Abstract

Drag–inertia falling liquid films exhibit complex interfacial dynamics, including recirculation zones, wave asymmetry, coalescence, and dripping, governed by the interplay of viscous and inertial forces with gravity and surface tension. These behaviours are highly sensitive to substrate geometry, whether the films flow over inclined surfaces, within narrow channels, or beneath planar and corrugated surfaces. Understanding these dynamics is essential for optimizing thin-film processes in coatings, microfluidics, printing, and heat exchangers. The present work employs two-dimensional numerical simulations based on the finite-volume method and the Volume of Fluid (VOF) approach to capture interfacial evolution. The governing incompressible Navier–Stokes equations are solved using an OpenFOAM-based framework. The two-dimensional assumption is appropriate for the present study, which focuses on predominantly streamwise wave dynamics and interfacial evolution over finite domains where spanwise variations remain weak.

To begin with, for films over an inclined surface, the modulation of surface tension on the inertial variations of traveling solitary waves is explored through a coupled analysis of Reynolds and Capillary numbers. The study shows how this coupling modifies flow recirculation patterns, which in turn govern the characteristics of the resulting waves. A film-depth-averaged force balance model is introduced to capture the asymmetry between the tail and front zones, thereby revealing the underlying physics. Particular focus is placed on the impact of Capillary number on wave speed, velocity profiles, and flow reversal, offering new dynamic insights. The findings are consolidated in a regime map delineating the key mechanisms governing the drag–inertia regime for such a flow configuration. Three distinct wave structures beneath the solitary hump are identified: moderate solitary waves without recirculation, strong solitary waves with recirculation near the onset of recirculations, and waves exhibiting either decreasing or amplitudes

approaching a limiting value depending on the Capillary number. The analysis is restricted to a fixed inclination and imposed monochromatic inlet forcing.

Next, the interaction of asymmetrical waves and the coalescence of two identical liquid films falling along the walls of a narrow channel are investigated. Tilting the channel breaks symmetry, with one film remaining Kapitza-driven, while the hanging film additionally undergoes Rayleigh–Taylor instability. Variations in confinement and inertia generate diverse waveforms, streamwise phase differences, and coalescence scenarios involving air entrapment, plug formation, and flooding. Wall shear stress is analyzed, and regression relations are obtained for its extrema in non-coalescing cases. Localized stresses up to an order of magnitude higher than in non-coalescing films are identified and mapped during coalescence. Coalescence is suppressed at moderate inclinations but reappears at higher angles due to enhanced wave growth on the hanging film. Scaling laws for the minimum coalescence distance exhibit a non-monotonic trend with confinement and a distinct Reynolds number dependence for vertical and inclined configurations. An empirical expression is proposed for the threshold confinement marking the onset of coalescence as a function of Reynolds number and inclination. The study considers initially symmetric inlet forcing with a quiescent surrounding gas phase and constant liquid properties associated with a fixed Kapitza number, while neglecting external gas-flow effects.

Lastly, the dripping transitions of films beneath planar and periodically corrugated inclined surfaces are examined by varying the Reynolds number, inclination, and surface geometry. Space–time plots reveal a traveling wave in non-dripping films and bulge formation in dripping cases, with both behaviours strongly influenced by corrugations, which favour dripping by droplet detachment at lower inclinations than planar surfaces. The temporal variation of amplitude displays a single peak for the planar non-dripping wave, whereas corrugations give rise to multiple peaks and troughs. In the dripping case, the bulge height grows exponentially until breakup. Temporal force analysis shows that inertia remains nearly constant in planar non-dripping conditions and dominates cross-stream gravity. In contrast, corrugations induce oscillations in both forces, amplifying the gravity component and promoting early dripping. Near the onset of breakup, these oscillations decay, and detachment occurs when gravity exceeds inertia. A threshold analysis identifies stable, dripping, and air-entraining films, with large corrugations inducing air entrainment caused by merging interfacial bulges, which accelerates droplet detachment via neck thinning. The investigation is limited to

a fixed Bond number, constant liquid volume, and transitions involving a single traveling bulge.

This dissertation aims to advance the understanding of film dynamics across diverse geometric configurations through comprehensive numerical investigations.

Keywords: Interfacial flows, Falling liquid films, Surface waves, Coalescence, Dripping, Kapitza instability, Rayleigh-Taylor instability.