The cavitation phenomenon: a literature survey

A. Alhelfi & B. Sunden
Department of Energy Sciences, Lund University, Sweden

Abstract

The meaning of the word cavitation is not known or understandable to many people. The definition, which is commonly known, for such phenomena is that the formation of cavities or bubbles is encouraged by a pressure change in the surroundings. However, cavitation is much more complex. A large amount of research work and studies on the dynamics of the cavitation phenomenon via numerical investigations or by means of experimental studies have been performed in this sense over past years in order to improve the understanding of the various physical processes involved in this phenomenon. This paper presents a literature survey of existing studies on the cavitation phenomenon and aims to give a comprehensive collection of knowledge about it. The present work does not aim to review all published results in this field. The paper focuses on specific available published results, concerning the most common cavitation types especially acoustic cavitation. The authors like to provide some recommended notices and the main efforts which must be carried out to develop and contribute more efficient knowledge about the real situation and the main results associated with this phenomenon.
Keywords: cavitation, ultrasonic, bubble dynamics, acoustic, sonoluminesence, bubble motion equations, sonochemistry.

1 Introduction

Cavitation phenomena have been perceptible for a long time. The fundamental knowledge of this science has been derived from marine technology. In the last years of the eighteenth century, complications with design and development of ship propellers happened; the plans at that time were to control and achieve higher ship speeds.

In 1894 the British torpedo-boat destroyer “Daring” sailed at a speed less than the fast speed design. The actual speed was 24 kn, while it was expected to be

WIT Transactions on Engineering Sciences, Vol 83,
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/HT140311

27 kn. The engineers thought the reduced speed was due to the formation of water vapour bubbles on the blades, and in that way the propeller performance and consequently the speed was reduced. At the same time, another ship met a similar problem and it was realized that, when the propeller starts to work, high pressure gradients occurred, and liquid around the propeller was torn apart and bubbles were formed. A large part of the engine power was consumed in the formation of these bubbles instead of moving the ship forward. The second problem appearing was that the implosion of these bubbles was accompanied by high pressure and temperature and as a consequence, erosion and pitting of the propeller blades occurred. Following a proposal by Thorneycroft and Barnaby, 1895 [1], to explain and define this phenomenon of harmful propeller behavior, the word "Cavitation" was introduced and it is derived from the Latin word "cavus" which means "hollow" in English [2].

The understanding of the dynamics of the cavitation phenomenon is of importance in many various applications, and the phenomenon plays an important role in different areas of science and technology including industrial processes, power systems, propulsion systems, turbo-machinery, ships, submarines, hydraulics, acoustics, cleaning, sonochemistry and medicine. However, well-known effects of the cavitation phenomenon include generation of excessive vibration and noise, erosion, reduced hydraulic performance and structural damages. Despite that the cavitation phenomenon has damaging effects, it was soon also realized that the cavitation can be useful and it has become a field of huge interest in different scientific subjects and applications.

2 Cavitation classification

Depending on the principles of the cavitation phenomenon, there are different types of cavitation as listed below [3].

2.1 Acoustic cavitation

This type of cavitation occurs when a liquid is subjected to a sound wave. Usually the acoustic waves create pressure variations through the liquid and if these variations in the pressure are great enough the cavities will grow. The tiny bubble is thus set into motion (expansion and compression). Acoustic cavitation can be classified into stable and transient cavitation [4, 5].

- **Stable cavitation**

Stable cavitation is defined by the creation and oscillation of gas bubbles in a liquid.

- **Transient cavitation**

Transient cavitation comes up when bubbles collapse and release a large amount of energy.

www.witpress.com, ISSN 1743-3533 (on-line)

2.2 Hydrodynamic cavitation

This type of cavitation is induced by pressure variation in a flowing liquid. Hydrodynamic cavitation can be further classified into three types:

- **Travelling cavitation**

Travelling cavitation occurs when a bubble or a cavity grows and travels along with the liquid motion and accordingly expands and collapses.

- **Fixed cavitation**

Fixed cavitation occurs when a cavity or a bubble is attached to a rigid boundary or an immersed body and remains fixed at a certain position during an overall unsteady state.

- **Vortex cavitation**

Vortex cavitation occurs in the courses of vortices, which form in regions of high shear, and often occurs on the blade tips of propellers. Thus it is also called tip cavitation.

2.3 Optic cavitation

This type of cavitation is produced by photons of high intensity, which are rupturing the liquid.

2.4 Particle cavitation

This type of cavitation is produced by any other type of high energy elementary particles, e.g. a proton.

It has been pointed out that optic and particle cavitation requires an intensive energy source, e.g. laser. Because of the expensive operation cost, these methods are not appropriate for large-scale processes. On the other hand acoustic and hydrodynamic cavitation has more potential towards large scale applications, mainly due to the simplicity of inducing the cavitation [6].

The acoustic cavitation is considered as one of the more recently observed phenomenon and is used presently more and more. It basically uses the ultrasound and bubble power in the applications. A multitude of useful physical and chemical processes is promoted by ultrasonic cavitation.

The chemical effects of using sound waves in the cavitation phenomenon to enhance the chemical reaction processes were first recognized by Richards and Loomis [7]. On the other hand, the first applications reported in the literature were the use of ultrasound induced cavitation to degrade a biological polymer [8]. The enormous development which happened has led to more interest of using the sound technologies to induce cavitation and to discover more applications, such as, sonochemistry [9–15], boiling heat transfer [16], cleaning of nanoparticles [17], design of sonochemical reactors [18, 19], degradation of chemical or biological pollutants [20–25], production of polymer [26], oil and natural gas industry [27], and improved adhesion [28]. The advantage of using acoustic cavitation for these applications is that much more mild operating conditions are utilised in comparison to conventional techniques and many reactions which may require toxic reagents or solvents are not necessary [29].

Also, cavitation plays a major role in various medical applications, such as, generation of both intended surgical effects and unwanted collateral effects [30], controlled permeation of cell membrane [31–35], fat loss technology [36], removal of kidney stones [37], and drug release by using acoustic cavitation as a triggering mechanism. By using micelles, liposomes, microbubbles, or polymers that encapsulate the drug, the mechanical or chemical effects induced by ultrasound have been shown to trigger drug release in a controlled manner [38–41], and treating cancerous cells or tumors [42].

3 Bubble motion equation

In 1917, Lord Rayleigh [43] published the first mathematical model describing a cavitation event concerned with hydrodynamically-generated cavities in an incompressible fluid and neglected surface tension and liquid viscosity. The governing equation reads,

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}\left[P(R) - P_\infty\right] \tag{1}$$

where R is the bubble radius, $\dot{R}$ is the bubble surface velocity, $\ddot{R}$ is the bubble surface acceleration, ρ is the liquid density, P_∞ is the liquid pressure far from the bubble, *P(R)* is the liquid pressure at the bubble surface, and also *P(R)* represents the pressure for the bubble content.

The study of the cavitation phenomenon performed by Lord Rayleigh's was extended by many investigators and scientists including Plesset and others [44–53] and the modified Rayleigh equation became often called the Rayleigh-Plesset equation.

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}\left[P_g(t) - \frac{2\sigma}{R} - 4\mu\frac{\dot{R}}{R} - P_\infty(t)\right] \tag{2}$$

where P_g is the gas pressure inside the bubble, σ the surface tension, and μ is the liquid viscosity.

The first systematic treatment of acoustically-generated cavities was carried out by Blake [51], followed by Noltingk and Neppiras [52, 53]. Since then, many groups have become active.

A polytropic approximation for the gas inside the bubble was assumed by Noltingk and Neppiras [52, 53], and they neglected the effect of liquid viscosity. The initial internal pressure of the gas inside the bubble was assumed to follow,

$$P_{go} = P_o + 2\sigma/R_o \tag{3}$$

Based on the Rayleigh-Plesset equation, the equation describe the motion of the bubble surface as,

$$R\ddot{R}+\frac{3}{2}\dot{R}^2=\frac{1}{\rho_L}\left[\left(P_o+\frac{2\sigma}{R_o}\right)\left(\frac{R_o}{R}\right)^{3\gamma}-\frac{2\sigma}{R}-P_\infty(t)\right] \tag{4}$$

where P_o is hydrostatic pressure in the liquid, σ the surface tension, R_o is the initial bubble radius, and γ specific heat ratio of the gas.

Poritsky [54] added a liquid viscosity term to eqn. (4), and the resulting equation is known as the Poritsky equation.

$$R\ddot{R}+\frac{3}{2}\dot{R}^2=\frac{1}{\rho_L}\left[\left(P_o+\frac{2\sigma}{R_o}\right)\left(\frac{R_o}{R}\right)^{3\gamma}-\frac{2\sigma}{R}-4\mu\frac{\dot{R}}{R}-P_\infty(t)\right] \tag{5}$$

For acoustic cavitation phenomenon the pressure at infinity varies as follows [55],

$$P_\infty(t) = P_o - P_A \sin \omega t \tag{6}$$

where P_o is the hydrostatic pressure, P_A is the time dependent acoustic pressure, and ω is the angular frequency.

Neppiras [56], stated that "eqn. (4) accurately describes the motion of the cavity-surface over a limited number of cycles for all types of stable cavitation, and also for transients where the bubble surface velocity never exceeds about 1/5 of the velocity of sound", but under violent transient conditions the bubble surface velocity may approach, or exceed, the velocity of sound.

A first step towards a more realistic treatment was the assumption that the motion in the liquid is isentropic (constant sound velocity). Such a treatment was carried out by Trilling [57]. The equation of state defining the sound velocity then becomes,

$$P/\rho = \text{constant};\ \partial P/\partial\rho = c^2 = \text{constant} \tag{7}$$

where P, ρ are the liquid pressure and density respectively, and c is the sound velocity.

The "Acoustic Approximation" implied by using the state equation (7) confines the treatment to cases where the velocity is always small compared with c, that is, the "Acoustical Mach Number", $M = \dot{R}/c \ll 1$ [56].

Many modifications introduced to include the sound speed effect in the bubble dynamics, and the most important ones were invented by Keller and co-workers [58–60], and become well known as the Keller-Kolodner equation. This equation reads,

www.witpress.com, ISSN 1743-3533 (on-line)

$$R\ddot{R}\left(1-\frac{\dot{R}}{c}\right)+\frac{3}{2}\dot{R}^2\left(1-\frac{\dot{R}}{3c}\right)=\frac{1}{\rho_L}\left(1+\frac{\dot{R}}{c}\right)\left[P_L(R)-P_\infty(t)\right]+\frac{1}{\rho_L}\frac{R}{c}\frac{d}{dt}\left[P_L(R)-P_\infty(t)\right] \quad (8)$$

where R is the bubble radius, c speed of sound in the liquid, $\dot{R}$ is the bubble surface velocity, $\ddot{R}$ is the bubble surface acceleration, ρ_L is the liquid density, and $P_L(R)$ is the liquid pressure at the bubble surface.

The above equation is of great historical importance and is fundamental in the analysis of bubble behaviour.

4 Physics of bubble oscillations in acoustic cavitation

The ultrasound is a type of sound wave and it is propagated in a series of compression and rarefaction waves induced in the molecules of the medium through which it passes. At sufficiently high power the rarefaction cycle may exceed the attractive forces of the molecules of the liquid and cavitation bubbles will form. After the formation of the bubbles in the liquid, the sound pressure field (Ultrasound) forces these bubbles into nonlinear oscillation, this phenomenon is called acoustic cavitation.

During the acoustic cavitation, bubbles produce high power and this phenomenon has caught the attention of scientists and researchers and is still the focus of many research works. During this process, the bubble is compressed which leads to generation of short flashes of light periodically and production of very high pressure and temperature at the end of the collapse event. These parameters with high values can be harnessed in different medical and industrial applications.

4.1 Light emission-sonoluminescence

The story of light emission from bubbles started in 1933 by two different groups of researchers. Marinesco and Trillat [61] subjected water to a high intensity ultrasound and placed a photographic plate into the water. They observed a blackening of the plates. The mechanism was unclear. Frenzel and Schultes [62], conducted similar experiments and found that it was not the ultrasound directly that was blackening the plates but the bubbles appearing upon rupturing the liquid.

Gaitan [63] succeeded to present the first recorded observation of sonoluminescence generated by a single bubble under the action of a sound field. Sonoluminescence (SL) is the phenomenon of light emission associated with the collapse of bubbles oscillating under an ultrasonic pressure field [64]. Sonoluminescence phenomenon can be divided into single bubble sonoluminescence (SBSL) and multiple bubble sonoluminescence (MBSL). The first one characterizes the emission of light from a single acoustically driven bubble in a liquid. On the other hand, the second type refers to the light emitted by multiple bubbles at higher acoustic pressures [65]. These flashes of light have intense ultraviolet light, see fig. 1, which activate the catalysts to decompose the organic compounds in water. Thus, the researchers and scientists continue to

www.witpress.com, ISSN 1743-3533 (on-line)

study this phenomenon to find out the conditions that give the highest flashes in water to apply this phenomenon in the water-treatment techniques [66]. According to Google scholar about 7940 articles containing the term sonoluminescence have been published since 1990.

Figure 1: Colour photograph of the light emitted by a trapped, positionally unstable bubble. Adapted from reference [71].

4.2 Temperature and pressure during bubble collapse

The bubble in acoustic cavitation produces very high pressure and temperature during collapse. As a result of the intensive compression of the bubble content during the collapse in liquids under ultrasound, the temperature can approach thousands of degrees Celsius, thus reaching the conditions on the surface of the sun. Also, the pressure can increase up to hundreds of atmospheres, approaching a condition which is similar to the pressure at the bottom of the ocean [67], see fig 2. Temperature and pressure fields inside an acoustic bubble, represent the most important characteristics of the acoustic cavitation process. These conditions represent the driving forces for many processes.

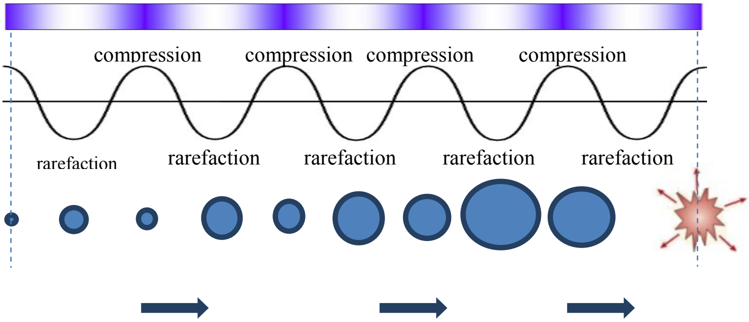

Figure 2: Acoustic cavitation mechanism. Adapted from references [68–70].

5 Conclusions

This article gave a comprehensive collection of knowledge and explanation of the principles of the acoustic cavitation phenomenon in order to bring more attention to it and provided basic information for researchers who like to simulate and study this field.

The study of the cavitation phenomenon might be the start in seeking the answers to many questions: What are the major forces which effect bubble dynamics? Where are these forces coming from?

Some types of cavitation phenomena have negative effects that include generation of excessive vibration and noise, erosion, reduced hydraulic performance and structural damages. Thus, the main focus here should answer the question, how to prevent cavitation?

However, despite that some types of cavitation have damaging effects, it was also realized that other types can be useful and it has become a field of huge interest in different scientific subjects and applications. The main focus in this case should answer the question, how to develop these types? How to establish more reasonable models to investigate the bubble dynamics?

Finally the research in this field should pay more attention to the future of acoustic cavitation.

References

[1] Thorneycroft, J. & Barnaby, S.W., Torpedo-boat destroyers. *Institution of Civil Engineers*, **122(51)**, 1895.

[2] Weitendorf, E.A., On the history of propeller cavitation and cavitation tunnels. *Proc. of the 4th Int. Conf. on Cavitation*, California Institute of Technology, Pasadena, CA USA, 2001.

[3] Alhelfi, A., On bubble dynamics in acoustic cavitation. *Thesis for the degree of Licentiate of Engineering*, Department of Energy Sciences, Lund University, Sweden, ISSN 0282-1990, pp. 2-4, 2013.

[4] Vanhille, C. & Pozuelo, C., Acoustic cavitation mechanism: A nonlinear model. *Ultrasonics Sonochemistry*, **19(2)**, pp. 217-220, 2012.

[5] Saclier, M., Peczalski, R. & Andrieu, J., A theoretical model for ice primary nucleation induced by acoustic cavitation. *Ultrasonics Sonochemistry*, **17(1)**, pp. 98-105, 2010.

[6] Cornel, J., A closer look at acoustic cavitation. *Eindhoven University of Technology, Chemical Engineering and Chemistry*, Process Development Group, 2005.

[7] Richards, W.T. & Loomis, A.L. The chemical effects of high frequency sound waves I. A preliminary survey. *The American Chemical Society*, **49(12)**, pp. 3086-3100, 1927.

[8] Brohult, S., Splitting of the haemocyanin molecule by ultrasonic waves. *Nature,* **140**, 1937.

[9] Suslick, K.S., Goodale, J.W., Schubert P.F. & Wang, H.H., Sonochemistry and sonocatalysis of metal-carbonyls. *The American Chemical Society*, **105(18)**, pp. 5781-5785, 1983.
[10] Suslick, K.S., Sonochemistry. *Science Magazine*, **247(4949)**, pp. 1439-1445, 1990.
[11] Suslick, K.S., The chemistry of ultrasound. *Encyclopaedia Britannica*, Chicago, pp. 138-155, 1994.
[12] Seidi, S. & Yamini, Y., Analytical sonochemistry; developments, applications, and hyphenations of ultrasound in sample preparation and analytical techniques. *Central European Journal of Chemistry*, **10(4)**, pp. 938-976, 2012.
[13] Tandiono, Ohl, S.W., Ow, D., Klaseboera, E. & Wongb, V., Sonochemistry and sonoluminescence in microfluidics. *PNAS*, **108(15)**, pp. 5996-5998, 2011.
[14] Rooze, J., Rebrov, E., Schouten, J. & Keurentjes, J., Dissolved gas and ultrasonic cavitation-A review. *Ultrasonics Sonochemistry*, **20(1)**, pp. 1-11, 2013.
[15] Segebarth, N., Eulaerts, O., Reisse, J., Crum, L. & Matula, T., Correlation between acoustic cavitation noise, bubble population, and Sonochemistry, *J. Phys. Chem. B*, **106(35)**, pp. 9181-9190, 2002.
[16] Zhou, D.W., Liu, D.Y., Hu, X.G. & Ma, C.F., Effect of acoustic cavitation on boiling heat transfer. *Experimental Thermal and Fluid Science*, **26(8)**, pp. 931–938, 2002.
[17] Minsier, V. & Proost, J., Shock wave emission upon spherical bubble collapse during cavitation-induced megasonic surface cleaning. *Ultrasonics Sonochemistry*, **15(4)**, pp. 598-604, 2008.
[18] Kim, K.Y. & Kwak, H.Y., Predictions of bubble behavior in sulfuric acid solutions by a set of solutions of Navier-Stokes equations. *Chemical Engineering Science*, **62(11)**, pp. 2880-2889, 2007.
[19] Ashokkumar, M., The characterization of acoustic cavitation bubbles – An overview. *Ultrasonics Sonochemistry*, **18(4)**, pp. 864–872, 2011.
[20] Suslick, K.S., The chemical effects of ultrasound. *Scientific American*, **260(80)**, pp. 80-86, 1989.
[21] Singla, R., Ashokkumar, M. & Grieser, F., The mechanism of the sonochemical degradation of benzoic acid in aqueous solutions. Res. *Chem. Intermed.*, **30 (7-8)**, pp. 723-733, 2004.
[22] Nikolopoulos, A.N., Markopoulou, O.I. & Papayannakos, N., Ultrasound assisted catalytic wet peroxide oxidation of phenol: kinetics and intraparticle diffusion effects. *Ultrasonics Sonochemistry*, **13(1)**, pp. 92-97, 2006.
[23] Naddeo, V., Belgiorno, V. & Napoli, R., Behaviour of natural organic matter during ultrasonic irradiation. *Desalination*, **210(1-3)**, pp. 175-182, 2007.
[24] Garbellini, G.S., Ultrasound in electrochemical degradation of pollutants (Chapter 10). Electrolysis, ed. V. Linkov, InTech, pp. 205-226, 2012.

[25] Sharma, S. K. & Sanghi, R., *Advances in Water Treatment and Pollution Prevention*, Springer Dordrecht Heidelberg New York London, pp. 76, 2012.
[26] Teo, B.M, Ashokkumar, M. & Grieser, F., Microemulsion polymerizations via high-frequency ultrasound irradiation. *J. Physical Chemistry B*, **112(17)**, pp. 5265- 5267, 2008.
[27] Leong, T.S., Wooster, T.J., Kentish, S.E. & Ashokkumar, M., Minimising oil droplet size using ultrasonic emulsification. *Ultrasonics Sonochemistry*, **16(6)**, pp. 721-727, 2009.
[28] Holtmannspötter, J., Wetzel, M., Czarnecki, J.V. & Gudladt, H.J., How acoustic cavitation can improve adhesion. *Ultrasonics*, **52(7)**, pp. 905-911, 2012.
[29] Leong, T., Ashokkumar, M. & Kentish, S., The fundamentals of power ultrasound - A review. *Acoustics Australia*, **39(2)**, pp. 54-63, 2011.
[30] Brujan, E.A., Collapse of cavitation bubbles in blood. *Europhysics Letters*, **50(2)**, pp. 175-181, 2000.
[31] Cochran, S. & Prausnitz, M., Sonoluminescence as an indicator of cell-membrane disruption by acoustic cavitation. *Ultrasound in Medicine & Biology*, **27(6)**, pp. 841-850, 2001.
[32] Guzman, H.R., Nguyen, D.X., Khan, S. & Prausnitz, M.R., Ultrasound-mediated disruption of cell membranes. I. Quantification of molecular uptake and cell viability. *J. Acoust. Soc. Am.*, **110 (1)**, pp. 588-596, 2001.
[33] Sundaram, J., Mellein, B.R. & Mitragotri, S., An experimental and theoretical analysis of ultrasound-induced permeabilization of cell membranes. Biophysical, **84(5)**, pp. 3087-3101, 2003.
[34] Zhou, Y., Yang, K., Cui, J., Ye, J.Y. & Deng, C.X., Controlled permeation of cell membrane by single bubble acoustic cavitation, *Journal of Controlled Release*, **157(1)**, pp. 103-111, 2012.
[35] Fan, Z., Liu, H., Mayer, M., & Deng, C.X., Spatiotemporally controlled single cell sonoporation. *PNAS Early Edition*, pp. 1-6, 2012.
[36] Serdev, N.P., Ultrasound assisted liposculpture – UAL: A Simplified safe body sculpturing and aesthetic beautification technique (Chapter 9). Advanced Techniques in Liposuction and Fat Transfer, ed. N. Serdev, InTech, pp. 135-150, 2011.
[37] Pishchalnikov, Y.A., Sapozhnikov, O.A., Bailey, M.R., Williams, J.C., Cleveland, R.O., Colonius, T., Crum, L.A., Evan, A.P. & McAteer, J.A., Cavitation bubble cluster activity in the breakage of kidney stones by lithotripter shock waves. *J. of Endourology*, **17(7)**, pp. 435-446, 2003.
[38] Marin, A., Sun, H., Husseini, G.A., Pitt, W.G., Christensen, D.A. & Rapoport, N.Y., Drug delivery in pluronic micelles: effect of high-frequency ultrasound on drug release from micelles and intracellular uptake. *Journal of Controlled Release*, **84(1-2)**, pp. 39-47, 2002.
[39] Unger, E.C., Porter, T., Culp, W., Labell, R., Matsunaga, T. & Zutshi, R., Therapeutic applications of lipid-coated microbubbles. *Advanced Drug Delivery Reviews*, **56(9)**, pp. 1291-1314, 2004.

[40] Rapoport, N., Note Combined cancer therapy by micellar-encapsulated drug and ultrasound. *International Journal of Pharmaceutics*, **277(1-2)**, pp. 155-162, 2004.
[41] Coussios, C.C. & Roy, R.A., Applications of acoustics and cavitation to noninvasive therapy and drug delivery. Annual Review of Fluid Mechanics, **40**, pp. 395-420, 2008.
[42] Kennedy, J.E., High-intensity focused ultrasound in the treatment of solid tumours. *Nature Reviews-Cancer*, **5(4)**, pp. 321-327, 2005.
[43] Rayleigh, L., On the pressure developed in a liquid during the collapse of a spherical cavity. *Philosophical Magazine*, **XXXIV(34)**, pp. 94-98, 1917.
[44] Plesset, M.S. & Zwick, S.A., A nonsteady heat diffusion problem with spherical symmetry. *Journal of Applied Physics*, **23(1)**, pp. 95-98, 1952.
[45] Plesset, M.S. & Zwick, S.A., The growth of vapor bubbles in superheated liquids. *Journal of Applied Physics*, **25(4)**, pp. 493-500, 1954.
[46] Plesset, M.S., Physical effects in cavitation and boiling, *Proc. of 1st Symposium Naval Hydrodyn*, Washington D.C, pp. 297-323, 1956.
[47] Plesset, M.S. & Hsieh, D.Y, Theory of gas bubble dynamics in oscillating pressure fields, *Physics of Fluids*, **3(6)**, pp. 882-892, 1960.
[48] Plesset, M.S., Bubble dynamics. *Proc. of the Symposium on Cavitation in Real Liquids*, General Motors Research Laboratories, Warren, Michigan, 1962.
[49] Plesset, M.S., & Richard B.C., Collapse of an initially spherical vapor cavity in the neighborhood of a solid boundary. *Journal of Fluid Mechanics*, **74(1)**, 1971.
[50] Plesset, M.S., & Prosperetti, A., Bubble dynamics and cavitation. Annual Review of Fluid Mechanics, **9**, pp. 145-185, 1977.
[51] Blake, F.G., Acoustics Research Laboratory, Technical Memo, No. 12, Harvard University, U.S.A., 1949.
[52] Noltingk, B.E. & Neppiras E.A., Cavitation produced by ultrasonics. *Proceedings of the Physical Society*, Section B, **63(9)**, pp. 674-685, 1950.
[53] Neppiras, E.A. & Noltingk B.E., Cavitation produced by ultrasonics: Theoretical conditions for the onset of cavitation. *Proceedings of the Physical Society*, Section B, **64(12)**, pp. 1032-1038, 1951.
[54] Poritsky, P., The collapse or growth of a spherical bubble or cavity in a viscous fluid. *Proc. of the 1st US National Congress in Applied Mathematics (ASME)*, 1952.
[55] Alhelfi, A., Sunden, B. & Yuan, J., Modeling of spherical gas bubble oscillation in acoustic pressure field. *Proc. of the 8th Int. Conf. on Multiphase Flow*, Jeju, Korea, May 26 - 31, 2013.
[56] Neppiras, E.A., Acoustic cavitation. Physics Reports, Review Section of Physics Letters. **61(3)**, pp. 159-251, 1980.
[57] Trilling, L., The collapse and rebound of a gas bubble. *J. Appl. Phys.*, **23(1)**, pp. 14-17, 1952.
[58] Keller, J.B. & Kolodner, I.I., Damping of underwater explosion bubble oscillations. *J. Appl. Phys.*, **27(10)**, pp. 1152-1161, 1956.

[59] Epstein, D. & Keller, J.B., Expansion and contraction of planar, cylindrical, and spherical. *Acoustical Society of America*, **52(3B)**, pp. 975-980, 1972.
[60] Keller, J.B. & Miksis, M., Bubble oscillations of large amplitude. Acoustic Society of America, **86(2)**, 1980.
[61] Marinesco, M. & Trillat, J. J., Action of supersonic waves on photographic plates, C. R. Acad. Sci. (Paris), 196, PP. 858-860, 1933.
[62] Frenzel, H. & Schultes, H., Luminescence in ultrasound irradiated water, Z. Phys. Chem. B, 27, pp. 421-424, 1934.
[63] Gaitan, D., An experimental investigation of acoustic cavitation in gaseous liquids. National Center for Physical Acoustics, Technical Report, 1990.
[64] Kappus, B., Bataller, A. & Putterman, S.J., Energy balance for a sonoluminescence bubble yields a measure of ionization potential lowering. Physical Review Letters, **111(23)**, pp. 234301-5, 2013.
[65] Suslick K.S. & Flannigan, D., Inside a collapsing bubble: Sonoluminescence and the conditions during cavitation. The Annual Review of Physical Chemistry, **59**, pp. 659-683, 2008.
[66] Godinez, F. & Navarrete, M., Application of the aqueous sonoluminescence in the photo catalysis. *Proc. of the 1st IWA Mexico National Young Water Professionals Conference*, 2008.
[67] Alhelfi, A. & Sunden, B., Bubble power and ultrasound. *Enhanced Research in Science Technology & Engineering*, **2(11)**, pp. 130-134, 2013.
[68] The Sonochemistry Centre at Coventry University. http://www.sonochemistry.info/introdution.htm
[69] Royal Society of Chemistry, Sonochemistry – beyond synthesis. http://www.rsc.org/education/eic/issues/2009Sept/SonochemistryBeyondSynthesis.asp
[70] Sana, S., Rajanna, K., Reddy, K., Bhooshan, M., Venkateswarlu, M., Kumar, M. & Uppalaiah, K., Ultrasonically assisted regioselective nitration of aromatic compounds in presence of certain group V and VI metal salts, *Green and Sustainable Chemistry*, **2(3)**, pp. 97-111, 2012.
[71] Lauterborn, W. & Kurz, T., Physics of bubble oscillations. IOP Publishing Ltd, Rep. Prog. Phys. 73, 2010.