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Andreas Acrivos Dissertation Award: Onset of Dynamic Wetting Failure - The Mechanics of High-Speed Fluid Displacement

ERIC VANDRE, University of Minnesota

Dynamic wetting is crucial to processes where a liquid displaces another fluid along a solid surface, such as the deposition of a coating liquid onto a moving substrate. Dynamic wetting fails when process speed exceeds some critical value, leading to incomplete fluid displacement and transient phenomena that impact a variety of applications, such as microfluidic devices, oil-recovery systems, and splashing droplets. Liquid coating processes are particularly sensitive to wetting failure, which can induce air entrainment and other catastrophic coating defects. Despite the industrial incentives for careful control of wetting behavior, the hydrodynamic factors that influence the transition to wetting failure remain poorly understood from empirical and theoretical perspectives. This work investigates the fundamentals of wetting failure in a variety of systems that are relevant to industrial coating flows. A hydrodynamic model is developed where an advancing fluid displaces a receding fluid along a smooth, moving substrate. Numerical solutions predict the onset of wetting failure at a critical substrate speed, which coincides with a turning point in the steady-state solution path for a given set of system parameters. Flow-field analysis reveals a physical mechanism where wetting failure results when capillary forces can no longer support the pressure gradients necessary to steadily displace the receding fluid. Novel experimental systems are used to measure the substrate speeds and meniscus shapes associated with the onset of air entrainment during wetting failure. Using high-speed visualization techniques, air entrainment is identified by the elongation of triangular air films with system-dependent size. Air films become unstable to thickness perturbations and ultimately rupture, leading to the entrainment of air bubbles. Meniscus confinement in a narrow gap between the substrate and a stationary plate is shown to delay air entrainment to higher speeds for a variety of water/glycerol solutions. In addition, liquid pressurization (relative to ambient air) further postpones air entrainment when the meniscus is located near a sharp corner along the plate. Recorded critical speeds compare well to predictions from the model, supporting the hydrodynamic mechanism for the onset of wetting failure. Lastly, the industrial practice of curtain coating is investigated using the hydrodynamic model. Due to the complexity of this system, a new computational approach is developed combining a finite element method and lubrication theory in order to improve the efficiency of the numerical analysis. Results show that the onset of wetting failure varies strongly with the operating conditions of this system. In addition, stresses from the air flow dramatically affect the steady wetting behavior of curtain coating. Ultimately, these findings emphasize the important role of two-fluid displacement mechanics in high-speed wetting systems.