

Flow-Induced Dynamic Surface Tension Effects at Nanoscale

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The aim of this study is to investigate flow-induced dynamic surface tension effects, similar to the well-known Marangoni phenomena, but solely generated by the nanoscale topography of the substrates. The flow-induced surface tension effects are examined on the basis of a sharp interface theory. It is demonstrated how nanoscale objects placed at the boundary of the flow domain result in the generation of substantial surface forces acting on the bulk flow.

1. Introduction

The distinctive feature of fluid motion at nanoscale is its strong coupling with the dynamic processes in the interfacial layers formed at the boundaries between the phases.^{1,2} For example, we know from recent experiments that slippage of liquids at solid substrates results in enhanced liquid transport through nanoscale capillary channels, up to 45–400 times higher in comparison to the theoretical predictions based on the no-slip boundary condition.^{3,4} The slippage of liquids is only one manifestation of interfacial dynamic properties. Another effect associated with the formation of interfacial layers and widely exploited to control nanoflows is surface tension.^{5–9}

If a moving contact line is present, the dynamic surface tension effects manifest themselves in the dependence of the contact angle $\theta_d(u_c)$ formed between the moving free surface and the solid substrate on the velocity of the triple-phase contact line, u_c .^{6,7,9} This can be illustrated by the Young equation, $\cos \theta_d \sigma_{GL} = -\sigma_{LS} + \sigma_{GS}$, where σ_{GL} , σ_{LS} , and σ_{GS} are the surface tensions of gas–liquid, liquid–solid, and gas–solid interfaces, evaluated at the contact line. The dependence $\theta_d(u_c)$ implies that at least some of the surface tensions are not equal to their equilibrium values when the contact line is at rest. The velocity dependence of the dynamic contact angle is only one part of its general dependence; apart from the substrate velocity, the contact angle is a function of the entire flow field at the contact line region. This effect is known as the nonlocality of dynamic contact angle or, in macroscopic context, as the hydrodynamic assist of dynamic wetting, which has been used for decades in the coating industries.^{10,11}

Studies of the effects of dynamic wetting on smooth flat surfaces (in particular the effect of nonlocality) have revealed several characteristic features of the interfacial phase dynamics. Slippage of liquids and the dynamic surface tensions are closely interrelated; the σ_{GL} and σ_{LS} surface tensions at the contact line deviate from the equilibrium values

and equilibrate over the distance, away from the contact line region, defined by the characteristic diffusion time in the interfacial layer, that is, by the characteristic time of the formation of the interfacial layers.^{7,10–17} This scenario has been further supported by the evidence from independent studies of viscous flows over the surfaces with variable wettability, where the changes of the liquid–solid interfacial energy $\sigma_{LS}(x)$ have been achieved by chemical patterning of the substrate.^{18,19}

In this paper, we investigate another effect, which is associated with forming interfaces and especially relevant to nanofluidic flows, of coupling of the surface topography and the flow-induced surface tensions. The question is, what if we change the flat geometry of the solid surface by placing a tiny, nanoscale obstacle on the surface? The effect of a particle arrested on a substrate is well-studied for macroscopic incompressible flows.^{20,21} However, if the obstacle is, approximately, the size of the interfacial layer, where the incompressibility condition is relaxed to account for surface tension, then one would expect to observe completely new effects, since the presence of an obstacle may disturb the surface phase density equilibrium state (by compressing the liquid in the interfacial layer, for example) and cause variations in the surface tension, similar to the well-known Marangoni phenomenon, though in this case solely induced by the surface topography. In this connection, we note that the size of the interfacial layer, h , is on the order of a few nanometers, $h \approx 1 - 4$ nm, for simple fluids²² so that already nanoscale objects should be able to affect the equilibrium state of the surface phase at the substrates.

From the experimental point of view, several observations, especially using the fluorescence recovery technique and nanoparticles seeded on the substrate in a controlled manner,^{23–25}

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