Interplay between microdynamics and macro rheology in vesicle suspensions

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Abstract
The microstructural dynamics of objects suspended in a fluid determines the macroscopic response of the suspension. For example, as shown by Dunker and Misbah [1] the viscosity of a dilute suspension of fluid-filled vesicles is a non-monotonic function of the suspension concentration. This stems from the fact that below a certain critical viscosity the vesicles perform a tank-treading motion and the rotational flow is dominated by the viscosity of the encapsulated fluid, while above this critical viscosity the viscosity is dominated by the viscosity of the external suspending fluid. This minimum in the viscosity occurs at a critical viscosity contrast which is independent of the suspension concentration. The system undergoes a transition from tank-treading to tumbling, which is triggered by increasing the viscosity contrast above this critical value. The transition is caused by the rotational flow of the encapsulated fluid that induces a boundary layer on the vesicle surface. This boundary layer increases the effective viscosity. In contrast to a recent work by Lindqvist et al. [5] performed in the unbounded limit and for a single vesicle (dilute limit) [1,2], we recover the non-monotonic behavior of the intrinsic viscosity versus the viscosity contrast – even in the presence of bounding walls. The interplay between the wall-induced lift force and increasing the viscosity contrast causes the vesicle-free boundary layer to become narrower, and results in higher intrinsic viscosity. This is similar to the Dunker-Misbah effect [1,2]. The observed non-monotonic behavior of the intrinsic viscosity versus the viscosity contrast is a consequence of the boundary layer thickness and not due to the vesicle-dynamical transition as in the case of the Dunker-Misbah effect [1,2]. For these simulations, the wall effects are dominant and hide the contribution of the vesicle-dynamical transition. Thus, in order to capture the Dunker-Misbah effect one should decrease confinement to lower values, as is done in the present work.

Method
Our two-dimensional fluid-fluid simulations are based on a combination of the lattice-Boltzmann and the immersed boundary methods. We use lattice Boltzmann method as fluid solver to compute the flow of the encapsulated and the suspending fluids and we use the immersed-boundary method for coupling the flow field and the vesicle dynamics. The vesicle dynamics is computed for a single vesicle in a shear flow and for vesicle–vesicle and vesicle–wall hydrodynamic collisions. For the vesicle–vesicle and vesicle–wall collisions we implemented a two-way coupling. For the vesicle–wall collisions we used a viscoelastic membrane model for the vesicle. For the vesicle–vesicle collisions the vesicle is modeled as a rigid particle. The transition from tank-treading to tumbling is triggered by increasing the viscosity contrast above a critical value, which is determined from the evolution in time of the inclination angle.

Rheology of a fluid containing a single vesicle (dilute limit)

The dye-molecular behavior at the macroscopic level is caused by the events of the tank-treading and the tumbling regimes. The change in flow dynamics is reflected in the macroscopic viscosity, which is a non-monotonic function of the viscosity contrast. The transition from tank-treading to tumbling is triggered by increasing the viscosity contrast above a critical value. The viscosity contrast is defined as the ratio of the viscosity of the internal fluid to the viscosity of the external suspending fluid. The viscosity of the internal fluid is determined by the experimental conditions and the experimental setup. The viscosity of the external suspending fluid is determined by the experimental conditions and the experimental setup.

Rheology of a suspension of vesicles (non-dilute limit)

The intrinsic viscosity is defined as the ratio of the shear viscosity to the shear stress. The shear viscosity is determined by the flow dynamics of the vesicle suspension. The shear stress is determined by the flow dynamics of the vesicle suspension. The intrinsic viscosity is a non-monotonic function of the concentration. The transition from tank-treading to tumbling is triggered by increasing the concentration above a critical value. The concentration is defined as the number of vesicles per unit volume.

References

Discussions and conclusions
We recover the non-monotonic behavior of the intrinsic viscosity versus the viscosity contrast – even in the presence of bounding walls and non-zero Reynold number. It is in contrast to recent work by Lamoure and Gompper [3], where we found that the effect proposed by Dunker and Misbah [1,2] persists even for non-dilute suspensions of vesicles and when we vary the deformability and the swelling degree of the vesicles. The effect becomes less pronounced at higher swelling degrees and at higher concentrations (limit of dense suspensions) where the tumbling motion is inhibited. This can be understood by means of the vesicle–vesicle and vesicle–wall hydrodynamic collisions that then become more important. Let us now close the question about the origin of the apparent contradicting behaviors of the intrinsic viscosity versus the viscosity contrast (1, 2, 4-6) reported in different studies [1,4-6, 10] if we disregard errors in the measurements, numerical artifacts or the contribution of thermal fluctuations, the influence of the wall confinement remains the main possible origin. The data of Lamoure and Gompper [3] are obtained at higher degrees of confinement (\( \gamma = 0.30 \) and 0.35). The walls are too close that they strongly influence the dynamics and the microstructures formed by the vesicles. In our case, such higher confinement do not even allow for the tank-treading to tumbling transition to take place at \( \Lambda \leq 7.8 \).

The interplay between the wall-induced lift force and increasing the viscosity contrast causes the vesicle-free boundary layer to become narrower, and results in higher intrinsic viscosity. This is similar to the Dunker-Misbah effect [1,2]. The observed non-monotonic increasing behavior of the intrinsic viscosity with the viscosity contrast in Ref. [2] is mainly due to the variation of the vesicle–wall boundary layer thickness, and not due to the vesicle-dynamical transition as in the case of the Dunker-Misbah effect [1,2]. For these simulations, the wall effects are dominant and hide the contribution of the vesicle-dynamical transition. Thus, in order to capture the Dunker-Misbah effect one should decrease confinement to lower values, as is done in the present work.

References