On evaporation of thin liquid films subjected to ultrasonic substrate vibration

Amin Rahimzadeh, Morteza Eslamian *

University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai, 200240, China

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ABSTRACT

Theoretical and experimental studies on evaporation of thin and ultrathin liquid films (all volatile or liquid solutions) are desirable, but scarce. In this context, excitation of thin liquid films by (ultrasonic) vibration is also an interesting theoretical and applied research direction affecting the hydrodynamics, stability, and evaporation of thin liquid films. In this study, the evaporation history of drop-cast stationary and excited thin liquid films subjected to vertical and horizontal ultrasonic vibration is studied, and unprecedented results are obtained and discussed. The evaporation history of two model thin liquid films is captured using video camera and high precision digital balance. Since evaporation of excited thin films by substrate vibration resembles forced convection, the convective heat transfer coefficient and consequently the evaporation rate of the excited thin films are expected to increase compared to those of non-excited thin films. Experimental results substantiate this hypothesis. It is further shown and discussed that the films excited by horizontal ultrasonic substrate vibration evaporate faster than those excited by vertical vibration.

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1. Introduction

Evaporation from the free surface of a liquid exposed to surrounding gas may be realized in various natural phenomena and practical applications. Depending on the characteristic lengths, the problem may be treated differently. For instance, estimating liquid evaporation rate in thick or deep liquid layers, such as swimming pools, ponds and lakes, is a classic design problem, e.g. [1–3]. For very shallow layers of liquids or simply thin liquid films, interaction between the liquid-gas and solid-liquid interfaces and the disjoining pressure as a result of intermolecular forces may affect the evaporation, although the shallow depth assumptions may bring about some major simplifications to governing equations [4–6]. Evaporation from the surface of thin liquid films has existing and potential applications, such as in heat pipes and evaporators [7,8]. And, if a thin film of a liquid solution is used instead of a completely volatile liquid, the solvent evaporation and solute precipitation leaves behind a thin solid film. This is a favorable process for the fabrication of thin solid films in the field of solution-processed thin film devices with ubiquitous presence in existing and emerging technologies, such as thin film organic electronics and photovoltaics [9]. Understanding the physics of thin liquid film evaporation is therefore essential for achieving desired device or process performance, by controlling the evaporation rate. Application of multicomponent solvents with different boiling points [10], anti-solvent to accelerate solvent evaporation [11], suppression of dewetting in crystalline films, such as perovskites [12], employing patterned substrates with a gradient in thermal conductivity, to prepare patterned films [13,14], and imposing ultrasonic vibration to control the film structure and evaporation rate [15–19] are some of the attempts made to control the drying and morphology of the ensuing thin solid films. The abovementioned works concern the development of advanced materials and device fabrication, without particular focus on transport phenomena associated with liquid film evaporation in microscale. This work addresses the problem of thin film evaporation from a fluid and thermal point of view.

To establish the argument and to justify the need for the present work, we start with some notable researches performed on deep liquids subjected to natural convection, and then most relevant works on evaporation of thin liquid films are reviewed. Numerous works have been performed on natural and forced convection over a deep layer of liquid. For instance, Bower and Saylor [1–3] studied evaporative natural convection over liquid surface in a walled container and obtained correlations between the Sherwood (Sh) and Rayleigh (Ra) numbers in the form of $Sh = B Sc^{1/3} Ra^{\alpha}$, where B and α are constants. In the correlation developed by Bower and Saylor $B = 0.230$ and $\alpha = 0.321$. These simple correlations may be used to estimate the evaporation rate. Unfortunately, in the case of thin liquid films, there is no such correlation, due to the presence of other important variables, as discussed above. There are very few experimental works that consider evaporation of thin liquid

* Corresponding author.
E-mail addresses: Morteza.Eslamian@sjtu.edu.cn, Morteza.Eslamian@gmail.com
(M. Eslamian).

Nomenclature

A'	Hamaker constant
A	area of the liquid film (m^2)
A_0	vibration amplitude (m)
a, b	dimensional constants in Eqs. (1) and (2)
B	*Sh-Ra* correlation constant
c	solution concentration-weight fraction (−)
E	evaporation term (m/s)
E_0	pure liquid (solvent) evaporation term (m/s)
e	evaporation term in Eq. (5) (1/s)
g	gravitational acceleration (m/s^2)
h_0	mean film thickness (m)
h_c	convective heat transfer coefficient ($J/m^2 K$)
h	film thickness (m)
j	evaporative mass flux ($kg/m^2 s$)
k	wave number (1/m)
$\dot{m}$	evaporation mass flow rate (kg/s)
n	drying exponent in Eq. (4)
r	drop and film effective radius (m)
Ra	Rayleigh number (−)
s	perturbation growth rate (1/s)
Sc	Schmidt number (−)
Sh	Sherwood number (−)
t	time (s)
T_0	liquid bulk temperature (K)
T_∞	ambient gas bulk temperature (K)
x	horizontal direction (m)
V	drop or film volume (m^3)
v_l	rate of change of film thickness (vertical velocity of interface) due to evaporation (m/s)

Greek symbols

α	exponent of *Ra* in *Sh-Ra* correlation
μ	viscosity (kg/ms)
ρ	liquid density (kg/m^3)
σ	surface tension (N/m)
ω	equal lateral and vertical vibration frequency (Hz)
$\mathcal{L}$	latent heat of vaporization (J/kg)

films in microscale [20,21]. Hanchak et al. [20,21] experimentally studied thin film evaporation at different temperatures, where nanoscale reflectometry was used to measure the time-varying film thickness. They also performed a numerical study of thin film evaporation based on lubrication approximation that included the van der Waals interaction, and the film thickness was computed and compared with the experimental data. Similarly, Sait and *Ma* [20,21] designed an experimental setup to measure the transient film thickness and temperature in an evaporative thin liquid film, using nonintrusive methods. The film was locally heated using a laser beam with known heat flux, and the time varying temperature, film thickness, and heat flux were measured. They also observed creation of instability and uncertainly in their measurements, because evaporation tends to make the thin liquid film unstable, to be discussed later. The dewetting, pattern formation and rupture phenomena associated with evaporating thin liquid films has been experimentally studied, as well, e.g. [22,23], although finding the thin film evaporation rate is not the focus of such works.

Several theoretical models have been developed to simulate evaporation/condensation of thin liquid films. A one-sided model, in which dynamics of the liquid is decoupled from dynamics of the surrounding gas and vapor has been proposed by Bulerbach et al. [24]. Oron and Bankoff [25,26] used this model to evaluate dynamics of liquid films, neglecting the thermocapillarity and vapor thrust. Ajaev [27,28] considered thermal effects, surface tension, and disjoining pressure to study evolution of thin liquid films. Later, Sultan et al. [29] developed a two-sided model, in which the effect of both liquid and vapor phases on the stability of evaporating thin liquid films is considered. The abovementioned studies show that the evaporation loss of a liquid film should be considered when analyzing dynamics, stability, and evolution of thin liquid films [4,5,6,30]. Thiele et al. [23] have established and reviewed mathematical equations of evolution of liquid films, where the role of evaporation/condensation on stability is elucidated (evaporation destabilizes the liquid film). 3D numerical analysis of evolution of volatile and nonvolatile liquid films shows the thinning, formation of peaks and holes, as well as ridges in nonvolatile films, whereas a fully volatile film vanishes as it evaporates [31]. Molecular dynamics (MD) simulation of evaporation and condensation of ultrathin liquid films of argon has been performed [32]. The evolution of film thickness and net mass flux were obtained and evaluated against the kinetic theory of gases. A non-evaporating layer was detected due to strong intermolecular forces at very low thicknesses. Peng et al. [33] studied the rupture dynamics of ultrathin films of aqueous NaCl in the absence and presence of a homogenous electric field by MD simulations, considering evaporation and its interplay with surface forces. They observed that rupture and evaporation of thin films is accelerated as a result of the imposed electric field. In another MD simulation, Nagayama et al. [34] investigated the evaporation of ultrathin liquid films formed on a nanostructured surface, where it was found that the evaporation rate in the case of a nanostructured substrate is higher than that of a flat substrate. Lee and Son [35] solved the complete set of multiphase transport equations for a liquid solution on a vertically heated moving plate, a process that occurs in dip-coating. The process was found to be affected by the plate withdrawal velocity. In a thin liquid film on a horizontal plate there is usually no driving force for liquid motion, whereas in a vertical film, liquid motion is induced as a result of gravity and plate withdrawal. The problem of Marangoni convection in evaporating thin films and its effect on film instability has been studied, as well, e.g. [36], although the focus has been more on stability than finding the evaporation rate.

Thin liquid films may be prepared by various casting methods, such as drop-casting, used in this study. In drop-casting, droplets with an initial momentum impinge a wetting surface. The maximum spreading of an impinging droplet with respect to the droplet initial diameter is a function of significant dimensionless parameters, i.e. *Re* and *We* numbers, where the substrate wettability, roughness, and surface energy are additional influencing parameters. A wetting surface (small contact angle) favors droplet spreading and the formation of a thin liquid film [37,38]. While numerical and experimental works on evaporation of suspended and sessile droplets are abundant, as summarized in Ref. [39], theoretical and particularly experimental works on evaporation of thin liquid films are limited, as outlined above. Nevertheless, since a highly spreading droplet forms a liquid film, some aspects of thin film evaporation may be similar to that of a sessile droplet. Hence, for a liquid film prepared by drop-casting and similar methods, the film evaporation behavior may be somewhat understood by study of the evaporation of a sessile droplet. When a liquid droplet gently touches a solid substrate, it attains its equilibrium state according to Young's equation, which is a force balance between the three binary interfacial tensions, assuming that other forces such as gravity are insignificant [40,41]. Then, if the surface is heated, the droplet starts to evaporate, possibly in several stages, until it vanishes or dries, depending on whether it is completely volatile or a solution droplet. Three ideal modes or stages of sessile droplet evaporation may be hypothesized as that depicted in Fig. 1: (1) constant contact angle evaporation; (2) constant radius evaporation; (3) a complex combination of the previous modes [42]. The first mode may occur when the droplet is unpinned from an ideal substrate (no friction force), while the contact angle remains constant during