

Diffusive and thermodiffusive transfer of magnetic nanoparticles in porous media^{*}

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Abstract. Experimental results on mass transfer within a thin porous layer saturated with ferrofluid are outlined in this paper. From the analysis of particle concentration distribution across the layer it is shown that both the mass diffusion and the Soret coefficients of nanoparticles are remarkably less than those measured in free fluid. The particle transport coefficient changes due to an external uniform magnetic field qualitatively well agree with the predictions of existing theoretical research. The magnetic field that is oriented transversely to the porous layer causes an increase in the diffusion coefficient and a decrease in the Soret coefficient whilst the longitudinal field causes a reduction of the mass diffusion and an intensification of the particle thermodiffusion.

1 Introduction

A strong anisotropic magnetic Soret effect in ferrocolloids has been recognized [1]. Theory says that direct influence of a field on nanoparticle thermophoretic motion is limited; the main reason of magnetic Soret effect is changes in the mass diffusion under the effect of internal magnetic field gradients due to development of a non-uniformity of particle concentration. The main conclusions of the theory of magnetic Soret effect have been confirmed experimentally. Two principally different techniques, relaxation measurements of optically induced thermal grating in thin ferrofluid layers [2,3] and direct measurements of particle dynamic separation in thermodiffusion columns [4–6], both testify the theoretically predicted anisotropy of nanoparticle Soret coefficient in the presence of magnetic field. Unfortunately, both measurement techniques allow obtaining quantitatively safe results only in case of relatively small magnetic fields [7]. Under stronger fields the separation process is disturbed by appearance of thermomagnetic convection. To avoid the influence of this parasitic convection, mass transfer experiments are performed employing thin ferrofluid layers which are delimited by permeable walls [8] or by measuring the particle transfer through porous membranes [9]. Whilst nanoparticle size remains significantly less than the size of pores, we may believe that the transport properties of the ferrocolloid are close to those of homogeneous dispersion.

However, in filters of low porosity and of small grains the diffusive and thermophoretic transport of nanoparticles may be supported by specific magneto-osmotic phenomena [10] and by originating of a thermomagnetic pressure gradient due to the difference in fluid temperatures on both sides of the layer [11]. In order to eliminate these parasitic processes, in the research presented in this paper we have performed particle transfer experiments in a ferrofluid-saturated porous layer enclosed within rigid non-permeable walls.

2 The physical model

2.1 Formulation of the physical situation

Transfer of the magnetic nanoparticles of a ferrofluid is investigated in a porous layer of a flat cylindrical shape. The layer is composed of ten coaxial, tightly packed sub-layers. The mass transfer coefficients are evaluated from measurements of particle concentration across the layer, where the mass transfer is initiated in two ways: a) the development of concentration profile from initial stepwise distribution (in this case experiments are referred to as diffusion experiments) and b) development of concentration difference from a homogenous distribution due to the application of a temperature difference on fluid borders (thermodiffusion experiments). The cases are summarized in fig. 1.

In all experiments, there is no mass flux through any wall. In thermodiffusion experiments (fig. 1a), a temperature gradient is set along the cylinder's axis, which is aligned with gravitational field. Temperatures at top and

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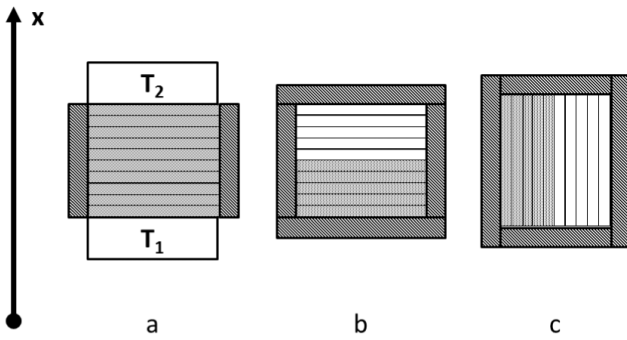


Fig. 1. Layouts of porous layers in various experiments. Case a: thermodiffusion experiments; b: diffusion experiments, magnetic field parallel to concentration gradient; c: magnetic field diffusion experiments, magnetic field normal to concentration gradient.

bottom walls are kept constant, with $T_{\text{top}} > T_{\text{bottom}}$. There is no heat flux through the side walls. The external magnetic field, if present, is also aligned with temperature gradient and gravity field. As stated, the initial concentration distribution of magnetic particles is homogenous throughout the porous environment.

In diffusion experiments, likewise, no mass flux through any wall is allowed. However, no temperature gradient is present and no heat flux through top and bottom walls is allowed. Five of the ten sub-layers are homogeneously saturated with ferrofluid, while the other five are saturated with pure carrier fluid. Two configurations of the experiment are used. In one, referred to as “parallel” configuration (fig. 1b) initial concentration gradient is aligned with gravitation field and external magnetic field, if present. In the other (“normal”; fig. 1c), the porous layer is inclined by a straight angle, so that the initial concentration gradient is normal to the external magnetic (if present) and gravitation fields.

2.2 Unsteady diffusion of ferroparticles in a flat layer partially filled with ferrofluid

Let us consider the development of a concentration profile of nanoparticles in a flat layer of thickness $2a$. Initially, one half of the layer at $a > x > 0$ is filled with a ferrofluid of particle concentration $c = 2c_0$ whereas the second half at $0 > x > -a$ is filled with the corresponding carrier liquid. We introduce C as $C = c/c_0 - 1$, where $c = c(x, t)$ denotes the actual particle volume concentration. It is important to note that the volume concentration here is that of particles in the ferrofluid, regardless of what volume share of porous environment the fluid takes. Treating ferrofluid as a binary mixture, where the solid phase is made of magnetic nanoparticles along with their surfactant layer, we can use equations for colloid mass transfer [1]. The development of concentration profile of nanoparticles is governed by the diffusion equation written in non-dimensional form

$$\frac{\partial C}{\partial \tau} = \frac{\partial^2 C}{\partial X^2}, \quad (1)$$

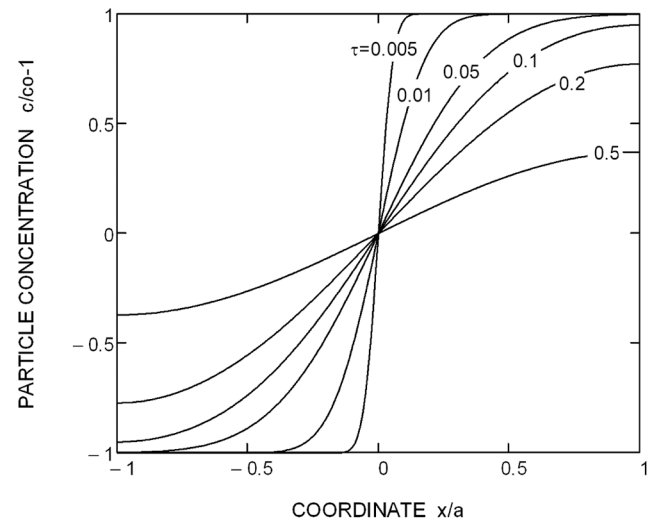


Fig. 2. Particle concentration distribution in diffusion experiments at different values of τ .

with boundary conditions

$$\left. \frac{\partial C(X, \tau)}{\partial X} \right|_{X=1} = \left. \frac{\partial C(X, \tau)}{\partial X} \right|_{X=-1} = 0. \quad (2)$$

Here $\tau = \frac{Dt}{a^2}$, $X = \frac{x}{a}$. The initial stepwise distribution of concentration at $t = 0$ may be presented in a form of Fourier expansion

$$C(X, 0) = 2 \sum_{k=1}^{\infty} \frac{\sin(\beta_k X)}{\beta_k}, \quad (3)$$

with $\beta_k = (2k - 1)/\pi$. The solution to eq. (3) is then

$$C(X, \tau) = 2 \sum_{n=1}^n e^{-\beta_n^2 \tau} \frac{\sin(\beta_n X)}{\beta_n}. \quad (4)$$

The development of concentration distribution curves is shown in fig. 2. The numbers in the frame denote values of time τ . At low τ the development of concentration profile may be described employing the unsteady boundary layer approximation. The solution of boundary layer equation by Laplace transformation for this regime gives

$$C(X, \tau) = \text{erf} \left(\frac{X}{2\sqrt{\tau}} \right). \quad (5)$$

If $\tau > 0.1$ only the first summand in (4) should be taken into account when analyzing the concentration profiles (the so called “regular regime”). For layers of thickness $2a = 1$ mm this regime corresponds to the duration of the experiment approximatively equal to 24 hours.

2.3 Development of particle concentration under non-isothermal conditions

Let us consider the development of particle concentration in ferrofluid layer of non-permeable ends at $x_L = \pm a$, the

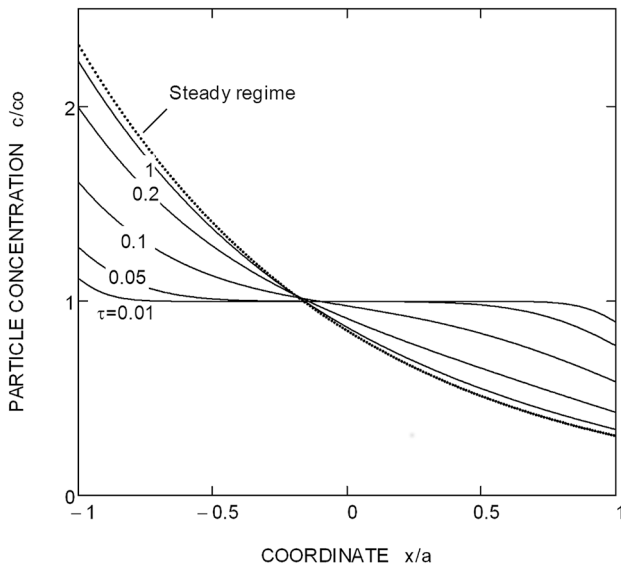


Fig. 3. Particle concentration distribution in thermodiffusion experiments at $k = 1$ and different values of τ .

sedimentation force is aligned along the x axis. The mass transfer equation, initial and boundary conditions obey the following non-dimensional form:

$$\frac{\partial C}{\partial \tau} = \frac{\partial^2 C}{\partial X^2} + k \frac{\partial C}{\partial X},$$

$$\frac{\partial C}{\partial X} \Big|_{X=\pm 1} + kC|_{X=\pm 1} = 0 \quad \text{and} \quad C|_{t=0} = 1. \quad (6)$$

Here $C = \frac{c}{c_0}$, where $c = c(x, t)$ with c_0 being the initial uniform particle volume concentration at $t = 0$; $k = S_T \Delta T / 2$, with S_T the particle Soret coefficient and ΔT the difference in wall temperatures $\Delta T = T(a) - T(-a)$.

Implementing the Laplace transform for solving the problem, we obtain the following dependence of distribution of concentration across the channel:

$$C(X, \tau) = 1 - k \sum_{n=0}^{\infty} \frac{4i\beta_n [1 - e^{-\frac{1}{4}(\beta_n^2 + k^2)\tau}]}{\cos \beta_n (\beta_n^2 + k^2)^2}$$

$$\times \left[(k - i\beta_n) \sinh(k + i\beta_n) e^{-(\frac{k}{2} - i\frac{\beta_n}{2})X} - (k + i\beta_n) \sinh(k - i\beta_n) e^{-(\frac{k}{2} + i\frac{\beta_n}{2})X} \right]. \quad (7)$$

Here $\beta_n = n\pi$.

The development of concentration profiles across the layer is shown in fig. 3. At the initial stage of separation when $\tau \ll 1$ the development of concentration profile near the layer walls follows the formula which is obtained under the boundary layer approximation:

$$C(X, \tau) = 1 \pm \frac{2k\sqrt{\tau}}{\sqrt{\pi}}$$

$$\times \left[e^{-\frac{(X \pm 1)^2}{4\tau}} - \sqrt{\frac{\pi}{\tau}} \frac{X \pm 1}{2} \operatorname{erfc} \left(\frac{X \pm 1}{2\sqrt{\tau}} \right) \right]. \quad (8)$$

However, a more beneficial regime for the determination of the Soret coefficient is the steady distribution of particles which is reached in durable experiments approximately at $\tau > 1$. The condition of steadiness of the mass transfer inside the layer together with the mass conservation equation $\int_{-a}^{+a} c(x) dx = 2c_0$ gives the following simple distribution of particles across the channel:

$$C(X, \tau) = \frac{k \exp(-kX)}{\sinh k}. \quad (9)$$

For layers of thickness $2a = 1$ mm this regime again corresponds to the duration of the experiment approximately equal to 24 hours.

3 Experimental methodology

3.1 Experimental setup and methods

The porous layer used in experiments is $\delta = 1.3$ mm in height and $d_{\text{layer}} = 67$ mm in diameter. The layer itself is made of ten sheets of filter paper saturated with ferrofluid (or carrier liquid) and pressed together to form a continuous porous environment. Filter material has been found to be inert to components of ferrofluids used in our experiments. Porosity of the layers is measured as the ratio of free (or pore) volume to total volume of the porous material and found to be $\varepsilon = 0.33$. Pore diameters are specified by the manufacturer to be in range $d_{\text{pore}} = 9\text{--}20$ μm . The temperature difference between top and bottom walls in thermodiffusion experiments is $\Delta T = 40$ K. The magnetic field, when present, is applied by an electromagnet with an iron core. Since the size of the core exceeds that of the experimental device itself, magnetic field is easily homogeneous, as is confirmed by measurements.

Only final states of each experiment are investigated. Particle distribution is attained by splitting the layers apart after the experiment is finalized and measuring magnetic particle concentration in samples from each layer individually. Concentration of magnetic material is determined from magnetization $M = \varphi M_S$, where M_S denotes saturation magnetization of the material. Magnetization of the samples is measured using a vibration sample magnetometer (Lake Shore Cryotronics Co., model 7404 VSM). Absolute accuracy of measurements is given by the manufacturer to be better than 2% of the reading value. Experimental work has, however, shown that the measurement error for particle concentration will be higher, which is largely attributed to a parasitic processes taking place upon ending the experiment, including the splitting of the layers. Resulting accuracy is estimated to be around 10% of the measurement value.

3.2 Overview of ferrofluids used in experiments

Two major types of ferrofluids are identified by the method of colloidal stabilization. Aggregation of particles is countered either by applying a surfactant to form

Table 1. Properties of magnetic fluids.

Ferrofluid:	df-105	S-1	U5	FF13-04
Particle material	Fe ₃ O ₄	Fe ₃ O ₄	Fe ₃ O ₄	Fe ₂ O ₃
Carrier fluid:	tetradecane	tetradecane	undecane	water and citrate
Method of stabilization:	surfaced	surfaced	surfaced	ionic
Surfactant	oleic acid	oleic acid and lauric acid	oleic acid	–
Most expected particle moment (A m ²)	2.29E-19	2.96E-19	2.34E-19	6.46E-19
Most expected particle diameter (nm)	9.64	4.72	9.70	13.60
Particle volume concentration (%)	4.75	1.48	4.00	0.87
Soret coefficient in free fluid (1/K)	0.15	0.02	0.15	0.00
Diffusion coefficient in free fluid (m ² /s)	1.86E-11	4.05E-11	3.50E-11	1.34E-11

a layer of molecules that covers the particles, or forming a double ionic layer around the particles. Both kinds of ferrofluid are used in experiments described in this article. Surfactant-based ferrofluids are manufactured at the Institute of Physics, University of Latvia, while the single ionic ferrofluid is provided by the Department of Theoretical Physics, University of Latvia. Oleic acid and lauric acid used as surfactants were provided by Sigma-Aldrich.

An overview of ferrofluids used is given in table 1. The values of Soret coefficient are measured directly with the method of Forced Rayleigh scattering, while diffusion coefficients are either measured in magnetic grating experiments or calculated from Stokes' formula. The accuracy of S_T measurements is estimated to be approximately 10% due to lack of detailed information about the colloid optical refractive index [12], while the accuracy of D measurements is about 5%, the uncertainty is mostly due to particle polydispersity.

It should be noted that, while a ferrofluid with ionic stabilization could have a negative Soret coefficient, the ionic ferrofluid FF 13-04 actually has a Soret coefficient $S_T = 0$ —no particle transfer under temperature field was observed in free fluid in forced Rayleigh scattering experiments.

3.3 Convective stability analysis

It is necessary to ensure that the diffusive mass transfer is not disrupted by convective flow. In the presence of Soret effect the convective processes in fluid-saturated porous layers should be considered taking into account both the thermal as well as the solute buoyancy. However, in colloids the double diffusive convection may be considered introducing significant simplifications.

The particle diffusion coefficient D is significantly lower than the colloid thermal diffusivity α (the Lewis number $Le = \alpha/D \gg 1$) and due to high Soret numbers the solutal buoyancy significantly exceeds the thermal buoyancy (in steady mass transfer regime the ratio $N = S_T/\beta_T \gg 1$, β_T is the fluid thermal expansion coefficient). In ref. [13] it is shown that under such conditions (approximately starting with $LeN > 10$) the convective stability in fluid-saturated porous media is gov-

Table 2. Convective stability criteria for ferrofluids used in the experimental work.

Fluid	$Ra_p (B = 0)$	$Ra_p (B = 0.1 \text{ T})$
df105	−2.18	55.6
S-1	−0.18	0.33
U-5	−0.75	2.65
FF13-04	3.50	13.83

erned by one criterion, by the solute Rayleigh number $Ra_p = Ra_\varphi Da$ with Ra_φ being the Rayleigh number for a homogeneous liquid and Da —the Darcy number $Da = K/\delta^2$ (K is the layer permeability, $\delta = 2a$ is the thickness of the layer). Considering a top heated layer in the presence of vertical magnetic field $B = \text{const}$, with the account for magnetic buoyancy force [14], the Rayleigh number Ra_p may be written as follows:

$$Ra_p = Ra_{pm} + Ra_{pg} = \mu_0 \frac{K(\varepsilon\varphi_0 M_s L(\xi) S_T \Delta T)^2}{\eta D(1 + \gamma L'(\xi))} - \frac{\delta\beta_\varphi \rho g \varphi_0 S_T \Delta T K}{\eta D}. \quad (10)$$

Here $\gamma = \varphi_0 \xi M_S / H$ is a parameter of particle magnetic interaction (φ_0 being the volume concentration of particles), the parameter $\xi = \mu_0 m H / k_B T$, the parameter β_φ is defined as $\beta_\varphi = \frac{1}{\rho_0} \frac{\partial \rho}{\partial \varphi}$ (here ρ is the ferrofluid density and ρ_0 is ferrofluid density at $t = 0$), M_S is the saturation magnetization of particle material, m the magnetization of a single particle, $L(\xi) = \coth(x) - \frac{1}{x}$ is the Langevin function and $L'(\xi)$ is the derivative of Langevin function, α_T is the pyromagnetic coefficient and η is the fluid effective viscosity.

The condition for onset of a convection in layers of rigid boundaries is the reaching of a critical value $Ra_{cr} = 4\pi^2$. The negative sign of the gravitation summand in Ra_p means that within $B = 0$ the fluid heating above cannot induce the convection. Contrarily, applying vertical magnetic field always causes a convective destabilization of the fluid.

Values of Ra_p for physical parameters of the performed experiments are summarized in table 2. The permeability

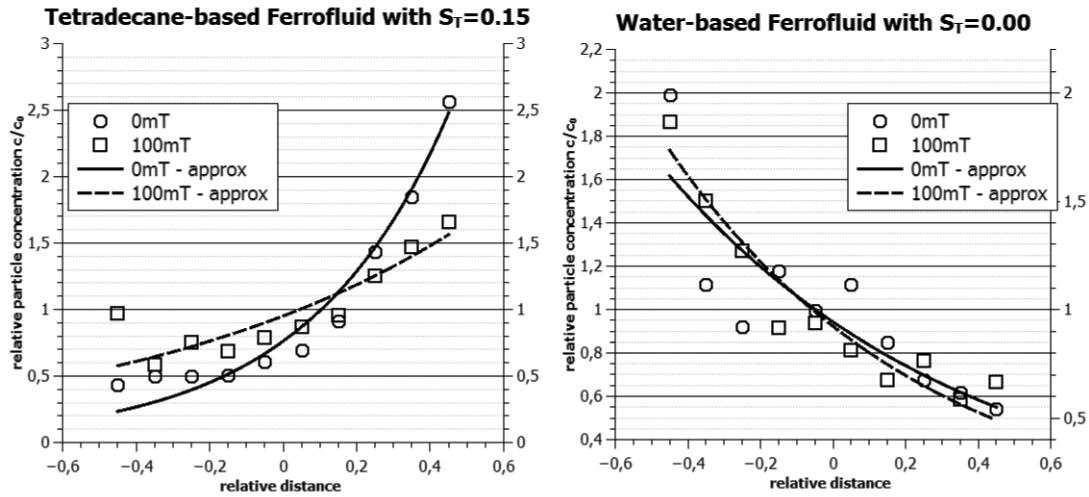


Fig. 4. Relative concentration profiles for surfaced (df-105) and ionic (FF 13-04) ferrofluid. The temperature gradient is directed toward positive distance values, opposite to the direction of gravitation force.

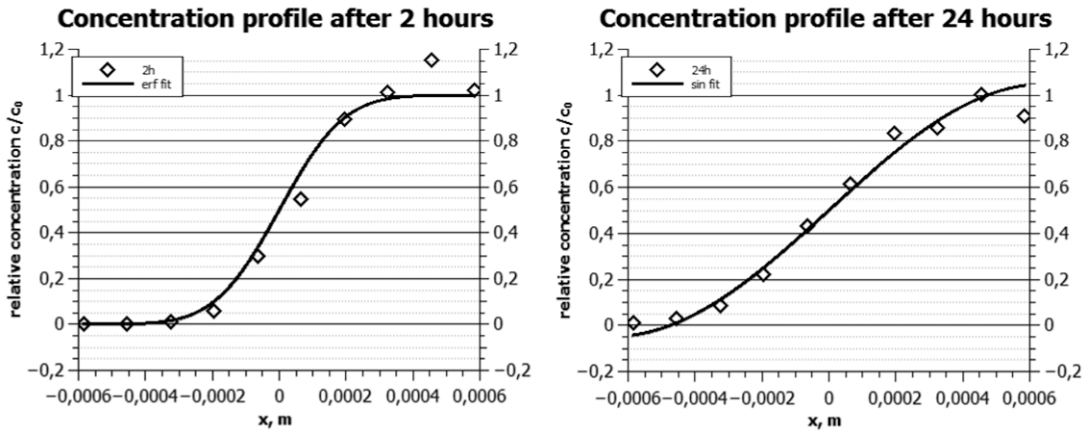


Fig. 5. Concentration profiles in parallel configuration diffusion experiments with no magnetic field, performed with surfaced ferrofluid df-105, after 2 and 24 hours; positive x corresponds to the bottom half of the layer.

K is calculated by using the Kozeny-Carmen relation [15].

$$K = \frac{d^2 \varepsilon^3}{172.8(1 - \varepsilon)^2} \tag{11}$$

The filter porosity $\varepsilon = 0.33$ is detected experimentally, the mean pore size $d = 2 \mu\text{m}$ is taken from the filter documentation. As it is seen, even in the presence of magnetic field the loss of convective stability of the fluid in porous layer is not expected.

4 Experimental work and results

4.1 Mass transfer coefficients in a porous environment

Thermodiffusion experiments are conducted for 24 hours. Experimental values of effective separation (Soret) coefficient are attained by fitting eq. (9) to experimental data. Examples of data with the respective approximation functions are presented in fig. 4. It should be pointed out that

for the ferrofluid sample FF 13-04 with $S_T = 0$, the particle flow is directed toward higher temperatures.

In diffusion experiments, measurements after various intervals of time have passed — 2, 4 or 24 hours — observing the decay of the initial step-like concentration profile. At sufficiently small values of Fourier number, as is the case in both two- and four-hour experiments, the concentration profile is described by eq. (5). In 24-hour experiments, particle distribution is described by eq. (4). As an example, data from 2- and 24-hour diffusion experiments of a surfaced ferrofluid in parallel configuration are given in fig. 5.

While two- and four-hour experiments are performed, it is noted that certain disturbances in particle distribution appear in early stages of diffusion experiments. These are most likely related to non-diffusive mass transfer processes taking place in the moment of forming a continuous porous layer from the ten separate layers. With this in mind, only results from 24-hour experiments are used and analyzed further.

Table 3. Results from parallel configuration experiments without magnetic field. R^2 denotes the coefficient of determination.

Ferrofluid	S_T , 1/K	$S_{T,\text{exp}}$, 1/K	R^2	D , m ² /s	D_{exp} , m ² /s	R^2
df-105	1.50E-01	4.75E-02	0.99	1.86E-11	1.56E-12	0.98
S-1	2.00E-02	5.64E-03	0.59	4.05E-12	2.98E-14	0.96
U5	1.50E-01	6.21E-02	0.98	3.50E-11	1.60E-12	0.94
FF13-04	0.00E+00	-3.00E-02	0.72	1.34E-11	3.71E-12	0.98

Table 4. Comparison of experimental and theoretical values of relative S_T .

Ferrofluid	$S_{T,\text{experimental}}$ (100 mT)/ S_T (0 mT)	$S_{T,\text{theoretical}}$ (100 mT)/ S_T (0 mT)
df105	0.480	0.482
U-5	0.560	0.618
S1	0.035	0.034
FF1304	-0.739	-0.323

Table 5. Comparison of experimental and theoretical values of relative D for ferrofluid df-105 at both experimental configurations.

Field orientation	$D_{\text{experimental}}$ (100 mT)/ D (0 mT)	$D_{\text{theoretical}}$ (100 mT)/ D (0 mT)
parallel	1.35	1.97
normal	0.92	0.81

Results of parallel configuration experiments with no magnetic field have been summarized in table 3. S_T and D are values of Soret and diffusion coefficients in a free fluid while $S_{T,\text{exp}}$ and D_{exp} are experimental values of both coefficients.

The accuracy of the fitting procedure by which experimental values of coefficients is attained is described by the coefficient R^2 . Following from the considerations about measurement accuracy, the experimental coefficients $S_{T,\text{exp}}$ and D_{exp} cannot be expected to have an accuracy of more than 10%. It is immediately noticeable that a strong decrease in both Soret and diffusion coefficients has been observed.

4.2 Effects of magnetic field on particle transfer

Thermodiffusion experiments are performed in magnetic field of $B = 100$ mT, with a temperature gradient parallel to the concentration gradient and the magnetic field. Values of relative experimental and theoretical Soret coefficient are summarized in table 4. Considering the significant changes in particle transfer coefficients in the porous environment, all values are relative to the experimental value of S_T at $B = 0$ mT in the porous layer, not free fluid.

A theoretical model to predict changes in the Soret coefficient in the presence of magnetic field is described in detail in ref. [16]. By introducing a particle flux associated with magnetic sedimentation and assuming that an

external uniform magnetic field is aligned with temperature gradient, as is the case in our thermodiffusion experiments, we can introduce the effective magnetic Soret coefficient

$$S_{T,M} = S_T \left[\left(1 - \frac{\gamma L^2(\xi)}{1 + \gamma L'(\xi)} \cdot \frac{\alpha_T}{S_T} \right) / \left(1 + \frac{\gamma L^2(\xi)}{1 + \gamma L'(\xi)} \right) \right]. \quad (12)$$

Here α_T is the pyromagnetic coefficient.

As measurements follow the same methodology, experimental coefficients in table 4, and in table 5, attained in a magnetic field are assumed to have the same 10% accuracy.

In the case of diffusion experiments, where the temperature gradient is zero but there is a concentration gradient and an external magnetic field, aligned along the concentration gradient and gravity field, is present, the effect of magnetic field on diffusion coefficient can be expressed, again, following the theoretical model of ref. [17], as

$$D_{M,\text{parallel field}} = D \left(1 + \frac{\gamma L^2(\xi)}{1 + \gamma L'(\xi)} \right). \quad (13)$$

This approach only accounts for particle transfer caused by inhomogeneity of the magnetic field due to particle distribution. When the field is aligned perpendicular to the particle concentration gradient, this would play no part in particle transfer coefficient changes.

Another cause of changes in diffusion coefficient is related to magnetic interaction between the particles [17]. According to the model presented there, mass diffusion

coefficient in a magnetic field normal to the concentration gradient is

$$D_{M,\text{normal field}} = D \left(1 - \frac{\lambda\gamma L^2(\xi)}{1 + \lambda\gamma L'(\xi)} \right). \quad (14)$$

Here λ is a parameter of magnetic interaction called the effective field constant and can be calculated within the effective field model presented in ref. [18]. For ferrofluid df-105, it is found to be $\lambda = 0.286$.

Diffusion experiments are performed in both field orientations with fluid df-105 at $B = 100$ mT. Experimental and theoretical values of the diffusion coefficient are given in table 5. As before, all values are relative to experimental value at zero magnetic field. Theoretical values in parallel and normal fields are calculated by eqs. (13) and (14), respectively.

5 Analysis

A conclusion can immediately be drawn from these results, that both diffusion and Soret coefficients in the porous environment are significantly lower than in free fluid. It should be noted that the decrease of transfer coefficients does not always correspond to particle transfer being hampered. This is demonstrated by Soret coefficient for ferrofluid FF 13-04, that has turned negative in the porous layer. No particle transfer induced by a temperature gradient was observed in free fluid for FF 13-04, corresponding to Soret coefficient of zero. In this case, particle transfer has appeared, not been diminished.

Within the current experimental body of work and theoretical considerations, no clear explanation for the change in any of the coefficients has been found. One of the possible causes of decrease in diffusion coefficient is related purely to the geometry of the porous layer, namely to tortuosity of the environment that should decrease diffusion coefficient through prolongation of the actual path for particles to travel to cover some effective distance. However, quantitative estimation of this effect is a problem, since tortuosity of an environment is not considered to be measurable experimentally and lack of a theoretical model that would clearly correspond to our filter layer structure prevents us from attaining a theoretical value. Under the assumption that the layer has a porous structure, a decrease by an order of magnitude is not to be expected.

Soret coefficient being significantly lower in a porous environment than it is in a free fluid is an entirely unexpected result. In binary gas or liquid mixtures, usually the reduction of diffusion and thermodiffusion coefficients in porous systems is equivalent (at least if convective processes are not involved), because changes in both coefficients are driven by tortuosity [19]. Therefore, the Soret coefficient remains unchanged, as previous experimental research has confirmed [20]. Ferrocolloids are somewhat more complicated systems with notable differences in particle thermodiffusive transport mechanisms. A possible reason for changes in transport coefficients in a porous medium concerns gradients of chemical potential

near colloidal particles and pore walls that could cause slip velocity to appear, through a mechanism described in [21]. In the case of lyophilic solid/liquid interface, slip velocity would be directed toward higher temperatures. Such mechanism of particle transport might be more significant in surfaced colloids like ferrofluids due to the presence of surfactant molecules. Thus, advective flux of the particles toward higher temperatures might be induced by pore walls. While qualitatively plausible, quantitative predictions of the proposed transfer mechanism would require knowledge not only of parameters of the porous layer, but also of chemical potential gradients near particle surface in the ferrofluid. The lack of such knowledge prevents solid conclusions on the possible role of this transfer mechanism. However, initial experimental work with ferrofluids with increased surfactant concentration seems to indicate an according increase in particle transfer toward higher temperatures. Correlation between concentration of the surfactant and particle transfer under temperature gradient calls for additional experimental work before any real conclusions are drawn.

While it is undeniable that diffusive mass transfer of colloidal particles in a porous medium is significantly affected by the porous medium itself through mechanisms not fully understood, measurements of mass transfer coefficients undergoing changes when a ferrofluid is subjected to a magnetic field give results well comparable with theoretical values. Theoretical models presented in refs. [16] and [17] give reasonably accurate predictions of dependence of mass diffusion and Soret coefficients in a magnetic field.

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