FERROFLUIDS
Synthesis, properties and applications

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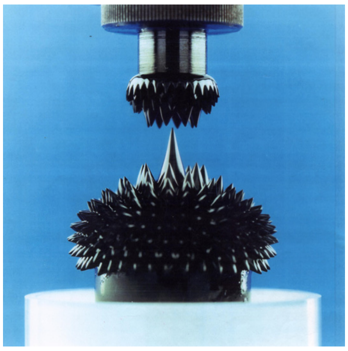

SUMMARY

Ferrofluids (also called magnetic fluids or magnetic nanofluids) are a special category of nanomaterials which exhibit simultaneously liquid and superparamagnetic properties. The possibility of magnetic control over their properties and flow triggered both basic and application orientated researches. The talk will summarize results on ferrofluid synthesis, properties and ferrohydrodynamics, as well as on engineering and biomedical applications.

Lecture to be given at the
European Summer School on Magnetism

"New magnetic materials and their applications"

9-18 September, 2007 Cluj-Napoca (Romania)

1. INTRODUCTION

Ferrofluids (known also as magnetic fluids) are a special category of smart nanomaterials, in particular magnetically controllable nanofluids [1]. These types of nanofluids are colloids of magnetic nanoparticles, such as Fe_3O_4, γ-Fe_2O_3, $CoFe_2O_4$, Co, Fe or Fe-C, stably dispersed in a carrier liquid [2]. Consequently, these nanomaterials manifest simultaneously *fluid* and *magnetic* properties. Macroscopically, the introduction of magnetic forces into the fundamental hydrodynamic equations for the quasihomogeneous magnetizable liquid medium gives rise to the magnetohydrodynamics of magnetic nanofluids (ferrofluids), known also as *ferrohydrodynamics* and opens up an entire field of new phenomena [3] and promising applications [4]. From a microscopic point of view, long-range, attractive van der Waals and magnetic forces are ubiquitous and therefore must be balanced by Coulombic, steric or other interactions to control the colloidal stability of dispersed nanoparticle system, even in intense and strongly non-uniform magnetic field, specific to most of the applications [5, 6].

Many of the envisaged applications, e.g., rotating seals or bearings, require magnetic fluids with high magnetization and at the same time, with long-term colloidal stability. These requirements are difficult to fulfill simultaneously and implies severe conditions on the stabilization procedures applied during the synthesis of magnetic nanofluids.

The composition, structure and properties of various types of ferrofluids will be presented, refering also to technological and biomedical applications envisaged for these nanofluids [2, 5].

2. SYNTHESIS OF FERROFLUIDS

The synthesis of ferrofluids has two main steps: (a) the preparation of nano-sized magnetic particles (2-15 nm) and (b) the subsequent dispersion/stabilization of the nanoparticles in various non-polar and polar carrier liquids. In what concerns the ferrite nanoparticles, the most efficient route is the chemical co-precipitation process [2]. Depending on the carrier properties and applications envisaged, different procedures of ferrofluid synthesis were developed, which will be shortly reviewed [5]. The stabilization mechanisms of magnetic nanoparticles in various kind of carrier liquids, which should prevent irreversible particle agglomerate formation even in intense and strongly non-uniform magnetic field, will be discussed.

3. CHARACTERIZATION

3.1. Structural investigations and colloidal stability In the case of sterically stabilized nanoparticles in various carrier liquids, the type and quality of surfactants used, as well as the temperature of the medium will determine the efficiency of particle surface covering and, consequently, the balance between attractive and repulsive interactions between particles. The attractive interactions, when preponderant, may lead to various types of agglomerates, usually in the shape of linear chains quasi-parallel to the applied magnetic field or drop-like aggregates [7]. The agglomeration processes are not desired in the case of magnetic fluids used in most of the applications; therefore the characterization methods are mainly focused on these processes and on their consequences in the macroscopic behaviour of the fluids.

One of the most efficient methods of nanostructural investigation is based on small angle neutron scattering (SANS) [8]. This method is applied to reveal structural features at the scale of 1-100 nm and it will be presented in detail, beside results of TEM, DLS and magnetogranulometric analyses.

3.2. Magnetic properties Magnetization curves can be extensively used for the study of both particle interactions and agglomerate formation, processes which strongly influence the rheological and magnetoheological behaviour of magnetic fluids. Saturation magnetization *(M_s)*, initial susceptivity *(χ_i),* full magnetization curves (*$M=M(H)$* or *$M/M_s(H)$*, (*H*-intensity of applied magnetic field) and magneto-granulometric analysis (mean magnetic diameter $<D_m>$ and standard deviation σ), at various values of the volumic concentration of magnetic nanoparticles, give an insight on microstructural characteristics of various samples to be compared [9,10]. The dimension of the clusters can give a first hint about both the degree of particle dispersion and the strength of the interparticle interactions. Usually, it can be analyzed via optical methods (e.g. DLS). In spite of the clustering process, the net attractive inter-particle interactions (considered as dipole-dipole type) should be quite weak, due to the steric repulsion induced by the double coating layers. The attractive interactions are considered to induce only perturbations of the main anisotropy energy of the particles. *Temperature dependent Mössbauer spectroscopy* [11] is providing information on particle phase composition, local structure and symmetry, local magnetic interactions inside the particle and Néel-type relaxation phenomena.

3.3 Rheological and magnetorheological properties [12] depend especially on composition, particle volume fraction and degree of colloidal stability of ferrofluids, as well as on the intensity of applied magnetic field. Methodology of investigations on flow properties and main results will be reviewed, with strong emphasis on specially tailored ferrofluids for applications.

4. FERROHYDRODYNAMICS

Equations of ferrohydrodynamics, developed initially by Neuringer and Rosensweig [3], will be synthesized. First, the equations resulting for a quasihomogeneous ferrofluid in the quasistatic approximation will be presented, which correspond to a diluted ferrofluid, with pointlike magnetic dipoles and ideal Langevin behavior of magnetization in a slowly varying field. Next, the model of ferrofluids with internal rotations (Shliomis [13], Rosensweig [14]) taking into account the relaxation of magnetization by Néel or Brown type mechanism, will be shortly outlined.

5. TECHNOLOGICAL and BIOMEDICAL APPLICATIONS [1-6, 15-17]

Synthesis of new type of hybrid nanostructured materials: polymeric nanocomposites, magnetically controlled gels and emulsions; Dynamic sealing with magnetic fluids; Magnetic fluid bearings; Moving coil speakers with magnetic fluid damping and cooling; Inertia dampers with magnetic fluids; Sensors and actuators; Magnetohydrostatic separation; Surface finshing techniques; Non-destructive testing; Domain pattern investigations; Multifunctional magnetic particles, magnetic nanobeads; Magnetic cell separation; Magnetic contrast agents, MRI; Hyperthermia of tumors; Magnetic drug delivery.

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