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In-situ Observation of Boiling Dynamics on Fuel Cladding Surface in Non-pressurized Water Using Acoustic Emission Method

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1. Introduction

In the PWR primary coolant system, a phenomenon of axial offset anomaly (AOA) can be caused due to accumulated boron hide out in porous CRUD deposition on the fuel cladding surface [1-2]. Up to now, the CRUD deposition has been well known to be driven by subcooled nucleate boiling (SNB) on the cladding surface based on large scale experimental work [3-5]. Therefore, monitoring and evaluation of the SNB-phenomenon is an important approach to study the CRUD deposition. Many attempts have been made to study the SNB and CRUD deposition using thermal hydraulic or model calculation [1, 3]. However, a comprehensive understanding of the SNB during CRUD deposition is still far from being realized.

Acoustic emission (AE) technique, as an in-situ nondestructive evaluation (NDE) method, has been widely used to monitor the boiling activity in containers and pipes [6-8]. Accordingly, this work aimed to investigate the exact AE characteristics of SNB-phenomenon on the fuel cladding surface at atmospheric pressure, with the purpose of providing an experimental groundwork for the AE investigation on SNB in high-temperature pressurized coolant system.

2. Experimental

A Zirlo cladding tube with an internal electric heater inserted was placed vertically to provide the surface for boiling test, which was carried out in a water-filled glass flask whereby the occurrence of boiling could be visibly observed. The test water was prepared with dissolving 3.5ppm Li and 1500ppm B following the condition of the primary coolant system. The initial temperature of the internal heater was set much higher than the saturation point of water causing nucleate boiling. Then the temperature of the internal heater was controlled to decrease gradually to generate the SNB and finally closed down after the disappearance of the boiling phenomenon. During this test, the photographic and video observations were also made.

The AE sensor (Type R3a, Physical Acoustic Corporation, USA) was directly coupled to the upper end of the cladding tube surface. The other end of the sensor was connected to the AE system (PCI-DISP, PAC) via a pre-amplifier (Type 2/4/6, PAC) set at 40dB. The background noises were tried to be minimized and the threshold value was carefully determined as 40dB. The AE signals were filtered by a band pass between 10 kHz and 100 kHz.

3. Results and discussion

3.1 AE results

Fig. 1 shows the raw AE signals detected during the boiling test. Considering the direct coupling of sensor to the tube surface, the raw signals are believed to be mixed of boiling-AE and heater noise-AE. Based on the occurrence of boiling and the process control for test, the evolution of AE signals was divided into three zones (Fig. 1), i.e., boiling, no-boiling, and no-heating zones, respectively. In no-boiling zone, the AE frequency presented to be a band of 8-26 kHz, which disappeared when the heater was shut down in the no-heating zone. Therefore, the AEs between 8 and 26 kHz were associated with the heater noise. After filtering the AEs between 8 and 26 kHz from the raw data, the boiling AEs were extracted, as shown in Fig. 2.

3.2 Optical images of SNB

Based on the water temperature and visual observation, two SNB zones were confirmed. The frames analysis on the videos which were taken by a digital camera with 30fps in SNB zone 1 and 2 were shown in Fig. 3. In SNB zone 1, the bubble formed and grew on the cladding surface, and then collapsed on the surface. In SNB zone 2, the bubble grew on the cladding surface, then departed from the surface and rose up gradually. Finally, the bubble collapsed nearby the cladding tube. Obviously, the main difference between SNB zone 1 and 2 is the occurrence of bubble departure in SNB zone 2.

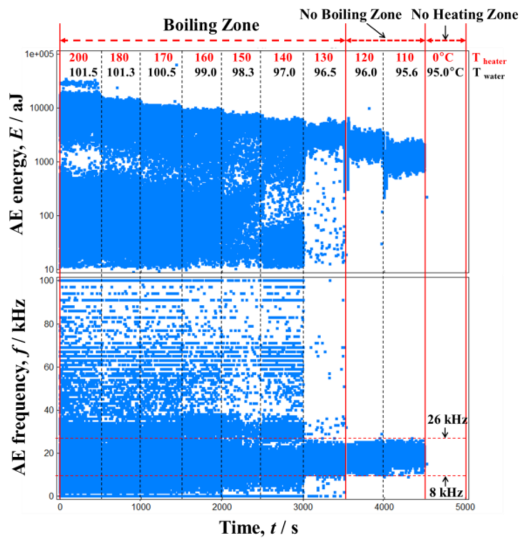

Fig. 1 Raw AE signals detected during the boiling test at 1atm in the frequency and energy domain, respectively.

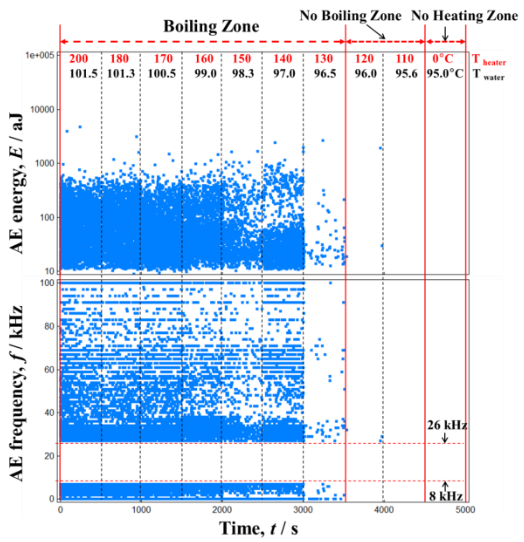

Fig. 2 Boiling AE signals in energy and frequency domain extracted after filtering the 8-26 kHz heater noise.

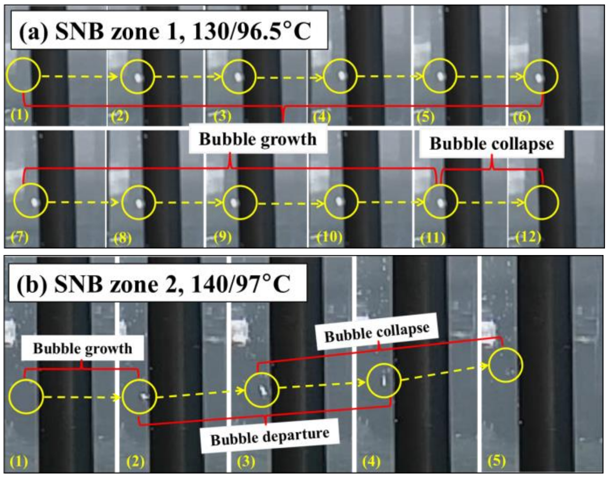

Fig. 3 Optical images of the SNB under different conditions of temperature: (a) T_{heater}/T_{water} = 130/96.5℃; (b) T_{heater}/T_{water} = 140/97℃, respectively. (Note that the interval time between frames is 1/30s.)

3.3 AE identification of SNB

The AE signals from SNB zone 1 and 2 were further analyzed with a cross-plot analysis of the corresponding AE energy and amplitude, respectively. The results were shown in Fig. 4. Taking the AE signals of SNB zone 1 into consideration, they could be roughly divided into three different groups, i.e., group 1, 2, and 3, respectively. Group 1 contains most of the AE signals. In similarity, the AE behavior of SNB zone 2 presented to be in three groups. However, the amount of the AE events from SNB zone 2 is larger than that from the SNB zone 1. This could be attributed to a positive dependence of the extent of SNB on the value of delta T between internal heater and water. (Delta T1 was 33.5℃ and delta T2 was 43.0 ℃, respectively).

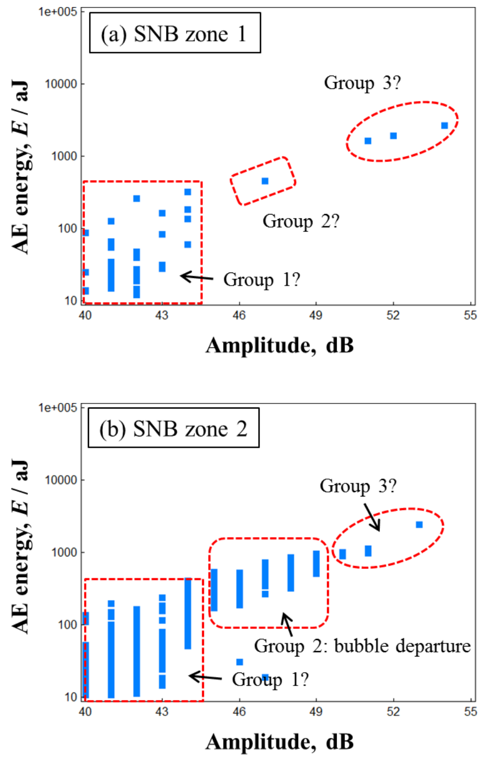

Fig. 4 Cross-plot analysis of AE energy and amplitude of the AE signals from the SNB zone 1 and 2, respectively.

In SNB zone 2, attentions should be paid to the occurrence of AE group 2, the corresponding group of which is barely existent in SNB zone 1. Considering the main difference between the images of SNB zone 1 and 2, it is believed that the AE group 2 may originate from the bubble departure during the bubble evolution in SNB. This finding reveals the potential of using AE method to quantitatively evaluate the CRUD deposition with respect to the main role of bubble departure in assisting the CRUD deposition [5]. Moreover, AE groups 1 and 3 seem to be in correlation with the bubble growth and collapse. However, the confident correlation between them does need to be further validated.

4. Conclusions

In this study, we conducted an in-situ experimental observation of the bubble dynamic of SNB in non-pressurized water at atmospheric pressure using AE method. The AE of heater noise was confirmed to cluster between 8 and 26 kHz. Three AE groups were detected during the boiling process in the SNB zones. AE group 1 and 3 seemed to be the results of bubble growth and collapse, while bubble departure from the cladding surface was reasonably associated with an isolated AE group 2. The results reveal that monitoring of the SNB-AE signals could be served as a NDE means to quantitatively evaluate the CRUD deposition.

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