Acoustic Emission of a Single Bubble Activities

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Abstract-----**The phenomena of bubble in a two-phase gas liquid system is encountered in many industries such as nuclear reactor, hydro-station, chemical, pharmaceutical, liquid-piping transportation and petrochemical. As results of bubble/cavitation phenomena such a lack of equipment efficiency, vibration, noise and solid surfaces erosion can occur. There has been no research so far on the Acoustic Emission (AE) energy of bubble burst and its correlation with bubble size. AE in this investigation covers the frequency range of between 100 kHz to 1000 kHz.**

This study shows that the AE from bubble formation and bubble burst were detected by the AE sensor. However, it was found that there was no AE detected from a single bubble rising. The results show that with increasing bubble size, the AE of bubble burst also increases. Statistically, it was found that the best AE parameter indicator for bubble study was AE amplitude. It was also found that liquid viscosity apparently affects the bubble AE.

Keywords---**Acoustic Emission (AE), bubble dynamics,**

1. INTRODUCTION

Application of Acoustic emission (AE) technology is not limited to defect or events detection, but it can be used as monitoring tool for various types of industry such as chemical processing plants, petroleum engineering using gas-lift pumps, and medical. In addition, the acoustic technique can employed to determine the size defect or void such as bubble or cavitation in two phase gas-liquid system.

The influence of acoustic energy in bubble/cavitation inception and collapse for chemical processes has been explored [peter et al]. Bubble oscillation and bubble burst generate pressure waves which can be detected across a wide frequency band. Acoustically, the size of the bubble can be determined by using the unique formula (equation 1) known as natural frequency of oscillation of the bubble which was introduced by Minneart (1933) [7]:

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

where f_o is the resonance frequency of bubble**,** d is the equilibrium bubble diameter radius, γ is the polytropic constant of the gas inside the bubble, P_o is the hydrostatic pressure and ρ the liquid density.

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To date, acoustic bubble measurement has been undertaken with a hydrophone (range 0.006 Hz to 30 kHz). No work has been done in measuring the size of a single bubble using high frequency AE Technology. This paper discusses the first attempt to correlate AE with bubble dynamics, in particular bubble size.

Sound emitted from bubble oscillation and burst at the free surface is dependent on bubble size. The duration of stress pulse from a single bubble collapse/burst is very short (in µs). However, its sound spectrum contains energy in quite high frequency range [27]. AE of bubble burst might be related to bubble size.

The aim of the experiment was to assess the ability of AE technology to detect bubble formation released when there is collapse/pinch-off from an underwater nozzle, natural frequency of bubble during rising and bubble burst at a free surface. furthermore, to correlate with bubble size.

2. BUBBLE FORMATION MECHANISM AND THE USEFULNESS OF BUBBLE PROPERTIES IN RESEARCH

Bubble dynamics/evolution are divided into 5 categories; (1) bubble formation at the nozzle, (2) bubble rising velocity, (3) bubble coalescence, (4) bubble splitting and (5) bubble burst [4], [5], [16]. Davidson and Harrison (1971) in their book entitled "*Fluidization*" elucidate the concept of the "*initial layer*" and "*incipient fluidization rate*" in bubble formation in the fluidized bed. "Initial layer" is defined as the layer that covers the nozzle area (i.e. the hole's diameter) where it is raised when air injection is introduced to form a bubble, while the "incipient fluidization rate (U_{mf})" is defined as the minimum flow rate when the bubble starts to develop. Any flow in excess of U_{mf} will traverse up through the bed in the form which is described as bubble [16]. Once the void at the grid hole has reached its upper limit of size, the void wall is pressured from all sides by the surrounding fluid. Concentration of fluid particles is greater at the 'neck' of the void which makes it become the weakest area of the interface. Eventually, the '*neck*' collapses, due to the force of the liquid stream at this weakest point.

As the gas flow rate is increased, it promotes two consecutive bubbles which coalesce at the end of nozzle causing shape oscillation in the initial bubble [8]. Shape distortion can be seen as the effect of "*ripples*" on the bubble surface/wall, progressing up the bubble and then moving down after reaching bubble's top. Ripple occurs because of bubble detachment from the nozzle and also due to the contact of the bubble with its successor. The

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so-called "*spherical harmonic*" occurs as a result of the ripple moving up and down at the bubble wall. The external distortion that causes "ripple" on the bubble due to detachment from the nozzle tip and coalescence with a successor has been discussed in detail with high speed photography images by Leighton et al., (1991).

The evolution of the bubble following the bubble collapse/pinch-off at the 'neck' is the bubble rising with velocity, known as "*bubble terminal velocity*" [4]. Sometimes during the bubble's ascent, the phenomenon of bubble splitting could occur. Very little research has been found on bubble splitting. However, a fundamental work on the energy concerns during bubble splitting would be interesting to explore. The form known as a '*knife*' shape usually happens at the top of the bubble where it is the splitting point for the bubble.

The final bubble evolution/dynamic is bubble burst, which happens at the free surface. It was found that the research done by Divoux et al., (2008) was very close to this study where they used lower frequency microphone to record sound pressure. They investigated the relationship of AE from bubble burst at the free surface of non-Newtonian fluid, with the bubble length just before the bubble burst. Bubble shape, especially bubble length, has a correlation with bubble burst sound [24]. They observed that the duration of signal increases with the bubble length.

3. EXPERIMENTAL APPARATUS

The apparatus employed for acoustic monitoring and signal acquisition in this investigation is shown in Figs 1 and 2.

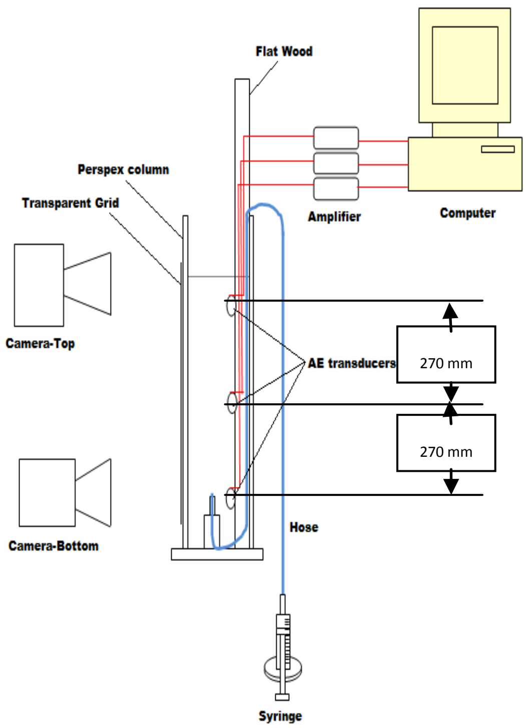

Fig 1 Schematic diagram of preliminary experiment

The fluidized bed used was 150 mm diameter by 1500 mm height and was made of Perspex pipe. Three broadband piezoelectric transducers (Physical Acoustic Corporation type WD) were fitted into the liquid in the bed so that the active face was facing the AE source. The distance between sensors was 270 mm (see Fig 2). The transducers had an operating frequency of 100-750 kHz and amplification at 60 dB was applied. The sample rate for acquisition of AE waveform was set at 2 MHz.

A single bubble was created as gas was forced through a nozzle underwater by the gradual depression of a syringe plunger.

For acquisition, a trigger level at 24 dB was set, and whenever this level was exceeded, data from all three sensors was acquired simultaneously. In addition, the two cameras continuously recorded the motion at every bubble throughout the test. A total of 150 tests were undertaken.

A video camera was centred at the orifice where the bubble was formed and another camera was centred at the free surface where the bubble burst. In this experiment, bubble size was assumed to be proportionate with nozzle size.

Threshold level was set at 24 dB to eliminate background noise. Since this experiment was done manually with two cameras, they were triggered simultaneously, prior to the manual creation of the bubble.

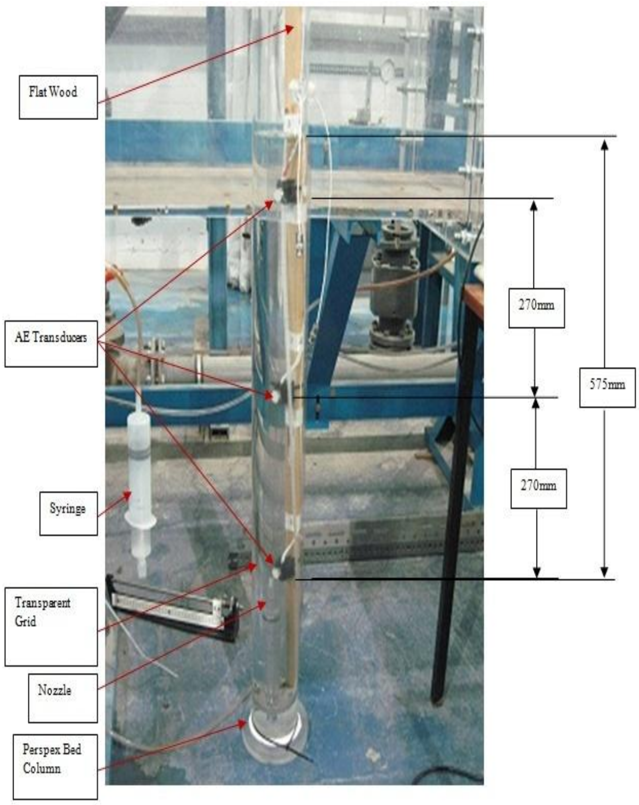

Fig 2 AE Transducer locations in the main column

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4. EXPERIMENTAL PROCEDURE

The calibration of the sensors was done prior to the experiment with the main amplifier set up at gain 60 dB and 40 dB. The pencil lead break (0.3mm) was applied for verification of sensitivity levels [23]. The results of the transducers/sensors' calibration is shown in Table 1.

Table 1 The amplitude recorded of sensor calibration with lead pencil 0.3mm

	Sensor 1	*Sensor 2*	*Sensor 3*
Gain 60 db	78	78	78
Gain 40 db	78	78	78

Signals would be picked up by AE sensors upon the potential AE sources of bubble activities; e.g. bubble collapse/pinch-off at the nozzle tip, bubble oscillation during rising, and bubble reaches/hit and burst at the water surface, were observed and statistically analysed. Five AE parameters were compared in this initial investigation; AE Amplitude (dB), AE Count, Average Frequency, AE Absolute Energy and AE Rise Time.

About 50 samples were tested during this experiment for each hose size in water and saturated salt water. However, only selected samples were chosen for the analysis. To observe the effect of viscosity of the fluid on AEs, two fluid conditions were investigated; plain water with a viscosity of 1 cP and salt water with a viscosity of 2 cP.

5.0 VELOCITY OF THE ACOUSTIC EMISSION WAVE

With the fixed distance between the sensors in the column and the detection of wave travelling time detected by the sensors, the velocity of the acoustic wave in the liquid can thus be determined (v =distance/time).

Table 2 Average Velocity of the AE Wave in Water

Size	Average velocity of Acoustic Wave in Water (m/s)	Average velocity of Acoustic Wave in Salt water (m/s)
1 (1.4 mm)	1284	1456
2 (4.4 mm)	1351	1535
3 (8.4 mm)	1483	1576

In water, the average velocities of the acoustic wave obtained were 1284 m/s, 1351 m/s and 1483 m/s for size 1, size 2 and size 3 respectively, while the average velocities of the acoustic wave in salt water were 1456 m/s, 1535 m/s and 1576 m/s for size 1, size 2 and size 3 respectively. These results show that the velocity of the acoustic wave in water and salt water increases with the increasing size of bubble burst.

The results of these experiments show that the average velocity of the AE wave is higher in salt water compared with an acoustic wave velocity in water. The speed of sound in water is about 1480 m/s [3], while in sea water the speed of sound is somewhat higher at 1543 m/s [22]. This shows that liquid viscosity affects the velocity of the AE wave. The results obtained were close to the classical acoustic velocity in water and salt water.

6.0 Statistical Analysis on AE parameters of Bubble Burst

The bubble burst at the free surface is independent of other parameters except for bubble size and liquid viscosity. Thus the bubble burst event was taken in this experiment and statistically analysed to determine the best AE parameter indicator. Tables 3 shows the average and standard deviations for comparison between AE parameters (AE Amplitude, AE Count, AE Average Frequency, AE Absolute Energy and AE Rise Time) from sensor-3 (bubble burst). The average calculation set out in Table 3 was taken from 25 test samples. Noted here, the results are based on the raw data taken from the AE system. The result of certain AE parameters is disputed when the standard deviation has a higher than average value as shown in Table 3 (AE count, AE Average Frequency, AE Absolute Energy and AE Rise Time). This gives indication for further analysis; careful measures and consideration are needed such as background noise elimination from waveform analyse.

Generally the results show the trend that the bigger the bubble size, the bigger the AE amplitude, AE Absolute Energy, AE Count and AE Rise time. In contrast, the AE Average Frequency decreases with increasing bubble size.

As seen in Table 3, the average AE amplitude difference between the sizes was roughly about 4 dB. AE amplitude parameter shows a linear proportion compared to the other AE parameters. The consistency of the AE amplitude of bubble burst was also seen in salt water; the average AE amplitude difference between the sizes was roughly similar as in water, about 4 dB.

Figs 3 provides a clear visualisation of the effect of viscosity on the AE of bubble burst. As a comparison with water (1 cP), salt water which is double viscosity (2 cP) was used in the experiment. The results show the average amplitude difference between the viscosities (water and salt water) was roughly about 3 dB for all sizes.

Statistical analysis set out in Table 3 shows that standard deviation of size 1 is the lowest compared with size 2 and size 3. The trend shows that standard deviation increases with rising bubble size. The consistency (variance) of AE in water is better than in salt water, as it can be seen that standard deviation in water is lower than in salt water.

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Tabulated AE rise time data as a function of size and viscosity is presented in 3. It shows a similar trend with AE amplitude in water and salt water, where AE rise time increases with the size increase. However, AE rise time in salt water is less, compared with water. In conclusion, AE amplitude shows consistent data for bubble study where it increases proportionate with size and viscosity.

Table 3 Average comparison of AE Amplitude of Bubble Burst for all sizes

	Size 1 (1.4 mm)				Size 2 (4.4 mm)				Size 3 (8.4 mm)			
	Water		Salt Water		Water		Salt Water		Water		Salt Water	
	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
AE Amplitude	26.1	2.5	29.9	4.5	30.4	3.0	36.6	6.0	34.8	4.1	37.7	5.4
AE Average Count	2.5	2.3	4.7	4.4	5.1	3.7	8.2	9.4	15.8	9.9	18.4	11.1
AE Average Frequency	262.7	2.84.00	340.6	351.0	239.1	301.1	236.3	268.9	105.2	117.0	124.5	73.7
AE Absolute Energy	0.7	0.3	1.3	0.9	1.3	1.9	4.9	15.4	4.4	3.6	10.2	13.7
AE Rise Time	17.0	57.4	11.2	28.5	93.3	220.8	54.3	110.8	129.8	191.6	62.5	133.8

In this experiment, where a single bubble was created by gradually pressing a syringe plunger, it was found that the best indicator was AE amplitude. AE amplitude shows a better linear proportion with the lowest standard deviation compared to the other AE parameters.

7.0 AE Waveform of Bubble Formation and Bubble Burst and

Figs 5 and 7 (top) show typical AE waveforms associated with bubble formation and bubble burst. The waveforms shown are from bubble size 3 (8.4 mm) in water.

Figs 3 and 4 show the example of plots for AE amplitude, comparing bubble formation and bubble burst in water and salt water for bubble size 2 (4.4 mm). This shows that the energy of bubble burst at the free surface is higher than the energy of bubble formation at the underwater nozzle.

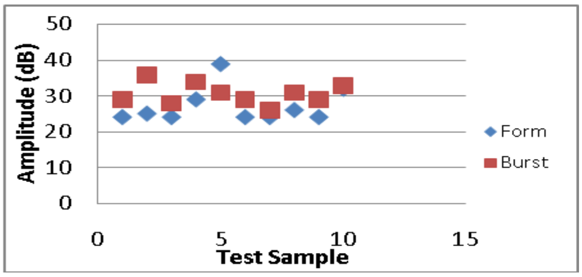

Fig 3 Example Comparison of AE Amplitude of Bubble Formation and Bubble Burst in Water, Size 2 (4.4 mm)

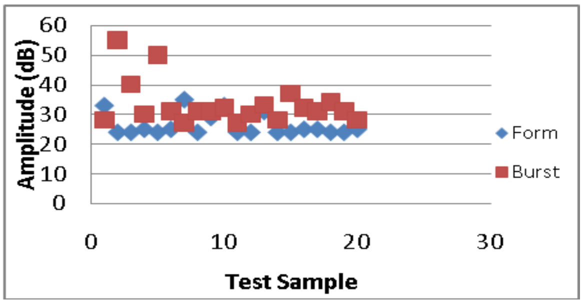

Fig 4 Example Comparison of AE Amplitude of Bubble Formation and Bubble Burst in Salt Water, Size 2 (4.4 mm)

Both plots, in water and salt water, show that AE amplitude of bubble burst is higher than bubble formation.

Spectrogram is time-frequency portraits of signals (Fig 5 and Fig 7 -bottom). It is a plot of the intensity of the frequency content of the signal as time progresses. From the analysis of spectrogram using Matlab as shown in Fig 5 (bottom) and 7 (bottom), it can be seen that the frequency range of the bubble burst is higher than background levels. Whilst the frequency range of bubble formation, as shown in Fig 5, was comparable to background levels though stronger in intensity. In

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addition, the comparison of spectrograms show that the AE duration of bubble burst event is longer than the AE duration of bubble formation event. AE duration of bubble burst at free surface takes approximately 3.5 x 10^{-4} s (Fig 7), while the AE duration of bubble formation at nozzle is approximately 1 x 10^{-4} s (Fig 5).

Wavelet analysis of the signal from bubble formation at underwater nozzle and collapse at free surface is shown in Figs 6 and 8 give more detailed time-frequency description compared with spectrogram analysis. The time-frequency plot associated with this particular AE event, Fig 8, showed a high frequency content of between 100 kHz to over 600 kHz, associated with the AE released during collapse.

In this study the time-frequency plot employed the software AGU-Vallen wavelet (see Figs 6 and 8) that specially developed for AE signal by Vallens Systeme GmbH and Aoyama Gakuin University (AGU) [25, 26].

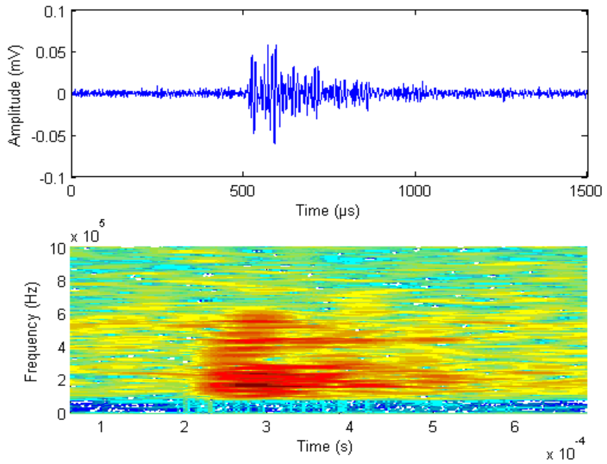

Fig 7 Example (Test Sample-43) of waveform (top) and spectrogram (bottom) of bubble burst from nozzle size 8.4 mm in water (1 cP)

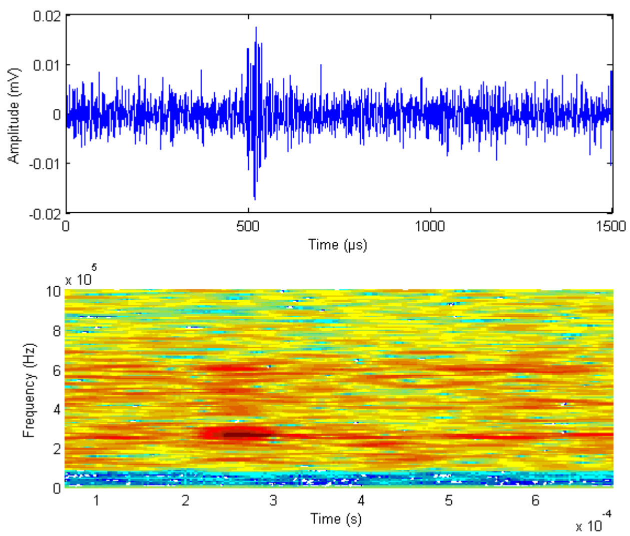

Fig 5 Example of waveform (top) and spectrogram (bottom) of bubble formation from nozzle size 8.4 mm in water (1 cP)

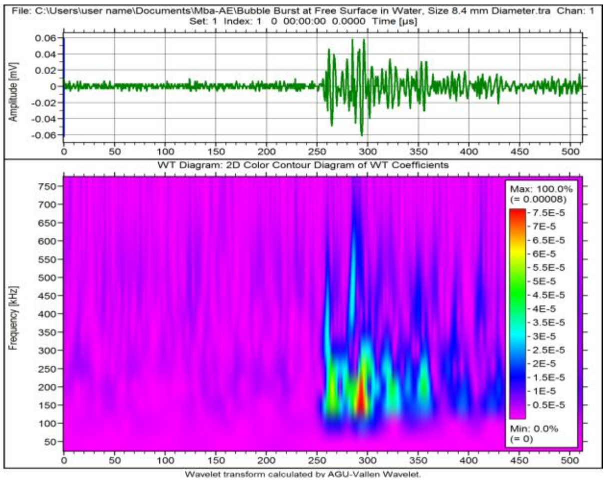

Figure 8 Example of waveform (top) and spectrogram (bottom) of bubble burst from nozzle size 8.4 mm in water (1 cP)

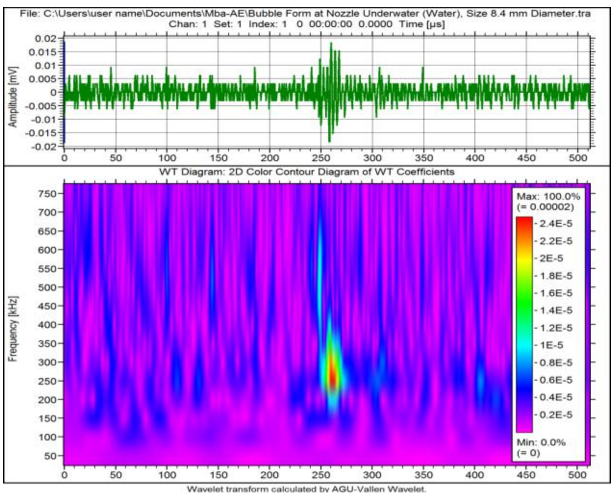

Figure 6 Typical waveform (top) and wavelet (bottom) associated with bubble formation (nozzle size 8.4 mm in water (1 cP))

8. CONCLUSION

This study demonstrates that AE of a single bubble inception and burst can be detected by AE technology. However, a burst in AE waveform obtained is representing for the whole experiment duration (e.g. see Fig 8 and 8 – top) caused considerable high standard deviation of AE parameters as tabulated in Table 3. Only AE amplitude parameter shows a reliable result. This suggests a further waveform analysis need to be performed, e.g. average AE duration based on the selected region of waveform and AE energy based on the area under selected region of waveform.

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

i) AE technology is capable of detecting single bubble dynamics, formation and burst.

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ii) AE technology can be used to measure the velocity of the acoustic wave.

iii) The best AE parameter indicator for bubble study is AE amplitude, which shows a consistent result with the lowest standard deviation among the AE parameters analysed. Furthermore, the amplitude parameter shows a distinctive regime in the plot graph as a function of bubble sizes and viscosities.

iv) It was established that the AE amplitude of bubble burst at the free surface increases when the bubble size increases.

v) It was established that the AE of bubble burst at the free surface augments when the viscosity of liquid increases.

vi) The initial results show that it is feasible for AE to be used in a two-phase gas-liquid system. In addition, it utilises a simple apparatus and is reliable for on-line monitoring in a two-phase liquid gas system. Furthermore, it can be used in opaque tanks in many branches of industry, ranging from nuclear to petrochemical.

vii) The observations made from this investigations show that the AE sensor does not detect the AE of bubble oscillation.

REFERENCES

[1] C. E. Brennen. *Cavitation and Bubble Dynamics*.Oxford University Press. 1995.

[2] S. Al-lababidi, A Addali, H Yeung, D Mba and F Khan, '*Gas void fraction measurement in two-phase gas/liquid slug flow using acoustic emission technology',* Journal of Vibration and Acoustics, ASME, IN PRESS, 2009.

[3] T.G Leighton. "*Acoustic Bubble detection-1: the detection of stable gas body*." Environmental Engineering, 1994, p.p 9-16,

[4] N.N. Sinha. "*Characterization of Liquids Using Gas Bubbles*." United States Patent No: US 7,010,962 B2. Mar. 14, 2006.

[5] M. Strasberg. "*Gas Bubbles as Source of Sound in Liquids*." The Journal of the Acoustical Society of America, 28, 1, 1956.

[6] T.G. Leighton and A.J. Walton. "*An Experimental Study of the Sound Emitted from Bubbles in a Liquid*." European Journal of Physics, 98-104, 1987.

[7] M. Minnaert. "*On Musical Air-Bubbles and the Sounds of Running Water*," Philosophical Mag. 16., 1933, p.p 235-248

[8] T.G. Leighton, K.J. Fagan and J.E. Field. "*Acoustic and Photographic Studies of Injected Bubbles*." Eur. J. Phys. 12, 1991, pp. 77-85

[9] A.B. Pandit, J. Varley, R.B. Thrope and J.F. Davidson. "*Measurement of bubble size distribution: An Acoustic Technique*." Chemical Engineering Science, Vol 47, No 5, 1992, pp. 1079-1089.

[10] T.G Leighton, A.D. Phelps, D.G Ramble and D.A. Sharpe. "*Comparison of the Abilities of Eight Acoustic Techniques to Detect and Size a Single Bubble*." Ultrasonics 34, 1996, pp. 661-667.

[11] J.W.R. Boyd and J. Varley. "*Acoustic Emission Measurement of Low Velocity Plunging Jets to Monitor Bubble Size*." Chemical Engineering Journal, 97, 2004, pp. 11-25

[12] J.R. Matthews and D.R. Hay. "*Acoustic Emission*." Gordon and Breach, 1983.

[13] G.G. Yen and H. Lu. "*Acoustic Emission Data Assisted Process Monitoring*." ISA Transactions 41, 2002, p.p 273-282.

[14] V. Holler, M. Ruzicka, J. Drahos, L. Kiwi-Minsker, A. Renken. "*Acoustic and Visual Study of Bubble Formation Processes in Bubble Column Staged With Fibrous Catalytic Layers*." Catalysis Today, 79-80, 2003, p.p 151-157

[15] Werner Lauterborn and Claus-Dieter Ohl. "*Cavitation Bubble Dynamic*." Ultrasonics Sonochemistry, 4, 1997, p.p 65-75,

[16] J.F. Davidson and D. Harrison, *Fluidization*. Academic Press. 1971.

[17] M.S. Longuet-Higgins, Bryan R. Kerman and Knud Lunde. "*The Release of Air Bubble from an Underwater Nozzle*." J. Fluid Mech, Vol. 230, 1991, p.p 365-390.

[18] Anonymous. "*Visualisation of bubble coalescence in a coalescence cell, a stirred tank and a bubble column*." Chemical Eng. Science. Vol 53. No 23. (1998).

[19] R. Manasseh, G. Riboux. F. Risso. "*Sound generation on bubble coalescence following detachment*." International Journal of Multiphase Flow. 2008,

[20] R. Manasseh, G. Riboux, A. Bui and F. Risso. "*Sound emission on bubble coalescence: imaging, acoustic and numerical experiments*." 16th Australasian Fluid Mechanics Conference Crown Plaza, Gold Coast, Australia 2-7 December 2007.

[21] L.S. Fan and K. Tsuchiya. "*Bubble Wake Dynamics in Liquids and Liquid-Solid Suspensions*." Butterworth-Heinemann, Boston, 1990, p.p 39-47.

[22] A. Wissler and V.A. Del Grosso, "*The velocity of Sound in sea Water*", The Journal of Acoustical Society of America, vol. 23, no 2, 1951, p.p 219-223.

[23] T. Holroyd. "*Acoustic Emission & Ultrasonic*." First Edition. Coxmoor Publishing Company, Oxford, 2000.

[24] T. Divoux, V. Vidal, T. Divoux, and F. Melo, J.-C. Géminard, "*Acoustic emission associated with the bursting of a gas bubble at the free surface of a non-Newtonian fluid*" Phys. Review, E 77, 2008

[25] M.A. Hamstad. "*An illustrated of the use and value of a wavelet transformation to Acoustic Emission Technology*", [Online]. Available: http://www.Vallen.de/2download/pdf/hamstad.pdf

[26] Free Download AGU-Vallen Wavelet. Available: http://www.Vallen.de/wavelet/

[27] M. S. Plesset. '*Shockwaves from Cavity Collapse'*. The Royal Society,XXI, pp 241-244 1966

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