INSTABILITY OF FILMS FLOWING OVER TOPOGRAPHY WITH EDDIES

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Summary An experimental study of the stability of a viscous gravity-driven free surface film flowing down a strongly corrugated incline is presented. We observe eddies appearing in the troughs of the undulated substrate which serve as fluidic roller bearings for the liquid flowing above and an appearance of a resonance phenomenon. We investigate the subtle interplay between eddy size, free surface shape and its stability. We find that the flow can be stabilized against long wave perturbations up to Reynolds numbers which are more than three times larger compared to the flow over a flat incline.

INTRODUCTION

The physics of thin liquid film flows has been studied over the last decades with increasing interest due to their importance for many environmental systems like the liquid film covering an eye, avalanches or glacier flows and also for industrial systems like heat exchangers or evaporators. Especially in coating applications the understanding of the stability of the flow is of major interest to achieve a fast and uniformly thin coating results.

Benjamin [1] and Yih [2] analyzed the stability of a liquid flowing down a flat incline and found the flow to become primarily unstable at a critical Reynolds number $\mathrm{Re_c}$ which only depends on the channel inclination angle α: $\mathrm{Re_c} = (5/4)\cot\alpha$, where Re is defined as $\mathrm{Re} = u_\mathrm{s} h \nu^{-1}$ with u_s, h and ν being the free surface velocity, the film thickness and the kinematic viscosity of the flow.

Since the flow over a perfectly flat incline is a theoretical construct only, which cannot be observed in nature, one has to take corrugations at the substrate, either natural or machine-made, into account. Theoretical considerations [3] and experiments [4] on the stability of a flow over weakly corrugated surfaces have been carried out by Wierschem et al. who found that the presence of an undulation which is shallow compared to the film thickness tends to stabilize the flow. Further theoretical works on the stability of Newtonian and non-Newtonian liquids over a wide range of Reynolds- and Kapitza numbers show, that a wall corrugation may have a stabilizing as well as a destabilizing influence on the flow.[5, 6, 7, 8] The group of Bontozoglou [9] introduced rectangular periodic corrugations to the substrate and found experimentally a development of three–dimensional free surface structures accompanied by a remarkable stabilization at high Reynolds numbers.

Introducing sinusoidal periodic substrate corrugations of an amplitude comparable to the film thickness and the wavelength of the corrugation leads to formation of eddies in the throughs of the channel [10] which serve as fluidic roller bearings for the liquid flowing above.

Here we study the primary convective instability of a viscous gravity–driven Newtonian liquid flowing down an incline with a strong sinusoidally undulated bottom profile which causes eddies to appear in its troughs.

SYSTEM AND SETUP

We measure the free surface instability of a gravity–driven viscous film flowing down a $170\,\mathrm{mm}$ broad channel with a sinusoidally undulated aluminum substrate with an amplitude a of 4 mm and a wavelength λ of 20 mm (see Figure 1). The mean inclination angle α of the channel has been kept constant at $10^\circ \pm 0.05^\circ$. When the average film thickness becomes sufficiently large at given substrate topography, eddies emerge in the troughs of the undulation as described very detailed e.g. by Scholle et al. [10].

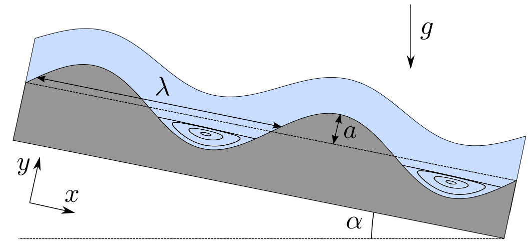

Figure 1. Film flowing over an undulated topography with eddies in the troughs.

A pump provided an adjustable volume flux $\dot{V}$, which dictates the Reynolds number, from a fluid reservoir into a smaller inflow tank on top of the channel. The constant volume flux was perturbed sinusoidally in time by a paddle which oscillated within the liquid of the small inflow tank. The evolution of the generated waves, whose amplitude was small compared to the film thickness, was measured in the middle of the channel at two different points in downstream direction in a similar fashion as described in [11] at different excitation frequencies.

RESULTS

We report on a subtle interplay between the generation and growth of eddies in the troughs of the undulation with increasing Reynolds number and the shape of the free surface and its stability. This yields a second window of stable flow configurations at Reynolds numbers, which are more than three times larger than the critical Reynolds number from the classical result for the flow over a flat substrate at the same mean inclination angle.

These findings are of major relevance for the understanding of environmental systems or for improving industrial applications like for example the optimization of the throughput in coating applications.

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