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Subcooled flow boiling visualization in mini channel using synchrotron X-ray : a preliminary test

Minjae Kim[a], Hyunwoong Lee[a], Ho Jae Kwak[b], Dong In Yu[c], Hyungdae Kim[a*]

[a]*Department of Nuclear Engineering, Kyung Hee University, Republic of Korea*

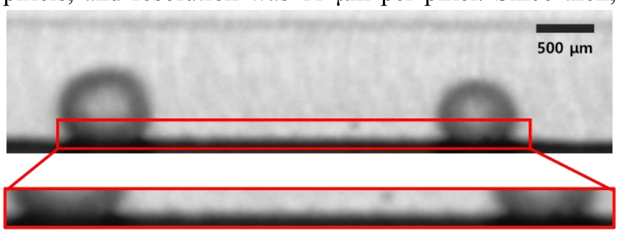
[b]*Industrial Technology Convergence Center, Pohang Accelerator Laboratory, Pohang, 37673, Republic of Korea*

[c]*Department of Mechanical Design Engineering, Pukyong National University, Busan, 48547, Republic of Korea*

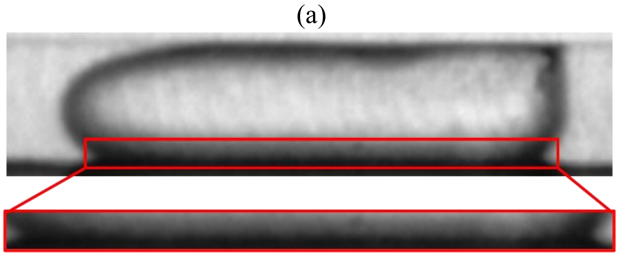
**Corresponding author: hdkims@khu.ac.kr*

1. Introduction

Subcooled flow nucleate boiling phenomenon occurs at local points of the hot channels in nuclear power plant. When the applied power from fuel exceeds the ability of heat removal by nucleate boiling, the heat flux at those points goes over critical heat flux (CHF) and departure of nucleate boiling (DNB) occurs. Fuel temperature suddenly increases by DNB, and fuel could be damaged. It is directly related with severe accident in nuclear power plant. Therefore, much research has been conducted to interpret the boiling mechanism. To analyze physical phenomena in flow boiling, researchers have visualized the bubble behavior to quantify parameters. Gunther et al. [1] introduced a high-speed camera photographic study on nucleate boiling and studied bubble growth and condensation process. Situ et al [2] used high-speed camera to capture the short bubble-growth period setting the frame rate as 5000 fps. The image size was 80×128 pixels, and resolution was 11 μm per pixel. Since then, most of studies in flow boiling utilized visible light camera like high-speed camera to acquire dynamic bubble behavior data.



(a)



(b)

Fig. 1 High-speed camera image at flow boiling and distortion effect in 1 mm×1 mm micro-channel.

High-speed camera can capture the bubble dynamics due to high frame rate. But detailed bubble information around the wall is hard to acquire because visible light near the wall is severely refracted and the resulting images near the triple contact line of the bubbles are considerably distorted. Fig. 1 shows the micro-channel flow boiling captured by high-speed camera at pretest using transparent channel. Its spatial resolution is 2.2 μm per pixel. The liquid-vapor interfaces are blackened by distortion, then it is difficult to figure out. But, to analysis flow boiling mechanism, the interface behavior linked to heat transfer mechanism is needed to know.

Pohang Light Source (PLS-II) at Pohang Accelerator laboratory (PAL) is a unique particle accelerator facility which produces the synchrotron radiation in Korea. In this work, using the synchrotron X-ray, we develop the synchrotron X-ray visualization technique at subcooled flow boiling.

2. Experiment

2.1 Flow loop

The subcooled flow boiling experiment of water was conducted in a range of 26-78 kg/m²s of mass fluxes, 5-10°C of inlet subcooling, 230-360 kW/m² of heat fluxes, under 0.91 bar of pressure, respectively. Fig. 2 shows flow loop which involves the test section for X-ray visualization, a pre-heater for inlet subcooling control, a bath circulator for condensing heated water, a gear pump, and a flow meter. The experimental setups were installed in the PLS-II 9D beamline hutch, and remotely controlled due to the radiation shield.

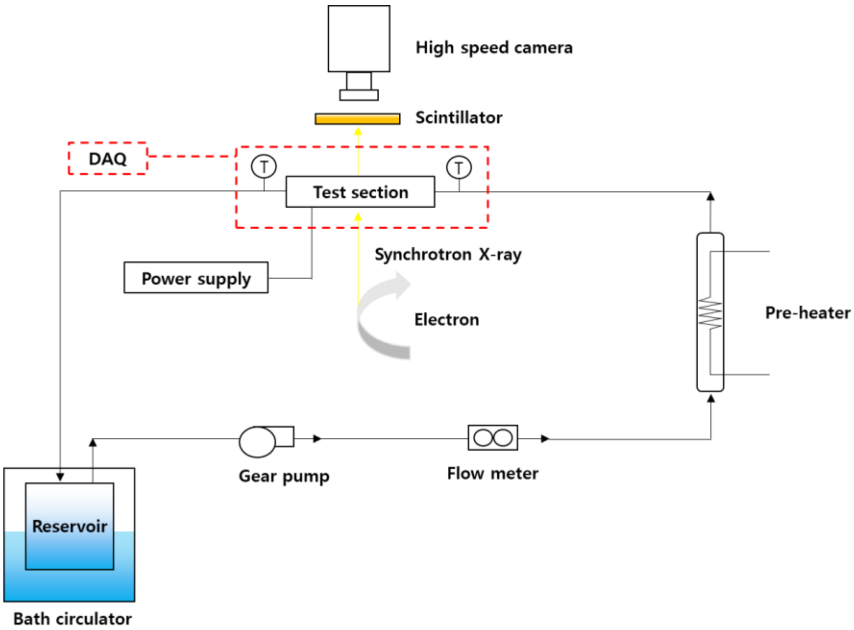


Fig. 2 Schematic of experimental flow loop.

2.2 Test section

Fig. 3 shows the schematic of the test section. Two cartridge heaters are inserted to the two aluminum blocks respectively, and the blocks clamp the plate which is welded to the mini flow channel. PEEK components cover the aluminum overall to insulate.

The mini channel is made of aluminum which is a low atomic number material. The inner diameter is 2.8 mm, and the wall thickness is 100 μm. It permits the stronger beam intensity so that the better-quality images are obtained. In the 9D beamline, the white beam from bending magnet was utilized for X-ray imaging with broad photon energy range. The most energy range is 20-30 keV. In this energy level, using X-ray transmission calculator written by Thomas Weingartner [3], calculated X-ray transmission at 200 μm Al wall is beyond 80% on the energy range. For comparison, if wall thickness is 2.2 mm, X-ray transmission is calculated barely 15-50%.

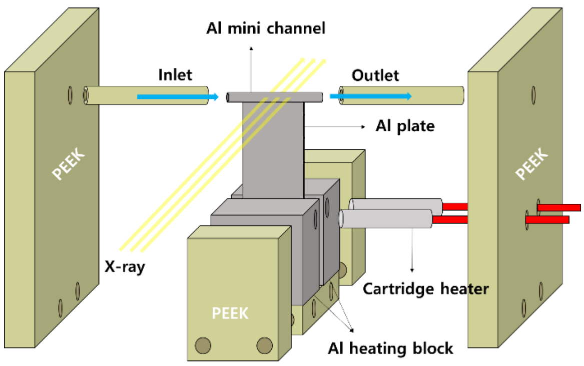


Fig. 3 Schematic of test section.

3. Results and Discussion

In subcooled flow boiling, nucleate the boiling including isolated bubble and slug bubble is successfully observed. Fig.4 shows bubble growth process. Exposure time is 30 μs, frame rate is 4000 fps and spatial resolution is 1.1 μm / a pixel. Unlike high-speed camera image using visible light, the synchrotron X-ray image reduces the darkening effect and the distortion around interface.

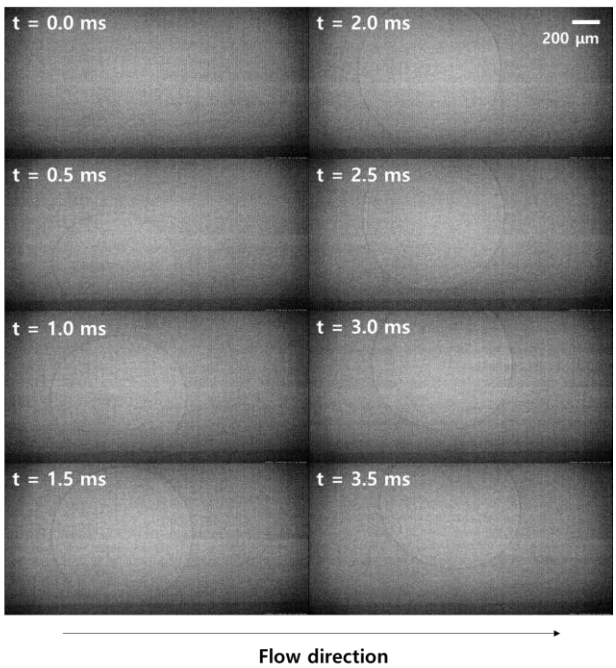


Fig. 4 Bubble growth process captured by synchrotron X-ray

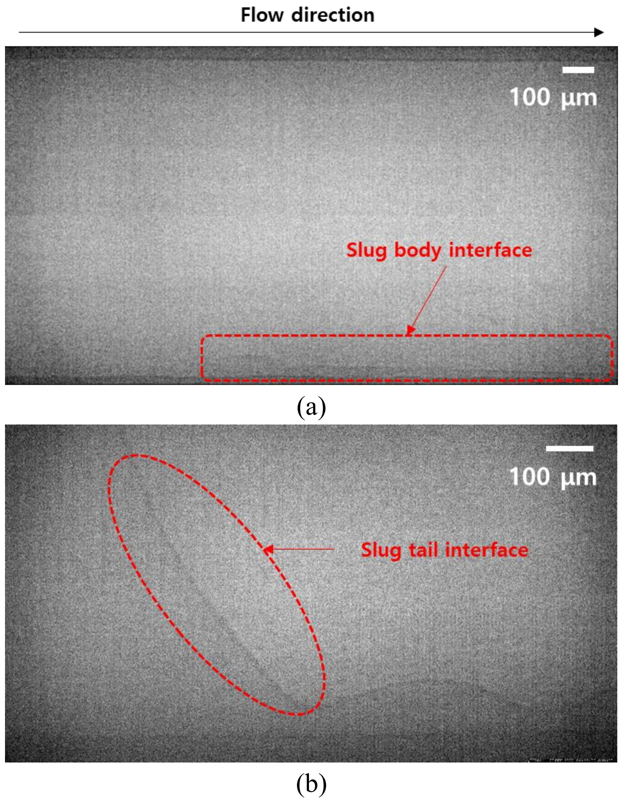


Fig. 5 Slug bubble interface image in different channel wall thickness

Fig.5 shows the body and tail of a slug bubbles. The liquid film could be observed underneath the slug bubble, whereas the high-speed camera imaging is hard to catch it as seen in Fig.1 (b). In Fig.5 (a), the slug bubble interface looks like being cut off. The difference between (a) and (b) is that (b) is the original test section data, but (a) is the other test section data. Its channel inner diameter is 1mm, wall thickness is 1.1 mm, exposure time is 80 μs, frame rate is 4000 fps and spatial resolution is 1.1 μm/pixel. Although the exposure time of (a) is higher than (b), we cannot find slug bubble interface when approaching to the tail of slug. This is the effect of X-ray attenuation. Along the X-ray transmission calculation, 50-85% beam is lost. Thus, in terms of image quality, the thickness of channel wall is crucial.

4. Conclusion and further work

In the present work, using the synchrotron X-ray in PAL, subcooled flow boiling phenomenon in mini channel is successfully observed. As against visible light visualization, the distortion around interface is significantly improved. Therefore, we can observe more detailed bubble behavior using the synchrotron X-ray.

Further study will be conducted to measure the parameters of bubble behavior in subcooled flow boiling using the synchrotron X-ray. In addition, finding more detailed flow boiling characteristic from high quality image data is expected.

ACKNOLEDGEMENT

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