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In-situ Monitoring of Sub-cooled Nucleate Boiling on Fuel Cladding Surface in Water at 1 bar and 130 bars using Acoustic Emission Method

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1. Introduction

Crud is a corrosion product deposited on fuel cladding surface in pressurized water reactors [1]. When cruds are deposited on the fuel cladding surface, boron can be accumulated in the pores of the deposits as a concentrated liquid or solid phase of boron chemicals. This boron can change the distribution of neutron flux and power along the axes of the fuel assemblies. It can then cause an axial offset anomaly and a power reduction of the NPPs consequently [2]. This phenomenon can decrease core shutdown margin, and lead to a down-rating of the plant. In addition, the crud may also accelerate the corrosion rate of the cladding materials, which is referred to as crud induced localized corrosion [3].

Crud deposition is accelerated on the wall surfaces under a heat transfer condition of subcooled nucleate boiling (SNB) [4,5]. The SNB process occurs when the outer cladding wall temperature is higher than the saturated coolant temperature and the bulk coolant temperature remains below the saturation temperature. In this condition, the superheated coolant adjacent to the wall surface starts to nucleate bubbles at preferential sites on the cladding surface. Crud deposition increases through a sufficient corrosion product supply around the steam-liquid interface of a boiling bubble. Therefore, the understanding of this SNB phenomenon is important for effective and safe operation of nuclear plants.

The experimental SNB studies have been performed in visible conditions at a low pressure using a high-speed video camera [6,7]. However, the visualization tests are hard to apply to the SNB phenomena occurring under a high temperature and high pressurized water condition such as the primary coolant system.

Meanwhile, an acoustic emission (AE) method is an on-line non-destructive evaluation method to sense transient elastic wave resulting from a rapid release of energy within a dynamic process. This method is widely used in metal corrosion [8], plastic deformation [9], crack growth [10], and various chemical engineering processes including bubble dynamics [11]. Some researchers have investigated boiling phenomena using the AE method [12]. However, their works were performed at atmospheric pressure conditions.

Therefore, the objective of this work is for the first time to detect and monitor SNB on fuel cladding surface in simulated PWR primary water at 325^{o}C and 130 bars using an AE technique. To achieve this goal, a series of visualization tests is performed first to identify a correlation between water boiling phenomenon and AE signals in a transparent glass cell at 1 bar. Based on the visualized tests at 1 bar, the AE signals obtained at 325^{o}C and 130 bars are analyzed in terms of various AE parameters.

2. Experimental

The experimental apparatus used for boiling test and AE data acquisition at 1 bar is schematically shown in Fig. 1. The boiling test was carried out in a transparent glass cell so that the boiling phenomenon could be observed visibly. The water boiling was realized via a stepwise heating the cladding tube (ZIRLO^{TM}, Westinghouse, USA) by the internal heater (heated zone = 250 mm, maximum power = 80 W/cm^2). The detailed control of the water boiling process is as follows: First, the bulk water was heated to 95^{o}C using a hot plate, i.e., 5^{o}C lower than the saturation temperature at 1 bar. When the temperature of the bulk water was stabilized at 95^{o}C, the power of the hot plate was switched off. Afterwards, the internal heater was quickly powered on and the cladding tube was heated until the temperature of the internal heater (T_{IH}) was stabilized at 120^{o}C. At this stage, the boiling behavior on the cladding surface was observed using a digital camera and the AE data was simultaneously acquired for 500 s. After these measurements were done, the cladding tube was heated by stepwise increasing the T_{IH} from 120^{o}C to 180^{o}C with an increment of 20^{o}C per step. At each step of temperature, observation of the boiling behavior and acquisition of the corresponding AE data were made for 500 s.

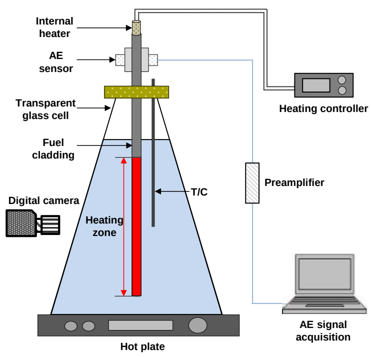

Fig. 1 Schematic of experimental apparatus used in the test at 1 bar.

The boiling test in a flow water condition was performed in a circulation loop with a mass flow rate of about 280 ml/min at 130 bars. The circulating loop system consisted of the following main components: solution tank, high pressure pump (HP pump), preheater, back pressure regulator (BPR), heat exchanger and test section equipped with a cladding tube as shown in Fig. 2. The inlet water into the test section was preheated and the bulk water temperature in a test section was maintained at 325^{o}C. Similar to the tests at 1 bar, the cladding tube was heated using an internal heater by stepwise increasing the T_{IH} from 340^{o}C to 400^{o}C with an increment of 20^{o}C. At each temperature, the AE data were measured for 500 s.

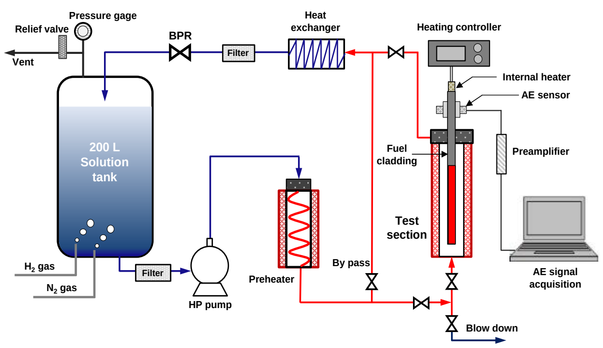

Fig. 2 Schematic of the circulating loop system used in the test at 130 bars.

In attempting to investigate the boiling behavior on the fuel cladding surface, an AE sensor was directly coupled to the upper end of the fuel cladding tube, as shown in Figs. 1 and 2. The AE sensor was connected to a preamplifier (2/4/6 Preamplifier, Physical Acoustic Corporation, USA), then the preamplifier was connected to the AE signal acquisition system. The obtained AE signals can be analyzed by various AE parameters in AE-win software (Model: PCI-2, Physical Acoustic Corporation, USA). The AE sensor (type R3a, 30-75 kHz resonant frequency, MISTRAS, PAC, USA) was chosen to collect the AE-boiling signals, which were filtered using a low pass of 100 kHz. In this test, the AE signals were amplified with a gain of 40 dB, and the threshold value set at 48 dB to eliminate the background noises.

3. Results and discussion

3.1 Analysis of water boiling- AE signals at 1 bar

Fig. 3 shows the visualization images of the water boiling and the raw AE data in average frequency domain obtained during the boiling test at 1 bar. As shown in Fig. 3 (a), the boiling process was divided into four zones, i.e., A, B, C and D. No water bubble was observed in zone A, and single-phase natural convection from the heated surface to the bulk water without formation of bubbles was observed. Water boiling,

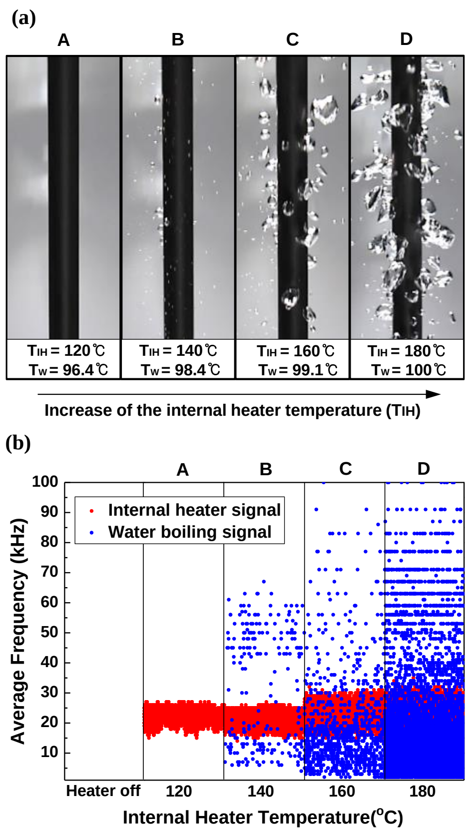

Fig. 3 (a) The visualized images showing the evolution of the boiling process; (b) The AE signals of the water boiling and internal heater in average frequency domain versus the temperature of internal heater during the test at 1 bar.

which means nucleate boiling in this condition was observed in zone B, C, and D. In case of the zone B, bubbles began to form on the cladding surface, and collapsed immediately near the cladding surface. With the increase of the T_{IH}, bubbles size, density and nucleation sites in the zone C were increased. During water boiling in this zone, bubbles were formed on the cladding surface and departed from the surface, and then finally collapsed in the solution. In the boiling zone D, bubbles having large size and nucleation sites of high density were observed on the cladding surface. Then, water temperature (T_W) was raised up to 100^{o}C, which is equal to saturation temperature at 1 bar. Bubbles were observed to rise to the water surface and burst, which means that the saturation boiling was reached.

Combined with the above observation, the AE signals obtained during the test were analyzed. Fig. 3 (b) shows the AE signals in average frequency domain, which was also divided by four zones (i.e., A, B, C, and D) corresponding to Fig. 3 (a). When the use of internal heater did not start, no AE signal was detected. However, when the internal heater was operated in zone A, the AE signals were densely detected in a narrow band between 15 kHz to 30 kHz. Considering water boiling was not present yet, the AE signal of the zone A was attributed to the internal heater noise. As the bubbling zone moved from B to C and D, the distribution of the AE signals was expanded to a wider frequency range. The AE signal density was also apparently increased. These changes are in good agreement with the boiling behavior observed in Fig. 3 (a). Therefore, the new group colored in blue is reasonably attributed to the boiling process, while the group in red color is from the internal heater.

With increase of T_{IH}, the density of the boiling signals increased both in high frequency range and in low frequency range. In addition, their distribution was concentrated more in a low frequency range than a high frequency range. According to an equation between AE frequency and bubble diameter [12], the AE frequency of bubble is inversely related to the bubble diameter. In addition, from above visualized result, the bubble size confirmed to be increased with the boiling zones moved from B to D. This means that the signal of a low frequency is generated from big bubbles, while the signal of a high frequency is emitted from small bubbles, in this frequency data. Therefore, this frequency data showed that the boiling signals were detected successfully corresponding to visualized boiling behavior.

3.2 Analysis of water boiling- AE signals at 130 bars

Fig. 4 shows the AE raw data in average frequency domain obtained at 130 bars. The AE signals having two different characteristics were detected as the test at 1 bar. One of them was detected in the form like a band in the frequency range of between 10 kHz to 30 kHz, and the other was relatively widely distributed in the frequency range of between 1 kHz to 72 kHz. According to previous result, it is known that the signals concentrated in the range of 10 kHz to 30 kHz is the heater signals, and the signals distributed in the range 1 kHz to 72 kHz is the boiling signals.

The boiling signals were distributed evenly in the range of each T_{IH}. In addition, the boiling density was increased slightly with the increase of T_{IH}. Considering that the bubble size in a low frequency range was increased as the AE frequency data at 1 bar, the change of bubbles size with the increase of T_{IH} at 130 bars condition was no significant difference. Furthermore, boiling density also seems not significantly increased with increasing the T_{IH}. The bubble size and density can be affected by flow parameters, such as mass flux, sub-cooling and high pressure. It was reported that higher pressure makes the size of the bubbles smaller, while higher sub-cooling causes faster bubble collapse in the cycles of bubble growth and collapse [13,14]. Therefore, the bubble size and density in flow boiling condition at 130 bars can be decreased by flow parameters.

4. Conclusions

We successfully observed the boiling AE signals in primary water at 1 bar and 130 bars using AE technique. Visualization test was performed effectively to identify

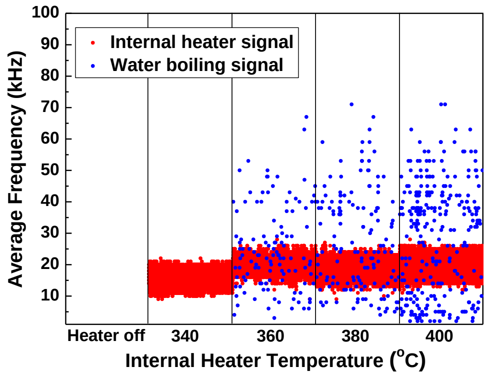

Fig. 4 The AE signals of the water boiling and internal heater in average frequency domain versus the temperature of internal heater during the test at 130 bars.

a correlation between water boiling phenomenon and AE signals in a transparent glass cell at 1 bar, and the boiling AE signals were in good agreement with the boiling behavior. Based on the obtained correlations at 1 bar, the AE signals obtained at 130 bars were analyzed. The boiling density and size of the AE signals at 130 bars were decreased by the flow parameters. However, overall AE signals showed characteristics and a trend similar to the AE signals at 1 bar. This indicates that boiling AE signals are detected successfully at 130 bars, and the AE technique can be effectively implemented in non-visualized condition at high pressures.

Acknowledgments

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