Research Article

Surface Modification and Characterisation of Magnetite Nanoparticles for Biomedical Applications

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Abstract Infrared spectroscopy was used to confirm incorporation of magnetic particles into dispersion system. Synthesis of magnetite particles was performed by chemical coprecipitation: average particle diameter $\langle d \rangle$ = 20 nm, X-ray density ρ = 5.2 g·cm^{-3}. The samples of magnetite nanoparticles suspended in water-based (surfactant were sodium oleate, 0.5% aqueous solution of hydrochloric acid, 3% aqueous solution of pectin) and polyethylene-based (PEG1500:PEG400 8:2) were investigated. Using IR-spectroscopy the chemical interaction of SAS molecules with the surface layer of magnetite iron cations was determined.

Introduction

The history of application of highly dispersed magnetic materials (nano and micronsized) is associated with technical progress. The first magnetic fluids were designed for use in technology. This idea led to the introduction of fundamentally new technical devices and the development and improvement of technological processes. On the basis of the experience gained, researchers showed interest in their use in medicine and pharmacy [1-10]. One can assume that this was the impetus for the design of medicines with magnetic nanoparticles.

There are several directions of using magnetic fluids in medicine and pharmacy. Particles are used with preliminary (if necessary) surface modification to achieve biocompatibility and specific functionality. They can be directed by an external magnetic field. After magnetic localization of the drug, the required therapeutic or diagnostic actions are carried out.

Surface modification of nanoparticles in contemporary studies is performed not only for the purpose of stabilization. Surface substances alter the solubility of nanoparticles, decrease their phagocytosis, toxicity, and immunogenicity, and also provide the attachment of ligands and drugs and the capture by target cells [11-13]. Various monomeric (carboxylates, phosphates), inorganic (silica, gold, silver, gadolinium), and polymeric (dextran, PEG, polyvinyl alcohol, etc.) coatings are used.

The possibility to control the movement of magnetic agents saturated with drug substances using an external magnetic field is based on the unique hydrodynamic properties of such systems. In the numerous studies on magnetically controllable transport of drugs, it was noted that the use of a magnetic fluid makes it possible to increase the local concentration of various drugs in the target organs, significantly reduce the dose of the drug, and, consequently, minimize the toxic and allergic reactions of the body [14-16].

Creation of new drugs with magnetic properties in different forms by the use of the magnetic component in their composition makes it possible to optimally combine pharmacological and magnetically controllable properties of the drug, which can be applied both in the traditional way and by using its special magnetic properties.

The conditions of stabilization of magnetic nanoparticles in such systems can be defined by structural - rheological properties of the dispersion medium. In the case of using of polar dispersion unstructured environment (such as water) stability of the systems can be achieved using electrostatic and steric stabilization factors. In a viscous base the stabilization of magnet particles is possible without using of surfactant, due to the forces of viscous resistance of the dispersion medium.

For the such systems the nature of interaction of adsorbent-adsorbat between the particles of magnetic phase and surfactant molecules (or environment) should be determined, that affects the state of the surface and subsurface layers of magnetic nanoparticles and thus on their magnetic properties and the magnitude of the magnetic interparticle interaction.

Considering the importance of these samples for biomedical applications and the fact that most applications require the use of this material in the form of aqueous colloidal suspensions, it is worth studying the magnetite surface chemistry and the stability of the particles in water. The aim of this work is to investigate the aggregation and sedimentation stability of the synthesized magnetite particles in v*arious rheological* dispersion medium, to determine the interaction of "adsorbent - adsorbat" between the particles of magnetic phase and the stabilizer molecules.

Materials and Methods

The samples of magnetite nanoparticles suspended in water-based (surfactant were sodium oleate, 0.5% aqueous solution of hydrochloric acid, 3% aqueous solution of pectin) and polyethylene-based (PEG1500: PEG 400 8:2) were investigated. Synthesis of magnetite particles was performed by chemical coprecipitation: average particle diameter $<d> = 20$ nm, X-ray density $\rho = 5.2$ g·cm^{-3}.

The value of ξ-potential was determined experimentally by means of moving boundaries technic. Sedimentation stability of dispersions was studied using the *changes* in the *suspension optical* properties, LMF – 72M *photometer* was used.

Infrared spectra of the magnetite nanoparticles and systems were recorded between 4000 and 400 cm^{-1} in order to confirm the nature of the coating and its bonding to the surface. Samples were prepared by diluting the samples in KBr at 2% by weight and pressing into a pellet.

Results and Discussion

According to the type of carrier liquid, two types of ferrofluids are distinguished: an aqueous ionic ferrofluid and a surfaced organic-based one. Ionic ferrofluids demonstrate several specific phenomena as well as may be used as precursors for a wide class of surfaced ferrofluids. Surfaced ferrofluids based on low-evaporating non-polar liquids keep their fluid properties in a rather wide temperature range. This is important for practical applications. Synthesis of these two types of ferrofluids requires an elaboration of appropriate solubilisation procedures for magnetite particles.

Table 1: Electrokinetic potential of dispersion, average size and aggregation degree of magnetic phase

The composition of dispersed systems	ξ-potential, 10^2 V	Average size of particles, nm / degree of aggregation, %		
		1 day	7 days	60 days
magnetite/water	4.28	120/40	120/40	120/40
magnetite/5% solution of HCl/water	6.28	60/10	60/10	60/10
magnetite/sodium oleate /water	6.95	80/20	80/20	80/20
magnetite/3% solution of pectin/water	7.08	80/20	80/20	80/20

The obtained values of electrokinetic potential of research systems and sedimentation results are presented in Table 1. It was found relatively high values of electrokinetic ξ-potential for all experimental systems. Adding the stabilizer

led to an increase in potential values on average by 45% and sedimentation stability constants at 60%. The efficiency of the electrolyte can be explained with the formation of the electrical double layer on the surface of magnetite particles.

The suspension with the pectin solution (anionic polyelectrolyte) seems to provide *the best properties*. On the surface of the micelle core (magnetite particles) the anions of D-galacturonic acid (the main component of pectin) were adsorbed. This increases the stability of the dispersion system and facilitates the spatial structuring of colloidal particles (granules).

For the magnetite particles in the PEG-based dispersed systems using Rebinder's effect and Deryagin's rule an algorithm was developed. It was founded, that the disperse system PEG/magnetite has the necessary *condition* for *sedimentation stability*: low sedimentation rate of the magnetic phase ($2.15 \cdot 10^{-9}$ cm·s^{-1}) and high value of the measures of kinetic stability ($45 \cdot 10^{5}$).

The type of the interaction between the stabilizer molecules and the magnetite particles was determined using IR-spectra analysis (Fig. 1).

In the resulting spectra of the samples (fig. 1 *a, b*), a band exhibits in the range 3200-3600 cm^{-1}. A broad absorption band of medium intensity in *a* spectrum, and the high intensity in *b* spectrum (Fig. 1), are associated with – OH groups stretching.
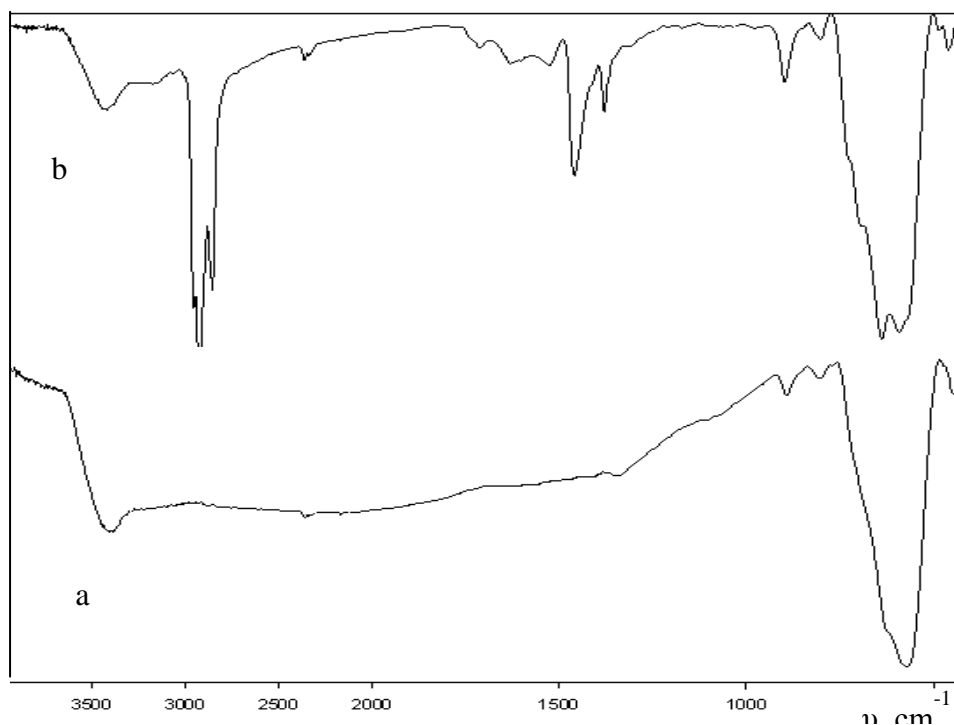

Figure 1: IR - spectra of synthetic magnetite nanoparticles (a)
magnetic system magnetite/sodium oleate/water (b)

The bands in FTIR spectrum of magnetic system *(*fig. 1, b) show the existence of the hydroxide groups in the water and sodium oleate (region 2950 – 2850 cm^{-1}), C=O vibrations (1712 cm^{-1}), bending of C=C (1457 cm^{-1} and 1377 cm^{-1}). The peaks at 2953 and 2854 cm^{-1} are attributed to the rocking –CH$_2$ and –CH$_3$. The peaks at 1457 cm^{-1} and 1377 cm^{-1} – bending of –CH vibrations.

Infrared studies indicated the presence of a strong absorption line in pure magnetite *(*fig. 1, *a*) located at 570 cm^{-1} which was attributed to the stretching vibration of Fe-O in tetrahedral sites. Shifting the absorption maximum of this bond and its splitting (587 cm^{-1} and 634 cm^{-1} (Fig. 1*b*)) may be attributed to the influence of surfactant molecules, with their interference in the subsurface layer of magnetic nanoparticles and chemical bonding with iron cations.

Conclusions

IR-spectra were used to confirm the nature of interaction of adsorbent-adsorbat between the particles of magnetic phase and surfactant molecules. Surfactant is covalently attached to the iron oxide surface and helps to isolate the nanoparticles. Chemical bonding of the surface atoms of the magnetic particles with the stabilizer molecules reduces the "magnetic size" of the particles. Besides excessive local concentration of the stabilizer molecules on the surface of the particles forms the paramagnetic layer. Thus, on the one hand due the presence of surfactant prevents aggregation of the particles in the medium with low structural and mechanical resistance on the other, the use of stabilizer (oleic acid and its salts) leads to decrease in the magnetic properties of such a system that should be considered.

Polyethylene glycol and PEG derivatives are the most effective and widely used polymer for improving nanomaterial stability. PEG with a uniform and ordered chain structure is easily absorbed at the surface of magnetite, and acts as a dispersion stabilizer. When the surface of the colloid adsorbs this type of polymer, the activities of the colloid greatly decrease. By using PEG as a surfactant, we prevented particle growth, decreased interparticle interactions, and controlled the morphology. PEG reduces the tendency of particles to aggregate by steric stabilization, thereby producing formulations with increased stability during storage and application.

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