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Thin film evaporation in microchannels with slope- and curvature-dependent disjoining pressure

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ABSTRACT

Physics of thin film evaporation plays a critical role in designing highly efficient micro-scale thermal management systems. In such systems, envelope of the evaporating thin film is an extended meniscus beyond the apparent contact line at a liquid/solid interface, which experiences strong intermolecular forces because of micro-scale interactions. Traditionally, such forces are represented by disjoining pressures that are postulated solely on the basis of the local film thickness, disregarding the local slope and curvature of the interfacial profile. In the present study, an improved model for evaporation in thin liquid films in microfluidic channels is developed, which explicitly takes into account the slope and curvature dependence of the disjoining pressure, under the assumption of a steady meniscus in existence with its own vapor. Such an improved formalism essentially prevents the contact line movement without slip, and allows an asymptotic merging of the evaporating interfacial profile to an infinitesimally thin non-evaporating adsorbed film. Implications of this rigorous disjoining pressure model on the thermo-physics of thin film evaporation in a kinetically controlled limit are investigated in details, and contrasting confluences as compared to the traditional descriptions of the disjoining pressure are emphatically pinpointed.

1. Introduction

Rapid advancements in integrated circuits for various applications (such as high density semiconductor processors for microelectronic devices) have been generating ever-increasing demands for developing more efficient thermal management protocols, commensurate with the constraints of their miniaturized length scales. Since such high rates of local heat dissipation cannot be addressed by traditional cooling strategies, the needs for micro-scale thermal management systems have been found to be inevitable. Evaporation of thin liquid films has long been recognized as a means of dissipating high local fluxes in many of these applications, including heat pipes for aerospace thermal control, electronics cooling, desalination systems, and process heat exchangers. Fundamentally, most of these arrangements, characterized by low thermal resistances, rely on change-of-phase heat transfer mechanisms for augmenting the rate of heat dissipation without incurring sensible temperature rises beyond critical limits.

When a liquid (coolant) meets a solid substrate (device), the extended meniscus may be divided into the following three distinct regions (see Fig. 1): an adsorbed (non-evaporating) region, an intrinsic meniscus region where the capillary forces dominate, and an intermediate thin-film transition region where the effects of long-range intermolecular forces may strongly be felt. Previous studies [1] have demonstrated that significant improvements in the heat dissipation characteristics may be achieved by enhancing the extent of the thin film evaporating region, which may be perceived as an extended meniscus beyond the apparent contact line at a liquid/solid interface. When heat flux is added to the thin film region, the film tends to get rid of the same through an evaporative transport of mass. This may be achieved by exploiting certain intrinsic flow actuation mechanisms prevalent within the thin film as a combined consequence of the local gradients in the surface tension forces (because of a continuously varying interfacial curvature) as well as the local gradients in the intermolecular forces, without necessitating any external pumping. A comprehensive understanding of the coupled interfacial physics, fluid flow and heat transfer mechanisms in the thin film evaporating region, therefore, remains critical towards an optimal design of micro-scale thermal management systems exploiting such intrinsic effects.

Numerous research investigations have been reported in the literature for elucidating the fundamentals of thermo-physical transport in evaporating thin liquid films. Potash and Wayner [1] first described an evaporating meniscus that extended beyond the apparent contact line, and developed a mathematical model for

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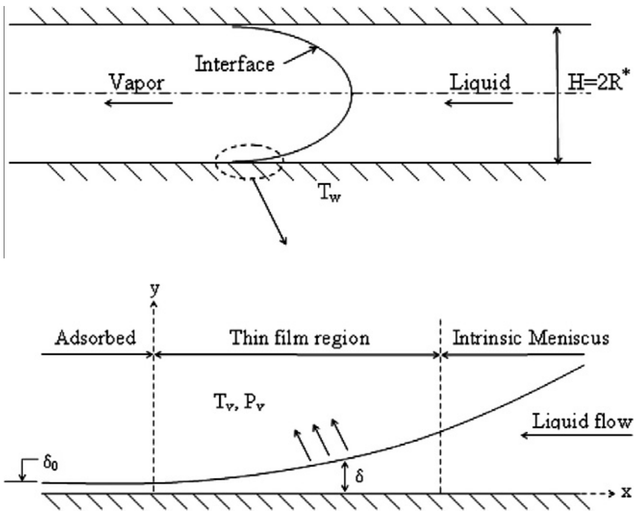

Fig. 1. Schematic of an evaporating thin film in a microchannel maintained at constant temperature.

the extended meniscus using the Derjaguin–Landau–Verway–Overbeek (DLVO) theory. Wayner et al. [2] subsequently pioneered the concept of enhanced capillary transport by employing small-scale grooves, and inferred that thin film evaporation is intensely related to the thermal state of the liquid–vapor interface. These fundamental considerations were further advanced by various researchers [3–13] considering the implications of combined mass and momentum transport in conjunction with additional micro-scale effects [14–21]. Ma et al. [22], in a recent investigation, have addressed the above problem by incorporating inertial effects in their momentum transport considerations. Of late, issues of Marangoni (surface-tension-gradient-driven) instabilities [23] have also been addressed in the context of thin film transport in an evaporating meniscus. It can be noted in this context that several researchers have employed the diffuse interface model for analyzing spreading and rupture of the liquid films and for studying the underlying transport phenomena, as evident from several studies reported in the recent past [24–26].

Most of the above-mentioned investigations have lead to a common consensus that interfacial forces may drastically change the characteristics of thin liquid films when in contact with a solid. This phenomenon may primarily be attributed to the fact that at this scale, the fluid no longer remains homogeneous. A gross manifestation of the resultant intermolecular forces, governing the pertinent interfacial transport characteristics, may be represented by the disjoining pressure, which determines the stability and wettability of the thin liquid films. For thin liquid films of uniform thickness (δ), the disjoining pressure may be approximated in the leading order to be a function of the film thickness only. However, for varying film thicknesses leading to an asymptotic merging of the liquid with the solid substrate, the disjoining pressure becomes unbounded as $\delta \to 0$. Such dependence of the disjoining pressure solely on the film thickness does not remain far from being questionable. Hocking [27] first attempted to rectify this discrepancy by deriving a form of the expression of the disjoining pressure that depends not only on the film thickness, but also on the film slope, based on the earlier developments of Miller and Ruckenstein [28]. However, one critical inconsistency that still remained with the underlying theoretical development originated from the fact that these derivations were based on the consideration of constancy of an intermolecular potential on the liquid–vapor interface only, disregarding the requirement of enforcing the same within the inner region of the liquid film as well under equilibrium conditions. Secondly, Hocking took the disjoining pressure same as the above-mentioned intermolecular potential, which remained to be justified. Subsequently, Indeikina and Chang [29] also derived an expression for slope-dependent disjoining pressure, though not rigorously established through the equilibrium constraints. It is also important to mention here that the above modified considerations of disjoining pressure allowed a contact line to move without slip, in clear disagreement with the molecular simulation predictions. In fact, when a liquid film merges on a substrate, an infinite-force singularity is likely to result at the contact line if the film is to be moved along the substrate [30]. Origin of this singularity stems from the fact that a fluid particle needs to turn through a finite angle at the contact line within an infinitesimal distance [31]. The only mechanism by which this singularity manifested through an unbounded interfacial force may be relieved is through an interfacial slip [32–36]. However, in the absence of any interfacial slip, such forcing condition at the interface is clearly unphysical in nature, since it permits the contact line movement even without slip. In an effort to overcome these constraints, Wu and Wong [37] derived an alternative expression for slope-dependent disjoining pressure that contained higher order terms (film-curvature dependent), which physically ensured the locking of any contact line motion without slip. Dai et al. [38], in a subsequent study, pinpointed certain discrepancies in the derivations of Wu and Wong [37], and suggested some corrections. However, considerations of an evolution of the thin liquid film towards a dry-out limit, as attributed to thermo-kinetically driven evaporation processes, remained beyond the scope of their study.

Although the above-mentioned recent studies have suggested a strong dependence of the disjoining pressure on the local slope and curvature of the liquid film, research investigations on thin film evaporation have classically ignored such variations and have considered the disjoining pressure to be a sole function of the local film thickness, disregarding the higher order derivatives of the interfacial profile. As a consequence, the resulting theoretical developments have not been able to elucidate situations concerning any advancement of the contact line in meeting the solid substrate without necessitating the imposition of an interfacial slip. Accordingly, the past theoretical developments on thin film evaporation, including the most recent ones, have been forced to consider a threshold finite non-limiting value of the adsorbed film thickness, which acts as an initial condition for determining the interfacial profile in the thin film region. Clearly, such formalisms do not permit the consideration of an asymptotic merging of the interfacial profile in the thin film region to an infinitesimally thin adsorbed film layer. However, such considerations may be critically important towards an accurate resolution of the evaporating meniscus as well as a physically rich explanation of the onset of the dry-out region, which in reality is expected to be a strong function of the slopes and curvatures of the thin film profiles.

Aim of the present study, accordingly, is to investigate the thermo-physical transport phenomena in thin liquid films by considering slope- and curvature- dependences of the disjoining pressure, in addition to its traditional dependence on the local film thickness. A comprehensive mathematical model is developed in this regard and is numerically solved, under the assumption of a steady meniscus in existence with its own vapor, in an effort to determine the interfacial profile in the thin film region and to predict the rate of interfacial heat transfer, as a fundamental design basis for micro-scale thermal management systems. Contrasting predictions from the present model and the traditional models considering slope- and curvature-independent disjoining pressures are also emphatically pinpointed, so as to reveal the consequences of the underlying micro-scale transport mechanisms on the thin film interfacial profile as well as the pertinent thermo-fluidic characteristics.