

ABSTRACT

Garg, Vishrut PhD, Purdue University, December 2018. Dynamics of Thin films near Singularities under the influence of non-Newtonian Rheology. Major Professors: Osman A. Basaran.

Free surface flows where the shape of the interface separating two fluids is unknown a priori are an important area of interest in fluid dynamics. The study of free surface flows such as the breakup and coalescence of drops and thinning and rupture of films lends itself to a diverse range of industrial applications, such as inkjet printing, crop spraying, foam and emulsion stability, and nanolithography, and helps develop an understanding of natural phenomena such as sea spray generation in oceans, or the dynamics of tear films in our eyes. In free surface flows, singularities are commonly observed in finite time, such as when the radius of a thread goes to zero upon pinchoff or when the thickness of a film becomes zero upon rupture. Dynamics in the vicinity of singularities usually lack a length scale and exhibit self-similarity. In such cases, universal scaling laws that govern the temporal behavior of measurable physical quantities such as the thickness of a film can be determined from asymptotic analysis and verified by high-resolution experiments and numerical simulations. These scaling laws provide deep insight into the underlying physics and help delineate the regions of parameter space in which certain forces are dominant, while others are negligible. While most previous works on singularities in free-surface flows deal with Newtonian fluids, many fluids in daily use and industry exhibit non-Newtonian rheology, such as polymer-laden, emulsion, foam, and suspension flows.

Here, thinning and rupture of a thin film of a power-law fluid on a solid substrate under the balance between destabilizing van der Waals pressure and stabilizing capillary pressure is analyzed. In a power-law fluid, viscosity is not constant but is proportional to the deformation rate raised to the $n - 1$ power, where $0 < n \leq 1$ is the power-law exponent ($n = 1$ for a Newtonian fluid). In the first part of the problem, use is made of the slenderness of the film and the lubrication approximation is applied to the equations of motion to derive a spatially one-dimensional nonlinear evolution equation for film thickness. The variation with time remaining until rupture of the film thickness, the lateral length scale, fluid velocity, and viscosity is determined analytically and confirmed by numerical simulations for both line rupture and point rupture. The self-similarity of the numerically computed film profiles in the vicinity of the location where the film thickness is a minimum is demonstrated by rescaling of the transient profiles with the scales deduced from theory. It is then shown that in contrast to films of Newtonian fluids undergoing rupture for which inertia is always negligible, inertia can become important during thinning of films of power-law fluids in certain situations. The critical conditions for which inertia becomes important and the lubrication approximation is no longer valid are determined analytically. In the second part of the problem, thinning and rupture of thin films of power-law fluids in situations when inertia is important are simulated by solving numerically the spatially two-dimensional, transient Cauchy momentum and continuity equations. It is shown that as such films continue to thin, a change of scaling occurs from a regime in which van der Waals, capillary, and viscous forces are important to one where the dominant balance of forces is between van der Waals, capillary, and inertial forces while viscous force is negligible.

When a gas bubble of radius R immersed in a liquid of density ρ and viscosity μ approaches a solid wall such that the Reynold's number $Re = \rho VR/\mu \ll 1$, where V is its velocity of approach, a thin film of the liquid forms between the bubble and solid surface, which drains and finally ruptures if long range van der Waals forces between the bubble interface and solid surface are attractive in nature. In the third part of this problem, three dimensional axisymmetric simulations are performed to study the buoyancy driven approach of an air bubble immersed in a power-law liquid towards a horizontal solid wall. The late-stage dynamics of bubble approach are observed to obey the scaling laws determined previously for supported film rupture of power-law fluids, thus clearly demonstrating the universality of the self-similar regimes discovered in this problem.