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The effect of soluble surfactants on the linear stability of liquid film flow

George Karapetsas and Vasilis Bontozoglou

Department of Mechanical Engineering, University of Thessaly,
GR-38334 Volos, Greece

Abstract

The formation of instability waves in gravity-driven liquid films flowing down inclined surfaces is of importance in a broad range of engineering, geophysical and biomedical applications. It is known that these instabilities can be significantly affected by the presence of surfactants, and the role of insoluble surfactants (i.e. species that are assumed to reside only on the interface) has been repeatedly addressed[1]. Soluble surfactants have been investigated to a lesser extent, and a mechanistic understanding of their role appears to be missing. These species are expected to exhibit more complex behaviour, because interfacial dynamics is intricately coupled with mass exchange with the bulk.

In the present work, we investigate analytically and computationally the linear stability of liquid film flow in the presence of a surfactant of arbitrary solubility. The Navier–Stokes equations are supplemented by mass balances for the concentrations at the interface and in the bulk and by a Langmuir model for adsorption-desorption kinetics at the interface. The resulting linear eigenvalue problem is solved analytically in the limit of long-wave disturbances and numerically (by a finite-element method) for disturbances of arbitrary wavelength.

The instability is shown to be a long-wave one, and to depend only on surfactant solubility and interfacial concentration. Insoluble surfactants stabilize the flow most effectively at maximum concentration (closest interfacial packing), whereas strongest stabilization moves to lower concentrations with increasing solubility. Disturbances of finite wavelength are found to be significantly more stable than long-wave ones, because interfacial gradients are intensified by the shorter length scale. Also, sorption kinetics begins to play a a key role, with very slow kinetics leading to a virtually frozen interface and an insoluble-like behaviour[2].

The analysis permits an extention of the physical mechanism of the long-wave instability in order to take into account the presence of the surfactant. The longitudinal flow perturbation, known to result from the perturbation shear stress which develops along the deformed interface[3], is shown to contribute a convective flux that triggers an interfacial concentration gradient. This gradient is, at leading order, in phase with the interfacial deformation, and as a result produces Marangoni stresses that stabilize the flow. The strength of the interfacial concentration gradient is shown to be maximum for an insoluble surfactant and to decrease with increasing surfactant solubility. The decrease is explained in terms of the spatial phase of mass transfer between interface and bulk, which mitigates the interfacial flux by the flow perturbation and leads to the attenuation of Marangoni stresses.

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