Monitoring of Bubble Formation during the Boiling Process Using Acoustic Emission Signals

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Abstract— *The bubble cavitation 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. This study identifies the feasibility of the use of the Acoustic Emission technology to detect and monitor bubble formation throughout boiling processes. To undertake this task a special purpose test-rig was employed. It was concluded that bubble formation is detectable with AE technology and there is a clear correlation between increasing AE levels and the bubble formation during the boiling process.*

Keywords— Acoustic Emission (AE), Vibration and Noise, Solid Surface Erosion Bubble Formation, Boiling.

I. INTRODUCTION

The most widely recognised effect of the cavitation process known as cavitation erosion. Cavitation erosion can be defined simply as the removal of metal from the surface of pumps and valves caused by stresses associated with the collapse of vapour bubbles in the fluid. All types of metallic solid whether hard or soft metal, brittle or ductile are susceptible to damage by cavitation erosion.

Bubble cavitation is an undesirable phenomenon because causes increase in maintenance costs, reduction of production and revenue and decrease the life of the equipment. It is also a dynamic phenomenon that occurs in fluid flows when local pressure is lower than the saturated vapour pressure at ambient temperatures [1]. The growth and collapse of cavitation bubbles lead to the erosion or pitting of metal surfaces and causes high vibration and noise [2]. Operating a pump under cavitation conditions for a long time causes impeller vane pitting. The amount of metal lost depends on the material of the impeller, the degree of cavitation and the time between two successive pressure waves [3]. Noise and vibration phenomenon are an index of cavitation, caused by the implosion of bubbles near a solid surface. This phenomenon causes component damage of pumps and valves. The intensity of the noise and the vibration depends on the number and size of bubbles. In other words, large numbers of small bubbles produce a high-frequency noise and vibration, while a limited number of large bubbles create a low-frequency noise and vibration [4].

Several studies for developing the application of the Acoustic Emission technology for bubble 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 valves and centrifugal pumps, for monitoring and diagnosis of cavitation phenomena at an early stage, before it can be detected by other means. Acoustic Emission (AE) is defined as the range of phenomena that results in the generation of structure borne and fluid-borne propagating waves due to the rapid release of energy from localised sources within and/or, on the surface of a material [5]; typical frequency content of AE is between 100 kHz to 1 MHz.

Alfayez et al. [4]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 detection of cavitation phenomena in globe valves, where found a good agreement results between two techniques on acceptable levels of accuracy. In another investigation, Neill et al.[7]employed the AE method for 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. 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. Osterman et al. [10] suggested a visualisation method for the detection of incipient cavitation, and make a comparison with pressure oscillations measured by a hydrophone on several openings of the valve. They prove that the visualisation method was more accurate than hydrophone measurement. Rahmeyer [11] studied the noise limit of cavitation, as well as the cavitation limits of initial, critical, early damage, and choking cavitation for butterfly valves based on the analysis of experimental data. He set 85 dB as the limit of the cavitation noise level and discussed the effects of the limit on upstream pressure and valve size. Cudina et al.[12] Investigated the mechanism of noise generation, which is responsible for the damage of equipment. Three measurement methods were used: the first measurement is sound pressure level (SPL) in the surrounding air, the second depends on analysis of underwater acoustic quality, and the third depends on the measurement of structural vibration. Experiments show that the best method is structure vibration, because it gives a good result. Moreover, it can detect faults at an early stage when compared with other methods.

It can be concluded that off the shelf, most of the published attempts, for earlier detection of bubble formation, have made use of AE analysis, in which the AE data was used to monitor the bubble formation in pumps and valves. There are potentially unlimited opportunities for a wide scope to develop methods, tools and applications for effective diagnostic systems. This can be implemented by expanding the area of research to also assess the feasibility of the use of the Acoustic Emission technique for bubble formation in boiling processes. For practical side, the boiler heat transfer is used in many industrial processes such as heat exchange in the chemical industry, steam power plants and other processes. The capability to diagnosis and early detection of bubble formation during the boiling process is also very important to nuclear safety and in many another industrial processes [13]. Keeping this in mind, this work builds further on the previous 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.

II. TEST RIG LAYOUT AND EXPERIMENTAL SETUP

For this study, boiling tests were performed using a specially purpose test-rig, as shown in figures 1 and 2. It consisted of a manual fill water boiler with 28 cm internal diameter and 33 cm height. The maximum capacity of the boiler is 20 litre. The boiler is made of stainless-steel and has been coated to prevent any heat losses to its surrounding environment. The boiler 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 attached to the bottom of the boiler, 4 cm from the bottom surface, to detect the initiation of bubble formation whilst channel 2 was positioned 18 cm atopchannel-1 to monitor bubble bursts and oscillations when the bubbles rise up to the free surface at high water levels, see figures 1 and 2. The acoustic sensors were connected to a data acquisition system via a preamplifier, set at 40 db gain. The system was continuously set to acquire AE waveforms at a sampling rate of 2 MHz. The software (signal processing package “AEWIN”) was incorporated within a PC to monitor AE parameters such as r.m.s and absolute energy (recorded at a time constant of 10 ms and sampling rate of 100 Hz). The absolute energy is a measure of the true energy and is derived from the integral of the squared voltage signal divided by the reference resistance (10 k-ohms) over the duration of the AE signal. In addition to continuous recording of AE absolute energy (Atto-Joules - 10^{-18} Joules), traditional AE parameters such as counts, amplitude and ASL were also measured. The ASL is a measure of the continuously varying and averaged value of the amplitude of the AE signal in decibels (dB). The ASL is calculated from the r.m.s measurement and is given as [14]:-

$$ASL = 20\ x\ Log_{10}\left(1.4\ x\ rms\ (mV)/100\right) \qquad [1]$$

It is worth to mention that the traditional AE parameters were calculated over a threshold of 36 dB. The threshold value was set at approximately 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 20-seconds. To implement this, a thermocouple was fixed inside the boiler 3 mm above the surface of the boiler heater.

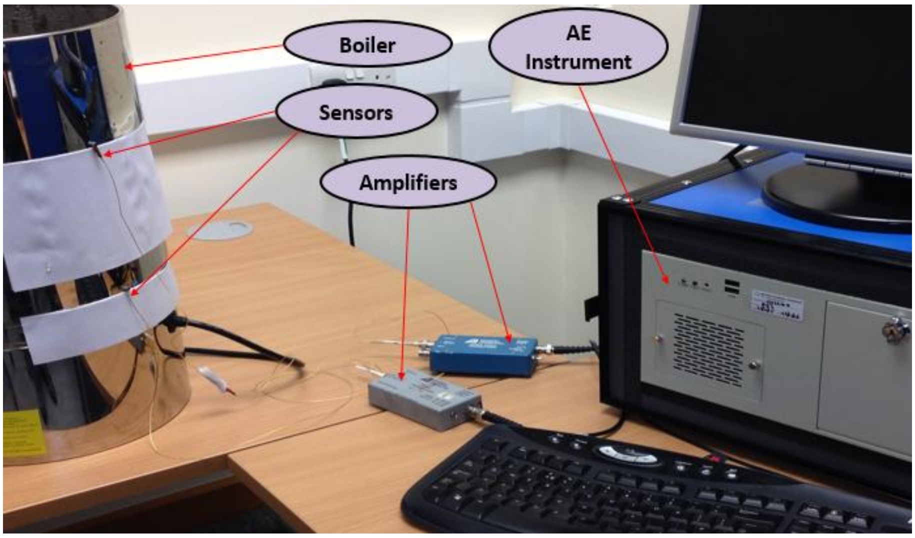

FIGURE 1: BOILER TEST-RIG

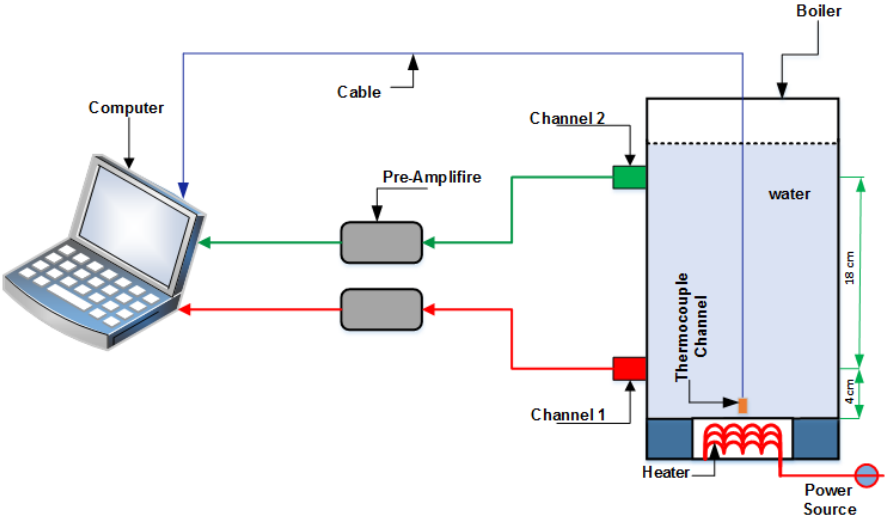

FIGURE 2: SCHEMATIC OF THE DATA ACQUISITION SYSTEMS

III. EXPERIMENTAL RESULTS OBSERVATIONS AND DISCUSSIONS

3.1 Calibration

Prior to 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 form of amplitude or intensity) and it is expressed in decibels (dB's) [14]. Attenuation test was carried out prior to 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 maximum signal amplitude of ten pencil breaks from each position was calculated. Signal amplitude and relative attenuation were calculated using the following equation [14]:

$$A_V(dB) = 20 \times Log_{10}\left(\frac{V_s}{V_d}\right) \qquad [2]$$

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 3.

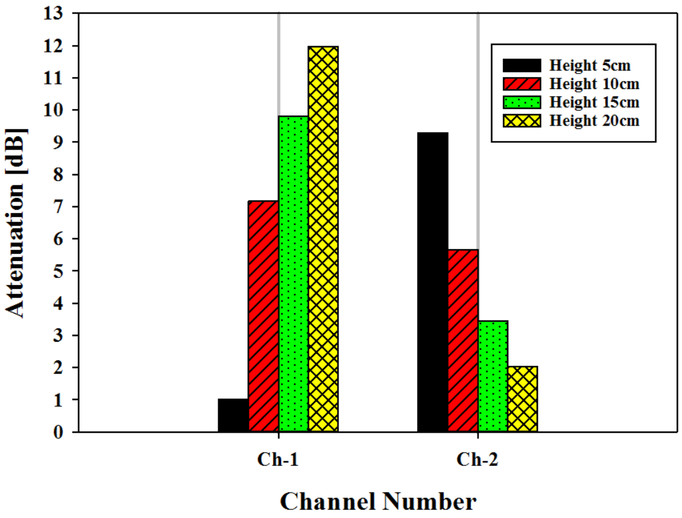

FIGURE 3: RELATIVE ATTENUATION AT FOUR DIFFERENT HEIGHTS

3.2 Boiling Tests

In this research work, tests were undertaken at two different levels of water ranging from 10 cm to 20 cm. For this particular paper two experimental cases are presented that reflect the general observations associated with over a dozen experimental tests. Case I is for a water level of 10 cm whilst Case II presents results for a test water level of 20 cm. It is worth mentioning that tests were terminated once the water temperature reached 100 ^{o}C (Boiling Temperature). It should also be noted that the onset water temperature condition for all tests was recorded at room temperature (25^{o}C). Continuous observations of the relation between the variation in trends of AE-energy (atto-joule) and temperature (^{o}C) with time (sec), where the boiler was filled with water up to10 cm height, is presented in figure 4.

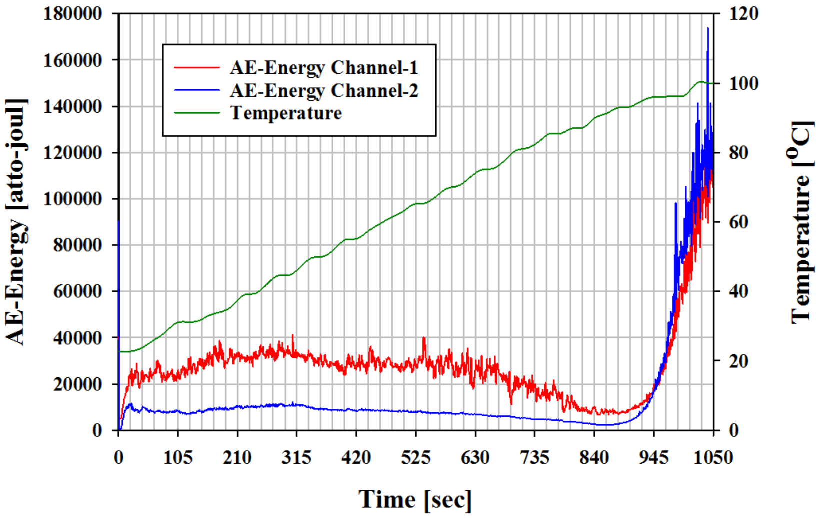

FIGURE 4: OBSERVATIONS OF BOILING TEST (Water Level 10 cm)

It was observed that during the first 800-seconds into operation high AE emission levels were recorded at channel 1 whilst the measured AE energy levels by channel 2 remained almost constant. This was expected as at this stage, small size bubbles formed and departed from the heating element surface into the surrounding water due to the heat exchange with the cold water; this dynamic motion was earlier picked up by channel 1 as it was located 4 cm above the bottom. Also was noted that at this stage AE energy levels recorded an average of approximately 30000 atto-joule in channel 1 and the average water temperature was found to be 50 ^{o}C, shown in figure 4. As the water approached the boiling phase (945 – 1050 seconds testing and a water temperature between 98 ^{o}C to 100 ^{o}C), significant increase in AE-energy from 10000 atto-joule to approximately 140000 atto-joule in channel 2 was observed, see figure 4. This increase was attributed the heat that was gained by the water. Further, this heat caused a huge departure of the formed bubbles towards the top surface, whereeventually big bubbles started to burst on the termination of test, as both their size and internal energy increased.

Figure 5 below shows the continuous monitoring of boiling test at the water level of 20 cm. This case presents different trends to that noted earlier in case I. In this particular test, a gradual increase in AE energy levels recorded at both channels was noted during the period from 0 to 1176 seconds into testing. After 441 seconds, higher AE energy levels from channel 2 was recorded. These levels reached a value of 120000 atto-joule due to the departure of small bubbles from the heating surface to the top of the water. As the water started to approach the boiling phase, approximately 1323 seconds into testing, the AE energy levels from both channels(channel 1 and channel 2) started to increase steadily; the reason behind this increase was the formation of more bubbles, which collide with each other and combined to produce even more bubbles that have big size and high internal energy. On the termination of the test (1470 seconds), the AE energy levels increased significantly to its maximum value; AE-energy, recorded at channel 2, reached about 200000 atto-joule, see figure 5. In this period, the heat increased and the bubbles burst near a free surface occurred.

Interestingly observations of the AE waveform, sampled at 2MHz showed changing characteristics as a function of time. Typical AE waveforms recorded after run-in and on the termination of testing are presented in figure 6. It clearly shows AE transient events, observed on the termination of the test; the eventual transient events were corresponded to the boiling frequency of the water.

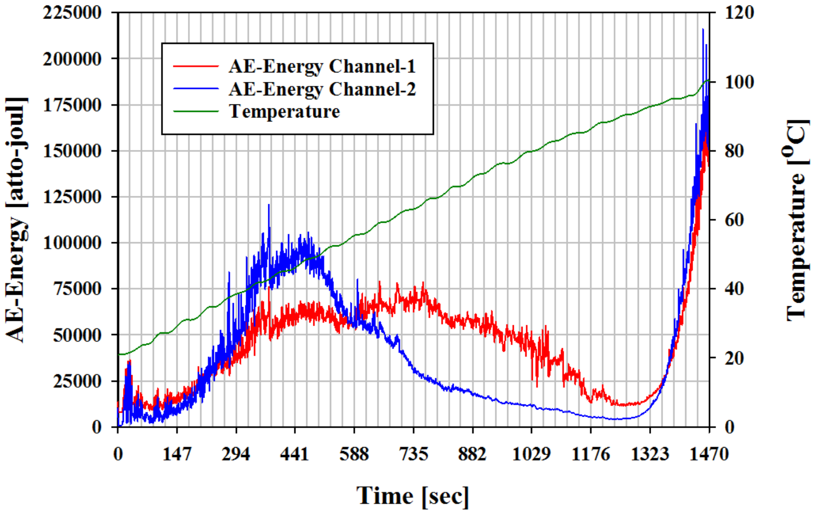

FIGURE 5: OBSERVATIONS OF BOILING TEST (Water Level 20 cm)

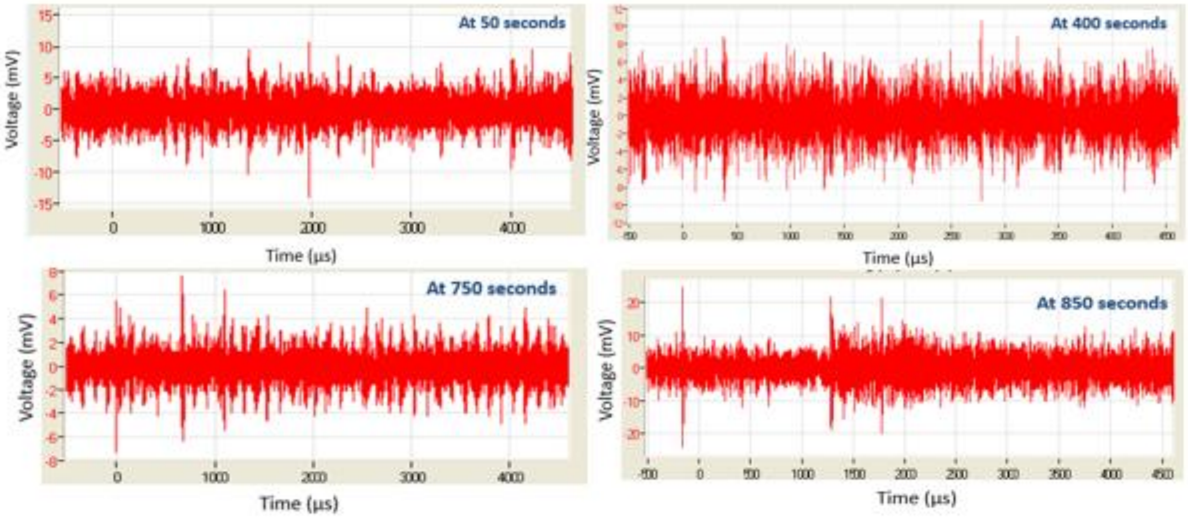

FIGURE 6: AE WAVEFORM ASSOCIATED WITH THE BOILING TEST PRESENTED IN FIGURE 4

Thus far the observations have shown AE to monitoring the formation of bubbles during the boiling process. The next phase of analysis involved employing statistical techniques to identify the formation of bubbles throughout the tests period. The techniques employed for this assessment included the Energy Index (EI) and Kolmogorov-Smirnov Test (KS-test). EI can be defined as the square of the ratio of root mean square of a defined segment ($RMS_{segment}$) in a given signal to the overall root mean square ($RMS_{overall}$) of the same signal. The technique was successfully applied to simulated and experimental data of gears and bearings [5 and 15]. For this particular investigation every AE waveform, recorded throughout the tests, was split into one hundred segments and EI was calculated using equation (3).

$$\textbf{\textit{Energy Index}} = \left(\frac{\textbf{\textit{RMS}}_{\textbf{\textit{Segment}}}}{\textbf{\textit{RMS}}_{\textbf{\textit{Overall}}}} \right)^2 \qquad [3]$$

Data analysis was also undertaken using Kolmogorov-Smirnov test (KS-test) which is one of the most widely used tests for goodness-of-fit. The test is basically working on null hypotheses. A null hypothesis means that the cumulative density function (CDF) of AE signal $S(t)_1$ is statistically same as the cumulative density function of AE signal $S(t)_2$ [5 and 16]. KS-test was used to compare the similarity probability of AE waveforms sampled at 2MHz. Similarity probability was found by calculating the maximum absolute distance (D) between the CDF's of AE waveforms using the equation (4).

$$\boldsymbol{D} = \max \left| \boldsymbol{S(t)}_1 - \boldsymbol{S(t)}_2 \right|_{-\infty < t > \infty} \qquad [4]$$

For this particular study, AE waveform at 105-seconds operation was taken as reference template, as this AE waveform showed the lowest transient characteristics. To extract features from the AE signals, EI and KS values have been calculated. As the results were scattered, the following exponential model was employed to fit the extracted features.

$$f = y_0 + ae^{bt} \qquad [5]$$

In the above function *f* is the magnitude of the signal feature; here is the value of EI or KS values, *a*, *b*and y_0 are the model constants, and *t* is the time. Figure 7 shows the fitted results and table 1 summarizes the general optimal estimated constants for the exponential model.From the fitted results presented in figure 7, a relative increase in EI level in the test run between 420-seconds to the termination of the test was noted; an EI value of 6.2 after 420-seconds operation was recorded. After running of 1050-seconds, water reached the boiling phase and therefore it was noted that EI raised to its maximum value of 16.5, see figure 7.This highlights the fact that EI values are just as sensitive to changes in water state as the continuous measurement of AE parameters such as energy; reinforcing the observations presented in figure 4.

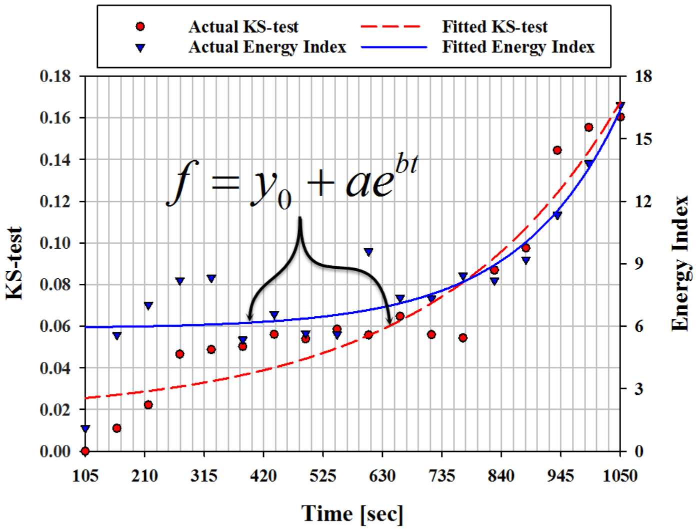

FIGURE 7: EI AND KS-TEST RESULTS ASSOCIATED WITH THE BOILING TEST PRESENTED IN FIGURE 4

The KS-test undertaken at the 105seconds period of operation had a value of zero, see figure 7. After running for 210seconds, KS values started to grow steadily with progressed time. On termination of the test (1050-seconds), a KS value of 0.167 was recorded, see figure 7. These results suggest that the bubble formation development could have been identified.

TABLE 1
ESTIMATED CONSTANTS FOR THE EXPONENTIAL MODEL

f	y_0	a	b	R^2
KS-test	0.017	0.006	0.003	0.895
EI	5.894	0.030	0.006	0.768

The results presented in figure 7 show that the KS and EI are sensitivity to periods of high transient AE activity, that are typically attributed to a boiling water andbubble formation. As such the continuous monitoring of bubble formation during boiling processes employing techniques such as the KS and EI would offer the operator a relatively more representative tool for observing high transient type activity. This conclusion was reached as the EI and KS showed the high sensitivity from the start position to 1050-seconds of operation (point of bubble formation) with the variation in water status.

IV. CONCLUSION

The study has demonstrated that AE parameters such as energy are reliable, robust and sensitive to the detection of incipient bubble formation and its propagation to the top water surface levels during the boiling processes. It is concluded that condition monitoring of bubble formation using AE technology can complement other existing condition monitoring technologies all of which are aimed at reducing energy losses and improving life cycle costs.It was indicated that the presence of bubble formation in boiling processes is detectable with AE technology by applying standard time analysis techniques such as EI and KS statistic. Finally, this paper presents the early investegations in the application of the AE technology to monitoring bubble formation in boiling processes and future developments will be reported in the soon future.

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