International Journal of Thermal Sciences 105 (2016) 75–82

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Stability of an evaporating meniscus: Part II – Experimental investigation

John Polansky*, Tarik Kaya

Carleton University, Department of Mechanical and Aerospace Engineering, Ottawa ON, Canada

ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form
25 February 2016
Accepted 28 February 2016
Available online xxx

Keywords:
Meniscus instability
Evaporating meniscus
Thin films

ABSTRACT

An experimental investigation was carried out to study the instability of an evaporating meniscus formed within a channel using three different fluids: n-pentane, iso-octane and acetone. To correlate the instability with the applied thermal load, a mathematical model was presented relating the height of a meniscus to the applied superheat. The results of this study found two different instabilities. An instability for n-pentane and iso-octane (alkanes) was found to occur for a narrow range of low heater settings of approximately 0.2 W. This instability was of a high frequency and low amplitude nature. With additional increases in heater power, this instability subsided giving way to stability. At higher heater power settings, greater than 1 W, another instability was found to occur for all three fluids. The second kind of instability had large amplitude oscillations and was persistent for heater settings beyond that of instability initiation. Given the persistent nature of the second instability, an investigation of the required superheat versus channel width revealed that each fluid required greater superheats for decreasing channel widths. Furthermore, each fluid had a different range of superheats required to destabilize the meniscus with n-pentane being the lowest and iso-octane the largest.

1. Introduction

Phase change heat transfer has been applied to a wide array thermal management problems spanning power plants, computers and lasers. In these applications, an evaporating meniscus could be used to enhance heat transfer. Under certain conditions, the equilibrium of the evaporating meniscus may be disturbed, leading to the rupture or collapse of the thin film upon the solid wall. The meniscus stability is therefore important for the successful operation of these devices. The stability of an evaporating meniscus is a complicated topic as it involves several complex phenomena together: evaporation, long-range molecular and viscous forces, surface tension, vapor recoil, and thermocapillarity. The principal mechanisms responsible for the meniscus instability were discussed in the first part of this two part study along with a review of previous theoretical works.

These theoretical works have successfully demonstrated that the major trends of thin film instability can be predicted qualitatively. However, the need for experimental work has been a short coming as noted in Oron, Davis and Bankoff's [1] explicit call for more experimental thin-film works. Since their call for experimental studies, more experimental works have been published in the general area of thin films [2], with limited number pertaining to niche area of evaporating meniscus stability, for example [3,4].

Amongst the first to experimentally observe meniscus instability was Preiss and Wayner [5], in their experimental studies of evaporating menisci. This experimental study was principally focused on changes in curvature of the meniscus as evaporation rates were increased. In their pursuit of greater changes in meniscus geometry, they briefly reported the observation of meniscus instability. This finding of their study also included notes as to sputtering prior to the onset of meniscus instability. These observations would in turn inspire a series of experimental works focused on the instability itself.

This work was followed up by Pratt, Brown and Hallinan [3] with a pair of experimental studies on evaporating meniscus instability. Their work saw the development of two different experiments with the most fundamental being a heated cylindrical capillary tube within an atmospherically controlled chamber. Using high-speed photography, they were able to observe changes in the contact line region around the time of destabilization. Additionally, the experiments collected capillary wall temperature measurements

* Corresponding author.
E-mail address: john.polansky@carleton.ca (J. Polansky).

http://dx.doi.org/10.1016/j.ijthermalsci.2016.02.018
1290-0729/

Nomenclature

Latin

a	Clapeyron coefficient [kg/m^2 s K]
C	Accommodation coefficient [-]
f	Frequency [Hz]
g	Gravitational acceleration [m/s^2]
h	Average meniscus height [m]
h_{fg}	Latent heat [J/kg]
j	Mass flux [kg/m^2 s]
M	Molar mass [kg/kmol]
P_v	Vapor pressure [Pa]
R	Universal gas constant [J/mol K]
t	Time [s]
T	Temperature [K]
u	Average velocity [m/s]
W	Channel width [m]

Greek

ΔT	Superheat [K]
μ	Dynamic viscosity [Pa s]
ρ	Density [kg/m^3]
σ	Surface tension [N/m]

Subscripts

amb	Ambient
exp	Experimental data
l	Liquid
v	Vapor
w	Wall

above and below the meniscus. These temperature measurements were used to formulate a simplified criterion from which to infer the potential for meniscus instability. The stability criterion was developed upon the Cartesian stability model framework of Burelbach, Bankoff and Davis [6], and demonstrated a correlation between their experimental data and analytical model.

The experimental study of meniscus stability was furthered in the work of Buffone, Sefiane and Christy [7], in which they focused on the hydrodynamics and stability of a meniscus subject to a temperature gradient. Using both high speed and infrared cameras they were able to investigate the interface dynamics and changes in the contact angle. The addition of micro PIV, allowed for the measurement of the vorticity in the corner region of the meniscus. Upon heating, the meniscus demonstrated a change in bulk flow vorticity direction in addition to changes in the contact angle and meniscus height. This work was continued by Buffone, Sefiane and Easson [8] with a closer look at the Marangoni-driven meniscus instability. Their linear stability model suggested the instability was attributed to a self-induced regional temperature gradient in the thin-film region.

Plawsky et al. [9] investigated the thin-film region within the confines of a constrained vapor bubble. Their work was able to investigate the film thickness and local curvature using interferometry. From their experiments the film was destabilized with the application of strategically placed heaters and coolers. The destabilized film displayed some degree of oscillation which led to temporal changes in local curvature and thickness. This work was then expanded upon by Panchamgam et al. [10], from which they used the experimental data to seed their numerical model. When the steady state experimental data were used in the model, the interface was noted to have a local cooling zone and a wall slip condition.

Harmand et al. [4] experimentally investigated the stability of a meniscus in a narrow capillary channel. The experiments used a Tantalum coated micro-channel in an ambient atmospheric environment with ethanol, acetone, FC-72 and water as the working fluids. The meniscus was fed using a programmable pump and observed using both high-speed and infrared cameras. The unheated stable menisci were observed to have unique and complex shapes in the long axis direction of the channel. These complex interface shapes may be attributed to the end effects of the channel. The thermal imaging of the capillary wall demonstrated a non-linear temperature distribution in the region of the meniscus. The meniscus was destabilized with the nature of the instability having large scale motions over an extended period of time.

The theoretical study of evaporating meniscus instability presented in Part I of this two part work, looked at the potential for instability using a linear stability analysis. Given the complexities surrounding the experimental study of evaporating meniscus instability, model verification is challenging. The linear stability model identified the evaporating thin-film region as the likely origin of instability. However, a targeted experimental investigation of this region is currently beyond direct experimental observation, making verification of the model's prediction unfeasible. The results of the linear stability model are dependent on the perturbation wavenumber, which cannot be readily measured through experimentation. However, there are some interesting comparisons still possible as will be addressed later.

The main objective of the present work is to experimentally study the stability of evaporating meniscus. For this purpose, an experimental setup is developed using large aspect-ratio channels to minimize the end effects. The experiments are intended to identify meniscus instability in a range of channels (0.3–1 mm) and for three fluids (n-pentane, iso-octane and acetone). All the experiments were carried out in a sealed chamber saturated with the working fluid. At the onset of instability, the meniscus height is collected along with high-speed video to capture the nature of the instability. The measured meniscus height is then used to calculate the applied superheat by using a mathematical model. The results of the work are then presented with a thorough disclosure of the nature of the instability and a discussion on the relation between channel width and the required superheat to achieve instability.

2. Experimental setup and procedure

The experimental setup consists of a vacuum chamber situated atop a granite table resting on air bags and rubber matting as illustrated in Fig. 1. The air bags and rubber matting serve to minimize mechanical perturbations from the surrounding environment. The vacuum chamber allows for the evacuation of air and recharging with a single species to maintain a working fluid saturated test environment. Furthermore, the vacuum chamber provides sufficient volume to approximate the test environment as uniform.

The chamber was instrumented with T-type thermocouples (Omega 5SRTC-GG-T-30-36) of ±0.5 K accuracy and a pressure transducer (Omega PX429-015A5V) of accuracy of ±81 Pa. A thermopile array (Melexis 90620) was used to obtain infrared images of the test section. This array has an equivalent temperature detection of 0.08 K and a central pixel accuracy of ±1 K ($\pm 0.015\ |T_{target} - T_{amb}|$).