Critical cavitation	Here the noise is light and continuous and vibration minimal. Minor damage may occur after long time periods.
Incipient damage cavitation	Here definite damage occurs to solid boundaries and both noise and vibration levels have increased. Sweeney C.E. (1974) defined this level to correspond to a surface pitting rate of 1 pit/in^2 minute.
Choking	Both noise and vibration levels become objectionable. Erosion reaches its maximum intensity.

Unfortunately, the above terms are descriptive only (except that relating to incipient damage), and are therefore subject to individual interpretation. The most important cavitation level is believed by the author to be that of incipient cavitation, as this represents the onset of the phenomenon. In other words, no cavitation occurs until the incipient point is reached, while beyond this point, cavitation occurs. Also, it should be noted that 'cavitation' is a broad term and, as can be seen from the above classifications, the severity of the phenomenon requires quantification. Later in the text, a method is put forward to be used when attempting to decide on the incipient cavitation level.

In a static system, ie. one where a liquid is held in a container with one surface exposed to the atmosphere, the liquid will boil if the temperature is raised high enough for the vapour pressure to equal the ambient pressure. By changing the ambient pressure, the temperature at which boiling occurs will also change, an increase in pressure requiring an increase in the boiling temperature, and vice versa. Thus, if the pressure is reduced sufficiently, the liquid will boil at the ambient temperature, the pressure then being known as the vapour pressure.

In a dymanic system, ie. one where a liquid flows through an orifice, the temperature change across the orifice is relatively small. Downstream of the orifice, the lowest pressure region of the system occurs opposite the vena contracta; here it is easily possible for the vapour pressure of the liquid to be reached and for boiling to occur.

To distinguish between boiling and cavitation the following definition is used : Boiling can be described as a process caused by an increase in temperature at a constrant pressure; and cavitation as being caused by a decrease in pressure at a constant temperature (Knapp R.T. et al 1970). Both boiling and cavitation are characterised by the growth of bubbles (or cavities), resulting in a two-phase flow.

2.1 BUBBLE GROWTH

The following sub-sections discuss various aspects of bubble growth, in order to highlight the relevance of this information to the problem under investigation.

2.1.1 GASEOUS AND VAPOUR BUBBLES

Two phenomena are commonly called cavitation : 'aeration' (gaseous cavitation) and 'cavitation' (vaporous cavitation).

Both are characterised by the production of bubbles at a point in the flow where a sudden and sufficient drop in pressure occurs.

Aeration bubbles are primarily caused by gaseous diffusion at pressures above the vapour pressure (Strasberg M. 1955), such bubbles growing relatively slowly and being carried along in the flow. The conditions for diffusion are that the gas must be in contact with the liquid, and a partial pressure imbalance must exist to promote a transfer of molecules from the liquid to the gas. To grow a bubble by diffusion it has been calculated that 15 s could be required for a bubble radius to change from 0,01 mm to

0,1 mm (Epstein P.S. and Plesset M.S. 1950). In a flow situation it is unlikely that such a bubble would be able to stay in a low pressure region long enough for sufficient growth to occur.

A secondary mechanism of pressure reduction to aid bubble growth, appears to be a more valid reason for aeration bubbles being seen in flowing water. Referring back to the case of bubbles being carried along in the flow, if these bubbles were trapped on fixed boundaries the necessary growth could conceivably occur before the bubbles (nuclei) are carried away by the flow. Such a theory was put forward by Harvey E.N. et al (1944) who suggested that gas bubbles could be held in cracks on solid boundaries; the bubble would grow as the boundary passed from high pressure to low pressure regions, the bubble being released when it had grown out of its crack. This possibility is examined further in Section 2.1.3.

Bubble growth is also caused by evaporation at an air/liquid boundary, the air vapour pressure being less than the liquid vapour pressure (Strasberg M. 1955). The rate of evaporation at a surface is given by the following equation (Whillier A. 1967).

$$M_e = \frac{h_c\, A\, Le^{\frac{2}{3}}}{C_p} \left(\frac{\phi\, e_{db} - e_s}{P} \right) \qquad 2.1$$

$$Le = \left(\frac{\text{Prandtl Number}}{\text{Schmidt Number}} \right)^{0,66}$$

2.2

As can be seen from equation 2.1, the vapour pressure and bulk pressure are important variables (and obviously temperature), and changes in there values could significantly affect the evaporation rate. Temperature changes occur whenever the pressure changes, the temperature affecting the vapour pressure of the liquid and hence bubble occurrence. As in the case of the diffusion bubble, pressure reduction aids bubble growth.

Generally, the rate of growth of a bubble due to evaporation is higher than that due to diffusion. However, it is highly probable that bubble growth is a combination of diffusion, evaporation and pressure changes in the flow passage. In Section 2.1.3 bubble growth due to pressure changes is dealt with, the relevance of the work of Harvey E.N. et al (1944) being there explained.

2.1.2 NUCLEI

Nucleation has long been recognised as being important in bubble formation. The presence of nuclei appears to have been first reported by Tomlinson C.R. (1867) who used carbonated water in a sealed contained, bubbles being observed on the surface of the container (the bubbles were here considered to be formed from surface entrained gas). On opening the container a few bubbles were released (no prior agitation having been performed). However, if the liquid was first agitated, a relatively large number of bubbles was subsequently released. Tomlinson's work was extended by Harvey E.N. et al (1944), who suggested that the observed bubbles were held on microscopic surface cracks and suspended solids, growth being due to a difference between the liquid vapour pressure and the bubble pressure. Another theory by Fox F.E. and Herzfold K.F. (1954) proposed that bubbles were enclosed by mono-molecular organic shells preventing the bubbles from being dissolved. Organic shells, however, have been found to modify both evaporation rates and surface tension at a surface (Bikerman J.J. 1958). Also, the shell could be either rigid or elastic; if rigid then growth would be relatively slow, while if elastic the bubble might burst into a number of separate bubbles rather than grow. It was demonstrated by Messino C.D. et al (1967), using acoustic techniques, that the number of bubble forming nuclei present in water increased as the percentage of suspended solids was increased, thereby supporting the theory of Harvey E.N. et al (1944). Knapp R.T. (1958) carried out a series of experiments based on the latter's work, the conclusions reached being consistent with those of Harvey E.N. et al (1944).

Furth R.E. (1940) and Fisher J.C. (1948) presented work on the theory of holes in liquids, whereby randomly positioned holes (approximately two atomic radii in diameter) are postulated to exist in a liquid, the number of holes ranging between a hundredth and a tenth of the total number of atoms present. The holes were believed to form weak spots in the liquid, thereby providing sites for rupture to occur and bubbles to be formed if a tensile load were to be applied to the liquid. This provides a possible explanation as to the base source of nuclei - the production of visible bubbles occurring in localised high velocity, low pressure areas (such as the impeller of a centrifical pump).

The analysis of Harvey E.N. et al (1944) is generally accepted in preference to that of Fox F.E. and Herzfold K.F. (1954), as it accounts for both bubble presence and observed bubble behaviour. However, it does not invalidate the work of the latter which describes important factors which may influence bubble growth.

In the work of Harvey E.N. et al (1944), Fox F.E. and Herzfold K.F. (1954), Furth R.E. (1940), and Fisher J.C. (1948), the assumption is made that a discontinuity of some form exists in the liquid and growth occurs when energy (heat, kinetic, chemical, etc) is put into the system at this point. Resisting bubble growth are the tensile strength and the viscous properties of the liquid. Regarding tensile properties, tensile stresses in liquids have been measured by a number of observers : Berthelot M. (1850), Dixon H.H. (1909), Meyer J. (1911), Vincent R.S. and Simmonds G.H. (1943) and Rees E.P. and Trevena D.H. (1967) - the values for water varying between 1,3 and 15,0 MPa. Overton G.D.N. and Trevena D.H. (1980) suggested that the observed variation was due to the number of free nuclei in the water causing weak spots, thus indicating that a liquid property such as air content plays an important role in providing the necessary nuclei for cavitation (See Section 2.2.1).

Overall, the conclusion reached from a study of work reviewed is that microscopic bubbles which are already present in a liquid are responsible for cavitation; however their exact nature or form does not appear to be conclusively known. As fas as this study is concerned, high pressure opration should act to diminish the formation microscopic bubbles (and so limit the occurrence of cavitation).

2.1.3 BUBBLE GROWTH

Harvey E.N. et al (1944) proposed a mechanism to explain the growth of bubbles from surface (i.e. crack) entrained gas; the following section enlarges upon the necessary mechanism. Growth of a free bubble in a pressure field is also explained by reference to the Poritsky H. (1952) analysis.

Harvey Analysis

Gas bubbles are held in cracks on a hydrophobic surface, and three liquid states are examined :

i)	Under-saturated
ii)	Saturated
iii)	Super-saturated

These are defined as follows :-

UNDER-SATURATED

Liquid at the bubble boundary is under-saturated relative to the bubble; hence there is a driving force to promote a transfer of gas/vapour from the bubble to the liquid. The bubble decreases in size (Figure 2.1a), and as a result the interface moves into the crack, with consequent change of boundary radius R, and contact angle θ. After time t the interface at the crack wall moves due to surface tension effects, and the initial radius and contact angles are re-established (Figure 2.1b).

From the initial equilibrium conditions,

Radius = R_e
Contact Angle = θ_e

The radius and contact angle change to

$$R_t < R_e$$
$$\theta_t < \theta_e$$

After time t the boundary moves at the crack wall to regain the equilibrium condition, as given by

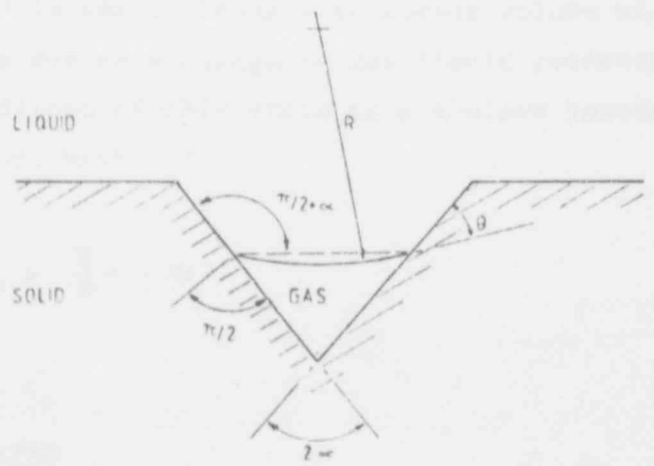
$$R_t > R_e$$
$$\theta_t > \theta_e$$

The pressure balance across the boundary is given by

$$P_g + P_v - P_w = \frac{-2S}{R} \qquad 2.3$$

The liquid saturation state at the boundary will also change with time, thereby reducing the rate of gas/vapour transfer - which suggests that it may be impossible for the bubble to become completely dissolved.

a) INITIAL CONDITION



b) CONDITION AFTER TIME t

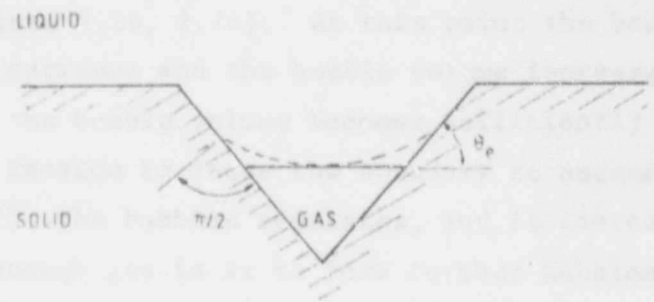


FIGURE 2.1 CRACK BUBBLE - UNDERSATURATED LIQUID

SATURATED

The liquid at the boundary is saturated (in equilibrium), and the driving force to promote gas/vapour transfer across the boundary is zero. Changes in bubble volume will therefore be due to a change in the liquid pressure. A general conditoon of this state is a concave boundary (Figure 2.1b), with

$$\theta_e > \frac{\pi}{2} + \alpha$$

SUPER-SATURATED

Liquid at the boundary is in a super-saturated state relative to the bubble; a driving force therefore exists to promote gas/vapour transfer from the liquid to the bubble.

Initially, the bubble is in an equilibrium state (Figure 2.2a). Due to gas/vapour transfer the bubble volume then increases. Growth occurs by the curved interface moving along the surface of the crack until the entrance is reached (Figure 2.2b, 2.2c). At this point the boundary is held at the entrance and the bubble volume increases. Eventually, the bubble volume becomes sufficiently large for surface tension to cause the boundary to become convex (Figure 2.2d), the bubbles separates, and it leaves the crack with enough gas in it to form further bubbles.

FREE BUBBLE GROWTH

One particular analysis that treats the growth of a free bubble in a liquid is that of Poritsky H. (1952). The assumptions used in the analysis are that the bubble is spherical at all times, and that there is no growth due to diffusion or evaporation.

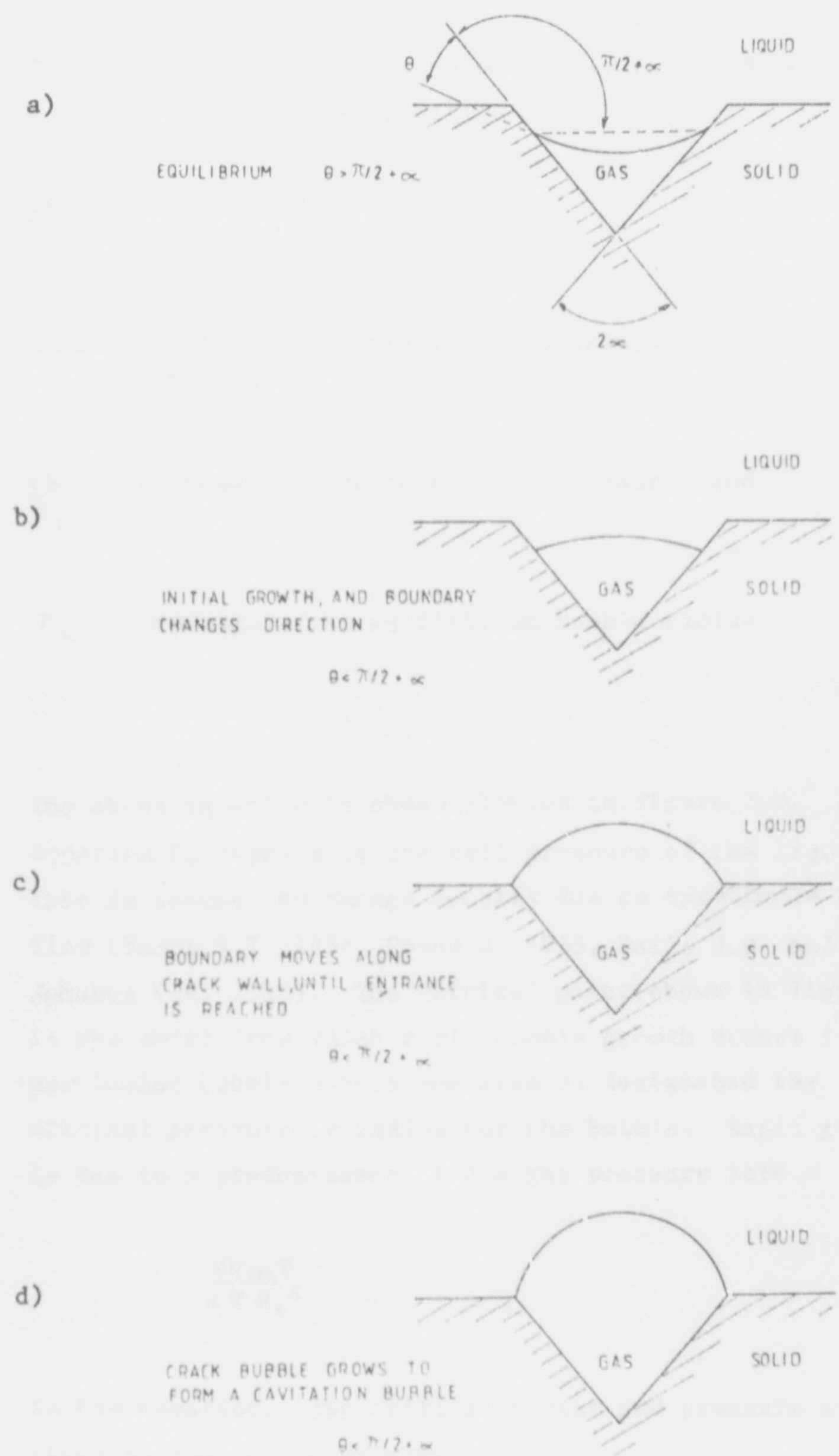


FIGURE 2.2 CRACK BUBBLE - SUPERSATURATED LIQUID

The derived equation for the bubble equilibrium radius for a particular pressure condition is

$$\frac{3RmT}{4\pi R_e^3} - \frac{2S}{R_e} = P_w - P_v \qquad 2.4$$

where $\frac{3RmT}{4\pi R_e^3}$ represents gas pressure

$\frac{2S}{R_e}$ represents surface tension pressure, and

R_e represents the equilibrium bubble radius

The above equation is shown plotted in Figure 2.3. In the equation P_w represents the wall pressure of the liquid; this is assumed to change locally due to turbulence in the flow (Knapp R.T. 1958, Rouse H. 1953, Daily J.W. and Johnson V.E. 1956). The critical point shown in Figure 2.3 is the point from which rapid bubble growth occurs for a particular bubble - this can also be designated the critical pressure or radius for the bubble. Rapid growth is due to a predominance of the gas pressure term

$$\frac{3RmT}{4\pi R_e^3}$$

in the equation. The critical radius and pressure are given by the following equations :

$$R_{CR} = \left(\frac{9RmT}{8\pi S}\right)^{0,5} \qquad 2.5$$

$$P_{CR} = P_V + \frac{3RmT}{4\pi R_{CR}^3} - \frac{2S}{R_{CR}} \qquad 2.6$$

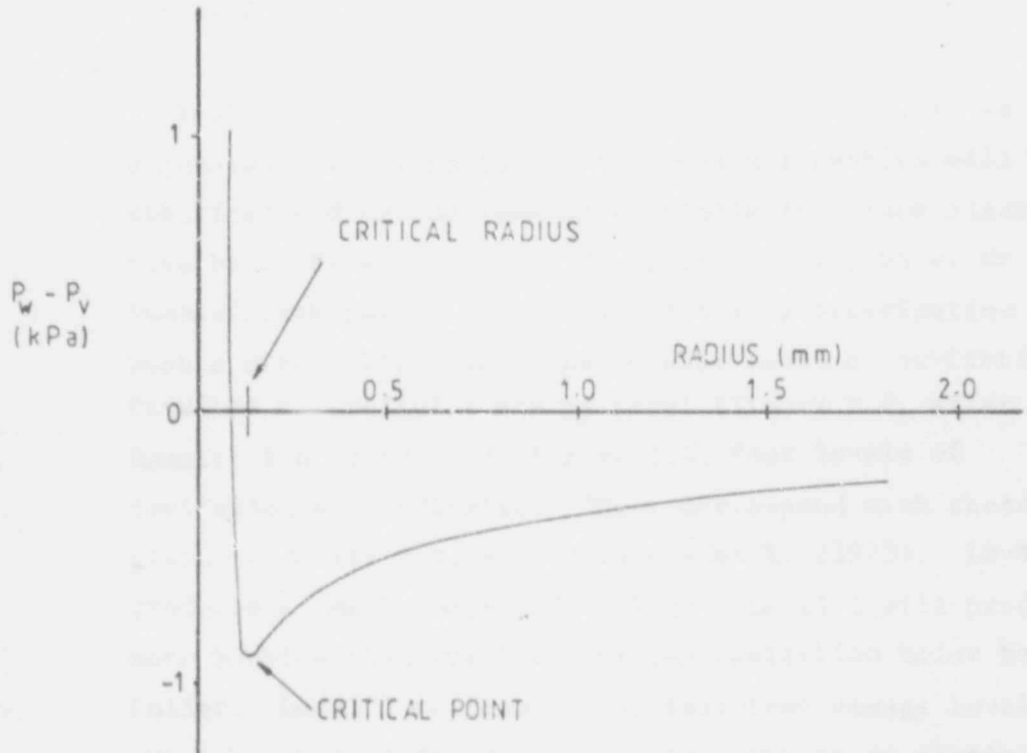


FIGURE 2.3 FREE BUBBLE GROWTH

The calculated critical pressure is a theoretical term, and can give results which are below the vapour pressure of the liquid in question. The theoretical requirements for the formation of a bubble are therefore met. However, as stated previously, the equation does not account for diffusion or evaporation at the bubble wall (Harvey E.N. et al 1944); however, the analysis does demonstrate the possibility of rapid growth of a bubble in a changing pressure field.

From the foregoing discussion in Section 2.1.3, it is suggested that it is improbable that all bubbles will be spherical and of the same size; similarly, crack sizes will also be different. Generalizing this to a bubble, or bubble/crack pair, it is proposed that a distribution of bubble sizes exist, and a particular level of cavitation requires a particular energy level (Figure 2.4, after Hammitt F.G. 1963). In Figure 2.4, four levels of cavitation are indicated. These correspond with those given by Tullis J.P. and Govindarajan R. (1973). Level 1 produces a small number of bubbles. Level 2 will produce more bubbles than level 1, and the cavitation noise becomes fuller. Level 3 represents the incipient damage level which has been defined as a pitting rate on an aluminium surface of 1 pit/in^2 min (Sweeney C.E. 1974). Level 4 is choking cavitation. Assuming that the cavitation energy requirement is provided by the pressure drop created as the fluid flows over a disturbance, then as the flow increases, the turbulence and number of vortices produced per unit time will also increase, thus providing a higher available total energy. This means that more energy is available to grow a range of cavitation bubble sizes as the pressure drop increases.

2.2 FACTORS AFFECTING CAVITATION INCEPTION

All liquid parameters affect, in some way, the growth of bubbles. Table 2.1 below lists some of the parameters and briefly describes their effect on bubble growth.

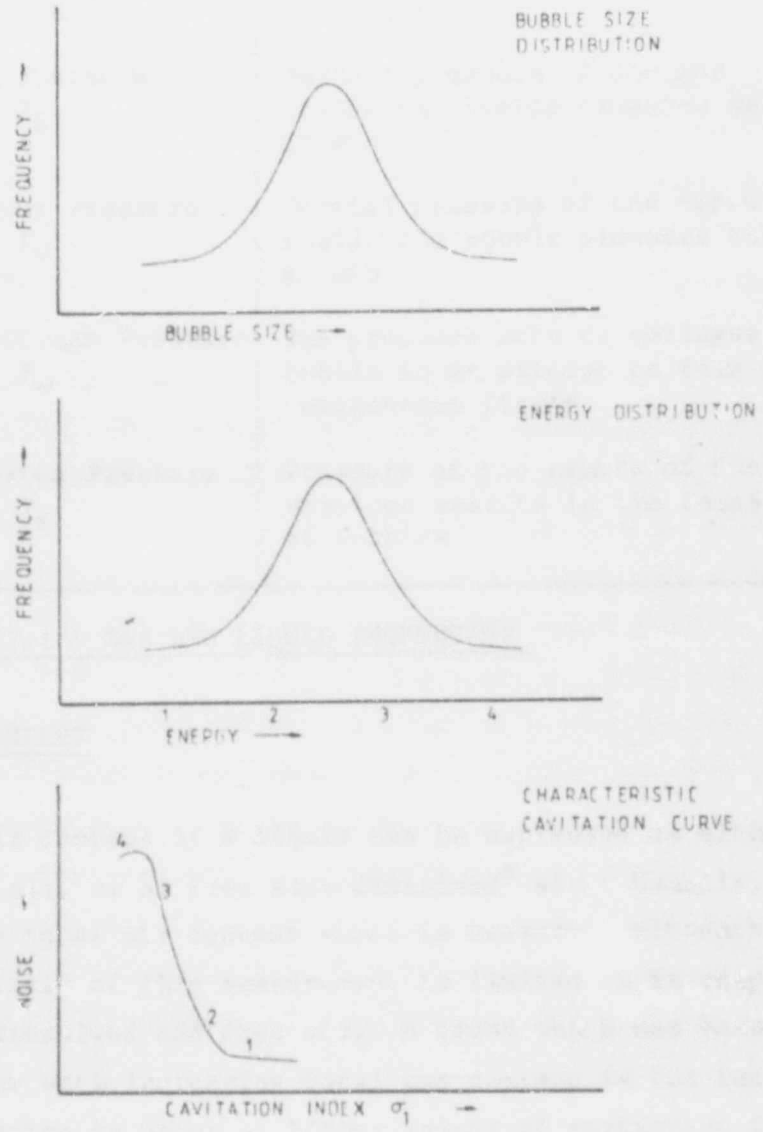


FIGURE 2.4 ENERGY AND BUBBLE SIZE DISTRIBUTION FOR CAVITATION BUBBLES

TERM	EFFECT
Surface tension $\frac{2S}{R}$	Tends to collapse the bubble and decrease growth rate
Viscous Forces $4\mu\frac{du/dt}{R}$	Decrease rate of bubble growth and collapse, due to viscous inertia of the liquid
Gas Pressure P_g	Partial pressure of the gas inside the bubble promotes bubble growth
Vapour Pressure P_V	Partial pressure of the vapour inside the bubble promotes bubble growth
Free Stream Pressure P_∞	The pressure acts to collapse any bubble in an attempt to form a homogeneous liquid
Vortex Pressure P_ϵ	Pressure at the centre of the vortices assists in the formation of bubbles

TABLE 2.1 - GAS AND LIQUID PROPERTIES

2.2.1 AIR CONTENT

The air content of a liquid ca be expressed as either total air, or as free plus dissolved[a] air. Usually, it is the total air content which is measured, although the usefulness of this measurement is limited as it comprises both dissolved and free air. A trend which has been evident with increasing total gas content is for incipient cavitation to occur at higher values of cavitation index[b] (Williams E.E. and McNulty P. 1955, Ripken J.F. and Killen J.M. 1963, and Ruggeri R.S. and Gelder T.F. 1963).

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a - Dissolved air in this instance refers to a true intermolecular solution of air and water

b - Cavitation index is defined as $\sigma_i = \frac{P_D - P_V}{P_U - P_D}$
(See Section 2.4)

Williams E.E. and McNulty P. (1955) only measured the total gas content - which thus limited the value of their investigations. They did, however, note that the point at which the onset of cavitation occurred, showed considerable scatter. This was attributed to changes in free air content, although, with the equipment available, this could not be established. Ripken J.F. and Killen J.M. (1963) were able to measure both the total and the free gas content on their experiments. In one experiment, the free air content was varied for a constant flow velocity, and a similar trend to that shown in the total air content experiment of Williams E.E. and McNulty P. (1955) was observed, thus suggesting that the free air content of a liquid is of equal importance to the total air content when predicting the onset of cavitation. A further set of experiments by Ripken J.F. and Killen J.M. (1963) showed the effect of velocity and of total and free gas contents on cavitation inception. By increasing the total air content, inception occurred at higher index values, but at higher velocities, inception appeared to become less dependent on gas content. Ruggeri R.S. and Gelder T.F. (1963) also measured cavitation behaviour when the total air content was adjusted. Three liquids were used - tap water, distilled water, and demineralized water - a trend similar to that noted by Ripken J.F. and Killen J.M. (1963) being noted in each case. In the free gas content experiment of Ripken J.F. and Killen J.M. (1963), the free air content was adjustable, and it was noted that cavitation inception occured at a higher value of the cavitation index for a higher flow velocity. The same result was also noted for a higher free air content, although at low flow velocities the free air content did not seem to influence cavitation behaviour significantly.

2.2.2 PRE-PRESSURIZATION AND PRESSURE LEVEL

The effect of pressure on cavitation inception has been reported on by several authors - Harvey E.N. et al (1944); Knapp R.T. (1958); and Ripken J.F. and Killen J.M. (1963). Harvey E.N. et al (1944) demonstrated the effect of subjecting a sample of water to a pressure of 16 000 PSI (110,3 MPa) immediately before its use in a static (non-flowing) test operation. The result was an increase in liquid tensile strength (cavitation resistance). Knapp R.T. (1958) also noted that the liquid tensile strength in a static system increased after pre-pressurization. The effect of pre-pressurization in a static system appears to either force free air into a true solution or to reduce the bubble size (Ripken J.F. and Killen J.M. 1963). A further aspect of pre-pressurization in a static system is the gas/liquid stabilization time. Using a closed system and adjusting the pressure level, Ripken J.F. and Killen J.M. (1963) recorded the free air content of the liquid. It was noted that approximately five minutes were required for the water and free air to stabilize as a solution after a change in pressure. The maximum pressure used corresponded to 20 feet of water (61 kPa).

The general conclusions which can be drawn from the above are that an increase in pressure will increase the tensile strength value of a liquid, and that a finite time is required for free gas/liquid conditions to stabilize after a change in pressure. This implies that bubble sizes will change (and so, therefore, will the critical point in Figure 2.3). In a mine water reticulation system, the effect of a high system pressure will thus be to provide the water with a certain level of resistance to cavitation.

In a dynamic (flow) system, the opposite effect to that of pre-pressurization seems to occur. The work of Tullis J.P. and Ball J.W. (1974) on valves, and Ball J.W. et al (1975) on orifice plates, indicates that as the upstream pressure is increased the cavitation resistance of the water decreases. In other words, the effect of the rate of velocity or pressure drop across an orifice on the occurence of cavitation at various upstream pressures is not a linear function.

There appear to be two possible explanations for this trend. Firstly, the pressure of the nuclei trapped on surfaces or suspended solids (Harvey E.N. et al 1944). In neither of the above two cases were the test rigs cleaned to remove surface nucleation sites, and since the water was obtained from a large open reservoir, it would be in a saturated condition with an undetermined quantity of suspended solids in it. Obviously, the testing of equipment such as valves requires a large supply of water. Correspondingly, results are only indicative of the cavitation performance of similar but different sized equipment. Secondly, increased turbulence with an increase in flowrate may have reversed the trend of the static system (Daily J.W. and Johnson V.E. 1956, Daily J.W. et al 1961). As the flow rates increase, the number of vortices (turbulence) may increase; or the pressure drop between the outside and the eye of the vortices may have increased, thereby providing greater energy for the formation of cavitation bubbles. Either explanation could account for the difference between the static and dynamic systems - however, these aspects do not appear to have been furhter investigated to date.

2.2.3 DELAY TIME

The cavitation delay time is an effect associated with a change from non-cavitation to cavitation (for an unchanged flow and pressure condition). As an effect, it appears to have been studied by relatively few people, but both Hall J.W. and Treaster A.L. (1966), and Pearce I.D. and Lichtarowicz A. (1971) observed and studied the phenomenon.

Hall J.W. and Treaster A.L. (1967) used a 1,5 inch diameter test section, the maximum upstream pressure being 33 PSI A (228 kPa abs); to produce cavitation, ogives were used. These had different surface finishes, namely those corresponding to stainless steel, Teflon and Teflon-coated stainless steel (both Teflon and stainless steel are hydrophobic). The results showed delay times of 0,5 s for the Teflon models, compared with 6 s for the stainless steel. This was said to indicate a dependence on surface nuclei rather than on free stream nuclei. Other conclusions found were that the delay time decreases with increasing velocity, system size and dissolved air content, thus suggesting that small systems constructed of small bore piping will be associated with long cavitation delay times. Further, the suggested dependence on surface nuclei tends to support the work of Harvey E.N. et al (1944).

Pearce I.D. and Lichtarowicz A. (1971) used a test rig based on an oil hydraulic circuit having small diameter piping, and so were able to utilise higher static pressures. For water the maximum pressure and flow were 3450 kPa and 0,5 l/s. The cavitating devices used were long orifices [a] with diameters ranging from 1,3 mm to 2,6 mm (a 'small' system such as that described by Hall J.W. and Treaster A.L. (1966)). Their conclusions were similar to those of Hall J.W. and Treaster A.L. (1966), though it was also observed that the presence of a pressure tap at the vena contracta (point of minimum pressure) reduced cavitation delay times to zero. This was suggested as being due to a static column of liquid being in contact with a vena contracta. Perhaps an alternative reason was

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a - Defined as devices where the ratio of length to orifice diamter exceeds 0,1 (Miller D.S. 1971) that air was present in part of the pressure tap; this fed the low pressure area with air, and so masked the delay time before cavitation began. The contents of the pressure tap (water or air) were not noted in the experiments. It is not known whether this reported effect is relevant to the present experiments; however, it is recognised as a phenomenon relevant to cavitation occurrence. In relation to the mine water systems its occurrence would probably be undetected due to the system's vastness and remoteness, but it may result in effects which are otherwise unexplainable.

2.2.4 SURFACE ROUGHNESS

Surface roughness can be described as that either of isolated elements of various sizes and shapes, or as a uniformly distributed roughness similar to that which collects inside a pipe after a number of years, the effect of the roughness being to modify the flow velocity gradient at the surface (boundary layer) by retarding flow, thereby increasing local turbulence. From observations of flow across a flat plate, it was noted by Daily J.W. and Johnson V.E. (1956) that the turbulent boundary layer was made up of vortices, with cavitation bubbles forming in the vortices at the centre of the boundary layer.

Using a pipe with a turbulent boundary layer, Arndt R.E.A. and Ippen A.T. (1968) observed cavitation occurring at the centre of the boundary layer. This was for both types of roughness, minimal cavitation occurring at the actual wall. A similar result had previously been obtained by Hall J.W. (1960) who concluded that the occurrence of cavitation was dependent on roughness height and low velocity. Generally, an isolated roughness was observed by Arndt R.E.A. and Ippen A.T. (1968) to assist cavitation formation more than distributed roughness, so indicating that velocity gradient and its associated pressure effects are important in determining the incipient cavitation level.

In the mine situation an isolated roughness element could be associated with the protrusion into a pipe of a misplaced gasket or an exceptionally large piece of scale, whereas distributed surface roughness would be the result of a build-up of scale on the inside of the pipe through water condition and time. Should cavitation bubbles be formed by either of these means, they could provide nuclei for further growth when the flow passed through an orifice.

A further investigation of surface irregularities was carried out by Ball J.W. (1976). Here the surface irregularities arise from hydraulic structure misalignments (eg. flanged pipes bolted together). As with the findings of Hall J.W. (1960) and Arndt R.E.A. and Ippen A.T. (1968), cavitation was found to occur at higher cavitation indices (see Section 2.4) associated with higher flow velocities. Ripken J.F. and Killen J.M. (1963) also observed cavitation differences when rotating a smooth disc through water, and then a pegged disc through the same water. The pegged disc was shown (acoustically) to begin cavitating before the smooth disc, this being attributed to turbulence effects.

2.3 BUBBLE COLLAPSE

Collapse of a cavitation bubble occurs when the bubble moves from its inception location, eg. the centre of the forming vortices, to a relatively high pressure region, the collapse force being sufficient to cause permanent damage to a solid boundary (ie. erosion). Collapse pressures of single bubbles have been theoretically calculated by a number of investigators over the last 70 years : Rayleigh O.M. (1917) calculated 1030 MPa; Naude C.F. and Ellis A.T. (1961) 1300 PSI (9 MPa); and Hickling R. and Plesset M.S. (1964) 10 000 MPa. These differ considerably, which raises the question - was the methodology applied to the formation of a single bubble the same in each case?

Alternative approach were put forward by Rao N.S. and Thiruvengadam A. (1961) and Hammitt F.G. (1963). They hypothesized distributions of bubble energy for cavitation initiation (the distribution after Hammitt F.G. (1963) being shown in Figure 2.5). With very light cavitation, the bulk of the energy produces bubbles which have very little potential to cause damage, but some bubbles formed are capable of causing considerable damage. As the level of cavitation increases, progressively more bubbles capable of causing damage are created, fewer non-damaging bubbles being formed. At the maximum cavitation level, the majority of the bubbles formed have the potential to cause damage. The remaining few bubbles are carried along with the flow and have no damage potential.

Generally speaking, the above mentioned analyses were based on experimental evidence (eg. photographic), the analysis being fitted to the observations. Further to this, various other observations on bubble shape and collapse were noted :

(i) The collapsed bubbled are initially non-spherical, and finally become micro-jets. See Section 2.3.1 (Collapse Shape).

(ii) The cavitation bubbles rebound after initial collapse. See Section 2.3.2 (Bubble Collapse Rebounds).

When compared with bubble growth, bubble collapse appears to have been studied less, though its significance is of equal or greater importance as its result is frequently erosion.

2.3.1 COLLAPSE SHAPE

The non-spherical shape of collapsing cavitation bubbles has been observed from photographic studies. Ellis A.T. (1955) observed non-spherical collapses and at a later date

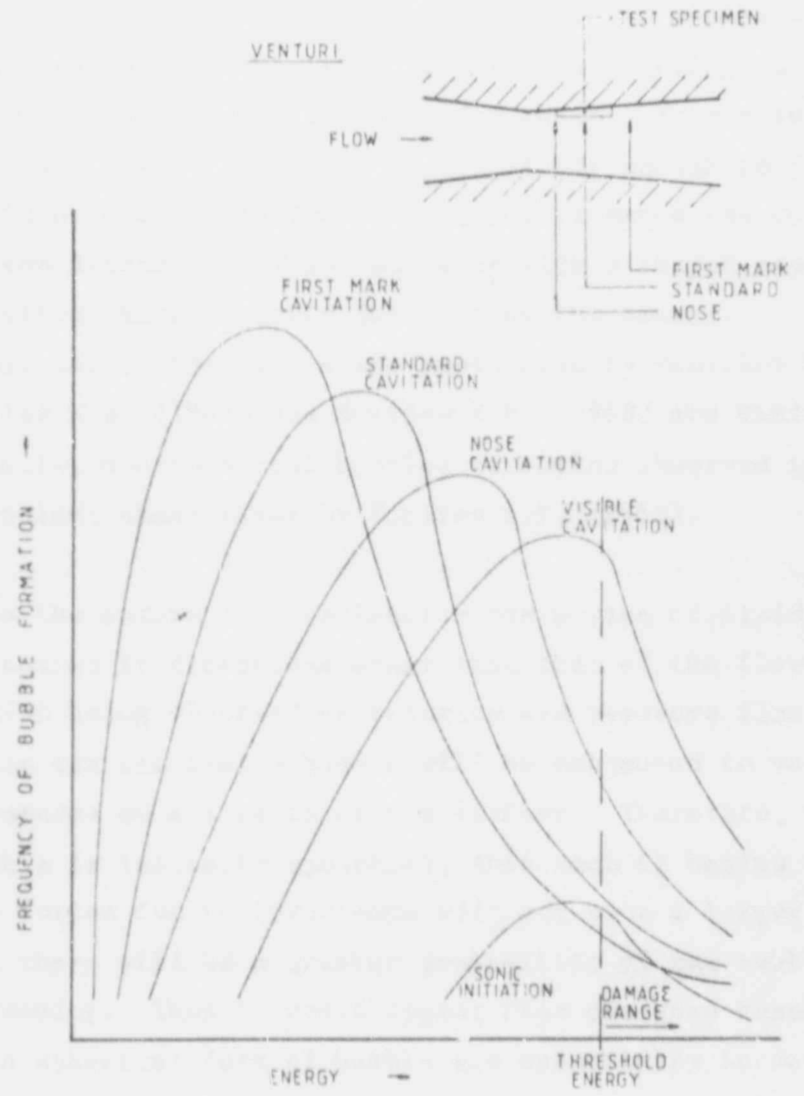

FIGURE 2.5 HYPOTHESIZED BUBBLE ENERGY SPECTRA FOR A CAVITATING VENTURI (HAMMITT F.G. 1963)

Naude C.F. and Ellis A.T. (1961) both theorized and then observed non-spherical collapses. In both cases the shape at collapse was that of torus, the core being a water jet travelling at high velocity. This was reconfirmed at later dates by Shuttler N.D. and Mesler R.B. (1965) and Kozirev S.P. (1968). According to Shuttler N.D. and Mesler R.B. (1965), the damage to solid boundaries was caused by a pressure pulse mechanism, the water jet forming as the bubble shape changes to that of a torus. This also created a pressure wave (pressure pulse) strong enough to damage a solid boundary. Kozirev S.P. (1968) likened the collapse to the detonation of an explosive with a shaped cavity, the resulting high velocity jet causing the damage. Essentially the mechanisms postulated by Shuttler N.D. and Mesler R.B. (1965) and Kozirev S.P. (1968) are similar. Finally, non-spherical bubbles were also observed in a free turbulent shear layer by Kozirev S.P. (1968).

From the nature of turbulence - the motion of fluid molecules in directions other than that of the flow, this motion being observed as velocity and pressure fluctuations - one can see that a bubble will be subjected to varying pressures on all parts of its surface. Therefore, if a bubble is initially spherical, then once it begins to grow, the forces due to turbulence will act over a larger area and there will be a greater probability of the bubble deforming. Thus it would appear that analyses based solely on a spherical form of bubble are essentially incomplete. Unfortunately, there appears to be no theoretical treatment of the collapse of a non-spherical bubble, thus experimental work to indicate collapse shapes and mechanisms is of importance to the understanding of cavitation erosion.