The study on the magnetic separation efficiency of the reverse water technological liquids from scales in industrial production. Part 1. The problems’ analysis and solutions

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Abstract. The causes leading to the technological equipment contamination of for rolling mills and consequently the environment are analyzed. The prospects of using the magnetic separators are substantiated. In order to reduce water consumption to a minimum by rolling production and to reduce the emissions of scale with oil products on its surface into a water body by ten times, high-quality treatment of reversed water by permanent magnet separators with a fineness of 1–2 μm is required. The mathematical modeling methods of the quality characteristics separation for monodisperse and polydisperse aqueous ferromagnetic suspensions are considered. It is shown that the required refinement can be achieved in multi-row magnetic separators.

Introduction
Rolling like any industrial production is accompanied with a large water consumption. The increasing shortage of water resources, the need to improve the environmental friendliness of industrial production and the high costs for the consumed water resources are observed [1]. In connection with the foregoing, a transition to the reverse water supply instead of the running water supply was made in the second half of the last century at the metallurgical industries. The used cleaning agents (filters, sedimentation tanks) did not provide the high-quality water purification from the fine particles of scale (0.1 - 2 μm), which led to their accumulation in reversed water. In the studies conducted by the authors in the conditions of the current production, it was found that the ferro-particles concentration in the water of the circulating systems reaches 5000 mg / dm$^3$. At the same time, up to 10 - 15% (of the scale mass) of the oils entering the water from the mill lubrication systems are adsorbed on the ferro-particles’ surface. Part of the scale precipitates in the tanks of the circulating systems, a significant part settles on the metal structures of the rolling mills, including the forming rolls of the rolling mills. The accumulation of scale on the forming rolls leads to a deterioration in the conditions of their interaction with the rolled strip. Accordingly, the quality of the strip is deteriorating. On the strip’s surface, the structural defects (“ripples”, etc.) are manifested [2]. The rolled strip’s welding with the forming roll and its impulse occurs often. The accidents’ elimination causes a decrease in the rolled steel production. With the periodic discharge of water effluents from the circulating systems of the rolling mill, the scale could not escape into the environment. For example, at the bottom of the Sheksninskoye reservoir, so many ferromagnetic scale deposits of have been accumulated over the years, that it can be mined as a raw material.
To drastically reduce the wastewater discharges volume, it is necessary to bring the reverse water treatment system’s quality to a new level. Magnetic rod magnetic separators were experimentally created earlier, which provided on the one hand, greater productivity (up to 100 m$^3$/h per 1 m$^2$ of separator area), and on the other hand, satisfactory quality of treated water [3]. The cleaning efficiency determined by the purification degree (the relative proportion of scale removed during cleaning) reached 85 - 90%. However, the high cost of magnetic systems (with permanent magnets) made their wide distribution difficult. Therefore, there is an actual mass optimization task of permanent magnets and of the magnetic separators’ cost while ensuring a given degree of purification.

The purpose of this research is to reduce water consumption to a minimum by rolling mills, up to one or two intakes to compensate for losses in 2 to 3 years, provided that it is cleaned with magnetic separators, to reduce the emissions into the water body of scale with oil products on its surface by ten times, the unit cost per unit volume of purified water and rolled products.

To achieve this goal, it is necessary to develop magnetic separators (MPS) that provide fineness of cleaning $d_{50} = 1-2 \mu$m (median particle size separated during cleaning at $e = 0.5$, GOST R ISO 21501-4-2012).

The development of magnetic system (MPS) rational constructions required the process optimization of ferromagnetic particles removal from the water process liquid (WPL).

At the initial stage of the simulation, the motion of a single particle in the magnetic field was considered. Since the degree of purification $e$ is an integral characteristic, and it is strictly mathematically possible to describe only the trajectory of a single particle of a given size $d$ under the influence of the forces on it in the cleaning zone, it is possible to numerically determine the value of $e$ by calculating the trajectory of the particle in the working space of the separator magnetic system.

The particle’s trajectory is the locus of the points through which the particles pass sequentially. Each point is characterized by the geometric coordinates $x, y, z$. When during the movement the coordinates take the values corresponding to the magnetic rod surface, this means that the particle is attracted to its surface and removed from the WPL. In this case, the degree of purification is 1, otherwise it is 0.

Sequentially, placing the MPS beginning at the cross-sectional points within a certain distance from the plane of magnetic rods’ placement, and each time determining the value of $e$ for the given point, it is possible to estimate the value of $e$ from the given size particles for the MPS as a whole.

By sequentially changing the particle size and performing the calculation, it is possible to obtain the locus - the main technical characteristic for any separator, including the magnetic one (Fig. 1). On the $e (d)$ curve there is a point with coordinates $e = 0.5$ and $d_{50}$ - a fineness characteristic of separator cleaning when separating a set of polydisperse single particles belonging to ferromagnetic impurities.

The characteristic $e (d)$ depends on many factors $e (d, v_{liqn}, a, R, d_{sl})$, where $v_{liqn}$ is the input speed of the WPL (m/s); $a$ is the characteristic size of the magnetic system — the distance between the axis of the magnetic rods (m); $R$ is the characteristic size of the permanent magnet, the magnetic rod’s radius (m); $d_{sl}$ – is the ferro-sludge sediment layer’s thickness on the surface of the magnetic rod (mm).
The general task for the magnetic separation characteristics’ mathematical modeling is divided into three stages: modeling of the class dependences $\varepsilon(d)$ of one separation stage for a single ferro-particle; modeling of the class dependences $\bar{\varepsilon}(\bar{d}_{\text{in}})$ - for the average degree of purification of one separation stage with a polydisperse distribution of ferrous impurities in WPL, which is integrally related to the degree of purification $\varepsilon(d)$:

$$\bar{\varepsilon}(\bar{d}_{\text{in}}) = \int_0^\infty \varepsilon(d_f) f_i(d_f) d(d_f),$$

and matches the expression

$$\bar{\varepsilon} = (C_i - C_o)(C_i)^{-1},$$

where $d = d_f$ is the size of the ferro-particle (microns); $\bar{d}_i$ is the average size of the distribution for the dispersed composition of the ferro-particles entering the separator inlet ($\mu$m); $f_i(d_f)$ is the mass density probability, density distribution of the initial polydisperse ferromagnetic impurities ($m^{-1}$); $C_i$ and $C_o$ are the average mass concentrations of impurity particles in the WPL, respectively, at the inlet and outlet of the separator ($g/l$).

At the third stage, mathematical modeling of the class dependences $\bar{\varepsilon}(\bar{d}_{\text{in}})$ of a multi-row separation system is carried out with a polydisperse distribution of ferromagnetic impurities in the WPL. Moreover, the characteristic $\varepsilon(d)$ is basic, its graph is displayed by the non-periodic curve (Fig. 1).

Using the software package of Mentor Graphics - FloEFD, a research of the nature of the flow around a grid of cylindrical magnetic rods has been made (Figure 2).

To determine the quantitative dependences of the purification degree on the WPL flow rate, the value of which varies in different sections of the separator, it is necessary to construct the mathematical model of the $\nu_{\text{liq}}$ flow rates of the WPL stream. At the same time, we use the resulting picture of the cylindrical magnetic rods flow around an aqueous process fluid. There are no vortices of streamlines in the WPL transfer sites: $\text{rot } \nu_{\text{liq}} = 0, \nu_{\text{liq}} = \text{grad } u$, where $u$ is the potential of the flow velocities, therefore, the fluid motion transfer potential theory can be applicable.
Due to the similarity of the flow patterns around the frontal sections of the cylinders with water flow surface, Fig. 2 and Fig. 3 (laminar flow), the mathematical model of an ideal liquid flow past a single cylinder in the polar coordinate system is taken and the procedure for correcting streamlines with imposing system conditions is applied.

The mathematical model described streamlines with an ideal liquid on a single cylinder in Fig. 3 is given [4]:

\[
v_{liq r} = v_{liq n} \cos \varphi (1 - R^2 \cdot r^{-2}); \quad v_{liq \varphi} = v_{liq n} \sin \varphi (1 + R^2 \cdot r^{-2}).
\]  

(3)

To describe the picture of the liquid flow around the frontal section of magnetic rods, we substitute the correcting variables \( k_1 \) and \( k_2 \) in (3) as follows:

\[
v_{liq r} = k_1 v_{liq n} \cos \varphi (1 - R^2 \cdot r^{-2}); \quad v_{liq \varphi} = k_2 v_{liq n} \sin \varphi (1 + R^2 \cdot r^{-2}).
\]  

(4)

1. By imposing a continuity condition for the flow \( Q_r(\varphi) = Q_\infty \equiv 0.5(\alpha v_{liq n} l) \), where \( Q_r(\varphi) \) — determines the surface flow \( \Omega_\alpha \), we get:

\[
k_2 = [1 - k^2(\sin \varphi)^2]^{-1},
\]  

where \( k = 2Ra^{-1} \).

2. From the flow velocity potentiality condition in the left side of the magnetic rods’ first row:

\[
v_{liq \varphi} = -\partial u(\varphi \partial r)^{-1}; \quad v_{liq r} = \partial u(\partial r)^{-1},
\]

we get:

\[
k_1 = -(k\sqrt{1-k^2} \cos \varphi)^{-1} \arctan[(k \cos \varphi) (1 - k^2)^{-0.5}].
\]  

(6)

For monodispersed ferromagnetic impurities

The characteristic of the purification degree for one separation stage, consisting of many parallel separation elements, is formed in each magnetically active separation element (Fig. 2). The purification degree is expressed in terms of the critical value \( \varphi_n = \varphi_n(d) \) of ferro-particle entry angle of size \( d \) into the separation element at which the particle will be at the boundary of two states (ingress a magnet or breakthrough a magnet):

– for the first stage:

\[
\varepsilon_1(d) = \sin \varphi_n(d);
\]  

(7)

– for the subsequent stages, the entire flow is concentrated in a rectangular progressive jet with an average speed \( \bar{v}_{liq} \), height \( a = 2R \), width - \( l \):

\[
\varepsilon_2(d) = [\sin \varphi_n(d) - k](1 - k)^{-1}.
\]  

(8)
The critical values of $q_n$ correspond to the ferro-particles’ trajectories, closed at the output sections of the magnetic rods. In Fig. 4, in relative values $\lambda(\tau)$, the results of numerical modeling of these sections of the trajectories for a single-row magnetic separator are presented, where $\lambda$ is the removal of the ferro-particle from the cylindrical magnetic rod axis, $\tau$ is the relative time interval. The small particles are carried away by the flow. The larger particles move along the saddle-shaped trajectories. The criterion for extracting a ferro-particle from WPL is the condition $|\lambda| \geq |\lambda_{gr}|$, where the parameter $\lambda_{gr}$ is proportional to the magnetic rod surface radius.

According to the program of numerical simulation for the ferro-particles’ trajectories for each value of the ferro-particle size $d$, the critical angle $q_n(d)$ of its entry into the separator is determined, all of which form the characteristics (5) and (6) determining the purification degree of the separators for monodisperse particles. The result of such modeling is a numerical-graphic class of quality characteristics for the purification of aqueous suspensions from ferro-particles (Fig. 5), each of which corresponds to the sediment layer thickness of the ferro-sludge $d_{sl}$ deposited on the surface of the magnetic rod and the inlet velocity $v_{liqn}$ of the WPL flow.

![Figure 4. The paths sections’ class of the ferro-particles at the separator outlet](image)

$\nu_{liqn} = 0.03$ m/s and different sizes of ferro-particles: 1; 2; 3; 4; 5 and 6, respectively, with $d_{sl} = 1; 2; 2.5; 3; 4; 5$ $\mu m$

![Figure 5. Dependence class $c(d)$ for one row of the magnetic separator:](image)

1, 2, 3, 4 and respectively with $d_{sl} = 0; 1; 2; 3.3$ mm

The developed modeling techniques have been tested using the experimental studies. In [3], a “WPL-Vita-S / EO” cleaning unit was described, which was integrated at the “West Siberian Metallurgical Plant” JSC into a production system for cooling coolant during roll grinding. During the tests, the reverse water was purified from the ferro-particles with a size of not more than 20 $\mu m$. The ferro-particles size distribution law is close to normal with the parameters $\bar{d} = 10$ $\mu m$, $\sigma_1 = 3.33$ $\mu m$. The mechanical impurities concentration in the coolant supplied for cleaning is 80 ... 210 mg / dm$^3$. 
The “WPL-Vita-S / EO” cleaning unit provided a capacity of up to 10 m$^3$/h and was a three-stage cleaning system built on the basis of gravitational sedimentation, a flotator and a single-row magnetic rod magnetic separator. The first circuit, consisting of a flotation plant operator and TGO, carried out the preliminary cleaning - from oils and coarse particles. The second circuit, consisting of a magnetic separator, was intended for relatively fine cleaning of the ferro-particles.

Ø32 mm magnetic rods from the relatively cheap ferrite-barium permanent magnets were used in the magnetic separator.

As a result of pilot tests, several types of dependences of the purification average degree $\bar{\varepsilon}(v)$ on the WPL speed $v$ were obtained for different mass initial concentrations of $C_i$ ferro-particles, which are presented in Figure 6. The speed value was selected from the range of 0.001; 0.025; 0.05; 0.1; 0.15; 0.2; 0.25 m/s, the value of $C_i$ and was set from a row of 40; 80; 120; 180; 200 mg / dm$^3$.

During the experimental technical studies, it was found that in the purification mode (flow rate was 0.001 m/s, the initial average concentration of ferro-particles was 40 mg / dm$^3$), there was no magnetic coagulation in the “Vita” unit, that is, the ferro-particles did not interact with each other. For this operation mode of the separator, the values of $\bar{\varepsilon}_k(v_k)$ were calculated according to the method described above.

When calculating the average degree of purification $\bar{\varepsilon}$, the normal logarithmic law of the size distribution of the dispersed composition for the initial ferro-particles was accepted ($\bar{d}_i = 10 \mu m$, $\sigma_i = 3.33 \mu m$). The calculated values $\bar{\varepsilon}_k(v_k)$ were marked by the points on the graph in Figure 7. The solid line corresponds to the experimental dependence (according to Figure 6, curve 5).

The studies have shown that according to the Fisher criterion (with a risk level of not more than 1%), the developed mathematical model of the WPL purification degree is adequate to the experimental data.

Under real conditions, the process of WPL cleaning from polydisperse impurities takes place in successive stages of a multi-row magnetic separator, while the separator changes (converts) the dispersed composition of impurities. When creating magnetic separators, it is necessary to know the characteristics of multi-row separators with a polydisperse distribution of impurities. In Figure 8, a) shows the block diagram of an $N$-line separator, and in Figure 6 b) its resulting equivalent block diagram is given.
From a functional point of view, the separator can be considered as a system to which the input action is applied and from which the response at the output is removed.

According to Figure 8 b), the dispersed phase enters the separator inlet with the initial average mass concentration of ferro-particles \( C_{\text{inp}} = C_i \) and the mass \( M_{\text{inp}} \) at the output we get the purified WPL with the concentration \( C_{\text{out}} = C_0 \) and the mass \( M_{\text{out}} \). By entering the gear ratio

\[
\bar{L}(\bar{d}_{\text{inp}}) = M_{\text{out}}M_{\text{inp}}^{-1} = C_{\text{out}}C_{\text{inp}}^{-1},
\]

it is possible to determine the mass concentration of the impurity deposited in the separator \( C_{\text{st}} \)

\[
C_{\text{st}} = [1 - \bar{L}(\bar{d}_{\text{inp}})]C_{\text{inp}}.
\]

By dividing the distribution of polydisperse impurities into separate fractions by size, it is possible to determine the mass of the fraction in a unit volume supplied to the input of the separator

\[
C_{\text{out}} = C_{\text{inp}}\left[1 - \int_0^\infty \varepsilon(d_f)f_{\text{inp}}(d_f)d(d_f)\right] = [1 - \bar{\varepsilon}(\bar{d}_{\text{inp}})]C_{\text{inp}} = C_{\text{inp}}\bar{L}(\bar{d}_{\text{inp}}),
\]

where \( \bar{\varepsilon}(\bar{d}_{\text{inp}}) \) is the average value of the purification degree of the separator with a polydisperse composition of ferro-particles, determined by dependence (1). Here: \( \bar{d}_{\text{inp}} \) – is the arithmetic value of the ferro-particle’s diameter entering the separator, m; \( f_{\text{inp}}(d_f) \) is distribution function of the dispersed composition of ferro-particles by size at the inlet of the separator, m\(^{-1}\); \( d_f \) – is the effective size of the ferro-particle, m; \( \varepsilon(d_f) \) is the degree of separator purification depending on the diameter of single ferro-particles \( d_f \) in WPL.

From the standpoint of the system theory, the separator converts the spectral composition of ferro-particles, in other words, changes the probability density distribution function by size, which at the output can be expressed by the following formula:

\[
f_{\text{out}}(d_k) = \Delta m_{\text{out}}(\Delta d_k C_{\text{out}})^{-1}.
\]

Expressing \( \Delta m_{\text{out}} \) and \( C_{\text{out}} \) respectively by formulas (11) and (12), and passing to the limit as \( \Delta d_k \to 0 \), we obtain the transformation law of the impurities’ dispersion composition at the outputs of the separator:

\[
f_{\text{out}}(d_f) = \frac{\Delta m_{\text{out}}(\Delta d_k C_{\text{out}})^{-1}}{\Delta d_k C_{\text{out}}} = L(d_f)f_{\text{inp}}(d_f)[\bar{L}(\bar{d}_{\text{inp}})]^{-1},
\]

where

\[
f_{\text{inp}}(d_f) = dm_{\text{inp}}(C_{\text{inp}} dd)\].
Applying the expressions (11) and (12) to (14), we obtain the expression for transforming the ferro-particles dispersed composition distribution at the output of the magnetic separator

\[ f_{\text{out}}(d_f) = \left[1 - \varepsilon(d_f)\right]\left[1 - \bar{\varepsilon}(\bar{d}_{\text{inp}})\right]^{-1} f_{\text{inp}}(d_f). \]  

(15)

Let us consider the separation process in a multi-row separator consisting of \( N \) successive stages (Figure 8, a)), where \( M_k \) is the mass and \( C_k \) is the average mass concentration of ferro-particles in the WPL at the output of the \( k \)th row \((k = 1, \ldots, N)\); \( \bar{L}_k \) is the average value of the corresponding stage’s gear ratio:

\[
L_1 = \bar{L}_1(\bar{d}_{\text{inp}}) = C_1(C_{\text{inp}})^{-1}; \quad \bar{L}_2 = \bar{L}_2(d_1) = C_2C_1^{-1}; \ldots; \quad \bar{L}_N = \bar{L}_N(d_{N-1}) = C_{\text{out}}(C_{N-1})^{-1},
\]

(16)

where \( d_1, \ldots, d_{N-1} \) is the arithmetic average of the size of the ferro-particles entering the input of the second, third, ..., \( N \)th separation stages, respectively.

The resulting transfer function, according to its equivalent circuit in Fig. 8 b), is expressed by the formula:

\[
\bar{L}(d_{\text{inp}}) = C_{\text{out}}C_{\text{inp}}^{-1} = \prod_{k=1}^{N} \bar{L}_k(d_{k-1}).
\]

(17)

The average degrees of purification for each stage are respectively equal:

\[
\bar{\varepsilon}_1 = \bar{\varepsilon}_1(\bar{d}_{\text{inp}}) = 1 - \bar{L}_1; \quad \bar{\varepsilon}_2 = \bar{\varepsilon}_2(d_1) = 1 - \bar{L}_2, \ldots; \quad \bar{\varepsilon}_N = \bar{\varepsilon}_N(d_{N-1}) = 1 - \bar{L}_N.
\]

(18)

Expressing \( \bar{L}_k \) from (18) and substituting in (17), we obtain:

\[
\bar{L}(d_{\text{inp}}) = \prod_{k=1}^{N} \left[1 - \bar{\varepsilon}_k(d_{k-1})\right].
\]

(19)

The average purification degree of a multi-row separator based on (10) and (18) will be determined as follows:

\[
\bar{\varepsilon}(d_{\text{inp}}) = (C_{\text{inp}} - C_{\text{out}})C_{\text{inp}}^{-1} = 1 - \bar{L}(d_{\text{inp}}) = 1 - \prod_{k=1}^{N} \left[1 - \bar{\varepsilon}_k(d_{k-1})\right],
\]

(20)

where the average degree of purification of the \( k \)th stage is calculated by the formula

\[
f_{k-1}(d_{\text{fr}}) - \text{is the probability density of the ferro-particles’ distribution by size at the k-stage input (or at the k – 1-stage output), which is determined by using the expression (14) as follows:}
\]

\[
f_{k-1}(d_f) = \Delta m_{j,k-1}(\Delta d_jC_{k-1})^{-1} = L_{k-1}(d_f)\Delta m_{j,k-2}(\Delta d_j\bar{L}_{k-1}C_{k-2})^{-1} = L_{k-1}(d_f)f_{k-2}(d_f)\bar{L}_{k-1}^{-1}
\]

(21)

In (21), \( \Delta m_{j,k-1} \) is the mass of particles in a unit volume of liquid at the output of the \( k – 1 \) series, the sizes of which lie in the interval \((d_j – d_j + \Delta d_j)\), \( m \); \( L_{k-1}(d_f) \) is the transmission coefficient of the \( k – 1 \) stage in mass concentration for monodisperse ferro-particles in WPL:

\[
L_{k-1}(d_f) = 1 - \varepsilon_{k-1}(d_f).
\]
According to the proposed methodology, the required number of the separation rows for a separator with a capacity of 100 m$^3$/h (see Table 1) was estimated to ensure an average degree of purification $\bar{\varepsilon}(\bar{d}_{\text{imp}}) = 0.94$ with the following initial data: $C_i = 80$ mg/l; $C_d = 5$ mg/l; $a = 48$ mm; $v_{\text{lmq}} = 0.03$ m/s and the use of expensive (neodymium-boron), but quality permanent magnets.

**Table 1.** Required number of rows in the separator for different distributions the dispersed composition of ferromagnetic particles in WPL

| $\bar{d}_i$, $\mu$m | 10    | 5     | 2.5   | 1     |
|---------------------|-------|-------|-------|-------|
| $\sigma$, $\mu$m    | 3.3   | 1.7   | 0.83  | 0.33  |
| $N$                 | 1     | 1     | 3     | 7     |

From the data in the Table 1 it follows that with the normal-logarithmic law of the distribution of polydisperse ferro-impurities with the parameters $\bar{d}_i = 1$ $\mu$m and $\sigma = 0.33$ $\mu$m, the initial given requirements for the efficiency of cleaning WPL from ferro-particles $\bar{\varepsilon} = 0.94$ can be satisfied in separators with seven rows of magnetic rods.

Thus, the studies using the mathematical models and developed programs have shown that the required fineness of descaling water treatment for descaling at a given performance and purity can be provided on the basis of multi-row separators of neodymium-boron permanent magnets. Moreover, with a decrease in the ferro-particles’ size, the number of separation rows increases. This makes it possible to determine the minimum required number of rows of magnetic rods.

**Summary**

The causes leading to the technological equipment and the environment pollution in rolling mills are analyzed. The prospects of using the magnetic separators are substantiated. To reduce water consumption by rolling production and emissions of scale and petroleum products on their surface to a minimum, tens of times better purification of reversed water in permanent magnet separators with a fineness of 1–2 $\mu$m is required.

Mathematical modeling methods of cleaning quality characteristics for monodispersed and polydisperse ferromagnetic impurities in WPL are considered. It is shown that the required refinement can be provided by the n-row magnetic separators. The minimum number of magnetic rods’ rows is calculated, which makes it possible to optimize the cost of cleaning systems. The 2nd and 3rd parts of this series of articles disclose the ways to increase the magnetic separators’ efficiency.

**References**

[1] The federal target program “Development of the water management complex of the Russian Federation in 2012 – 2020”, Decree of the Russian Federation Government, April 19, 2012 N 350.

[2] GOST 21014-88. Hire of ferrous metals. Terms and definitions of surface defects. Introduced on 01.01.90. Moscow, Publishing house of standards, 1988.

[3] Bulyzhev E M, Bogdanov A Y, Menshov E N, Krasnova M E, Kondratiev N N, Javakhia G A, Tereshonok E P 2010 A new generation of power purifiers for aqueous process fluids (UlSTU, Ulyanovsk).

[4] Wallander S V 1978 Hydromechanics’ Lectures (Leningrad University PH).