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Visualization and acoustic emission monitoring of nucleate boiling on rough and smooth fuel cladding surfaces at atmospheric pressure

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ABSTRACT

The purpose of this work is to evaluate nucleate boiling phenomena occurring on as-received rough and chemically etched smooth fuel claddings in water at atmospheric pressure using the visualization method and the acoustic emission technique. The onset of nucleate boiling on the smooth cladding surface occurred at higher temperature than on the rough cladding surface. The visible boiling phenomena remarkably decreased on the smooth cladding surface compared with those on the rough cladding surface. The density and energy of AE signals emitted from vapor bubbles on the smooth cladding surface decreased than those on the rough cladding tube. The variation trend of AE signals was in good agreement with the visualization results. Therefore, it is expected that the AE technique can be effectively utilized to monitor the boiling behaviors on the heated surfaces even under non-visualized conditions.

1. Introduction

The Sub-cooled nucleate boiling (SNB) process helps to quickly and efficiently carry away the heat energy on a heated surface, resulting in an increase in the heat transfer coefficient. Therefore, SNB is a major factor in many industrial processes where liquid is used as a coolant, and has been widely investigated in nuclear power industries to enhance the efficient heat transfer on the fuel assemblies (Corletti and Hochreiter, 1991; Kang, 1998). Although favorable in terms of its thermal efficiency, the SNB process on the fuel cladding assembly is known to enhance the formation of corrosion products, called crud, that deposit on the fuel cladding surface (Ferrer et al., 2012; Deshon, 2004). Crud deposition can lead to operational and safety problems, such as a reduction in thermal conductivity, crud-induced localized corrosion, and the axial offset anomaly (AOA) (Deshon, 2004; Deshon et al., 2011; Uchida et al., 2011). Above all, because the AOA phenomenon leads to a loss of shutdown margin and safety reduction of a nuclear power plant, it is important to control SNB on the fuel cladding to prevent or mitigate this phenomenon.

SNB depends on diverse factors, such as the property of fluid, the pressure of system, the heat flux on heated surface, the temperature of coolant, and the properties of the heated material surface (Bang et al., 2004; Rabiee and Atf, 2017; Bombardieri and Manfletti, 2016). Therefore, many researchers have investigated to elucidate the correlations between the boiling dynamics and the above factors. Especially, the surface roughness is an important factor to affect the SNB phenomenon, because it is directly related with the density of the active nucleation site and the departure frequency of bubbles on the heated surface. Active nucleate site density and boiling heat transfer are affected by the shape of the nucleation site or surface roughness. Many studies regarding the effect of surface roughness have reported that nucleate boiling occurs easily on the rough surface than the smooth surface (Jones et al., 2009; Alam et al., 2013; Kang, 2000). The surface wettability is also one of the key factors affecting the bubble formation and departure dynamics from the heated surface. However, several studies regarding the effect of wettability on the bubble dynamics have reported conflicting results: for hydrophilic surface, the bubble departure frequency increases (Harada et al., 2010; Cheedarala et al., 2016; Yang et al., 2016) or reduces (Phan et al., 2009). The difference of these studies seems to occur because the boiling behavior is affected by not only the surface wettability but also other surface properties, such as thermal resistance and roughness of materials. Consequently, it is expected that the SNB behavior on the fuel cladding surface also is affected by changes in the surface roughness and wettability.

Studies for the boiling characteristics on the heated surface have been mainly investigated through visualization methods using high-speed video cameras (Bang et al., 2004; Michaie et al., 2017; Paz et al., 2015; Ramaswamy et al., 2002; Nishio and Tanaka, 2004), laser interferometry (Voutsinos and Judd, 1975), and infrared thermometry (Golobic et al., 2012). Among these methods, the high-speed video

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camera is widely used to obtain a better understanding of the bubble dynamics, such as the bubble growth, collapse, and departure or boiling dynamics including natural convection, sub-cooled nucleate boiling, and saturation boiling. This method is effective to observe the momentary boiling dynamics at a heated narrow region. However, because the materials of nuclear power plant, such as the fuel cladding tube or the steam generator tube, are accompanied by various boiling dynamics over a wide region with the deviation of coolant temperature, it is necessary to evaluate the overall boiling behavior as well as the specific observation of boiling dynamics.

Meanwhile, an acoustic emission (AE) technique is an on-line nondestructive evaluation method used to sense transient elastic waves resulting from a rapid release of energy within a dynamic process (Scruby, 1987). This technique has been efficaciously used to diagnose metal corrosion (Wu et al., 2016), plastic deformation (Kumar et al., 2015), and the initiation and propagation of micro-cracks (Ai et al., 2010). In addition, the AE technique is currently being utilized as a complementary method in the characterization of mechanisms of the bubble formation process. Several AE studies on boiling dynamics and bubble formation have proven the feasibility of this technique based on experimental data obtained from various AE parameters under certain conditions (Yiyu et al., 1985; Chicharro and Vazquez, 2014; Husin and Mba, 2010; Carmi et al., 2011; Alhashan et al., 2016; Tang, et al., 2015). However, studies for the boiling characteristics on the different heated surfaces have been actively investigated through visualization methods, while there have been no studies that clearly prove the difference in boiling behavior varying with the different surface characteristics using the AE technique to date.

Therefore, the objective of this work is to understand the difference in nucleate boiling occurring on the rough and smooth cladding surface, and to evaluate the correlation between the boiling behavior and the boiling-AE signals on the two different cladding tubes through the visualization method and the AE technique. To achieve this goal, a series of visualized boiling test was conducted in a transparent glass cell under atmospheric pressure. AE signals obtained during the boiling test were analyzed in terms of the various AE parameters. We believe that the results obtained in this work can contribute to the effective monitoring of the boiling phenomenon even under non-visualized conditions, where vapor bubbles are forming at high pressures and high temperatures.

2. Experimental methods

2.1. Specimen preparation

ZIRLO™ cladding, which is commonly used as a fuel cladding material, was chosen as a test tube. The chemical composition and mechanical properties of the cladding tube are shown in Table 1. The dimensions of the test cladding tubes were an outer diameter (OD) of 9.5 mm, an inner diameter (ID) of 8.3 mm and a length of 550 mm.

We prepared the tube specimens with two different surface states: an as-received cladding tube and a chemically etched cladding tube. The chemically etched cladding tube was prepared through immersion in an acid solution composed of 45 vol% nitric acid (65%-HNO_3), 5 vol % hydrofluoric acid (48%-HF), and 50 vol% distilled water for 3 min at room temperature. To prevent chemical-etching on the inner surface, one end of the cladding tube was welded with a zirconium disc to

Table 1
Chemical composition and mechanical properties of ZIRLO™.

Composition (wt.%)					Mechanical properties (at RT)		
Sn	Fe	O	Nb	Zr	YS (MPa)	UTS (MPa)	Elong. (%)
1.0	0.1	0.12	1.0	Bal.	612.5	819.2	15.8

provide a leak-tight joint. In addition, the tube was etched by a length of 300 mm from the closed end so that a heated zone of a rod-type internal heater (heated zone = 250 mm) was within the etched length. After the chemical etching, the cladding tube was rinsed immediately in distilled water for 10 min using an ultrasonic cleaner to avoid staining of the surface with the residual etching chemicals.

2.2. Surface characterizations

The surface roughness was measured within an area of 800 µm × 800 µm using a non-contacting surface profiler. In this paper, the arithmetical mean roughness (Ra) is used. During the measurement process, the surface images were also observed using a topographical scanning method.

The wettability of the two different cladding tubes was analyzed by using the contact angle analyzer. The static contact angle can be measured only on a flat surface. Therefore, part of the as-received cladding tube was segmented into small rectangle pieces and their OD sides were ground with silicon carbide (SiC) papers to have a flat surface. At this time, the roughness of the flat surface was controlled to be the same as that of the as-received cladding tube. Some of the flat pieces were chemically etched. The static contact angles on the flat specimens with two different surface states were measured at room temperature under air conditions. A water droplet (3 µl of deionized water) was first placed downward onto the specimen surface using a syringe. A side-view image of the droplet was then captured using a high-resolution camera, and the static contact angle was finally determined using image analysis software. Measurements were made at three different points on the specimen surface, and were repeated twice at each point. In this paper, the mean value is reported along with the standard deviation.

2.3. Experimental set up

Fig. 1 shows a schematic of the experiment apparatus and AE data acquisition system used for the boiling test. The internal heater of a rod-type was inserted into the fuel cladding tube in order to provide the heat source on the cladding surface, and the gap between the cladding tube (ID = 8.3 mm) and internal heater (OD = 8.2 mm) was filled with MgO paste. In addition, to detect the AE signal emitted on the cladding surface, the AE sensor was coupled with the AE sensor holder and then directly attached to the tube at a position of 65 mm away from the upper end of the cladding tube. In present work, a low frequency AE sensor (type R3a) was chosen to collect the boiling AE signals. The resonant frequency range of this sensor is from 25 kHz to 70 kHz, and the working temperature is within the temperature range of −65 °C to 175 °C. The AE sensor was connected to a preamplifier and the preamplifier was then connected to the AE signal acquisition system. The AE signals were amplified with a gain of 40 dB, and the threshold was set at 48 dB to eliminate background noises.

The prepared fuel cladding tube was equipped in the transparent class cell that a primary water was stored. The simulated primary water was prepared using high purity demineralized water with the resistivity above 18 MΩ·cm and nuclear grad chemicals of LiOH and H_3BO_3. The solution was 3.5 ppm Li and 1500 ppm B in weight, which was used to simulate a primary water environment in a pressurized water reactor.

2.4. Visualization and AE measurements

Table 2 shows the main experimental conditions for the boiling test on the as-received cladding and the chemically etched cladding. To provide efficiently the condition of nucleate boiling on the fuel cladding surface, the temperature of the primary water (T_W) was heated to 95 °C using a hot plate, i.e., 5 °C lower than the saturation temperature under atmospheric pressure. When T_W was stabilized at 95 °C, the power of the hot plate was switched off. The internal heater was then quickly powered on, and the cladding tube was heated until the temperature of