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Growth of Bubble layer and Onset of Flow Instability in a vertical Narrow rectangular channel

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1. Introduction

The onset of flow instability is one of the important boiling phenomena since it may induce the premature critical heat flux (CHF) at lowest heat flux level due to sudden reduction of the flow in a cooling channel. [1] Even numerous studies have been constantly conducted to date, however the prediction of OFI is still questionable for wide range of conditions especially for low mass flux condition in narrow rectangular channel as reported in the previous works [2]. In addition, the understanding of subcooled flow boiling structures at OFI is not sufficient due to lack of studies with visualization. In this regards, OFI experiment for downward and upward flow boiling in a narrow rectangular channel are newly conducted while visualizing boiling structure. Image processing method is adopted to quantify bubble layer thickness, which is turned out to be important factor to understand the OFI.

2. Methods and Results

2.1 Experimental description

The experimental facility (KAIST flow boiling test facility) used for the subcooled flow boiling experiment especially 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. A narrow rectangular flow channel having width and gap of 40.0 and 2.35 mm, respectively are formed in the test section part, which are heated by direct Joule heating from both sides. The heated area is 30.0 mm (heated width) × 350.0 mm (heated length) for each side.

For each experimental run, subcooled flow boiling of deionized water was developed in the flow channel under same mass flux and inlet subcooling condition as escalating heat flux with less than 30 kW/m^2 until the occurrence of OFI. The OFI detection was performed by monitoring of pressure drop fluctuation. When OFI occurs, abnormal fluctuations with large amplitude (> 200 % of normal fluctuation) are observed. One of example are shown in Fig. 2 (for G = 500 kg/m^{2}s, T_i = 40℃ with upward flow).

In addition, flow boiling structures at the most downstream of section including 15 mm - length for the end of heaters are visualized using high speed visualization (HSV) technique. Images with high spatial resolution of ~0.03 mm are captured at a frame rate of 1,000 fps using a high speed camera (Photron, FASTCAM SA-Z). The experimental conditions for OFI experiment are summarized in Table 1.

Table I: Experimental condition

Mass flux (kg/m^{2}s)	200, 300, 400, 500
Inlet temperature (℃)	30, 40, 50
Outlet pressure (bar)	~ 1.1
Flow direction	upward / downward

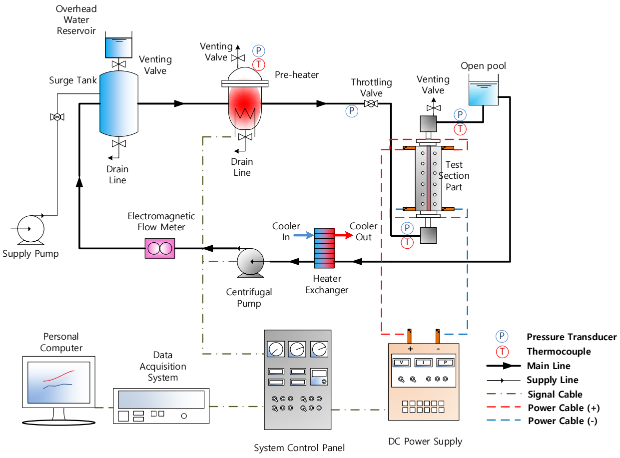

Fig. 1. Schematic diagram of KAIST flow boiling loop (for upward flow)

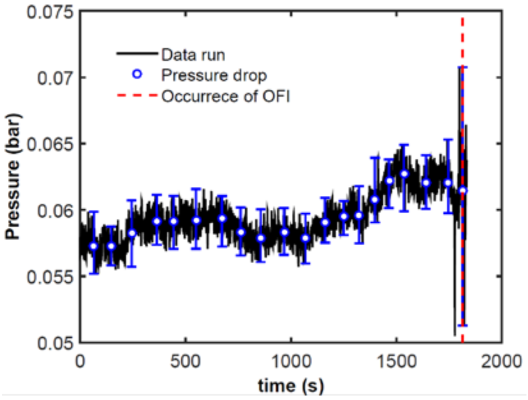

Fig. 2. Detected pressure drop and occurrence of OFI for and experimental run

2.2 Image processing method

In order to measure quantified thickness of vapor layers on the boiling surfaces from captured images by high speed video, a code for an image processing is developed using MATLAB script. Fig. 2. shows an example of the progress of the image processing for detection of two-phase boundaries, performed by the MATLAB code with an image (for G = 500 kg/m^{2}s, T_i = 40 ℃ and upward flow condition). During the process, grayscale, binary and closing images are produced and boundary detection is conducted with the final image. The output for the thickness of vapor layers along y direction in the image are shown in Fig. 3. Bubble layer thickness is defined based on the average of thickness of vapor layers on the left and right side of heater.

$$\delta = \frac{\delta_L+\delta_R}{2} \quad (1)$$

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

$$\delta_{BL} \equiv \delta_{max} \approx D_d \quad (2)$$

$$\delta_{mean} = \frac{1}{L_0 t_0} \iint \delta(y,t)\, dydt \approx \frac{A}{P_H}\langle\alpha\rangle \quad (3)$$

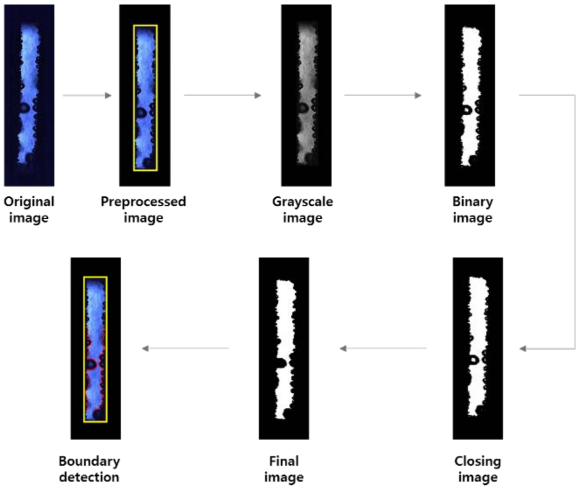

Fig. 3. Image processing and boundary layers detection

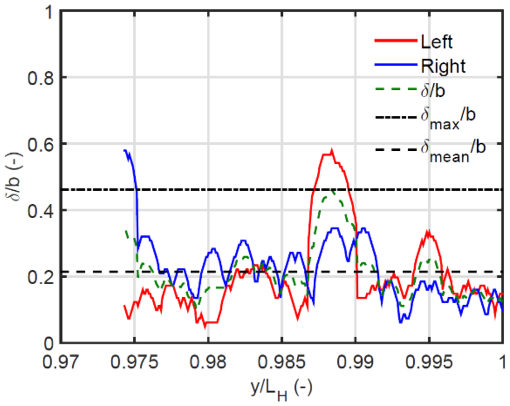

Fig. 4. Measured the vapor layer thickness along y direction

2.3 OFI for upward and downward flow

All OFI data gathered in this study are shown in Fig.5. For downward flow, OFI are well predicted by the correlation proposed by Lee et al. [2].

$$G_{sat} = \frac{P_H L_H q''}{A C_{pl}(T_{sat}-T_i)} = 0.58\, G_{OFI} - 27 \quad (4)$$

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

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 on bubble dynamics.

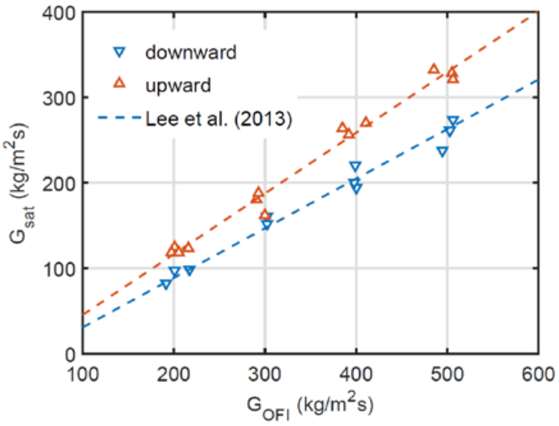

Fig. 5. OFI data for downward and upward flow

2.4 Development of Bubble layer thickness and OFI

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., onset of emergence of facing bubble layers, which was reported in previous work [2]. Fig. 6. shows that the results from the visualization with quantified bubble layer thickness. When the bubble layer thickness reaches the half of gap size (which refers the emergence of facing bubble layers), OFIs are detected. However, the heat flux at OFI is enhanced for upward flow since the degree of the growth of boundary layer thickness for the similar increment of heat flux are reduced for upward flow.

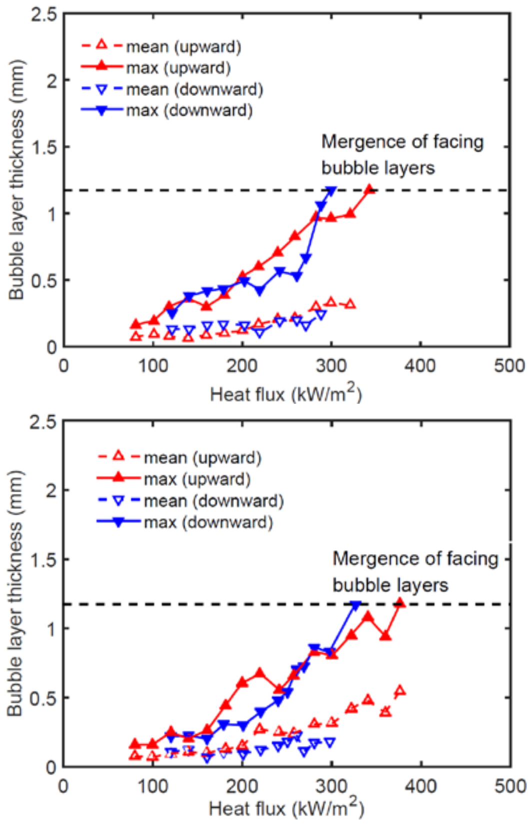

Fig. 6. Bubble layer thickness vs. heat flux (a) G = 400 kg/m^{2}s, T_i = 30 ℃, (b) G = 500 kg/m^{2}s, T_i = 40 ℃

3. 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 layers are obtained by using image processing method. Based on observation and analysis, the merging of facing vapor layers on opposite boiling surfaces is the key phenomena triggering OFI for both upward and downward flow. However, the degree 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.

REFERENCES

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[2] J. Lee, H. Chae, S.H. Chang, Flow Instability during Subcooled Boiling for a Downward Flow at Low Pressure in a vertical Narrow Rectangular Channel, Int. J. Heat Mass Transf., Vol. 67, pp. 1170–1180, 2013.