

Dynamics, stability, and thermodynamics of deformable biological membranes interacting with Newtonian and viscoelastic fluids

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Abstract:

Biological membranes are ubiquitous for the regular functioning of our human body. If we view our body from a micro perspective, we are made up of objects that are deformable in nature. This could be a blood vessel or a cell membrane containing nutrients. Fluid-structure interactions lie at the heart of these phenomena. Moreover, when one inspects these biological membranes, they would come across a plethora of complex macromolecules that make up such systems. An example of such a system is the lipid bilayer that surrounds most of the cells in our body. These bilayers are made up of phospholipid molecules interspersed with cholesterol and other molecules. Due to the nature of the cholesterol molecules and steric effects, they prefer one type of lipid molecule over the other thereby leading to phase separation on the cell membrane surface. This phase separation has been understood experimentally in systems involving no flow or other complex dynamics. This phase separation is the basis of the formation of lipid rafts which is key in the transport of nutrients across such membranes. Analyzing these systems is of importance from a fundamental as well as an applied perspective to tune therapeutics as well as processing techniques. In this thesis, we try to evaluate deformable biological aspects from multiple lenses -- fluid dynamics, mechanics, and thermodynamics. The major questions we intend to answer are given below:

- **How do elastic sheets deform under the action of flow due to complex, polymeric fluids?**

When a fluid starts flowing through a conduit with deformable walls, the conduit develops a peeling front that propagates down the channel. In this project, we investigate what occurs to the deformation profile when the fluid is non-Newtonian (e.g., a polymeric solution). The fluid obeys a simple Phan Thien Tanner model, and the walls are linearly elastic. Assuming a shallow channel, we use the lubrication approximation to arrive at a reduced 1-D nonlinear partial differential equation that describes the channel deformation profile in space and time. Similarity solutions and scaling laws are developed to relate the peeling profile to material properties of the fluid. We find that shear thinning of a polymeric fluid causes the peeling front to propagate down the channel faster than a Newtonian fluid with a similar zero shear viscosity. The peeling front scales as a power law with respect to time $x \sim Ct^a$, where a is smaller than the value found for a Newtonian fluid ($a = \frac{1}{2}$), but with an order of magnitude larger value for the pre-factor C .

- **How does the stability of multicomponent vesicles get altered by hydrodynamics?**

During the process of cell-death or apoptosis, cells fragment and pinch off into smaller debris. The breakup of tubular, cellular membranes is important to understand such systems as well as reproductive processes like mitosis. In this project, we analyze the hydrodynamic stability of tubular, phospholipid membranes containing multiple lipids. The membrane can bend, and the lipids can undergo phase separation into two phases (liquid ordered and liquid disordered

phases). Due to the composition-dependent bending stiffness and the coarsening dynamics associated with phase separation, we observe phenomena very distinct compared to membranes containing a single phospholipid. For example, while single component lipid membranes undergo pearling instabilities under tension reminiscent of a Rayleigh Plateau instability for liquid threads, we find that multicomponent membranes can undergo additional non-axisymmetric instabilities such as buckling and wrinkling. We perform a linear and weakly nonlinear stability analysis of different deformation modes, examining the roles of bending stiffnesses, line tension, phospholipid mobility, and surface viscosity. We also support this analysis with an energy analysis of each mode. We conclude by comparing against previously published experimental data.

- **How do nearly spherical multicomponent vesicles deform under shear flow?**

Vesicles are sacs of fluid enclosed by a phospholipid membrane. These entities are used in cells for compartmentalization, trafficking, and signaling, and are also used in industry for applications like drug delivery. Understanding how vesicles deform and stretch under flow is important in understanding biological processes fundamental to life as well as materials processing of these entities. Currently, most flow studies of vesicles have examined vesicles containing one lipid, whereas in most applications, the vesicle membrane contains multiple phospholipids that can phase separate into different domains. It is unclear how phase separation alters the stretching dynamics, and how the flow alters the phase separation. In this study, we investigate the dynamics of multicomponent vesicles in shear flow by solving the flow equations (Stokes equations) inside and outside the vesicle along with the phase separation equations (Cahn-Hilliard equation) on the vesicle membrane, in the limits of small deformations and small fluctuations in surface compositions. We use a Canham-Helfrich model with a composition dependent bending stiffness to induce the coupling of shape and composition on the vesicle. We inspect two limits in this study being characterized by the Peclet number, which measures the relative ratio of flow and coarsening timescales. We find that the coupling of flow and phase separation can give rise to a plethora of dynamical behaviors (swinging, tumbling, phase treading, breathing, tank treading), many of which are not seen for single component vesicles.