Domain structures in thin channels with ferrofluids

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Many experiments (see, for example, [1]) demonstrate that under low (but room) temperatures and/or high enough magnetic fields ensembles of magnetic particles in ferrofluids undergo condensation phase transitions – particles unite into dense bulk aggregates (drops) aligned along the applied field. The physical reason of these condensation phenomena lies in the magnetodipole interaction between the particles, which effectively acts as an attraction between them. Applied magnetic field aligns magnetic moments of the particles along the field direction what leads to increase of their attraction and stimulates the phase transitions.

Experiments [1] exhibit an interesting feature of the phase transitions in ferrofluids filling thin (1μm – 1mm) channels placed into perpendicular magnetic field. The matter is, after the phase separation the dense phase presents not one simply connected volume (as it takes place in the classical case of a system with infinite volume), but ensemble of discrete cylindrical domains aligned along the field. It should be noted that these domain structures are also often observed in experiments with the MRS and systems similar to them. The typical diameter of the domains in experiments with the ferrofluids is about several microns, that is why they are seen by usual microscopes. The main physical reason of formation of the discrete domains lies in the competition between the capillary effects on the domain boundaries, which tend to amalgamate the domains into one massive phase with a minimal surface, and demagnetizing effects, which tend to transform the domains into very thin "needles" [2].

Interesting effect of the domain structure inversion from the state "dense domains in dilute environment" to the state "cylindrical holes of density in the dense simply connected phase" has been observed in some experiments. Obviously, appearance of the domain system in the gap as well as its inversion can not but influence on various macroscopical properties of ferrofluids.

The aim of this work is theoretical study of the domain structures in ferrofluids as well as transformations of these structures from the direct (Fig 1.a) to the inverse (Fig1.b) form.

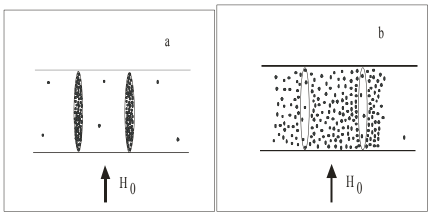

Figure 1: a) The direct with the dense domains, and b) inverse, with the "holes", domain structures in ferrofluid.

We considered a ferrofluid, filling a flat gap with the finite thickness L, placed into perpendicular magnetic field H_0. The conditions of the ferrofluid separation into the dense and dilute phases as well as the total volumes of these phases has been determined from the standard thermodynamical conditions of equalities of the particle chemical potentials and osmotic pressures in the coexisting phases. The shape of the domain has been determined by balancing of the demagnetizing and capillary effects. It was shown that the domain diameter D depends on the gap thickness L as $D \sim L^{2/3}$. For weak magnetic fields H_0 the following dependence has been obtained $D \sim H_0^{-2/3}$; when the magnetic field increases D tends to a certain saturated magnitude. These results are in agreement with known experiments.

In order to study thermodynamical stability of the direct and inverse structures we estimated the free energies of the ferrofluid in the states with the dense domains and holes of density. These free energies have been estimated taking into account the capillary effects on the domain boundaries, demagnetizing effects of the domains and interaction of the ferrofluid with the applied magnetic field.

Comparing the free energies of the ferrofluid in the direct and inverse states allows to determine what of these states is stable under given extrenal conditions. The results of this analysis are presented in Fig.2 in the form of phase diagrams. The regions above the diagrams correspond to the inverse state, below them – to the direct state.

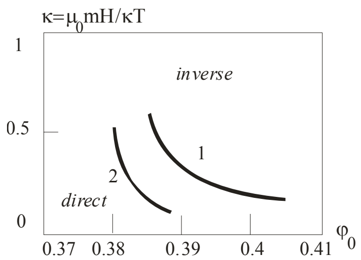

Figure 2: The phase diagrams of the direct – inverse structure transition; φ_0 is hydrodynamical volume concentration of the particles. Lines 1 and 2 – $L/d=10^4$ and 10^5, d is hydrodynamical diameter of the particle.

These diagrams indicate that the structure inversion takes place only when the applied field and volume concentration of particles in ferrofluid are high enough. The same conclusion follows from the known experiments.

Appearance of the dense “bridges”, linking the gap walls, can lead to the elastic response of the system to the static shear in the gap plane and, therefore, to the yield stress effects. These and other rheological effects, provided by the bulk structures in ferrofluids, are considered in the work [3].

Conclusion

Both types of the domain structures (direct and inverse) observed in experiments with magnetic suspensions filling finite channels (gaps) are studied theoretically.

The dependencies of the domain diameters on the applied magnetic field as well as on the gap thickness are estimated. Our results show that the transition from the direct to the inverse structure can take place when both the total concentration of the particles and applied magnetic field are high enough.

The results of analysis are in agreement with known experiments.

References

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