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Microbubble return phenomena during subcooled boiling on small wires

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Abstract

An experimental investigation was conducted to explore the characteristics of subcooled boiling on microwires of 25 and 100 μm diameter. Microbubbles were observed to return to the wire surface after detachment, with two types of bubble return identified, i.e., isolated bubble return, and bubble return with liquid–vapor trailing jets. The former mode of bubble return occurred when isolated small bubbles (of less than 50 μm diameter) were generated from bubble collapse, while in the latter mode, a larger bubble (of up to 200 μm in diameter) at the end of a liquid–vapor jet issuing from the wire departed and then returned to the wire surface. The numerical simulations conducted show that the isolated bubble return is caused by large temperature gradients in the vicinity of the wire which lead to Marangoni flows and result in a strong thrust force driving the bubble back to the wire. Existence of large temperature gradients close to the microwire surface was demonstrated by experimental measurements, confirming numerical predictions. The numerical model accounts for the influence of noncondensable gas on the vapor saturation temperature as well as the interfacial condensation coefficient. The presence of noncondensable gas facilitates bubble return.

Keywords: Bubble dynamics; Bubble departure; Bubble return; Subcooled boiling; Microbubble; Microwire; Noncondensable gas

1. Introduction

The motion of bubbles near heated surfaces has significant consequences on boiling heat transfer and boiling regime transitions. Bubble departure, bubble coalescence, bubble motion along a heated surface, and the interactions among bubbles have been widely investigated [1–6]. With boiling finding newer applications in areas such as electronics cooling, bioengineering and spacecraft thermal control, there is need for a better understanding of bubble dynamics under the special conditions of these applications.

Detailed studies of bubble dynamics were undertaken by a number of researchers. Kowalewski and Pakleza [7] observed different kinds of bubble shapes at the moment of bubble departure. Depending on the heater size, surface superheat and the degree of liquid subcooling, the bubble shapes varied from spherical to strongly deformed columns of nearly cylindrical shape. For bubbles that were larger than 3 mm in diameter, the bottom surface was seen to be concave, with a conical hollow shape filling as much as half of the bubble. Shoji and Takagi [8] conducted a series of boiling experiments on artificially created nucleation sites with different geometries. Analysis of the time history of the wall temperature suggested the existence of low-dimensional chaos. Marek and Straub [20] studied the bubble behavior in subcooled pool boiling. A bubble in subcooled liquid could grow or shrink according to the heat and mass transfer at its top, and even a steady-state mass flow through the bubble could be maintained.

Greater diversity of bubble motion was visually observed under microgravity conditions. Small bubbles were observed to move towards larger bubbles, with the heat flux being increased by as much as 30% compared to similar experiments conducted under terrestrial conditions [9–11]. Straub [12] investigated boiling on a

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Nomenclature

D_b	vapor bubble diameter (m)
D_w	heater wire diameter (m)
h_{fg}	latent heat of evaporation (J/kg)
h_i	equivalent interfacial heat transfer coefficient (W/m^2 K)
h_c	condensation coefficient (W/m^2 K)
h_e	evaporation coefficient (W/m^2 K)
$\overline{M}$	molecular weight (kg/mol)
$\overline{R}$	universal gas constant (J/mol K)
p_l	liquid pressure (N/m^2)
p_v	vapor pressure (N/m^2)
q''_w	wire surface heat flux (W/m^2)
q''_i	interfacial heat flux (W/m^2)
R	bubble radius (m)
T_b	liquid bulk temperature (K)
T_w	average wire temperature (K)
T_i	liquid temperature at interface (K)
T_s	saturation temperature (K)
T_v	vapor temperature (K)
Greek symbols	
β	liquid thermal expansivity (1/K)
δ	liquid layer thickness (m)
θ	polar angle
ν	kinematic viscosity (m^2/s)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Ns/m^2)
ρ_l	liquid density (kg/m^3)
ρ_v	vapor density (kg/m^3)
σ	surface tension coefficient (N/m)
$\hat{\sigma}$	accommodation coefficient
Subscripts	
b	liquid bulk; bubble
c	condensation
e	evaporation
l	liquid
i	interface
s	saturated
v	vapor

0.26-mm-diameter spherical heater at a subcooling of 2–3 K. They observed that a bubble could stay suspended and immobile in the liquid a small distance away from the heated surface and then return to the surface, from which it departed again. Bubble coalescence was concluded to be one of the important factors for overall heat transfer and the evaporation of the micro liquid wedge between the bubble and the hot surface and the interfacial Marangoni flow were suggested as the dominant mechanisms for bubble motion under microgravity conditions [11,12].

For microbubbles, interfacial effects can generally be comparable to, or much greater than, gravitational effects. For example, a 100-μm-diameter water bubble has a buoyancy-to-surface tension ratio of order 10^{-4}. Under the strong influence of interfacial effects, microbubbles have been seen to exhibit interesting dynamic behaviors [15,16].

The present work investigates microbubble dynamics through boiling experiments conducted on very thin wires under terrestrial gravity conditions. Particular attention is paid to two types of bubble return phenomena. Visual observation of microbubbles produced in the experiments is complemented by theoretical analysis.

2. Experimental setup

The experimental apparatus used in the present study consisted of a test section, power supply and high-speed photography system, as schematically shown in Fig. 1(a). The test section is a transparent glass vessel with dimensions 23 cm × 23 cm × 23 cm in which a 49 mm long platinum wire of diameter 25 or 100 μm was installed in a

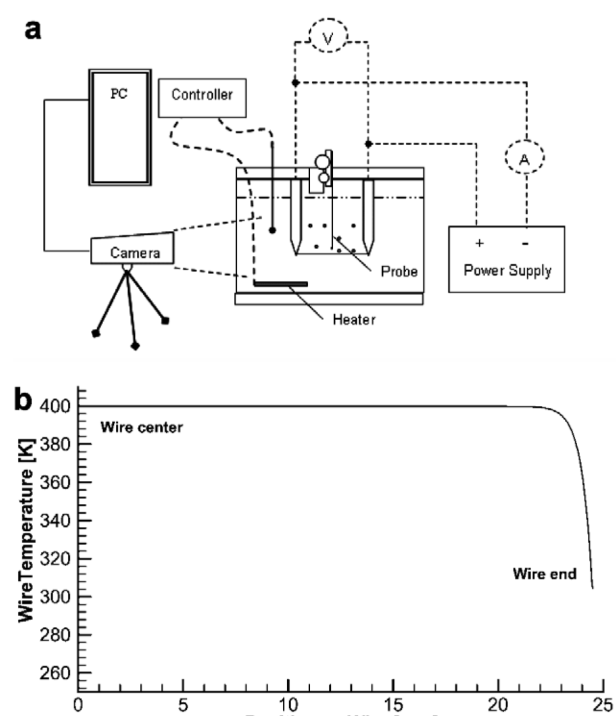

Fig. 1. (a) Experimental setup and (b) calculated temperature profile along the wire ($D_w = 100$ μm).