Alternatives of multiparameter expressions for filtration magnetophoresis efficiency

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Abstract: — The paper delivers and comments upon expanded (including individual parameters of ferroparticles filtration magnetophoresis in a granular matrix) alternatives of expressions suitable for calculating the resulting parameter of magnetophoresis efficiency ψ as a relative reduction of ferroparticles initial concentration in the medium filtered. For this purpose, we employ a well-reputed model of a matrix as an exponential ferroparticles absorbing screen the application of which in the expression for ψ is justified with the account for real diagnostics of the share λ of magneto-active fraction of particles entering magnetic separation zone. The paper demonstrates that alongside with acknowledged resulting parameter ψ it is reasonable to use another parameter, more convenient for testing the data, the so-called ξ-parameter as a logarithm of ψ-parameter deficit (with the account for value λ). We pay special attention to discussing the character of impact on ξ (and ψ) of such parameters as the filter-matrix granules diameter, magnetized field intensity and average induction in the matrix, matrix (chips) packing density, and initial concentration of ferroparticles.

Key words: ferroparticles, magnetophoresis, exponential absorbing screen, magneto-active fraction share, efficiency characteristics

1. Introduction

Magnetophoresis is widely used to separate ferroparticles (particles possessing ferro- and ferromagnetic properties, e.g. solid particles of iron and a number of its compounds, as well as other chemical compounds) from fluids and gases. It is quite broadly applied in magnetic apparatuses (separators) including filtration equipment (analysers *inter alia*).

The outcomes of applying this filtrational magnetophoresis depend on the degree of its theoretical and technological thoroughness, primarily, on the comprehensiveness of elucidating and examining the parameters of such a process.

Many researches to some extent mention the importance of a comprehensive range of parameters characterising both design features and the operating zone functional regimes of magnetophoresis (for a filtration magnetic separator they note its main working body, i.e. a magnetized filter-matrix), as well as the properties of ferroparticles and the carrying medium. Among these parameters are the length of magnetophoresis zone (in particular, the length and thickness of filter-matrix layer) L [1 – 4], the magnetic field level (intensity H, induction B) [5 – 9], size of ferroparticles δ [1, 5, 10 – 17] and their magnetic susceptibility χ [10, 11, 13, 15, 18], velocity υ [1 – 3, 5, 7 – 9, 15] and viscosity η [15, 16] of the flow incoming the magnetophoresis zone etc.

It is clear that establishing adequate dependences would greatly contribute to real advancement of theory and technology of magnetophoresis and would facilitate laying the foundations of this process. These expressions would have to functionally demonstrate to which extent some magnetophoresis parameter affects the outcomes of this process (the efficiency of ferroparticles separation from the flow passing through the magnetophoresis zone).

2. Main results and their discussion

As for filtration magnetophoresis, we employ granular media in forms of granule-balls loadings, loadings of ground chips (Fig. 1) etc. as magnetized filter-matrices through which various fluids and gases pass in order to separate ferroparticles from them (the containments happen on the granule surfaces). Here, just as in other cases of magnetophoresis the challenge is to obtain an integrated dependence which would functionally unite

Fig.1 Picture of a filter-matrix in the form of balls and ground chips loadings.

(summarize) all the set of magnetophoresis parameters through some resulting parameter. In order to solve the task, we believe it is necessary to take into consideration the following four principles.

Firstly, applicably to the 'single-sort' ferroparticles subjected to magnetophoresis, we can acknowledge a well-known equation of an absorbing screen as the basic equation providing information on ferroparticle concentration decrease in the medium flow c (their initial concentration equalling c_0) as it goes through a filter-matrix, the absorbing screen equation has an exponential view [1, 3, 16, 17, 19-21]:

$$c = c_0 \exp(-\alpha \cdot x), \qquad (1)$$

where: x is a current value of thickness (some value of the overall length L) of the filter-matrix, α is the filter-matrix absorption index of ferroparticles, it is also often called an absorption coefficient (the latter is disputable as in this interpretation there arises a seeming association of parameter α with a constant).

Secondly, when choosing a resulting parameter in the target integrated dependence, it is fair to give preference to such a key parameter (especially often used in practice) as a relative reduction of ferroparticle concentration, resulting from magnetophoresis ψ (magnetophoresis efficiency).

It is appropriate here to specially discuss the issue (oftentimes a neglected one) dealing with defining this parameter applicably to such particles most often subjected to magnetophoresis as ferriferous additions, especially in connection with using equation (1), which is true for magneto-active particles, i.e. the ones possessing ferro- and ferromagnetic properties.

Thus, the existing traditional methods aimed at controlling such additions (as a rule, they are impurities in the form of wear-out or equipment corrosion effects) allow defining the so-called total content of iron. For instance, it concerns widely spread photometric methods, which presuppose some conditioning of the analysed medium sample by appropriate reagents, logically with the iron transfer into its ionic form (the iron here may have initially been a compound of various elements and could have been a constituent part of both magneto-active and magneto-passive compounds-impurities).

In this connection, let us mention in passing that it is always worth treating cautiously the available data, unfortunately abundant one, on some medium seemingly containing ferrous oxide only. The matter is, these data are often obtained by a quasi-translation of the content of the defined (e.g. by photometry) total iron into formal content of ferrous oxide. That is why when dealing with magnetophoresis tasks, such data may be misleading and have nothing to do with the information on the actual content of really present (reasonably, different in composition) ferriferous impurities.

Consequently, when using such a common resulting parameter as magnetophoresis efficiency ψ, operating by parameters of iron concentration (measured by a traditional method) before magnetophoresis C_0 and during it C, it is necessary to take into consideration real presence of magneto-active and magneto-passive particles fractions [20, 21]. Paper [22] also speaks about the necessity for accounting for these pertinent particle fractions. Thus, having regard to $C_0=c_0+c_{00}$ and $C=c+c_{00}$ (c_{00} is the concentration of iron in magneto-passive additions, i.e. the ones not subjected to the magnetic field influence) in matters of magnetophoresis responsible for magnetic separation (localization) of magneto-active fraction of particles, the definition for ψ should be put down as [20, 21]:

$$\psi = \frac{C_0 - C}{C_0} = \frac{c_0 - c}{c_0} \cdot \frac{c_0}{C_0} = \frac{c_0 - c}{c_0} \cdot \lambda \,\text{x}100\%, \qquad (2)$$

where $\lambda=c_0/C_0$ is a fractional share of magneto-active particles in ferriferous additions (to be more exact, it is the concentration ratio of iron present in magneto-active impurities-particles as to the total concentration of iron present in all ferrous additions and its various compounds). Herewith, to define value λ we can use the methods of control based on the same principle of filtration magnetophoresis: the method of two or three points of the absorbing filtration screen and/or the method of polycyclic magnetic separation of ferroparticles [23].

Thus, from (2) and (1) follows a basic expression for resulting parameter ψ, from which we can observe the nature of layer's length L (or its current thickness x, i.e. one of magnetophoresis parameters) of the magnetized filter-matrix [20, 21] impact on ψ:

$$\psi = \lambda\left[1 - \exp(-\alpha \cdot L)\right]. \qquad (3)$$

Thirdly, alongside with the generally accepted resulting parameter ψ it stands to reason, as will be demonstrated further on, to use one more resulting parameter, i.e. the so-called ξ-parameter [20], the semantic reading of which (and connection with ψ) is indicated by expression (3), namely:

$$\xi = -\ln\left(1 - \frac{\psi}{\lambda}\right). \qquad (4)$$

One of the main advantages of using parameter ξ, which is essentially a function in the exponent of expression (3) for ψ, is the fact that basing on (3) and (4) one should expect that in practice there is a direct proportional connection between ξ and L:

$$\xi = \alpha \cdot L\,, \qquad (5)$$

i.e. connection (5) becomes, per se, a unique criterion for demonstrative testing of experimental data against the model considered here.

Sure enough, this connection finds real support if the obtained multiple practical data for ψ on L (Fig. 2a) are to be rendered according to (4) into data of ξ on L (Fig.2b). For more clarity, these data, if we use individual values of the absorption index α, can be depicted in coordinates ξ/α on L (Fig. *3*), in which the whole array of data is integrated by a singular dependence governed by the

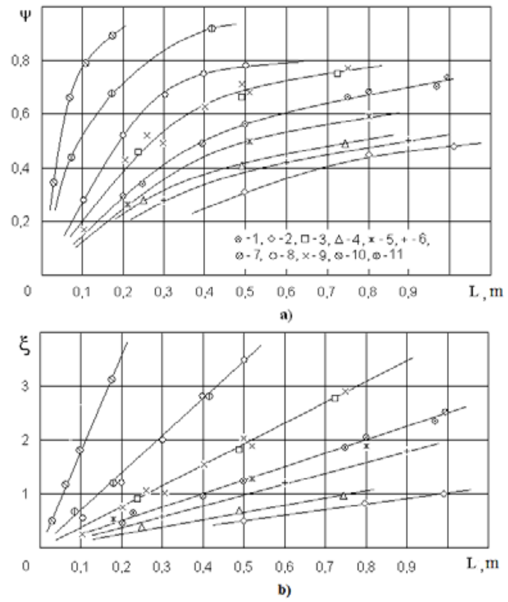

Fig.2 Magnetized filter-matrix impact on ψ-parameter (*a*) and ξ- parameter *(b)* of magnetic separation of ferriferous inclusions (impurities) of some technological media, the experimental data characteristics – in Table 1.

Table 1. Characteristics of experimental data shown in Fig. 2

№№ in Fig.2	Medium containing ferroimpurities	Magnetized filter-matrix	*H*, *kA/m*	*υ*, *cm/s*
1	Industrial condensate returned to the thermoelectric power station, λ=0.7-0.9	Balls, diameter 5*mm*	55	5.6
2	–‖–‖–	Balls, diameter 7*mm*	50	14
3	Gaseous ammonia, λ=0.7-0.9	Ground chips	80	175
4	–‖–‖–	–‖–‖–	80	700
5	25%-ammonia aqua, λ=0.6-0.8	–‖–‖–	80	4.2
6	Thermoelectric power station vapour, λ=0.5-0.7	–‖–‖–	35	400
7	Feed water for thermoelectric power plant unit, λ =0.7-0.9	Balls, diameter 5*mm*	90	5.6
8	Liquid ammonia, λ=0.7-0.9	Balls, diameter 2,4*mm*	80	14
9	–‖–‖–	Ground chips	80	11
10	Circulation water of the rolling mill, λ=0.9-1	Balls, diameter 6*mm*	40	7
11	Water suspension of industrial condensate ferroimpurities, λ=1	Balls, diameter 5,7*mm*	75	5.6

right angle bisectrix chosen for such integration of the coordinates.

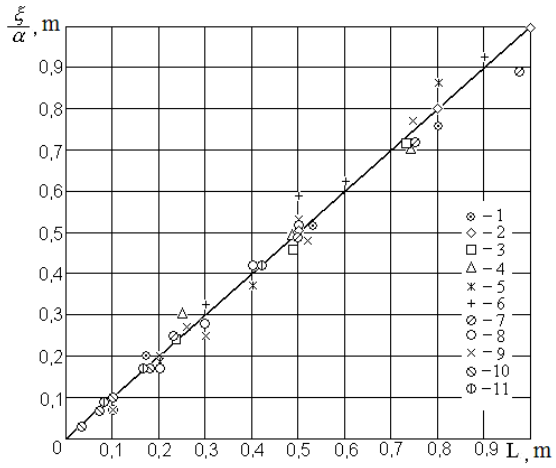

Fig.3 Integration of data shown in Fig.*2a* by a single dependence (governed by the right angle bisectrix in the chosen system of coordinates).

Fourthly, to have an expanded view of expression (3) we have to fully develop its constituent, absorption index α or, which is much the same – to expand parameter ξ, since alongside with (3) we can write down the following expression for ψ:

$$\psi = \lambda\left[1-\exp(-\xi)\right], \qquad (6)$$

which follows from (3) and (5) or directly from definition (4).

In other words, we have to determine functional nature of how magnetophoresis individual parameters, many of which are mentioned above, influence α and/or ξ.

Theoretical and experimental research (in the targeted experiments we used both industrial and artificially prepared media) demonstrates that, in particular, when applying an idealized matrix, i.e. the one made of balls loading with accuracy to the dimensional constant k_1, functional view of the test resulting parameter ξ is close to an exponential one:

$$\xi = \frac{k_1 \chi \delta^2 H_*^z L}{\eta \upsilon d^2}, \qquad (7)$$

where H_* =H/1$A/м$ is the intensity of the magnetized field reduced to a dimensionless form (due to the fractional exponent z for H). Herewith, if we process in Excel available experimental dependences of ξ on H, in the frameworks of an exponential view of this function, with defining 'individual' values of z and their further averaging, then in contrast to [21] where value z is estimated by value $z \cong 0.75$, the refined value will amount to $z \cong 0.7$.

With the account for (7) expression (6) for ψ-parameter will be written as:

$$\psi = \lambda\left[1-\exp\left(-\frac{k_1 \chi \delta^2 H_*^z L}{\eta \upsilon d^2}\right)\right]. \qquad (8)$$

A distinctive particularity of expressions (7) and (8) which feature all the afore-mentioned parameters (they are also talked about in many reference sources) is the presence of such a parameter, which is unfortunately often neglected, as the matrix granules diameter d. Meanwhile, its role is substantial as follows from (7) and (8) as well as form experimental argument in Fig. 4 *a*, *b*.

Table 2. Characteristics of experimental data shown in Fig. 4

№ in Fig.4	Medium containing ferro-impurities	*L*, *cm*	*H*, *kA/m*	υ, *cm/s*
1	Industrial condensate returned to the thermoelectric power station, λ=0.7-0.9	100	55	5.6
2	Liquid ammonia, λ=0.7-0.9	40	70	5.6
3	Water suspension of a magnetite, the particles dimensions are mainly 3-5μm, λ=1.0	4.2	30	5.6

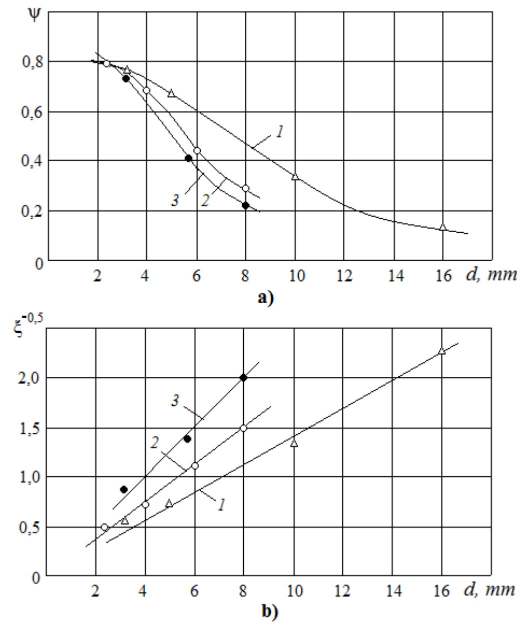

Fig.4 Filter-matrix balls diameter impact on ψ-parameter (*a*) and exponential function of ξ-parameter (*b*), the data characteristics – in Table 2.

So, if the primary data, i.e. the ones for ψ on d (Fig. 4*a*), are to be presented in handy here coordinates which expression (7) points at, viz. in coordinates $1/\sqrt{\xi}$ on d (Fig.4*b*), then we can assure the truth of direct proportional dependence of $1/\sqrt{\xi}$ on d. Hence, such an important role of granule diameter, namely the inverse square ($\xi \sim 1/d^2$) as it is expressed in (7), must be imperatively taken into account in theoretical and practical issues of magnetophoresis.

There is one more singularity of expressions (7) and (8) which is worthy special attention and analysis, this is, as noted above, the presence of a fractional exponent z for magnetizing field intensity H. However, we should say that it can cause some inconvenience, making expressions cumbersome to use, and making us reduce parameter H to a dimensionless form, and thus, reconcile the dimension of parameter k_1.

Yet, this inconvenience can be avoided if we take a more universal parameter of the magnetizing field average induction B in the granular matrix instead of magnetizing field intensity H. So, if we turn to the field dependence of induction B in the matrix consisting of a balls loading, i.e. dependence of B on H (the magnetization curve), it is easy to make sure in the following. This dependence turns out to be perfectly well characterized by a function close to an exponential one, at that $B \sim H^{0.7}$, in a quite wide range of H=20-120kA/m in which matrix magnetic separators usually operate.

Consequently, expressions (7) and (8) for ξ-parameter and ψ-parameter which contain a similar exponential function ($H^{0.7}$) can be written with accuracy to dimension factor k_2 in the following view:

$$\xi = \frac{k_2 \chi \delta^2 BL}{\eta \upsilon d^2}, \quad \psi = \lambda \left[1 - \exp\left(-\frac{k_2 \chi \delta^2 BL}{\eta \upsilon d^2} \right) \right], \quad (9)$$

moreover, these expressions are true not only for granular matrices with virtually stable density of packing granules (balls), viz. $\gamma \approx 0.6$, but also for other granular matrices susceptible to changes in the density of packing γ, in particular, matrices in the form of ground chips loading. Thus, the research exhibits that for such a matrix in a quite wide range, virtually in the one H=(20-120)·10^3A/m, the same connection $B \sim H^{0.7}$ holds firm, besides, in the range of γ=0.2-0.46 the expression for B takes the view of $B \sim \gamma \cdot H^{0.7}$.

The implication therefrom is that with using parameter H, we should also introduce parameter γ into the number of magnetophoresis characteristics (in case of using these and other matrices susceptible to any changes of packing density γ). This would mean that expressions (7) and (8) for ξ-parameter and ψ-parameter with the accuracy to a single dimension factor k_3 are put down in a somewhat expanded view:

$$\xi = \frac{k_1 \chi \delta^2 \gamma H_*^z L}{\eta \upsilon d^2},$$

$$\psi = \lambda \left[1 - \exp\left(-\frac{k_1 \chi \delta^2 \gamma H_*^z L}{\eta \upsilon d^2} \right) \right] \qquad (10)$$

herewith, parameter d should be regarded as an equivalent diameter of the ground chips particles.

The research on the chips matrix packing density γ impact on the efficiency of ferroparticles magnetic separation ψ (Fig. 5*a*) proves that $\xi \sim \gamma$ (Fig. 5*b*), which signifies the validity of expressions (10) for ξ-parameter and ψ-parameter if applying chip matrices.

It should also specially be noted that initial concentration of impurities subjected to magnetic action can be included (or mentioned) in the number of parameters capable of influencing the efficiency of magnetophoresis ψ. For instance, if we speak of separating ferriferous impurities, it can be, as a rule, iron concentration measured traditionally, e.g. by photometry (which has the disadvantages noted above).

Experiments conducted with artificially produced low-concentration suspensions of magnetite only ($C_0 = c_0$) show that it is hardly worth talking about impact of c_0 on ψ, at least when the initial concentration c_0 (mass share) of ferroparticles changes within limits of 3-4 orders, up to values of $c_0 \approx 10^{-4}$ (Fig.*6*). Therefore, a not uncommon direct dependence between c_0 and ψ appears to be stipulated by redistribution on shares of magneto-active and magneto-passive fractions, i.e. by change of value λ. It is quite possible in some technological process at the cost of uncontrollable introduction of magneto-active particles due to wear-out and/or corrosion of the equipment, change of qualitative composition of particles on exposure to temperatures etc.

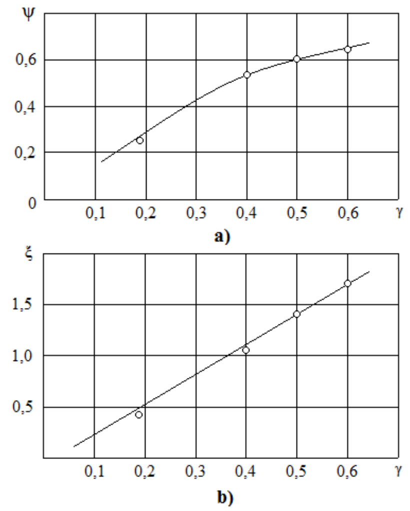

Fig.5 Chips filter-matrix packing density influence on ψ-parameter (*a*) and ξ-parameter (*b*), of magnetic separation of ferriferous inclusions (impurities) of the industrial condensate L=100*cm*, H=60*kA/m*, υ=1.4*cm/s*, λ=0.7-0.9.

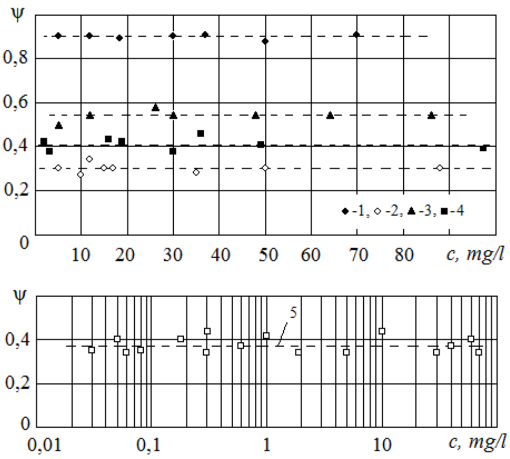

Fig.6 Experimental argument for self-similar behaviour of ψ-parameter in ferroparticles filtration magnetophoresis with the change of their initial concentration (in the magnetite suspension); the dimensions of particles in the disperse phase (mainly): *1* and *2* – more or less 8μm (L = 4.2*cm*), *3* and *4* – 3…5μm and 1…5μm respectively (L =6.4*cm*), *5* – less than 3μm (L = 50*cm*); υ= 4.7-5.6*cm/s*.

3. Conclusion

Thus far there has accumulated a huge array of data concerning the information on ferroparticles magnetophoresis being affected by various parameters characterising both design features and the operating zone functional regimes of magnetophoresis (for a magnetized granular matrix of a filtration magnetic separator), as well as the properties of ferroparticles and the carrying medium. Among these parameters are the length of magnetophoresis zone L, the magnetic field level (intensity H, induction B), size of ferroparticles δ and their magnetic susceptibility χ, velocity υ and viscosity η of the flow etc.

However, regardless quite extensive data, we have to state that there are no sufficient analytical dependences which would fully integrate these parameters, including those applicable to the conditions of filtration magnetophoresis in a granular matrix.

The present paper features expanded expressions containing individual parameters of filtration magnetophoresis and suitable for calculating a resulting parameter – ferroparticles magnetophoresis efficiency ψ, i.e. relative to reduction of ferroparticles concentration in effect of magnetophoresis. For this, we applied as a foundation a well-proven model of a filter-matrix as an exponential screen absorbing ferroparticles, the use of it in expression for ψ is justified with the account for real diagnosis of fraction share λ of magneto-active particles entering magnetophoresis zone.

We manifest that alongside with a known resulting parameter ψ it stands to reason to employ a more convenient resulting parameter ξ= -ln(1- ψ/λ), which is a functional connection of magnetophoresis individual parameters in an analytical expression for ψ. Herewith, an alternative ξ-parameter provides an opportunity to relatively easily test (with clear illustration) the role of individual parameters in order to legalise this role in the form of corresponding exponential functions, in particular $\xi \sim \chi$, $\xi \sim \delta^2$, $\xi \sim 1/\upsilon$, $\xi \sim 1/\eta$ and others.

As to identifying the significance of other parameters of filtration magnetophoresis, the paper has:

– paid attention to the formerly ‘shadow’ parameter of the filter-matrix granules diameter d, the importance of which is quite fundamental: $\xi \sim 1/d^2$

– shown that instead of magnetizing field intensity H present in the test expression for ξ with a fractional exponent ($\xi \sim H^z$, its refined value makes up $z \cong 0.7$) it is more preferable to use the parameter of the average induction B of the field in the matrix. The latter has a more convenient connection with ξ, namely, $\xi \sim B$, as for the most practical range of H=20-120kA/m the nature of magnetization curves for granular matrices is close to exponential one of the form $B \sim H^{0.7}$

– demonstrated that if we do not resort to using parameter B (limiting ourselves only to stating parameter H), then in case of using filter-matrices with variable packing density γ (a chip matrix), expressions for ξ and ψ should feature parameter γ, in doing so $\xi \sim \gamma$

– argued on the so far uncertain issue of a possible impact of the ferroparticles initial concentration c_0 on ψ. Exemplifying by characteristic low-concentration suspensions of a magnetite, we demonstrate that at least in the limits of ferroparticle concentration (mass share) varying from $c_0=10^{-8}$ to

– $c_0=10^{-4}$ parameter c_0 does not influence ψ. Moreover, in some cases when such impact may be observed, it more likely happens due to the change of λ parameter, i.e. owing to the specifics of operating machinery and some redistribution of the fractions of ferriferous impurities which enter the zone of magnetic separation

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