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Identifying bubble occurrence during pool boiling employing acoustic emission technique

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ABSTRACT

This paper reports the results of a study for the early detection of bubble formation during the boiling process using acoustic emission. The feasibility of using AE technology to detect and monitor early bubble formation during pool boiling is assessed, and the results show that AE technology is an affective tool for this purpose. There is a clear correlation between the AE signal levels and height of the water level above the heated surface during the boiling process. The different types of heated fluid influence AE energy levels during the bubble formation process. Statistically, it was found that the best AE parameters to indicate bubble formation were AE-RMS, AE-Energy and AE-Amplitude.

1. Introduction

Cavitation is an undesirable phenomenon generated by pressure waves associated with bubble formation and collapse in a liquid and can cause serious damage to hydraulic components, increasing maintenance costs, decreasing the life of equipment, and reducing production and revenue. Cavitation occurs when a liquid is subjected to pressure fluctuations which cause pockets of the fluid to experience local pressures which are equal to or lower than the saturated vapour pressure at the given temperature [1,2]. Vapour bubbles form and collapse into micro-jets leading to erosion and pitting of material surfaces, and causing high levels of noise and vibration, indeed the pressure pulse emitted by the bubble collapse creates shock waves [3,4]. The operation of a centrifugal pump under bubble cavitation conditions for a significant time causes pitting and erosion of the impeller vane [2]. When the bubble cavities collapsed, they produced sound and dissipated energy in the water [5].

Cavitation collapse depends on the number and size of the bubbles. In other words, large numbers of small bubbles create a high-frequency noise and vibration, while a limited number of large bubbles produce a low-frequency noise and vibration [6]. A bubble in order of 6 µm diameter will produce sound with a peak frequency of about 500 kHz, and 10 µm diameter yields 300 kHz, as shown in Fig. 1, which suggest the peak frequency of the pulse is inversely proportional to the bubble diameter [7].

To decrease the damage caused by cavitation, bubble formation must be monitored and diagnosed in rotating machines and valves [2].

Alhashan et al. [8] used the AE technique to monitor bubble formation during the boiling process. They found a clear association between increasing AE levels and bubble formation. Benes and Uher [9] found that the parameters of the AE signal correlated with overheating during heat transfer and it was established that the AE signal could be used to predict the boiling phenomena. Carmi et al. [7] used AE in a flow boiling experiment for detection of bubble transit, noting the possibility of using AE for the detection of bubble dynamic events at an early stage in the boiling process. Baek et al. [10] found that bubble density increases with the increase of the liquid temperature. Furthermore, they identified a relation between the water boiling phenomenon and the AE signals in a transparent glass cell at 1 bar. The AE technique has been used to diagnose bubble formation and monitor bubble departure from the heating surface of a boiler to the top of the water free surface. It was established that the AE-RMS is a sensitive, reliable and robust parameter for monitoring bubble dynamics its propagation to the water surface during the boiling process [11]. This work will focus on monitoring of bubble activity and their departure from heating surface to the water free surface, where finally the bubbles burst at free surface.

In an investigation of two-phase flows, Masjedian et al. [1] used two methods, characteristic diagrams and acoustic analysis, in the monitoring and diagnosis of cavitation phenomena in globe valves. They found good agreement between the two methods at acceptable levels of accuracy. Jaubert et al. [12] noted that AE is a good method for the detection of cavitation phenomena in pumps and valves. This detection can be at an early stage, which makes it possible to study incipient

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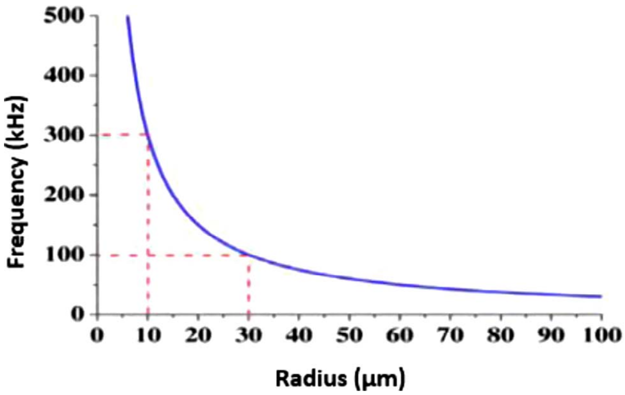

Fig. 1. Relation between frequency and bubble size [7].

cavitation phenomena. Alfayez et al. [13] demonstrated the use of AE technique for the detection of cavitation in centrifugal pumps and found that this was a method to determine the best efficiency point. Neill et al. [4] used AE technology for the monitoring and detection of cavitation phenomena in a centrifugal pump and claimed it was a more accurate method than using vibration measurement. Osterman et al. [14] used a visualisation method for the detection of incipient cavitation and made a comparison with pressure oscillations measured by a hydrophone on various openings of a valve. They found the visualisation method was more accurate than hydrophone measurement. Shuib [15] found that when bubble size and liquid viscosity increase, the level of AE signals also increase. One particular item of interest in this programme was the investigation of AE energy radiated from bubble formation. The bubble formation phenomena has potential energy which depends on the pressure within the bubbles and their volume.

Acoustic Emission is a physical phenomenon that occurs where transient high frequency elastic waves are emitted by a sudden release of energy from local sources within the body of a solid or liquid, such as might occur in turbulent flow or with cavitation [16–18]. Application of AE is not limited to detection and diagnosis of cavitation in hydraulic systems such as centrifugal pumps and valves; it can be used as a monitoring tool for different types of industries such as petroleum engineering using gas-liquid pumps [19], mechanical processes such as bearings and gearbox faults [20], and chemical processing plants [21].

Here, the AE technique is applied to the monitoring and detection of bubble formation during pool boiling while the bubbles are still in their early stages of development [8]. To date, published work shows few attempts to apply the AE technique to the monitoring and detection of bubble formation in pool boiling [9,7]. There are many different ways of monitoring and detecting bubble formation in boiling processes, valves and pumps, including vibration, but AE is a useful technique because its frequency range is about 100 kHz–1 MHz [22,23] so the range of frequency for the AE sensor is above the limit of human hearing and above most environmentally generated noise.

Most of the published reports on bubble formation and collapse that made use of AE methods were to observe cavitation in centrifugal pumps and valves. Here, this area of research has been expanded to assess the feasibility of the use of the AE technique for monitoring bubble formation in boiling processes. Heat transfer in so-called boilers in used in many industries such as chemical, manufacturing and power plants. The capability for early detection and diagnosis of bubble formation during the boiling process to identify such phenomena as overheating is also relevant to nuclear safety and many another industrial processes [7,24].

Bubble formation is considered one of the most common causes of failure in process systems and the early detection and of bubble formation during fluid transportation in pipes, valves and centrifugal pumps would be immensely beneficial. A condition monitoring programme that could successfully detect the early signs of bubble formation to be used as a warning signal for control purpose to avoid the consequence of bubble collapse (cavitation) is highly desirable. This investigation addresses the applicability of AE techniques to detect bubble formation characteristics (such as bubble size, bubble generation rate, and detachment of bubbles during pool boiling) to monitor and detect liquid properties and the liquid level above the heated surface. The boiling process provides a good opportunity to study bubble formation due to the controlled increase of liquid temperature. In addition, this will provide a good opportunity to characterise and differentiate between bubble formation and its bursting at the free surface during the boiling process. Finally, this research will provide a new reference for the use of the AE technique for monitoring of bubble activities in process systems.

2. Mechanisms of acoustic emission created from bubbles

Bubble formation, collapse and burst generate pressure waves which can be detected within a wide frequency band. The size of the bubble can be calculated using Eq. (1) for the natural frequency of oscillation of the bubble, derived by Minneart [25].

$$f_0 = \frac{1}{\pi d}\sqrt{\frac{3\gamma P_0}{\rho}} \tag{1}$$

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

The sound caused by bubble occurrence, oscillation and burst at the free surface is dependent on the bubble's size. The period of the pulse produced by bubble collapse and burst is very short, in the order of ms [13]. For pool boiling The bubble's development can be divided into five stages: (1) bubble formation at the heat exchange surface, (2) initial bubble increase in size, (3) bubble coalescence, (4) splitting of bubbles, and (5) bubble bursts at the free surface [15,16]. Neill et al. [4] found that the energy density created by bubble formation is high and includes associated shock waves in the surrounding liquid which can be observed using an AE sensor [26]. Leighton et al. [27] concluded that many sources of sounds in oceans were caused by pressure waves generated by gas bubbles inside the liquid. It is known that the pressure pulses associated with bubble formation and bursting at the surface of the liquid act as sources of acoustic emission [28,29]. Bubble activity as a source of AE and acoustic energy release into the surrounding fluid from the bubble formation and collapse have been used to determine fluid properties [30]. In pool boiling the highest acoustic emission occurs as the bubbles are detached from the heated surface [31]. Blanchard et al. [32] observed that such bubbles coalesce in tap water more readily than in sea water. Abe [33] found that sea water foams more than fresh water. and that bubbles produced in sea water are smaller and continue for longer than in pure water.

Ceccio et al. [34] confirmed there is a significant difference between bubble occurrence in salt water and fresh water. It was noted that the acoustic emission from bubble cavitation in fresh water was lower than that produced by salt water. Additionally, they pointed out that small bubbles provided higher frequency acoustic emission compared to large bubbles. Bubbles of similar size created similar acoustic emission regardless whether they were in salt water or fresh water, and the chemical differences did not appear to influence the sound directly [34].

3. AE parameters

Root Mean Square (RMS) is a measure of the continuously varying AE signal "voltage" into the AE system. It is an electrical engineering power term defined as the rectified, time averaged signal, measured on a linear scale and recorded in volts. This measure is often used for signal analysis [18,35]. RMS can be calculated as: