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Can hydrodynamic contact line paradox be solved by evaporation–condensation?

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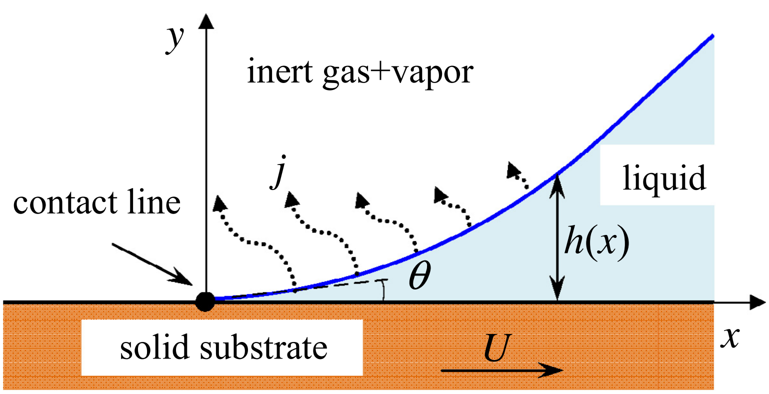
GRAPHICAL ABSTRACT



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ABSTRACT

We investigate a possibility to regularize the hydrodynamic contact line singularity in the configuration of partial wetting (liquid wedge on a solid substrate) via evaporation–condensation, when an inert gas is present in the atmosphere above the liquid. The no-slip condition is imposed 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. The coupling between the liquid meniscus curvature and mass exchange is provided by the Kelvin effect. The atmosphere is saturated and the substrate moves at a steady velocity with respect to the liquid wedge. A multi-scale analysis is performed. The liquid dynamics description in the phase-change-controlled microregion and visco-capillary intermediate region is based on the lubrication equations. The vapor diffusion is considered in the gas phase. It is shown that from the mathematical point of view, the phase exchange relieves the contact line singularity. The liquid mass is conserved: evaporation existing on a part of the meniscus and condensation occurring over another part compensate exactly each other. However, numerical estimations carried out for three common fluids (ethanol, water and glycerol) at the ambient conditions show that the characteristic length scales are tiny.

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1. Introduction

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]. As an immediate consequence, a droplet cannot slide over an inclined plate, or a solid cannot be immersed into a liquid.

Despite the fact that this paradox is known for decades, it is still a subject of intense debate (see for instance [3]).

Contact line motion is in fact a multi-scale problem, and microscopic effects must be considered in the vicinity of the contact line to solve the above-mentioned paradox (see [4,5] for reviews). One can make a distinction between approaches for which the dissipation is located at the contact line itself, from models where dissipation is assumed to be of viscous origin, inside the liquid. In the former class of models, referred as molecular kinetic theory, the contact line motion is driven by jumps of molecules close to the contact line [6]. In the latter approach, based on hydrodynamics, some microscopic features are to be included. Hocking [7], Anderson and Davis [8], Nikolayev [9] solved such a problem by incorporating the hydrodynamic slip. In the complete wetting case, the van der Waals forces cause a thin adsorbed film over the substrate, which relieves the singularity. For such a case, Moosman and Homsy [10], DasGupta et al. [11], Morris [12], Rednikov and Colinet [13] considered the pure vapor atmosphere and the substrate superheating. Poulard et al. [14], Pham et al. [15], Eggers and Pismen [16], Doumenc and Guerrier [17], Morris [18] investigated the diffusion-limited evaporation, when an inert gas is present in the undersaturated atmosphere. Up to now, the case of partial wetting and diffusion-controlled phase change received less attention. Berteloot et al. [19] proposed an approximate solution for an infinite liquid wedge on a solid substrate using the expression of the evaporation flux given by Deegan et al. [20]. The singularity is avoided by assuming a finite liquid height at a microscopic cut-off distance, imposed *a priori*.

Wayner [21] suggested that the contact line could move by condensation and evaporation while the liquid mass is conserved. During the advancing motion, for instance, the condensation may occur to the liquid meniscus near the contact line while the compensating evaporation occurs at another portion of the meniscus. Such an approach seemed very attractive [22,23] since it could provide a model with no singularity although completely macroscopic, avoiding microscopic ingredients such as slip length or intermolecular interactions. Rigorous demonstrations of the fact that change of phase regularizes the contact line singularity has been done recently by two independent groups [24–26], for the configuration of a liquid surrounded by its pure vapor. In this configuration, evaporation or condensation rate is controlled by the heat and mass exchange phenomena in the liquid. Such a situation occurs e.g. for bubbles in boiling. The Kelvin effect has proved to be very important because it provided a coupling between the liquid meniscus shape and mass exchange. In the present work, we explore a possibility of relaxation of the contact line singularity by the phase change in the contact line vicinity in a common situation where a volatile liquid droplet is surrounded by an atmosphere of other gases like air. This case is more challenging than the case of the pure vapor, because the evaporation or condensation rate is controlled by the vapor diffusion in the gas, which results in non-local evaporation or condensation fluxes [16].

The following physical phenomena need to be accounted for in such a problem.

- The concentrational Kelvin effect, i.e. a dependence of the saturation vapor concentration on the meniscus curvature. This effect is expected to be important in a small region of the liquid meniscus very close to the contact line, that we call microregion (Fig. 1d). In this region, high meniscus curvature is associated to the strong evaporation or condensation. The microregion size is expected to be below 10–100 nm.
- A region of mm scale, where the surface curvature is controlled by the surface tension, and (depending on the concrete macroscopic meniscus shape) gravity or inertia (Fig. 1b). The viscous stresses associated with the contact line motion and phase change are negligible here.
- A region of intermediate scale (Fig. 1c), where both capillary forces and viscous stresses are important. This region is known to be described by the Cox–Voinov relation [27,28]

$$h'(x)^3 = \theta_V^3 + 9Ca\ln(x/\ell_V), \tag{1}$$

  with $h'(x)$ the liquid slope at a distance x from the contact line and $Ca = \mu U/\sigma$ the capillary number (μ is the liquid viscosity, σ the surface tension and U the contact line velocity, assumed to be positive for the advancing contact line). It is a solution of Stokes equations in lubrication approximation that satisfies the boundary condition of vanishing curvature at large x. Note that large at the intermediate scale x remains small at the macroscopic scale associated with the macroscopic radius L of meniscus curvature (defined e.g. by the drop size when controlled by capillarity). Similarly, the curvature L^{-1} can be considered as negligible with respect to curvatures induced by strong viscous stresses in the intermediate region. Eq. (1) is valid for small capillary numbers, below the Landau–Levich transition for the receding contact line [5]. ℓ_V is a length of the order of the microregion size and is called the Voinov length while θ_V is the Voinov angle. The Cox–Voinov relation provides a good description of the intermediate region because of the strong scale separation between the capillarity controlled region and microregion. In contact line motion models, the Voinov length and angle can be obtained by the asymptotic matching to the microregion, while the asymptotic matching to the capillarity controlled region provides the following relation for the effective contact angle θ_{eff} (cf. Fig. 1b),

$$\theta_{eff}^3 = \theta_V^3 + 9Ca\ln(L/\ell_V). \tag{2}$$

  The L value depends on the concrete macroscopic meniscus shape [5]. Since we are interested in the relaxation of the contact line singularity, the capillarity-controlled region is not considered here, and the liquid meniscus is assumed to be a liquid wedge in both the intermediate region and microregion.
- Because of the long range of the concentration field controlled by vapor diffusion in the air, one needs to consider one more scale much larger than that of the liquid meniscus. In the following, we assume that at this scale the liquid meniscus is a semi-infinite ($x \in [0, \infty]$) layer of the negligibly small height that covers the solid substrate (Fig. 1a).

2. Problem statement

The problem to be considered is a liquid wedge posed on a flat and homogeneous substrate moving at constant velocity U, in a situation of partial wetting. The atmosphere surrounding the substrate and the liquid consists of an inert gas saturated with the vapor of the liquid, cf. Fig. 1a (an instance of such an atmosphere is wet air at atmospheric pressure, room temperature and relative