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Some problems of mass transfer in magnetic colloids near a filtrating element in high-gradient magnetic separation

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Abstract—Based on analytical and numerical solutions for the problems of unsteady-state diffusion and hydrodynamics, an analysis of the characteristics of mass transfer on a high-gradient magnetic separation (HGMS) filtrating element (transversely magnetized microcylinder) is carried out. The following problems have been considered: (i) the influence of boundary conditions on mass transfer rate, (ii) the effect of the relationship between the magnetophoretic transport and diffusion on mass transfer rate, (iii) mass transfer characteristics associated with the nonlinearity of the diffusion equation at high concentrations, (iv) hydrodynamic stability of a mixture in the presence of magnetic stratification. Experimental investigations have shown that the nonuniformity of magnetization in the course of the magnetophoresis of particles may lead to a kind of magnetodiffusional convection.

INTRODUCTION

DURING the early stages of HGMS studies the attention of investigators was primarily given to the means of separating magnetically weak, but comparatively large particles in a high-gradient field. Theoretical studies were based on calculations of the trajectories of particles in a potential or viscous flow around a filtrating element in the form of a magnetized cylinder or a sphere with account for the spatial distribution of magnetophoretic force. The predicted quantity, i.e. a capture radius, was used as the determining parameter in calculations of the separation characteristics of a real filter [1]. A vast amount of work is available in the present literature in which different aspects of this approach are refined to make the conditions of magnetic filter separation more realistic. In recent times attention has turned to the use of the HGMS technique for separating mixtures of submicron particles (see, e.g. refs. [2–5]). In this case, the description of the filtration process becomes more complicated because of the necessity to take into account the Brownian diffusion of particles. Hence, the trajectory technique breaks down and the problems of filtration should be considered as the problems of convective mass transfer. The problem is also complicated by the fact that the involvement of diffusion in the concentration equation requires a new boundary condition which is of fundamental importance for the filtration processes. Moreover, in a precise formulation of the problem for describing mass transfer on a filtrating element one should not overlook a number of new phenomena that owe their appearance to the fact that, with account for the magnetization of a mixture, the equations of convective diffusion, hydrodynamics and of the magnetic field become interrelated.

The problems of high-gradient magnetic separation are also of great interest for the specialists working in the field of ferrofluids. It appears that operation of many devices using magnetic fluids is greatly affected by the magnetodiffusion of colloidal particles. It is found that the containing pressure of ferrohydrodynamic seals is dependent on time [6] and that magnetodiffusion brings a complexity into the operation of magnetofluid printing devices [7]. In what follows, the basic mass transfer characteristics of magnetically polarizable fluids are described which have a close bearing to the operation of HGMS devices with separation of submicron particles.

EQUATIONS OF CONVECTIVE DIFFUSION IN A NON-UNIFORM MAGNETIC FIELD

The analysis carried out on the basis of the thermodynamics of irreversible processes shows that the mass flux of a paramagnetic component in a binary solution is governed by the equation [8]

$$\mathbf{j}_k = -D_k \nabla \rho_k + \frac{D_k}{c_k \mu_k^c}[-(V_k - V)(\nabla p_1 + \rho \mathbf{g}) + \mu_0 (M_k - M)\nabla H] \quad (1)$$

where D_k is the molecular diffusion coefficient of component k, M_k and V_k are the specific magnetization and specific volume of component k, respectively. To consider gravitational sedimentation independently and apart from pressure diffusion, the gravitational part of the pressure gradient is written separately: $\nabla p = \nabla p_1 + \rho \mathbf{g}$. It should be noted that the quantity M in the magnetodiffusional term of equation (1) stands for the specific magnetization of the medium: $M = cM_k$ ($c = \rho_k/\rho$ is the magnetic component concentration in the solution). A similar relationship is

NOMENCLATURE

a	particle radius
A_g	dimensionless parameter of gravitational precipitation
A_m	dimensionless parameter of magnetic precipitation
Bi	diffusional Biot number
c	volume fraction of particles
D_k	Brownian diffusivity of particles
H	magnetic field strength
K	parameter of magnetic saturation
m	magnetic moment of colloidal particles
M	specific magnetization
p	pressure
Ra	gravitational Rayleigh number (diffusional)
Rm	magnetic Rayleigh number (diffusional)
Sc	Schmidt number
Sh	Sherwood number
t	time
T	absolute temperature
v	flow velocity
x	longitudinal coordinate
y	transverse coordinate.

Greek symbols

α	dimensionless parameter of magnetophoresis
η	dynamic viscosity
μ	magnetic permeability
μ_0	magnetic constant
ν	kinematic viscosity
ξ	parameter of the Langevin function
ρ, θ	cylindrical coordinates
τ	diffusional Fourier number, Fo
Ψ	scalar magnetic field potential.

Subscripts

c	concentrational
g	gravitational
m	magnetic
0	at infinity
w	at the wall.

also valid for a magnetic colloidal solution of Brownian particles the diffusion coefficient of which is determined by the relation $D_k = kT/f$, where f is the hydrodynamic resistance coefficient (for spherical particles of radius a), $f = 6\pi\eta a$. As is known, the magnetization of colloids is rather well governed by the superparamagnetic approximation

$$M_k = M_s L(\xi), \quad L(\xi) = \operatorname{cth}\xi - \frac{1}{\xi}, \quad \xi = \frac{\mu_0 m_k H}{kT} \tag{2}$$

where $m_k = (4\pi/3)a^3 M_s$ is the magnetic moment of a particle, M_s is the saturation magnetization of the particle material.

Mass transfer in magnetic sedimentation is determined by solving the mass conservation equations jointly with the motion and continuity equations which, disregarding the negligible pressure diffusion under the effect of ∇p_1 and omission of the terms due to the mutual migration of mixture components, can be written in dimensionless form as [8, 9]

$$\frac{\partial c'}{\partial \tau} + \mathbf{v}' \cdot \nabla c' = \Delta c' + \nabla \times \left[A_g \frac{\mathbf{g}}{g} - A_m M_k'(1-c') \nabla H' \right] c' \tag{3}$$

$$\frac{1}{Sc}\left(\frac{\partial \mathbf{v}'}{\partial \tau} + (\mathbf{v}' \cdot \nabla)\mathbf{v}'\right) = -\nabla p_1' + \Delta \mathbf{v}' + Ra \frac{\mathbf{g}}{g} c' + Rm\, M_k' \nabla H' c' \tag{4}$$

$$\nabla \cdot \mathbf{v}' = 0. \tag{5}$$

Here $\mathbf{v}' = \mathbf{v}L/D_k$, $M_k' = M_k/M_0$, $p_1' = p_1 L^2/\eta D_k$, $\tau = D_k t/L^2$, $c' = c/c_0$, $H' = H/H_0$, $Ra = (V_k - V)gL^3\rho_0 c_0/\nu D_k$ and $Rm = \mu_0 M_0 H_0 L^2 c_0/\nu D_k$ are the gravitational and magnetic Rayleigh numbers, $Sc = \nu/D_k$ is the Schmidt number, A_g and A_m the dimensionless parameters of gravitational and magnetic sedimentation which, with account of $c_k \mu_k^c = kT/m_g$ [8] (m_g is the mass of a particle), can be written as $A_g = gL(V_k - V)m_g\rho_0/kT$, $A_m = \xi$. It follows from equations (3)–(5) that even in the case of maximum dilution, there might occur, besides forced convection, also free convection due to gravitational and magnetic stratification of a mixture.

The dimensionless parameters will now be estimated for magnetodiffusion of a magnetic colloidal solution in a non-uniform field in regard to the physical quantities typical of HGMS. Let the characteristic dimension of a filtrating element be $L = 10^{-4}$ m, $H_0 = 10^5$ A m^{-1} and the radius of colloidal particles be equal to $a = 5 \times 10^{-9}$ m. If their concentration is $c_0 = 10^{-4}$, the physical properties of the solution are almost the same as those of a carrier liquid, for example: $\rho_0 = 10^3$ kg m^{-3}, $\nu = 10^{-6}$ m^2 s^{-1}, $D_k = 5 \times 10^{-11}$ m^2 s^{-1}, $(V_k - V) = 8 \times 10^{-4}$ m^3 kg^{-1}, $M_0 = 80$ A m^2 kg^{-1}. These estimates yield the following dimensionless values: $Sc = 2 \times 10^4$, $Ra = 20$, $Rm = 2 \times 10^5$, $A_g = 6 \times 10^{-5}$, $A_m = 6$. When the radius of particles increases, Ra and Rm decrease, while A_g and A_m increase. The increase of the size of the filtrating element leads to higher ratios A_g/A_m, i.e. to the higher contribution of gravitational convection. Yet, the influence of gravitational effects in colloidal systems is generally negligible as compared with magnetic effects in a high-gradient field. The above estimates demonstrate that the HGMS of Brownian particles differ qualitatively from the HGMS of micron-size particles. The gravitational precipitation of particles is negligibly small, but at the same time the possibility is offered for the variation of mass transfer by magnetic convection which exerts a strong influence on the filtrating efficiency in the course of HGMS.

MASS TRANSFER DURING MAGNETODIFFUSION IN THE BOUNDARY LAYER

Allowance for the Brownian diffusion in magnetic separation problems brings about an increase in the order of the mass transfer differential equation. Therefore, a new boundary condition for concentration should be formulated. Some of the authors [2–4] adopt the condition of a closed surface, $j_w = 0$, which undoubtedly can be applied only to an ideally stable mixture, for example, to a specially stabilized ferrofluid. However, our experience shows that in this case too, especially in the presence of a high field gradient directed along the surface, a portion of colloidal particles precipitates irreversibly onto mass transfer surfaces [8]. Several works have been reported [10, 11] which deal with the kinetics of magnetic flocculation of colloidal dispersions in a non-uniform field. However, the aspects of the interaction of particles with an extended surface are not as yet generally known and, therefore, as of now the only possibility is to formulate the third-kind boundary conditions by analogy with heterogeneous chemical reactions in molecular solutions. Since the reaction of particle precipitation appears to be of the first order, the boundary condition can be assumed as linear: $j_w = \gamma c_w$, where γ is the particle adsorption rate constant. The quantity γ in this statement needs to be determined from experiment.

Now, the specific features of mass transfer brought about by surface processes will be considered using as an example one-dimensional unsteady-state diffusion in the boundary layer at $\mathbf{v} = 0$, $A_g = 0$ and $A_m M_k' \nabla H' = \alpha = \text{const}$. The solution of equation (3) in the maximum dilution approximation in the case of a dimensionless mass flux on the wall $Sh = j_w x / c_0 D_k$ (Sherwood number) yields [12]

$$Sh = \left(\frac{\alpha}{2} + Bi\right) e^{(\alpha + Bi)Bi\tau} \operatorname{erfc}\left(\alpha + \frac{Bi}{2}\right)\sqrt{\tau} - \frac{\alpha}{2}\operatorname{erfc}\left(\frac{\alpha}{2}\sqrt{\tau}\right). \quad (6)$$

As seen from relation (6) presented in Fig. 1, the effect of magnetic sedimentation on the concentrational boundary layer bears a close analogy to the blowing or suction of a boundary layer. At positive values of the parameter α a pattern is observed similar to the boundary layer displacement in porous injection. At negative values of α, conversely, the curves of the

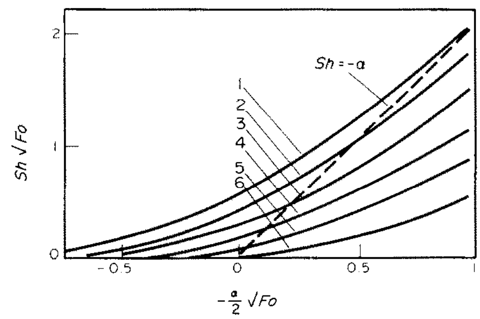

FIG. 1. Mass transfer in the boundary layer at different values of $Bi\sqrt{\tau}$: 1, ∞; 2, 1; 3, 0.5; 4, 0.3; 5, 0.2; 6, 0.1 ($\tau = Fo$).

mass transfer coefficients asymptotically approach the relation $Sh = -\alpha$, which corresponds to the conditions of conductive transport of substance in intensive suction. In our problem this region fits a situation when the mass transfer rate is determined solely by the magnetophoretic transport of particles to the mass transfer surface. The Biot number $Bi = \gamma x / D_k$ has a marked effect on the transition from the diffusional to the phoretic regime of mass transfer. At large values of Bi this transition terminates at the values of $\alpha\sqrt{\tau}$ of order -2; with a decreasing Bi the critical value of α^* increases as $\alpha^* \sim (Bi\tau)^{-1}$.

In the case of a closed surface $j_w = 0$, when $Bi \to 0$, equation (6) gives

$$\frac{c_w}{c_0} = \left(1 + \frac{\alpha^2}{2}\tau\right)\operatorname{erfc}\left(\frac{\alpha}{2}\sqrt{\tau}\right) - \alpha\sqrt{\left(\frac{\tau}{\pi}\right)}\, e^{-(\alpha^2/4)}. \quad (7)$$

It is seen that at negative α the concentration of particles in the boundary layer increases with time as $c_w/c_0 = \alpha^2\tau$, therefore, the infinite dilution approximation becomes inadequate. In this case equation (3) would be nonlinear even at constant values of D_k and α. In this case the problem of one-dimensional diffusion can be solved by the integral method [13]. The relation $c_w = f(\alpha\sqrt{\tau})$ for a closed surface at several values of c_0 is presented in Fig. 2. At positive values of α the solution of the non-linear problem agrees well with exact solution (7). At negative α, due to magnetophoretic force saturation in equation (3), the increase of the concentration of particles on the mass transfer surface becomes slower. The larger the initial concentration c_0, the sooner the steady-state distribution of concentration is attained in the boundary layer. This is in agreement with the results of experiments obtained when studying the time dependence of containing pressure of ferrofluid seals with magnetic fluids of various concentrations [6, 14]. It should be noted that at high concentrations the diffusion equation may also become nonlinear because of the relative motion of particles and of the carrier liquid, as well as due to the interaction of particles [4, 11]. According to ref. [4], the mobility of particles in highly concentrated colloids decreases even more than it follows from equation (1):

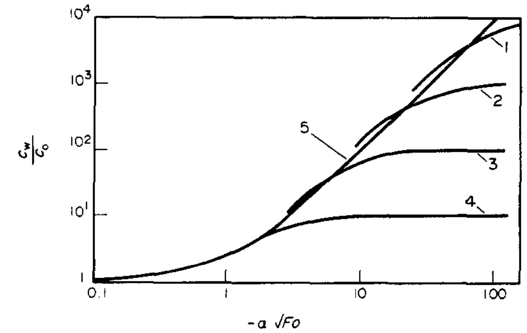

FIG. 2. Concentration of particles on the wall ($Bi = 0$) at different values of c_0: 1, 10^{-4}; 2, 10^{-3}; 3, 10^{-2}; 4, 10^{-1}; 5, exact solution (6) for $c_0 \to 0$.

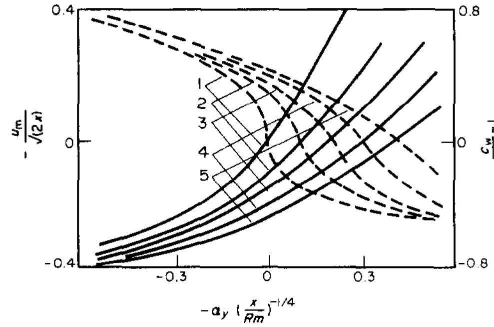

FIG. 3. Mean convection velocity in the boundary layer (dashed lines) and concentration of particles on the wall (solid lines) at different values of $Bi/Rm^{-1/4}$: 1, 0; 2, 0.1; 3, 0.2; 4, 0.3; 5, 0.4.

$n = n_0(1-6.55c)$. Moreover, there is also an increase of the diffusion coefficient: $D_k = D_0(1+1.45c)$. An approximate method of the solution of boundary layer equations [13] allows one to take into account these relations.

The novel phenomenon for magnetic filtration is magnetic convection in colloidal solutions. It is known [8] that non-threshold convection in an isothermal magnetic fluid without taking into account pressure diffusion occurs when

$$Rm\, M_k' \nabla c' \cdot \nabla H' \neq 0. \tag{8}$$

Since both the magnetic force in the equation of motion (4) and the magnetophoretic force of particle transport in the diffusion equation (3) depend on the same vector factor $M_k \nabla H$, condition (8) is evidently fulfilled only in the case when the mass transfer boundary surfaces are not orthogonal to the vector $M_k \nabla H$. As the simplest example, consider the problem of steady-state magnetodiffusional convection in a flat boundary layer, when the vector $M_k \nabla H$ is directed at a certain angle to the mass transfer surface. In the Boussinesq linear approximation, the problem can be solved by using the local similarity method combined with the integral technique [8]. Figure 3 presents the predicted concentrations on the wall and mean convection velocity

$$u_m = \delta^{-1} \int_0^\delta u \, dy$$

for different values of the Biot number for the case when $Sc \to \infty$ typical of magnetic colloidal solutions. It is seen that convection in the boundary layer changes its direction at $\alpha = Bi$, when the concentration of particles across the entire boundary layer is uniform and equal to c_0 (here $M_k \nabla H =$ const.). For a closed surface ($Bi = 0$) at small values of the parameter $\alpha_y (Rm)^{-1/4}$, the solution of the boundary layer problem gives a simple analytical relation for the mean convection velocity

$$\frac{u_m}{D_k}\sqrt{\left(\frac{L^3}{2 \times RM}\right)} = 0.387\left[\alpha_y\left(\frac{x}{LRm}\right)^{-1/4}\right]^{0.4}. \tag{9}$$

To obtain numerical estimates, the following values will be used which are characteristic of HGMS: $H_0 = 8 \times 10^3$ kA m^{-1}, $L = 10^{-4}$ m, $c_0 = 10^{-3}$. For magnetic particles of radius 10^{-8} m in kerosene, equation (9) yields $u_m = 5.4$ mm s^{-1}. The velocity of convection increases with the size of particles reaching 85.5 mm s^{-1} at $a = 10^{-6}$ m. Consequently, diffusional magnetic convection can be quite vigorous and even comparable in magnitude with the filtration rate in HGMS.

MASS TRANSFER ON A HGMS FILTRATING ELEMENT

Usually, a filtrating element in HGMS is taken to be a transversely magnetized microcylinder with the magnetic permeability μ_i. When the magnetic permeability of the surrounding fluid μ_a is small in comparison with μ_i and the dependence of μ_a on both the field and spatial coordinates can be neglected, the magnetic field distribution near the cylinder in an external homogeneous field H_0 can be described by the simple magnetic potential expression in the form $\Psi = -K(r/r_0)\cos\theta$, where $K = (\mu_i - \mu_a)/(\mu_i + \mu_a)$ is the cylinder magnetic saturation coefficient, θ is the angle between the radius vector and the direction of the magnetic field. The problem of mass transfer on the cylinder can be solved analytically only in the case of non-diffusional approximation and without taking into account convection [15]. When both the Brownian diffusion and magnetic convection were taken into account, the problem was solved numerically by the finite difference method [9]. Some of the predicted results for the concentration field around a non-saturated cylinder with $K = 1$ and the closed wall ($j_w = 0$) are given in Fig. 4(a), in non-diffusional approximation; Fig. 4(b), taking into account the Brownian diffusion; Fig. 4(c), taking into account diffusional magnetic convection. The pattern of the concentration distribution corresponds to the time $\tau = 0.14$ at the following magnetic parameters: $A_m = 2$, $Rm = 5 \times 10^5$. The isoconcentration lines in Fig. 4 have the spacing of $\Delta c' = 0.12$. Without regard for the

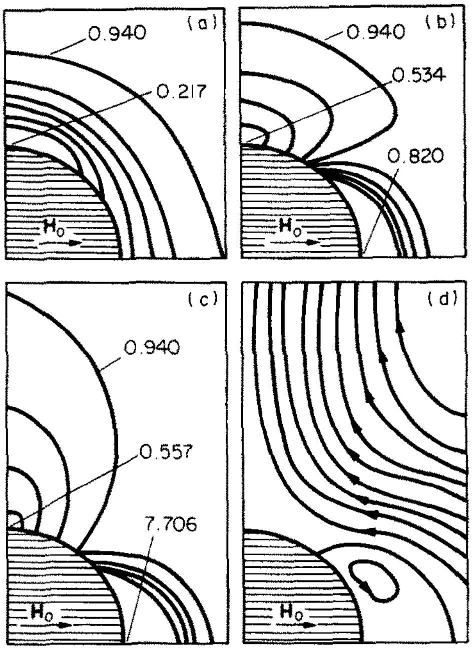

FIG. 4. Concentration field near the transversely magnetized cylinder: (a) non-diffusional approximation [17]; (b) Brownian diffusion of particles is taken into account; (c) with account for diffusional convection; (d) stream function lines in magnetic convection, $Fo = 0.14$, $\alpha = 2$, $Rm_c = 5 \times 10^5$.

Brownian diffusion, the concentration of particles near the cylinder surface decreases not only in the regions where they move away (near $\theta = \pm\pi/2$), but also in the regions of their arrival (near $\theta = 0$ and π). This is associated with a sharp acceleration of particles near the surface according to the law const./r^5. Under steady-state conditions when $\tau \to \infty$ the concentration at the point $\theta = 0$ monotonously approaches the value $c' = 0.25$. When the diffusion of particles is taken into account, the picture of the process varies substantially. In the regions with $\theta = \pi/2$ the concentration decreases as before, but on the surface it is higher than in the case of the non-diffusional approximation. At the same time, in the region of the accumulation of particles near $\theta = 0$ the concentration increases drastically. This increase slows down gradually with an increasing Biot number. It should be noted that high sensitivity of c_w to Bi at $\theta = 0$ offers encouragement for the possible experimental determination of the rate of particle precipitation on a surface.

Figure 4(d) presents the results obtained from a simultaneous solution of the diffusion and convection equations. The development of the concentration field around the cylinder is accompanied by intensive convective motion, with the convection being of non-threshold type, since the magnetic force $M_k \nabla H$ is not orthogonal either to the surface $r' = 1$ or to the iso-concentration lines. Four large eddies are formed that close at infinity (Fig. 4(d)). Moreover, at a certain instant of time four symmetric microeddies are formed near the cylinder surface. The convection noticeably changes the configuration of the concentration field. Just as in thermal convection in the temperature field, convective plumes are formed in the regions of the greatest repulsion at $\theta = \pm\pi/2$. In the regions with $\theta = 0$ and π, convection leads to an increase of concentration as compared with the prediction without regard for convection. Thus, magnetic convective motion enhances mass transfer on a filtrating element. Note that the magnetic parameters α and Rm in HGMS may be even higher than those used in numerical calculations the results of which are given in Fig. 4.

MEASURED CONCENTRATIONS OF PARTICLES IN HGMS IN MAGNETIC FLUIDS

To verify the results obtained, experiments were conducted to study the mass transfer of colloidal particles of a magnetic fluid near a transversely magnetized microcylinder. The experiments were carried out using a holographic microinterferometry technique [16]. The concentration field was determined by the method of double exposition. In order to avoid thermal convection, the test cell was thermostatically protected. Experiments were carried out with diluted magnetite colloidal solutions in kerosene and water. The colloids were stabilized with oleic acid or other strong surfactants. In addition to electronic-microscopic measurements, the concentration and size of particles were also determined from the curve of sample magnetization measured by a vibration sample magnetometer. For this purpose it was assumed that the magnetization of fluid obeyed the Langevin function (2). To estimate the degree of the mixture polydispersity, the size of particles was determined from the initial magnetic susceptibility and from the asymptotic relation $M_k = f(1/H)$ in strong fields. For different samples the mean particle radius varied over the range from 5 to 9 nm with the halfwidth of the dispersion curve of the order of 30–40%. In order to exclude the uncertainty in the determination of K, measurements were taken at small values of the magnetizing field H_0 which did not exceed 0.15 T. In this case $K = 1$ irrespective of the magnetic permeability of the material of the filtrating element. Moreover, mass transfer near the cylinder involved the initial region of the magnetization curve with $\xi \ll 1$, thus allowing a comparison of experimental results with numerical studies performed in the paramagnetic approximation $M_k = \kappa H$.

Experiments conducted with different magnetic fluids show that the concentration distribution of particles depends strongly on the aggregation stability of a colloid. In non-stable dispersions, irreversible sedimentation of particles on the cylinder surface in the regions near $\theta = 0$ and π was observed. Holograms show a decrease in the concentration gradient near the surface, which is typical for mass transfer problems with the Biot number being different from zero.

Unfortunately, it is difficult to obtain high quality holograms, since, because of the relatively small volume of the test cell, the precipitation of particles on the filtrating element leads to a decrease of the mean particle concentration in the solution, and the interference bands on the holograms gradually disappear. Moreover, it is difficult to carry out a quantitative analysis because of the change in the profile of the filtrating element due to a dense layer of precipitated particles. In kerosene based magnetic fluids, it is possible to completely rule out the possible particle precipitation on the cylinder surface, especially at small magnetic field strengths, by taking necessary means to ensure that the adsorption layers of surfactants are preserved on particles on dilution. In this case, mass transfer near the surface of the filtrating element corresponds to the condition $j_w = 0$.

A typical interferogram photograph of the concentration distribution in a stabilized colloidal solution of magnetite in kerosene with oleic acid as a stabilizer is presented in Fig. 5 ($c_0 = 0.18$ wt %). The experiment was conducted under such conditions that the dimensionless mass transfer parameters were nearly the same as those used in the numerical solution given in Fig. 4. The difference in the concentrations of the two neighbouring interference bands is the same as in Fig. 4 and is equal to $\Delta c' = 0.12$. It is seen from Fig. 5 that in the regions close to $\theta = \pm\pi/2$ there is a decrease of concentration which is characteristic of paramagnetic separation, whereas in the maximum field regions at $\theta = 0$ and π near the cylinder surface, there is a sudden growth of concentration which is specific to magnetophoresis combined with the Brownian diffusion of particles on a closed surface. Accurate determination of c_w at $\theta = 0$ is difficult not only because of the fine structure of interference bands, but also because of a considerable decrease in the optical transparency of the wall layer due to a high increase in the concentration of particles. Comparison of Figs. 4 and 5 shows that the interference picture of the concentration field is in good agreement with theoretical results obtained with account for the magnetic diffusional convection.

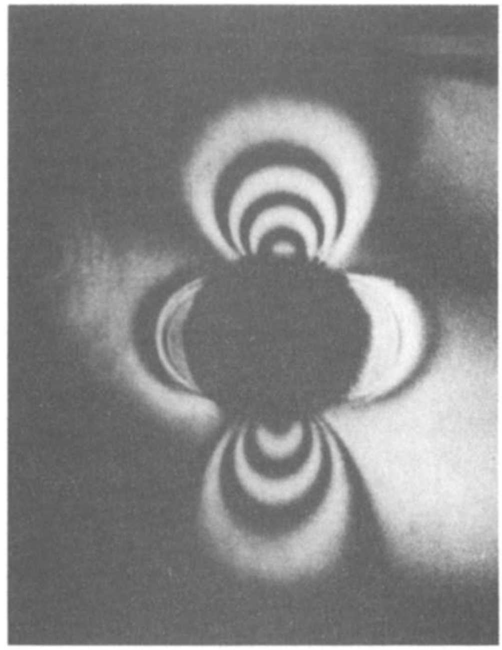

FIG. 5. The interferogram photograph of the concentration field. The cylinder of 0.65 mm radius in a uniform magnetic field with $B_0 = 0.065$ T, $t = 1800$ s. Magnetite in kerosene, particles of radius $a = 6$ nm.

CONCLUSION

The results obtained clearly demonstrate that mass transfer of Brownian particles in HGMS differs, in principle, from that of large particles. Great attention should be paid to the conditions of particle sedimentation on the surfaces of filtrating elements which depend to a considerable extent on the kinetics of the magnetic flocculation of colloidal dispersions. Also essential is the problem of diffusional magnetic convection which may have a marked influence on the efficiency of HGMS, especially when filtrating elements are not very tightly packed. Some other problems may turn up in the case of large concentrations of a magnetic phase in a fluid. For instance, the magnetic field distribution near a filtrating element becomes dependent on the concentration of particles and, consequently, the mass transfer problem requires a combined solution of the diffusion and magnetic field equations. The intrinsic field of a magnetic colloid affects the stability of diffusion fronts. It was shown in ref. [17] that magnetostatic instabilities lead to a microconvective agitation of diffusional layers and to the enhancement of mass transfer.

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QUELQUES PROBLEMES DE TRANSFERT DE MASSE DANS LES COLLOIDES MAGNETIQUES D'UN ELEMENT FILTRANT DANS UNE SEPARATION A FORT GRADIENT MAGNETIQUE

Résumé—On développe une analyse des caractéristiques du transfert de masse pour une séparation magnétique à gradient élevé (HGMS) à partir de solutions analytiques et numériques (microcylindre transversalement magnétisé). Les problèmes suivants sont considérés : (1) l'influence des conditions aux limites sur le transfert de masse, (2) l'effet de la relation entre le transport magnétophorétique et la diffusion sur le transfert de masse, (3) les caractéristiques du transfert de masse associées à la non-linéarité de l'équation de diffusion aux fortes concentrations, (4) stabilité hydrodynamique d'un mélange en présence de la stratification magnétique. Des études expérimentales montrent que la non-uniformité de la magnétisation au cours de la magnétophorèse des particules peut conduire à une sorte de convection magnéto-diffusionnelle.

PROBLEME DER STOFFÜBERTRAGUNG IN MAGNETISCHEN KOLLOIDEN AN EINEM FILTERELEMENT BEI STARKER MAGNETISCHER TRENNUNG

Zusammenfassung—Auf der Grundlage von analytischen und numerischen Lösungen für instationäre Probleme der Diffusion und der Hydrodynamik wurde eine Untersuchung des Stoffübergangs an Filterelementen (transversal magnetisierte Mikrozylinder) bei starker magnetischer Trennung durchgeführt. Folgende Probleme werden betrachtet: (a) der Einfluß der Randbedingungen auf die Stoffübertragung; (b) die Auswirkung des Verhältnisses zwischen magnetophoretischem Transport und Diffusion auf die Stoffübertragung; (c) Stoffübergang in Verbindung mit der Nichtlinearität der Diffusionsgleichung bei hohen Konzentrationen; (d) die hydrodynamische Stabilität eines Gemisches bei magnetischen Einwirkungen. Experimentelle Untersuchungen haben gezeigt, daß die Ungleichförmigkeit der Magnetisierung im Verlauf der Teilchenmagnetophorese zu einer Art von magnetodiffusionaler Konvektion führen kann.

НЕКОТОРЫЕ ПРОБЛЕМЫ МАССОПЕРЕНОСА СУБМИКРОННЫХ ЧАСТИЦ ВБЛИЗИ ФИЛЬТРУЮЩЕГО ЭЛЕМЕНТА ПРИ ВЫСОКОГРАДИЕНТНОЙ МАГНИТНОЙ СЕПАРАЦИИ

Аннотация—Основываясь на аналитических и численных решениях задач нестационарной диффузии и гидродин амики, в работе проведен анализ особенностей массообмена на фильтрующем элементе ВГМС в виде пеперечно намагниченного микроцилиндра. Рассматриваются следующие проблемы: (1) влияние граничных условий на интенсивность массообмена; (2) влияние соотношения между магнитофоретическим транспортом и диффузией на интенсивность массообмена; (3) особенности массопереноса, связанные с нелинейностью уравнения диффузии при больших концентрациях; (4) гидродинамическая устойчивость смеси при наличии магнитной стратификации. На основании результатов экспериментальных исследований показано, что неоднородность намагниченности при магнитофорезе частиц может привести к свособразной магнитодиффузионной конвекции.