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Subcooled Flow Boiling with Analysis of Acoustic Signal Behavior

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1. Introduction

The critical heat flux (CHF) phenomenon is a rapid decrease in the heat transfer coefficient as the phase of the working fluid in the boiling heat transfer system changes into a gas, resulting in a rapid increase in surface temperature and physical destruction of the heating surface. CHF is an important variable in reactor design, safety analysis, heat exchanger design, and electronic component cooling devices, and for safe and economical design, an accurate understanding of CHF and reliable prediction models are needed. In the past decades, many studies have been conducted to understand the CHF triggering mechanism of flow boiling, and a liquid sublayer dry-out model [1,2], bubble crowding model [3], interfacial lift-off model [4], etc. have been proposed. However, due to complex physical phenomena and the difficulty of mathematical expressions for CHF, predictive models are mainly based on a limited range of experimental data.

To better understand the critical heat flux phenomenon and to develop a system capable of diagnosing the heat transfer phenomenon inside the system, we conducted an acoustic emission signal measurement and analysis study along with flow boiling heat transfer CHF experiments. The objective of this flow boiling AE study is 1) to figure out the relationship between flow boiling heat transfer phenomena with acoustic emission signals, 2) to identify critical heat flux mechanisms through visualization data and AE signal features, and 3) to identify features that allow early warning before critical heat flux occurs. In this study, the acoustic emission signal generated from flow boiling was measured and compared with high-speed images to analyze the characteristics of flow boiling from the visual and acoustic viewpoint.

2. Experiments

To measure acoustic emission signals under flow boiling conditions, the flow boiling experiment was conducted using an experimental loop built as shown in Fig. 1. The experimental loop consists of a surge tank, centrifugal pump, preheater, test section, and heat exchanger for vertical upward flow boiling heat transfer. The test loop piping is a 3/4 in. SS316 pipe and the preheater are located in the middle of the pump and the test part, and controls the inlet temperature of the test part of the working fluid through PID temperature control and acts as a resistance to flow changes. The flow rate of the loop was adjusted using a pump and a bypass flow path, and the experiment was performed under atmospheric pressure conditions. The test section is composed of a transparent quartz glass window to visualize the flow boiling phenomenon from the side and front in a 35 mm*70 mm SS316 square duct. The boiling heat transfer phenomenon through the visualization window was captured with a high-speed camera. The heat exchanger maintains the heat balance of the loop by removing heat from the heating section transferred to the working fluid. The used heater was silicon substrate-based ITO heater with heating area of 15mm x 32mm.

The flow boiling experimental conditions were atmospheric pressure conditions, 25 K subcooling at the entrance of the test section, and a flow rate of 25 lpm (mass flux: 165 kg/m^{2}s) using DI Water as the working fluid, and the temperature of the heating surface was calculated through an infrared-temperature calibration.

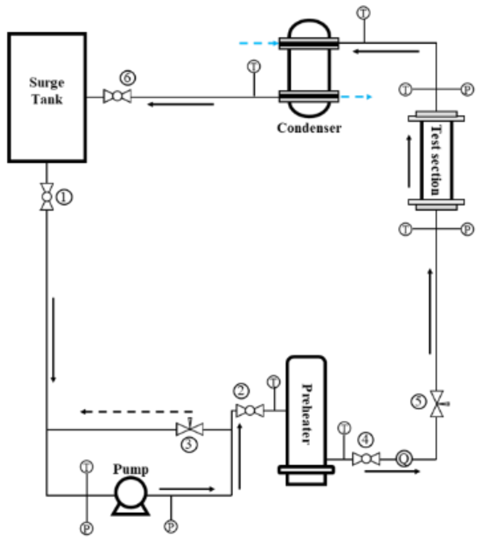

Fig. 1. Diagram of flow boiling experimental apparatus.

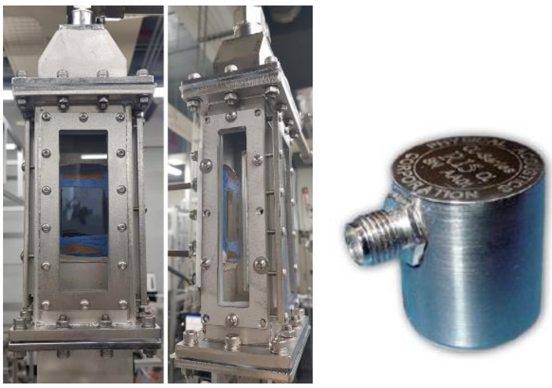

Fig. 2. Test section and contact acoustic emission sensor.

3. Results and Discussion

3.1 Flow boiling experiment results

Flow boiling heat transfer experiments were conducted under atmospheric pressure conditions and low mass flow rates with a loop design limit of 25 lpm (165 kg/m^{2}s). After the flow rate and temperature reached the steady state, heat flux was applied to the heating surface of the test section, and the experiment was conducted until the CHF was reached and the heating surface was damaged due to rapid temperature increase. The main results of the experiment are shown in Fig. 3. boiling curve and Fig. 4. visualized high-speed images of the flow boiling heat transfer phenomenon by heat flux, with a detailed description as follows.

At heat flux of 0 kW/m^2, acoustic emission signals by flow were measured, and at heat flux of 50 kW/m^2, there was no boiling, but the temperature of the heating surface reached 90℃, resulting in a mixture of natural convection and forced convection by pumps. For boiling to occur on the heating surface, the wall temperature must be at least a certain temperature higher than the saturation temperature of 100℃ of the working fluid, and onset of boiling (ONB) occurred at heat flux of 200 kW/m^2 and 18K of the wall superheat. Nucleate boiling bubbles occurred at heat flux of 200 kW/m^2, but due to the 25K subcooling of the working fluid, the bubble was very small in size and condensed at the same time as it was produced, so there was no departure from the heating surface. As the heat flux increased from 400 kW/m^2 to 1200 kW/m^2, the departure of very small bubbles increased, and at 1600 kW/m^2 to 2000 kW/m^2 the merged bubbles occurred, moving upward from the bottom of the heating surface to the top of the heating surface as shown in Fig. 4. The size of the merged bubbles increased up to 2000 kW/m2, accelerated the departure cycle, and CHF occurred at the heat flux of 2050 kW/m^2 and the wall superheat temperature of 59K.

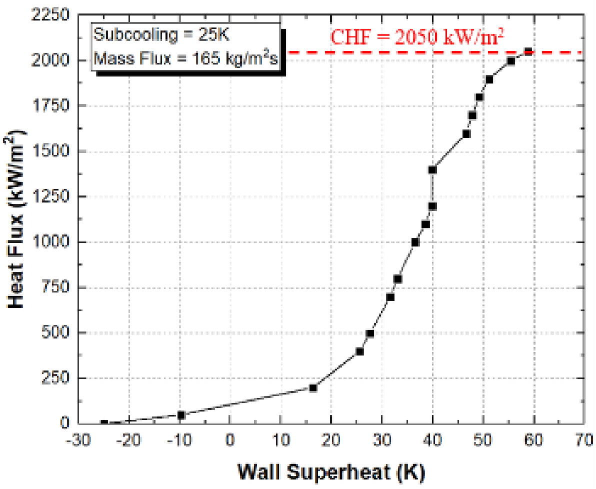

Fig. 3. Steady state boiling curve of subcooled flow boiling experiment.

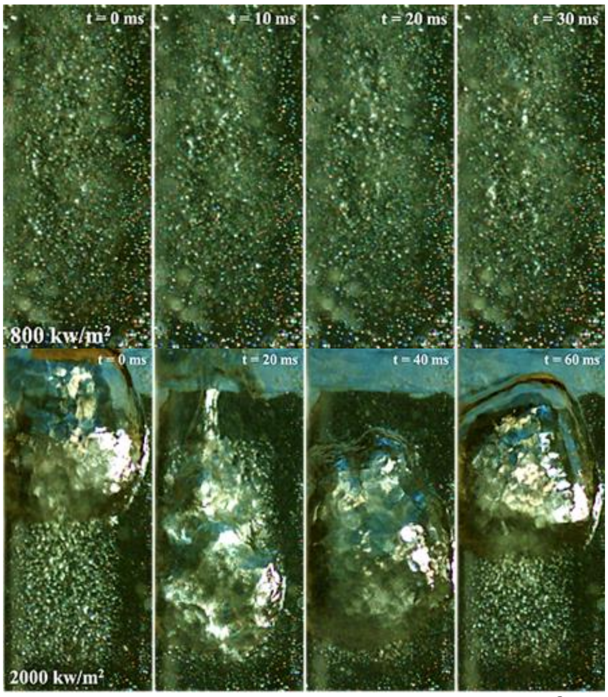

Fig. 4. High-speed video results at heat flux of 800 kW/m^2 and 2,000 kW/m^2.

The flow boiling CHF under subcooled and low-quality conditions is generally very similar to the pool boiling CHF mechanism [5]. Because the vapor mass formed at the bottom of the heating surface departs to the top of the heating surface, less contact with the working fluid increases the dry region formation and temperature at the top of the heating surface, and CHF occurs when high heat fluxes make it impossible to rewet the working fluids due to local dry area expansion and temperature rise.

3.2 Acoustic analysis results of flow boiling

Before measuring the flow boiling experimental acoustic emission (AE) signal, the background signal (or background noise) was measured by adjusting the AE measuring threshold voltage, and 30dB was selected as the threshold amplitude. AE signal generated by flow and boiling is converted into an electrical signal via a contact acoustic sensor, amplified by the pre-amplifier, and passed to the AE signal processing system for user visibility. The measured signal is an electrical signal sine wave, and for interpretation, representative parameters for each acoustic emission signal, such as event count, amplitude, energy, and frequency were extracted. The descriptions of each parameter are as follows.

1) Counts: The number of occurrences of AE signals with amplitude greater than the voltage threshold set.
2) Amplitude: the amplitude of the AE signal being measured.
3) Frequency: The frequency of the AE signal being measured.

4) Energy: Indicates the elastic deformation energy in the medium that produces AE signals

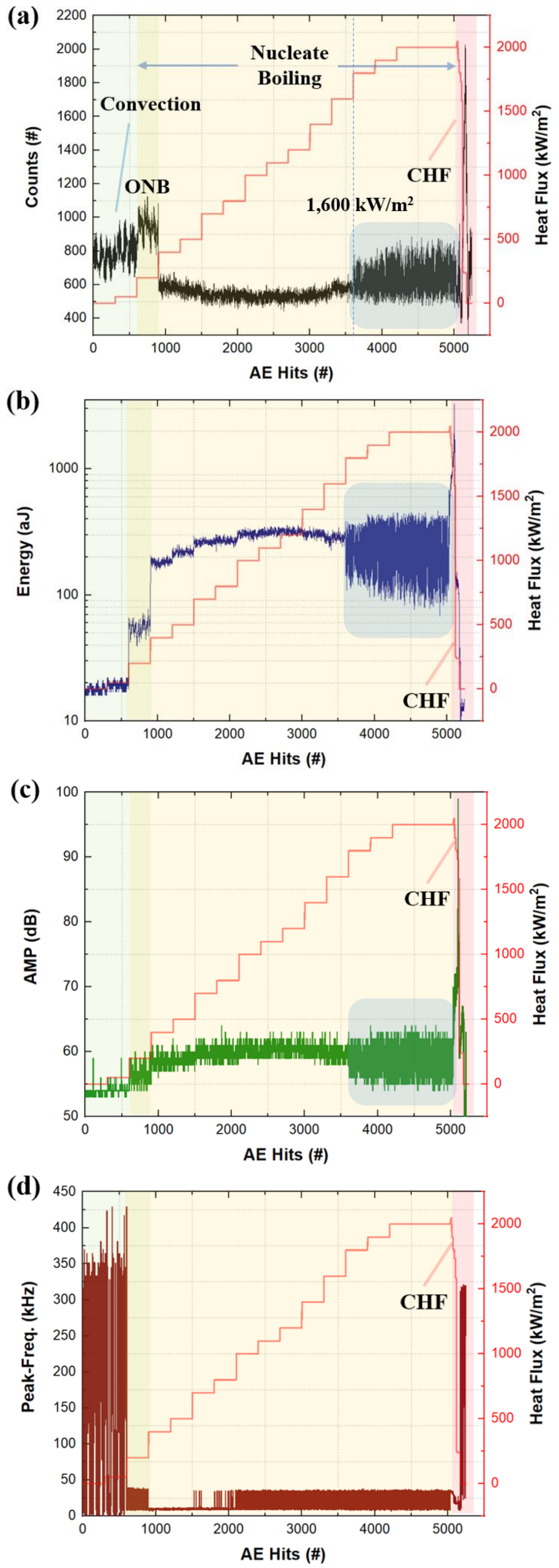

Fig. 5. Analysis of AE signal features (a) Counts, (b) Energy, (c) Amplitude, and (d) Peak frequency.

Fig. 5 shows the change in AE signal characteristics according to the heat flux and boiling heat transfer regimes at the number of events, energy, amplitude, and peak frequency. In a convection regime, the number of events by flow is measured more than the number of events produced by boiling, but the energy, intensity, and amplitude of the signal are very small. The peak frequency distribution of AE signals is not constant and is over a wide range, a phenomenon that occurs when signals from various sources of sound are measured rather than signals measured by one or two physical phenomena. The main phenomenon is the flow and nucleate bubble, department, and merge from ONB to CHF occurrence in flow boiling experiments.

After ONB, AE signal characteristics are similar to the increase in heat flux, and then the values of the count, energy, and amplitude are scattered as if they were vibrating from the heat flux of 1800 kW/m^2. This vibration-like change can be understood from the flow boiling visualization result according to time changes in Fig. 4, where periodically merged boiling bubbles cover the entire heating surface and are rapidly moved and depart from the bottom to the top of the heating surface. Because of the generation, movement, and departure of periodically merged boiling bubbles, they prevent the generation of nucleate boiling and the generation of AE signals by flow, resulting in a small number and weak AE signals.

4. Conclusions

In this study, the characteristics of the convection regime, ONB, nucleate boiling regime, and CHF were identified through the AE signal analysis, and although it was a non-linear result, it was found that there is a boundary to distinguish each regime and the flow boiling heat transfer phenomena.

The meaning of this result is that the characteristics of the AE signal in the flow boiling heat transfer system, which cannot be visualized, are considered to be useful for determining whether there is an ONB inside the system, the generation of merged boiling bubbles, heat flux identification, and early warning before the occurrence of CHF.

Acknowledgement

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