The study on the magnetic separation efficiency of the reverse water technological liquids from scales in industrial production. Part 2. Improving the design efficiency of magnetic separators by determining the cleaning modes’ rational parameters

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Abstract. The causes and modes of stable and reliable functioning of magnetic separators based on the developed mathematical theory of magnetic deposition process for ferromagnetic particles on the surface of magnetic rods in an aqueous suspension stream are revealed. The limiting thicknesses of the ferro-sludge layers deposited on the surface of the magnetic system, the threshold flow rates of aqueous technological fluids, the criterion conditions for the ferroparticles deposition and the zone of the working region responsible for the magnetic coagulation process in magnetic separators are determined. The correct method for assessing the stability of the cleaning characteristics of the magnetic separators with a scatter of the ferroparticles’ initial parameters, the permanent magnets and dynamic viscosity of the process fluid has been depicted.

Introduction
During the reverse water purification from ferro-impurities systems operation, the rational modes and the stability of their functioning are important. Therefore, when creating magnetic separators, it is necessary to take into account the gradual accumulation of a ferro-sludge layer on the magnetic rods’ surface, which negatively affects the purification efficiency characteristics. This layer, on the one hand, reduces the intensity of magnetic forces in the separation working area, and, on the other hand, leads to the cross section narrowing of the flow passing between the opposite magnetic rods and an increase in the transfer speed of the WPL. Therefore, after a certain time interval, the ferro-sludge should be removed from the clearance (Figure 1).

In this regard, it is important to determine the numerical and analytical criteria allowing to correctly assess the influence factor of the surface layer for ferro-sludge on the magnetic separator cleaning quality.

First, the mathematical modeling problem of the distribution characteristics for the magnetic field intensity was solved for different thicknesses of the ferro-sludge surface layer [1]. The results of numerical simulation are presented in the form of a characteristics’ graphic class in Figure 2.

It is important to mention that in the iron ores magnetic concentration researches [2], an exponential law for the decrease in the intensity of the magnetic field when moving away from the...
magnetic field sources in the absence of a ferro-sludge layer on the magnetic system surface was established. The dependencies presented in Figure 2, confirmed the exponential law of a decrease in the magnetic field strength in the presence of a ferromagnetic deposit on the magnetic system surface for the magnetic separators.

**Figure 1.** The shape and structure of the sediment on the magnetic rods’ surface of the magnetic system when it is removed

**Figure 2.** The results of the distribution numerical simulation in the radial direction from the magnetic field magnetic rod axis: a - for different thicknesses of the surface sediment of the ferro-sludge $d_{sl} = (1$ - 0 mm, 2 - 2 mm, 3 - 4 mm, 4 - 8 mm, 5 - 12 mm, 6 - 16 mm, 7 - 20 mm); b - the maximum field strength dependence on $d_{sl}$

The characteristic class on Figure 2a is convenient to represent in the class of exponential functions for two reasons. Firstly, because the exponent corresponds to a physically realizable expression, then we have:

$$\bar{H}(r, d_{sl}) = \bar{H}_m(d_{sl}) 10^{-\alpha_1(r-r_2)} = \bar{H}_m(d_{sl}) e^{-\alpha_1(r-r_2) \ln 10},$$  \hspace{1cm} (1)

where $\alpha_1$ is the coefficient characterizing the dependences slope $\bar{H}(r, d_{sl})$ on Figure 2a.
Secondly, the exponential functions are the solutions of a linear differential equation with constant first-order coefficients, which integral curves can be combined with the graphic class [3], then we have:

\[ d\bar{H}_r(dr)^{-1} + (\alpha_1 \ln 10)\bar{H} = 0. \]  

(2)

It is known from the theory of differential equations that each integral curve corresponds to one initial condition, therefore, in (1) the values of the magnetic field strength on the magnetic rod surface with ferro sludge will be equal to \( \bar{H}(r - r_2 = 0) = \bar{H}_m(d_{sl}) \), which are presented in Figure 2, b with square marks. In the same figure, the solid line shows a graph of the approximated dependence modeling the “initial conditions” of a given class of dependencies for different values of \( d_{sl} \):

\[ \bar{H}_m(d_{sl})(\bar{H}_{m0})^{-1} = q_2 \cdot d_{sl} + q_1 + q_3 \cdot e^{-q_4 d_{sl}}, \]  

(3)

where \( q_1, q_2, q_3, q_4 \) - are the approximation coefficients, which are determined by numerical and graphical dependencies.

The obtained model of the magnetic field intensity distribution (3) was used for mathematical modeling of the purification degree characteristics obtained in the numerical-graphic class \( \varepsilon(d, d_{sl}) \) form.

However, the criterion conditions and threshold characteristics for WPL purification from the ferro-particles can be determined from the analytical solution of differential equations’ system for the ferro-particles motion under the magnetic field forces action in the WPL flow. This problem was solved within the framework of the approximation for strongly diluted (low concentrated) suspensions, when the distances between the ferro-particles in the aqueous suspension are much larger than the sizes of the ferro-particles, therefore, any interaction forces between the particles in an external gradient magnetic field can be neglected. This simplification corresponds to real levels of reverse water pollution in various industries (Table. 1).

Table 1 presents the comparison between the average statistical distances of the particles \( \bar{l} \) with their average sizes \( \bar{d} \) at different working mass concentrations of ferro-particles \( C_1 \) in an aqueous suspension, kg / m³: as it seems, \( \bar{d}/\bar{l} \ll 1 \) - the interaction of particles is neglected.

| Parameters                  | Circulating lubricating and cooling fluids | Circulating WPL of gas cleaning systems | Circulating WPL of mining and processing plants | Circulating WPL of rolling mill systems |
|-----------------------------|------------------------------------------|----------------------------------------|------------------------------------------------|----------------------------------------|
| \( C_1, \ g/l \)            | < (1 - 2)                                | < 10                                   | < 10                                           | 0.1 - 0.2                              |
| \( d_1, \ \mu m \)          | 1 - 1000                                 | 0.3 - 1                                | 50 - 1000                                      | 0.1 - 2                                |
| \( d/l \)                   | <0.06                                    | <0.13                                  | <0.13                                          | <0.03                                  |

If there is an absence of interaction between the particles, the motion of each can be considered as a single particle motion.

The differential equation system describing the movement of ferro-particles contains two nonlinearities:

\[
\begin{align*}
\mathbf{v} &= \mathbf{v}_m + \mathbf{v}_{liq}; \\
\mathbf{r} &= \mathbf{r}(0) + \mathbf{r}_m + \mathbf{r}_{liq} \\
\frac{d\mathbf{r}_m}{dt} &= \mathbf{v}_m; \\
\frac{d^2\mathbf{r}_m}{dt^2} + K_c \frac{dr_m}{dt} &= f_{mr},
\end{align*}
\]  

(4)
where \( v_m, r_m \) – determine the relative speed and movement; \( v_{liq}, r_{liq} \) – denote the wearable speed and movement; \( r(0) \) is the initial radial coordinate; \( f_m(r) = 0.5 \mu_0 \nu V_f \chi_f \nabla(H^2) \), – is the gradient magnetic force; \( V_f \) is the ferro-particle volume; \( \chi_f \) is the magnetic susceptibility (which is smaller than 50 \( \mu m \) for ferro-particles) depends not only on the field strength \( H \) (for \( H < H_s \) – saturation intensity), but also on the particle size: \( \chi_f = \kappa_f(d)H \) [2]. In (1) \( m = m_f + m_{liq} \) the resulting mass, consisting of the particle mass and the attached mass of the liquid, kg; \( K_{cz} = 3 \pi \eta d \) is the proportionality coefficient in the Stokes formula, kg \( \cdot \) \( s^{-1} \) (at Reynolds numbers \( Re < 3 \)); \( \eta \) is the dynamic viscosity coefficient of a liquid medium.

The analytical solution of system (4) can only be determined approximately. In this case, the nonlinearity of the right-hand side of the differential equation system dynamics (4) is eliminated by a piecewise linear approximation of the force, then the dependence (1) is replaced by the following linear dependence

\[
f_{mk} = f_k - \alpha_{ok} r,
\]

where \( f_k \) and \( \alpha_{ok} \) are the approximation constants at \( k = 1, 2 \), characterizing the force effect on the ferro-particle, which significantly decrease with increasing thickness of the ferro-sludge layer \( d_{sf} \) as follows:

\[
f_k = K_k(a)\alpha_{ok}, \quad \alpha_{ok} = K_{ok}(a)\mu_0 a_1 \kappa_f V_f H_n^3(d_{sf}).
\]

In (6) the proportionality coefficients \( K_k(a), K_{ok}(a) \) depend on the distance \( a \) between the magnetic separator field sources’ axis, \( \mu_0 \) is the magnetic constant.

Based on a linear approximation, we divide the working separation area into the area of a weak field and the area of a strong field (according to Figure 3, a).

To overcome the metric nonlinearity in the differential equation system (4)

\[
r = \left[ (x(0) - r_{mx} - \bar{v}_{liq} t)^2 + (y(0) - r_{my})^2 \right]^{0.5},
\]

where \( \bar{v}_{liq} \) is the average flow rate, we transform the differential equation system (4) into a new system represented in the polar coordinate system with independent variables \( r, \varphi \), [4]:

\[
\begin{align*}
\frac{m}{d} \frac{d v_m}{dt} + K_{c1} v_m - \alpha_{ok} r &= -f_k; \\
\frac{d r}{dt} &= -v_m - \bar{v}_{liq} \cos \varphi; \\
r \frac{d \varphi}{dt} &= \bar{v}_{liq} \sin \varphi.
\end{align*}
\]

**Figure 3.** Piecewise-linear approximation of the magnetic force (a), dependence of the approximation error in the area of a strong field when moving away from the axis of the magnetic rod symmetry (b)
In the system (8), nonlinearity is concentrated in the third equation. The variation range of the variable $r$ is limited by the design factor $(r_{\text{min}}/r_{\text{max}}) \geq 0.7$, therefore, in this equation, the variable $r$ is replaced by the average value $\bar{r}$, i.e. the equation parameter. As a result, the system (8) is reduced to an ordinary linear differential equation with the constant coefficients:

$$m \frac{d^2r_m}{dt^2} + K_{c1} \frac{dr_m}{dt} - \alpha_{0k} r_m = -f_k - f_{eq}(t), \quad (9)$$

but with an additional heterogeneous part $f_{eq}(t)$, which is a time function,

$$f_{eq}(t) = \alpha_{0k} \bar{r} \{\beta + \alpha \text{sign}(\varphi - 90^\circ) \left[ ct \varphi_0 e^{-v_{\text{liqr}}(\varphi)t} - t g\varphi_0 e^{-v_{\text{liqr}}(\varphi t)^{-1}} \right] \}, \quad (10)$$

playing the role of an additional equivalent force, which takes into account the nonlinear effect contained in the expression (7). This becomes possible due to the differential equation system’s transformation into a form in which the metric nonlinearity (7), which directly affects the ferro-particle dynamics through the Newton equation in the system (4), is transformed into the parametric nonlinearity of the kinematic equation - the third equation in the system (8).

By the nature of the change in force $f_{eq}(t)$, the separator working area is conditionally divided into three characteristic zones with different dynamics of the ferro-particles’ movement (Table 2).

In the first zone, all forces and direction of flow coincide, the flight time of this zone is the smallest, the conditions are favorable for the particles’ deposition with a small entrance angle $\varphi_0$. In the second zone, the intensity of the additional force decreases with increasing angular coordinate $\varphi_0$. The trajectories can be saddle-shaped, the flight time within the zone slows down by two to three times. In the third zone, the additional force becomes negative (counteracting); the trajectories may be saddle-shaped, but some particles, having dispersed in the previous zones, are deposited on the magnetic system. The particles not deposited on the magnetic rod are discharged from the separation section in this zone.

Table 2. Three zones of ferro-particles’ interaction with an external magnetic field in a water stream.

| $\varphi_0 \leq \varphi(t) \leq 90^\circ$ | $90^\circ < \varphi(t) \leq 180^\circ - \varphi_0$ | $\varphi(t) > 180^\circ - \varphi_0$ |
|--------------------------------------|-----------------------------------------------|-----------------------------------|
| $f_{eq1,2}(t) > 0$ accelerates       | $f_{eq1,2}(t) > 0$ accelerates                 | $f_{eq1,2}(t) < 0$ counteracts     |
| $v_r = - v_m - v_{\text{liqr}}(\varphi)$ | $v_r = - v_m + v_{\text{liqr}}(\varphi)$    | $v_r = - v_m + v_{\text{liqr}}(\varphi)$ |
| The zone of absolute acceleration to the magnet | The zone of portable reaction to the magnet | The zone of portable and additional reaction |

The second zone is favorable for the interaction of moving the ferro-particles under the action of external magnetic forces. A more massive ferro-particle, which is affected by a greater force, accelerates in the water stream to higher speeds than a smaller one. Therefore, in the process of movement, a larger ferro-particle catches up with a smaller one, and they stick together under the action of dipole - dipole forces, and, moreover, the combinations can be repeated. A larger particle is more likely to settle on the magnetic system and therefore it is characterized by a large value of the purification degree.

The process of combining the ferro-particles into larger aggregates under the influence of a magnetic field is called magnetic coagulation or magnetic flocculation. During magnetic coagulation, the ferro-particles aggregate into chain or filamentous structures oriented along the magnetic lines of force. During magnetic flocculation, the ferro-particles aggregate into flocs, which are the spherical-shaped formations, also oriented along the magnetic lines (Figure 1.).

The coagulation process under certain conditions is always present in magnetic separators, however, the task of determining the change in the dispersed composition of ferro-particles in suspensions due to the phenomenon of magnetic coagulation has not yet been solved. Therefore, there
were no methods for magnetic coagulation accounting in the magnetic separators design. Moreover, the experimental data demonstrate that the magnetic coagulation is not always present, there are threshold concentrations of ferromagnetic suspensions at which it appears. Such features of the magnetic coagulation manifestation do not allow establishing its influence empirically. Therefore, the urgent task of constructing the magnetic coagulation mathematical model is actualized. The solution to the problem will be presented in the third article of the cycle.

The linear differential equation (DE) (9) - (10), has an analytical solution, on the basis of which the criteria for the possibility of deposition or breakthrough of a specific size ferro-particle are determined. For example, in the following expression:

\[ \bar{v}_m \bar{v}_{lq}^{-1} = v_k \left[ f_k (\alpha_{ok} \bar{r})^{-1} - 1 \right], \]

where \( \bar{v}_m \) is the average speed of the ferro-particle in the separator, \( \bar{v}_{lq} \) is the average flow rate, \( v_k \) is the generalized parameter that increases with increasing the ferro-particle size \( d \). The ratio \( f_k / \alpha_{ok} \bar{r} \) characterizes the geometric factor. If \( v_k < 1 \), then the precipitation is impossible, if \( v_k \geq 1 \), then the additional criteria for the ferro-particle precipitation are required. For example, in Fig. 4 the additional criteria are presented in the form of a class characteristics, where \( B_k (t_{01}) \) is a generalized parameter that characterizes the force impact at a point in time; \( t_{01} \) – is the time the ferro-particle reaches the critical boundary between the second and third zones:

\[ t_{01} = 2\bar{r} \bar{v}_{lq}^{-1} \ln(\text{ctg}0,5\varphi_n). \]

From the dependencies in Figure 4 it follows that the closer the ferro-particle, which has not settled on the magnetic rod, is located to the magnetic rod, (lower value \( \varphi_n \)), the more chances it has for getting on the magnetic rod at the exit from the second zone, since \( B_k (t_{01}) \) can vary from 0.1 to 2.5.

**Figure 4.** The criteria for the deposition or non-deposition of ferro-particles:

- \( B_k (t_{01}) < B_{kpr} \) – deposition is not possible;
- \( B_{kpr} < B_k (t_{01}) < B_{kab} \) – additional studies are required;
- \( B_k (t_{01}) > B_{kab} \) – deposition guaranteed

An analytical solution for the equations’ system of the ferro-particle trajectory (4) allows constructing an exponential model of a dependences’ class for the purification degree of one separation stage with the following form:

\[ \varepsilon(d, d_{st}, a) = 1 - e^{-h(d_{st}, a)d}; \quad h(d_{st}, a) = B_0(a) e^{-\gamma(a)d_{st}} + B_1(a)d_{st}, \]

where \( B_0(a), B_1(a), \gamma(a) \) are the constant coefficients, which parametrically depend on the cell size \( a \) of the magnetic separator’s magnetic rods, which are established on the basis of the obtained criteria for the ferro-particles deposition.
The numerical-analytical criterion characterizing the maximum permissible level of ferro-sludge accumulation on the magnetic rods’ surface of the magnetic system is related to the accumulation rate for ferro-particles sediment. On the first row magnetic rods, the sludge thickness is the largest, and the rate by mass of the ferro-particles precipitation in the unit volume taking into account (13) at a given speed \( Q G_i \) and the mass of ferromagnetic impurities in the WPL at the input of the first row, where \( Q \) is the separator capacity, \( m^3/s \), is described by the formula:

\[
m_{i1} = Q G_i \tilde{e}_1 \approx Q G_i (1 - e^{-h_1 \tilde{a}_1}).
\]

(14)

and for the \( k \)-series magnetic rods it is described by the formula:

\[
m_{ik} = Q G_i (\tilde{e}_{k-1} - \tilde{e}_k) = Q G_i (1 - e^{-h_k \tilde{a}_1}) e^{-\tilde{a}_1(\sum_{k=1}^{k-1} h_k)}.
\]

(15)

It follows from (15) that there exists a limiting value of the ferro-particles precipitate thickness \( d_{slp} \), at which the deposition rate drops steeply and a high-quality separation process is impossible (dependence \( m_{i1}[h(d_{slp})] \) in Figure 5, confirmed by the experimental studies). To determine \( d_{slp} \), the following conditions are sufficient:

\[
m_{i1}[h(d_{slp})] = 3^{-1}(2m_{i1}[h(0)]).
\]

(16)

where the function \( h(d_{slp}) \) corresponds to the formula (13)

**Figure 5.** The dependence of the sediment accumulation speed for ferromagnetic particles on the magnetic rod

The developed analytical model of the ferro-particles’ trajectories was the source of the disclosed theoretical concepts (zone concepts of the separator working area, criteria for the deposition or ferro-particles’ breakthrough, the criterion of the maximum possible magnetic separator performance) and the mathematical model basis of the characteristics’ class for the separator purification degree.

The approximate mathematical modeling procedures are a source of errors. When analyzing the error, two main sources of errors were taken into account - a systematic one, due to the modeling error and random, due to the errors of the initial parameters: magnetic properties of ferro-particles, permanent magnets and dynamic viscosity of WPL, which vary according to the random laws.

Modelling errors are due to two approximations. The first approximation is associated with the replacement of an exponentially varying magnetic force (1) by its piecewise linear approximation (5). The deviation of force takes the following form:

\[
\Delta f_{mk}(r) = f_{ok} - \alpha_{0k} r - f_{mr}(r), \quad (k = 1, 2).
\]

(17)

The deviation \( \Delta f_{mk}(r) \) is represented in two components: the first \( \Delta f_{m1}(r) \) in the strong field between the two dependences of the magnetic force (Fig. 3) and approximated by the following expression:
Dependence (18) is presented in Figure 3b (continuous curve). The second component seems to be the maximum error Δf_{m2}(0.5α), due to the zero approximation of the field intensity at the separator’s input:

\[ Δf_{m2}(0.5α) = f_{m0} 10^{-3}α(0.5α−R). \]  \hspace{1cm} (19)

The second approximation is due to averaging the kinematic differential equation of the system (8) over the radial variable \( r \) and the integral approximation of obtained by the joint integration of the second and third differential equation of the system (8):

\[ \Delta r_{liq} = \bar{v}_{liq} \int_{\varphi_n}^{\varphi} \cos \varphi \left( \frac{d}{d\varphi} \right) d \varphi = \bar{r} \int_{\varphi_n}^{\varphi} \cot g \varphi d \varphi = \bar{r} \sigma(\varphi), \]  \hspace{1cm} (20)

where \( \sigma(\varphi) = \ln \sin \varphi \cdot \sin^{-1} \varphi_n \), which is approximated by the following function:

\[ \sigma(\varphi) \approx \beta + 2\alpha \cdot \text{sign}(\varphi - 90°) \cot g \varphi. \]  \hspace{1cm} (21)

Expression (20) forms the general solution of the differential equation system (8) in the form

\[ r = r(0) - \Delta r_m - \Delta r_{liq}. \]  \hspace{1cm} (22)

where \( r(0) \) is the initial coordinate of the ferro-particle; \( \Delta r_m \) is the relative displacement due to magnetic force; \( \Delta r_{liq} \) is the portable movement due to the WPL flow. The deviation of the ferro-particle portable shift value \( \delta r_{liq} = \Delta r_{liq}^* - \Delta r_{liq} \) from the true value \( \Delta r_{liq}^* \), which is the integral of the second differential equation (DE) system (8):

\[ \Delta r_{liq}^* = \int_{\varphi_n}^{\varphi} r \cot g \varphi d \varphi. \]  \hspace{1cm} (23)

The resulting deviation is:

\[ \delta r = r^* - r = \delta r_m - \delta r_{liq}, \]  \hspace{1cm} (24)

where the ferro-particle relative displacement deviation \( \delta r_m = r_m^* - r_m \) is determined from the differential equation:

\[ d^2 \delta r_m (dt^2)^{-1} + K_c m^{-1} \cdot d\delta r_m \cdot (dt)^{-1} = \Delta f_{mk}(r) \cdot m^{-1}, \]  \hspace{1cm} (25)

obtained from the difference of dynamic differential equations’ systems (1) and (8), respectively.

The expressions (17) - (25) estimate the error in modelling the purification degree \( \Delta e(d_f) = e(d_f) - e(d_f^*) \), where \( e(d_f^*) \) is the degree of purification corrected for the systematic error are used. An example of calculating the error \( \Delta e(d_f) \) is presented in Figure 6.

The errors in the initial parameters of the ferro-particles magnetic properties, permanent magnets, and the dynamic viscosity of WPL affect only the relative motion of the ferro-particles (they do not affect the portable motion), therefore, we determine the relative velocity \( \Delta v_m \) deviation from the differential equation (26):
Fig 6. The characteristics of the purification degree: 1 - modelled dependence $\varepsilon(d_f)$; 2 - adjusted dependence $\varepsilon(d_f^*)$

$$md\Delta v_m \cdot (dt)^{-1} + K_n\Delta v_m = -\Delta F_p.$$ (26)

On the right-hand side of (26), $\Delta F_p$ is the deviation from the original control, in which the total error of the force is determined by the rule of summing the component errors, considered as independent random variables (27):

$$\Delta F_p = \pm \left| v_m \frac{\partial K_n}{\partial \eta} \Delta \eta \right| \pm \left| v_m \frac{\partial \Delta \rho}{\partial \alpha} \Delta \alpha \right| \pm \left[ \left( \frac{\partial f_{m0}}{\partial \eta} \right)^2 (\Delta \eta)^2 + \left( \frac{\partial f_{m0}}{\partial \alpha} \right)^2 (\Delta \alpha)^2 + \left( \frac{\partial f_{m0}}{\partial \rho} \right)^2 (\Delta \rho)^2 + \left( \frac{\partial f_{m0}}{\partial \zeta} \right)^2 (\Delta \zeta)^2 \right]^{0.5}$$ (27)

where $V_f$ is the volume of the ferro-particle, $m^3$; $\rho_f$ is mass density of the ferro-particle, $kg/m^3$; $\chi_{m0}$ is a maximum value of the magnetic susceptibility of the ferro-particle material.

For example, we restrict ourselves to the following values of the relative errors (28):

$$\Delta \eta^{-1} = \Delta \rho_f \rho_f^{-1} = \Delta \alpha_1 \alpha_1^{-1} = \Delta \chi_{m0} \chi_{m0}^{-1} = \Delta \zeta \zeta^{-1} = \pm 0.1.$$ (28)

Figure 7 shows the boundaries of the purification degree caused by the $\pm$ 10% scatter of the parameters of the initial ferro-particles, permanent magnets, and the dynamic viscosity of the WPL, on which $\varepsilon(d_f^{-\Delta})$ corresponds to a negative 10% scatter of all parameters; $\varepsilon(d_f^+\Delta)$ - corresponds to a positive 10% spread of all parameters.

Fig 7. The boundaries of the purification degree due to ten percent scatter of the initial parameters for WPL ferro-cleaning magnetic system:

$$1 - \varepsilon(d_f^{-\Delta}); 2 - \varepsilon(d_f^{+\Delta}); 3 - \varepsilon(d_f)$$

Note that Fig. 6 and Fig. 7 show the most important sections of the purification characteristics degree that are responsible for the high levels of purification that are no worse than $C_0/C_I \leq 0.1$ ($\varepsilon \geq 0.9$).
Thus, the proposed methods’ system for modelling and calculating the magnetic separators provides high accuracy in constructing the cleaning quality characteristics (with an error of no more than 2.5% at high levels of purification ($C_o \cdot C_i^{-1} \leq 0.1$).

This technique allows evaluating the purification degree stability $\varepsilon(d_f)$ when exposed to the variations in the initial data parameters (magnetic parameters of ferro-particles, magnetic field strength, and WPL dynamic viscosity). In particular, at high levels of purification ($C_o \cdot C_i^{-1} \leq 0.1$), when the initial parameters are spread by 10%, the degree of purification is not more than 2.5%.

Summary
1. A mathematical theory of the magnetic deposition process for ferro-magnetic particles in a stream of water suspension corresponding to the parameters of the reversed water for many technological processes of mechanical engineering and ferrous metallurgy, including for rolling mills, based on which we define:
   - maximum thicknesses of the ferro-sludge layer deposited on the surface of the magnetic separators’ system, to which a process of high-quality purification of water process liquids from ferrous impurities is guaranteed;
   - deposition criteria, determined by the threshold flow rates of water process liquids;
   - three zones of ferro-particles’ interaction with an external magnetic field in the working area of magnetic separators, important for assessing the effect of ferrous impurities’ aggregation on the magnetic separation efficiency.

2. The correct method for assessing the cleaning characteristics stability of magnetic separators with a scatter of the initial magnetic parameters of ferro-particles, permanent magnets and dynamic viscosity of the process liquid has been presented.

3. The developed mathematical theory of the magnetic deposition process of ferro-magnetic particles made it possible to reveal the causes and modes of stable and reliable operation of the magnetic separators, which improve the quality of wastewater magnetic treatment from ferro-magnetic impurities.

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