

ABSTRACT

Wagoner, Brayden W. Ph.D., Purdue University, August, 2021. Electrohydrodynamics of free surface flows of simple and complex fluids. Major Professors: Michael T. Harris and Osman A. Basaran

For centuries, fluid flows (hydrodynamics) and electromagnetic phenomena have interested scientists and laypeople alike. The earliest recording of the intersection of these two ideas, electro-hydrodynamics, was reported four centuries ago by William Gilbert who observed that static electricity generated from rubbed amber could “attract” water. Today electrohydrodynamic phenomena are the underlying mechanisms driving the production of nano-fibers through electro-spinning, printing circuitry, and electrospraying, which John Fenn used in his Nobel prize winning work on electrospray ionization mass spectrometry. In all of these applications, a strong electric field is used to deform a liquid-gas interface (free surface) into a sharp conical tip. Unable to sustain these large interfacial stresses, a thin jet of fluid emerges from the tip of the cone and may subsequently break into a stream of smaller droplets. This tip-streaming phenomenon demands fundamental understanding of three canonical problems in fluid mechanics: electrified cones (Taylor cones), jets, and droplets.

In this thesis, the electrohydrodynamics of free surface flows are examined through both analytical and numerical treatment of the Cauchy momentum equations augmented with Maxwell’s equations. Linear oscillations and stability of (inviscid) conducting charged droplets are examined in the presence of a solid ring shaped constraint. Here the constraint gives rise to an additional mode of oscillation—absent in the analysis of a free (unconstrained) droplet. Interestingly, the amount of charge necessary for instability, the Rayleigh charge limit, is unaltered by the constraint, but the mode of oscillation associated with instability changes. While all of the aforementioned applications involve electrified liquid-gas interfaces, recent experiments reveal a previously unknown type of streaming can occur for droplets suspended in another fluid. In these experiments, the suspending fluid is more conductive and an external electric field drives the initially spherical drop to adopt an oblate shape. Based on the viscosity ratio between the drop and suspending fluid, two different

types of instability were observed: (i) if the drop is more viscous, then the drop forms a dimple at its poles and ruptures through its center, a phenomenon that is now referred to as dimpling, and (ii) if the suspending fluid is more viscous, then the drop adopts a lens-like shape and emits a sheet from its equator that subsequently breaks into a stream of rings and then tiny droplets, a phenomenon that is now called equatorial streaming. The physics of these two instabilities are far beyond the applicability of linear theory, requiring careful numerical analysis. Here steady-state governing equations are solved using the Galerkin finite element method (GFEM) to reveal the exact nature of these two instabilities and their dependence on the viscosity ratio. The fate of these drops once they succumb to instability is then analyzed by fully transient simulations.

Lastly, in a growing number of applications, the working fluid is non-Newtonian, and may even contain suspended solid particles. When non-Newtonian rheology is attributable to the presence of polymer, the dynamics is analyzed by means of a DEVSS-TG/SUPGFEM algorithm that is developed for simulating viscoelastic free surface flows. When complex fluid rheology is due to the presence of suspended solid spherical particles, both early-time (linear) and asymptotic dynamics are uncovered by coupling the motion of the particles and Newtonian fluid implicitly in a GFEM fluid-structure interaction (FSI) algorithm. These novel algorithms are used to analyze the pinch-off dynamics of liquid jets and drops.