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Investigations on the effects of heater surface characteristics on the bubble waiting period during nucleate boiling at low subcooling

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ABSTRACT

In nucleate boiling the 'bubble waiting period', that is, the time duration between the departure of a grown bubble and the start of the formation of a new bubble from a cavity, plays a crucial role for the total heat transfer. Experiments were performed to study the influence of the heater surface characteristics on this parameter. A femtosecond pulsed laser was used to produce nano- and micro-patterned surfaces with roughness in the range of micrometers on stainless steel heater surfaces. Boiling experiments were conducted on a vertically oriented heater at atmospheric pressure and with degassed deionized water. Bubble generation, departure, sliding, detachment and inception of the next bubble have been recorded by high-resolution optical shadowgraphy. Bubble waiting periods were found to be longer for low-wettability smooth and rough surfaces. High-wettability rough surfaces showed a shorter bubble waiting period. The shortest (approximately 3 ms) and the longest (approximately 30 ms) bubble waiting periods were found for well-wetting surfaces with Sq = 0.18 µm and for low-wetting surfaces with 0.12 µm, respectively. These corresponding roughness heights are denoted as 'optimal roughness heights'.

1. Introduction

Nucleate boiling is an efficient mode of heat transfer which has numerous applications in heat transfer process engineering and has been widely investigated in the past. Further improvement of the boiling heat transfer in practical applications requires a more in-depth understanding of the fundamental physics of nucleate boiling. The visual perception of nucleate boiling is that of the so-called bubble ebullition cycle (Fig. 1). At a nucleation site, which is often assumed to be a small cavity with a minute amount of entrapped gas, a steam bubble starts growing once the critical thermodynamic conditions for evaporation are reached. At a certain point the balance of forces on the bubble leads to a departure from its position. The time t_d between the inception and departure of a growing steam bubble is referred to as the departure period. The time period t_w between the departure and the formation of a new bubble nucleus at the same site is referred to as bubble waiting period [1–3]. The bubble frequency $f = (t_w + t_d)^{-1}$ along with the nucleation site density N_n, the bubble departure diameter D_d and the latent heat of evaporation h_{lv} are the key parameters which make up the total evaporative heat flux

$$\dot{q}_{ev} = \frac{\pi}{6} D_d^3 \rho_v h_{lv} f N_n \quad (1)$$

in nucleate boiling. Different groups found that the bubble waiting period is around 7.5 times [4,5] and others, that it is more than 2 times [6,7] longer than the departure period. Basu et al. [3] proposed a correlation for the waiting as a function of wall superheat ΔT_w in the form

$$t_w = 139.1(\Delta T_w^{-4.1}) \quad (2)$$

The authors did not find significant dependency between subcooling and the bubble waiting period. Whereas Philips et al. [8] found that along with the wall superheat, liquid subcooling and thermal diffusivity had to be taken into account to predict the bubble waiting period. Other groups brought even more parameters into the discussion, e.g. bulk liquid velocity, heater surface characteristics, heat flux and others [9,10]. Maity [11] reported that the bulk liquid velocity increase causes an increase in the bubble waiting time. In the next sections we will briefly summarize the findings from previous studies with a particular focus on the bubble waiting period and discuss the role of surface characteristics in detail from our point of view.

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Nomenclature

A	area (m^2)
c_p, Cp	specific heat capacity (J kg^{-1} K^{-1}), heat capacity (J kg^{-1})
d_w	bubble base diameter (m)
D	diameter (m)
f	bubble frequency (s^{-1})
g	gravitational acceleration (= 9.81 m s^{-2})
h	Heat transfer coefficient (W m^{-2} K)
h_{lv}	latent heat of evaporation (J kg^{-1})
k, K	thermal conductivity (W m^{-1} K^{-1}), constant (dimensionless)
X_{sm}	the mean width of surface profile dips (m)
N_n	nucleation site density (m^{-2})
Pr	Prandtl number (dimensionless)
$\dot{q}$	heat flux (W m^{-2})
$\dot{Q}$	rate of heat flow (W)
Re	Reynolds number (dimensionless)
S, Sq	suppression factor, root mean square roughness height of the surface (μm)
t	time (s)
T	temperature (K)
V	volume (m^3)

Greek symbols

δ	thermal liquid layer thickness (m)
ΔP	difference in vapor pressure corresponding to ΔT
ΔT_{sub}	subcooling temperature (K)
ΔT_w	wall superheat (K)
θ	liquid contact angle (°)
σ	surface tension (N m^{-1})
ρ	density (kg m^{-3})

Subscripts

act	activation
adv	advancing
conv	convective
d	departure
eq	equivalent
ev	evaporation
hys	hysteresis
l	liquid
ml	microlayer
nb	nucleate boiling
rec	receding
refill	refilling
sat	saturation
tp	two-phase
v	vapor
w	heater wall, waiting period
x	normal to the heater wall
y	upward direction
∞	bulk

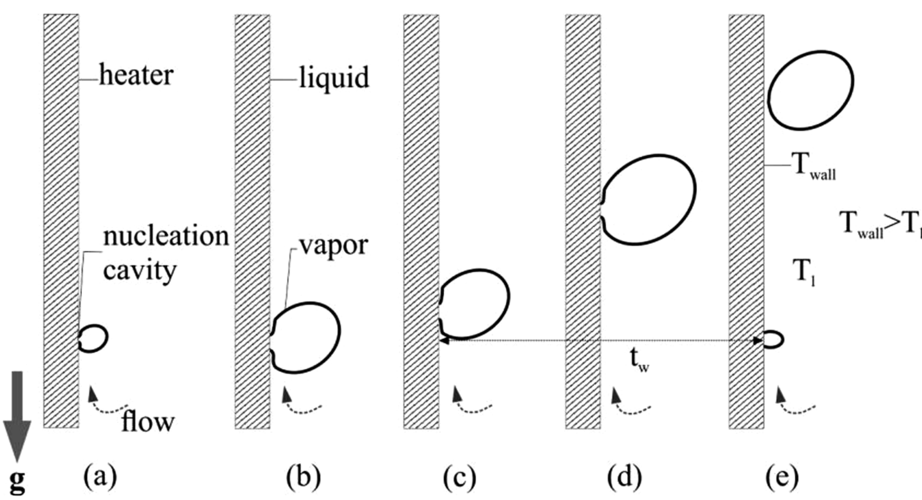

Fig. 1. Typical behavior of a nucleating steam bubble on a vertical heater wall. Left: (a) bubble nucleation, (b) bubble growth at the nucleation cavity, (c) having reached a critical size the bubble departs from its originating cavity, (d) the bubble slides a certain distance along the heater surface, (e) the bubble detaches from the wall and a new bubble is generated. The bubble waiting period is from (c) to (e).

1.1. Momentum and heat transfer in the thermal liquid layer during the bubble waiting period

Hsu and Graham's [1] analysis indicates that the waiting period is dependent on the surface cavity size, the bulk temperature of the fluid and the thermal boundary layer thickness δ. Their observation confirmed that when the bubble leaves the cavity, the fluid volume around the cavity is replenished by cold liquid. Then the liquid layer at the departed bubble base area is heated and the thermal layer is re-established in the vicinity of the bubble nucleation site. The distortion of the thermal boundary layer during the bubble detachment was observed in different experiments [12–14]. Hsu and Graham also noted that the thermal layer recovery is dependent on the subcooling. Thus higher subcooling makes the waiting period quite longer than the bubble growth period. They assumed that fluid agitation is strong beyond the boundary layer and accurate prediction of waiting time is hence impossible unless this thermal layer is fully characterized. Fig. 2 shows the mechanistic concept of bubble instigation which is reproduced from Graham and Hendricks [15] and is based on the experimental findings of Hsu [16]. We see that temperatures of liquid layer and the thermal layer thickness (δ) increase with heater wall temperature (T_w) and they vary with time. According to Hsu [16], the nucleation proceeds only when the surrounding liquid is sufficiently warmer than the gas in the bubble. In another words, the bubble waiting period ends when the liquid temperature profile meets the critical bubble nucleation temperature. At this time, the thermal layer thickness also reaches a critical fraction of the bubble height (Fig. 2c). The heat transfer mechanisms from the heated wall to the bulk liquid through the thermal liquid layer influences the bubble inception. Amongst others, Ali and Judd [2] argued, that the growth of the thermal boundary layer and the subsequent bubble nucleation is governed by the combined effects of conductive and convective heat transfer to the liquid in the wake of rising bubbles.