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Evaporation of an isolated liquid plug moving inside a capillary tube

Vyas Srinivasan [a], Victor Marty-Jourjon [b], Sameer Khandekar [a,*], Frederic Lefèvre [b], Jocelyn Bonjour [b]

[a] *Indian Institute of Technology Kanpur, Kanpur 208016, India*
[b] *Université de Lyon, INSA-Lyon, CETHIL UMR5008, F-69621 Villeurbanne, France*

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ABSTRACT

The paper reports an experimental study to understand the evaporation mechanism of a partially wetting isolated liquid plug (methanol) of length L moving inside a long, dry, horizontal circular glass capillary tube (ID = 1.5 mm). The plug (with specified range of non-dimensional L/D ratios) is pushed from rest by controlled injection of air from one side, till a quasi-steady terminal plug velocity is achieved in the adiabatic section (non-heated length) of the capillary tube. Under such conditions, the drainage of thin-film occurring at the receding interface and its subsequent dewetting is well predicted by existing literature. The plug is then allowed to move through the heated section maintained at constant wall temperature (lesser than the saturation temperature of methanol). The drained film now starts evaporating rapidly, drastically affecting the bulk transport behavior. High resolution videography, coupled with laser confocal microscopy provides vital bulk as well as local information, including time-varying plug length, film thickness and local dewetting behavior near the contact line. Experimental results obtained for different wall temperatures and different initial L/D ratios of liquid plug suggests that the Taylor's law for predicting drainage characteristics under adiabatic flow conditions is valid, even for cases where there is a continuous evaporation of thin-film. The study thus provides a framework for modeling evaporative flux based on simple hydrodynamic theory of film drainage.

1. Introduction

The issue of evaporating liquid interface inside a micro-channel ($Bo < 2$) is an active area of research as it is often encountered in applications such as micro-heat pipes, pulsating/oscillating heat pipes [1], microscale chemical reactors, flow-boiling in the context of electronics cooling [2], etc. Due to the dominance of surface tension in microchannel geometries, in most cases referred above, moving liquid interfaces are associated with Taylor flows, a unique two-phase flow patterns which is characterized by liquid plugs separated by gas/vapour-bubbles.

When a static liquid meniscus is formed inside a capillary tube, the apparent contact angle of the meniscus is governed by the capillary forces and the equilibrium shape can be predicted by the Young–Laplace equation, as shown in Fig. 1(a). The eventual shape of the meniscus is greatly influenced by the wettability of the solid–liquid combination under consideration. In case of partially or completely wetting fluids, the meniscus thus formed usually spreads out in a direction parallel to the solid wall of the tube, due to the strong interaction of van der Wall forces [3]. Referring to Fig. 1(a), this result in three regions of interest, namely:

- An adsorbed layer, which is typically a few microns thick (containing few liquid molecules). While developing mathematical models, this adsorbed layer is generally treated as a non-evaporating region due to the strong dominance of molecular van der Wall forces which prevent its evaporation.
- An extended meniscus region or the 'thin-film' region, which acts like a transition region, where the effect of long range molecular forces (disjoining pressure) are felt. This region of thin-film is of tremendous importance, since this is the region where the maximum heat transfer/evaporation occur due to its low thermal resistance [4].
- The intrinsic meniscus which forms the apparent macroscopic interface, due the influence of capillary forces.

Thus, it is now well understood that the majority of the heat transport mechanism is from the thin-film region. Deryagin et al. [5], in their pioneering work demonstrated the liquid pressure reduction near the thin-film region and attributed it to the disjoining pressure. Wayner and his co-workers extensively worked on the evaporation mechanism in the thin-film region and have shown how it plays a crucial role in determining the apparent

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[*] Corresponding author. Tel.: +91 512 259 7038; fax: +91 512 259 7408.
E-mail address: samkhan@iitk.ac.in (S. Khandekar).

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Nomenclature

Bo	Bond number $\left(\frac{\rho g D^2}{\sigma}\right)$
Ca	Capillary number $\left(\frac{\mu V}{\sigma}\right)$
D	diameter of capillary tube (m)
e_c	critical thickness of film before dewetting (m)
L	liquid plug length (m)
ΔL	incremental change in length of liquid plug (m)
r	radius of capillary tube (m)
T	temperature (°C)
Δv	change in volume of liquid plug (m^3)
V	velocity of fluid (m/s)
Δx	incremental change in position of liquid plug's receding meniscus (m)

Greek Symbols

θ_e	equilibrium contact angle (°)
μ	viscosity (Pa-s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
δ	liquid thin-film thickness (m)

Subscripts

exp	experimental
th	theoretical
i	initial

contact angle of the macroscopic meniscus region. For example, Preiss and Wayner [6] from their experimental study concluded that the fluid flow from the bulk liquid that feeds the evaporating meniscus causes the change of interfacial curvature. Also, Potash and Wayner [7] showed that a change of disjoining pressure along the meniscus creates a substantial pressure gradient, which drives the liquid supply from the bulk into the thin film during its evaporation. Since then, various mathematical models were proposed based on augmented Young–Laplace equation, which described force balance on thin-film based on the disjoining pressure [8,9]. A review on mathematical modeling of thin-film evaporation is extensively dealt by Wayner [10]. Swanson and Herdt [11] incorporated three-dimensional Young–Laplace with Marangoni convection, van der Waals dispersion forces and non-equilibrium interface conditions to augment the existing model. This study highlighted that the change in wall superheat had no effect on the meniscus profile. Morris [3] developed an analytical expression for heat transfer due to evaporation of thin-film of a completely wetting static meniscus. This work gave the relationship of heat flow in terms of the contact angle, superheat and material properties and can also be applied to different tube geometries. Recently, Biswal et al. [12] studied the impact of including interfacial slip in the evaporation of thin-film. Based on their semi-analytical solution, it was concluded that the interfacial slip thickens the liquid film, which in turn lowers the mass transfer from the thin-film to the vapour phase. A drawback of most of these mathematical models is the fact that they consider a completely wetting fluid at static conditions. Though these models provide an excellent understanding of the transport mechanism in the thin-film region, they cannot be used to predict the heat transfer of a typical engineering system, which usually has partially wetting liquids under dynamic conditions. Experimental studies on the measurement of thin-film thickness during evaporation, for wetting as well as non-wetting fluids, are limited, due to the inherent complexities involved in finding local transport parameters such as temperature and mass flux which require high-response non-contact local measurement techniques to resolve the spatial and temporal scales at the evaporating meniscus.

The dynamics of the moving contact line, even under adiabatic conditions (without any associated evaporation), is in itself a separate topic of research, which is neatly summarized recently by Snoeijer and Andreotti [13]. From a classical viewpoint, Taylor [14], experimentally measured the amount of liquid left behind on the inside of the tube wall due to drainage, when a liquid plug (glycerine-water solution), was blown out from it by pushing it with air. With these range of experiments, the average thickness of the liquid layer being drained out in the form of a thin film from the moving liquid plug was determined. Bretherton [15] was able to predict the thin-film thickness analytically for the case of low Bond number and Weber number, where the effects of both gravity and inertia were neglected. This seminal work showed the dependence of thin-film thickness on the Capillary number (Ca) of the flow, the proposed functional form of the power law scaling was $\delta = fn(Ca)^{2/3}$, typically applicable for low Ca ($Ca < 0.03$) systems. This dependence of the film thickness on the flow velocity is generally referred in the subsequent literature as Taylor's law. It was also deduced that the net pressure drop due to the thin-film can be correlated with the flow Capillary number. Later, Tanner [16] was able to relate the apparent dynamic contact angle of the meniscus (See Fig. 1(b)) to the static contact angle and the Capillary number. From there on, several works on the hydrodynamics [17–19] have been carried out to study the influence of inertia, interfacial slip and wettability on the thin-film thickness and the resulting pressure drop thereof during its meniscus motion. With the intention of extending the Taylors law validity to inertia dominated regimes on the thin-film thickness, Aussillous and Quere [20] performed similar experiment as that of Taylor [14], except that they used a low-viscosity liquid at a high velocity. Hence, they scrutinized the validity of Taylors law for a large variation of Ca. Eventually, they proposed a modified Taylors law which was applicable in the entire range of $10^{-06} < Ca < 1.4$. In recent times, the adiabatic experiments of Han et al. [21] incorporating non-intrusive high precision techniques have also revealed that for $Ca < 0.025$, the effect of inertia is negligible and the original Taylors law scaling holds quite well. They also showed that the overall length of the liquid plug has negligible influence on the liquid film thickness which gets laid down, with an exception of small liquid plugs ($L/D < 2$), where relatively thicker films were observed.

It must be noted that all the above referred studies deal only with the hydrodynamics of the liquid thin-film, which gets laid down during liquid plug motion, under adiabatic conditions. Limited studies [22,23] are available which simultaneous focus on thermal as well as hydrodynamic transport mechanism of the liquid thin films. Moriyama and Inoue [24] measured the film-thickness formed when a vapour bubble grows in a superheated liquid. They reported monotonically increasing interface velocity with the initial superheat. In their study, the film thickness was estimated based on the transient variation of wall temperature, by assuming that the change in temperature is due to the heat taken by the thin-film to evaporate completely. A recent review by Zhang and Utaka [25] provides valuable insight into the research conducted on two aspects of thin-film, namely: the thickness of thin-film and its evaporation characteristics. However, this review