Liquid wedge motion by evaporation/condensation controlled by diffusion

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Since the seminal article by Huh and Scriven [1], it is well known that the standard hydrodynamics fails in describing the motion of the triple liquid-gas-solid contact line in a configuration of partial wetting. Their hydrodynamic model based on classical hydrodynamics with the no-slip condition at the solid-liquid interface and the imposed to be straight liquid-gas surface predicts infinitely large viscous dissipation. If the normal stress balance is considered at the free surface, such a problem has no solution at all [2]. Among different mechanisms that are proposed to relieve the singularity (see [3] for a review), the present study focuses on the evaporation/condensation phenomena induced by the deformation of the profile close to the contact line (Kelvin effect). The demonstration of the fact that change of phase regularizes the contact line singularity has been done recently by two independent groups [4,5], for the configuration where the liquid is surrounded by its pure vapor. In this configuration, evaporation or condensation rate is controlled by the heat exchange phenomena. Such a situation occurs e.g. for bubbles in boiling. In the present work, we address a much more common situation where a volatile liquid droplet is surrounded by an atmosphere of other gases like air. This case is more challenging, since the evaporation or condensation rate is controlled by the vapor diffusion in the gas, which results in a non-local evaporation or condensation flux [6, 7].

The studied geometry is a liquid wedge of infinite length on a solid substrate (fig. 1). The no-slip condition is assumed at the solid-liquid interface and the system is assumed to be isothermal. The mass exchange dynamics is controlled by vapor diffusion in the inert gas and interfacial kinetic resistance. Two different causes of departure from thermodynamic equilibrium are investigated. In the first configuration (fig.2, left), the atmosphere is saturated and the substrate moves at a steady velocity with respect to the wedge. In the second configuration (fig.2, right), the substrate is motionless and evaporation-condensation occurs in the non-saturated atmosphere, which causes the liquid motion inside the wedge. A perturbation analysis is performed with a model based on the lubrication equations for liquid phase and the diffusion equation in gas phase. Beyond the micro-region, asymptotic developments are carried out for modeling the visco-capillary intermediate region and matching the micro- and intermediate regions.

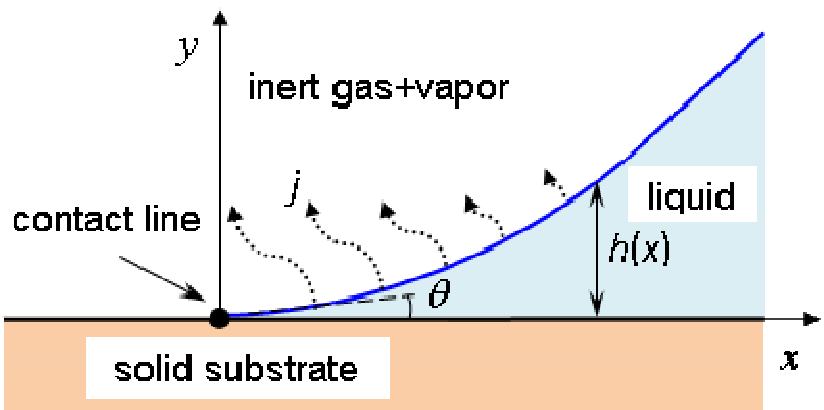

Fig. 1: Liquid wedge on a solid substrate.

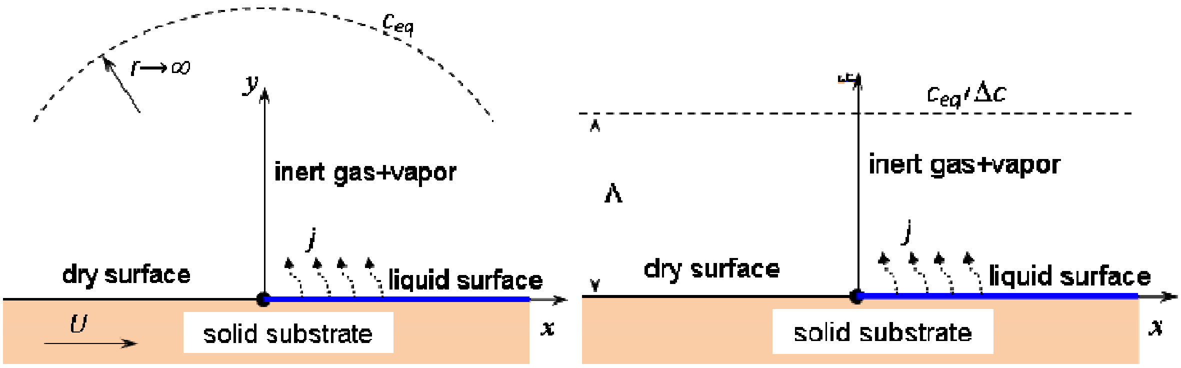

Fig. 2, left: first configuration. The substrate is moving at velocity U. The gas domain is semi-infinite, and the vapor concentration c_{eq} at infinity corresponds to the saturated vapor pressure above a flat liquid surface (the system is at thermodynamic equilibrium when U=0). Right: second configuration. The substrate is motionless, and a vapor concentration $c_{eq}+\Delta c$ is imposed at a distance Λ from the substrate (the system is at thermodynamic equilibrium when $\Delta c = 0$).

For the first configuration, it is shown that from a mathematical point of view, Kelvin effect relieves the contact line singularity, and all the physical quantities (meniscus curvature, mass flux, etc) become large but finite at the contact line. However, for two common fluids (water and ethanol) under the ambiant conditions, the characteristic length scale of the Kelvin effect is very small, leading to liquid thickness inconsistent with the continuum mechanics. For such fluids, to make the model self-consistent, one needs to rely on another microscopic singularity relaxation mechanism like e.g. hydrodynamic slip. The second configuration is also analysed. Differences and similarities with the first one are pointed out.

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