INTERPARTICLE INTERACTION EFFECT ON MAGNETIZATION DYNAMICS OF MULTICORE IRON OXIDE PARTICLES IN ALTERNATING MAGNETIC FIELD

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Abstract

Magnetic multicore iron oxide particles are nowadays intensively studied for application in magnetic hyperthermia. These particles compose of superparamagnetic iron oxide cores densely packed due to magnetic interactions. The magnetic interaction leads to the increase of energy barrier of magnetization reversal and therefore the heating losses in alternating magnetic field can be enhanced. However, the magnetization dynamics of such systems in alternating magnetic field remains still unclear. Apparently, the main parameters influencing the interaction with magnetic field are the morphology of single cores and multicore particles as well as the intercore and interparticle magnetic interactions. In the current work, we investigate the effect of interparticle interactions between the multicore particles on the heating efficiency of magnetic dispersions in alternating magnetic field. Two types of multicore particles were prepared: naked multicore particles displaying dipole-dipole interactions and multicore particles with surface coating preventing the interaction of multicores. Both types of multicore particles were composed of 13 nm iron oxide cores and have the hydrodynamic size of about 85 nm. To study the absorption of AMF energy, multicore particles were dispersed in media with different viscosity (water and agarose). It was demonstrated that covered multicore particles display significantly higher heating efficiency in both media than naked particles, which is associated with the elimination of dipole-dipole interaction between multicores.

Keywords: Iron oxide nanoparticles, multicore particles, magnetic interaction, specific loss power, hyperthermia

1. INTRODUCTION

Magnetic multicore iron oxide particles (MCPs) have recently received much attention from the viewpoint of their application for magnetic hyperthermia cancer treatment [1-4]. These MCPs represent dense aggregates of superparamagnetic iron oxide nanoparticles. The magnetic interaction between nanoparticles in aggregate increases the energy barrier of magnetization reversal and as a result, the material may generate large amount of heat when exposed to radiofrequency alternating magnetic field (AMF) of low intensity. This feature makes MCPs a promising candidate for magnetic hyperthermia treatment of cancer, when the tumor with embedded magnetic material is heated up to 42 - 45 °C under exposure to AMF of moderate amplitude and frequency. The heating efficiency of the magnetic material is quantified by specific loss power (SLP) that is the amount of heat generated by unit mass of magnetic material.

The heat loss of magnetic particles in AMF is determined by the high of the energy barrier of magnetization reversal, which in turn depends on material intrinsic properties (magnetic anisotropy, magnetization saturation) and on interparticle magnetic interactions. Several heating mechanisms are possible, associated with Neel and Brown relaxation losses and hysteresis loss [4]. Non-interacting spherical superparamagnetic nanoparticles of magnetite/maghemite (diameter, *d,* less than 12 nm) showed very low SLP value because of a low relaxation loss power due to low energy barrier. With the increase of nanoparticles size, the energy barrier and coercivity increase reaching maximum at *d* of about 15 nm and then again decreases after transition to multi-domain state (d > 80 nm) [4, 5]. As to the effect of magnetic interparticle interactions on heating efficiency, non-monotonic dependence of SLP on nanoparticles concentration and aggregation state, i.e. on

hydrodynamic size, is reported [3]. It is explained by the competition between short-distance (intercore) and long-distance (multicore-to-multicore) magnetic dipolar interactions on energy barrier. Therefore, there are two pathways to increase the losses: either to search for the optimal size of single non-interacting nanoparticles or to take under control the effect of interparticle interactions on magnetization dynamics. Though, the second pathway seems to be effective, there is no quantitative theory describing the magnetization dynamics in the system of interacting nanoparticles in AMF. According to the recent published results, SLP value is related to the system dependent demagnetizing effects, which in turn depend on the internal properties of MCPs, such as core size distribution, their spacing inside the aggregate, hydrodynamic size of the MCPs as a whole, magnetic interaction between the individual cores within the aggregate, as well as on multicore-to-multicore dipolar interaction in dispersive media [1-3, 6-8]. In the current work, we investigate the effect of multicore-to-multicore interactions on the magnetization dynamics of MCPs. To this end, two types of MCPs were prepared: naked MCPs displaying dipole-dipole interactions and MCPs with citric acid surface coating preventing the interaction of multicores.

2. EXPERIMENTAL PART

2.1. Synthesis of magnetic cores

Magnetic cores that form MCPs represent iron oxide magnetic nanoparticles prepared by coprecipitation method according to the previously elaborated protocol [9, 10]. Briefly, solution of iron (II) and iron (III) chlorides with molar ratio Fe^{2+} : Fe^{3+} = 1 : 2 was slowly added into the ammonia solution (0.38 M) heated up to 70 °C and stirred at 700 rpm in argon atmosphere. After the whole salts solution was added, the mixture was kept at 70 °C and stirred for one hour. The prepared dark-brown sediment of magnetic nanoparticles was then decanted and washed with demineralized water.

2.2. Synthesis of naked MCPs

In order to obtain naked MCPs the peptization method was applied. The sediment of iron oxide nanoparticles obtained by coprecipitation was treated with 0.001 M HCl until the pH of the dispersion was around 2.5 and ultrasonicated. After this, dark-brown supernatant comprising MCPs was observed and collected by holding the remaining sediment with magnet.

2.3. Synthesis of MCPs with surface coating

Preparation of MCPs with surface coating was done by the modification of naked MCPs obtained by peptization. Citric acid was used as a modification agent. The solution of citric acid with concentration providing the formation of monolayer on the particles surface was mixed with the particles dispersion and heated to 80 °C under continuous stirring. Coated multicore particles were separated by permanent magnet and dispersed in demineralized water at different concentrations.

2.4. Characterization

The morphology of iron oxide nanoparticles was evaluated from transmission electron microscopy (TEM) on JEOL JEM - 2100F. Hydrodynamic size and zeta potential of MCPs were measured by Dynamic Light Scattering (DLS) and Laser Doppler Velocimetry by Zetasizer Nano ZS, Malvern Instruments. The concentration of iron oxide in dispersions and iron content was determined by Energy Dispersive X-ray Fluorescence spectroscopy by ARL Quant'X EDXRF Analyzer, Thermo Scientific. To evaluate the heating efficiency of MCPs in dispersion, a home-made device was used that is able to generate AMF of 1048 kHz frequency and 5.9 kA / m amplitude. The device consists of a signal generator Agilent 33521A, RF broadband amplifier AR RF/Microwave Instrumentation 800A3A, induction coil (90 mm diameter), interchangeable capacitors and magnetic field sensor. The heating efficiency was evaluated for the aqueous dispersions of

MCPs as well as for the dispersions in viscous agarose (3 wt. % of agar). The test tube with the dispersion was placed inside the coil in a polystyrene sample holder. The temperature was measured with monitoring system ReFlex 4, Neoptix and fiber optic temperature sensor T1S-03-PT06 inserted directly in the dispersion. SLP was calculated according to equation: $SLP = dT / dt \cdot c / m$, where T is temperature, t is time, c is heat capacity and m is mass of iron in the dispersion.

3. RESULTS AND DISCUSSION

Iron oxide nanoparticles that constitute MCPs were obtained by coprecipitation method under the synthesis conditions previously established in our laboratory. Rapid homogeneous nucleation and diffusion-controlled growth of nanoparticles was ensured during the synthesis that provide uniform, highly crystalline nanoparticles of 13 nm with polydispersity of 0.3 [10, 11]. Bare iron oxide nanoparticles obtained easily aggregate due to magnetic interaction forming aggregates with different hydrodynamic sizes. Though according to their size nanoparticles should be superparamagnetic, they display ferromagnetic like behavior with non-zero hysteresis and sextets on Mossbauer spectra [9]. Interparticle magnetic interactions account for ferromagnetic-like behavior and thus influence considerably on the heat generation in AMF. As-synthesized nanoparticles dispersed in viscous agarose display SLP of 8 ± 1 W / g_{Fe}. Although the heating rate is high and hyperthermia temperatures can be reached within tens of seconds, the SLP value is rather low. To increase the SLP, the elimination of aggregates (MCPs) with certain diameter is required. This was done by peptization method. Treatment of as-synthesized nanoparticles gathered in aggregates with diluted hydrochloric acid results in protonation of the particles surface and MCPs with certain size, depending on the medium pH, peptize forming stable aqueous dispersion [12]. In the current work, two types of iron oxide MCPs were prepared: (a) naked MCPs, obtained by peptization of coprecipitated iron oxide nanoparticles and (b) MCPs with surface coating, obtained by modification of naked MCPs with citric acid (**Figure 1**).

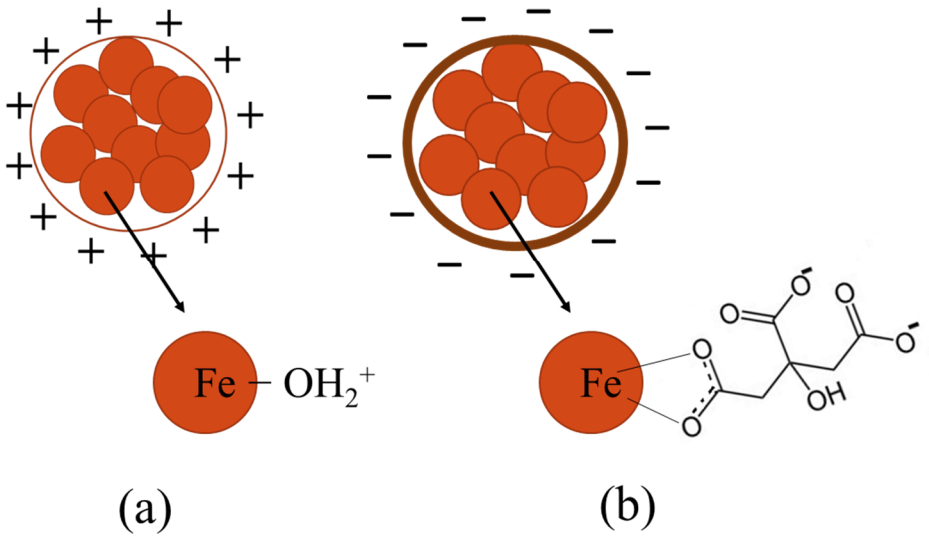

Figure 1 Schematic representation of electrostatic stabilization of (a) naked MCPs and (b) citric acid covered MCPs in aqueous dispersions

Citric acid chemically binds to the iron oxide surface by one of its carboxyl groups and other two provide negative surface charge and electrostatic stabilization [13]. As the molecule of citric acid is rather small, modification does not considerably effect on the hydrodynamic size of MCPs and only changes the surface zeta potential (**Table 1**). However, the presence of surface coating on MCPs significantly effects on its heating efficiency in AMF.

Table 1 Colloidal properties and SLP of the MCPs dispersions

Sample	Hydrodynamic size, nm	Zeta potential, mV	Concentration of iron oxide in dispersion, wt. %	SLP in aqueous dispersion, W / g_{Fe}	SLP in agarose dispersion, W / g_{Fe}
Naked MCPs	85	+45	0.06	42 ± 5	28 ± 6
			0.2	44 ± 2	29 ± 3
			1	48 ± 1	21 ± 1
Citric acid coated MCPs	85	-20	0.06	61 ± 3	54 ± 2
			0.2	52 ± 1	48 ± 4
			1	51 ± 2	43 ± 1
			5	46 ± 1	41 ± 3
			6	40 ± 4	32 ± 4

In addition to magneto-structural properties of MCPs and magnetic interactions, magnetization dynamics is also dependent on the medium viscosity. Therefore, the heating efficiency of MCPs was studied on their dispersions in media of low and high viscosity, i.e. in water and in agarose. As can be seen from **Table 1**, the SLP for naked MCPs significantly decreases when they are immobilized in high viscosity medium that can be explained by inhibition of Brown relaxation. Increase of the concentration of iron oxide in dispersion up to 1 wt. % does not significantly effect on the heating efficiency. Further increase of concentration results in particles sedimentation.

When naked MCPs were coated with citric acid, their heat outcome visibly increased, thus displaying that elimination of multicore-to-multicore interaction leads to the increase of heating efficiency. In contrast to naked MCPs, concentration of coated MCPs could be increased up to 6 wt. % keeping the dispersion stability. However, with the increase of concentration, SLP decreases indicating that multicore-to-multicore interactions become stronger. It should be also noted, that there is no such a significant drop of SLP for coated MCPs in agarose. Therefore, it is possible to conclude, that the main mechanism responsible for the magnetization dynamics of coated MCPs in AMF is the Neel relaxation.

4. CONCLUSION

To demonstrate the effect of magnetic dipole-dipole interaction on magnetization dynamics of MCPs in AMF, two types of MCPs were prepared: naked MCPs exhibiting dipole-dipole interactions between them and MCPs with citric acid coating preventing this type of interactions. It was verified that dipole-dipole interaction impairs the heating ability. Coated MCPs display better heating than naked MCPs both in aqueous and viscous agarose media. However, the heating ability of coated MCPs decreases with the increase of concentration in dispersion due to strengthening of multicore-to-multicore interactions.

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