

ABSTRACT

Kamat, Pritish M. Ph.D. ChE, Purdue University, August 2017. A STUDY OF SINGULARITIES IN DROPS AND BUBBLES UNDER THE INFLUENCE OF NON-NEWTONIAN SURFACE AND BULK RHEOLOGY. Major Professor: Prof. Osman A. Basaran.

Fluid-fluid interfaces are incredibly complex physical structures. Imbued with an excess energy—or in mechanical terms, a surface tension σ —these interfaces are considerably influential at small scales of droplets and bubbles, and in these systems, they are responsible for a plethora of beautiful and dramatically complex phenomena. The study of these interfacial phenomena, the so-called ‘free surface flows’, lends itself to a variety of applications which are at once, as mundane as liquid dripping from a faucet or rain splashing over the windscreen of a car, and at the same time extremely useful in industry and scientific analysis – some examples include drop-on demand manufacturing, ink-jet printing, spray coatings, electrospray generation, and DNA microarraying. Here, we are concerned with a subset of free surface flows which involves the bifurcation of an interface to form two new interfaces (‘rupture’), or the merging of two interfaces to form a single continuous entity (‘coalescence’). Both archetypes involve the generation of extremely high pressures and near-infinite velocities in the fluid close to the interface in finite time and are the most common examples of hydrodynamic (finite-time) singularities.

The flow dynamics near these singularities is highly non-linear and often difficult to resolve owing to the minuscule scales involved, however theoretical work in this area over the last few decades has revealed the existence of self-similarity and universal scaling laws that govern its behavior, which have subsequently been verified by high-speed imaging experiments and numerical simulations. These scaling laws offer immense utility, not only by clarifying the underlying physics, but also by providing useful information that can be translated to industrial applications such as predicting the occurrence of satellites in drop formation or estimating residence times for designing industrial phase contactors and separators. Whereas the majority of the work on singularities treats liquids that are pure and Newtonian, liquids in real-life applications are rarely so, instead containing dissolved polymers, suspended particles, and/or surfactants which impart unto them a

non-Newtonian rheology. In this work, we use high-accuracy numerical simulations of the equations of motion, in concert with experiments and theory, to probe the effects of surfactants on the rupture of liquid threads in air, and the effects of deformation rate thinning (power-law) bulk rheology on the coalescence between two drops in a gas, or between two bubbles in a liquid.

In the rupture of surfactant-laden liquid threads, we perform experiments revealing the phenomenon of surfactant-driven microthread cascades—a series of progressively thinner threads that telescope out from the rupture location—for the first time in a real system. We then clarify the long-standing controversy over the prominence of Marangoni stress contributions—arising from gradients in surface tension when surfactants are non-uniformly distributed—to the well-known observation of decelerated thinning in the presence of surfactants and also elucidate their critical role in the formation of microthread cascades. By examining cascade formation in unprecedented detail, we show the important role played by inertia in the problem, unearth novel intermediate self-similar scaling regimes observed heretofore only in the creeping flow limit, and subsequently validate a hypothesis made nearly a quarter-century ago regarding how cascades form in thread rupture. Additionally, we investigate the effects of surfactants in the stabilization of liquid filaments, and clarify inconsistencies in the current understanding of surfactant effects on the stability of liquid jets.

In the second part of the dissertation, we explore the effect of deformation rate thinning (power-law) rheology on coalescence phenomena. We reveal a novel scaling regime in the coalescence of power-law liquid drops in air, where inertial, viscous, and capillary forces are in balance. Next, the coalescence of bubbles in a power-law liquid is investigated in the limits of small viscosity and in the creeping flow limits. At small viscosities, using simulations we demonstrate complex scaling behaviors and transitions, and reveal the existence of the inviscid potential flow solution obtained by Keller in 1983, at finite viscosities. In the creeping-flow limit, where inertia is absent, we use thin film theory to obtain the scaling laws governing bubble coalescence and verify theoretical predictions using simulations of the full 2D equations. Remarkably, in the limit of large but finite viscosity, we find that the creeping flow solution breaks down at early times revealing the presence of hitherto unknown scaling regimes where inertia is dominant.