Theoretical and Experimental Study of Non-spherical Microparticle Dynamics in Viscoelastic Fluid Flows

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Abstract

Particle suspensions in viscoelastic fluids (e.g., polymeric fluids, liquid crystalline solutions, gels) are ubiquitous in industrial processes and in biology. In such fluids, particles often acquire lift forces that push them to preferential streamlines in the flow domain. This lift force depends greatly on the fluid's rheology, and plays a vital role in many applications such as particle separations in microfluidic devices, particle rinsing on silicon wafers, and particle resuspension in enhanced oil recovery. Previous studies have provided understanding on how fluid rheology affects the motion of spherical particles in simple viscoelastic fluid flows such as shear flows. However, the combined effect of more complex flow profiles and particle shape is still under-explored. The main contribution of this thesis is to: (a) provide understanding on the migration and rotation dynamics of an arbitrary-shaped particle in complex flows of a viscoelastic fluid, and (b) develop guidelines for designing such suspensions for general applications.

In the first part of the thesis, we develop theories based on the second-order fluid (SOF) constitutive model to provide solutions for the polymeric force and torque on an arbitrary-shaped solid particle under a general quadratic flow field. When the first and second normal stress coefficients Ψ_1, Ψ_2 satisfy $\Psi_1 = -2\Psi_2$ (corotational limit), the fluid viscoelasticity modifies only the fluid pressure and we provide exact solutions to the polymer force and torque on the particle. For a general SOF with $\Psi_1 \neq -2\Psi_2$, fluid viscoelasticity modifies the shear stresses, and we provide a procedure for numerical solutions. General scaling laws are also identified to quantify the polymeric lift based on different particle shapes and orientation. We find that the particle migration speed is directly proportional to the length the particle spans in the shear gradient direction (L_{sg}), and that polymeric torques lead to unique orientation behavior under flow.

Secondly, we investigate the migration and rotational behavior of prolate and oblate spheroids in various viscoelastic, pressure-driven flows. In a 2-D slit flow, fluid viscoelasticity causes prolate particles to transition to a log-rolling motion where the particles orient perpendicular to the flow-flow gradient plane. This behavior leads to a slower overall migration speed (i.e., lift) of prolate particles towards the flow centerline compared to spherical particles of the same volume. In a circular tube flow, prolate particles align their long axis along the flow direction due to the extra polymer torque generated by the velocity curvature in all radial directions. Again, this effect causes prolate particles to migrate slower to the flow centerline than spheres of

the same volume. For oblate particles, we quantify their long-time orientation and find that they migrate slower than spheres of the same volume, but exhibit larger migration speeds than prolate particles. Lastly, we examine the effect of normal stress ratio $\alpha = \Psi_2/\Psi_1$ on the particle motion and find that this parameter only quantitatively impacts the particle migration velocity but has negligible effect on the rotational dynamics. We therefore can utilize the exact solution derived under the corotational limit ($\alpha = -1/2$) for a quick and reasonable prediction on the particle dynamics.

We next experimentally investigate the migration behavior of spheroidal particles in microfluidic systems and draw comparisons to our theoretical predictions. A dilute suspension of prolate/oblate microparticles in a density-matched 8% aqueous polyvinylpyrrolidone (PVP) solution is used as the model suspension system. Using brightfield microscopy, we qualitatively confirm our theoretical predictions for flow Deborah numbers $0 < De < 0.1-$ i.e., that spherical particles show faster migration speed than prolate and oblate particles of the same volume in tube flows.

we finally design a holographic imaging method to capture the 3-D position and orientation of dynamic microparticles in microfluidic flow. We adopt in-line holography setup and propose a straightforward hologram reconstruction method to extract the 3-D position and orientation of a non-spherical particle. The method utilizes image moment to locate the particle and localize the detection region. We detect the particle position in the depth direction by quantifying the image sharpness at different depth position, and uses principal component analysis (PCA) to detect the orientation of the particle. For a semi-transparent particle that produces complex diffraction patterns, a mask based on the image moment information can be utilized during the image sharpness process to better resolve the particle position.

In the last part of this thesis, we conclude our work and discuss the future research perspectives. We also comment on the possible application of current work to various fields of research and industrial processes.