ONSET OF FLOW INSTABILITY DUE TO THE MERGENCE OF FACING BUBBLE LAYERS IN A VERTICAL NARROW RECTANGULAR CHANNEL

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ABSTRACT

The understanding and prediction of the onset of the flow instability (OFI) in narrow rectangular channels is very crucial for design and safety analysis concerning the systems such as high power research reactors using plate-type fuels since the phenomena could lead premature critical heat flux (CHF) at the lowest heat flux level. OFI would be defined as the minimum of demand curve (pressure drop versus mass flux curve) for first approximation but many correlations and models have been developed based on presumed critical point of the boiling phenomena since the change of boiling structure are intrinsically related to the characteristic of the curve. However, the initiating key phenomena has not been well understood and discrepancies between amongst models are still evident. Recently, we investigated OFI for subcooled downward flow boiling in a narrow rectangular channel uniformly heated from both sides under atmospheric pressure focusing on the boiling mechanism at OFI using high-speed visualization (HSV). The results showed that the coalescence of facing bubble layers on the boiling surfaces are the critical point of the boiling, which initiates the two phase flow instability due to the sharp and abrupt increase of channel pressure drop. In this study, we conducted more detailed investigations with image analysis on the growth of bubble layers for not only downward flow but also upward flow. The subcooled flow boiling was developed as the wall heat flux was escalated until OFI occurrence for high inlet subcooling condition (>50K) and low mass flux with low *Peclet* number (<14,000) and the gap, width, heated width and heated length of the channel were 2.35, 40, 30 and 350 mm, respectively. Interestingly, since the degree of the bubble growth on boiling surfaces were different between upward and downward flow due to the buoyancy effect, the occurrence point of the coalescence and OFI was changed depending on the flow direction. With

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the analysis on the obtained experimental data, modeling for predicting OFI based on the new concept were discussed.

KEYWORDS
onset of flow instability; narrow rectangular channel; subcooled flow boiling; high-speed visualization; bubble boundary layer;

1. INTRODUCTION

Flow boiling is microscopically or macroscopically susceptible to various instabilities in nature. From a macroscopic view point, the flow instability is defined as an unstable flow, which can be caused by small perturbations when a system has multiple solutions for the given boundary conditions. [1] The unstable flow may initiate local degradation of heat transfer and even lead to the critical boiling phenomenon known as critical heat flux (CHF), which can cause mechanical damage of heat-flux-controlled system due to an abrupt reduction of the heat transfer coefficient (HTC). Since CHF is induced by flow instabilities, which is called premature CHF, is well below stable (or actual/normal) CHF [2,3], the understanding and prediction of onset of flow instability has been considered as important issue for systems with high thermal power density such as nuclear power plants and compact heat exchangers.

One of good example to show the importance of the phenomena in nuclear system could be found in the thermal-hydraulic design and safety analysis for research reactors using multi-channels configuration. Since the external pressure drop for all individual channels are kept almost same, there is a certain starting point of flow boiling in which the internal pressure drop in a subchannel increases with small reduction in mass flux due to the increase of voidage for given heat flux condition. Therefore, the onset of flow instability (OFI) in which flow in the channel may immediately excurse to single vapor phase due to any perturbation in multi-channels is generally expressed for the first approximation as follows:

$$\left.\frac{\partial \Delta P}{\partial G}\right|_{internal} \cong 0 \tag{1}$$

Since the flow instability may lead to premature CHF, it has been generally recommended [4] that RRs be designed with sufficient margins for not only CHF but also OFI as well for normal operating and transient conditions. Even though the finding the minimum of the internal characteristic curve for OFI evaluation is the one of proper approach, however, the prediction for internal pressure drop including void faction in subcooled boiling for various channel configuration is still challenging.

Instead, correlations and models for critical point of the boiling such as onset of significant void (OSV) or the point of net vapor generation (PNVG) has been generally considered as the signals for OFI since this is the point where a rapid increase in the void fraction commences. Whittle and Forgan's correlation being widely used for OFI prediction for research reactor [4–6] was proposed based on the assumption that onset of bubble detachment at channel exit would be closely related to OFI. Several authors [7–9] verified that OSV correlation for upward flow proposed by Saha and Zuber [10] well-predict the OFI data for downward flow condition as well but Johnston [7] reported the correlation failed to predict downward OFI data at low mass flow condition (Low *Pe*). Lee and Bankoff [11] in their critical reviews for OSV showed that OSV correlation by Saha and Zuber remains the most accurately predictive and simple correlation among relevant correlations and models in comparison with OSV and OFI data in the previous study.

On the other hand, flow pattern transition has been pointed out as the critical point, which induces the OFI and the minimum premature CHF. Bergles et al. [12] concluded based on their CHF experiment with flow pattern observation by means of electrical probe, the minimum CHF at low pressure was induced by the onset of slug flow. Mishima and Nishihara [3,13] showed that the minimum boundary of premature CHF at low pressure and low velocity conditions was well fitted by churn to annular flow transition. Recently, flow boiling structure at OFI was observed or visualized in relevance to mini-/microchannel. The elongated bubble [14] or slugs generated by coalescence of bubbles [15,16] were observed at OFI.

Very recently, Lee et al. [17] experimentally investigated the OFI for downward flow boiling in a narrow rectangular channel heated from both-sides while focusing on the observation of the boiling structure at OFI by using high speed visualization (HSV) technique. It was demonstrated that OFI was triggered by the abrupt perturbation of the pressure drop caused by the merging of facing bubble (for Pe <14,000) or wavy vapor layers (for Pe >14,000) on the opposite side of the heaters. In this study, further experiment was conducted to investigate the OFI for upward flow as well. In addition, the thickness of bubble layers for various fluid conditions were analyzed by using image processing method, which was appeared as crucial parameter for prediction of the coalescence of facing vapor layers and, therefore the OFI.

2. Method

2.1. Experimental method

In this study, subcooled flow boiling in a test section having narrow rectangular channel configuration was developed using experimental facility while observing boiling structures with visualization technique until the occurrence of OFI. Detailed description of experimental facility, visualization technique and experimental procedures are as follows.

2.1.1. Experimental facility

The experimental facility (KAIST flow boiling test facility) used for the subcooled flow boiling experiment for upward flow is schematically shown in Fig. 1. The flow direction can be set to be downward flow by interchanging flexible pipes connected to inlet and outlet of test section part. The flow boiling loop in which the working fluid of deionized (DI) water was circulated through the main line is composed of the test section part, an open pool, a pan-type heat exchanger, a centrifugal pump, an electromagnetic flow meter, a surge tank and a preheater. The flow rate in the loop was adjusted by controlling the pump speed or throttling a valve at the upstream of the test section part and was measured with the flow meter of < ±0.8 % of uncertainty. Inlet subcooling of the working fluid was controlled by the preheater and the generated heat inside the loop was removable by the heat exchanger. The inlet/outlet pressure and temperature were measured with pressure transmitters and K-type thermocouples with an uncertainties of < ±0.25 % and < ±1.1ºC, respectively. An additional pressure transmitter was installed at the upstream of the throttling valve to quantify the amount of inlet throttling by the pressure drop across the valve. Boiling was induced by Joule heating of direct current supplied via power cables and DC power supply, with the maximum capacity of 150kW (50/3000A). The electrical voltage and current applied to the test section was measured by a power meter with an accuracy of ±0.25 %. The power of the preheater and DC power supply and pump speed were controlled by system control panel through signal cables and measured values (including temperature, pressure, flow rate, electrical current and voltage) were stored at intervals of 0.660 sec. using data acquisition system.

The inner structure of the test section is schematically shown in Fig. 2. Detailed description of the structure is omitted here since it is very similar to the test section used in the previous work (see [17]). A narrow rectangular flow channel with cross-sectional area of 40.0 mm (width) × 2.35 mm (gap) is formed inside of the test section. Two electrical resistors, which are SUS 304 plates of 30.0 mm (heated width) × 2.0 mm (thickness) × 350.0 mm (heated length) are vertically and oppositely embedded to provide uniformly heated surfaces on both sides. Temperature of heaters are monitored by spot-welded K-type thermocouples on the backside of them, and the flow boiling structure are observed and visualized through transparent windows, which are 6 mm-thick polycarbonate plates.

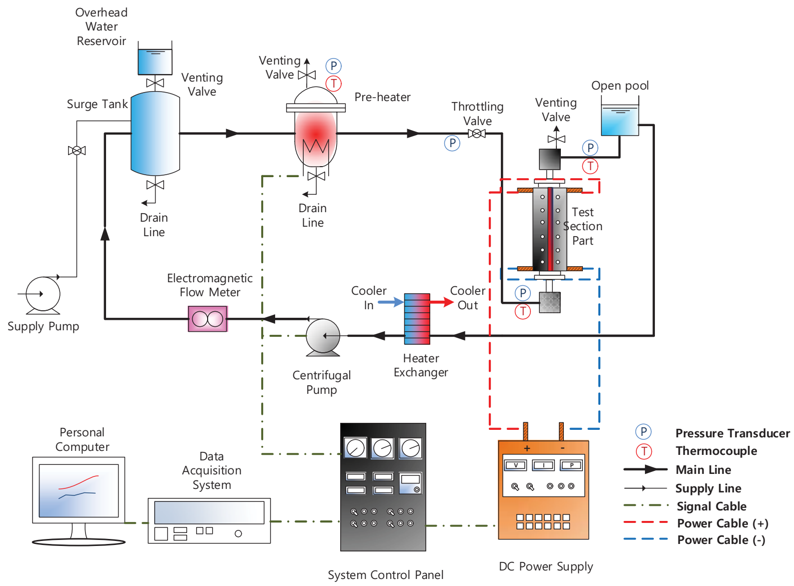

Figure 1. Schematic diagram of KAIST flow boiling test facility (upward flow)

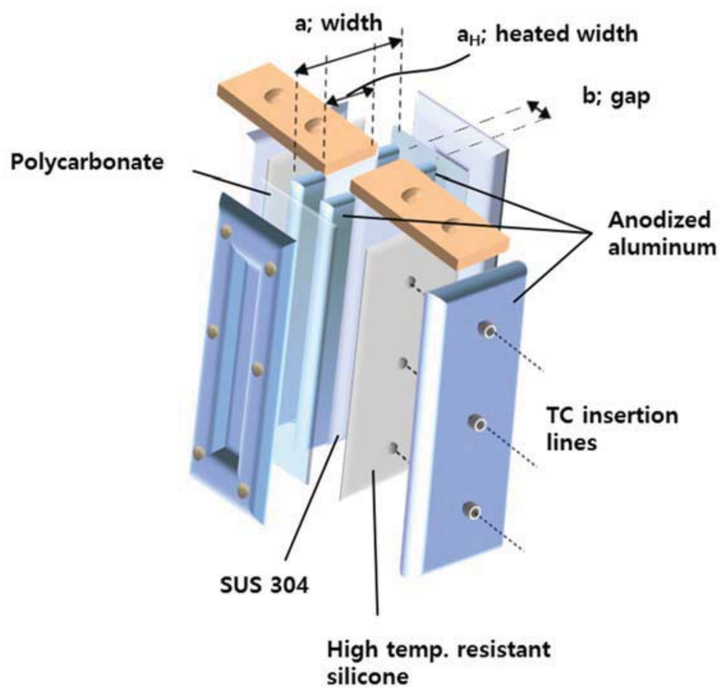

Figure 2. Schematic diagram of test section (3D cut view)

2.1.2. Visualization technique

Subcooled flow boiling structure in a narrow rectangular channel heated from both-sides is investigated using high speed visualization of side view of boiling (HSV-SVB) with backlighting method. Images of the most downstream region of 15 mm in length including 10 mm for the end of the heated section is captured with high spatial resolution of ~0.03 mm at a frame rate of 1,000 fps using high speed camera (Photron, FASTCAM SA-Z). LED light source (Optronis, MultiLED) is used for backlighting to visualize the bubble dynamics inside the channel.

2.1.3. Experimental procedure

Before experiment, the working fluid was circulated and heated up in the preheater for half an hour to expel non-condensable gas. In addition, the test section was heated to induce nucleate boiling on the heater surfaces to remove any entrapped air on themselves. Then, the mass flux and inlet subcooling were set to be desired conditions and preserved during experiment. Pressure drop across the throttling valve was kept to be > 1.0 bar to detect OFI by monitoring pressure drop fluctuation while preventing the flow excursion and premature CHF as reported in previous work [18]. For each step, heating power in the test section is escalated to be not exceeding the increment of heat flux with ~ 20 kW/m^2 and then steady state was confirmed to be reached. Recording data and observing flow boiling structure was conducted until the occurrence of OFI. When OFI occurs, abnormal fluctuations with large amplitude (> 200 % of normal fluctuation) were observed as one of example shown in Fig. 3 (for G = 500 kg/m^{2}s, T_i = 40 ºC with upward flow).

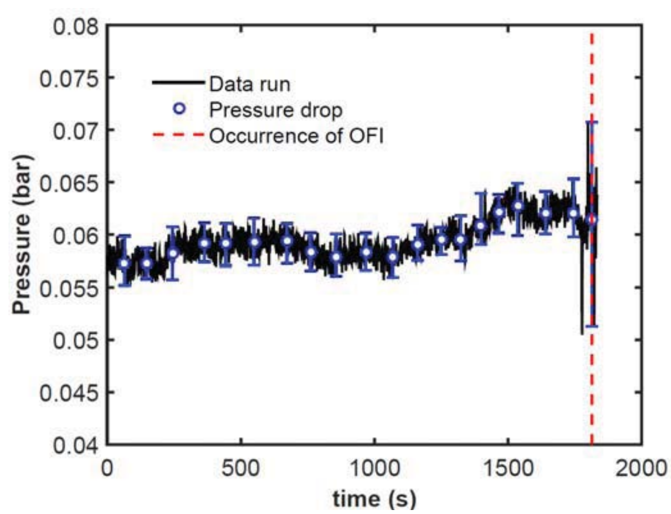

Figure 3. Detection of pressure drop and the occurrence of OFI

2.2. Image processing method

In the subcooled flow boiling regime, flow structure can be divided by subcooled liquid core region and vapor dominant region near at the boiling surface (called bubble boundary layer), as visualized in previous literatures [19–21]. The thickness of bubble boundary layer has been reported to be highly dependent on the inlet subcooling, mass flux, wall heat flux, and bubble size. Since the mergence of facing bubble layers on opposite heated sides is considered as key triggering phenomena of OFI in a narrow rectangular channel heated from both sides, measurement of bubble layer thickness for various conditions would be important. In order to derive quantified thickness of vapor layers on the boiling surfaces from captured images by HSV, own algorithm for automatic image processing has been developed using MATLAB script. Fig. 4 shows an example of the progress of the image processing for detection of two-phase boundaries, performed by the MATLAB code for an input image (for G = 500 kg/m^{2}s, T_i = 40 ºC, q'' = 340 kW/m^2 and upward flow condition). Firstly, preprocessed image is obtained from the original image through preprocessing, which includes vertical alignment, widow & boiling surface identification and cropping (Step 1). Then, preprocessed image is converted to a grayscale image, which carries only intensity information (Step 2). Binarization of the image is produced using Otsu's image thresholding method [22], which binarizes the grayscale image based on the optimum threshold of intensity with minimal intra-class variance (Step 3). Filling gaps and smoothing the outer edges is achieved using morphological close operation with a structure element, which size is less than 15 pixels (Step 4). Finally, the image is finalized with removing detected small white objects, which a set of pixels that form a connected group, by the filling them (Step 5). Detection of the boundaries and quantification of bubble layer thickness is performed with the final image using MATLAB algorithm. The output for the thickness of vapor layers along y direction in the image are shown in Fig. 5. Bubble layer thickness is defined based on the average of thickness of vapor layers on the boiling surfaces of the opposite heaters.

$$\delta = \frac{\delta_L + \delta_R}{2} \qquad (2)$$

Two crucial parameters, δ_{max} and δ_{mean} are derived from all sequence of images for total recording time (on an order of 0.1 sec.), which quantities could be characterized as the bubble departure diameter and volume and time-averaged void fraction, respectively.

$$\delta_{max} = max(\delta) \sim D_d \qquad (3)$$

$$\delta_{mean} = \frac{1}{L_0 t_0} \iint \delta(y,t)\, dydt \sim \frac{A}{P_H} \langle \alpha \rangle \qquad (4)$$

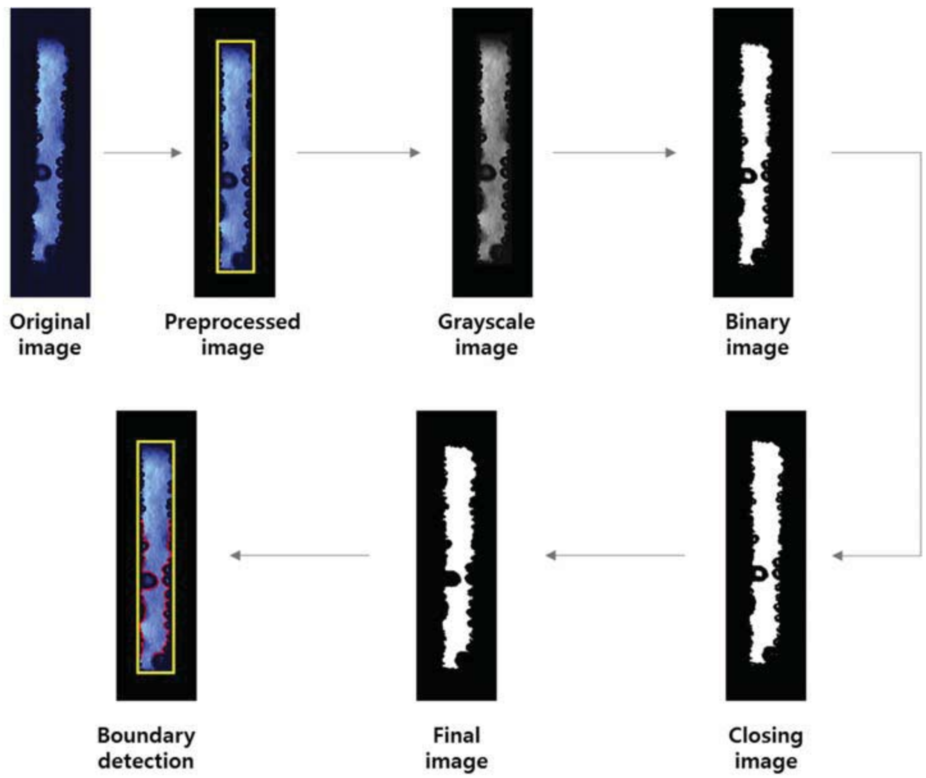

Figure 4. Boundary layer detection using image processing

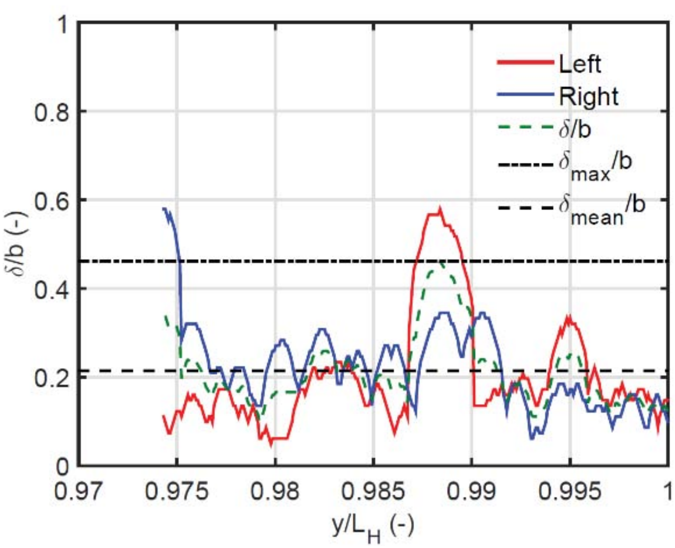

Figure 5. Derived bubble layer thickness along y direction

3. RESULTS AND DISCUSSION

3.1. Onset of flow instability results

All OFI data gathered in this study for the experimental conditions summarized in Table I are shown in Fig.6. For downward flow, OFI data are well predicted by the correlation proposed by Lee et al. [17], which was developed based on data for the onset of flow excursion under mass flux controlled and fully bypass open conditions in a narrow rectangular channel with a gap size of 2.5 - 4.1 mm.

$$G_{sat} = \frac{P_H L_H q''}{A C_{pl}(T_{sat} - T_i)} = 0.58\, G_{OFI} - 27 \quad (5)$$

Therefore, it was verified the rage of application of the correlation could be extended to the channel having gap size of 2.35 mm and the flow excursion should be induced for fully bypass open conditions.

For upward flow conditions, however, OFI is detected at almost 25% higher conditions than for downward in terms of heat flux for same inlet subcooling and mass flux. It clearly indicates the occurrence of OFI is influenced by the buoyancy effect, which is related to the bubble dynamics.

Table I. Experimental condition

Mass flux (kg/m²s)	200, 300, 400, 500
Inlet temperature (°C)	30, 40, 50
Outlet pressure (bar)	~ 1.1
Flow direction	upward / downward
***Peclet* number**	5,300-14,000

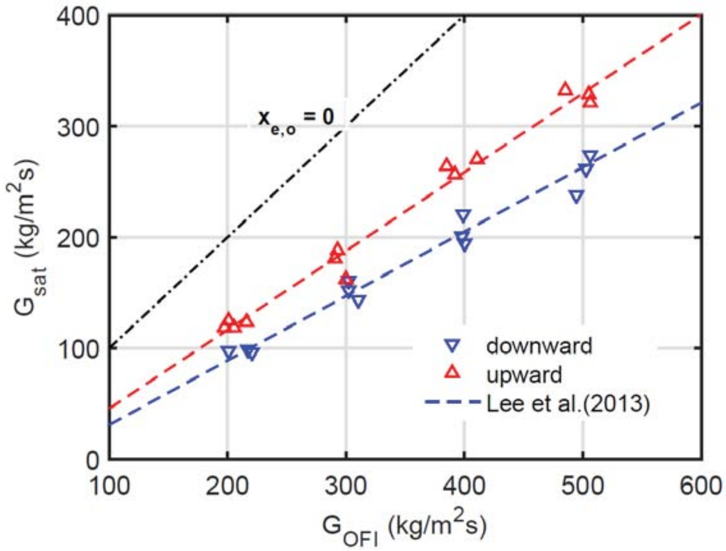

Figure 6. OFI data for downward and upward flow

3.2. Bubble layer thickness

Even conditions for the OFI occurrence are different for upward and downward flow, the triggering mechanism are verified to be identical from flow boiling visualization, i.e., the onset of mergence of facing bubble layers, which was reported in previous work [17]. Fig. 6 shows that mean and maximum bubble layer thickness with increasing heat flux for upward and downward flow condition, for same fluid conditions. The trends of the mean thickness, which would correspond to void fraction are similar for both flow direction and OFI are detected sometimes even before noticeable increase of mean thickness are not observed. However, at the point of OFI for all experimental conditions, maximum bubble layer thickness reaches the half of gap size (which refers to the mergence of facing bubble layers). Therefore, the point of merging phenomena rather than OSV is preferred to be used for OFI prediction. Furthermore, since the degree of the growth of (maximum) bubble boundary layer thickness for the similar increment of heat flux are reduced for upward flow, as a result, the mergence phenomena are delayed and therefore the heat flux at OFI is enhanced. In conclusion, modeling of bubble layer thickness including buoyancy effect is proposed as a more proper approach to predict the point of merging phenomena and the OFI for downward and upward flow in a narrow rectangular channel heated from both sides.

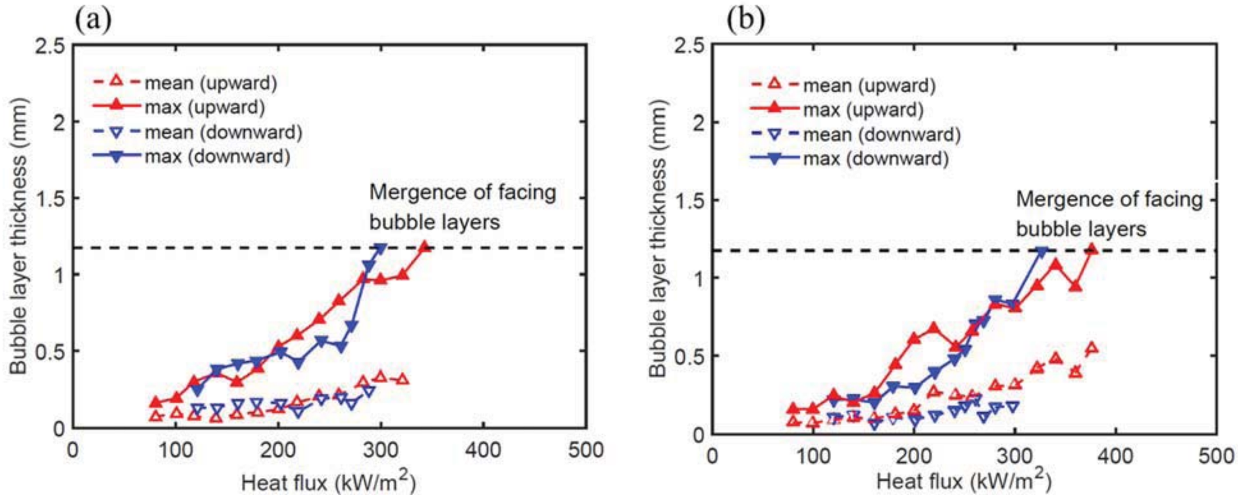

Figure 7. Bubble layer thickness vs. heat flux (a) G = 400 kg/m^{2}s, T_i = 30 ºC, (b) G = 500 kg/m^{2}s, T_i = 40 ºC

4. CONCLUSIONS

Experimental studies on OFI in a narrow rectangular channel having gap size of 2.35 mm was conducted not only for downward flow but also upward flow condition. Flow boiling structures are visualized using HSV method and also quantized bubble boundary layer thickness are obtained using image processing method. Based on the observation and analysis, the merging of facing vapor layers on opposite boiling surfaces is the key phenomena triggering OFI for not only for downward flow but also upward flow. However, the degree of the growth of bubble layer thickness at specific heat flux are highly depending on flow direction, the OFI for upward flow is occurred at more than 25% higher heat flux condition for same mass flux and inlet subcooling. An approach of mechanistic modeling based on the bubble layer thickness is proposed, for predicting OFI in a narrow rectangular channel heated from both sides.

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