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Single bubble dynamics during subcooled nucleate boiling on a vertical heater surface: An experimental analysis of the effects of surface characteristics

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ABSTRACT

In the present experimental study we investigated the effects of surface characteristics, such as wettability and roughness, on nucleate boiling in de-ionized water at a vertical heater. In the experiments, bubbles were generated from an artificial nucleation site on a stainless steel heater surface. High-resolution optical imaging has been used to capture the bubble life cycle, that is, departure, sliding, and lift-off. We found, that the lower wettability leads to larger departure diameter, longer sliding and larger lift-off diameter of bubbles. Also surface roughness effects have been analyzed and it was found that bubble departure and lift-off diameters are smaller and departure period is longer for a smooth surface. Bubble sliding velocity was found faster for a rough surface compared to a smooth surface. It was also found that the roughness is very influential to bubble growth and departure, which can be explained by considering its interaction with the microlayer underneath the bubble. An "optimal roughness", which accelerates the bubble growth, was found. The knowledge gained from this study shall be particularly useful to improve nucleate boiling models for numerical simulations.

1. Introduction

Nucleate boiling has attracted researchers for decades because of its wide range of technical heat transfer applications and hence a constant need for optimization. However, though nucleate boiling might seem to be a simple process at a first glance, it involves a considerable amount of multi-scale physics, which poses quite a challenge for numerical analysis. Hence, there are numerous investigations reported in literature, which were made to enhance our understanding of the phenomena associated with the nucleate boiling. One challenging aspect is the influence of the heated wall properties on bubble generation and departure. There the atomic structure of the solid (e.g. elemental composition, lattice structure and electronic properties), its nano-structure (e.g. nano-porosity, nano-layers) and microstructure (e.g. roughness) interplay with the heat transfer in a complex and yet not well known way. Empirical studies with advanced measurement techniques and sophisticated multi-scale numerical simulations are expected to help in the gradual disclosure of the physical principles.

In this paper we report on an experimental study, which was designed to investigate the influence of surface roughness and wettability on a single nucleated bubble on a vertical heater surface, something that to our knowledge is yet missing in literature. In order to stay close to practice we used a stainless-steel heater plate, which is common in many heat transfer applications. Before describing the study and its results, we will give a brief introduction to the current common knowledge and fundamentals of nucleate boiling and then summarize the most recent experimental findings in this field.

Fig. 1 shows a simple sketch of the general bubble life cycle at a vertical heater. The geometrical conventions in the following will be such, that x is the coordinate normal to the heater wall, y the coordinate in upward direction, D_y denotes the bubble width, that is, the diameter of its projection onto the heater wall, and D_x the bubble height normal to the heater wall. The gas-liquid interface approaches the heater wall with an 'advancing' contact angle, α (bottom) and 'receding' contact angle, β (top). The distance between the contact lines in vertical direction is referred to as base diameter, d_w. The '×' sign shown inside of the bubble is 'center of mass'. The bubble base diameter is an important parameter to calculate the forces, like surface tension, contact pressure and hydrodynamic pressure force. In consequence, the size of the bubble in

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Nomenclature

A	area (m^2)
C, *c*	constants
d_w	bubble base diameter (m)
D_{eq}	diameter (m)
D_x	bubble height (m)
D_y	bubble width (m)
g	gravity (m s^{-2}), growth
h_{lv}	vaporization heat (J kg^{-1})
Pr	Prandtl number
$\dot{q}$	heat flux (W m^{-2})
Q	heat (W)
R	radius (m)
Ra	roughness average (nm)
Rq	root mean square roughness (nm)
Rt	maximum height of roughness (μm)
t	time (s)
x	normal the heater wall
y	upward direction

Greek symbols

α	bubble advancing angle (°), thermal diffusivity of liquid (m^2 s^{-1})
β	bubble receding angle (°)
δ_m	microlayer thickness (m)
ΔT_{sub}	subcooling temperature (°K)
ΔT_w	wall superheat (°K)
θ	liquid contact angle (°)
ρ	density (kg m^{-3})

Subscripts

adv	advancing
b	base
cyc	cycle
eq	equivalent
ev	evaporation
g	growth
hys	hysteresis
l	liquid
i	initial
ml	microlayer
rec	receding
v	vapor

Superscript

0	initial

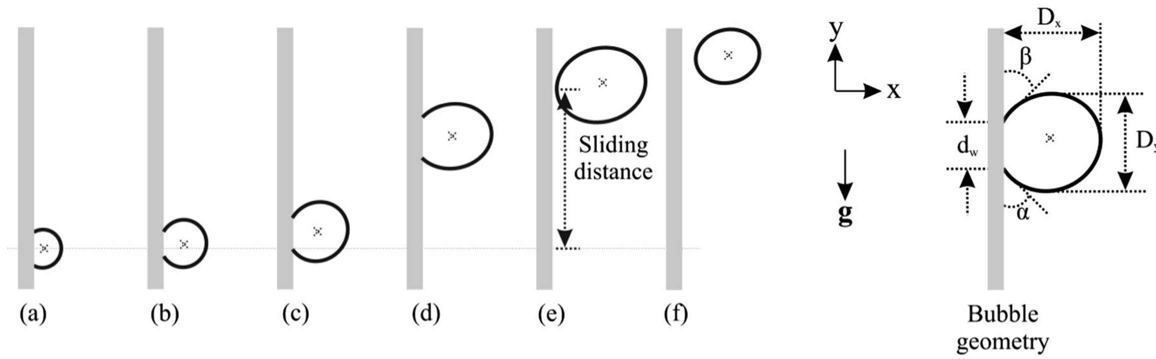

Fig. 1. Schematic diagram of general bubble life cycle (left): generation (a), growth (b), departure (c), sliding (d), lift-off (e), clear detachment (f) and bubble geometry (right).

its life cycle is quite dependent on bubble base diameter. The bubble's life cycle is also illustrated with the different sub-figures in Fig. 1. After its generation the bubble and its base expand while the bubble stays at its nucleation point. With the increase of bubble size the bubble tilts and hence its center of mass moves upward. The different forces namely growth force, buoyancy force, shear lift force, surface tension force, contact pressure force, etc. which are acting on a bubble and its foot, are well explained by several investigators [1,2]. These forces are acting in x- and y-directions of a bubble and the total sum of them changes with the bubble size and the base diameter. Due to certain force balance conditions, the bubble departs and slides upward along the wall. Fritz [3] correlated the bubble departure diameter by balancing buoyancy with surface tension force. Klausner et al. [1] improved this force balance relationship and stated that the point, at which the summation of forces along the flow direction is just greater than zero, is the bubble departure criterion. Thorncroft et al. [2] stated that pool boiling on a vertical surface is more complicated than horizontal pool boiling, because the bubbles grow at an angle with respect to the heater surface in response to the upward buoyancy force. Therefore, both the surface tension and growth force act normal and parallel directions to the wall. In this case, bubbles depart from the nucleation site by sliding, which is on the contrary to pool boiling on a horizontal heater. During sliding, the bubble base is still in contact with the heat transfer surface. Heat is transferred to the bubble through this contact area during sliding and hence bubble size still increases. The sliding in turn distorts the thermal boundary layer around the bubble. During sliding the bubble commonly grows and its base may shrink, expand or remain unchanged depending on the interaction of surface characteristics and the bubble base. However prior to bubble detachment from the heater surface, the bubble base shrinks and when it becomes zero the bubble leaves the heater surface. The bubble diameter at this condition is referred to as lift-off diameter. Generally the bubble lift-off diameter is larger than the bubble departure diameter for vertical pool and flow boiling whereas Ramanujpau et al.'s [4] experiment showed that bubble departure and lift-off diameters are the same in horizontal pool boiling. Various works focused on the thin liquid layer which forms beneath the bubbles to explain the bubble growth process. This layer, called microlayer,