Photographic Study on the Onset of Significant Void in Water Subcooled Flow Boiling at Low Pressure

Tomio Okawa, Yuya Endo, Hongji Li, and Hideki Takahashi

Abstract—**Visualization of bubbles' dynamics in vertical upward subcooled flow boiling was carried out to investigate the mechanisms causing the onset of significant void (OSV). It was found that formation of large bubbles is a key phenomenon since they were large in size as well as their lifetime was remarkably longer than those of the smaller bubbles. Most bubbles were detached from the heated surface to disappear immediately after nucleation or during rise along the vertical heated surface. Therefore, for the large bubbles to be formed, it was necessary to coalesce with other bubbles during the growth period at the nucleation site and the rising period along the heated surface. However, when the bubble size exceeded the critical value, the bubbles rose along the heated surface stably. Thus, the bubble lifetime was elongated substantially to contribute to the rapid increase of the void fraction.**

Keywords—**subcooled flow boiling, void fraction, onset of significant void (OSV), net vapor generation (NVG), bubble coalescence**

I.   Introduction

In subcooled flow boiling, void fraction is negligibly small just downstream of the point of the onset of nucleate boiling (ONB) and it increases rapidly when the local subcooling decreases sufficiently. This phenomenon is called the onset of significant void (OSV) or the net vapor generation (NVG). Accurate prediction of OSV is of considerable importance in various engineering plants since it affects the two-phase flow instability. In addition, in the case of light water reactors, it also influences the fuel burnup. Thus, several correlations were developed so far to predict the condition under which the OSV occurs [1, 2]. It is frequently postulated that bubbles are first attached to the heated surface and the OSV is incepted when the bubbles are detached from the heated surface [1]. However, the bubble detachment has been observed even at the ONB in water subcooled flow boiling at low pressure [3, 4]. The bubble detachment is not a main cause of OSV at least in this condition.

Since the OSV is an important thermal-hydraulic phenomenon in a variety of industrial plants such as the boilers and light water reactors, several empirical models have been developed to predict the OSV. However, the mechanisms causing the OSV has not still been elucidated. In the present work, measurement of void fraction and visualization of bubble motion in water subcooled flow boiling are carried out to elucidate the main mechanisms causing the OSV.

II.   Description of Experiment

Figure 1 depicts the schematic diagram of the experimental loop [5]. Filtrated, deionized and degassed tap water was used as the test fluid. First, the mass flux G was adjusted at the desired value using the flow control valves and the turbine flow meter and the preheater was used to set the inlet subcooling ΔT_{sub}. The fluid temperature and the pressure were measured at the inlet of the test section using the type-K thermocouple and the pressure transducer. The measurement accuracy was within ±2.5 K for the fluid temperature and ±5 kPa for the pressure. After exiting the test section, the test fluid entered the separator tank that was open to atmosphere. The vapor phase was condensed or released to atmosphere and the liquid phase was returned to the circulation pump through the plate-type heat exchanger where the fluid temperature was reduced by the heat transfer to the cooling water.

The schematic diagram of the test section is delineated in Fig. 2 [5]. A transparent and electrically-conductive ITO film was deposited on a sapphire glass plate for Joule heating using an AC power supply at 550 Hz. The two ends of the ITO film were covered with Au/Cr/Ni films that were used as the electrodes. The heated surface was 10 mm in width and 170 mm in length. The ITO film was covered with the Al_2O_3 film to avoid destruction due to electrolysis. As delineated in the figure, the glass plate was sandwiched by the two polycarbonate jigs to construct the rectangular flow channel on the ITO film. The flow direction was vertically upward and the size of the channel cross-section was 14 mm in width and 10 mm in height.
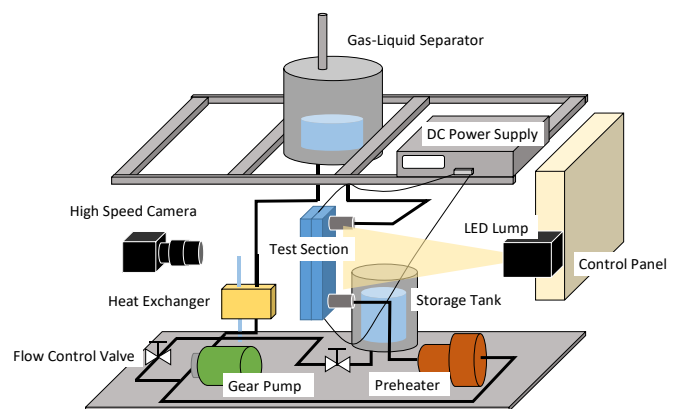

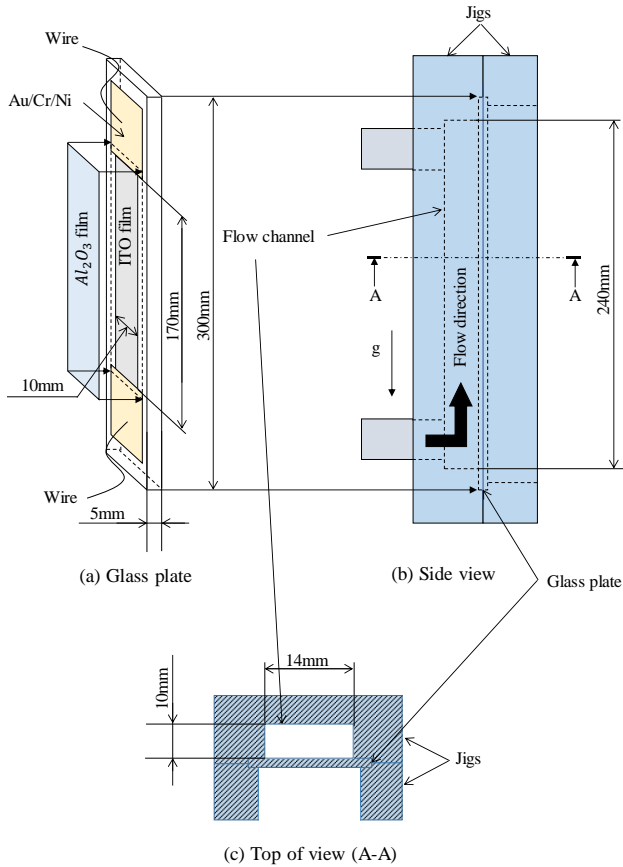Figure 1. Schematic diagram of experimental loop.

Tomio Okawa, Yuya Endo, Hongji Li, and Hideki Takahashi

The University of Electro-Communications

Japan

Figure 2. Schematic diagram of test section.

In the experiments, after adjusting the mass flux to G = 300 or 600 kg/m² and the heat flux to q_w = 500 kW/m², the inlet liquid subcooling was decreased step by step to cause the OSV in the test section. The spatial- and temporal-averaged void fraction was measured by the gamma densitometer (PM-1000, Nanogray Inc.) and the spatial distribution of the local, time-averaged void fraction was measured by the optical void probe manufactured by RBI instrumentation. The bubble dynamics was observed using the high-speed camera (Fastcam Mini UX50, Photron, Ltd.); the test section was backlit using a LED lamp.

III. Experimental Results

A. Void Fraction

The relationships between the liquid subcooling ΔT_{sub} and the void fraction α measured in the two conditions of G are displayed in Fig. 3. Here, the results measured by the gamma-densitometer and those by the optical probe were presented in Figs. 3(a) and (b), respectively. The measurement using the optical probe was made only for G = 300 kg/m². It can be confirmed that in both the experimental conditions, α was negligibly small when ΔT_{sub} was low and it started to increase rapidly to cause the OSV when ΔT_{sub} decreased sufficiently. Figure 3(b) indicates that bubbles were present only near the heated wall at high subcooling and they were detected all across the channel cross-section at low subcooling.
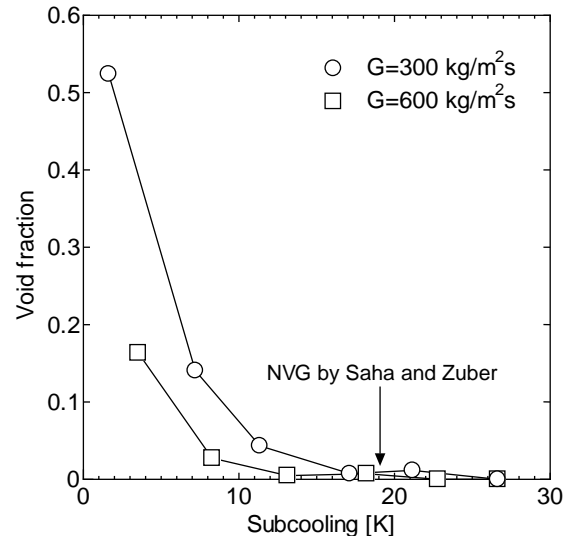
(a) Results measured by gamma-densitometer
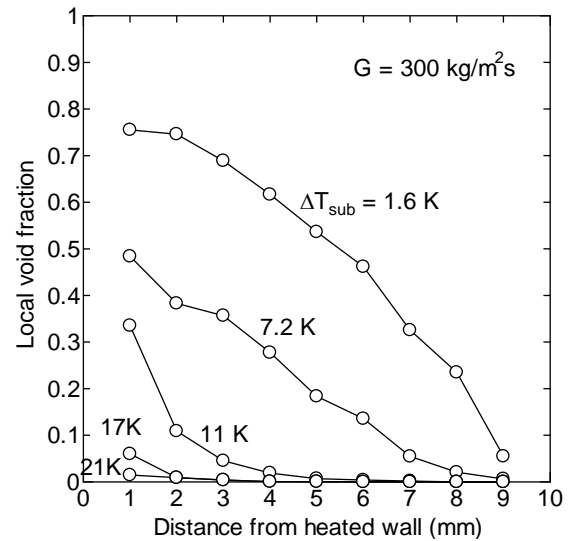
(b) Results measured by optical void probe

Figure 3. Relations between the liquid subcooling ΔT_{sub} and the void fraction α.

B. Bubble Dynamics

Typical snapshots of bubbles taken before and after the OSV are displayed in Figs. 4(a) and (b), respectively. It can be seen that only small bubbles were present in the flow channel before the OSV but a number of large bubbles were present after the OSV. After the OSV, almost all the bubble volume could be attributed to the large bubbles. It can therefore be postulated that the void fraction was negligibly small before the OSV because no large bubble was present and it increased rapidly after the OSV because the volume of large bubbles increased with a decrease in the liquid subcooling. This implies that the formation of large bubbles is the key phenomenon to cause the OSV at least in the present experimental setup.
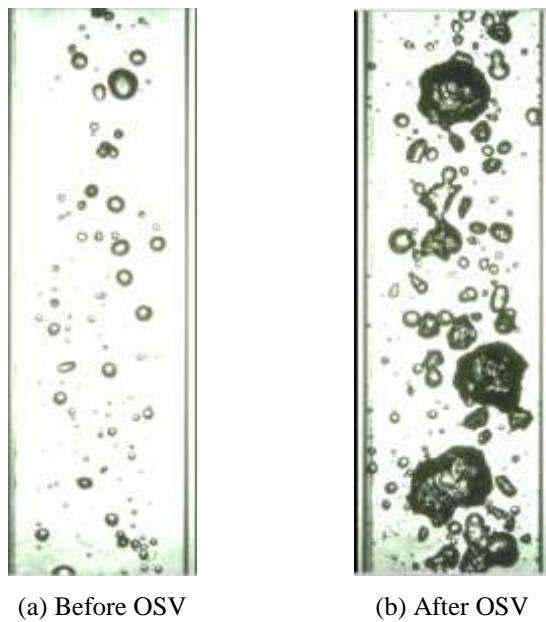
| (a) Before OSV | (b) After OSV |

Figure 4.Snapshots of bubbles in the test setion.
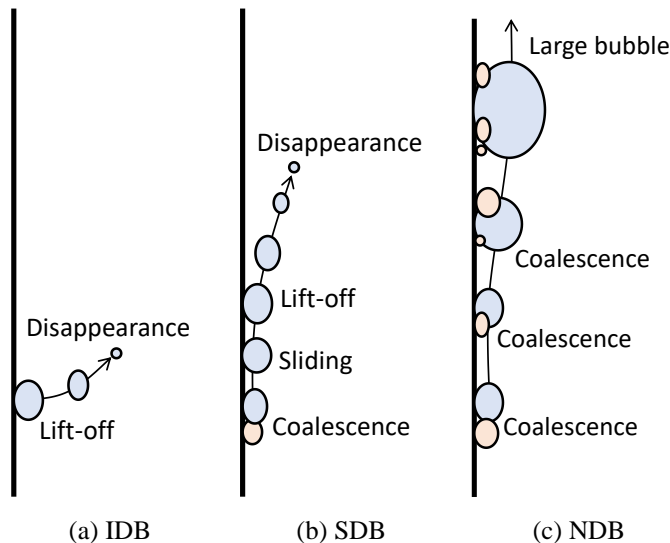

| (a) IDB | (b) SDB | (c) NDB |

Figure 5. Three bubble types observed in this work (IDB: immediately disappearing bubble, SDB: slowly disappearing bubble, NDB: non-disappearing bubble).

The processes for the large bubbles to be formed were explored using the movie data of bubbles. The bubbles produced in the present experiment could be classified into the three types that are illustrated in Figs. 5(a)-(c), respectively. First, all the vapor bubbles observed in the present experiment tended to be lifted off the vertical heated surface during the growth period on their nucleation sites. Thus, as shown in Fig. 5(a), most bubbles were detached from the heated surface immediately after nucleation to disappear due to heat transfer with the subcooled bulk liquid. These bubbles are called the immediately disappearing bubble (IDB).

When the bubble growing on the nucleation site coalesced with the other bubble produced at a different nucleation site, random motion was induced and some of the coalesced

bubbles survived the immediate detachment from the heated surface. Such bubbles rose along the vertical heated surface. However, as depicted in Fig. 5(b), they were usually detached from the heated surface within a short distance due to random motion induced by the interaction with eddies in liquid phase. In consequence, these bubble could not grow to large bubbles. These bubbles are called the slowly disappearing bubble (SDB).

Finally, when the bubbles survived the immediate detachment repeated the bubble coalescence with enough frequency, they could grow to large bubbles. The sufficiently large bubbles rose along the vertical heated surface under the influence of shear-induced lift force. The detachment from the heated surface rarely occurred probably because the bubble size was sufficiently greater than the eddy size in liquid. In consequence, the bubble lifetime was elongated remarkably when the bubble size exceeded the critical value. This can be assumed the main mechanism to cause the discontinuous increase of the void fraction at the OSV. It would therefore be concluded that the OSV is permitted when the vapor generation rate becomes sufficiently high to maintain the size of sliding bubbles that survived the disappearance immediately after the nucleation.

Conclusions

The mechanisms causing the OSV was explored for the subcooled flow boiling of water under low pressure and low mass flux conditions. The bubble lifetime was elongated remarkably when the bubble size exceeded the critical value since sufficiently large bubbles slid along the vertical heated surface and they were rarely detached from the heated surface. The sliding motion and the absence of detachment for the large bubbles were attributed to the shear-induced lift force and dilution of the effect of eddies in liquid phase, respectively. For the bubbles to grow to the large bubbles, they must survive the disappearance following the detachment from the heated surface during the growing period at the nucleation site and the sliding period along the vertical heated surface. It was discussed that bubble coalescence is the key phenomenon to enable the formation of the large bubbles.

Acknowledgment

References

[1] S. Levy, "Forced convection subcooled boiling prediction of vapor volumetric fraction," Int. J. Heat Mass Transfer, vol. 10, no. 7, pp. 951-965, 1967.

[2] P. Saha, N. Zuber, "Point of net vapor generation and vapor void fraction in subcooled boiling," Proceedings of the 5th International Heat Transfer Conference, Tokyo, pp. 175–179, 1974.

[3] R. Ahmadi, T. Ueno, T. Okawa, "Bubble dynamics at boiling incipience in subcooled upward flow boiling," International Journal of Heat and Mass Transfer, vol. 55, no. 1-3 , pp. 488-497, 2012.

[4] T. Okawa, T. Ishida, I. Kataoka, M. Mori, "Bubble rise characteristics after the departure from a nucleation site in vertical upflow boiling of subcooled water," Nuclear Engineering and Design, vol. 235, no. 10-12, pp. 1149-1161, 2005.

[5] K. Kaiho, T. Okawa, K. Enoki, "Measurement of the maximum bubble size distribution in water subcooled flow boiling at low pressure," International Journal of Heat and Mass Transfer, vol. 108, pp. 2365-2380, 2017.

[6] A. Tomiyama, H. Tamai, I. Zun, S. Hosokawa, "Transverse migration of single bubbles in simple shear flows," Chemical Engineering Science, vol. 57, no. 11, pp. 1849-1858, 2002.