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Pinning and flow regimes of thin liquid layers on a heterogenous substrate

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Transport in unsaturated macropores or fractured porous media displays intermittent water fluxes and preferential flow pathways [1]. Front instabilities play an important role in these dynamics. However, in porous media the modeling of the surface has to take into account chemical heterogeneities and/or topographic roughness. In fact, micro- or mesoscale heterogeneities are expected to affect the macroscopic movement of drops. For instance, they are responsible for contact angle hysteresis, the roughening of contact lines and the stick-slip motion of weakly driven contact lines [2].

The present contribution focusses on the spatio-temporal patterns of capillary- and wettability-dominated flow resulting from the interplay between driving and pinning forces. In particular, we consider a thin free-surface liquid film/drop on a substrate striped by defects driven by gravity. The defects are modeled using a spatially variable wettability leading to an evolution equation for the film height [3]. This approach enables one to (i) study the depinning transition employing tools from dynamical systems theory and bifurcation theory, and (ii) investigate the dynamics of the stick-slip motion that occurs after depinning on substrates with many defects. Recently, a specific numerical code has been developed to perform these tasks for a 3D system [4].

As results, one finds two stable steady-states (static liquid retained by "pinning" effect): liquid ridges and a discrete pattern of drops. Their stability domain has been determined in the parameter plane.
The drop depinning mechanism is related to bifurcations of homoclinic kind resulting in an intermittent flow consisting of two distinct evolution phases that take place on distinct timescales: the drop slowly stretches away from the defect but once it breaks away it slides over to the next defect [5].
Liquid ridge steady-states may depin as for drops leading to a stick-slip motion of liquid front. However, under appropriate conditions the ridges first break into drops via the Plateau-Rayleigh transverse instability.
Finally, for large flux the stick-slip motion stabilizes into stationary rivulet flow.
The different transition scenarios are examined together with the stability properties of the different possible states of the system [6].

This work points out the crucial influence of the substrate heterogeneities on the transport. Moreover, the complex coupling between the pinning force and the surface of the fluid has to be taken into account in order to capture the rich diversity of flux regimes.
Moreover, recently a phase-field model simulating front instability during water infiltration in soil used an evolution equation similar to thin free-surface films [7]. Therefore, our analysis may find applications for macroscopic models of transport through micropores too.

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