The Effect of Salt Water on Bubble Formation during Pool Boiling Using Acoustic Emission Technique

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Abstract: *The bubble formation phenomenon in two-phase gas/liquid systems happens in several hydraulic components, for example, valves and centrifugal pumps. This is a common occurrence, leading to a drop in hydraulic performance, reduction of equipment efficiency, possible damage to the structure of pump and valve components. In addition, it causes high vibration and noise and solid surface erosion. Previously published works show that acoustic emission (AE) techniques can be used for monitoring and detectingcavitation bubble formation and burst. Thegreat advantage of AE is that it can be used to monitor and detect bubble initiation at an early stage before it can be detected by other means. This study identifies the possibilities of AE technology to detect and monitor bubble formation and burst during pool boiling. Furthermore, this study will apply AE technique to characterise micro-mechanisms of the bubble formation process and monitor bubble departure (bubble dynamics) from the heating element to the top of the water.AE is a good technique for monitoring and detection of bubble formation and collapse, within a range frequency of approximately 20 kHz to 1 MHz[1].*
Keywords: *Acoustic Emission, bubble formation, boiling.*

I. Introduction

AE is a physical phenomenon occurring within or on the surface of material. Furthermore, it is defined as elastic waves generated by the rapid release of energy from localized sources within a material [2].Application of AE technique is not limited to detect of bubble formation and collapse in different types of hydraulic components such as valves and centrifugal pumps. However, the AE Technique can employ to detect and monitor of bubble formation at an early stage in boiling processes. The AE is more sensitive, reliable and robust for the monitoring of bubble formation and its propagation at the surface of the water during the boiling process [3].

Taihiret et al. [3]used the AE technique in the monitoring of bubble formation during the boiling process. They found that there is a clear correlation between increasing AE levels and the bubble formation during the boiling process. Benes and Uher. [4]found that the parameters of the AE signal are a correlated to overheating during heat transfer. It was confirmed that the AE signal could be used to predict the crisis of boiling. Alfayez et al. [5] found the AE method is a useful technique for incipient detection of cavitation with the RMS value of AE signal. In addition, there is a high possibility of determining the BEP (Best Efficiency Point) of a centrifugal pump or system. In his work, Masjedian et al. [6]used two methods; Characteristic diagrams and acoustic analysis in the detection of cavitation phenomena in globe valves, where found good agreement results between two techniques on acceptable levels of accuracy. In another investigation, Neill et al. [7] employed the AE techniquefor monitoring the cavitation phenomenon in a centrifugal pump and got a more accurate result than vibration signal. Husin et al.[8] used AE technology to detect bubble inception and burst. All studies have proved the feasibility of monitoring bubble condition and obtaining flow patterns during the gas-liquid flow phase by using the AE technique. Tan Lei et al. [9] simulated cavitation flow in centrifugal pumps at a low flow rate. They found good results by calculating the values of net positive suction head available when compared with experimental work. Bubble cavitation is an unacceptable phenomenon due to pressure drop. It reduces the efficiency and life of the pump. In addition, the micro jets caused by bubbles collapse cause impeller damage, vibration, and noise.Bubble formation and bubble burst generate pressure waves which can be detected within a wide frequency band. Moreover, the bubble size can be calculated by using equation (1), known as the natural frequency of oscillation of the bubble, which is created by Minneart[10].

$$f_0 = \frac{1}{\pi d}\sqrt{\frac{3\gamma P_0}{\rho}} \quad (1)$$

Where f_0 the resonance frequency of the bubble, d is the bubble diameter, γ is the polytrophic constant of the gas inside the bubble, P_0 is the hydrostatic pressure and ρ is the liquid density.

The sound created by bubble formation, oscillation and burst at the free surface is dependent on the size of the bubbles. The period of stress pulse caused by bubble collapse and burst is very short (ms) [11]. Acoustic emission of bubble burst is related to the size of the bubble [12]. The bubble dynamic is divided into five stages: 1) bubble formation at the bottom of the boiler surface, 2) bubble rising velocity, 3) bubble coalescence, 4) splitting of bubbles, 5) bubble burst at the free surface [13][14]. When the bubblecavitation collapse, it causes the sound (noise). Furthermore, its dissipation of energy in the water [8]. The pressure pulse emitted by the bubble collapse produces shock waves [15]. It is believed that the pressure pulses associated with the bubble formation and burst at the surface of the liquid are potential sources of acoustic emission[16][17].The mechanism of a pressure wave generation acoustic emission in bubble growth is as follows. In the growth of the vapour bubble wall, after reaching the critical radius, there comes a sharp decrease of internal capillary overpressure from the value given by Young-Laplace equation[18].

$$P_2 - P_1 = \frac{2\sigma}{r} \qquad (2)$$

Where P_2 and P_1 are the vapour and liquid pressure, σ is the surface tension, r is the radius ofthe bubble.

There is a wide range of possible applications in the detection and diagnosis of industrial processes. However, its AE technique for the diagnosis of boiling is less commonthan other AE applications [4].

Several studies for developing the application of the AE technology for cavitation monitoring have been undertaken over the last 20 years. These studies showed that AE technique could be used in different types of hydraulic components such as boiling processes, valves, and centrifugal pumps, for monitoring and diagnosis of bubble formation at an early stage before it can be detected by other means. Keeping this in mind, this work builds further on the previously published work by experimentally monitoring the bubble formation in boiling processes using Acoustic Emission signals. This study is the first of its kind to date.

1. Difference between Bubble Formation in Salt Water and Fresh Water

In the container filled with fresh water, many large bubbles appeared and disappeared in a short time. In the saltwater, there were no large individual bubbles. However, small bubbles were generated and persisted in the container for a very long time. Although the mechanism of bubble formation is the same in salt water and fresh water, there is a difference in the size of the bubbles. Small bubbles playa significant role in incipient cavitation [19]. Blanchard et al. [20] noted that the bubbles coalesce in tap water more than in sea water. Furthermore, the bubbles produced in sea water are smaller and continue longer than in pure water. Abe [21] found that sea water foams more than fresh water. Ceccio et al. [22]concluded that there is a significant difference between bubble cavitation in salt water and fresh water. It was observed that the acoustic emission of the bubble cavitation in fresh water was lower than that produced by salt water. Furthermore, they noted that small bubbles produce higher acoustic emission compared to large bubbles. Bubbles of similar size produced similar acoustic emission regardless whether they are in salt water or fresh water, and the chemical difference of the water does not appear to influence the acoustics directly.

2. Experimental Work

For this study, boiling tests were performed using a particular purpose test-rig, as shown in figures 1. It consisted of water boiler with 25 cm inner diameter and 33 cm height. The maximum capacity of the boiler is 30 litre. The pool boiling is made of stainless steel. It is integrated with a heater, located at the boiler bottom, to heat up the water inside the boiler. The rounded heater has an external diameter of 12 cm. A constant electrical power of 3 kW is fed to the boiler heater throughout the boiling experiments.

A commercially available piezoelectric sensor (Physical Acoustic Corporation type "PICO") with an operating range of 100-1000 kHz was used. Two acoustic sensors together were attached to the external surface of the boiler using superglue. It is worth mentioning that two AE channels were distanced 18 cm apart. The first channel was connected to the bottom of the kettle, 4 cm from the bottom surface, to detect the initiation of bubble formation while channel 2 was positioned 18 cm atopchannel 1 to monitor bubble formation, burst, and oscillations when the bubbles depart to the surface at high water levels (see figure 1). The acoustic sensors were connected to a data acquisition system by a preamplifier, set at 40 dB gain. The system is continuously set to acquire AE waveforms at a sampling rate of 2 MHz. The software (signal processing package "AEWIN") is incorporated within a PC to monitor AE parameters such as AE-RMS and AE-Energy (recorded at a time constant of 10 ms and sampling rate of 100 Hz).

It was used that the traditional AE parameters were calculated over a threshold of 36 dB. The threshold value was set at 3 dB above operational background noise. To ensure a consistent boiling process throughout the tests period, the measurements of the water temperature was continuously undertaken every 1 second. The thermocouple was fixed inside the pool boiling 3 mm above the surface of the boiler heater.
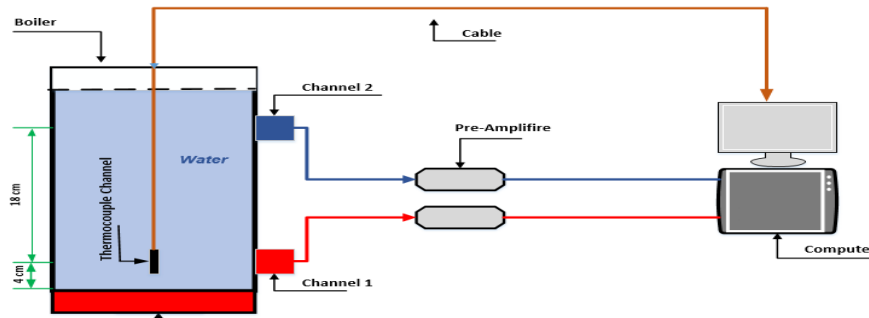
Figure 1: Schematic diagram of preliminary experiment

II. Results and Discussion

4.1 Calibration Test

Before testing, calibration tests were undertaken to understand the attenuation properties of the boiler material. Attenuation can be described as any reduction (or loss) in the AE signal strength (in the form of amplitude or intensity) and it is expressed in decibels (dB's) [23]. Attenuation test was carried out before laboratory tests. Hsu–Nielsen sources were used for attenuation tests. This test consists of breaking a 0.5 mm diameter pencil lead approximately 3 mm (+/- 0.5 mm) from its tip by pressing it against the surface of the piece. In this particular investigation, a detection threshold was set at 36 dB for the acquisition of AE's generated from the lead breaks at different heights ranging from 5 cm, 10 cm, 15 cm and 20 cm and an average value of the maximum signal amplitude of ten pencil breaks from each position was calculated. Signal amplitude and relative attenuation were calculated using the following equation [23]:

$$A_V(dB) = 20 * Log_{10}\left(\frac{V_s}{V_d}\right) \qquad (3)$$

Where V_s and V_d are the signal voltage at the signal source location and the signal voltage at the signal destination location respectively. Analysis revealed that the AE signals on the boiler surface are attenuated with increasing the distance from the emanating AE source as expected, shown in figure 2.
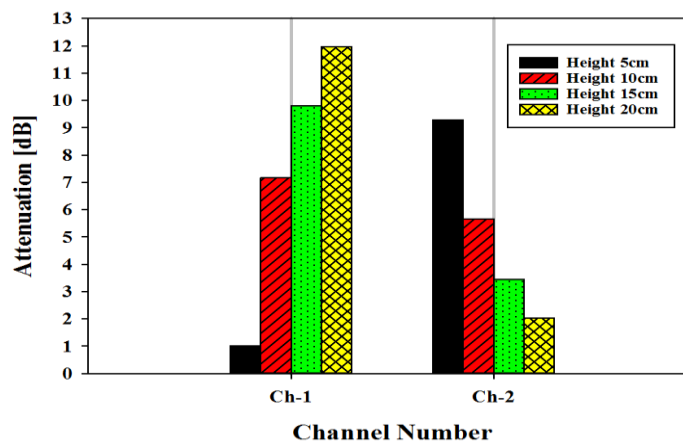

Figure 2: Relative attenuation at four different heights

4.2 Boiling Test
4.2.1 Effect of Salt Water on AE Signal

Tests were undertaken at two different levels of salt water, 4 cm and 12 cm. Case I is for a salt water level of 4 cm, while case II presents results for a salt water level of 12 cm. Tests were terminated once the water temperature reached 100 ^oC (boiling temperature). The onset water temperature condition for all tests was 20 ^oC. Furthermore, Concentration of the salt in the water is 30g / Littre. Figure 3below shows the relation between AE-RMS [v] and temperature [^oC] at the salt water level of 4 cm.
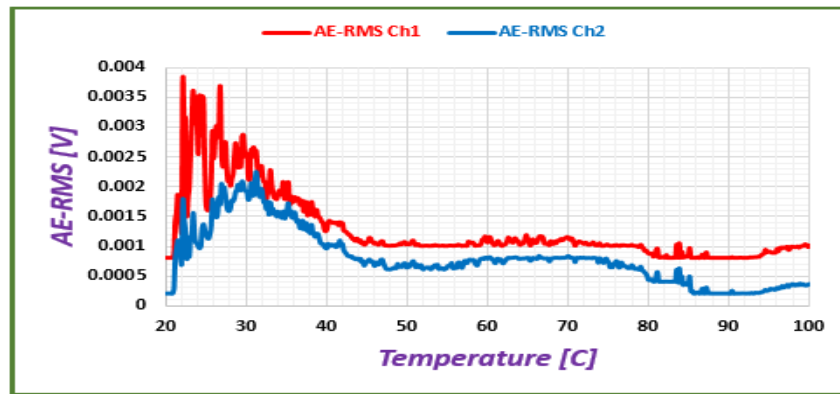
Figure 3: Observation of boiling test at salt water level of 4 cm

It was observed that the bubbles do not form on the heating surface between $20\,^oC$ and $22\,^oC$. Moreover, the heat transfers from heating elements to the water by natural convection. The value of AE-RMS ranked the highest for both channels, between $22\,^oC$ and $30\,^oC$. During this stage, the temperature increases and the bubbles start to form at a faster rate. The bubbles rise to the free surface, where they burst and release the vapour. As a result, the heat flux attains its maximum value. However, the value of AE-RMS in channel 1 is higher than that of channel 2, with 0.004 volts and 0.0024 volts respectively, because the position of channel 2 is far from the water surface. After that, the value of AE-RMS decreases significantly to approximately 0.001 volts in channel 1, and 0.0005 volts in channel 2, between $30\,^oC$ and $40\,^oC$. During this period, more bubbles form and rise to the surface, where they carry some water with them. This phenomenon is called *Liquid* Enterainment. Clearly, there is a stable value of AE-RMS for both channels, between $40\,^oC$ and $85\,^oC$, because few bubbles are formed at the bottom of the vessel (boiler). Between $85\,^oC$ and $95\,^oC$, the value of AE-RMS decreases gradually for both channels. At this stage, some of the bubbles rise from the heating surface to the surrounding water, while others combine with adjacent bubbles and stick to the internal surface of the boiler, causing reduction of AE-signal (attenuation). It was observed that when the salt water approaches the boiling stage between $95\,^oC$ and $100\,^oC$, the value of AE-RMS increases in both channels, as shown in figure 3. This temperature causes an increase in the heat flux, and more bubbles form and rise to the free surface, where large bubbles start to burst on the water surface at the end of the test. Furthermore, the size and internal energy of the bubbles increased.

Figure 4below illustrates the continuous monitoring and detection of bubble formation for salt water in the boiling test at the water level of 12 cm.
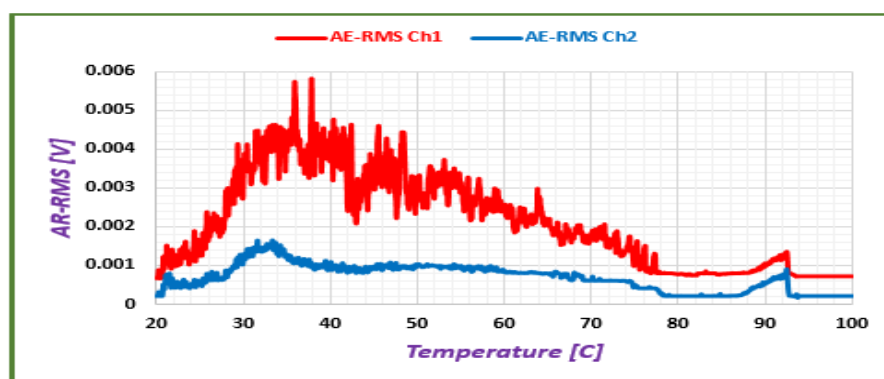

Figure 4: Observation of boiling test at salt water level of 12 cm

It was found that the value of AE-RMS in channel 1 was higher than that in channel 2, with 0.006 volts and 0.0018 volts respectively, because the position of channel 2 is far from the water surface. It was observed that the value of AE-RMS showed the same behaviour in both channels for all levels, but with different values. Overall, it can be concluded that when the water density increases, the value of AE signal decreases.

**4.2.2 Comparison of Bubble Formation between Pure Water and Salt Water**
Figure 5 below shows the relationship between AE-RME [V] and temperature [^0C] for channel 1, where the black line presents pure water and the red line shows salt water.
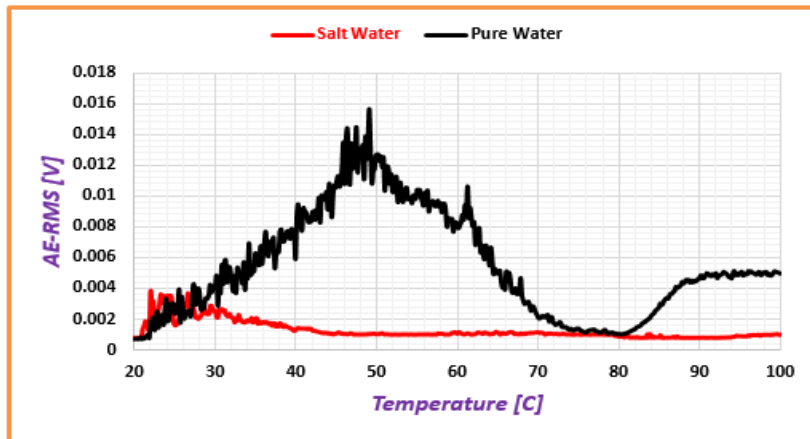
Figure 5: Correlation between salt water and pure water at water level of 4 cm (channel 1)

For pure water, a sharp transition in the AE activity occurs in pure water as shown in figure 5. This dramatic change indicates the initiation of the boiling process. More bubbles are formed and rise to the surface between 30^0C and 50^0C, due to the heat transferring from the heating element to the water, and the temperature increases. In salt water, the bubbles are formed between 22^0C and 30^0C. However, the value of AE-RMS in salt water is lower than that of pure water, with 0.004 volts and 0.016 volts respectively, because the density of salt water is higher than that of purewater. During 50^oC and 70^oC, the value of AE-RMS decreases dramatically to approximately 0.004volts for pure water. The value of AE-RMS drops significantly to approximately 0.0012 volts for pure water, between 70^oC and 80^oC. During this stage, the sensible heat changes to latent heat. Furthermore, when the bubbles form due to temperature changes, some of which rise from the heating surface to the surrounding water, while others combine with adjacent bubbles and stick to the internal surface of the boiler, causing attenuation of AE-signals. For these reasons the value of AE-RMS drops, because the bubbles reduce (attenuation) the AE-signals. When the water approaches the boiling stage between 88^oC and 100^oC, a slightly increased in the value of AE-RMS from 0.0012 volts to approximately 0.005 voltsin pure water wasobserved (see figure 5). This increase can be attributed to the heat that was gained by the water. This heat caused more bubbles to form and rise towards the surface, where eventually large bubbles started to burst on the water surface at the end of the test, as shown in figure 5, where the size of bubbles and their internal energy increased.

For the deeper level of water, at 12 cm (as shown in figure 6), there is a significant increase in the AE signal for pure water between 30^0C and 50^0C. During this period, the bubbles form and rise from heating surface to the cold water, and combine to create small bubbles. The value of AE-RMS ranked the highest, with 0.016 volts in pure water, because the densityofpure water is lower than that of salt water. For this reason, the value of AE signal in pure water is higher than that of salt water.
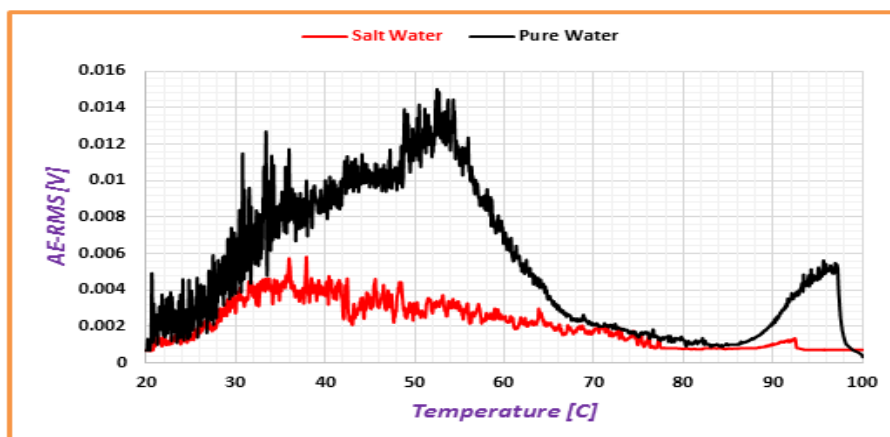
Figure 6: Correlation between salt water and pure water at water level of 12 cm (channel 2)

Overall, it can be concluded that the bubbles form and rise to the surface between 30^0C and 50^0C in pure water for all levels, and between 22^0C and 30^0C in salt water for all levels. Furthermore, the level of AE

signal in pure water is higher than that of salt water in both levels, because the pure water produces small bubbles, which creates a highfrequency.

III. Conclusions

This work has demonstrated that AE parameters such as AE-RMS are reliable, robust and sensitive to the detection of bubble formation and its propagation at the surface of the water during the boiling process. It is concluded that condition monitoring of bubble formation using AE technology can complement othercondition monitoring techniques, all of which are aimed at reducing energy losses and improving life cycle costs. AE technology is capable of detecting the dynamic formation and bursting of bubbles. AE data can serve as complementary information to other characterization techniques in detecting the initiation and progression stages in boiling process monitoring. It is a goodtechnique for the detection and monitoring of bubble formation at a very early stage. Furthermore, this method is necessary for predicting the incidence of boiling in nuclear reactors. This is also the case for monitoring heat exchanger systems in industrial chemical processes, detecting gas bubbles in the petrochemical industry, detecting gas layers in oil drilling, and monitoring and detection of cavitation phenomena in centrifugal pumps and valves. Finally, this work presents the early investigations in the application of AE technology for monitoring bubble formation in pool boiling.

Some results have been drawn from the conclusions of primary investigation:

- It was noted that when the water density increases, the value of AE signal decreases.
- It was established that the value of AE signal in pure water is higher than that of salt water.

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