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Electric and capillary instability of liquid rising between heated/cooled parallel plates and subjected to phase change: DC on perfect dielectric liquids

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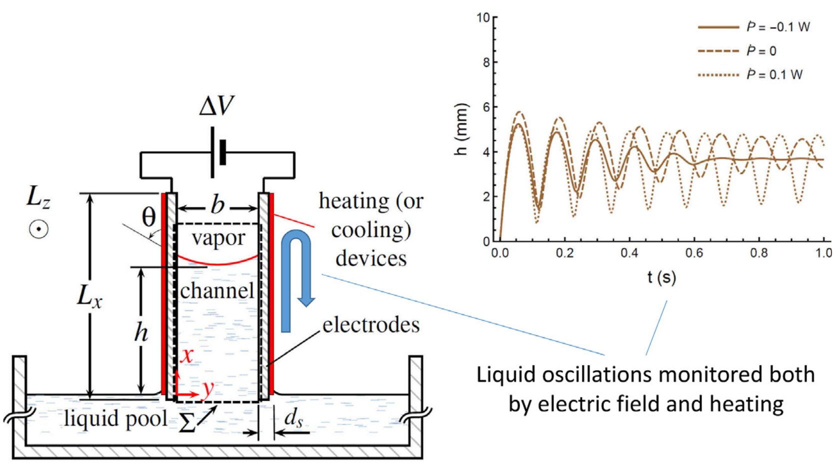
GRAPHICAL ABSTRACT



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ABSTRACT

Based on Lucas–Washburn's seminal works, a simple model governing the flow inside a narrow channel, partly dipped into a large pool filled with a dielectric liquid, is presented. The channel walls are electrically polarized and can be warmer or cooler than the pool liquid using an appropriate heating and cooling device. The liquid dielectric constant is assumed varying linearly with temperature and evaporation or condensation can occur at the meniscus surface. Linear stability analysis is performed near the equilibrium position demonstrating various effects of dielectrophoretic, capillary, gravity and viscous forces. For the investigated liquid's volatility, it is shown that only sufficiently heated electrodes can exhibit instabilities about equilibrium position, whereas cooling these electrodes leads always to an asymptotically stable liquid motion. A numerical investigation is also performed on the transient regime showing either monotonic or damped oscillatory liquid motion depending on viscous, capillary and dielectric effects. If channel walls are heated and the electric field magnitude is above a specific and finite threshold, liquid can be pushed out of the gap, preventing reentrance. This effect can lead to undesirable walls dry-out that would be detrimental to two-phase heat transfer devices. A comparative survey is also performed on two liquids typically found in applications involving thermo-electrohydrodynamics, namely hfe-7100 and hfe-7300.

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1. Introduction

The problem of liquid rise in capillaries has retained the scientists attention, at least from a phenomenological point of view, since the precursor work of Boyle [1]. It was approached quantitatively from porous media (and particularly soil) standpoint first by Heber Green and Ampt who carried out a theoretical analysis showing the time-square-root dependency of the liquid penetration distance into the capillary medium [2]. Independently, Lucas developed an equivalent mechanical model for liquid rise in cylindrical capillary tubes, using Darcy's law and Young–Laplace's equation balancing viscous and capillary forces, leading to similar results [3]. Washburn derived a slightly different equation by additionally taking gravity into account [4]. Bosanquet used a more fundamental approach to derive a momentum equation in which inertia was considered too [5]. He has shown that the results obtained earlier by Heber Green and Ampt, Lucas and Washburn were valid only at long penetration time where the velocity reaches its limit-value in horizontal capillaries indeed but a sufficiently short early stage also occurs where the meniscus penetration distance exhibits a combination of linear and exponential time laws. (It is worth to note here that connection between, on the one hand, liquid driven effects in capillary tubes, gaps and corners and, on the other hand, the repulsive-short-range and attractive-long-range interactions between molecules, derived from Lennard–Jones potential, was made first by Jones [6].)

Quéré experimentally investigated more specifically the early stage of liquid rise in capillary tubes [7]. He found that, at this stage, the meniscus displacement follows a linear time law and was able to explain this behavior by an analytical model in which viscous effects are neglected. He also reported unusually long damping oscillations for liquids with very low viscosity. Performing a perturbation method of the total energy balance about the equilibrium position, Quéré et al. and Lorenceau et al. derived a closed-form condition for liquid oscillations in a capillary tube of radius r to occur, namely $\Omega < 2$, $\Omega = 8\sqrt{2}\sigma^{1/2}r^{-5/2}\rho^{-3/2}g^{-1}$ (where σ is the surface tension, ρ the liquid density and g the gravitational acceleration) and were able to test experimentally its relevance [8,9].

O'Brien et al. experimentally investigated liquid penetration into (resp. around) a hydrophilic (resp. hydrophobic) material using an aqueous radioactive liquid [10]. They derived a model based on standard variational principle of free energy of a liquid column rising between two parallel and chemically dissimilar plates [11]. This model accounts for the exact liquid height, meniscus shape and contact line effect and was shown to predict exactly the *mean* liquid height at any gap width in opposite to Young-Laplace-based law relevant only when this width is very small or very large [12].

Using mechanical energy balance, Szekely et al. [13] analyzed the capillary rise kinetics between parallel plates. Considering the pressure drop along the liquid stream entering the gap, they derived an equation equivalent to Washburn's in which inertia is augmented by an *apparent mass* proportional to the gap width. Levine et al. [14] studied the influence on the overall drag force of the departure of the flow from Poiseuille's profile near the meniscus for capillary rise in two different geometries: inside cylindrical tube and between parallel-plate channel. The contact line is modeled using the Navier slip boundary conditions and the meniscus assumes a rigid spherical cap (resp. semilunar) shape for the tube (resp. channel) liquid flow. Their analysis hints at a possible dependency of the final height on the flow topology. They also suggested a new meniscus velocity law. Wolf et al. developed a CFD model based on lattice Boltzmann molecular method in order to simulate the liquid rise between parallel plates [15]. In addition, they modified Bosanquet's equation in order to take both the planar geometry and the dynamic contact angle (modeled by Schäffer and Wong [16]) into account. Fairly good agreement is observed between Lattice Boltzmann and modified Bosanquet's model solutions for different gravitational accelerations and gap widths. Also is reported the significant deviation of the dynamic contact angle from the static angle in the first rise stage. However, no noticeable influence of the flow details in the vicinity of the meniscus on ultimate liquid height is reported, in opposite to Levine et al. conclusions, suggesting the relevance of Poiseuille's approximation in such problems.

Capillary rise between parallel plates under microgravity was investigated both numerically, using global momentum balance, and experimentally, in a drop tower facility, by Dreyer et al. [17]. Only perfectly wetting fluids, *viz.* with zero static contact angle, were considered and the dynamic contact angle was modeled after Fritz [18]. Good agreement was found between numerical solution and experimental data. Three regimes of impedance (to the motive capillary force) were clearly identified, in the following order: (i) the reservoir inertial regime, where effective inertia (with apparent mass) competes capillarity, (ii) a convective regime where the liquid at the gap entrance impedes more importantly and (iii) a viscous regime where friction is the dominant impedance. Ramon and Oron extended Lucas–Washburn's equation in order to take phase change – occurring along the meniscus – into account and analyzed the liquid rise between parallel plates. Albeit a substantial temperature difference was considered (in order the phase change to be effective on the liquid rise), their model assumes the liquid held at uniform and constant temperature. They found that evaporation decreases systematically the final liquid height while condensation may either increase or decrease the latter according to whether effect of mass supply or pressure recoil prevails. More importantly, they have shown that for sufficiently high phase change rate, the liquid oscillations can be unstable.

In an attempt to extend the applicability of Jurin's law in the case of perfectly wetting liquids rising between two parallel plates, Moldovern and Gammon suggested using the gap width diminished by twice the thickness of the precursor adsorbed liquid layer instead of using the gap width itself [20]. The adsorbed layer thickness was calculated by balancing van der Vaals dispersive forces and gravity forces applied to a meniscus joining a vertical plate and an infinitely large pool, as far as this thickness was assumed very small compared with typical gap width. The new law they proposed showed fair agreement with their experimental data close to the critical temperature. Shortly later, Legait and De Gennes performed an asymptotic development and showed that, despite the submicroscopic thickness of the adsorbed layer, the confinement has a significant thickening effect on this thickness (by a factor 3/2) [21]. This correction led to even better agreement between the ultimately modified Jurin's law and Moldovern and Gammon experimental data.

Chen and Hsieh led both a theoretical and experimental survey of the entrance of aqueous (and so finite electrically conductive) liquids into a gap separating two dielectric-coated parallel plates and subjected to an electric field [22]. Expected to modify substantially the liquid rise dynamics, the electrowetting on dielectric (EWOD) effect, *viz.* the interaction between the liquid-dielectric solid substrate wettability and the electric field, was modeled after Kang [23]. The electric equilibrium contact angle is derived using either Lippmann's [24] equivalent circuit equation [25] or minimum free-energy condition for thermodynamic equilibrium [26]. The contact line friction is taken into account using Blake et al.'s model relating the departure from the equilibrium angle, the contact line velocity and the (activation) energy barrier linked with this motion [27]. In the same context, Wang and Jones studied the influence of the electrodes, slightly converging toward the top, on the rise of deionized water when an alternative electric field is applied [28]. They reported an electric field threshold above which the liquid rise equilibrium is no longer stable and successfully predicted the bifurcation associated with by an analytical model. Jones et al. investigated experimentally the rise of cryogenic deuterium, due to electric field, between plates either parallel or converging toward the top, where they noticed bifurcation, too [29]. The model developed by Wang and Jones was able to predict this bifurcation for increasing electric field but failed with decreasing electric field. They attributed the hysteresis to the high wettability of cryogenic fluids on glass