Rheology and Locomotion in Yield Stress Fluids

Farshad Nazarinasrabad

Abstract

The locomotion of microorganisms is a common phenomenon in diverse biological environments and significantly influences human health. For instance, Helicobacter pylori (H. pylori) rotate its helical tail to penetrate through gastric mucus, reaching the epithelial cell layer, which can lead to ulcers or cancer. Similarly, nematodes burrowing through wet soil contribute to soil aeration and fertility. Rheological measurements reveal that these environments exhibit strong yield stress behavior, characterized by solid-like behavior below a certain stress threshold (the yield stress). Key questions remain about how organisms overcome the yield barrier and swim through yield stress fluids.

Our first focus investigates the complex swimming behaviors of artificial macroscale helical swimmers in yield stress fluids. Using a custom-made rotational Helmholtz-coil, a constant torque is imposed on the swimmer that generates the rotational motion (Ω) and using particle image velocimetry (PIV) and particle tracking velocimetry (PTV) techniques, we identified three distinct stages of locomotion for the first time. Initially, the swimmer must exert enough torque to exceed the fluid's yield strain to enable rotation. However, even after this threshold is reached, movement doesn't occur unless the Bingham number is sufficiently below a critical value ($Bi \leq Bi_c$). By overcoming these two thresholds ($\varepsilon_{Y,}\ Bi_c$) the swimmer enters the third stage of motion and generates net forward motion. A key finding in the third stage is that for swimmers with a pitch angle (ψ) below 37[°], swimming speed in yield stress fluids is notably slower than in Newtonian environments and the yield stress hinder the swimming speed, but for those with $\psi \geq$ 45[°], yield stress fluids facilitate faster swimming (up to 10 times). The second part of the research focuses on the influence of swimmer geometry in yield stress fluids. Tail thickness, surface roughness, head size, and cross-sectional shape were systematically varied to assess their effects on propulsion efficiency. While the yield strain necessary to initiate movement remained largely independent of geometry, thicker tails reduced the critical pitch angle for locomotion and generated more effective shearing in the surrounding fluid, thus enhancing performance. However, beyond an optimal thickness, the tail's effectiveness diminished. Surface roughness, meanwhile, created an intriguing dual effect: it increased the torque required to overcome yield stress, but in turn, reduced wall slip, leading to greater propulsion efficiency once movement was established. The third part of this dissertation extends this work to investigate the drag of rotating and settling bodies in yield stress fluids. It examines how surface roughness and geometry influence yield limits, drag forces, and flow fields. The results show that rough surfaces increase the yield limit and enhance rotational energy transfer, resulting in larger yielded zones. Finally, we investigated the flow and structural properties of a model yield stress fluid based on 2D liquid foams in both linear and non-linear viscoelastic regimes. This part of the research focused on building and using a custom-built rheo-optical device to investigate the behavior of 2D-liquid foams, such as those used in toothpaste and soaps. Specifically, we aimed to understand how surfactant chemistry and surface conditions (e.g., roughness) affect foam stability and rheological performance. Two commercially available soap-based foams were studied under smooth and rough boundary conditions. Foam 1 consistently showed higher elastic and loss moduli compared to Foam 2, suggesting a less mobile liquid-air interface in Foam 1. Interestingly, while Foam 1 exhibited higher viscous stress, Foam 2 demonstrated yield stress behavior under smooth boundaries, a behavior absents in Foam 1. The findings from this research have broad implications across multiple fields. In biomedical engineering, understanding locomotion in complex fluids can inform the design of microrobots for medical applications, such as targeted drug delivery or infection treatment, and the knowledge gained from foam study is critical for improving the quality and foaming efficiency of these materials in personal care products.