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Performance of High Gradient Magnetic Filters with Granular Matrix

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ABSTRACT

The performance characteristics of high gradient magnetic filters composed of spherical ferromagnetic granules are determined in terms of dimensionless parameters for a wide range of system parameters. The results obtained are used to overcome some contradictions seen in the literature related to magnetic filters. They are in a good agreement with the experimental data given in the literature for the filters used in laboratories and industry.

INTRODUCTION

Some liquids and gases used in certain technological processes must be purified by eliminating dispersed fine particles to improve the quality of production to the highest level. Most technological liquids contain iron and its compounds because of corrosion. The removal of these species is of great importance for high purification of the fluid. Owing to their lower concentrations and fine dimensions, conventional mechanical and chemical cleaning methods are not sufficient to filter liquids containing these particles. For this reason, in recent years high gradient magnetic filters (HGMF) have been extensively used for purpose (1–3).

In magnetic filters the main part is a filter matrix which consists of a block of ferromagnetic elements (spheres, rods, stainless steel wool, etc.) that can

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be easily magnetized by an external uniform magnetic field. A high gradient magnetic field induced around the filter elements creates local capture zones. While the liquid or gas is flowing through the filter matrix, the magnetic particles are captured and accumulated in these zones. The strong mechanical and thermal resistance of the filter matrix enables liquids and gases with different chemical and physical properties to be purified with a high performance and filtration velocity (2–6). The convenience of using HGMF and its advantages have been proved by many experiments in the laboratory and successful applications in industry (6–12). Although there are some systematic approaches and results for the use and performance of HGMF (2, 13), a general theory about magnetic filtration has not been developed. Since the dependence of filter performance on the parameters of filtration systems in different applications is similar, a general and unifying treatment of HGMF which will yield a formula for the performance characteristics is aimed at in this paper. The determination of the filter parameters which appear in the derived formula to optimize filter performance for special industrial applications is also included.

BASIC INTERACTION

Technological liquids used in different fields of industry, especially in thermal and nuclear power stations, generally contain micron-sized iron particles (generally with magnetite properties and a diameter δ of 1–10 μm) with very low concentrations (7–14). For this reason, the fraction of ferromagnetic materials in the filter matrix must be relatively high (50–60%). The capture zones are essentially created around the contact points of the filter elements, and the captured particles are accumulated around these points. The materials used as the filter matrix elements are usually ferromagnetic chips and spheres of 2–10 mm diameter (2, 3, 13).

In most industrial applications it is mainly magnetic filters that are used for magnetic separation processes in which the dimensions and concentrations of magnetic particles are relatively higher than those in the condensates of thermal and nuclear power stations. These filters are generally made of fine steel wool with a packing fraction of 5% or less. Filters with such low packing fractions are not effective in thermal and nuclear power stations since particles with small dimensions and concentrations can not be captured efficiently. In order to increase the efficiency, either the packing fraction should be increased, which necessitates oversqueezing the steel wool and causes a high pressure drop across the filter ends, or a very high magnetic field intensity (up to 14 T) should be used (9), which may require the use of superconductors (superconducting HGMS filter) (15).

As with steel wool matrix filters, steel wire matrix filters also have low packing fractions and are widely used in magnetic separation processes to capture particles with relatively high concentrations and sizes. In the technological liquids considered in this paper, the concentrations and sizes of the particles are very small, and wire matrix filters (and steel wool filters) with low packing fractions are not effective (8, 9, 15).

Experience on the tests and usage of HGMF reveals that filter performance depends on the magnetic, hydrodynamic, and geometric parameters of the filter system. Hitherto, the results obtained about their dependence have not been sufficient to explain completely the extent of the effect of each parameter on filter performance, as noted below.

The parameters affecting filter performance can be classified as active or passive. Such active parameters as external magnetic field intensity H_0, filter length L, dimension of matrix elements d, and filtration velocity (bulk velocity V) can be measured or determined very easily. Passive parameters include the magnetic properties of particles (susceptibility k, magnetization M_s), the particle size (diameter δ), and the velocity of a liquid through pores (interstitial velocity v). Due to the impossibility of accurately determining the passive parameters, some contradictory results have been reported. According to Ref. 3, the performance of HGMF with spherical matrix elements is independent of the captured particle size, and the optimum bulk velocity of the liquid being filtered is about 0.3 m/s. On the other hand, results based on many other experiments indicate that one of the main parameters affecting filter performance is particle size, and the optimum filtration velocity is less or equal to 0.1 m/s (2). These results were obtained on the assumption of laminar flow through the pore, in which case the Reynolds number calculated for the diameter of the spherical filter elements used was 700 or higher. This is obviously impossible since the critical maximum Reynolds number for the laminar flow of liquids in granular media is about 100–120.

To overcome all of the above-mentioned conflicts, instead of considering each system parameter separately, a general expression of the performance of HGMF with a ferromagnetic granular matrix is derived according to a group of dimensionless parameters (V_m/V, Re_d, L_d) as in magnetic separation theory (1). In fact, these three dimensionless parameters involve all of the parameters of a filtration system. The first dimensionless parameter, V_m, is the magnetic velocity in magnetic separation theory, and it expresses the magnetic, geometric, and rheological properties of the system, and V is the filtration velocity. The second one, Re_d, is the Reynolds number, expressed in terms of the diameter of the spheres. Finally, $L_d = L/d$ is the dimensionless length of the filter matrix normalized with respect to the diameter d of the spheres. This approach to the evaluation of filter performance makes it possible to generalize and unify the theory of fine filtration and separation processes of liquids and gases. This is described in the following section.

THEORY

Consider a HGMF with spherical ferromagnetic filter elements, all with the same magnetic property. The force balance equation for particles carried by liquids through pores can be written as

$$\vec{F}_i + \vec{F}_m + \vec{F}_D + \vec{F}_g + \vec{F}_A = 0 \tag{1}$$

In this equation the forces acting on the particle are inertial, magnetic, drag, gravitational, and Archimedes forces, respectively. Due to the fine (small) dimensions of the particles, only $\vec{F}_m$ and $\vec{F}_D$ are dominant in the active zone. Considering only their radial components, the necessary condition for the capture of a particle is

$$F_m \geq F_D \tag{2}$$

With an equality condition of these forces, the capture radius of the active zone centered at the contact points of the spheres can be determined. In order to do this, explicit expressions of F_m and F_D are needed. The magnetic force acting on the fine particles in the pores between spherical magnetized granules is expressed as (2)

$$F_m = \frac{w_p k \mu_0 \mu_r^2 (\mu_r - 1) H_0^2 \left(\frac{r}{a}\right)}{a\left[1 + 0.5(\mu_r - 1)\left(\frac{r}{a}\right)^2\right]^3} \approx \frac{3 w_p k \mu_0 \mu_r^{1.38} H_0^2}{d\left(\frac{r}{a}\right)} \tag{3}$$

In this equation H_0 (A/m) and k are as defined before, μ_r is the relative magnetic permeability of the filter matrix elements, $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic permeability of free space, $d = 2a$ is the diameter (m) of the spheres, r is the radial distance (polar coordinate in m) from the contact points of the spheres, and w_p is the particle volume ($\pi\delta^3/6$ in m^3).

The general expression for the drag force F_D is

$$F_D = \frac{C_\delta \rho \pi \delta^2}{8} u^2 \tag{4}$$

which applies for all Reynolds numbers. In this equation C_δ is the drag coefficient, ρ is the liquid density (kg/m^3), and $u = |\vec{v}_p - \vec{v}|$ is the absolute relative velocity of the particle with respect to liquid flow velocity ($\vec{v}$) in the pore. When $F_m = F_D$, the particle is just suspended and the particle velocity $\vec{v}_p = 0$, hence $u = |\vec{v}|$.

The relation between the drag coefficient C_δ and Reynolds number Re_δ can be expressed as (16)

$$C_\delta = C\mathrm{Re}_\delta^{-\alpha}; \qquad 0 \leq \alpha \leq 1 \tag{5a}$$

Experience reveals that from the piecewise linearization of the logarithmic plot of C_δ versus Re_δ, the coefficient C and the exponent α may be approximated by

$$\begin{aligned} C &= 24, & \alpha &= 1 & &\text{for } \mathrm{Re}_\delta < 1 \\ C &= 30, & \alpha &= 5/8 & &\text{for } 1 \leq \mathrm{Re}_\delta < 10^3 \\ C &= 0.44, & \alpha &= 0 & &\text{for } 10^3 \leq \mathrm{Re}_\delta < 2 \times 10^5 \end{aligned} \tag{5b}$$

for spherical shaped particles. The Reynolds number is expressed by

$$\mathrm{Re}_\delta = \delta u/\nu \tag{5c}$$

where ν is the kinematic viscosity of the liquid.

With Eqs. (3) and (4) and by using Eq. (5), equilibrium condition $F_m = F_D$ can be expressed by

$$\frac{3\mu_r^{1.38}H_0^2}{dr_a} = \frac{3}{4}C\left(\frac{\delta u}{\nu}\right)^{-\alpha}\rho\frac{1}{\delta}u^2 \tag{6}$$

This equality can be written in dimensionless form:

$$\frac{V_m}{u} = \frac{3}{4}Cr_a\mathrm{Re}_d^{1-\alpha}\left(\frac{d}{\delta}\right)^{\alpha-1} \tag{7}$$

where

$$V_m = \frac{3k\mu_0\mu_r^{1.38}H_0^2\delta^2}{d\eta} \tag{7a}$$

$$r_a = r/a, \qquad \mathrm{Re}_d = du/\nu, \qquad \eta = \nu\rho \tag{7b,c,d}$$

are the magnetic velocity, dimensionless distance, and Reynolds number with respect to the diameter of the spheres and the dynamic viscosity, respectively.

In general, the velocity u of the liquid carrying the particles through the pores of the filter matrix depends on the geometry of the pores. It varies from zero at the contacts of the spheres to a maximum value at the centers of the pores. Since the dimensions of the pores are very small, technically it is very hard to determine the profile of this variance. However, as a result of many experiments performed by using laser–Doppler technology, this profile can approximately be expressed as (2)

$$u = k_v r_a^2 V \tag{8}$$

where the filtration (bulk) velocity V of the liquid can be determined very easily by measurement. Based on experiments, the empirical value of k_v varies between 10 and 20. Assuming $k_v = 16 \in [10, 20]$ and using Eqs. (7) and (8), the expression for the limit value R_{as} of the capture radius r_a is obtained as

$$R_{as}^3 = \frac{1}{12C}\left(\frac{V_m}{V}\right) \mathrm{Re}_d^{\alpha-1}\left(\frac{\delta}{d}\right)^{\alpha-1} \tag{9}$$

In principle, this equation is similar to the relations computed in magnetic separation theory (1, 4, 8, 9, 12, 14). It indicates that the radius of saturation of the capture zone depends on the flow regime of the fluid through the pores and the ratio of the particle size to that of the filter matrix elements. This result makes it possible to explain some of the contradictory statements appearing in the literature.

As the final step for arriving at the desired filter performance equation from Eq. (9), consider the formula

$$\psi/\lambda = 1 - e^{-\alpha L} \tag{10}$$

$$\alpha = \frac{3}{4d} R_{as}^3 \tag{11}$$

which is derived by an investigation of the effective cross section and volume of the capture zone (2), and where λ is the ratio of the mass concentration of ferromagnetic particles to that of all particles in the liquid, and ψ is the filter performance. Inserting Eq. (9) into Eq. (11) and then Eq. (11) into Eq. (10),

$$\frac{\psi}{\lambda} = 1 - \exp\left[-\frac{1}{16C}\left(\frac{V_m}{V}\right)\left(\mathrm{Re}_d \frac{\delta}{d}\right)^{\alpha-1} L_d\right] \tag{12}$$

is obtained for filter performance. In the domain of laminar flow ($C = 24$, $\alpha = 1$), this performance can be simplified to

$$\frac{\psi}{\lambda} = 1 - \exp\left[-2.6 \times 10^{-3}\left(\frac{V_m}{V}\right) L_d\right] \tag{13}$$

which is similar to the general expression determining filter performance in the processes of magnetic separation and filtration (8, 9, 12).

The formula in Eq. (12) for filter performance is valid for a very wide range of Reynolds number. By this formula the performance of a magnetic filter is expressed in terms of the dimensionless quantities V_m/V, Re_d, L_d, and δ/d. Although it is derived for spherical filter elements, similar equations have been determined and experimentally verified for HGMF with periodically ordered wire matrix elements (8, 12). But one important property of the result appearing in Ref. 12 which is special to HGMF with spherical matrix elements is that the effects of the hydrodynamic property (Re_d) and the geometric property (δ/d) appear together in the product $Re_d(\delta/d)$. This obviously means that the actual relative hydrodynamic property Re_d is scaled by the geometric property (δ/d), so that $Re_d(\delta/d)$ is the effective Reynolds number. For this reason, (δ/d) behaves as a scaling factor of the Reynolds number, but it is different from the known scaling reported in the literature (14).

RESULTS AND DISCUSSIONS

To justify the derived theoretical results about filter performance, both the results obtained experimentally on model filters tested in the laboratory (a sphere size of 5.7 mm in diameter was used in the filter matrix) and the results of tests on actual filters used in industry (with a sphere size of 5 mm in diameter), Eq. (13) is plotted in Fig. 1, which shows the variation of the

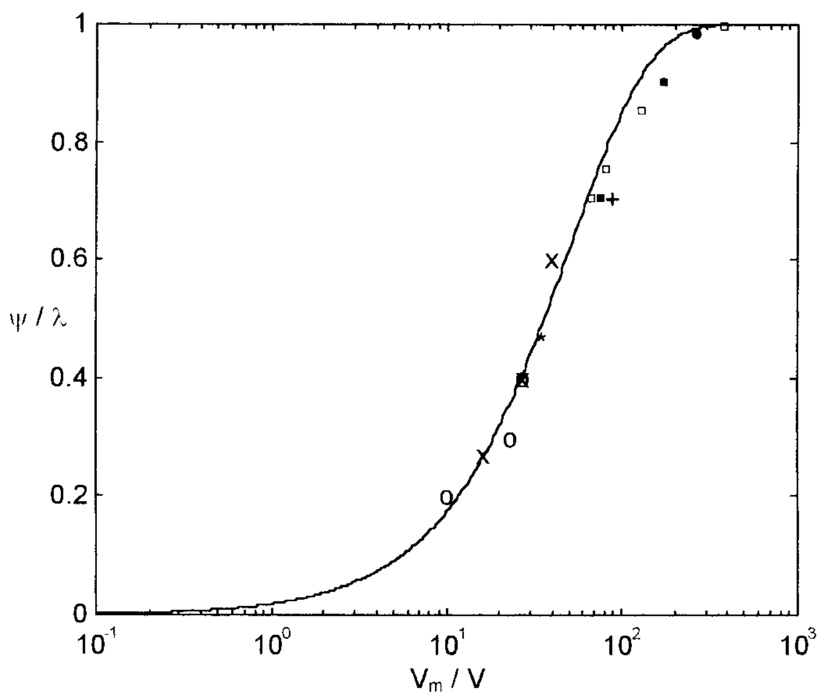

FIG. 1 Variation of filter performance with V_m/V; the continuous curve is computed from the theoretical result in Eq. (13). The points indicate the experimental data with parameters $H_0 = 30$, $\delta = 3$–5 (○), $\delta = 7$–9 (∗), and $\delta = 10$–15 (+); $H_0 = 52$, $\delta = 10$–15 (□); $H_0 = 75$, $\delta = 10$–15 (■); and finally $H_0 = 125$, $\delta = 3$–5 (×), $\delta = 10$–15 (●). In all cases H_0 in kA/m and δ in μm.

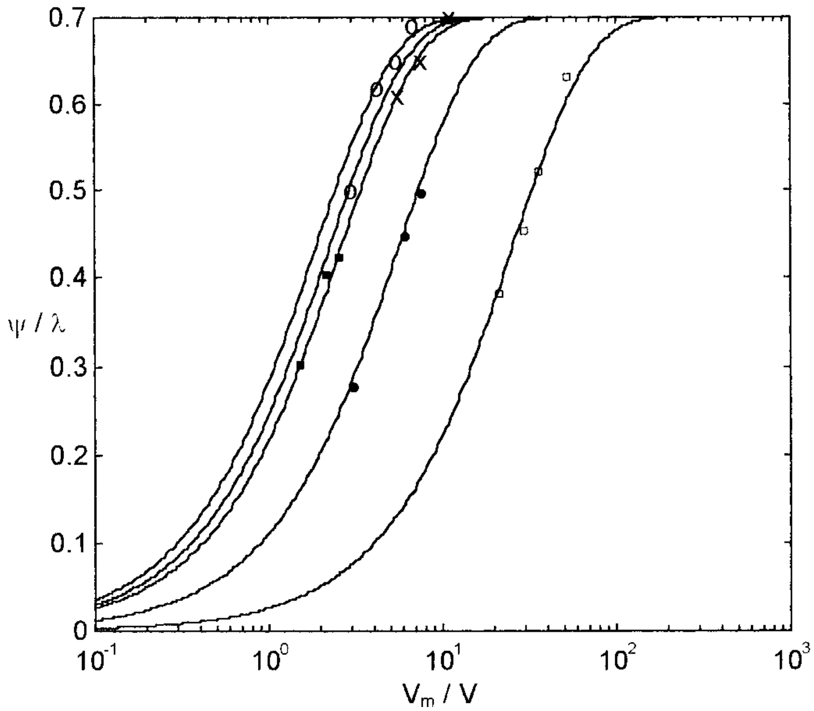

FIG. 2 Variation of filter performance with V_m/V; the continuous curve is computed from the theoretical result in Eq. (13). The points were obtained by measurements made on actual filters used in industry: × and ● are for liquid ammonia, ○ is for hydroelectric turbine water, and ■ (□) is for the condensates used in thermal (nuclear) power plants.

filter performance versus V_m/V. On the same plot the experimental data for the filtrations of artificial suspension containing magnetite (Fe_3O_4) particles are also shown for different system parameters. It is evident that in spite of a wide range of variation of parameter values, the experimental results are in a very good agreement with the theoretical curve.

Similar agreement is observed when measurements on the actual filters used in different industries are considered. Figure 2 compares the theoretical results with the data of measurements made for the filter systems indicated in the figure caption and where the parameters H_0, L_d, and V have the values: 80 kA/m, 166.7, 0.14 m/s for ×; 40 kA/m, 66.7, 0.08 m/s for ●; 90 kA/m, 200, 0.056 m/s for ○; 60 kA/m, 143, 0.056 m/s for ■; and 75 kA/m, 14.74, 0.056 m/s for □, respectively.

Based on Eq. (9), the variation of V_m/V versus the saturation radius R_{as} of the active zone around the contact points is plotted in Fig. 3 for different values of the Reynolds number. An increase of the Reynolds number apparently causes a decrease of the saturation radius. In laminar flow, for example $\delta = 1$–$2\ \mu$m, it is necessary that $(V_m/V) \leq 10$ to have particles captured in the pores up to the $R_{as} = 0.2$–0.4 range, which is a fact reported by many authors (2).

Dependence of filter performance on the dimensionless parameter δ/d is shown in Fig. 4. For the region $(\delta/d) < 10^{-5}$, the effect of a change of Reynolds number on filter performance is relatively small; i.e., the difference between the effects of turbulent and of laminar flows on filter performance becomes smaller. For the range $10^{-5} < (\delta/d) < 10^{-2}$, there is quite a large difference between filter performances, corresponding to different values of the Reynolds number. This range is the basic range for fine magnetic filtration processes; therefore, consideration of the variation of the Reynolds number in the evaluation of filter performance is inevitable. Note that since filter performance depends strictly on the product $\mathrm{Re}_d(\delta/d)$, many possibilities exist for the values of Re_d and (δ/d) to have a fixed value of filter performance as long as their product is the same. Hence, in many cases it is appropriate to investigate the variation of filter performance versus V_m/V by taking this product as a parameter; and this is shown in Fig. 5.

Since $C = 30$, $\alpha = 5/8$ is chosen, as in Fig. 4, so the plots in Fig. 5 are valid for turbulent flow, i.e., for the intermediate range of Re_d specified in

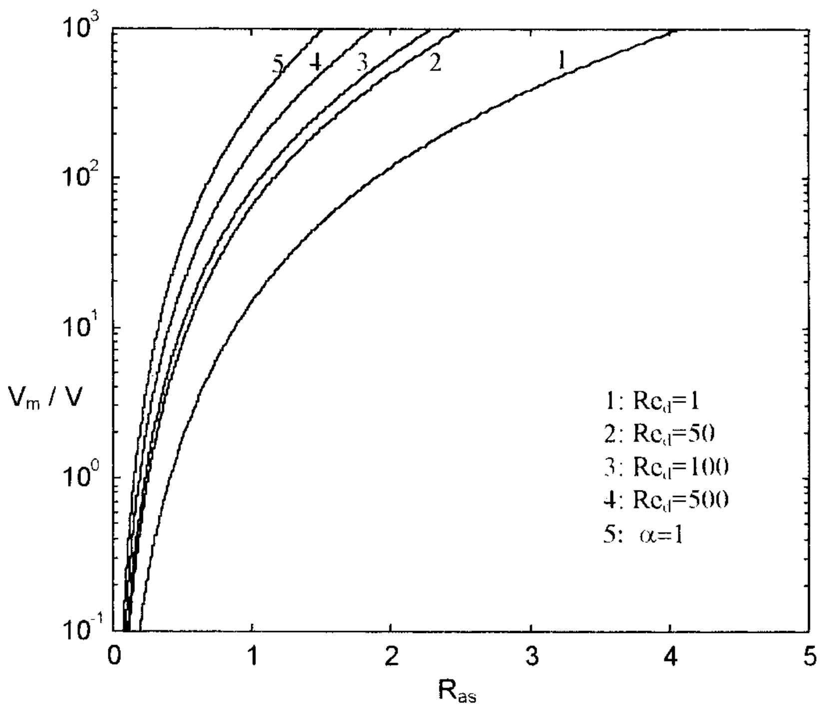

FIG. 3 Variation of V_m/V with the saturation radius R_{as} for different values of the Reynolds number.

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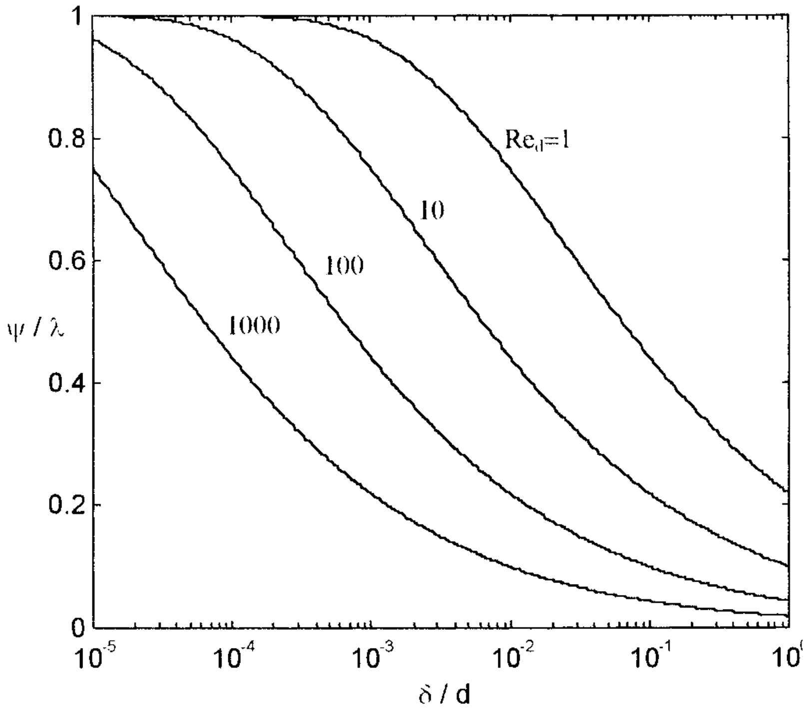

FIG. 4 Filter performance against (δ/d) for different Reynolds numbers; (V_m/V) = 16, L_d = 7.37.

Eq. (5b). Under these conditions the general formula in Eq. (12) for filter performance can be written as

$$\frac{\psi}{\lambda} = 1 - \exp\left[-\beta L_d \left(\frac{V_m}{V}\right)\right] \tag{14}$$

where

$$\beta = \frac{1}{480}\left(\mathrm{Re_d}\,\frac{\delta}{d}\right)^{-3/8} \tag{14a}$$

For each fixed β, Eq. (14) is exactly in the same form as Eq. (13); therefore, it represents the filter characteristics for both laminar and turbulent flows.

The practical importance of the expression in Eq. (14) is not only its universality for laminar and turbulent flows, but also its shape-invariance when it is plotted against a logarithmic axis, which is obviously seen in Fig. 5. For this reason it is sufficient to give a single plot [for example, for the value

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$\mathrm{Re_d}(\delta/d) = 1$, the bold curve in the figure] and to shift this plot to the left by the amount

$$-\frac{3}{8}\log\left[\mathrm{Re_d}\left(\frac{\delta}{d}\right)\right] \tag{15}$$

to obtain the filter performance for any value of $\mathrm{Re_d}(\delta/d) < 1$.

Although the plots shown in Figs. 1, 2, 3, and 5 are given for the range $V_m/V = 10^{-1}$–10^3, investigation of the experimental results in different areas in industry reveals that depending on the area for high filter performance (≥80%), V_m/V varies in specific ranges; for thermal power stations this range is 2–3, for nuclear and hydraulic plants it is 15–16 and 17–18, respectively. Figure 6 shows the ranges of values of particle concentrations (c) at the input and output of HGMF and the number (N) of industrial experiments they have measured (2), for different technological processes in industry. A detailed discussion of Fig. 6 is beyond the aim of this paper, however, a literature survey and research show that the indicated ranges of V_m/V as computed and arrived at are based on a sufficient number of experiments.

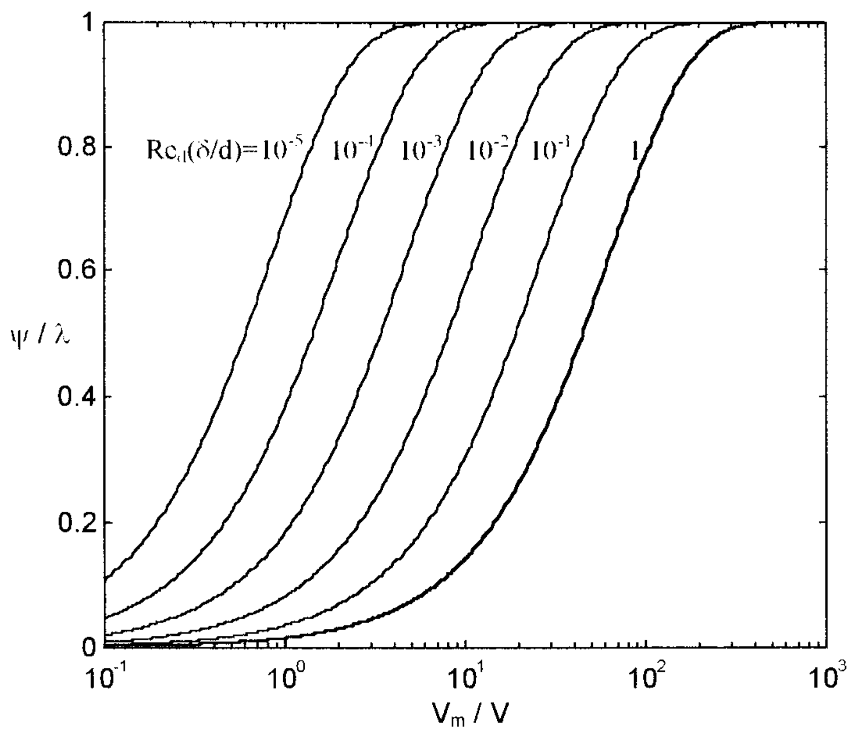

FIG. 5 Variation of filter performance versus V_m/V for different values of $\mathrm{Re_d}(\delta/d)$; a filter length of $L_d = 7.37$ and turbulent flow are assumed in the plots.

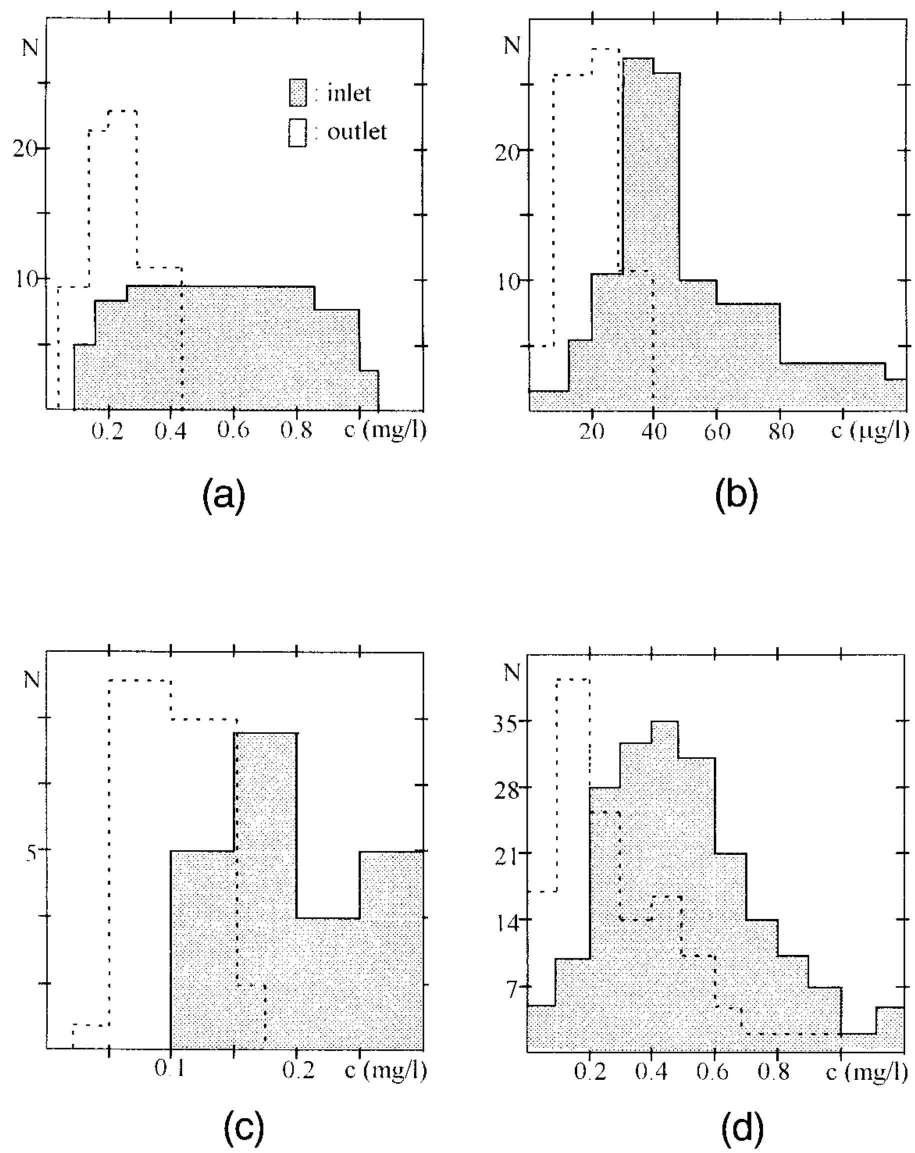

FIG. 6 Ranges of values of the inlet–outlet particle concentrations and the number of industrial experiments that they measured: (a) thermal power station, (b) hydroelectric power plant, (c) nuclear plant, (d) chemical industry. Computed range of V_m/V: (a) 2.5, (b) 17, (c) 15, (d) 3.

CONCLUSIONS

A general formulation is presented for the performance of high gradient magnetic filters which have a filter matrix composed of ferromagnetic spherical granules. The formula suggest that parameters affecting filter performance

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vary depending on the flow regime of the liquid through the pores. In laminar flow the performance depends on the dimensionless quantities V_m/V and L_d, while in turbulent flow it is also affected by the product $Re_d(\delta/d)$. The formulation presented leads to a single equation (Eq. 14) for both laminar and turbulent flows. Further, it makes it possible to justify filter performance for different values of this product (which includes many physical parameters such as interstitial velocity, viscosity of liquid, and diameters of the filter elements and particles) by simply shifting a template. Hence, depending on the values of filter parameters and of V_m/V (for which a range of values is determined in this article on the basis of many industrial experimental results scattered in the literature), the unknown filter performance can be determined or any filter can be designed to achieve the desired filter performance.

NOMENCLATURE

a	radius of matrix elements (spheres) (m)
C_δ	drag coefficient
C	coefficient in Eq. (5)
$\vec{d}$	diameter of the spheres (m)
$\vec{F}_A$	Archimedes force (N)
$\vec{F}_D$, F_D	drag force (N)
$\vec{F}_g$	gravitational force (N)
$\vec{F}_i$	inertial force (N)
F_m, F_m	magnetic force (N)
H_0	magnetic field intensity (A/m)
k	particle susceptibility
k_v	coefficient in Eq. (8)
L	filter length (m)
L_d	dimensionless length of the filter matrix normalized with respect to the diameter d of the spheres
M_s	magnetization of the particle (A/m)
r	radial distance (polar coordinate) from the contact points of the spheres (m)
r_a	dimensionless radial distance
R_{as}	limit (saturation) value of the capture radius r_a
Re_δ	Reynolds number which is expressed in terms of the diameter of the particles
Re_d	Reynolds number which is expressed in terms of the diameter of the spheres
u	absolute relative velocity of the particle with respect to liquid flow velocity in the pore (m/s)
V	filtration velocity (bulk velocity) (m/s)

V_m	magnetic velocity (m/s)
v_p	particle velocity (m/s)
w_p	particle volume (m^3)

Greek Letters

α	exponent in Eq. (5)
δ	particle size (diameter) (m)
η	dynamic viscosity ($Ns{\cdot}m^2$)
λ	ratio of the mass concentration of ferromagnetic particles to that of all particles in the liquid
μ_0	magnetic permeability of free space (H/m)
μ_r	relative magnetic permeability of the filter matrix elements
ν	kinematic viscosity of the liquid (m^2/s)
ρ	liquid density (kg/m^3)
ψ	filter performance

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