Feasibility study of acoustic-based analysis on vapor-liquid interface motion in CHF

Seok Bin Seo, In Guk Kim, In Cheol Bang*
Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST)., 50 UNIST-gil, Ulju-gun, Ulsan 44919
**Corresponding author: icbang@unist.ac.kr*

1. Introduction

Boiling crisis is a fundamental phenomenon beneath the transition between the nucleate boiling and film boiling. The occurrence of boiling crisis is generally referred as a critical heat flux (CHF) during the transient boiling, while the underlying mechanism of CHF has not been clearly revealed.

The hydrodynamic instability model, one of CHF models proposed by Zuber [1], suggested that the boiling transition was induced by growing interfacial perturbation between two fluids of different densities which later disrupts the liquid penetration to the heated surface. The most dangerous wavelength is calculated by first-order perturbation analysis of hydrodynamic stability where the interfacial disturbance is most likely to grow. Extended from Zuber's model, several researchers modified most dangerous wavelength based on their assumptions and experimental data [2,3]. However, the existence of critical wavelength has been verified only by indirect methods such as conceptual assumptions or visualized images.

The present paper employs acoustic emission (AE) technique to directly measure the wave information associated with the liquid-vapor interface motion. AE measurement has its advantages in non-destructive and in-situ diagnosis and monitoring the elastic wave propagated through the surface. The recent studies [4-6] provided the use of AE signal to detect the wave information during the quenching process, and further characterize the boiling crisis [6]. The present study analyzes the AE signal based on the hydrodynamic instability theory and characterizes it by wave information and visualized images to verify the feasibility of AE measurement for diagnosis of boiling crisis.

2. Experimental setup

The conventional pool quenching experiments were performed using small stainless steel 316L sphere with the diameter of 10mm. An imbedded thermocouple (K-type, φ=0.5mm, OMEGA) sheathed by Inconel was located at the center of the test section sphere. In this study, the working fluid is distilled water at the atmosphere pressure and room temperature. During the experiment, temperature history of the test section was measured accompanied with the optical visualization using high-speed camera. The scheme of the experimental facility is shown in Fig. 1.

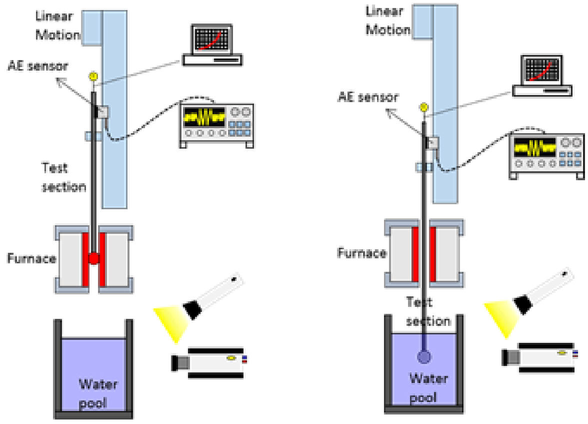

Fig. 1. The schematic diagram of experimental facility with AE sensor and high-speed camera.

For the measurement of AE signal, a contact pressure transducer (Micro30, MISTRAS) was installed on the rod of test section. The recorded AE signal was synchronized with the temperature and visualized images. A Fast Fourier Transform (FFT)-based nonparametric method was employed to analyze the AE signal in spectrum.

A test matrix of experiment is shown in table I. For each set of experiment, the test section is initially heated up to 850°C and submerged into distilled water with subcooling degree of 20°C. The surface condition was maintained in as-received condition without any treatment.

Table I. Test matrix of experiments

Test section conditions	
Test section material	Stainless steel 316L
Test section geometry	Sphere (D=10mm)
Initial temperature of test section	850 °C
Fluid conditions	
Cooling fluid	Water
Subcooling degree	20 °C

3. Results and Discussion

3.1 Boiling curve

Fig. 2 presents the resulting plot between surface temperature and heat flux by inverse heat transfer method. Following the boiling curve from high temperature, convective and radiation heat transfer through the vapor film is replaced with the nucleate boiling at the Leidenfrost point where the vapor film collapses resulting in the sharp rise of the heat flux. The boiling region of interest in this study is placed between Leidenfrost point and the maximum heat flux point, referred as transition boiling region. In the transition boiling region, the generation of bubbles and collapse of vapor film coexists due to the growing perturbation of liquid-vapor interface based on the hydrodynamic instability theory, thus the distinct wave information is expected.

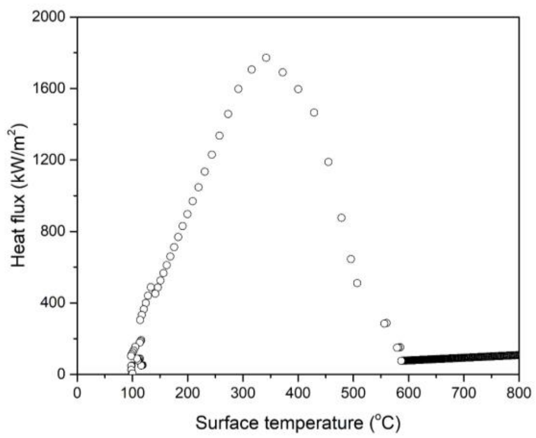

Fig. 2. Boiling curve by inverse heat transfer method

3.2 Acoustic characteristics

The absolute AE energy, which is a typical acoustic characteristic, is presented with boiling curve in Fig. 3. In the film boiling regime, the variation of absolute AE energy is small, while it drastically increased in the transition boiling regime. The maximum absolute AE energy appears near the transition point from the film boiling to nucleate boiling, clearly shown with the boiling curve. At each transition point between boiling regimes, absolute AE energy shows peak and then decreases to the certain point. These peak values in absolute AE energy gives the evidence of sudden change in boiling phenomenon. In principle, the largest energy is generated by the collapse of vapor bubble during the typical boiling, among the three major sources of AE: dramatic growth of vapor bubble, departure of bubble from the surface, and the collapse of vapor bubble. Then the peaks of AE energy at the transition points implies the initiation of vapor film collapse in film boiling and completed collapse of vapor blankets in transition boiling.

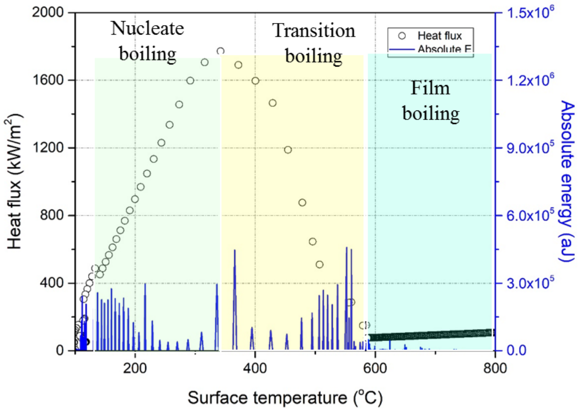

Fig. 3. AE absolute energy with boiling curve

Fig. 4 presents the visualized images during the boiling process together with AE energy plot. The images show that the strong perturbation of liquid-vapor interface, shown at 21~22 s, initiates the collapse of vapor film, finally leading to the boiling crisis. The synchronized results verify that the time period where the collapse of vapor film (or blanket) is initiated and completed, is consistent with the time period where the AE energy peaks. Thus, it is qualitatively clarified that the AE signal is highly associated with the boiling phenomena, especially liquid-vapor interface motion.

Fig. 5 presents the power spectrum density resulted from FFT analysis. The distinct power spectrum densities are clearly shown in different boiling regimes. In film boiling regime, peak of power spectrum density is placed in high frequency range, while the peak appears at low frequency region in nucleate boiling regime. In the transition boiling regime, both peaks appear, which is consistent with the feature of transition boiling that both generation of bubbles and collapse of vapor film coexists. In addition, the unique peak is placed at the highest frequency range near boiling crisis. The high frequency with high amplitude in film boiling provides high wave energy, while the number of events is small. This feature reflects the wavy motion of liquid-vapor interface attached to the surface due to the perturbation. On the contrary, the number of events increases in nucleate boiling, while wave energy of each decreases with low amplitude, reflecting conventional vapor bubble formation on the surface. Thus, it is qualitatively verified that the acoustic characteristics and vapor-liquid interface motion are highly associated.

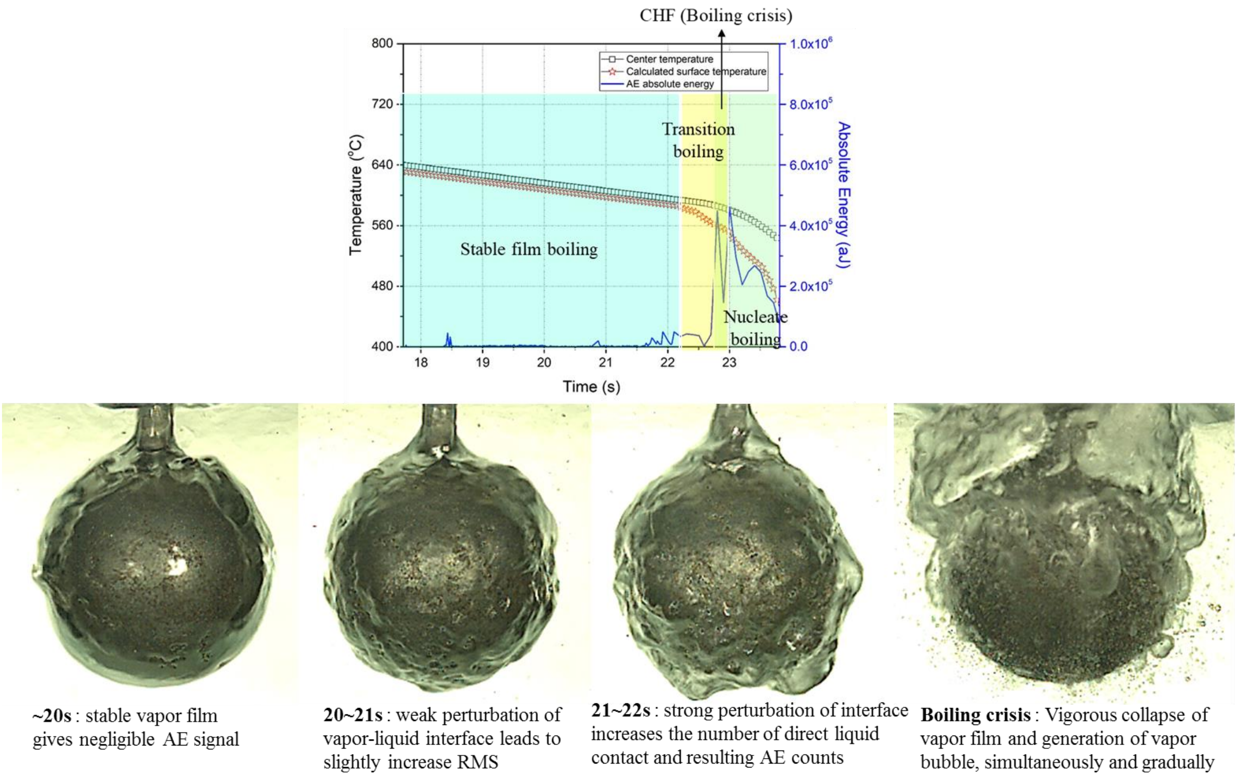

Fig. 4. Representative images of test section during each time period in AE absolute energy plot

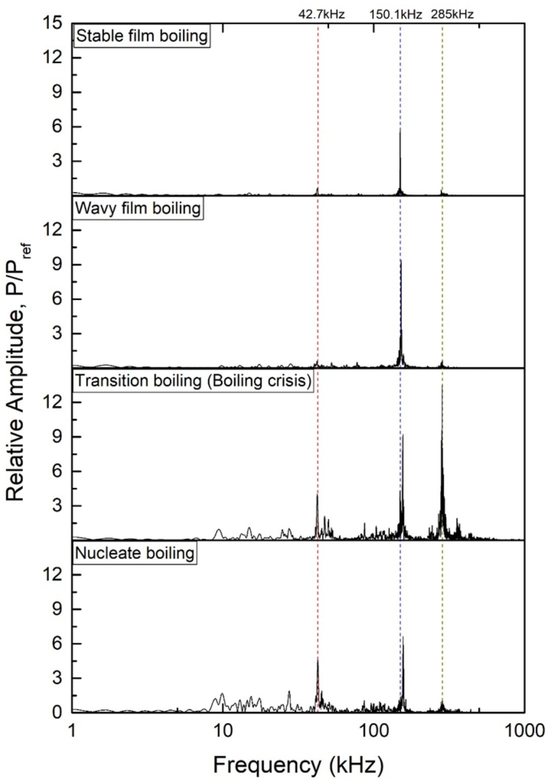

Fig. 5. Power spectrum density of AE signals in different boiling regimes

3.3 Hydrodynamic instability model and AE signal

The liquid-vapor interface motion is analyzed based on the visualized images. Fig. 6 shows the time-dependent history of vapor-liquid interface position analyzed from visualized images and its spectrum is shown in Fig. 7.

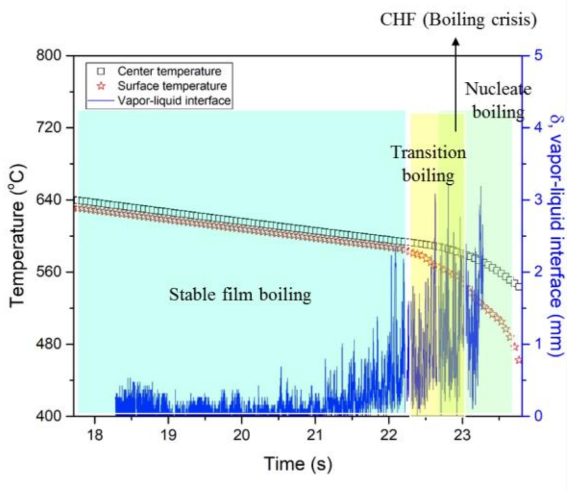

Fig. 6. Plot of vapor-liquid interface position with the time

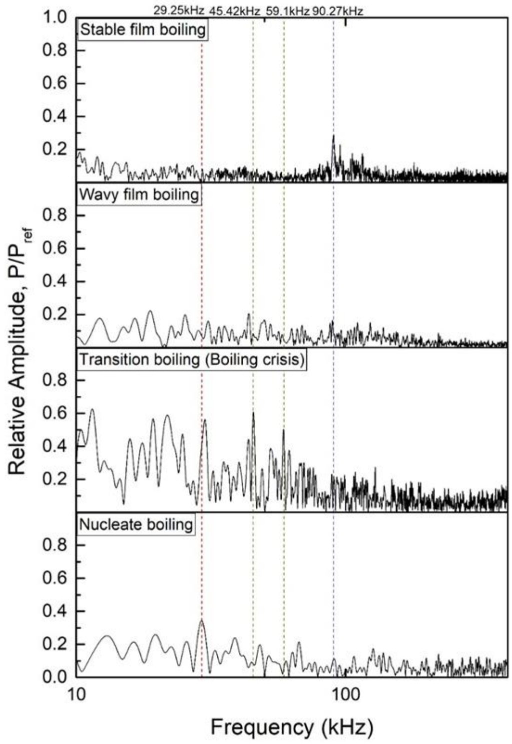

Fig. 7. Power spectrum density of vapor-liquid interface wave in different boiling regimes

The power spectrum of vapor-liquid interface showed distinct peaks in different boiling regimes, which is consistent with that of AE signals. Relatively higher amplitude in higher frequency range appears in film boiling than that in the nucleate boiling. In addition, combined peaks are placed in the transition boiling regime with unique peak representing the feature of boiling crisis. The high amplitude in high frequency range in film boiling refers the collapse of vapor film, or interface wave. Then its existence in transition boiling regime and the disappearance during transition to the nucleate boiling implies that the interface wave is the only possible parameter which dominates the critical point for boiling crisis. In addition, the unique peak near boiling crisis refers the distinct wave parameter, such as frequency, which is consistent with the fundamental assumption of hydrodynamic instability model that the perturbation of interface at the certain wave number leads to the boiling crisis. Finally, the relationship between the vapor-liquid interface motion and boiling crisis, and the qualitative evidence of hydrodynamic instability near boiling crisis is verified. The further study will quantitatively analyze the wave information from AE signal based on the theoretical development of the wave parameters.

4. Conclusions

The conventional pool quenching experiments accompanied with the optical visualization and measurement of AE signal are performed to figure out the relationship between the dynamic motion of vapor film and AE signal. The vigorous motion of vapor-liquid interface is observed which leads to distinct AE signal. It is also observed that the collapse of vapor film produces notable signal. The power spectrum densities of different boiling regions reflect their distinct wavy motion of liquid-vapor interface. Especially, the unique feature of AE signal is detected near boiling crisis. The visualized images of vapor-liquid interface motion verify the close relationship between interface wave and boiling crisis. The existence of vapor film collapse in transition boiling regime and its disappearance during transition to the nucleate boiling imply that the interface wave is the only possible parameter which dominates the CHF. It largely supports the fundamental assumption of hydrodynamic instability model, verifying the evidence of critical wave parameter of vapor-liquid interface near CHF.

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