International Journal of Thermal Sciences 97 (2015) 114–125

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Influence of surface wettability on bubble behavior and void evolution in subcooled flow boiling

Rouhollah Ahmadi [a, *], Tomio Okawa [b, c]

[a] School of New Technologies, Iran University of Science & Technology, Narmak, Tehran 1684613114, Islamic Republic of Iran
[b] Department of Mechanical Engineering, Osaka University, 2-1, Yamadaoka, Suita-shi, Osaka 565-0871, Japan
[c] Department of Mechanical Engineering and Intelligent Systems, The University of Electro-Communications, 1-5-1, Chofugaoka, Chofu-shi, Tokyo 182-8585, Japan

ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form
21 June 2015
Accepted 22 June 2015
Available online 17 July 2015

Keywords:
Subcooled flow boiling
Net vapor generation (NVG)
Onset of significant void (OSV)
Visual investigation
Surface wettability

ABSTRACT

Influence of heated surface wettability on bubble behavior and the mechanisms to cause net vapor generation (NVG) were explored experimentally in a vertical upward subcooled flow boiling. The cross-section of the heated channel was rectangular in shape and a part of one side of the flow channel was heated electrically using two cartridge heaters embedded in a copper block. Experiments were performed under various conditions of surface wettability and system pressure. On a hydrophilic heated surface, at boiling incipience all the bubbles departed from nucleation sites immediately after nucleation; and then, the bubbles were lifted off the heated surface at atmospheric pressure, whilst slid on the surface at elevated pressures. On the contrary, when the surface was hydrophobic, bubbles mostly stuck on the nucleation sites under the conditions close to boiling incipience at all the pressures tested in this work (100–400 kPa). It was hence confirmed that wettability of the heated surface has significant impact on the bubble behavior under low void fraction conditions. Using rather hydrophilic heated surface, two mechanisms causing a rapid increase in the net vapor generation rate were observed in two ranges of pressure. At atmospheric pressure, reattachment of the lift-off bubbles, and at moderate pressure, wake-effect of preceding sliding bubbles are triggering mechanisms of the significant increase of net vapor generation rate at the point of onset of significant void (OSV). An important result revealed in this work was that on a hydrophobic heated surface with high contact angle around 90°, bubble departure from all the nucleation sites which is a necessary condition to cause NVG, occurs in proximity to OSV. The bubble behavior after the departure was similar to those observed for the hydrophilic surface. The direct cause of OSV was hence not significantly different between the hydrophilic and hydrophobic heated surfaces, but the bubble departure from nucleation sites was a good indication of OSV when the heated surface was hydrophobic.

1. Introduction

In many models of subcooled flow boiling, the incipient point of net vapor generation (NVG) is defined as the position at which vapor bubbles depart from the nucleation sites and/or the heated surface [1]. The initial point of net vapor generation (NVG) has been studied extensively by Griffith et al. [2], Bowring [3] and Dix [4], Levy [5], Staub [6], Unal [7] and Kelly and Kazimi [8]. Various semiempirical correlations have been reported by these investigators. The development of these correlations was mainly based on a force balance on a departing bubble from the thermal layer adjacent to the heated surface with considering the temperature and velocity profiles in the channel. It is assumed that the bubble detachment is the result of the drag force overcoming the surface tension force acting on a bubble attached to the heated surface. In widely-accepted model by Saha and Zuber [9], it was supposed that both the hydrodynamic and heat-transfer mechanisms may apply, depending on thermal-hydraulic conditions.

In the net vapor generation models in subcooled flow boiling mentioned above, the modeling processes are based on the behavior of bubbles. Many experimental studies were hence carried out so far to observe bubble behavior in various configurations and different experimental conditions. It has been reported for water subcooled flow boiling that close to atmospheric pressure, bubbles

* Corresponding author. Tel.: +98 21 7322 5815; fax: +98 21 7724 0380
E-mail address: ahmadi@iust.ac.ir (R. Ahmadi).

http://dx.doi.org/10.1016/j.ijthermalsci.2015.06.012
1290-0729/

Nomenclature

G	mass flux (kg/m^{2}s)
Ja	Jakob number ($\rho_l c_{pl} \Delta T_w / \rho_v h_{fg}$)
N_b	the number of bubbles
N_{im}	the number of images
N_s	the number of nucleation sites
NVG	net vapor generation
ONB	onset of nucleate boiling
OSV	onset of significant void
P	pressure (Pa)
q_w	heat flux (W/m^2)
T	temperature (K)
V_0	volume of visualization section (m^3)
V_b	volume of bubble (m^3)
x_{eq}	thermal-equilibrium vapor quality
Greek symbols	
α	void fraction
ΔT_{sub}	liquid subcooling (K)
ΔT_w	wall superheated (K)
φ_1	contact angle before experiment (°)
φ_2	contact angle after experiment (°)
φ_m	mean contact angle
Subscripts	
b	bubble
w	wall

typically departed from nucleation sites to slide on the heated surface for a short distance; then, the bubbles tended to be lifted off the wall and collapsed in subcooled bulk liquid [10–12]. Whilst, in the experiments using FC-87 as a working fluid, bubbles departed from nucleation sites and slid on the surface for a long distance [13]. As for the influence of surface properties on the bubble dynamics and void fraction in subcooled flow boiling, little information is available. In the pool boiling experiments using a vertical heated surface, it was reported that bubbles were restricted to the wall to some extent when the heated surface was less wettable [14] and heat transfer was improved with an increase in the surface wettability [15]. A decrease in the contact angle usually decreases the population of active nucleation sites because of the reduction of the cavity radii of individual sites [16]. The distribution of cavities of different sizes and shapes strongly depends on the manufacturing processes and the procedure used to polish the surface. Basu et al. [17] showed the two necessary conditions for bubble nucleation: the corresponding cavity is available on the surface and the cavity is not flooded. They indicated that the flooding of cavities depends on the cavity shape and the surface wettability. For instance, as the contact angle approaches zero, all the cavities will be flooded and therefore the number of active nucleation sites diminishes with a decrease in the contact angle.

For subcooled flow boiling on a hydrophilic surface, the bubble behavior at boiling incipience was investigated and different mechanisms of void evolution at OSV were proposed by the same authors of this paper [18–20]. Under atmospheric pressure conditions, all the bubbles were propelled into the subcooled bulk liquid after nucleation and collapsed rapidly near their origin of nucleation [18]. In consequence, the bubble lifetime was short and the void fraction could not increase significantly just downstream of the point of the onset of nucleate boiling (ONB). It was found that further downstream of the point of ONB, some of the lift-off bubbles were reattached to the heated surface to slide on it for a long distance. This phenomenon contributed to the sharp increase of void fraction at the point of OSV [19]. Whilst, under moderate pressure conditions, it was observed that bubbles mostly slid on the heated surface at the incipient boiling point [18] and the significant increase of the void fraction at OSV was caused by the formation of large sliding bubbles that were produced in the wake region of the preceding sliding bubbles [20].

The mechanisms of OSV described above were derived based on the experiments using a rather hydrophilic heated surface. The present study therefore aims to understand the effect of surface wettability on the bubble dynamics and void evolution in subcooled flow boiling, using the contact angle of the heated surface as an important experimental parameter.

2. Experimental description

2.1. Experimental utilities

The thermal-hydraulic test loop and the vertical rectangular test section which were used in this study are depicted schematically in Fig. 1. Prior to the experiment, filtered and deionized tap water was kept boiling at least for an hour in a storage tank containing heaters for degassing. The loop was then vacuumed to deliver the degassed water from the storage tank by means of pressure difference. The fluid was preheated using two 5 kW sheath heaters to set the inlet subcooling, and then injected to a test section. It should be noted that a small part of liquid was delivered to a bypass line to control the system pressure by generating steam-water two-phase flow inside of it. As shown in Fig. 1b, a part of one side of the rectangular test section was heated using two cartridge heaters embedded in a copper block to produce boiling in the rectangular flow channel of 10 × 20 mm. In the test section, the two measuring sections with sight glasses were designed to acquire movie data. The positions of the measuring sections were 100 and 300 mm from the lower end of the active heated section. In this study, visualization was performed at the upper measuring section using a high speed camera and the flow parameters such as the flow rate, inlet and outlet pressure, wall temperatures and fluid temperatures were recorded using a data acquisition system.

In the previous studies, the bubble dynamics and void evolution mechanisms in subcooled flow boiling were investigated experimentally using a rather hydrophilic heated surface of low contact angle [18–20]. In this study, in order to identify the influence of the surface wettability, the contact angle of the heated surface of copper was changed parametrically. Pressure was also used as a main experimental parameter and set to 100, 200, and 400 kPa, approximately. It is necessary to notify that in all series of experiment mass flux G was fixed around 400 kg/m^{2}s. In each series of experiment, the values of pressure P, mass flux G and heat flux q_w were kept fairly constant and the liquid subcooling at the inlet ΔT_{sub} was decreased step by step. The range of ΔT_{sub} was set to cover whole subcooled boiling region from the condition of ONB and that close to saturation boiling. The main experimental conditions and the values of wall superheat ΔT_w, thermal equilibrium quality x_{eq}, average void fraction $<\alpha>$ and Jakob number Ja in each experimental run are listed in Tables 1–3. According to specification of instruments, the measurement accuracies of P, ΔT_{sub} and G were estimated less than 10 kPa, 2 K and 10 kg/m^{2}s, respectively. Further information about experimental facilities and procedures were extensively described in previous works [18–20].