Available online at www.sciencedirect.com
SCIENCE DIRECT®
International Journal of Heat and Mass Transfer 49 (2006) 4399–4406
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Subcooled boiling incipience on a highly smooth microheater ☆

Tailian Chen [a,*], James F. Klausner [b], Suresh V. Garimella [a], Jacob N. Chung [b]

[a] School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907-2088, USA
[b] Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32611-6300, USA

Received 4 November 2005; received in revised form 13 May 2006
Available online 3 July 2006

Abstract

Subcooled boiling incipience on a highly smooth microscale heater (270 μm × 270 μm) submerged in FC-72 liquid is investigated. Using high-speed imaging and a transient heat flux measurement technique, the mechanics of homogeneous nucleation on the heater are elucidated. Bubble incipience on the microheater was observed to be an explosive process. It is found that the superheat limit of boiling liquid is required for bubble incipience. It is concluded that boiling incipience on the microheater is a homogeneous liquid–vapor phase change process. This is in contrast to recent observations of low-superheat heterogeneous nucleation on metallic surfaces of rms roughness ranging from 4 to 28 nm [T.G. Theofanous, J.P. Tu, A.T. Dinh, T.N. Dinh, The boiling crisis phenomenon part I: nucleation and nucleate boiling heat transfer, Exp. Therm. Fluid Sci. 26 (2002) 775–792; Y. Qi, J.F. Klausner, Comparison of gas nucleation and pool boiling site densities, J. Heat Transfer 128 (2005) 13–20; Y. Qi, J.F. Klausner, Heterogeneous nucleation with artificial cavities, J. Heat Transfer 127 (2005) 1189–1196]. Following the explosive bubble incipience, the boiling process on the microheater can be maintained at much lower superheats. This is mainly due to the necking during bubble departure that leaves an embryo from which the next-generation bubbles grow.

Keywords: Bubble incipience; Microheater; Homogeneous nucleation

1. Introduction

The commercial success of bubble jet printers [4], among other microscale applications, has inspired many researchers to study the bubble formation mechanism in these microsystems. For such applications, the bubble produced from a microheater should be designed to function in a stable and controllable manner. Therefore, it is important to understand the bubble formation mechanisms on microheaters so that they may be optimally designed and operated. A number of previous studies have investigated the bubble formation mechanism. Iida et al. [5] used a 0.1 mm × 0.25 mm × 0.25 μm platinum film heater subjected to rapid heating (maximum 93×10^6 K/s). The heater temperature was correlated to its electrical resistance. The temperature measured at bubble nucleation suggested the occurrence of homogeneous bubble nucleation in their experiment. Lin et al. [6] used a 50 μm × 2 μm × 0.53 μm polysilicon resistance heater to produce microbubbles in Fluorinert liquids. Using a computational model and experimental measurements, they concluded that homogeneous nucleation occurs on the microline heater.

Avedisian et al. [7] performed experiments on a heater used in commercial thermal inkjet printers and comprising a mixture of tantalum and aluminum (64.5 μm × 64.5 μm × 0.2 μm) by applying voltage pulses of short duration. At extremely high heating rates (2.5×10^8 K/s), homogeneous nucleation at the heater surface was suggested as the mechanism for bubble formation, with the nucleation temperature increasing as the heating rate was increased. Zhao et al. [8] used a similar thin-film microheater, 100 μm × 110 μm in size, to investigate the vapor

☆ The experiments for this work were performed while the lead author was a post-doctoral research associate in the Department of Mechanical and Aerospace Engineering at the University of Florida.

* Corresponding author. Tel.: +1 765 494 6280; fax: +1 765 494 0539.
E-mail address: chent@ecn.purdue.edu (T. Chen).

0017-9310/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2006.05.008

Nomenclature

ΔT_s	superheat limit (K)	R	gas constant of FC-72 vapor
$\overline{M}$	molecular weight of FC-72 (g/mol)	T_l	liquid temperature (°C)
J	nucleation rate ($m^{-3}\,s^{-1}$)	T_e	threshold temperature (°C)
J_s	threshold nucleation rate ($m^{-3}\,s^{-1}$)		
P_l	bulk liquid pressure (Pa)	*Greek symbols*	
P_{sat}	saturation pressure of bulk liquid (Pa)	ρ_l	liquid density (kg/m^3)
r_s	threshold vapor embryo radius (m)	σ	surface tension (N/m)

explosion phenomenon. They placed the microheater on the underside of a layer of water and the surface temperature of the heater was rapidly raised (about 13×10^6 K/s) by electrical pulses of short duration. By measuring the acoustic emissions using a pressure transducer from an expanding volume of a vapor bubble, the dynamic growth of the vapor microlayer was reconstructed. A maximum pressure inside the vapor volume of 7 bar was calculated from the measured acoustic pressure.

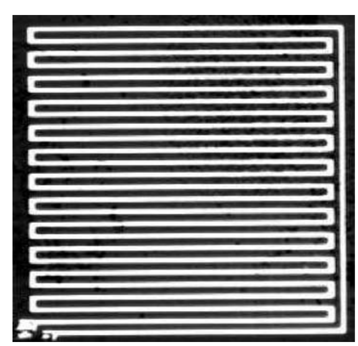
The heating rates in [5–8] were extremely high, and are believed to be important for the homogeneous nucleation process. In contrast, Theofanous et al. [1] observed low-superheat heterogeneous nucleation on a smooth titanium heater with 4 nm rms roughness submerged in water. Qi and Klausner [2,3] also observed low-superheat heterogeneous nucleation more recently on smooth brass (18 nm rms roughness) and stainless steel (28 nm rms roughness) surfaces submerged in ethanol. In contrast, Qi and Klausner [3] observed high-superheat incipience (60 K) on a nano-smooth silicon surface submerged in ethanol. A clear distinction between the required incipience superheat for metallic and non-metallic nano-smooth surfaces was reported. Recently, Balss et al. [9] investigated the effect of surface hydrophobicity on bubble incipience using a pulse-heated microheater and a novel laser strobe microscopy technique. Imaging rates of over 10 million frames/s were achieved. It was found that bubble nucleation requires a higher superheat and occurs at an earlier time for hydrophilic surfaces compared with those that are hydrophobic.

In the present work, bubble incipience on a smooth microscale heater (approximately 10 nm rms roughness) is further investigated. The objective of the work is to establish that bubble incipience under these conditions is indeed a homogeneous process and to elucidate the mechanics of the process. The present experiments have been performed on a resistance heater of size 270 μm × 270 μm, coated with silicon dioxide. A feedback circuit was employed to supply electrical current to the microheater in such a way that the average heater temperature was maintained constant. It should be noted that a constant temperature condition is useful for identifying the nature of boiling incipience because the degree of superheat is a controlling parameter. The incipience process was visualized from the side and the bottom of the semi-transparent heater, and the transient heat flux of the heater was simultaneously recorded. The time-resolved heat flux was obtained at a speed of over 4000 readings per second, which was greater than twice the imaging frame rate of 2000 frames/s. The flow visualization in side and bottom views and the simultaneous heat flux measurement provide sufficient information to allow a clear identification of the highly transient bubble incipience process.

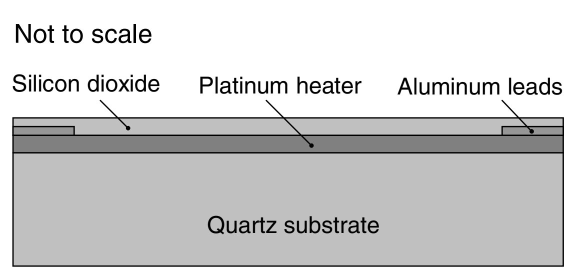
2. Experimental system

2.1. Microheater

The microheater used for this study is one of 96 individual microheaters laid out in a planar array. Only one heater is active during this investigation. As shown in Fig. 1, the microheater is a serpentine platinum resistance element fabricated on quartz substrate using standard microelec-



(a)



(b)

Fig. 1. (a) Serpentine filament microheater (270 μm × 270 μm) and (b) a schematic diagram of the fabrication arrangement on quartz substrate.