Identifying Heat Transfer Regimes by Acoustic Analysis in Pool and Flow Boiling

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1. Introduction

Ensuring the integrity of fuel rods during the operation and design basis accident (DBA) in the nuclear power plant (NPP) is major concerning issues to maintain the heat transfer and prevent the fission product release. when compared to boiling heat transfer and liquid single-phase heat transfer, a critical heat flux (CHF) or a departure from nucleate boiling (DNB) as known as a thermal margin of NPPs results in a low heat transfer coefficient due to the formation of a vapor film insulator on the fuel rods [1]. Thereby, CHF leads fuel rods to a sudden rise in temperature and cracking and melting. To prevent the thermal damage in fuel rods, the CHF prediction in NPPs has been conservatively derived from the experimental correlation using the parameter related to flow regimes and boiling phenomena such as temperature, pressure, and flow rate and, etc. However, this conservative approach is not an effective reactor design because it secures an excessive thermal margin. And there is a limitation that conventional diagnosis technologies such as thermocouples, flowmeters, and pressure gauges have a relatively long response time to the physical changes as shown in Table 1 so that these could not provide direct physical information to identify the flow and boiling phenomena [2].

For the improved safety and efficiency in NPPs, monitoring and identifying the physical parameters of the flow regime and boiling regime are essential. To do so, Acoustic analysis, a non-destructive diagnostic technology, is a promising method to measure the condition of an inaccessible system. Acoustics detects the acoustic emission (AE) signals from the system undergoing irreversible elastic changes, such as crack formation [3]. This technology looks forward to allows the real-time measurement of the flow and boiling information of the reactor system as well as the prediction of CHF.

There were fundamental studies of AE signal measurement of the boiling experiment to the identification of flow and boiling regimes [4-6]. Seo and Bang [4] conducted a quenching experiment with the frequency power spectrum analysis of boiling AE signals. They reported that each boiling regime had distinguishable AE frequency peaks, and the bubble collision and collapse showed a relatively higher AE frequency than the bubble growth. Under the pool boiling conditions, Sinha et al. [5] experimented and developed a frequency-based real-time power cut-off system when CHF occurs. Alssayh et al. [6] showed that statistical method-applied AE analysis successfully classified the two-phase flow regimes.

Table 1: Response time of diagnosis technologies [2]

Parameter	Instrument	$T_{Response}$ (s)	Structure
T	Thermocouple	1.0~3.0	Analog
P	Pres. gauge	1.0~2.0	Analog
Q	Flowmeter	0.05~2.5	Analog
AE	AE sensor	< 0.001	Digital

In this study, to identify both flow and boiling regimes inside the system non-destructively, a pool boiling experiment with measuring AE signals was conducted under atmospheric pressure using deionized water as a first step. At the same moment, visualized images were captured by a high-speed video (HSV) and Infrared (IR) thermometry. To classify boiling regimes, boiling heat transfer characteristics were analyzed based on AE signals features while compared with the visualized images. Then, the flow boiling experiment with measuring AE signals were designed to compare the AE data characteristics from pool boiling phenomena under low quality and subcooled condition.

2. Experiment

2.1 Pool Boiling Experiment

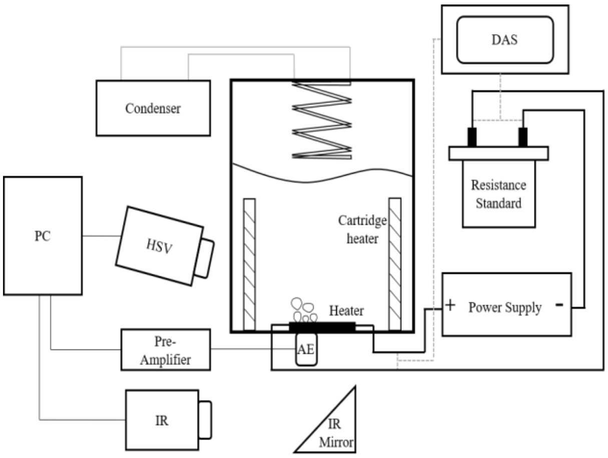

Fig. 1. Schematic design of the pool boiling experiment apparatus

As shown in Fig. 1, the pool boiling experiment apparatus composed of the boiling chamber, cartridge heater, condenser, power supply, resistance standard, HSV, IR camera. The 15 x 32 mm^2 plate SiO_2/ITO surface was used as a heater and electrically heated. Boiling phenomena were observed by HSV and the heater temperature was derived from IR thermometry. To measure the AE signals of boiling phenomena, a wide bandwidth frequency contact AE sensor was attached under the backside of the SiO_2/ITO surface and connected to a pre-amplifier and PC for AE data acquisition. The pool boiling experiment was the heat flux-controlled experiment such that the heat flux increased stepwise from 0 to CHF (~900 kW/m^2). The deionized water was used as a working fluid and all experiment was conducted under saturation condition and atmospheric pressure.

2.2 Flow Boiling Experiment

The flow boiling experiment loop was composed of the preheater, the test section, pump, condenser, surge tank. To compare the boiling AE characteristics from pool boiling, the test section used 15 x 32 mm^2 plate SiO_2/ITO heater, the same heater in pool boiling experiment, which electrically heated by 5.25kW power supply (150V, 35A) and heat flux can be applied until 3,125 kW/m^2. As same as in pool boiling, the flow and boiling phenomena were observed by HSV and the heater temperature was derived from IR thermometry. AE signal measurement was conducted in the same way. The experiment was carried out under low pressure and low mass flux (LPLF) conditions.

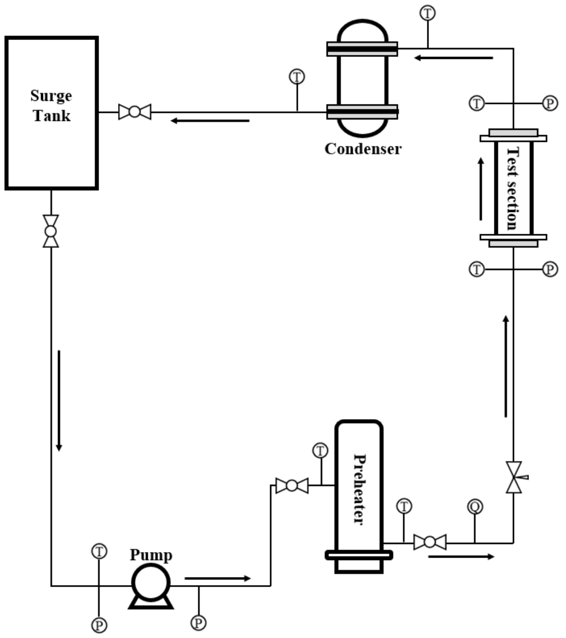

Fig. 2. Schematic design of the flow boiling experiment apparatus

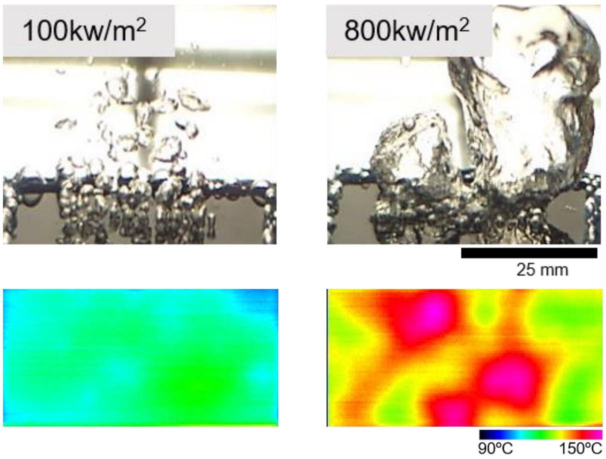

Fig. 3. High-speed images of boiling phenomena at low heat flux (upper left) and high heat flux (upper right), and temperature images of heater surface (bottom)

3. Result and Discussion

As a result, the CHF of the pool boiling experiment was 861 ± 40 kW/m^2 with wall superheat of 35 ± 0.4 K. Boiling phenomena were captured by HSV as shown in Fig. 3. At the low heat flux of 100 kW/m^2, the isolated nucleate boiling was observed while the coalescence nucleate boiling was observed due to the vigorous nucleation at the high heat flux of 800 kW/m^2. Such as, it was expected that these different boiling phenomena would affect the AE signal trend following the heat flux.

From the AE signal results, a total of ~16,000 AE signal data were measured and composed of ~2,900 AE data of natural convection regime, ~13,000 AE data of nucleate boiling regime and 6 AE data of CHF regime. Because the experiment was cut off for the heater protection from the thermal damages by the sudden temperature rise in the heater at CHF, the only six CHF AE data was measured. These AE data will be utilized to find the criteria that can classify the boiling regimes.

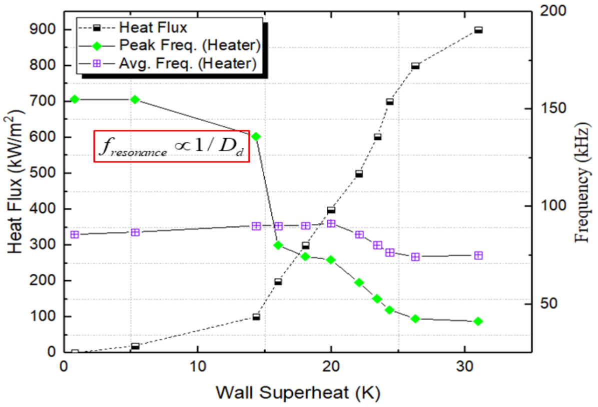

Fig. 4. Peak and average AE frequency in pool boiling following the heater wall superheat

As an acoustic analysis, the frequency analysis of AE signals was carried out to figure out the distinguishable characteristics. From Fig. 4 the pool boiling experiment with measuring AE signals showed that the count of the AE signal was determined by the bubble departure frequency at the heated surface. Besides, when the isolated nucleation and coalesced nucleation occurred, the different tendency in the maximum AE frequency was shown such that it was decreased in inverse proportion to the bubble departure diameter, meaning the coalesced bubble have low Laplace pressure and it led to low maximum AE frequency. While the conventional pool boiling studies have analyzed the visualized images and the temperature distribution images to identify the bubble departure diameter and departure frequency, this result is expected to provide that AE signal measurement can be used to identify the variation of departure diameter and frequency of the bubble without visualization.

As another acoustic analysis, the frequency and amplitude analysis, called power spectrum analysis, was performed by applying a Fast Fourier Transform. The Fourier transform is a decomposition of the signal measured over time into a periodic function having various frequencies. As a result, an energy spectrum density graph expressed as both amplitude and frequency was derived as shown in Fig. 5. The purpose of the power spectrum analysis is to determine the specific frequency that can classify each boiling regime. However, the specific frequency that can distinguish boiling regimes is not identified.

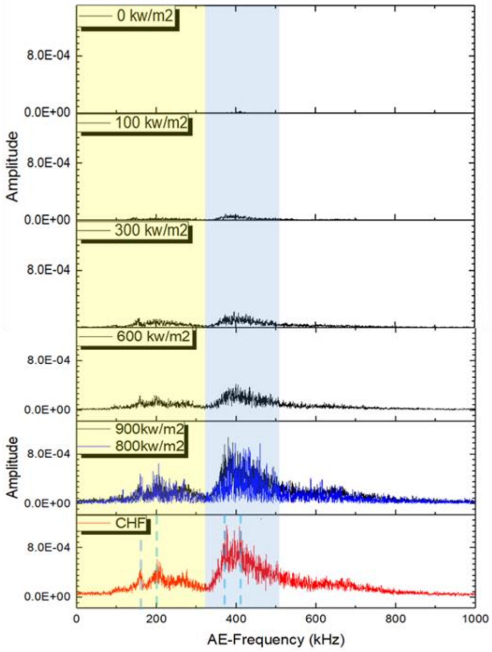

Fig. 5. Power spectrum analysis of pool boiling AE signals according to the heat flux

At the flow boiling experiment, the preliminary flow test was successfully finished. As a next step, using the pool boiling AE signal characteristics following each heat transfer regime, flow boiling experiment with measuring AE signals will be carried out in rectangular channel under low pressure and low mass flux (LPLF) condition. This experiment will show that it can be applied to identifying and monitoring technology of flow regimes and boiling regimes through acoustic analysis of measured AE signals.

4. Summary

Monitoring and identifying the flow and boiling phenomena within a nuclear power plant is the essential technology for the safety and effective operation. However, existing detectors such as thermocouples, flow meters, and pressure gauges could not provide sufficient information to classify the flow and boiling regime in the reactor. In this study, to identify boiling phenomena inside the system non-destructively, a pool boiling experiment with measuring acoustic emission (AE) signals from boiling phenomena was carried out under atmospheric pressure using deionized water, and for comparison, visualization by a high-speed video and Infrared thermometry was conducted at the same time. Using revealed AE signal characteristics from pool boiling, as the next step, flow boiling experiment with measuring AE signals will be carried out in rectangular channel under low pressure and low mass flux (LPLF) condition.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Energy Research Program through the National Research Foundation of Korea (NRF) funded by the Korea government (MSIT) (No. 2018M2B2A9066012).

REFERENCES

[1] Westinghouse Electric Company LLC., The Westinghouse Pressurized Water Reactor Nuclear Power Plant, 2006.

[2] J. B. Coble et al., A Review of Sensor Calibration Monitoring for Calibration Interval Extension in Nuclear Power Plants, Technical Reports. PNNL-21687, Pacific Northwest Natl. Lab. Richland, Wash, USA, no. August 2012.

[3] R. V. Williams and H. Saunders, Acoustic Emission, vol. 104, no. 1. 1982.

[4] S. Bin Seo and I. C. Bang, Acoustic analysis on the dynamic motion of vapor-liquid interface for the identification of boiling regime and critical heat flux, International Journal of Heat Mass Transfer, vol. 131, pp. 1138-1146, 2019.

[5] K. Nishant Ranjan Sinha et al., In-situ acoustic detection of critical heat flux for controlling thermal runaway in boiling systems, International Journal of Heat Mass Transfer, vol. 138, pp. 135-143, 2019.

[6] M. Alssayh, A. Addali, D. Mba, and T. Dao, Identification of Two-Phase Flow Regime Using Acoustic Emission Technology, International Journal of Mechanical and Production Engineering, no. 16, pp. 2320-2092, 2013.