FUTURE OF ELECTROTECHNICS: FERROFLUIDS

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Summary: Magnetic liquids enabled development of new devices and technologies that are a useful alternative to the existing ones. Many of these applications are still in progress and do not represent any break-through discoveries yet. Nevertheless one may expect that owing to their remarkable qualities magnetic fluids will become in the future a part of original projects. The research of magnetic liquids has a strongly multidisciplinary character. It is thus desirable for technicians of different specializations or other specialists (such as physicians, biologists, pharmacists etc.) to be acquainted with the qualities and existing applications of these perspective materials.

1. INTRODUCTION

In the 19th century some physicists (M. Faraday, T. J. Seebeck and others) verified their presumptions of the qualities of the magnetic field using liquids where fine metal dust was dissolved. A disadvantage of this environment was its instability - under the influence of gravity the dust tended to settle down. After more than 100 years physicists reopened the issue and found out that these liquids can be stable if the dust particles are very fine. With extremely fine ferromagnetic particles their sedimentation occurs after a longer time. In these liquids the *magnetic viscosity phenomenon* was disco-vered it means that when they are exposed to the magnetic field their viscosity increases. These liquids were labeled as *magnetic rheological*. Soon production technology was developed, their physical - chemical qualities were examined and their applications were searched for in technical, medical and biochemical practice. The 1st patents for using ferrofluids were gained by Jacob Rabinow [13] in 1940.

In the 50s and 60s of the 20th century research in ferrofluids was embargoed. Since 1970s the knowledge was disclosed and many papers in journals and books have been published. Many interesting and useful applications have been realized and patented. Complex mathematic-physical theories have been described that provide information about structure and behavior of ferrofluids in stationary and dynamic state. The solution of magnetic fields (electro-magnetic, thermal power etc.) is difficult in systems containing ferrofluids as they are in a very non-linear and anisotropic environment. Although many materials were published on ferrofluids, the development and mainly usage of these prospective materials is not fully exploited yet. Contemporary detailed knowledge about the ferrofluids is dealt with in works [1], [2] [11] [12] [15].

2. PHYSICAL-CHEMICAL PRINCIPLE OF FERROFLUIDS

Ferrofluids are permanently stable colloid suspensions of ferromagnetic particles in carrier liquid. Suspension stability here means the quality that the suspension remains permanently homogenous, it is the ferromagnetic particles do not separate from the carrier liquid and do not settle at the bottom of the container (do not sediment), neither creates mutual aggregations. To reach stability ferrofluids must contain ferromagnetic particles of the size 5 to 15 nm (1 nm = 10^{-9}m), so called *nanoparticles*. Nanoparticles are usually formed by one Weiss domain. As a result of spontaneous magnetization it has a magnetic moment and represents an elementary magnetic dipole. Elementary dipoles influence each other. To prevent their aggregation they are covered with stabilizer, i.e. a polymerous (macromolecular) coating, so called *detergent* formed by the chains of polar molecules (e.g. fatty acid), long 1 to 2 nm. Every chain is at one end bound with a nanoparticle and at the other end loosely attracted by the molecules of the carrier medium, Fig. 1. Detergent is thus a surface active material that prevents direct contact between nanoparticles, causes repulsive forces between them and so prevents their aggregation.

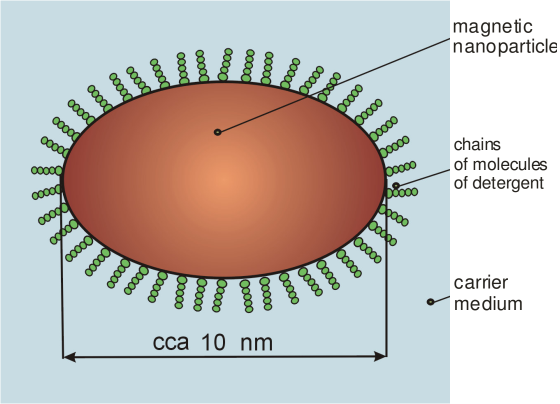

Fig. 1. Ferromagnetic nanoparticle with detergent coating in carrier liquid.

The most common materials for ferromagnetic nanoparticles are magnetite (Fe_3O_4), maghemite (Fe_2O_2), cobalt (Co), iron (Fe) or iron nitride Fe_xN). The carrier liquid can be water, various oils, usually syntactic on hydrocarbon base, glycol and their compounds. Typical magnetic liquid contains (in volume): 5% ferromagnets, 10 % detergent and 85 % carrier liquid. Its relative permeability $\mu_r \approx 5$

drops with temperature and at Curie temperature gets the value $\mu_r = 1$, saturation magnetization is about 1,3 T and working temperature is from –125 to 200 °C. With higher temperature and temperature changes chemical deterioration of detergent chains occur on the surface of nanoparticles, which leads to destabilization of ferrofluid. Ferrofluids durability is e.g. from 8 to 10 years. High quality ferrofluids with long durability are more expensive.

Nanoparticles move in carrier liquid by thermal (Brown) motion. If the liquid is not in the magnetic field, magnetic moments of nanoparticles are randomly oriented and the liquid is non-magnetic, Fig. 2. If the liquid is in the magnetic field, the nanoparticles are polarized, it is they turn in the direction of the magnetic field and make chains lying in the directions of the lines of force. This process leads to considerable changes of physical chemical qualities of ferrofluids. As for their mechanic-elastic qualities it is mainly viscosity – the magnetic viscosity phenomenon. Stable ferrofluid remains liquid even in a strong magnetic field, it means its particles do not sediment and do not aggregate in a strong magnetic field. Unless exposed to the magnetic field, it is isotropic, but in the magnetic field it becomes strongly anisotropic. The dependence of the magnetic inductance on the intensity of the magnetic field has in ferrofluids a course similar to that of solid ferromagnetics: with growing H increases B and asymptomatically approaches the state of saturation. In the linear magnetic field as a result of losses (hysteresis and eddy currents), during remagnetization of nanoparticles these are heated and the carrier liquid is heated as well which leads to decreasing of its viscosity.

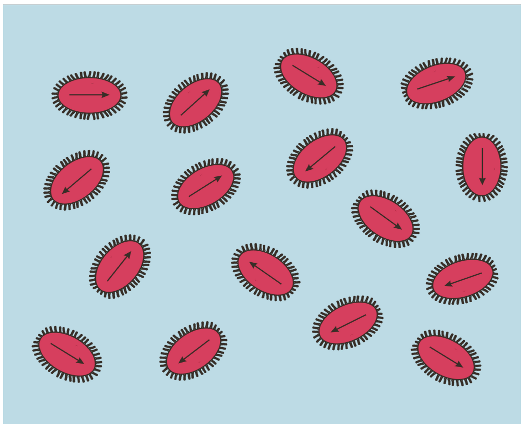

Fig. 2. Ferrofluid without the influence of outer magnetic field: magnetic moment of nanoparticles has random distribution.

In some applications ferrofluids are used with microparticles it is particles of the size from 5 to 15 µm. For these liquids the name is used – *magneto-rheoloigical liquids*. Microparticles are multi-domain ones, (non single-domain ones like nanoparticles) and are not magnetically polarized, do not have a magnetic moment. Magneto-rheological liquids contain a considerably larger volume of ferromagnetics, up to 70 % (of weight). They are not usually stable, it means their microparticles sediment and aggregate, the development of stable magneto-rheological liquids is one of the aims of the present research. They are used in situations when extremely strong magnetic viscosity phenomenon is required, in magnetic field they lose their liquidity and become solid.

Ferrofluids do not exist in nature; they are developed synthetically. Older production technologies were based on long term magnetic crushing of magnetite or ferrite particles in ball mills in deter- gent solution. The process of grinding lasted from 500 to 1000 hours and after finishing the centrifugal separation of bigger particles followed. At present faster and more effective ways are used, based on various chemical processes leading to precipitation of nanoparticles from solutions of ferrous salts. The obtained product must be purified, it is bigger particles are removed or by centrifugation or by sedimentation caused by gravity or non-homogenous magnetic field.

The producers offer a wide range of ferrofluids or magneto-rheological liquids that differ in their composition, physical chemical qualities and price and they recommend what applications they are suitable. Among important producers of these liquids and equipment using them are e.g. American company Lord Corporation Inc. and British company Liquids Research Ltd. [17].

3. FERROHYDRODYNAMICS THEORY

In this part we introduced a short synopsis of mathematical description of system with the ferrofluid, in the form of boundary value coupled problem, based on magnetically/mechanical fields. Magnetic field in the domain Ω is described by the equation

$$\mathrm{rot}\frac{1}{\mu}\mathrm{rot}\,\mathbf{A}(\mathbf{r}) = -\mathbf{J},\quad \mathbf{A}\in\Omega, \tag{1}$$

together with boundary condition for **A,** where by vector **r** is defined the point in the field, μ is the permeability, γ is the conductivity and **J** is the current density. The magnetic field strength is

$$\mathbf{H} = \frac{1}{\mu}\mathrm{rot}\,\mathbf{A} \qquad (\mathrm{div}\,\mathbf{A} = 0) \tag{2}$$

For 2D rotational symmetric system (r, z) with ferrofluid (see e.g. Fig. 4) hold true

$$(\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial A_\varphi}{\partial z}\right) + \frac{\partial}{\partial r}\left(\frac{1}{\mu r}\frac{\partial}{\partial r}\left(r A_\varphi\right)\right) = -\mathbf{J}, \tag{3}$$

$A_\varphi \in \Omega$, together with boundary condition and the magnetic field strength is

$$H_r = -\frac{1}{\mu}\frac{\partial A_\varphi}{\partial z},\; H_z = -\frac{1}{\mu}\left(\frac{\partial A_\varphi}{\partial r} + \frac{A_\varphi}{r}\right) \tag{4}$$

From generalized Navier-Stokes equations of conventional fluid mechanics may be deduced for incompressible isotropic ferrofluids and for the motionless system the ferrodynamic Bernoulli equation. In the steady state hat the form [14], [15]::

$$p^* + \rho g h - \mu_0 \overline{M} H = \text{const.}, \quad p \in \Omega \qquad (5)$$

with following boundary condition:

$$p^* + p_n = p + p_c \qquad (6)$$

were $p^* = p + p_\mathrm{s} + p_\mathrm{m}$ is composite pressure, p is thermodynamic pressure, p_s is magnetostrictive pressure, $p_\mathrm{m} = \mu_0 \overline{M} H$ is fluid-magnetic pressure, where $\overline{M} = \int_0^H M \, \mathrm{d}H$, $p_\mathrm{n} = \frac{1}{2}\mu_0 M_\mathrm{n}^2$ is magnetic normal traction, p_c is capillary pressure, p_0 is pressure in nonmagnetic fluid, ρ is particle mass density and $g = 9{,}8$ m/s.

For some applications the *dynamics of magnetic viscosity phenomenon* is important (e.g. for ferrohydrodynamic damper). In this cases is important the determination of the response of viscosity to the change of the outer magnetic field. Its value is calcu- lated in nanoseconds.

4. THE EFFECT OF THE MAGNETIC FIELD. EXPERIMENTS

To understand the behavior of ferrofluids in the magnetic field, some simpler experiments may be presented that show this physically complex environment sometimes behaves contrary to expectations.

Ferrofluid with free boundary in nonhomogenous magnetic field. If B reaches certain critical value, surface instability of ferrofluids occurs and its surface changes in a system of spikes directed in the course of magnetic lines of force. These spikes are the result of complex structural force ratio in non-linear anisotropic environment of the liquid where magnetic forces apply as well as gravitational force and surface tension. In Fig. 3 there is a Petri dish with ferrofluids and permanent magnet underneath.

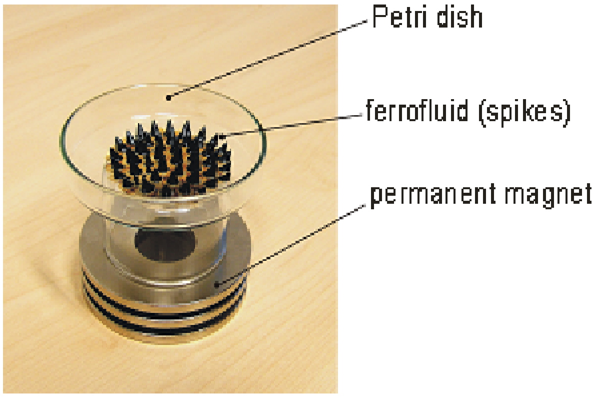

Fig. 3. Ferrofluid in a Petri dish in the magnetic field of a permanent magnet: its surface changed into a set of spikes.

Ferrofluid around a current-carrying wire. In Fig. 4 there is a Petri dish with ferrofluid. Conductor with current I, goes through the dish, which, as it is known, induces in its environment magnetic field of intensity $H = I/2\pi r$, where r is perpendicular distance from the conductor. Ferrofluid is absorbed by the non-homogenous magnetic field, so its originally flat surface changes its shape. In axial section ferrofluid surface is bounded by the curve type $y = \text{const.}/r$.

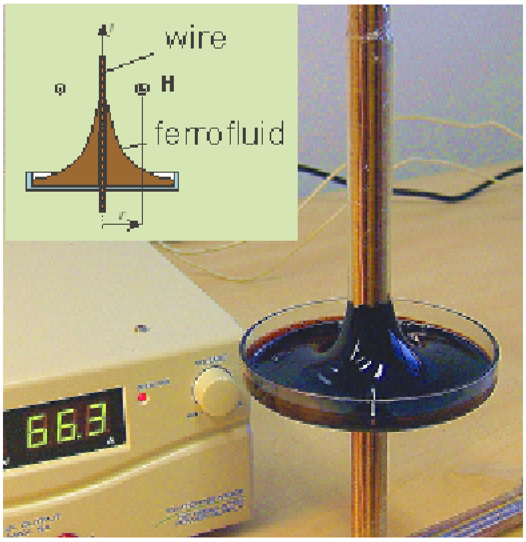

Fig. 4. Ferrofluid near a current-carrying wire.

Theoretical solution. On Fig. 5 is 1D domain Ω, $r \in \langle R, r_2 \rangle$, of ferrofluid. According to Bernoulli eq. (5) is

$$p^* + \rho g h - (\mu_0 M H) = p_2^* - \rho g h_2 - (\mu_0 M H)_2$$

If $r = r_2 \to \infty$, then $H(r_2) \to 0$, $M(r_2) \to 0$, $h = h_2 = 0$. If we neglect the capillarity, $p_\mathrm{c} = 0$, then according eq. (6):

$$h(r) = \text{const.}\, H(r) = \text{Const.}\frac{1}{r} \qquad (7)$$

The boundary between subdomains ferrofluid/air is not solid. *Herewith is characterized the coupled problem.*

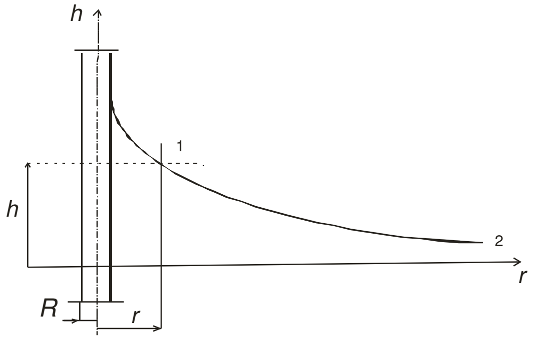

Fig. 5. To the influence of magnetic field of the current-carrying wire on the level of ferrofluids.

Levitation in ferrofluid. It is known that *permanent magnet cannot have stable levitation in stationary magneto static field.* (so-called Earnshaw Theorem). The situation changes when the medium, in which levitation occurs is ferrofluid. If we place a sealed dish with ferrofluid in a non-homogenous magnetostatic field, the ferrofluid will be drawn to the places with increasing field intensity, Fig. 6. Ferrofluid tension appears and if a non-magnetic body is immersed, the inner tension is broken and the body is exposed to forces that (together with the gravitational force) caused stable levitation of the body - so called *passive levitation of the non-magnetic body.*

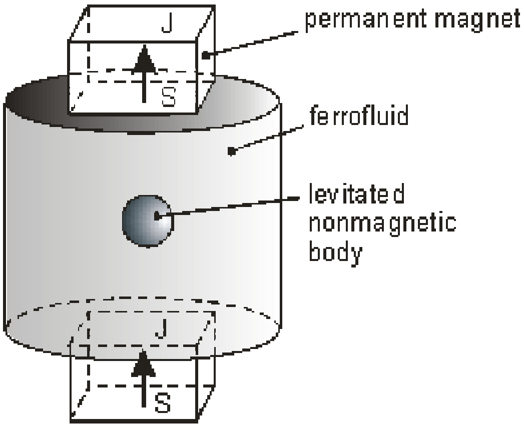

Fig. 6. To the levitation in ferrofluid.

5. USAGE OF FERROFLUIDS

Here some typical examples of useful usage of ferrofluids in technical areas.

Ferrohydrodynamic damper. Dampers used in machinery engineering dissipate kinetic energy of vibrating mechanism and so damp mechanic shocks and consequent vibrations. Conventional hydraulic dampers have constant damping, only in special cases their damping can be changes by regulation of fluid flow with a throttle valve. Ferrohydraulic dampers provide a more elegant solution. They are filled with ferrofluid that is exposed to the magnetic field of the coil induced by a controlled current signal. It changes the viscosity of the ferrofluids and the dumping increases. The current signal is, according a particular strategy controlled by an on-line sensor that reads the causes of vibrations.

In Fig. 7 there is one of construction variants of the ferrohydrodynamic damper.

Ferrohydrodynamic dampers were used in different equipments from fine measuring apparatuses to washing machines, lorry seats to the chassis dumper of means of transport and are very prospective. If a car moves at the speed of 72 km/h, it makes 2 cm distance in 1 ms. Conventional dampers react after 15 ms, the car then makes 30 cm before the damper reacts. The ferromagnetic damper reacts much faster, after 5 ms. The dampers reacts in 10 cm distance and the car gets over a bump without „bouncing“. More transmission of the vibrations to the driver cabin, limits transmission damping pre- vents the bouncing of wheels and thus a loss of adhesion between the tire and the surface which increases the stability of the car, mainly in curves. Magnetic dampers thus increase the safety and comfort ability of the ride, shorten braking reaction, improve the behavior of the car and extend its durability, mainly its tires.

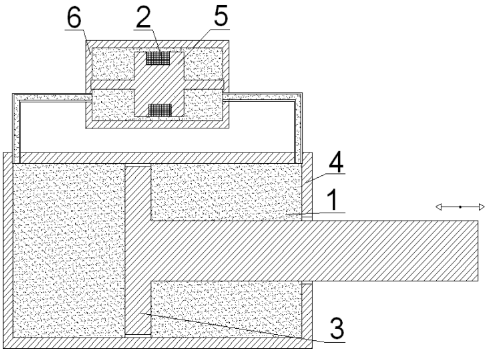

Fig. 7. Ferrohydrodynamic damper: 1 - ferrofluid, 2 – exciting coil, 3 – plunger of damper, 4 – damper shell, 5 – gap, 6 – throttle valve.

Another example is the damper for lorry seats. In Fig. 8 the envelopes of seat vibrations when using conventional (non-controlled) hydraulic damper with both strong a weak damping and magnetic (controlled) damper. Magnetic damper thus increases the comfort and safety of driving.

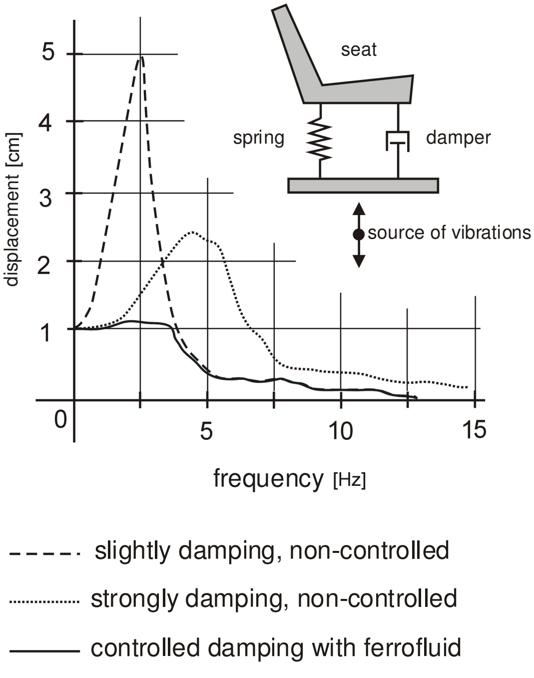

Fig. 8. Vibration of lorry seat with conventional (non-controlled) hydraulic damper and with a controlled magnetic damper.

Magnetic dampers are used also in house appliances, such as washing machines. In construction of buildings in seismically active areas buildings are planned that will have built in magnetic dampers and so will be resistant against earthquake.

Ferrohydrodynamic sealing. Using ferrofluids enables perfect sealing of a rotating shaft. The way of sealing rotating shaft with ferrofluid for magnetic material shaft is in Fig. 9. In mutually separated areas there are different pressures p_1, p2. On a permanent magnet in the shape of a short cylinder stand pole rods from magnetically soft material. Between the shafts and the pole rods there is an air gap of the size of several tenths of centimeter. In the air gap a strong magnetic field concentrates. To this area ferrofluid is pushed that is fixed by the influence of the magnetic field and has the function of sealing. For magnetic inductance in the air gap B ~ 1 T this sealing can keep the pressure difference $|p_1 - p_2| \sim 0,2$ to 1 atm. Based on the given principle multi-layer sealing are built, that enable to increase the overpressure$|p_1 - p_2|$ to the value over 10 atm.

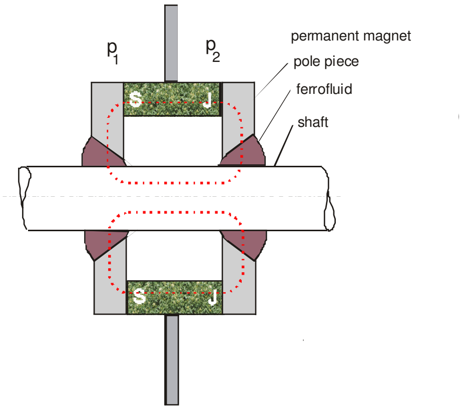

Fig. 9. Sealing magnetic shaft using ferrofluids.

In comparison to conventional (mechanical) sealing the given principle has considerable advantages. It is simpler and (and thus cheaper) more reliable and has a lower friction momentum (ferrofluid functions as a lubricant), high tightness, long durability (producers claim up to10 years) and can function in a wide temperature range from –100 °C to 200 °C. This way of shaft sealing is used also for identical pressures ($p_1 = p_2$), as effective dust proof sealing e.g. to protect bearing operating in dusty, chemically aggressive, toxic or biologically active environment.

Speakers with ferrofluid are constructed as common electrodynamic speakers: in the magnetic circuit with permanent magnet there is an air gap, in which a coil vibrates fed by acoustic signal and connected with the membrane, Fig. 10. Unlike the conven- tional solution, around the coil there is no air, but ferrofluid. By the influence of the strong magnetic field of permanent magnet the ferrofluid is permanently kept in the air gap. The acoustic performance is limited by the acceptable current load of the coil. As the thermal conductivity of ferrofluid is ten times bigger than thermal conductivity of air, it enables to increase current density in the coil and thus the acoustic performance of the speaker.

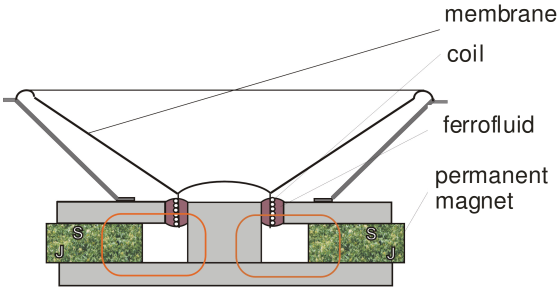

Fig. 10. Speaker with ferrofliud in the air gap.

Electrical machines with ferrofluids. For power transformers ferrofluid is used as a cooling medium. Unlike transformer oil it has a higher thermal conductivity, while its electric strength is basically the same. For rotating electrical machines ferrofluid is applied in the air gap between rotor and stator. It makes cooling better, but first of all it lowers the reluctance of the magnetic circuit of the machine and thus the magnetizing current of the machine. On the other hand, it increases the hydraulic reluctance of the rotation. This requires usage of ferrofluid with low viscosity and high permeability. The mentioned way is limited to slowly running machines. Experiments show that for rotating machines to 1000 turns /min the advantages prevail related with usage of ferrofluids.

6. FUTURE OF FERROFLUIDS

Even if ferrohydrodynamics represents a young science it enabled to realize new apparatuses and technologies, part of which has been presented here. Many are still in progress and do not represent breakthrough discoveries. Nevertheless it is expected that other new machinery and electrotechnical components and new production technologies will arise and that is why various research teams and production companies study ferrofluids. More detailed information is provided in the bibliography.

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