The unique properties of liquids that can interact with electric and magnetic fields are used in mechanical engineering, technology and medicine. The possibility of the influence of the magnetic field on the solid particles of the liquid in the pipeline allows cleaning of the solid walls of the pipeline, which is the object of the study. Magnetic liquids are solutions of ferromagnets in a liquid, and their physical properties in a magnetic field cause structural transformations in such liquids.

The treatment of electrically conductive liquids in a magnetic field and their use for cleaning water from oil or oil residues are considered. On the basis of numerical modeling, the movement of solid particles of magnetite, which is part of an electrically conductive liquid, was investigated by jointly solving the equations of Reynolds, Maxwell, non-discontinuity and the turbulence model. The physical phenomena of the movement of solid particles of magnetite-based conductive liquid in various elements of the pipeline were determined, which improved the parameters of cleaning liquids contaminated with oil and oil. The magnetic particles of the electrically conductive liquid quite nicely fill the boundaries of the intersection if there is a flow reversal, as it happens in radiators. An increase in the intensity of the magnetic field leads to a change in the velocity profile of the conductive liquid, which prevents magnetite particles from penetrating close to the wall. An increase in the power of the magnetic field makes it possible to detach the contamination from the walls of the pipeline together with the solid particle of magnetite. A 73 % increase in wear in certain sections of the pipeline is due to the effect of the centrifugal force acting on the particle during rotation.

The sudden expansion of the flow makes it difficult for particles to reach the pipe surfaces, which worsens the cleaning conditions. The number of particles on the surface is 82 % less compared to the absence of sudden expansion

Keywords: conductive liquid, magnetic field, purification of liquids, numerical calculation, local resistances

UDC 537.84

DOI: 10.15587/1729-4061.2023.274699

IMPROVEMENT OF CLEANING PARAMETERS OF PIPELINE ELEMENTS BASED ON SIMULATION OF MOVEMENT OF SOLID MAGNETITE PARTICLES IN ELECTRICALLY CONDUCTIVE LIQUID

Andrii Rogovyi
Doctor of Technical Sciences, Professor
Department of Hydraulic machines named after G. F. Proscura
National Technical University "Kharkiv Polytechnic Institute"
Kyrpychova str., 2, Kharkiv, Ukraine, 61002

Nataliia Chernetska-Biletska
Doctor of Technical Sciences, Professor*

Mariia Miroshnykova
Corresponding author
PhD*

Ihor Baranov
PhD, Associate Professor*

Yevhen Polupan
PhD
Department of Railway, Road Transport and Truck Machines**
*Department of Logistics Management and Traffic Safety in Transport**
**Volodymyr Dahl East Ukrainian National University
Tsentralnyi ave., 59-a, Severodonetsk, Ukraine, 93406

Received date 30.11.2022
Accepted date 15.02.2023
Published date 28.02.2023

***How to Cite**: Rogovyi, A., Chernetska-Biletska, N., Miroshnykova, M., Baranov, I., Polupan, Y. (2023). Improvement of cleaning parameters of pipeline elements based on simulation of movement of solid magnetite particles in electrically conductive liquid. Eastern-European Journal of Enterprise Technologies, 1 (5 (121)), 38–46. doi: https://doi.org/10.15587/1729-4061.2023.274699*

1. Introduction

fields can be prospectively used in mechanical engineering, technology, and medicine [1, 2]. Magnetic liquids are solutions of ferromagnets in a liquid, and their physical properties in a magnetic field cause structural transformations in such liquids.

From the very beginning of the discovery of the special properties of magnetic liquids, they began to be studied for the creation of many devices: magnetohydrodynamic pumps, magnetohydrodynamic electricity generators, handling of liquids in melts [3–5]. But, later, serious attention of researchers began to be attracted to the possibility of using magnetic and electrically conductive liquids to clean liquids (most often water) from oil stains or spills.

The Deepwater Horizon oil rig accident in the Gulf of Mexico in 2010 forced scientists to look for new ways to combat oil pollution. According to the works [6, 7], this way is the use of ferromagnetic nanoparticles that exhibit the properties of magnetic liquids. Particles of the liquid have a positive charge, which allows them to stick to molecules and macrovolumes of oil. Under the influence of a magnetic field, they can move in the direction specified by the cleaning operator.

Therefore, studying the behavior of magnetic liquids in a magnetic field and using them to clean water from oil or oil residues is an urgent task, the solution of which will lead to the development of an effective cleaning technology.

2. Literature review and problem statement

For the first time, the influence of the magnetic field on the hydrodynamic features of the flow of electrically conductive liquids was discovered using the example of the movement of mercury [8], but the analytical calculation of the flow characteristics of such liquids remains complicated. Since then, magnetic and electrically conductive liquids have attracted the attention of many researchers [9, 10], which increases the scope of their application. Due to the complexity of the processes that occur during the movement of a conductive liquid in magnetic and electric fields, most of the research was experimental. It was found that such liquids exhibit anomalous properties with respect to energy and pressure losses that do not correspond to the well-known classical Bernoulli equations. This happens as a result of the transformation of the velocity plot in the cross section and the change of the Coriolis coefficient. In addition, it was found that the transition from laminar to turbulent flow also occurs at critical Reynolds numbers that do not correspond to classical liquids [8, 11]. But at that time there were objective difficulties regarding the analytical or numerical calculation of the current. Attempts to solve the equations of motion of the flow of an electrically conductive liquid by analytical methods [12, 13] with the help of the Navier-Stokes equations were not successful for three-dimensional formulations. The main difficulty in solving the system of equations is the use of partial derivatives, equations with which can be solved only by numerical methods today [14, 15].

Numerical methods of solving the equations of motion of any liquids have developed in recent years, including for magnetohydrodynamics. This allows the use of CFD (Computational Fluid Dynamics) calculations for an adequate description of the behavior of magnetic liquids while simultaneously solving the averaged Navier-Stokes equations and Maxwell's equations [16, 17]. However, studies of the movement of magnetite particles have not yet been conducted. In addition, the calculation of wear and tear of the pipeline was not carried out due to the lack of purpose of using such liquids for cleaning.

Optimizing the characteristics and parameters of cleaning liquids from oil and oil stains is most often done empirically and experimentally. Magnetohydrodynamic liquids are quite expensive liquids, which means that experimental studies of their behavior also become very expensive [18, 19]. Mathematical modeling is used for detailed analysis of velocity and pressure distributions during liquid movement under the influence of a magnetic field and without the influence of a magnetic field. To reveal the physics of the occurring phenomenon, to analyze the movement of solid particles, if the liquid consists of them, is possible on the basis of the simultaneous solution of systems of equations. These systems should consist of the Reynolds equations, Maxwell's equations, liquid continuity equation, and solid particle dynamics equations [20, 21]. The solution is possible using modern software packages, such as the Ansys CFX software package [22]. This approach was used in many works [22] regarding numerical calculations, but they did not determine the wear of the pipeline by magnetic particles.

Thus, in order to improve the parameters of cleaning pipelines contaminated with oil and oil deposits, it is necessary to determine the physical phenomena of the movement of solid particles of an electrically conductive liquid based on magnetite in various elements of the pipeline.

3. The aim and objectives of the study

The aim of the study is to determine the patterns of flow of conductive liquid through local resistances. This will make it possible to determine and improve the parameters of cleaning pipeline elements with the help of conductive liquid.

To achieve the aim, the following objectives were set:

– improve the mathematical modeling of the movement of magnetite particles contained in the conductive liquid and the flow of the liquid itself by adding a model for calculating pipeline wear;

– verify the calculation of the conductive liquid in the software complex of numerical calculations;

– calculate the wear of the pipeline by magnetite particles;

– determine the influence of local resistances on the movement of magnetite particles.

4. Materials and methods of the study

The object of the study is a pipeline contaminated with deposits of oil and petroleum.

The research hypothesis is that the influence of a magnetic field on an electrically conductive liquid allows abrasive particles of magnetite to penetrate into the contact zone of oil pollution and pipeline walls and detach the pollution from them.

The accepted assumptions are that the wear of the pipeline walls by particles of conductive liquid indicates the presence of liquid particles near the walls and the basic cleaning of the pipeline. The shape of the magnetite particles is assumed to be spherical, and it is believed that the shape of the particles does not fundamentally affect the cleaning process, but it can affect the determination of the speed of the particles [23]

Adopted simplifications: the solid particle was assumed to be spherical. The conductive liquid was considered Newtonian, which is dependent on its composition and the time that has passed since its preparation [7, 10]. The conductive liquid was considered to be homogeneous, which is difficult to achieve under experimental conditions and is possible only in the first hours after preparation [3, 4, 11].

Numerical modeling of the movement of an electrically conductive liquid using the Ansys CFX software package with a student license was used to determine the movement parameters, which allows calculations for a grid division not exceeding 500,000 elements. Considering the fact that the study was carried out for individual local resistances, such a restriction on the grid is quite acceptable and does not affect the quality of the calculations. A mathematical model consisting of the Reynolds-averaged Navier-Stokes equations, Maxwell's equations, the continuity equation for an incompressible liquid and SST (Shear Stress Transport) equations of the turbulence model was used for the calculations.

The mathematical model of the movement of an electrically conductive liquid is generally accepted and described in studies [5, 13, 16, 20]. Adding the turbulence SST model to the calculation is a generally accepted universal approach that requires further confirmation of adequacy and verification regarding the determination of calculation error values [15, 22].

The Lagrangian approach was used to model the motion of solid particles. To calculate the flow of solid particles, it is possible to use two approaches, Lagrange and Euler. The Lagrange approach has certain advantages that are important for this study: the behavior of individual solid particles; much easier to model for particles of different sizes, resulting in different particle velocities. Using Euler's approach for a large number of particles makes it impossible to track individual particles [24].

When applying the Lagrangian approach, individual particles are tracked from the point of their entry into the computational domain to the boundary condition of exiting the domain or until some criterion for limiting the integration of the equations is met [25]. This integration limit can be entered into the calculation by the user. Two types of calculation are possible: when particles affect the movement of the main phase of a liquid or gas, and when particles do not affect the main phase. It is obvious that the calculation of the effect of solid particles on the main phase is much faster, but the accuracy of the calculation deteriorates. The influence of solid particles on the main phase is implemented due to an additional term in the equations for calculating the main liquid. Since each particle is tracked from the point of its introduction to the final boundary, the procedure for analyzing the trajectories of solid particles is based and applied only to the steady-state calculation of the main liquid.

After calculating the liquid flow, the calculation was verified by comparing the velocity distributions in the experiment and the calculation. In addition, the adequacy of calculations was established by comparing pressure losses in local supports.

Calculations of the wear of the pipeline with different local hydraulic resistances by magnetite particles were made on the basis of the Phinney erosion wear model.

5. Results of studies of the movement of conductive liquid in the pipeline

5. 1. Mathematical model of the movement of particles of an electrically conductive liquid

The change in the coordinate of the location of a solid particle in space with Cartesian coordinates $d\overline{x}_p$ takes place taking into account the speed of the particle ($\overline{V}_p = d\overline{x}_p / dt$) and the time step δt [26]:

$$\overline{x}_p^n = \overline{x}_p^0 + \overline{V}_p^0 \delta t, \tag{1}$$

where the indices n and 0 refer to the old and new values, respectively, $\overline{V}_p^0$ – the initial velocity of the solid particle. During direct integration, the particle velocity calculated at the beginning of the time step is assumed to be dominant throughout the time step. At the end of the time step, the new particle velocity is calculated using the analytical solution of the particle dynamics equation:

$$m_p \frac{d\overline{V}_p}{dt} = \sum \overline{F}, \tag{2}$$

where $\sum \overline{F}$ – sum of all forces acting on the particle, m_p – mass of the solid particle.

This equation is an example of a general transport equation:

$$\frac{d\phi_p}{dt} = \frac{(\phi_f - \phi_p)}{\tau} + R, \tag{3}$$

where φ – general transport variable, the index f indicates the value of the variable in the liquid surrounding the particle, τ – linearization coefficient; R – nonlinear source term. The analytical solution of the general transport equation can be written as follows [24]:

$$\phi_p = \phi_f + \left(\phi_p^0 - \phi_f\right) e^{-\frac{\delta t}{\tau}} + \tau R \left(1 - e^{-\frac{\delta t}{\tau}}\right). \tag{4}$$

To determine the value of the general variable property of the liquid, it is taken from the previous time step.

To determine the values of τ and R, it is necessary to take into account many parameters of the liquid: density, viscosity, and velocity. These values are calculated for each finite volume.

For a more accurate calculation of the behavior of solid particles in a liquid, it is necessary to take into account not only the effect of the liquid on the particle, but also the effect of solid particles on the flow parameters. This is the so-called two-way coupling.

Mathematical modeling of the movement of an electrically conductive liquid was carried out on the basis of the solution of the Reynolds-averaged Navier-Stokes equations with the equation of the SST turbulence model, the continuity equation and Maxwell's equations for the flow of an incompressible liquid [13, 15, 16]:

$$\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left([\mu + \mu_T] \frac{\partial u_i}{\partial x_j} \right) + f_i, \tag{5}$$

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{6}$$

$$\overline{f} = \left[\overline{j} \times \overline{B}\right], \tag{7}$$

$$\nabla(\sigma \nabla \Phi) = \nabla \cdot \left[\sigma \overline{u} \times \overline{B}\right], \tag{8}$$

$$\nabla^2 \Phi = \nabla \cdot \left[\overline{u} \times \overline{B}\right], \tag{9}$$

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j k) = \frac{\partial}{\partial x_j}\left([\mu + \mu_T] \frac{\partial k}{\partial x_j} \right) + P_k - \beta^* \rho k \omega, \tag{10}$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j \omega) = \frac{\partial}{\partial x_j}\left([\mu + \mu_T] \frac{\partial \omega}{\partial x_j} \right) - \rho \beta \omega^2 + Cd_\omega + \alpha \frac{\rho}{\mu_t} P_k, \tag{11}$$

where r – density; x_j – Cartesian coordinates; u_j – velocity projections in the Cartesian coordinate system; t – time; p – hydrodynamic pressure; f_i – projections of the vector of mass forces on the coordinate axis (in our case – the Lorentz force); μ – dynamic (molecular) viscosity; μ_T – turbulent dynamic viscosity; $\overline{j}$ – density of the electric current arising in the electrically conductive liquid, which moves at a speed $\overline{u}$ due to the local electric field; $\overline{B}$ – magnetic induction vector; Φ – scalar electrostatic potential; σ – electrical conductivity; k – kinetic energy of turbulent pulsations; P_k – generation term; Cd_w – cross term; a, b, b^* – empirical constants of the SST model; w – frequency of turbulent pulsations. Values of constants, generation and cross terms can be found in works [15, 23, 24].

Failure to take into account the influence of solid particles on the main flow is possible only if the concentration of particles is small and it can be considered that their influence on the main phase is such that it can be neglected. This calculation is simpler, because it is possible to first calculate the flow of the liquid, and then, based on the already calculated parameters, determine the main parameters of the movement of a solid particle (the so-called superposition method).

Among the forces acting on a solid particle, the aerodynamic drag force is taken into account, which is the force that most affects the trajectory of the solid phase [23, 25, 30]. The aerodynamic drag force is proportional to the shear rate, i. e. the difference in speed between the liquid $\overline{U}_F$ and the particle $\overline{V}_P$:

$$\overline{F}_D = \frac{1}{2} C_D \rho A_F \left| \overline{U}_F - \overline{V}_P \right| \left(\overline{U}_F - \overline{V}_P \right), \tag{12}$$

where CD – the drag coefficient; AF – the effective cross-sectional area of the particle. The drag coefficient is introduced to take into account the experimental results regarding the viscous drag of a solid sphere. This study used the determination of the resistance coefficient according to the Schiller-Neumann model [27]:

$$C_D = \frac{24}{\mathrm{Re}} \left(1 + 0.15 \mathrm{Re}^{0.687} \right), \tag{13}$$

where Re – Reynolds number.

The Finney model [24, 25] was used to calculate the wear of the pipeline walls. Pipeline wall wear due to the erosive effect of solid particles is a complex function of particle impact and particle and wall properties. It was found that for almost all metals, erosion varies depending on the impact angle and speed according to the ratio [28]:

$$E = k V_p^n f(\gamma), \tag{14}$$

where E – dimensionless mass; k – coefficient of the model; $f(\gamma)$ – dimensionless function of the impact angle γ (collision). The collision angle is calculated in radians and is determined between the tangent to the trajectory of the particle and the wall. The value of n for metals is in the range of 2...2.5.

Finney's model of erosive wear [29] relates the rate of wear to the rate of kinetic energy of particles hitting the surface using n=2 [24]:

$$E = k V_p^2 f(\gamma), \tag{15}$$

where

$$f(\gamma) = \frac{1}{3}\cos^2\gamma, \text{ if } \mathrm{tg}\gamma > 1/3,$$

$$f(\gamma) = \sin(2\gamma) - 3\sin^2\gamma, \text{ if } \mathrm{tg}\gamma \le 1/3.$$

In the Ansys CFX program, the need to adjust the coefficient k to obtain a dimensionless erosion coefficient is overcome by using the dependence:

$$E = \left(\frac{V_p}{V_0} \right)^n f(\gamma), \tag{16}$$

where $V_0 = \frac{1}{\sqrt[n]{k}}$ [30].

Equations (5)–(16) are a mathematical model that consists of the averaged Reynolds equations, Maxwell's equations, the continuity equation, the SST equations of the turbulence model, and the erosion wear model equations. Of course, each model individually is generally accepted and the adequacy of calculations based on them has been checked many times. But, taking into account the possible errors of numerical methods, the possibility of using these models together for calculations of the flow of an electrically conductive liquid requires additional verification.

5. 2. Sensitivity analysis of the numerical solution of the problem and its verification

To analyze the influence of the number of control volumes on the calculation results, a comparison of the results for five grids with and without the action of a magnetic field was carried out. The results are given in the Table 1. The influence of the grid division is determined based on a comparison of the results of the pressure calculation at the entrance to the pipeline element. This is an important value that affects the choice of a pump and hydraulic machines for pumping [31, 32]. Pumping of electromagnetic liquids can be implemented by classic hydraulic machines or jet pumps [33] by mixing the droplet phase and solid particles. Pump stations can control mixing in a jet pump based on a hydraulic drive [34, 35].

To compare the influence of the magnetic field on the liquid flow, the Hartmann criterion number $\left(Ha = BR\sqrt{\sigma / \rho\nu} \right)$, B –magnetic induction was chosen, R – pipe radius; σ – electrical conductivity of the liquid, ρ – liquid density, ν – kinematic density of the liquid.

Table 1

Pressure at the entrance to the pipeline element

The number of grid elements, million	Pressure, Pa	Hartmann number
0.1	2,320	0
0.2	1,590	0
0.3	1,890	0
0.4	1,805	0
0.5	1,845	0
0.1	11,500	50
0.2	12,100	50
0.3	10,900	50
0.4	11,250	50
0.5	11,300	50
0.1	41,500	100
0.2	40,000	100
0.3	39,500	100
0.4	39,900	100
0.5	40,000	100

The use of grids with the number of elements close to 500,000 is quite acceptable for the following studies. This can be assumed because the result of the calculation for grids with the number of elements more than 300,000 changes by no more than 3.6 %.

In this study, the verification of the mathematical model was performed on the basis of a comparison of the sum of the root mean square deviations of the speed values in comparison with the experimental data [36]. The sum of deviations using different turbulence models was compared. Thus, for the k-ε model, the sum of root mean square deviations of the speed values was equal to 0.057, for SST – 0.047, for

BSL (Menter Baseline Two-Equation Model) – 0.053. These sums of root mean square deviations were calculated for different values of the magnetic induction acting on the liquid. Thus, the comparison was made for Hartmann numbers Ha=0; 20 and 50. Then the average value of the sum of root mean square deviations was calculated for each turbulence model at different values of Hartmann numbers. The largest error in calculating the speed at a point for the above mathematical model was 12 %. The maximum integral error of liquid flow determination was 7 %.

5. 3. Calculation of pipeline wear by abrasive particles

Abrasion of the pipeline by abrasive particles of magnetite illustrates the possibilities of pipeline cleaning. The presence of uniform wear of the pipeline is an indication of the penetration of conductive liquid particles into the walls of the pipeline. This allows to count on the detachment of dirt particles from the walls.

Fig. 1 shows the results of calculating the trajectories of magnetite solid particles.

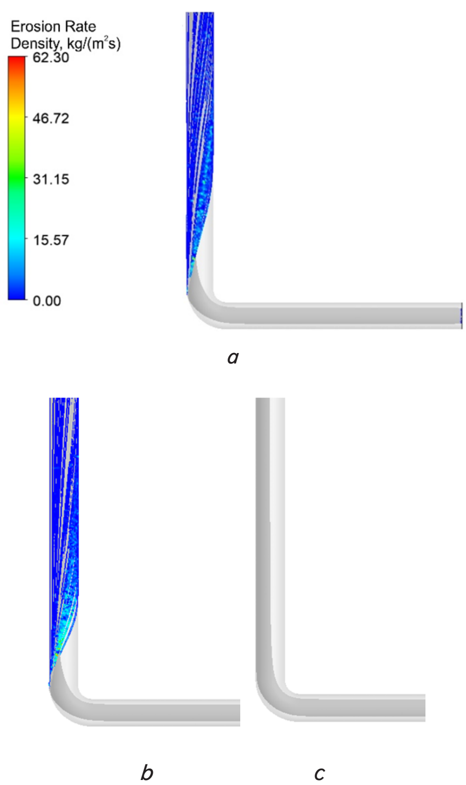

Fig. 1. Trajectories of magnetite particles in the pipeline: *a* – H_a=0; *b* – H_a=50; *c* – H_a =200

The trajectories of solid particles are colored according to their influence on the wear of the pipeline walls. For comparison, three pictures of the current at different Hartmann numbers are given.

For high-quality cleaning of pipelines, radiators and other flowing parts, a high-quality distribution of magnetic liquid along the pipeline cross-section is necessary for good penetration of magnetic particles into contamination. This is necessary so that, under the influence of the magnetic field, the elements of contamination are well removed from the flow parts together with the magnetic liquid. Having analyzed Fig. 1, it is possible to come to the conclusion that the magnetic particles of the conductive liquid quite well fill the boundaries of the intersection, if there is a flow reversal, as it happens in radiators. This can be seen very clearly from the results of the calculation of pipeline wear during the flow of conductive liquid with and without a magnetic field (Fig. 1, 2).

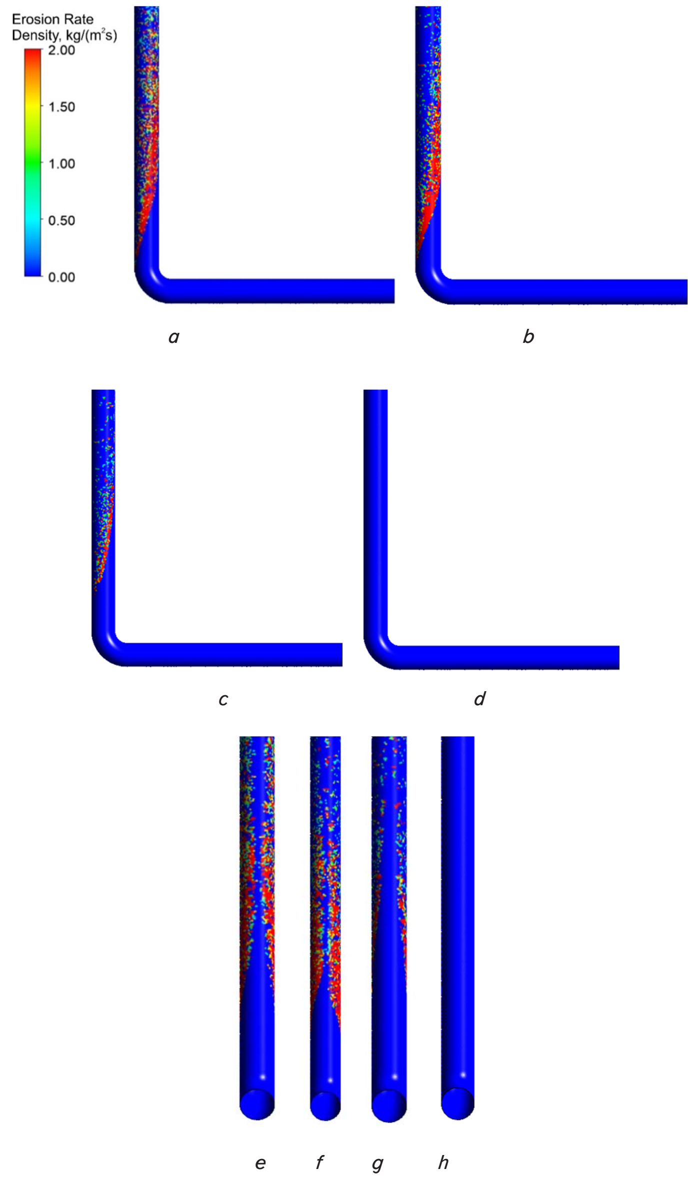

Fig. 2. Intensity of wear of pipeline surfaces during the flow of electromagnetic liquid with different Hartmann numbers: *a*, *e* – H_a=0; *b*, *f* – H_a=50; *c*, *g* – H_a=100; *d*, *h* – H_a=200

An increase in the intensity of the magnetic field leads to a change in the velocity profile [17] of the conductive liquid, which prevents magnetite particles from penetrating close to the wall, which can be seen in Fig. 2, *d*, *h*. On the other hand, an increase in the power of the magnetic field can allow the contamination to be detached from the walls of the pipeline together with a solid particle of magnetite, which can be seen in the figures. In addition, mathematical modeling based on numerical methods in a three-dimensional setting allows analyzing the necessary and sufficient parameters of the magnetic field for complete cleaning of pipelines from contamination.

5. 4. Influence of local resistances on the movement of magnetite particles and pipeline cleaning

The situation in pipelines with sudden expansion is more difficult in terms of the possibility of cleaning (Fig. 3). Solid particles, together with the liquid, break away from the walls and practically do not enter the wall areas.

The flow of conductive liquid under the influence of the magnetic induction vector has a greater opportunity to reach the pipeline walls as quickly as possible, that is, if there is a magnetic field with a magnetic induction vector with a projection in the y direction (Fig. 3, *c*).

To simulate the flow of conductive liquid in the radiator with an assessment of the possibility of cleaning it from contamination, a calculation model of several turns of the pipeline by 180° was created (Fig. 4).

The real model of the radiator was not used due to the large length of straight sections, which would significantly complicate the analysis of the calculation results and increase the required number of control volumes for a high-quality calculation.

The simulation results are shown in Fig. 5.

The magnetic field certainly affects the distribution of solid magnetite particles in the pipeline. The increase in wear in certain sections of the pipeline is associated with the effect of the centrifugal force acting on the particle during rotation. The absence of large changes in wear parameters in Fig. 5, *b–d* is explained by the insufficient influence of the magnetic field on the conductive liquid, which is confirmed by the wear characteristics shown in Fig. 5, *f*.

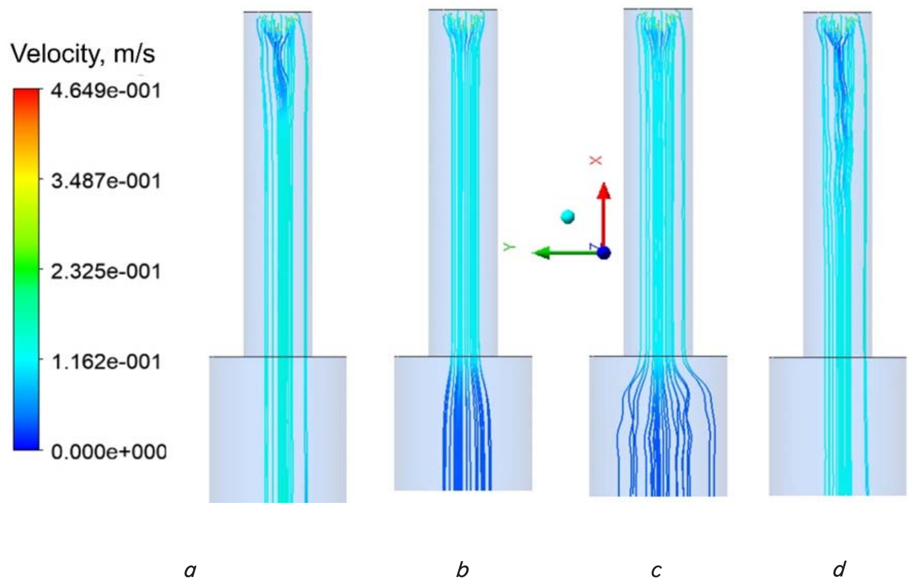

Fig. 3. Trajectories of magnetite particles in a pipeline with sudden expansion: *a* – H_a=0; *b* – H_a=250 *z*-direction; *c* – H_a=250 *y*-direction; *d* – H_a=50 *x*-direction

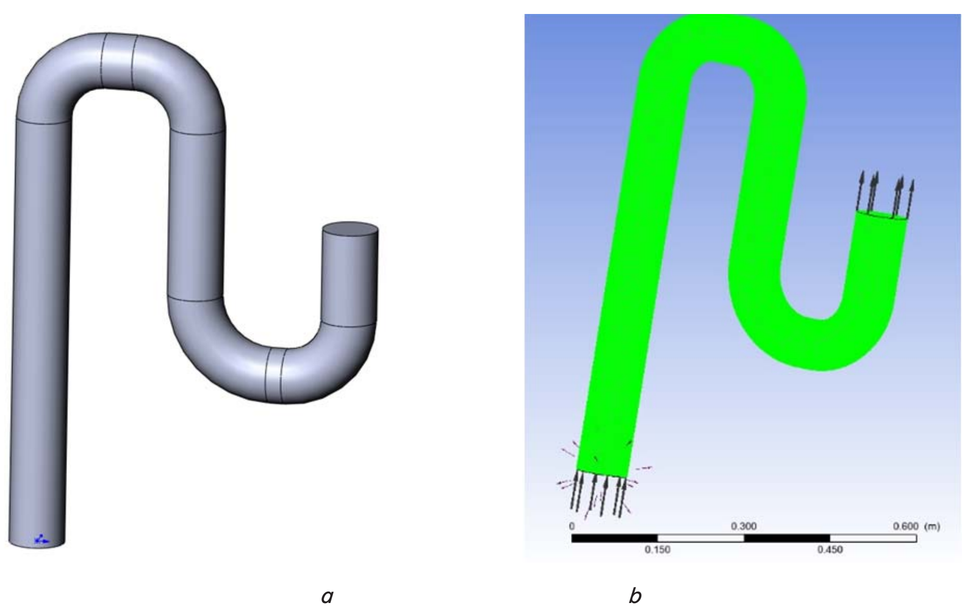

Fig. 4. Calculation models for determining the characteristics of the movement of conductive liquid through the radiator: *a* — solid-state model; *b* — grid model

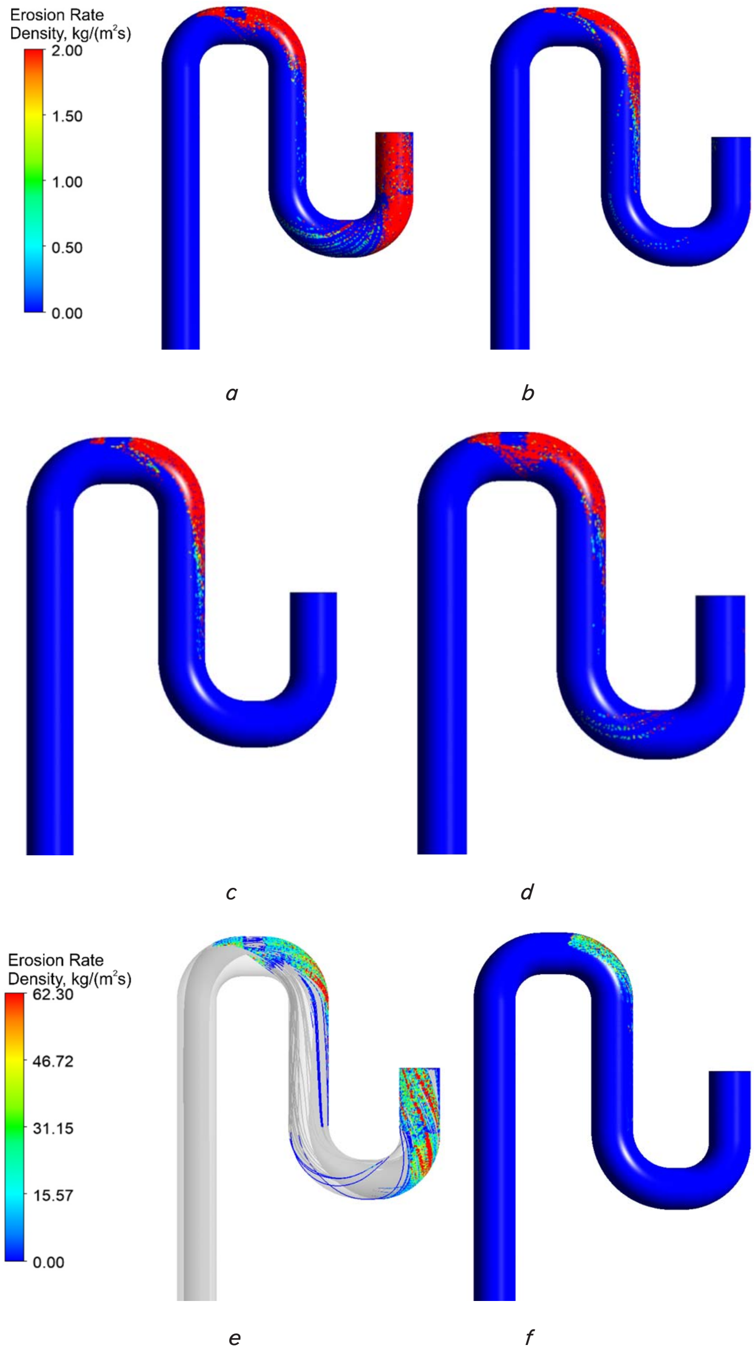

Fig. 5. Intensity of wear of pipeline surfaces during the flow of electromagnetic liquid with different Hartmann number through the radiator: *a*, *e* – H_a=0; *b* – H_a=100, *x*-direction; *c* – H_a=100, *y*-direction; *d* – H_a=100, *z*-direction; *f* – H_a=500, *z*-direction

6. Discussion of the results of the study of the movement of magnetite particles under the influence of a magnetic field in the pipeline

Numerical modeling of the flow of conductive liquid and calculation of pipeline wear by magnetite particles is a complex calculation that has certain disadvantages related to calculation errors. Calculation errors accumulate due to the increase in modeled parameters. Even the classical flow of an ordinary liquid through local resistances cannot be analytically calculated. On the other hand, the numerical calculation has errors that can exceed 20–30 % due to the occurrence of separation of the liquid from the walls and the complexity of calculating such flows. Therefore, complicating the calculation by adding Maxwell's equations and the wear model can provoke even greater errors. However, the results of the verification of the model (5)–(16) showed that the calculation of the flow of conductive liquid is adequate not only in terms of qualitative indicators, but also in terms of quantitative ones. A comparison of the velocity distributions in the pipe with the maximum sum of squared deviations of the relative velocities of 0.047 was made, which shows the sufficient quality and accuracy of the calculated parameters. In contrast to works [1, 29], where the simulation was carried out in a two-dimensional setting, the flow of liquid through local resistances has a three-dimensional character of detachments from the walls. This allows to assert the need to use three-dimensional modeling. This becomes possible with the use of modern software, as in works [2–7], but the obtained wear characteristics allow analyzing the possibility of cleaning the pipeline. The experimental studies conducted in works [18, 28] are valuable, adequate modeling of the flow of an electrically conductive liquid allows to significantly speed up and reduce the cost of scientific studies of such liquids. A similar approach to the modeling of abrasive particles used in works [12, 25, 26, 30] allows a qualitative assessment of wear parameters, but requires consideration of electromagnetic forces.

Modeling the flow through the pipeline (Fig. 5), as well as in the case of a smooth 90° turn (Fig. 1, 2), showed that the wear of the pipeline walls decreases with increasing magnetic field intensity. The hypothesis is confirmed that magnetite particles, which are part of the magnetic liquid, spread through the pipeline and reach almost all points of the pipeline without the effect of a magnetic field (Fig. 2, 5, *e*). The inclusion of a magnetic field makes it possible to hope that the magnetite particles will move at a distance from the walls and detach the contamination from the walls of the pipeline. It is expected that the greatest pollution can be deposited precisely in those zones where the maximum wear of the pipeline by solid particles occurs due to the action of centrifugal force (Fig. 1–3, 5). Thus, it can be assumed that the magnetite particles will spread well among the pollution and contribute to the cleaning of the walls of the radiator and the pipeline from oil and oil pollution.

The situation in pipelines with sudden expansion is more difficult in terms of the possibility of cleaning (Fig. 3). Solid particles, together with the liquid, break away from the walls and practically do not enter the wall areas.

This study was conducted for a certain electromagnetic liquid based on kerosene and magnetite particles, as the one that is most represented among commercial offers. But the flow characteristics and conclusions are made on the basis of dimensionless numbers. Therefore, the simulation results can be transferred to other liquids according to the rules of hydrodynamic similarity. The flows were analyzed for Hartmann numbers in the range 0...250 and Reynolds numbers in the range 5,000...150,000. Thus, the limitations of the study are such ratios of flow kinematic parameters, physical properties of liquids and electromagnetic fields that satisfy the given criterion numbers.

Further development of this research requires conducting experimental studies of the quality of pipeline surface cleaning, which cannot be assessed within the framework of mathematical models. This will be the subject of subsequent works on this topic.

7. Conclusions

1. The mathematical modeling of the movement of magnetite particles contained in an electrically conductive liquid and the flow of liquids has been improved by adding a model of erosive wear of the pipeline. Numerical calculation based on the mathematical model makes it possible to determine the kinematic parameters of the liquid and solid particles.

2. Verification of the model and sensitivity analysis has been carried out. The error characterized by the maximum sum of squared deviations of the relative velocities was equal to 0.047, which shows the sufficient quality and accuracy of the calculated parameters.

3. The increase in wear in certain sections of the pipeline by 73 % is associated with the effect of the centrifugal force acting on the particle during rotation. An increase in the intensity of the magnetic field leads to a change in the velocity profile of the conductive liquid, which prevents magnetite particles from penetrating close to the wall. On the other hand, an increase in the power of the magnetic field can allow to detach the contamination from the walls of the pipeline along with the solid particle of magnetite.

4. The sudden expansion of the flow makes it difficult for particles to reach the pipe surfaces, which worsens the cleaning conditions. The number of particles on the surface is 82 % less compared to the absence of sudden expansion.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no associated data.

References

1. Frank, M., Barleon, L., Müller, U. (2001). Visual analysis of two-dimensional magnetohydrodynamics. Physics of Fluids, 13 (8), 2287–2295. doi: https://doi.org/10.1063/1.1383785
2. Kim, S. (2021). Hydrodynamics of Anisotropic Liquid Crystals in an Applied Magnetic Field. SIAM Journal on Mathematical Analysis, 53 (3), 3123–3157. doi: https://doi.org/10.1137/19m1310062
3. Khan, M. A., Kosel, J. (2021). Integrated Magnetohydrodynamic Pump with Magnetic Composite Substrate and Laser-Induced Graphene Electrodes. Polymers, 13 (7), 1113. doi: https://doi.org/10.3390/polym13071113
4. West, D., Taylor, J. A., Krupenkin, T. (2020). Alternating current liquid metal vortex magnetohydrodynamic generator. Energy Conversion and Management, 223, 113223. doi: https://doi.org/10.1016/j.enconman.2020.113223
5. Lu, P., Fang, R., Ye, Q., Huang, H. (2020). Numerical Research on the Flow Fields in the Power Generation Channel of a Liquid Metal Magnetohydrodynamic System. ACS Omega, 5 (48), 31164–31170. doi: https://doi.org/10.1021/acsomega.0c04379
6. Ko, S., Kim, E. S., Park, S., Daigle, H., Milner, T. E., Huh, C. et al. (2017). RETRACTED ARTICLE: Amine functionalized magnetic nanoparticles for removal of oil droplets from produced water and accelerated magnetic separation. Journal of Nanoparticle Research, 19 (4). doi: https://doi.org/10.1007/s11051-017-3826-6
7. Ko, S., Kim, E. S., Park, S., Daigle, H., Milner, T. E., Huh, C. et al. (2016). Oil Droplet Removal from Produced Water Using Nanoparticles and Their Magnetic Separation. SPE Annual Technical Conference and Exhibition. doi: https://doi.org/10.2118/181893-ms
8. Hartmann, J., Lazarus, F. (1937). Hg-dynamics II. Experimental investigations on the flow of mercury in a homogeneous magnetic field. København. Available at: http://gymarkiv.sdu.dk/MFM/kdvs/mfm%2010-19/mfm-15-7.pdf
9. Alfvén, H. (1958). Magnetohydrodynamics and the thermonuclear problem. Proceedings of the Second Nations International Conference. Available at: http://www-naweb.iaea.org/napc/physics/2ndgenconf/data/Proceedings%201958/papers%20Vol31/Paper01_Vol31.pdf
10. Davidson, P. A. (1999). Magnetohydrodynamics in materials processing. Annual Review of Fluid Mechanics, 31 (1), 273–300. doi: https://doi.org/10.1146/annurev.fluid.31.1.273
11. Narasimha, R., Sreenivasan, K. R. (1979). Relaminarization of Fluid Flows. Advances in Applied Mechanics, 221–309. doi: https://doi.org/10.1016/s0065-2156(08)70311-9
12. Rogovyi, A., Neskorozhenyi, A., Krasnikov, S., Tynyanova, I., Khovanskyi, S. (2022). Improvement of Vortex Chamber Supercharger Performances Using Slotted Rectangular Channel. Advanced Manufacturing Processes IV, 552–561. doi: https://doi.org/10.1007/978-3-031-16651-8_52
13. Azimi, N., Rahimi, M., Zangenehmehr, P. (2021). Numerical Study of Mixing and Mass Transfer in a Micromixer by Stimulation of Magnetic Nanoparticles in a Magnetic Field. Chemical Engineering & Technology, 44 (6), 1084–1093. doi: https://doi.org/10.1002/ceat.202000030

14. Andrenko, P., Rogovyi, A., Hrechka, I., Khovanskyi, S., Svynarenko, M. (2021). The Influence of the Gas Content in the Working Fluid on Parameters of the the Hydraulic Motor's Axial Piston. Advances in Design, Simulation and Manufacturing IV, 97–106. doi: https://doi.org/10.1007/978-3-030-77823-1_10
15. Chernetskaya-Beletskaya, N., Rogovyi, A., Shvornikova, A., Baranov, I., Miroshnikova, M., Bragin, N. (2018). Study on the Coal-Water Fuel Pipeline Transportation Taking Into Account the Granulometric Composition Parameters. International Journal of Engineering & Technology, 7 (4.3), 240. doi: https://doi.org/10.14419/ijet.v7i4.3.19794
16. Widlund, O. (2000). Implementation of MHD model equations in CFX 4.3. Stockholm. Available at: http://ola.widlund.free.fr/doc/TRITA_CFX.pdf
17. Chernetskaya-Beletskaya, N., Rogovyi, A., Miroshnykova, M., Shtykov, A. (2021). Verification of electrically conductive fluid flow calculation in circular pipes. Collected Scientific Works of Ukrainian State University of Railway Transport, 196, 87–98. doi: https://doi.org/10.18664/1994-7852.196.2021.242076
18. Ahangar Zonouzi, S., Khodabandeh, R., Safarzadeh, H., Aminfar, H., Trushkina, Y., Mohammadpourfard, M. et al. (2018). Experimental investigation of the flow and heat transfer of magnetic nanofluid in a vertical tube in the presence of magnetic quadrupole field. Experimental Thermal and Fluid Science, 91, 155–165. doi: https://doi.org/10.1016/j.expthermflusci.2017.10.013
19. Andrenko, P., Rogovyi, A., Hrechka, I., Khovanskyi, S., Svynarenko, M. (2021). Characteristics improvement of labyrinth screw pump using design modification in screw. Journal of Physics: Conference Series, 1741 (1), 012024. doi: https://doi.org/10.1088/1742-6596/1741/1/012024
20. Pianykh, A. A., Arkhipov, G. V., Tretyakov, Ya. A. (2020). Mathematical Model of Magnetic Hydrodynamics and Heat Transfer in an Aluminum Reduction Cell. Russian Journal of Non-Ferrous Metals, 61 (1), 65–73. doi: https://doi.org/10.3103/s1067821220010125
21. Rogovyi, A., Korohodskyi, V., Khovanskyi, S., Hrechka, I., Medvediev, Y. (2021). Optimal design of vortex chamber pump. Journal of Physics: Conference Series, 1741 (1), 012018. doi: https://doi.org/10.1088/1742-6596/1741/1/012018
22. Luo, Y., Fan, X., Kim, C. N. (2021). MHD flows in a U-channel under the influence of the spatially different channel-wall electric conductivity and of the magnetic field orientation. Journal of Mechanical Science and Technology, 35 (10), 4477–4487. doi: https://doi.org/10.1007/s12206-021-0918-0
23. Sommerfeld, M., Sgrott, O. L., Taborda, M. A., Koullapis, P., Bauer, K., Kassinos, S. (2021). Analysis of flow field and turbulence predictions in a lung model applying RANS and implications for particle deposition. European Journal of Pharmaceutical Sciences, 166, 105959. doi: https://doi.org/10.1016/j.ejps.2021.105959
24. Ansys CFX. Available at: https://www.ansys.com/products/fluids/ansys-cfx
25. Rogovyi, A., Korohodskyi, V., Neskorozhenyi, A., Hrechka, I., Khovanskyi, S. (2022). Reduction of Granular Material Losses in a Vortex Chamber Supercharger Drainage Channel. Advances in Design, Simulation and Manufacturing V, 218–226. doi: https://doi.org/10.1007/978-3-031-06044-1_21
26. Appadurai, A., Raghavan, V. (2019). Numerical investigations on particle separation in dynamic separators. International Journal of Numerical Methods for Heat & Fluid Flow, 30 (4), 1677–1688. doi: https://doi.org/10.1108/hff-10-2018-0567
27. Su, W., Shi, X., Wu, Y., Gao, J., Lan, X. (2020). Simulation on the effect of particle on flow hydrodynamics in a slurry bed. Powder Technology, 361, 1006–1020. doi: https://doi.org/10.1016/j.powtec.2019.10.096
28. Hutchings, I. M. (1979). Mechanical and metallurgical aspects of the erosion of metals. Proceedings of the International Conference on Corrosion-Erosion of Coal Conversion System Materials. National Association of Corrosion Engineers, 393–428.
29. Dosanjh, S., Humphrey, J. A. C. (1985). The influence of turbulence on erosion by a particle-laden fluid jet. Wear, 102 (4), 309–330. doi: https://doi.org/10.1016/0043-1648(85)90175-9
30. Rogovyi, A., Khovanskyy, S., Grechka, I., Pitel, J. (2019). The Wall Erosion in a Vortex Chamber Supercharger Due to Pumping Abrasive Mediums. Advances in Design, Simulation and Manufacturing II, 682–691. doi: https://doi.org/10.1007/978-3-030-22365-6_68
31. Voloshina, A., Panchenko, A., Titova, O., Panchenko, I. (2021). Changes in the dynamics of the output characteristics of mechatronic systems with planetary hydraulic motors. Journal of Physics: Conference Series, 1741 (1), 012045. doi: https://doi.org/10.1088/1742-6596/1741/1/012045
32. Andrenko, P., Hrechka, I., Khovanskyi, S., Rogovyi, A., Svynarenko, M. (2021). Improving the Technical Level of Hydraulic Machines, Hydraulic Units and Hydraulic Devices using a Definitive Assessment Criterion at the Design Stage. Journal of Mechanical Engineering, 18 (3), 57–76. doi: https://doi.org/10.24191/jmeche.v18i3.15414
33. Syomin, D., Rogovyi, A. (2012). Features of a Working Process and Characteristics of Irrotational Centrifugal Pumps. Procedia Engineering, 39, 231–237. doi: https://doi.org/10.1016/j.proeng.2012.07.029
34. Sokolov, V., Porkuian, O., Krol, O., Stepanova, O. (2021). Design Calculation of Automatic Rotary Motion Electrohydraulic Drive for Technological Equipment. Advances in Design, Simulation and Manufacturing IV, 133–142. doi: https://doi.org/10.1007/978-3-030-77719-7_14
35. Panchenko, A., Voloshina, A., Luzan, P., Panchenko, I., Volkov, S. (2021). Kinematics of motion of rotors of an orbital hydraulic machine. IOP Conference Series: Materials Science and Engineering, 1021 (1), 012045. doi: https://doi.org/10.1088/1757-899x/1021/1/012045
36. Takeuchi, J., Satake, S., Morley, N. B., Kunugi, T., Yokomine, T., Abdou, M. A. (2008). Experimental study of MHD effects on turbulent flow of Flibe simulant fluid in circular pipe. Fusion Engineering and Design, 83 (7-9), 1082–1086. doi: https://doi.org/10.1016/j.fusengdes.2008.08.050