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MAGNETIC FLUIDS

The control of a liquid material by means of magnetic forces is a promising technique for numerous applications in various disciplines, as well as for basic research in flow mechanics. The magnetic fluids that will be discussed here enable this kind of control using weak magnetic fields on the order of 50 mT. Thus magnetic control can be achieved with magnetic fields of common permanent magnets or small field coils, making technical applications possible. The discussion will cover the basics of magnetic flow control in magnetic fluids, a number of flow phenomena illustrating the possibilities of magnetic control of liquids, several applications that have gained high commercial importance, and finally the change of properties of these liquids by the action of magnetic fields. But first the structure and the basic properties of magnetic fluids will have to be explained to make their unique behavior understandable.

As is well known, no elements or compounds exist that show magnetic ordering in the liquid state. For example, the Curie temperature of ferromagnetic materials is always much lower than their melting temperature. Thus they lose their ferromagnetic properties before becoming liquid. The only exceptions are helium (^3He) at very low temperatures, around 2 mK (1), and undercooled melts of Co–Pd alloys, found in 1996 (2, 3) to show a magnetic phase transition. These systems are both obviously of no technical importance concerning magnetic field controlled flows and related applications. Paramagnetic salt solutions exhibit force densities on the order of 50 N/m^3 in magnetic fields of about 40 kA/m with gradients around 10^6 A/m^2. These values for the field strength and its gradient are typical for controllable magnetic fields produced with coils made of normal conducting material on a laboratory scale. The above force densities on paramagnetic salt solutions are about three orders of magnitude smaller than the gravitational force density. Thus they are also not applicable for technical use.

Nevertheless, a material allowing control of its flow and physical properties over a wide range by means of a controllable magnetic force was expected to give rise to numerous new applications and thus would be of immense interest for technical use and basic research. Therefore in the early 1960s a lot of effort went into the development of a liquid material that can strongly be influenced by moderate magnetic fields. The final breakthrough came when Papell successfully produced stable suspensions of magnetic nanoparticles in appropriate carrier liquids (4). These suspensions show liquid behavior coupled with superparamagnetic properties. That means that moderate magnetic fields can exhibit magnetic forces on the liquid that are comparable to gravitational forces.

Intense efforts undertaken shortly after the discovery of a method of preparation of ferrofluids—as these suspensions are commonly called—led to the development of fluids exhibiting longtime colloidal stability and reproducible properties. Parallel with further development and improvement of the liquids themselves, technical solutions for numerous applications have been published, some of them gaining high commercial importance.

In the following, the composition and stability requirements of ferrofluids, as well as their most important magnetic properties, are examined. A discussion of the principles of magnetic flow control and some examples of flows induced by magnetic fields follow. Finally, some of their applications, having importance in everyday life, are presented to illustrate the wide range of applicability of these substances.

Structure of Magnetic Fluids and Basic Stability Requirements

Before discussion of the control of ferrofluids by means of magnetic fields, some basic information is necessary concerning their structural makeup and stability. As already mentioned, a ferrofluid is a suspension of magnetic nanoparticles in an appropriate carrier liquid. The first issue is the question of stability of such a suspension. It is obvious that the main stability requirements are stability against sedimentation in the gravitational field, against separation in common magnetic field gradients, and against agglomeration owing to the magnetic and van der Waals interactions between the particles. To fulfill the requirement that the suspension be stable against these influences, the thermal energy of the suspended particles must be larger than the respective energies characterizing the destabilizing actions. If this condition is valid, a particle's Brownian motion will be strong enough to keep it suspended against the destabilizing effects. The energy of a particle in the gravitational field is given by

$$E_{\mathrm{G}} = \Delta\rho\, Vgh \qquad (1)$$

where $\Delta\rho$ is the density difference between particles and carrier liquid, V the volume of a particle, g the gravitational acceleration, and h the typical height of the fluid column in the gravitational field. For particles with a diameter of about 10 nm, one can easily calculate that this energy is comparable with their thermal energy kT (k denoting Boltzmann's constant and T the absolute temperature) at room temperature. The same is valid for the dipole–dipole interaction energy of two identical particles in contact,

$$E_{\mathrm{D}} = \frac{\mu_0 M_0^2}{12} V \qquad (2)$$

and the particle's energy in a moderate magnetic field H up to 50 kA/m,

$$|E_{\mathrm{M}}| = \mu_0 M_0 V H \qquad (3)$$

(μ_0 denotes the magnetic constant and M_0 the spontaneous magnetization of the particle's magnetic material). The latter describes the energy barrier a particle has to overcome when leaving a region subjected to the field H toward a region where $H = 0$. Thus it is an idealization for a very strong magnetic field gradient modeled by a stepwise change of field strength.

The above mentioned energy comparisons show that thermal energy is able to keep particles in the manometer size range suspended against the destabilizing influences discussed. Nevertheless, a suspension of pure magnetic nanoparticles in a carrier liquid like oil or water would not be stable, since the particles woulomerate because of the van der Waals interaction. It can easily be shown that the van der Waals interaction energy, which is given here for two identical, spherical particles,

$$E_{\mathrm{W}} = -\frac{A}{6}\left[\frac{2}{l^2+4l} + \frac{2}{(l+2)^2} + \ln\left(\frac{l^2+4l}{(l+2)^2}\right)\right] \qquad (4)$$

(here $l = 2s/d$ is the distance s between the particles normalized to their diameter d, while A denotes the Hamaker constant, which is of the order of 10^{-19} N·m for magnetite in water), diverges as the distance between the particles vanishes. Their thermal energy therefore cannot be sufficient to redisperse particles that have been in contact. Thus the van der Waals interaction will cause an efficient agglomeration of particles and therefore a complete destabilization of the suspension. The only way to overcome this problem is to find a way to avoid any contact between the particles using a kind of spacer between the particles for which the Hamaker

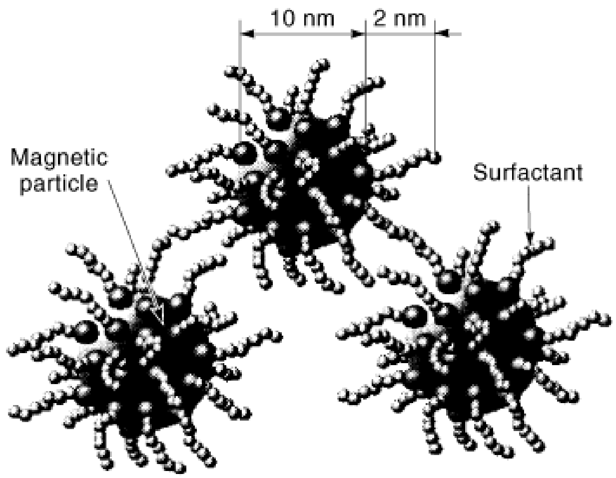

Fig. 1. Schematic representation of the coated magnetic particles in a ferrofluid. The size of the surfactant molecules has not been given to scale in order to make the figure clearer.

constant in the corresponding carrier liquid is zero. This means that the dielectric properties of the spacer and the liquid must be identical. To ensure this, the magnetic particles in a ferrofluid are covered with a surfactant consisting of long-chained molecules as shown in Fig. 1. These molecules must have a polar group, which attaches to the magnetic particles, and a nonpolar tail. The nonpolar tail has to be chosen so that its dielectric properties match those of the liquid. In this case, the surfactant molecules do not agglomerate due to the van der Waals interaction and, additionally, they provide a steric repulsion between two particles coming close to each other. The steric repulsion is a consequence of the reduction of the configuration room of the surfactant molecules. This repulsion keeps the particles at a relative distance in which the van der Waals interaction is unable to force them to agglomerate. The steric repulsion between the particles can be written in the form (5)

$$E_s = 2kT\pi d^2 \xi \left[2 - \frac{l+2}{t} \ln \left(\frac{1+t}{1+l/2} \right) - \frac{l}{t} \right] \qquad (5)$$

with $t = 2\ \delta/d$ the normalized thickness of the surfactant layer δ and ξ is the surface density of the surfactant molecules.

The stability criterion for magnetic fluids thus reduces to the question of how thick the surfactant layer has to be to provide efficient protection against agglomeration of the particles. Figure 2 shows a calculation of the total potential between two magnetic particles with 10 nm diameter in water, protected with a 2 nm thick surfactant. The particles are assumed to be made of magnetite (Fe_3O_4) and the total interaction potential is a combination of the magnetic dipole interaction, the van der Waals interaction, and the steric repulsion due to the surfactant. As seen, the contact between two particles is prevented by a potential barrier on the order of 20 kT.

The first stable ferrofluid of this kind was synthesized by S. Papell (4) in 1964. Further intensive research resulted in improved quality ferrofluids. Modern ferrofluids usually contain magnetite (Fe_3O_4) as the magnetic component. Carrier liquids can be different oils, water, kerosene, heptane, or some esters. The surfactant—as discussed previously—is always chosen to match the dielectric properties of the carrier liquid. As an example, acidic acid can be used for magnetite in water, but the composition of surfactants in commercial ferrofluids is a proprietary of the producers. The volume concentration of the magnetic component is usually of the order of

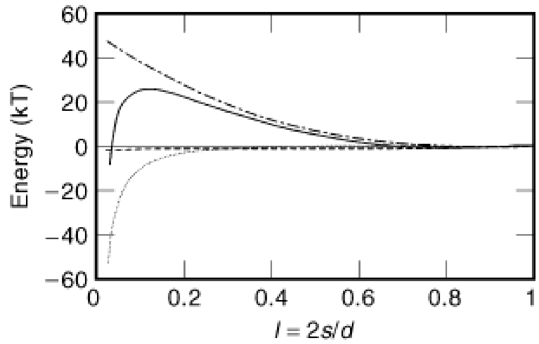

Fig. 2. The potential between two coated magnetic nanoparticles with 10 nm diameter. The dashed line represents the magnetic dipole attraction, the dotted line the van der Waals attraction, the dash-dotted line the steric repulsion, and the solid line the total potential, showing an energy barrier of 20 kT preventing particle agglomeration.

5 vol % to 15 vol % and the suspended particles are polydispers with particle sizes between approximately 3 nm and 20 nm.

Chemical Composition of Ferrofluids. Such suspensions of coated magnetic particles in a carrier liquid are commonly produced by chemical coprecipitation. Khalafalla and Reimers (6) coprecipitated magnetite from the reaction

$$\mathrm{FeCl_2 + 2\,FeCl_3 + 8\,NaOH \rightarrow Fe_3O_4 + 8\,NaCl + 4\,H_2O} \tag{6}$$

and boiled the coprecipitate in a mixture of petroleum and oleic acid. The petroleum was used as the carrier liquid, while the oleic acid served as the surfactant for the particles. Boiling in the presence of a carrier fluid and surfactant prevented the agglomeration of particles due to the van der Waals interaction. In a magnetic field gradient, the magnetic fluid has to be separated from the salt solution. Finally, the resulting ferrofluid could be obtained by diluting or concentrating the magnetic liquid filtrate. The different chemical processes and their details are rather complicated and not within the scope of this article. Thus the interested reader is referred to the corresponding literature (7) in this matter.

Magnetic Properties of Ferrofluids

As already mentioned, the unique properties of magnetic fluids—the combination of their liquid state with magnetic flow control—are the result of their superparamagnetic behavior. The magnetic particles are so small that they contain only one magnetic domain; thus they are called single-domain particles (8). If we assume, as a first approximation, that the particles do not interact with each other, the change of magnetization of the fluid M as a function of an applied magnetic field H and temperature T can be described similar to that of noninteracting magnetic dipoles. For those, Langevin (9) derived the well-known relation for $M(H,T)$ for paramagnetic systems:

$$\begin{aligned} M &= M_s\left(\mathrm{ctgh}\,\alpha - 1/\alpha\right) \\ \alpha &= \frac{\mu_0 m H}{kT} \end{aligned} \tag{7}$$

where M_s denotes the saturation magnetization of the liquid and m stands for the magnetic moment of a single particle. The latter is given by the volume of the particle V and the spontaneous magnetization of the magnetic material M_0 in the form

$$m = M_0 V \tag{8}$$

The relation in Eq. (7) can be approximated for small magnetic fields in the form

$$M \approx M_s \frac{1}{3} \frac{\mu_0 m H}{kT} = \chi H \tag{9}$$

giving an expression for the initial susceptibility:

$$\chi = \frac{1}{3} \Phi \frac{\mu_0 M_0^2}{kT} V \tag{10}$$

with Φ representing the volume concentration of the magnetic component. Since the magnetic moment m of the particles is on the order of $10^4 \mu_B$, the susceptibility of a standard ferrofluid (see Table 1) with a content of magnetic material of about 10 vol % reaches a value of about 0.6, as it can be seen from Fig. 3. This is 10^4 times larger than the initial susceptibility of paramagnetic salt solutions. Therefore the magnetic behavior of ferrofluids is called superparamagnetic. This superparamagnetism results in the fact that even small magnetic fields, say, between 10 mT and 50 mT, induce reasonable magnetization in a ferrofluid. Since the magnetic force density is given by

$$F = \mu_0 M \nabla H \tag{11}$$

laboratory-scale magnetic field systems produce reasonable forces acting on the liquid. A magnetic field of about $H = 20$ kA/m with a gradient of approximately $\nabla H = 7 \times 10^5$ A/m^2, as is typical for a small solenoid with a yoke, will exert a force density of about 14 kN/m^3 on the fluid. This is the same order of magnitude as the force density acting on a standard ferrofluid described in Table 1 in the gravitational field, which can be calculated to be 13 kN/m^3. Therefore the magnetic force exerted by such a magnetic field can lift the magnetic fluid against the gravitational acceleration and attract it toward the yoke, as shown in Fig. 4.

The second characteristic of the magnetization curve shown in Fig. 3—besides the high initial susceptibility—is the saturation magnetization M_s—the value to which M converges at high magnetic fields. This upper limit for M is given by the total number of particles suspended in the liquid. When all particles are aligned with the magnetic field direction, the fluid is magnetically saturated. Thus the saturation magnetization can be written in the form

$$M_s = \Phi M_0 \tag{12}$$

This shows immediately that a determination of the saturation magnetization of the fluid provides important information on the magnetic volume concentration. In addition, it can be seen from Eq. (10) that the initial susceptibility contains analogous information on the mean size of the magnetic particles. Furthermore, a more sophisticated analysis of the shape of the magnetization curve enables a determination of the particles' size distribution (10, 11). Thus it becomes clear that the investigation of the magnetization curve provides information on the internal structure and composition of the suspension, which is needed in numerous other experiments as well as in the design of applications using ferrofluids.

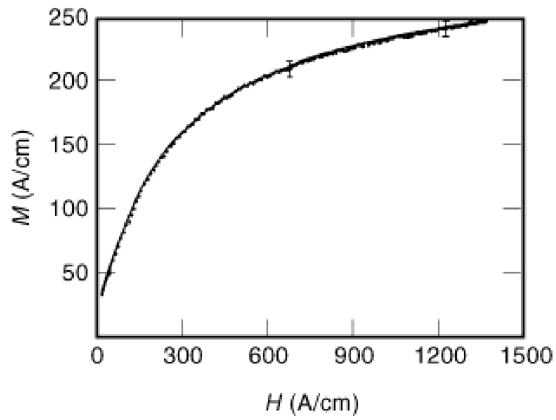

Fig. 3. A measured magnetization curve of a commercial ferrofluid.

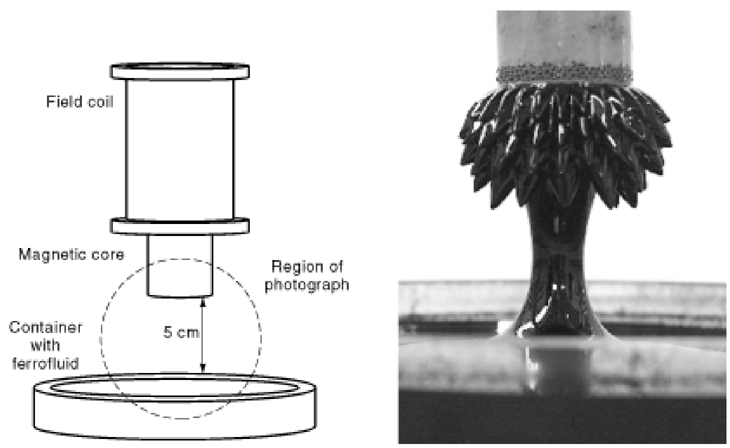

Fig. 4. The attraction of a magnetic fluid by a magnetic field. The coil at the top of the arrangement provides a magnetic field of about 20 kA/m with a gradient of about 7×10^5 A/m^2 at the top of the fluid pool. This gives rise to a force strong enough to lift the fluid against gravitational forces. (Left: schematic sketch; Right: photography with applied magnetic field.)

Relaxation of Magnetization. The relaxation of magnetization in a ferrofluid is determined by two different processes. On the one hand, the magnetization can relax by Brownian motion of the particles in the fluid; on the other hand, the magnetic moment can relax inside the particle without a movement of the particle itself—the so-called Néel relaxation process (12). The Brownian relaxation time is given by

$$\tau_B = \frac{3\widetilde{V}\eta}{kT} \tag{13}$$

Table 1. Characteristics of Ferrofluid APG 513 A

Ferrofluid	APG 513 A
Producer	Ferrofluidics
Carrier liquid	Diester
Magnetic material	Magnetite
Mean particle size, $\bar{d}$	10 nm
Thickness of surfactant (approx.), s	2 nm
Mean volume of magnetic particles, V	5.24×10^{-25} m^3
Mean volume of particles including surfactant layer, V	1.44×10^{-24} m^3
Volume concentration of magnetite, Φ	0.072
Saturation magnetization, M_s	32×10^3 A/m
Initial susceptibility, χ	0.8
Density, ρ	1.28×10^3 kg/m^3
Density of carrier liquid, ρ_0	1×10^3 kg/m^3
Dynamic viscosity, η	0.128 kg/ms
Kinematic viscosity, ν	1×10^{-4} m^2/s

where $\tilde{V}$ denotes the volume of the particles including the surfactant layer and η the dynamic viscosity of the liquid. For the Néel relaxation time,

$$\tau_{\mathrm{N}} = f_0^{-1} \exp\,(K_1 V/kT) \qquad (14)$$

where K_1 is the crystal anisotropy constant of the magnetic material and f_0 is a relaxation frequency given by the Larmor frequency of the magnetization vector in the anisotropy field of the particle. For a standard ferrofluid, as described in Table 1, the Brownian relaxation time will be about $\tau_{\mathrm{B}} = 1.1 \times 10^{-5}$ s, while the Néel relaxation will take place in $\tau_{\mathrm{N}} = 2.8 \times 10^{-10}$ s (for 10 nm particles). One can easily see that the Néel process will dominate for small particles, while the relaxation will be due to Brownian particle motion for large ones. Particles relaxing by the latter process are called magnetically hard. For magnetite, the transition size between both processes is about 15 nm in a fluid with viscosity about 10 times as high as that of water.

Magnetic Flow Control

Magnetic fields enable magnetic control of the flow of magnetic fluids. This control is provided by the action of the magnetic force, which was given in Eq. (11). Using this force, the equation of motion—the Navier–Stokes equation—can be written for a magnetic fluid in the form

$$\frac{dv}{dt} = \rho g h + \nu\,\nabla^2 v - \frac{1}{\rho}\mathrm{grad}\;p + \frac{\mu_0}{\rho} M\;\nabla H \qquad (15)$$

where v denotes the flow velocity in the fluid, ρ the fluid's density, p the hydrostatic pressure, and ν the fluid's kinematic viscosity. Along a streamline the situation can be described by the conservation of energy using the

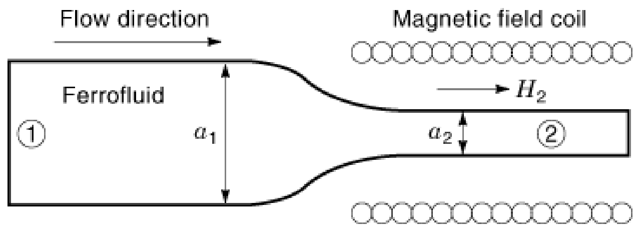

Fig. 5. A free magnetic fluid jet under the influence of a magnetic field parallel to the flow direction changes its diameter. The change of the diameter is calculated in the text using the ferrohydrodynamic Bernoulli equation.

Bernoulli equation, which is given by

$$p + \frac{\rho}{2}v^2 + \rho g h - \mu_0 \overline{M} H = \text{const.} \quad \text{with} \quad \overline{M} = \frac{1}{H}\int_0^H M\,dH \tag{16}$$

The consequences of the magnetic term in the Bernoulli equation can be illustrated by a discussion of the behavior of a free jet of magnetic fluid entering a magnetic field parallel to the flow direction of the fluid (see Fig. 5). To apply the Bernoulli equation to the problem, we choose a point outside the field ① and another one inside the region where the field is applied. ② Since the tangential component of the magnetic field is steady, the field strength in the fluid at point ③ is equal to the strength of the applied field. Furthermore, the pressures at points ① and ② are identical and equal to the ambient pressure. Thus Eq. (16) formulated for the two distinct points in the fluid reduces to

$$v_2^2 - v_1^2 = \frac{2\mu_0 \overline{M} H_2}{\rho} \tag{17}$$

Using the continuity equation, the velocity at point ② can be expressed as

$$v_2^2 = v_1^2 \frac{a_1^4}{a_2^4} \tag{18}$$

with the diameters of the jets at points ① and ② being a_1 and a_2, respectively. Using Eq. (18) in Eq. (17), the reduction of the diameter of the free jet as a function of the strength of the applied magnetic field can be obtained:

$$\frac{a_1}{a_2} = \left(1 + \frac{2\mu_0 \overline{M} H_2}{\rho v_1^2}\right)^{1/4} \tag{19}$$

For a standard ferrofluid entering a magnetic field of about $H = 20$ kA/m with a velocity of $v = 0.1$ m/s, the reduction of the size of the free jet is about a factor of 3, illustrating the immense effect of the magnetic field on the flow behavior of the magnetic fluid.

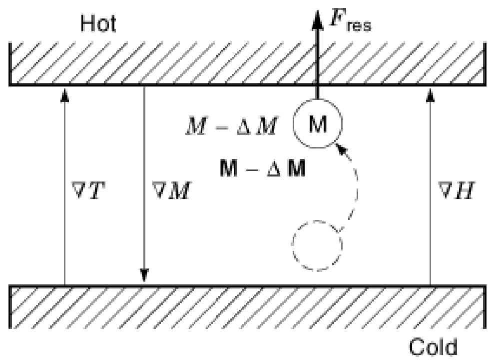

Fig. 6. The origin of the destabilizing force driving thermomagnetic convection. The explanation is given in the text.

More complicated effects, described by the Navier–Stokes equation for ferrofluids, can be considered, when investigating thermal transport in a magnetic fluid. In contrast to a normal liquid, the convective flow, enhancing the thermal transport due to thermal conductivity, can be controlled by the action of a magnetic field. The origin of the so-called thermomagnetic convection can be understood, if one assumes a cylindrical layer of magnetic fluid between two parallel plates under the influence of a temperature gradient (see Fig. 6). In addition, a magnetic field vertical to the plates is applied. Due to the superparamagnetic properties of the liquid, the temperature gradient induces a gradient of magnetization in the fluid. Thus an internal field gradient, which is antiparallel to the temperature gradient, occurs. If a volume element ΔV of the fluid is displaced adiabatically in the direction of the temperature gradient, it will come to a region of lower magnetization $M - \Delta M$. Therefore it will feel a magnetic force in the direction of the magnetic field gradient ∇H,

$$F_{\mathrm{R}} = -\mu_0 \, \Delta M \, \boldsymbol{\nabla} H \, \Delta V \qquad (20)$$

In the same way, a volume element of the fluid displaced antiparallel to the temperature gradient will also feel a resulting force in the direction of the initial disturbance. Thus the magnetic force has a destabilizing character, since it amplifies random disturbances. This means that a magnetic driving force exists in the fluid layer, which is able to drive a convective flow without the influence of gravitational acceleration or surface tension gradients.

A possibility for the description of the state of the system is given by the use of a dimensionless parameter, which is obtained by making the corresponding Navier–Stokes equation dimensionless. For the case of thermomagnetic convection, the corresponding dimensionless parameter is the magnetic Rayleigh number R_{m} (13, 14):

$$R_{\mathrm{m}} = \frac{\mu_0 K \, \boldsymbol{\nabla} H \, \Delta T \, d^3}{\kappa \nu} \qquad (21)$$

where $K = |\partial M/\partial T|$ is the pyromagnetic coefficient of the ferrofluid, and κ the ferrofluid's thermometric conductivity, d the thickness of the fluid layer, and ΔT the temperature difference in the fluid. The convective flow appears when the magnetic Rayleigh number, which can be changed by variation of the applied magnetic field, exceeds a certain critical value depending on the boundary conditions. The phenomenon of thermomagnetic convection has been studied experimentally (15), verifying the possibility of magnetic control of thermal transport in ferrofluids. The experimental results—which were obtained in an environment of strongly reduced

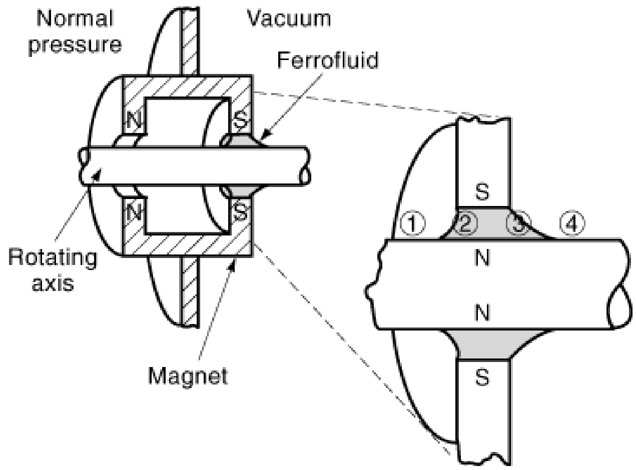

Fig. 7. Sketch of a ferrofluid sealing for a rotating shaft.

gravitational acceleration, to reduce the influence of normal gravitational convection—were in good agreement with various theoretical calculations based on an analysis of the Navier–Stokes equation for magnetic fluids (14, 16).

Applications of Magnetic Fluids

It is obvious that a magnetically controllable liquid is an interesting material for technical applications in various disciplines. The most famous use of ferrofluids is the sealing of rotating shafts. Conventionally, such sealings are made by oil seal rings or other mechanical devices. Such sealings experience strong friction, consuming energy and producing heat. The increased energy consumption and the heat production are unfavorable for many devices needing rotary feedthroughs. Thus one of the first realized applications was the ferrofluid sealing, easily withstanding pressure differences of about 1 bar and having the friction of a liquid in a small gap. As seen from Fig. 7, the rotating shaft is surrounded by a circular permanent magnet. A drop of ferrofluid is placed into the gap between the magnet and the rotating shaft, which is made from highly permeable material. Due to the strong magnetic field gradient in this region, a strong force is exerted on the fluid, fixing it in the gap. Using the Bernoulli equation discussed earlier, one can calculate the maximum pressure difference that such a device can withstand. The following assumptions are made:

- The pressures at point ① and ② as well as at points ③ and ④ are identical (see Fig. 7).
- Gravitational effects can be neglected.
- The magnetic field is homogeneous and tangential to the fluid surface and can be neglected at point ③ in comparison with point ②.
- The shaft is at rest.

Equation (16) then gives

$$p_1 - p_4 = \mu_0 \overline{M}(H_2)H_2 \qquad (22)$$

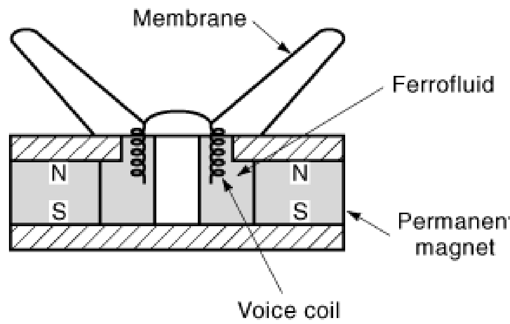

Fig. 8. Damping and cooling of voice coils in loudspeakers by means of ferrofluids.

Thus a pressure difference of about 1 bar can easily be sealed with such a device using a fluid with 12 vol % of magnetite and a magnetic field strength in the gap of about 1.8 T. Such a sealing will exert negligible friction on the rotating shaft compared to that of oil seal rings or comparable systems. Higher pressure differences can be sealed by an imovement of the magnetic poles and a reduction of the gap width (17) or by use of multistage sealings (18). Due to the development of ferrofluids, which are highly stable even in strong magnetic field gradients, such sealings could be adapted for applications with long lifetime requirements for the components. Currently, they are used in numerous devices like vacuum feedthroughs or hard disk drives.

The most important current application concerning the total volume of ferrofluid delivered (19) is the cooling and damping of loudspeakers. In this particular case, the voice coil of a loudspeaker is immersed in a ferrofluid. The fluid is held in the gap of the permanent magnet by the magnetic forces present there (see Fig. 8). Even at high amplitudes of the membrane, the magnetic forces are strong enough to avoid transport of fluid out of the gap. The fluid increases the heat transfer from the coil by approximately a factor of 3—making high-power loudspeakers much more reliable. A comparable heat reduction could be obtained with other liquids too, but these would not be fixed in the gap, and thus they are not applicable as a cooling agent in this case. In addition, the alternating magnetic field of the coil produces time-dependent changes of the viscosity of the fluid (the viscosity changes due to an applied magnetic field will be explained in the next section), which give rise to a dynamic damping of the loudspeaker (7). Both effects together improve the overall performance of loudspeakers, so that most speakers for high-quality sound systems, car audio systems, and high-power applications use ferrofluids for cooling and damping purposes. This application forced intense efforts in the development of ferrofluids that are stable in a high-temperature environment, since the liquids used in high-power loudspeakers have to withstand temperatures of about 120°C.

Another interesting application of ferrofluids is their utilization in density separation of various materials. Separating materials by density is based on the fact that a nonmagnetic particle, suspended in a magnetic fluid under the influence of a magnetic field gradient parallel to gravitational acceleration, will experience an additional magnetic force, which can counterbalance the gravitational one. The magnetic force $F_{\rm m}$ on a nonmagnetic body in a ferrofluid is given in the strong magnetic field limit by

$$F_{\rm m} = -\mu_0 MV\,\nabla H \qquad (23)$$

where M is the magnetization of the fluid, V the volume of the nonmagnetic body, and ∇H the magnetic field gradient. The body will be stably levitated (7) when this force counterbalances the gravitational force $F_{\rm g}$

$$F_{\rm g} + F_{\rm m} = -(\rho - \rho')gV + F_{\rm m} = 0 \qquad (24)$$

where ρ and ρ' denote the density of the fluid and of the body, respectively, while g is the gravitational acceleration. In addition, each displacement of the nonmagnetic body from the position where Eq. (24) is fulfilled must give rise to a repulsive force driving the body back to the equilibrium point. As seen from Eq. (24), bodies of different density will be levitated to different heights in the fluid, if they are subjected to a nonuniform magnetic field gradient parallel to gravitational acceleration.

Other applications (e.g., in medicine) are at present in development. For example, drugs can be attached to the surfactant molecules. After injection of the drug-carrying fluid into a blood vessel, it can be concentrated at a certain position by applying a strong magnetic field gradient (20). In this way the effect of the drug can be localized in the body (e.g., near an organ needing treatment), reducing unwanted side effects. Another upcoming therapy technique is the use of ferrofluids for cancer treatment by hyperthermia. The fluid particles are marked with tracer substances that are enriched in the tumor tissue. By applying an alternating magnetic field, the energy losses due to change of magnetization in the particles can be used to heat up the tissue (21). Thus the tumor itself can be destroyed by a technique that avoids side effects to other organs. Most of the medical applications are at the moment in a preclinical test phase, but they are expected to become common treatment techniques soon. The most important problem that will have to be solved is the synthesis of biocompatible magnetic liquids.

The above mentioned examples of applications show only a small cut from the wide field of use of ferrofluids. For a more detailed discussion, the interested reader can refer to (22) for more information on various kinds of applications of ferrofluids.

Viscous and Viscoelastic Properties of Ferrofluids

Besides the control of the flow of magnetic fluids and of the behavior of a nonmagnetic material suspended in a magnetic liquid, even the properties of ferrofluids can be dramatically changed by the influence of magnetic fields. The most famous effect in this context is the variation of the viscosity of magnetic fluids by a magnetic field. The basic effect, called rotational viscosity, can easily be understood if one considers the behavior of magnetically hard magnetic nanoparticles suspended in a ferrofluid in the case where the fluid is under the influence of a shear flow (Fig. 9). In this case, the particles will rotate along the shear plane, having the rotation axis in the direction of the vorticity of the flow. If a magnetic field is applied parallel to the vorticity, the magnetic moment will align with the vorticity and will not influence the rotation of the particles. In contrast, a field perpendicular to the vorticity will try to align the particle's magnetic moment perpendicular to its rotation axis. Since the moment is coupled to the particle itself, the rotation will cause the magnetic moment to move out of the field direction, resulting in a finite angle between moment and field direction. Thus a magnetic torque will appear, trying to realign the particle with the field direction. This magnetic torque is counteracting the mechanical torque due to viscous friction in the shear flow and thus hinders the free rotation of the particle. The hindrance of free rotation of the magnetic particles causes a macroscopic increase of the fluid's viscosity. For the field-dependent increase η_r, called rotational viscosity, 23 formulated a theory in 1972 showing that

$$\eta_{\mathrm{r}} = \frac{3}{2}\Phi' \eta_{(H=0)} \sin^2(\beta) \frac{\alpha - \tanh(\alpha)}{\alpha + \tanh(\alpha)} \qquad (25)$$

where β denotes the angle between the vorticity and the magnetic field direction, and α is the ratio of magnetic and thermal energy, as defined in Eq. (7). The existence of this change of viscosity has been proved experimentally by 24 for diluted ferrofluids containing cobalt particles. Later investigations using commercial ferrofluids with high volume concentrations around 10 vol % of magnetite as magnetic component have shown strong effects (25, 26), which cannot be explained directly by the theory of Shliomis (see Fig. 10). Together

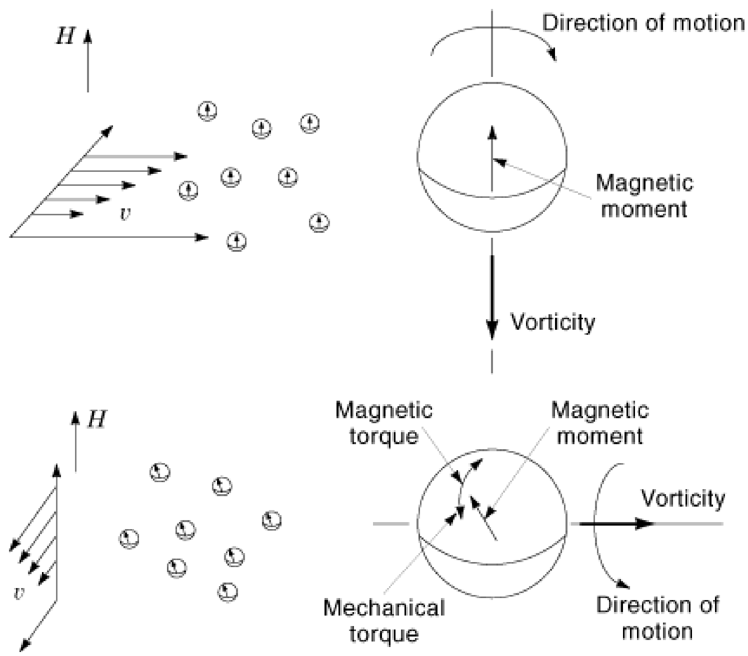

Fig. 9. The origin of rotational viscosity. Explanations are given in the text.

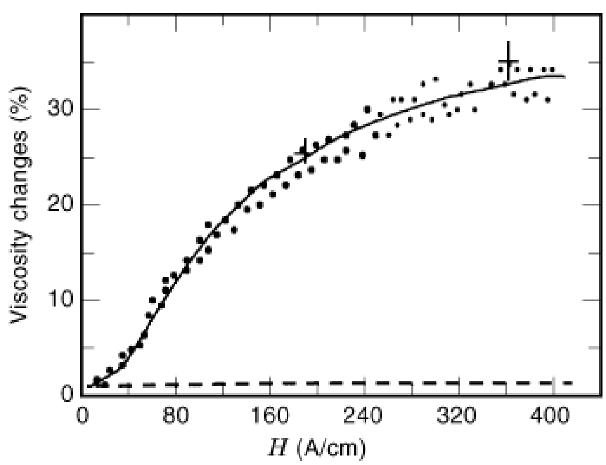

Fig. 10. Rotational viscosity of a concentrated commercial ferrofluid. The dashed line represents the theoretical prediction calculated for the fluid used in the experiments. The solid line is the best fit to the data. This fit strengthens the assumption that agglomerates of magnetic particles determine the fluid's behavior.

with new results on the viscous properties of ferrofluids, indicating that viscoelastic effects can be induced and controlled in the fluids by the use of magnetic fields (27), they show that a generally new understanding of the microstructure of ferrofluids must be found. The most reasonable explanation at present is the formation of particle clusters due to the magnetic interaction between small aggregates of particles (28). It has been predicted theoretically that such chains will give rise to essential changes of viscous and viscoelastic properties in ferrofluids (28, 29). These effects are expected to open new fields of application for magnetic and magnetorheological fluids (i.e., as the active medium in damping devices).

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