the intensity gradient will also increase. This causes a sharp increase in the transverse ponderomotive force at the surface of the purifier.



**Figure 5.** Dependence of the transverse component of the Stokes drag force on the coordinate  $\rho$

Due to the short transient time, which characterizes the increase in ponderomotive force at the filter surface? The development of the process in  $1 \times 10^{-3}$  s, which makes it possible to estimate the initial value of the ponderomotive force, which remains until the particle reaches the wall of the purifier and after reaching the wall its value does not change.

The force of resistance to the movement of the particle in the transverse direction from the side of the liquid must first increase, and in the surroundings of the wall quite sharply, and at the full approach of the particle to the wall fall to zero, because the movement of the particle in the transverse direction ends (the particle will not be able to break away from the wall due to a significant amount of ponderomotive force). The assumptions are confirmed by the calculated dependencies shown in Figures 4 and 5.

#### 4. Conclusion

The analysis of the obtained expressions and the results of calculations showed that in the purifier the movement of a particle in the longitudinal direction occurs as follows: until the particle reaches the side wall of the purifier, in the longitudinal direction it changes its position rather slowly due to the gradual change in the magnetic field strength and, consequently, the ponderomotive force.

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