Rheological properties of ferrofluids with bulk internal structures

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Many experiments (see, for example, [1]) demonstrate that bulk drop-like structures, aligned along applied magnetic field, occur in ferrofluids under action of this field. The typical thickness of these drops in known experimens varies from several to several tens of microns. The length of the domains as a rule is several tens times more than their thickness. These structures have been observed in many ferrofluids prepared with quite different ways (water and organic luquid based systems; the systems with particles, covered by surfactant, ionic and other screen layers, etc.). That is why appearance of the drop-like structures can be considered as a general and fundamental property of ferrofluids.

Obviously, the dense bulk drops can not but influence on various macroscopical properties of ferrofuids. Indeed, the strong increase of ferrofluid viscosity under action of the applied field has been observed in experiments, described in [2]. These strong magnetovisous effects have been explained in [2] under assumption that they were caused by the linear chain-like aggregates. However, since the appearance of these drops is quite common phenomenon for ferrofluids, the influence of these structures on macroscopical rheological effects in these systems worths attentive studying.

In the presented work we study influence of the bulk drop-like structures on the rheological properties of ferrofluids in two typical situations. First, when the size of the structures is much less than all sizes of the channel of the ferrofluid flow. In this case the ferrofluid behaves as a viscoelastic luquid.

We considered the bulk “drops” as nuclei of new dense phase, which appear in the ferrofluid under action of the applied field. Taking into account the destruction effects of the hydrodynamical flow, we have estimated the size, shape and volume concentration of the steady stable drops in the shear flowing ferrofluid. Estimates showed that for all experimentally interesting situations the drops are highly elongated. Rheological properties of the ferrofluid with elongated drops can be estimated by using the known results of hydromechanics of suspensions of non spherical particles (drops).

Known theoretical models of of the polar suspensions with the internal structures (drops, chains, etc.) neglect any interactions between them and suppose that the angle of the structure deviation from the field, under the shear flow, is vanishing. In these approximations we estimated the effective viscosity of the ferrofluid with bulk drops and got results about order of magnitude more than those in experiments. Then, by using the known approximations of hydromechanics of non dilute suspensions, we took into account the hydrodynamical interaction between the drops and finite magnitude of the angle of the drop deviation from the field as well.

In this case the results of calculations are very close to the known experiments. This allows us to conclude that the hydromechanical interaction between the internal structures in ferrofluids can play decisively important part in formation of macroscopical properties of these systems.

The second case, which we have considered, corresponds to the situation when the bulk drops overlap the channel of the ferrofluid flow. Structure of these domains, spanning the flat channels, placed into perpendicular magnetic field, is discussed in [3].

Appearance of the dence bulk "bridges" between 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. We studied these effects under strong assumption that the connection between the domains and the gap walls is rigid and the domains can not slip on the walls.

Traditionally, in the theories of MRS, ERF and systems similar to them, the yield stress τ_y is associated with this maximum of the stress-strain curve. However analysis shows that another mechanism of the yield stress formation is possible in ferrofluids. The point is, at a certain large magnitude of the strain, the separation of the "bridge" into two drops, twice shorter than the gap, is thermodynamically profitable. The distruction of the "bridges" means the end of the elastic reaction of the ferrolfuid on the applied mechanical stress and transition to the regime of viscous flow. Estimates show that the "bridge" separation must take place at shear rates significantly less than those which provide the maximum of the "stress-strain" curve. Thus the stress of the "bridge" destruction can be associated with the yield stress τ_y. Some typical results of the stress calculations are presented in Fig. 1.

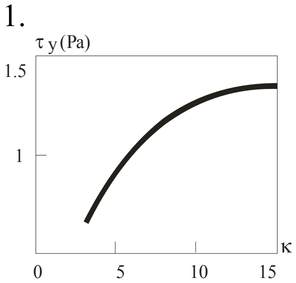

Figure 1: The typical dependence of the yield stress vs. dimensionless magnetic field $\kappa=\mu_0 H/kT$.

Analysis shows that $\tau_y \sim L^{-1/3}$, where L is the thickness of the channel with ferrofluid; when the applied magnetic field is weak, $\tau_y \sim H^{4/3}$. It should be noted that in the traditional theories, when the yield stress is associated with the maximum of the stress-strain curve, the yield stress dependence on L is negligible and the following relation $\tau_y \sim H^2$ is held. The yield stress dependences on H and L can be determined in experiments, what can help to clarify the real mechanism of the yield stress effects in ferrofluids.

We would like to stress that the analysis of the yield stress effects have been done under strong assumptions that there is no slipping of the domains on the channel walls and that the domains ("bridges") are hard, therefore can not flow. But in real experiments both of these assumptions may be not valid. Whereas the first, no slipping condition can be provided by a special state of the walls, the effect of the domain flow is inevitable and the elastic, therefore, yield stress effects can be detected only when the time of experiment is significantly less than the typical time of the domain flow. The magnitude of the domain flow time is discussed.

References

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