International Journal of Heat and Mass Transfer 54 (2011) 5612–5622

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Bubble nucleation, growth and surface temperature oscillations on a rapidly heated microscale surface immersed in a bulk subcooled but locally superheated liquid under partial vacuum

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ARTICLE INFO

Article history:
Received 10 May 2011
Received in revised form 30 June 2011
Accepted 30 June 2011
Available online 27 August 2011

Keywords:
Boiling
Superheated liquid
Homogeneous nucleation
Bubble nucleation
Surface tension
Bubble growth
Condensation
Temperature oscillations

ABSTRACT

The effect of ambient pressures below atmospheric, liquid subcooling and heating rate on bubble dynamics associated with rapid evaporation in highly superheated water is investigated. Platinum films of various aspect ratios are electrically heated under partial vacuum and the average metal film temperature monitored during a power pulse of duration of several tens of microseconds.

At high liquid subcooling, the surface temperature of the pulse-heated thin platinum strips is shown to oscillate with a frequency on the order of 0.5 MHz. The oscillation frequency increases with ambient pressure in the range 0.02 MPa and 0.101 MPa, and decreases with increasing ambient temperature at a fixed pressure. An unusual dynamic instability is observed in which the surface temperature is constant before relaxing into oscillations, and the delay to oscillations increases with decreasing pressure.

High speed imaging shows that the bubble growth phase of the oscillation is associated with surface heating and the collapse phase with surface cooling in the cyclic temperature history. These effects are explained by a bubble growth theory that includes a heat loss mechanism to the surrounding liquid. The nucleation temperature is unaffected by pressure in the sub-atmospheric range examined and it approaches the theoretical superheat limit for water at a heating rate of about 10^9 °C/s.

1. Introduction

Bubble nucleation and growth on microscale surfaces[1] immersed in sub-cooled liquids is an important process in applications that use bubble formation as a means to push fluid through microscale structures, as in thermal ink jet printing [2,3] and bubble pump designs [4–6]. Many parameters influence the phase change dynamics on microscale surfaces including gravity, liquid subcooling, and heater size [1,7,8] and pressure. Under some conditions the surface temperature can oscillate during the phase change process. Observed in the post-nucleation regime, oscillations have been noted for 65 μm square thin metal films immersed in water and aqueous methanol mixtures [9,10], 100 μm diameter by 4 cm long platinum wires in organic fluids [11] and for sub-microscale surfaces [12] under atmospheric pressure conditions. The existence of oscillations may signal an erratic bubble dynamic that influences the quality of the droplet ejection process and is therefore important to understand.

With reference to Fig. 1, five periods characterize the overall processes leading up to surface temperature oscillations for a microscale surface with a sustained constant heat input: an initial surface heating profile (1) that consists of a somewhat exponential form associated with liquid heating; a transition period (2) marked by an inflection point in the evolution of average surface temperature that signifies the state where a bubble is nucleated; a period similar to the first (3) but with an initially higher heating rate because heat transfer is now across a vapor layer (with lower thermal conductivity compared to the liquid) because the nucleated bubble expands laterally over the surface; and remaining periods where the surface temperature is constant (4) followed by an oscillatory period (5) that can sustain itself indefinitely for a constant heat input.

The present investigation is undertaken to further examine the surface temperature oscillation phenomenon and conditions that affect it. In particular, the influence of surface heating rate, ambient pressures below atmospheric, and bulk liquid subcooling are considered for heating times on the order of several tens of microseconds. By imposing sub-atmospheric pressure conditions the

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[1] A microscale surface is one for which the characteristic length of the heater, L, is much smaller than the Taylor wavelength [1] $L_{Tay} = \sqrt{\frac{\sigma}{g(\rho_L-\rho_g)}}$. For water at 403 K (the reference temperature at which properties in Table 1 are evaluated in the present study), $L_{Tay} \approx 2$ mm, though heaters with much smaller L (order of less than 100 μm) are used in this study.

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doi:10.1016/j.ijheatmasstransfer.2011.07.006

Nomenclature

AR	aspect ratio of heater (length divided by width)
C_p	Pt film specific heat (J kg^{-1} K^{-1})
g	acceleration due to gravity (m/s^2)
k_L	liquid thermal conductivity (W m^{-1} °C $^{-1}$)
k_s	solid thermal conductivity (W m^{-1} °C $^{-1}$)
L	length of heater (m)
N_s	number density of molecules at the surface (molecules/m^2)
N_o	number density of molecules in the bulk (molecules/m^2)
p_{in}	input power (W)
p_o	input power (W) for square pulse
P_o	ambient pressure
P_{sat}	pressure inside the bubble
R_c	critical bubble radius
R	bubble radius
R_1	fixed wheatstone bridge resistor (Ω)
R_2	fixed wheatstone bridge resistor (Ω)
R_3	adjustable resistor (Ω)
R_H	heater resistance (Ω)
R_L	lead resistance due to electrical connections (Ω)
R_T	$R_L + R_H$ (Ω)
R_∞	heater resistance at T_∞ = 22 °C
S	conduction shape factor (m)
t	time (s)
t_b	bubble growth time
t_w	waiting time
t_L	time for a bubble to reach size R_{ca} (s)
T	Platinum temperature (°C)
T_∞	ambient fluid temperature (°C)
T_{nuc}	bubble nucleation temperature (°C)
T_w	surface temperature (°C)
V_{in}	input voltage to bridge (V)
V_o	voltage amplitude for pulse input (V)
$\underline{V}_{out}$	bridge output voltage (V)

Greek letters

α	thermal diffusivity (m^2 s^{-1})
δ	separation of the equimolar surface from the surface of tension (m)
θ	contact angle
γ	voltage ramp rate (V/s)
ρ_L	density liquid (kg m^{-3})
ρ_g	density gas (kg m^{-3})
ρ_s	density of metal film (kg m^{-3})
σ	surface tension
τ	$\equiv t_b/t_w$
υ	volume of Pt film (m^3)

nucleation temperature will be constant. In saturated or superheated liquids, bubbles should always grow and not collapse and temperature oscillations should not occur. Thin metal films of high aspect ratio (AR) are employed to promote uniform surface temperatures during power pulses so that bulk subcooling will provide the primary mechanism for the collapse process that leads to surface quenching and an oscillating temperature history.

Water is selected as the working fluid because of the extensive property database available for it and familiarity with related experiments of rapid evaporation at the superheat limit [9,10,13–16]. Since surface temperature oscillations are speculated to track with bubble growth and collapse cycles as suggested by the schematics of Fig 1b and c, some visualizations of bubble morphology are also included using a laser flash method described previously [13]. For these visualizations, ethanol proved to have a more repeatable bubble morphology for the long pulse times investigated compared to water so some results on bubble dynamics are shown for ethanol and correlated to the temperature cycle.

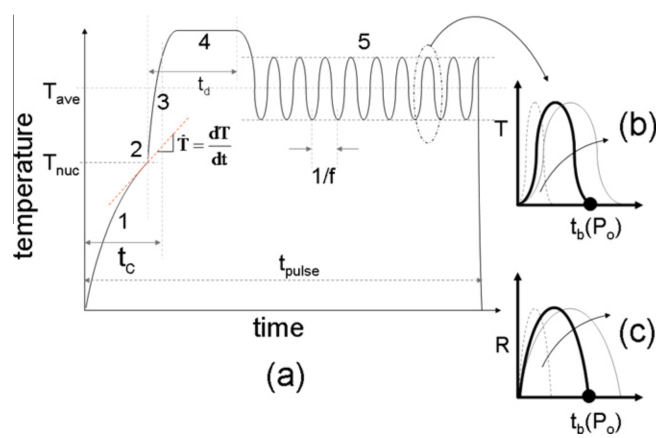

Fig. 1. (a) Illustration of temperature history for a pulse-heated microheater showing the stages prior to temperature oscillations. (b) Representation of one cycle of a temperature oscillation. (c) Suggested correspondence of one bubble growth and collapse cycle with a temperature cycle. Arrows in (b) and (c) show decreasing P_o or increasing T_∞.

2. Experiment

The heaters employed in the present investigation are layered structures consisting of a 300 µm thick Si wafer substrate, a 200 nm thick SiO_2 insulating layer, a 30-nm-thick titanium adhesion layer and a 200 nm thick Pt film on which the boiling process occurred. Fig. 2 is a cross-sectional schematic of the heater structure. Experiments were carried on platinum (Pt) films fabricated into several different ARs to facilitate measurements of the inflection point, delay time and oscillation frequency and photographing bubble shapes by high speed imaging. No single AR could allow for all such information.

Three ARs were examined. A 3 µm × 200 µm (AR = 67) Pt film was used for measurements of T_{nuc} because temperature is uniform along the length of such films. This device is essentially the same as used in a previous study [14]. Fig. 3 shows a photomicrograph of a representative heater. High AR films are not suitable for temperature oscillation studies because different boiling modes can co-exist over long surfaces, as shown in some visualizations of explosive bubble growth on 1.91 cm by 3.81 cm gold films in R-113 (CCl_2FCClF_2) [17]. Reducing the heater area appears to make the bubble morphology slightly more uniform by confining the bubble to a smaller footprint, which also facilitates photographing the bubble during its growth/collapse cycle. A 4 µm × 40 µm (AR = 10) Pt film and a 7 µm × 46 µm (AR = 6.6) Pt film were used for recording surface temperature oscillations and for photographing bubbles, respectively. Voltage pulses ranged from 30 µs to 90 µs for the detailed observations reported here.

The metal films were heated by passing a current through them. The films formed one leg of a Wheatstone bridge circuit as illustrated in Fig. 4. The arrangement is similar to that described previously [14]. The bridge consists of the Pt film heater (resistance