Coupled dynamics of liquid film assemblies: emergence vs. enslaving

Mathias Dietzel, Miklós Vécsei, Iman Nejati, Steffen Hardt
Institute for Nano- and Microfluidics, Center of Smart Interfaces, TU Darmstadt, 64287 Darmstadt, Germany

Summary

Based on two exemplary cases, it is demonstrated that joining several liquid layers dominated by interfacial stresses in one assembly gives rise to interesting dynamics, ranging from emergent stability behavior not observed for uncoupled layers to enslaving of one layer by another. While the former occurs when coupling several interfacial instabilities, the latter is promising for the fabrication of highly regular patterns on surfaces.

Keywords: Thin film, Kelvin-Helmholtz instability, Bénard-Marangoni instability, self-organization

1. Introduction

Interfacial or volumetric stresses arise in liquid films subjected to a gradient of a thermodynamic potential (e.g. temperature, electric or chemical potential), which may drive a convective fluid motion if a critical threshold is exceeded. Typically, the convection forms a periodic pattern in the spread direction of the layer, a classic example of a self-organizing system (SOS). Characteristically, SOSs show emergent behavior, i. e. the dynamics of the full system may be qualitatively different from the behavior of its constituents. Our work aims at extending this principle and analyze assemblies of individual SOS with respect to emergent phenomena.

In this context, we contrast the results of two corresponding studies: the first considers the coupled dynamics of two thin lubricating films sheared by a gas flow in a channel, while the second addresses cellular Bénard-Marangoni convection in a liquid layer when a thin lubricating film is placed between that layer and the supporting solid substrate.

2. Similar vs. disparate initial film thicknesses

The first system discussed is schematically shown on the left hand side of fig. 1 (a): the walls of a plane-parallel channel are covered with thin liquid films of similar initial thicknesses $h_1 \approx h_2$, which are sheared by a gas flow between the films (width $d = O(h_{1/2})$). This renders the films unstable to interfacial deformations with a characteristic wavelength λ in the flow direction of the gas. In the limit of $(h/\lambda)^2 \ll 1$ and small but non-vanishing Reynolds numbers of the gas flow, the system is fully described by two coupled evolution equations for the local film heights. Based on a linear and a weakly non-linear analysis, it is shown that both films become phase-synchronized even for surprisingly large differences between h_1 and h_2, while asymmetric deformations with respect to the channel center plane are quickly damped. This stands in contrast to what has previously been observed for related systems in which the instability was triggered by thermocapillary and gravitational stresses [1]. For $h_1 = h_2$, the films become fully synchronized and, in comparison with the case where only one of the films may deform, the coupling between the two films reduces λ by $\sqrt{2}$. Based on full numerical simulations, as illustrated on the right hand side of fig. 1 (a), the interaction between the shear-induced, Kelvin-Helmholtz-type instability and the Rayleigh-Plateau-type breakup of the elongated ridges is demonstrated.

Corresponding author is M.D., dietzel@csi.tu-darmstadt.de

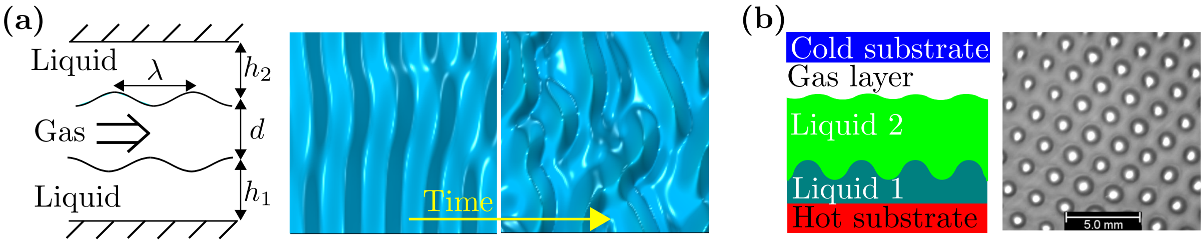

Figure 1: **(a)** Schematics of coupling (left, side view) and pattern (right, top view) of the shear-driven instability in thin films. **(b)** Experimental setup (left, side view) and pattern (right, top view) related to the Bénard-Marangoni convection developing in a thicker layer on top of a lubricating film.

The coupling observed in the previously described system is qualitatively compared to that observed in an experiment where a thin lubricating film is placed between a thicker liquid layer, immiscible with the first, and a solid substrate. Upon exposure of both layers to a transverse temperature gradient, the short-wavelength Bénard-Marangoni (BM) instability develops in the thicker layer. Marginal stability is attained at a lower value of the characteristic Marangoni number than in the conventional case without the lubricating film. The shear-stresses of the convection cells in the upper layer act upon the liquid-liquid interface and deform it according to the hexagonal pattern symmetry of the BM convection. Therefore, the evolution of the lower film is enslaved by the BM instability in the upper layer (see right hand side of fig. 1 (b)). However, despite the disparate ratio of the initial thicknesses, the deformation of the liquid-liquid interface is experimentally proven to stabilize the hexagonal convection pattern in the thicker layer, so that bifurcation to a different horizontal planform occurs at a higher Marangoni number than what is found in the conventional BM experiment [2]. Employing UV-curable liquids as lubricating film, the deformations can be solidified and used as a highly regular micro-lens array.

3. Conclusions

The dynamics of a system of two liquid layers sheared by a gas flow is characterized by a strong two-way coupling even for the case that the film thicknesses are significantly different. By contrast, an arrangement of a thin film with a much thicker film on top of it displays an ”enslaving” phenomenon when a temperature gradient is applied across the films. Specifically, this means that the thicker film dominates the dynamics of the conjugated layers and deforms the thin film by means of shear stresses. With such an arrangement large-scale patterned surfaces may be fabricated, which is of interest in a number of technical applications.

Acknowledgements

Financial support by the German Research Foundation (DFG) under the grant number DI 1689/1-1 is gratefully acknowledged.

References

[1] M. Vécsei, M. Dietzel and S. Hardt, Coupled self-organization: Thermal interaction between two liquid films undergoing long-wavelength instabilities, Phys. Rev. E, **89**, 053018, 2014

[2] I. Nejati, M. Dietzel and S. Hardt, Conjugated liquid layers driven by the short-wavelength Bénard-Marangoni instability: experiment and numerical simulation, J. Fluid Mech., **783**, pp. 46-71, 2015