THE AGGREGATION OF SUPERPARAMAGNETIC PARTICLES IN A FERROFLUID

Stanislav Čampelj[1], Marko Jagodič[2], Alenka Mertelj[1], Zvonko Jagličić[2], Darko Makovec[1]
[1] "Jožef Stefan" Institute, Jamova 39, Slovenia
[2]Institute of Mathematics, Physics and Mechanics, Jadranska 19, Slovenia

stanislav.campelj@ijs.si

Stable colloidal suspensions of magnetic nanoparticles called ferrofluids have attracted a lot of attention in recent years, since they can be used in numerous technological and medical applications [1-3]. For biomedical applications aqueous-based ferrofluids are being tested. Besides the requirements concerning their non-toxicity and biocompatibility, their behaviour in a magnetic filed is also of great importance. Under the influence of an external magnetic field, the nanoparticles of the ferrofluid undergo a major change in their ordering, forming agglomerates, which can lead to a phase separation. The transformations in the ordering of the nanoparticles in the ferrofluid and phase separation have a drastic effect on the rheological properties of the ferrofluid.

In the absence of a magnetic field the thermal energy, kT, prevails over the dipole-dipole interaction between superparamagnetic nanoparticles. As a result, the nanoparticles remain separated and suspended in a carrier liquid. A drastic change in their ordering occurs when they are exposed to a magnetic field. The dipole-dipole interactions prevail over kT and the nanoparticles start to form chain-like agglomerates. This agglomeration leads to a phase separation, resulting in two phases: the "liquid phase", containing a larger content of the nanoparticles; and the "gas phase", with a lower content of nanoparticles. The transition is usually described by the van der Waals "gas-liquid" phase transition [4-6].

In this work, the process of agglomeration was studied in a ferrofluid prepared by dispersing superparamagnetic nanoparticles of maghemite in water, using citric acid as the surfactant. The nanoparticles were 14 nm in diameter, with a saturation magnetization of 66 emu/g. The ferrofluid contained from 0.5 to 1.7 wt.% of magnetic phase.

The changes in the internal structure caused by the ordering of the nanoparticles in ferrofluids under the influence of an external magnetic field were studied with measurements of the rheological properties as a function of field strength, with dynamic light scattering (DLS), and with magnetic measurements. The rheological measurements showed the influence of the magnetic field on the rheological behaviour of the ferrofluid. With an increasing magnetic field, first the viscosity increases, as the character of the ferrofluid changes from a sol to a gel. At even higher magnetic fields, the gel transforms back to a sol and the viscosity decreases. These changes can be attributed to a gradual change in the ordering of the nanoparticles. In parallel, the changes in the internal structure during the process of phase separation were studied using DLS. The internal structures appearing in the ferrofluid were observed using an optical microscope. The magnetic interactions between the nanoparticles originating from the formation of the internal structure as a function of the magnetic field were also studied, using measurements of magnetization under zero field and field cooling (ZFC/FC) conditions. The ZFC/FC measurements showed an increase in the saturation magnetization at the blocking temperature, depending on the strength of the magnetic field at which the sample was frozen. The increase in the magnetization can be explained by the agglomeration of the particles. Once the particles come into close proximity, the coupling of the magnetic moments occurs, which increases the initial (H=0) susceptibility of the nanoparticles. The process was found to be totally reversible. When the magnetic field is cancelled, the magnetization reduces back to the original value, indicating that the particles in the formed agglomerates do not come into direct contact.

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Figures:

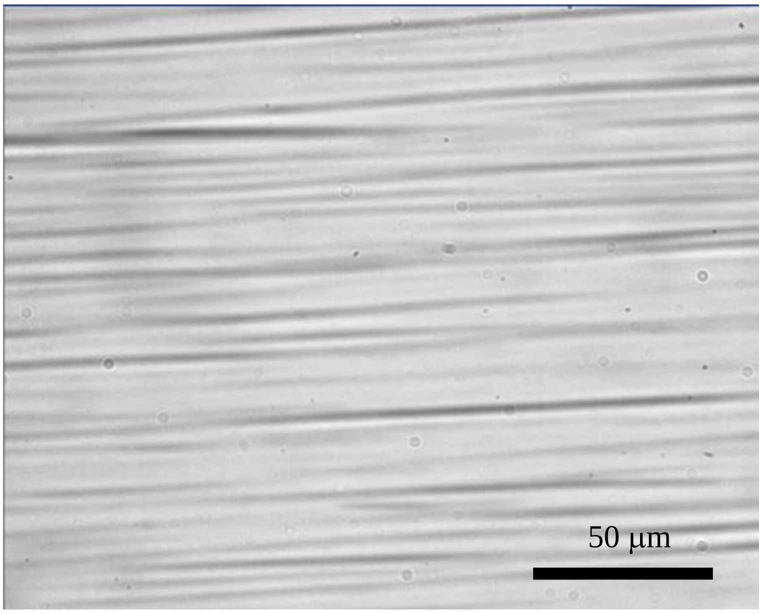

Figure 1: Micrograph shows phase separation into "liquid phase", containing a larger content of the nanoparticles (darker areas), and the "gas phase", with a lower content of nanoparticles (lighter areas) in the ferrofluid under the influence of a 270 mT magnetic field.