Chapter 4

Physics of cavitation:CAVITATION INCEPTION

Objective: *Description of the mechanism of cavitation inception, the phenomena which influence inception and the definition of the inception bucket*

Cavitation inception is important for two reasons. The first reason is that the radiated noise level of any form of cavitation is an order of magnitude higher than the noise level of a non-cavitating flow. This is used by Navy ships to detect and locate other ships and by torpedo's to home in on the ship. This is the Navy problem of cavitation inception and the inception speed of a navy ship is very important.
Commercial vessels generally are not interested very much in the precise inception of cavitation. Only special ships such as fishery research vessels require a high inception speed. However, for cavitation testing at model scale it is necessary that inception occurs in the properly scaled conditions. Otherwise no cavitation will appear. When cavitation inception is delayed at model scale, the properties and effects of developed cavitation cannot be investigated properly. This is the scaling problem of cavitation inception and this problem is occurs in any case when cavitation occurs.

Water and vapor are in equilibrium at the *equilibrium vapor pressure or shortly the* vapor pressure P_v. But is is still possible that no vapor (cavitation) is present when the local pressure is below the vapor pressure. In that case the difference between the vapor pressure and the local; pressure is called the fluid *tension. When the pressure is lowered the tension will increase and at some pressure vaporization will start. The pressure at which this occurs is the inception pressure and the difference between the vapor pressure and the inception pressure is called the* tensile strength of the fluid.

For cavitation inception nuclei are required, and these nuclei generally consist of small gas bubbles. In this chapter the behavior of nuclei in a pressure field is investigated.

4.1 Bubble Statics

Consider a gas/vapor bubble of radius R in a fluid with pressure p. The pressure inside the bubble is equal to the outside pressure p plus the surface tension $2s/R$. Here s is the surface tension in N/m. The pressure inside the bubble is the sum of the vapor pressure p_v and the partial gas pressure p_g. So

$$p + \frac{2s}{R} - \frac{K}{R_0^3} = p_v \tag{4.1}$$

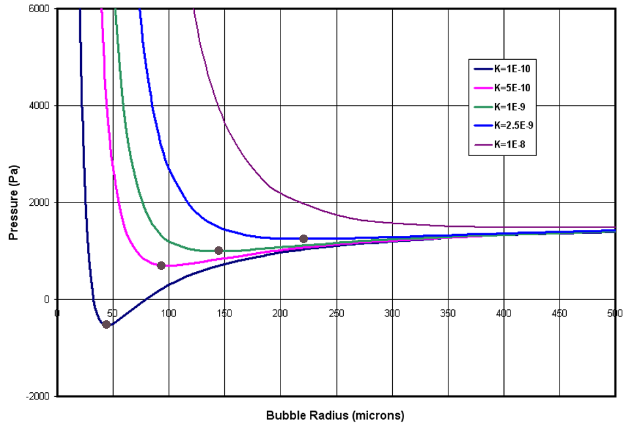

Figure 4.1: Bubble Radius as a Function of the Outside Pressure

In isothermal conditions the gas pressure is inversely proportional to the volume, so the gas pressure can be written as $\frac{K}{R^3}$, where K is a measure for the amount of gas in the nucleus. The relation between the bubble radius R and the pressure p is given in Fig.4.1 for a number of values of the amount of gas K.

The curve shows a minimum, and when the radius is at that minimum the radius *increases* with increasing pressure. This is an imaginary situation, which cannot exist. When the pressure reaches the minimum value equilibrium is no longer possible and the bubble will grow so rapidly that inertia terms have to be included in the equilibrium equation. The minimum radius at which a stable condition is possible is called the *critical radius*and the corresponding pressure the *critical pressure*. The critical pressure is often taken as the inception pressure, because at that pressure the nuclei are beginning to grow rapidly and will become visible. The critical pressure is indicated with a dot in Fig. 4.1. With increasing bubble size the critical pressure approaches the vapor pressure, but for smaller nuclei the critical pressure can be significantly lower than the vapor pressure.

The critical radius can be found from differentiation of the pressure:

$$\frac{\partial(p_0 - p_v)}{\partial R} = 0$$

from which condition it follows that

$$R_{crit} = \sqrt{\frac{3K}{2s}} \tag{4.2}$$

The pressure at which this critical radius is reached is taken as the inception pressure p_i. This pressure can be found by substitution of the critical radius in eq. 4.1 and is:

$$p_i = p_v - \frac{4s}{3R_{crit}} \tag{4.3}$$

The difference between the vapor pressure and the inception pressure, as expressed in eq. 4.3, decreases with increasing critical radius and thus with increasing nuclei size in the undisturbed flow.

This leads to the important conclusion that

The inception pressure depends on the size of the largest nuclei in the fluid

This conclusion can be expressed in a non-dimensional way. The pressure is expressed as the cavitation index

$$\sigma = \frac{p_0 - p_v}{1/2\rho V^2} \tag{4.4}$$

where p_0 is the pressure in the undisturbed flow at the same location. The surface tension s is expressed as the Weber number We

$$We = \frac{\rho V^2 r_0}{s} \tag{4.5}$$

where r_0 is the radius of the nuclei in the undisturbed flow. Eq. 4.1 is valid in the undisturbed flow as well as in the critical inception condition, so

$$
\begin{aligned}
p_0 - p_v + \frac{2s}{R_0} - \frac{K}{R_0^3} &= 0 \\
p_{crit} - p_v + \frac{2s}{R_{crit}} - \frac{K}{R_{crit}^3} &= 0 \\
R_{crit} &= (\frac{3K}{2s})^{\frac{1}{2}}
\end{aligned}
$$

Elimination of R_{crit} and p_0 and expressing the equations in cavitation index and Weber number results in [27]

$$
\frac{p_{crit} - p_v}{p_0 - p_v} = -\frac{2\frac{8}{\sigma We}^{\frac{3}{2}}}{3\sqrt{3}(1 + \frac{8}{\sigma We})^{\frac{1}{2}}}
$$

The tensile strength of the water, which is the difference between inception pressure and the vapor pressure, as expressed in the left hand of this equation can also be written in non-dimensional terms as

$$
\frac{\Delta\sigma}{\sigma}
$$

where

$$
\Delta\sigma = \frac{p_{crit} - p_v}{1/2\rho V^2}
$$

This gives the final non-dimensional form to the inception pressure:

$$
\boxed{\frac{\Delta\sigma}{\sigma} = -\frac{2\frac{8}{\sigma We}^{\frac{3}{2}}}{3\sqrt{3}(1 + \frac{8}{\sigma We})^{\frac{1}{2}}}}
$$

This equation gives the difference between the vapor pressure and the inception pressure in non-dimensional terms.

This has severe implications for scaling of cavitation inception. It means that, apart from the cavitation index σ also the Weber number We has to be the same at model and full scale. So the Weber number is an additional scaling law, introduced by the surface tension as a new parameter. The Weber number can also be derived as a scaling law using the Π-theorem as mentioned in [42]

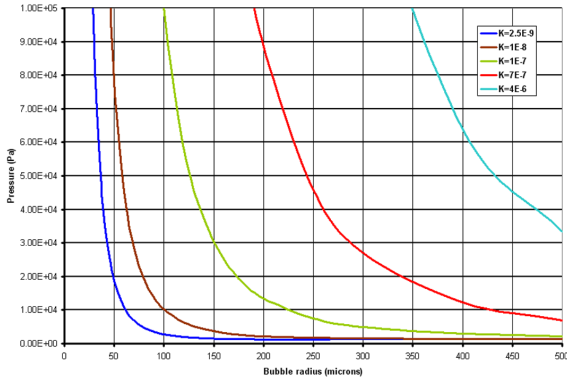

Figure 4.2: Bubble radius versus pressure for bubbles with a higher gas content

4.2 Gaseous Cavitation

The definition of the critical pressure as he inception pressure raises some problems. The first problem is that bubbles with a higher amount of gas do not become unstable (The two highest values of K in Fig.4.1). In experiments cavitation is mostly detected visually. This means that the cavity has to have a certain minimum size to be detected. Let us assume that this minimum size is 1 mm in diameter or 500 microns in radius, the end of the scale in Fig.4.1. The bubbles which do not become unstable in Fig.4.1 are detected at the vapor pressure, so inception is called at the vapor pressure. When the amount of gas increases the bubbles reach the visible size at a pressure above the vapor pressure.

In Fig. 4.2 the two highest gas contents of Fig.4.1 are plotted, together with three bubbles with a higher gas content. This Figure shows that for $K > 10^-7$ the nuclei become visible at a pressure above the vapor pressure. In that case the observation is called *gaseous cavitation* [21], which is not really cavitation, because the pressure inside the bubble is still higher than the vapor pressure. There is, however, a range of gas contents (or nuclei sizes) which has no critical radius but which still lead to a correct prediction of the vapor pressure as the inception pressure.

In Fig.4.2 the pressure has been extended to atmospheric pressure. This shows that in the same fluid at atmospheric pressure nuclei with a radius above 100 microns ($10^{-4}m$)will lead to gaseous cavitation. In experimental facilities the mean pressure in the test section is often lower, but that does not change the situation very much, since the curves are very steep. From Fig.3.3 it is found that these nuclei are relatively scarce in test facilities at low air contents, but not completely absent. An incidental observation of a visible bubble on a surface therefore does not necessarily mean inception. To avoid observation of gaseous cavitation the water in a test facility should not contain too many large bubbles. In that case all visible bubbles are cavitation bubbles with an inside pressure close to the vapor pressure which have reached the critical pressure.
When the observation is more careful, smaller bubbles can be observed, e.g. with a radius of 250 microns. This will increase the risk of observing gaseous cavitation.

When the pressure reaches the critical pressure equilibrium is no longer possible and the nuclei will grow dynamically and become visible cavitation bubbles. However, when the low pressure region is very small the time of growth will be very short and even when the nuclei have reached their critical size, they may still not reach a visible size. So we have to check our concept of inception in dynamic circumstances.

4.3 Bubble Dynamics

Vapor is relatively light relative to air. At the vapor pressure and at 15 degrees Celcius the the vapor density is $0.013kg/m^3$. The difference between the density of water and vapor in that condition is so large (a ratio of order 10^5) that the amount of water required to form vapor can generally be neglected

Assuming the flow to be inviscid and irrotational the bubble can be formulated as an unsteady source in potential flow. Assuming further that the behavior is isothermal and that no diffusion takes place through the bubble wall the unsteady equation of motions of a bubble becomes an extension of eq. 4.1

$$p + \rho_w R \frac{3}{2}\frac{\partial R}{\partial t} + \rho_w \frac{\partial^2 R}{\partial t^2} + \frac{2s}{R} = p_v + p_g \tag{4.6}$$

This dynamic terms were first derived by Raleigh(1917). Plesset [53] combined it with the contents of a gas-vapor bubble. This equation is therefore referred to as the *Raleigh-Plesset* equation. To investigate the dynamical behavior of a bubble we will consider its radius when subjected to a jump in pressure, as shown in Fig.4.3.

A nucleus with radius R_0 is present in a flow at pressure p_0 at time t=0. At time t=1 this nucleus enters a negative pressure peak. During the period t[1,2] the pressure is still above the critical pressure and the bubble will grow, but the increase in size is small.
At t=2 the critical pressure is reached and the bubble begins to grow more rapidly while the pressure decreases further. The growth of the bubble is such that the gas pressure in the bubble can be neglected at this stage as well as the surface tension. So the pressure inside the bubble is close to the vapor pressure The period t[2,3] is controlled by eq. 4.6.
During the period t[3,4] the negative pressure on the bubble is constant and equal to $pv - p_{min}$ and the rate of growth of the bubble becomes constant too. This rate of growth will be considered later. In principle the growth rate of the bubble is unrestricted as long as the pressure remains unaffected. In practice the bubble may grow to such a size

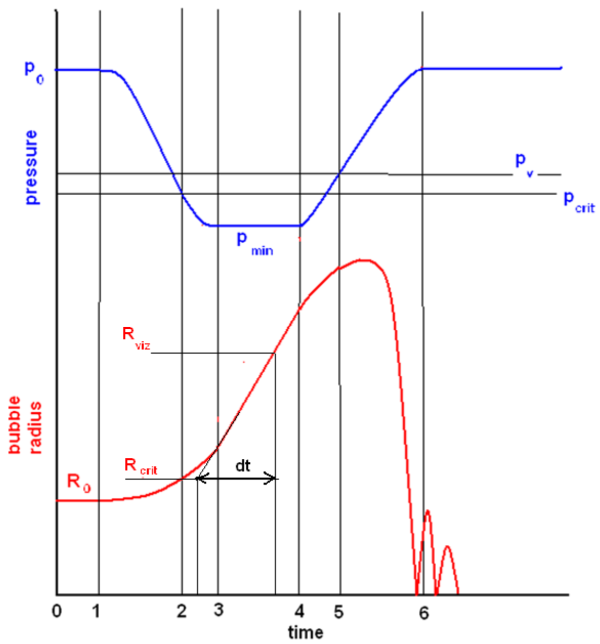

Figure 4.3: Bubble response to a pressure jump

Figure 4.4: High Speed Video:Implosion of spark generated vapor bubble. courtesy: MARIN

that the pressure is increased by the bubble size and this will restrain its growth. For simplicity we assume no interaction between the outside pressure and the bubble size.
In the period t[4,5] the negative pressure on the bubble will decrease, which slows down the growth of the bubble. At t=5 the vapor pressure is reached (note that the critical pressure does not play a rôle anymore) and the pressure difference on the bubble becomes positive. Due to the rate of growth of the bubble, there is an overshoot in the radius, after which the radius will begin to collapse. Due to the overshoot the rate of collapse is much greater than the linear rate of growth. When the bubble decreases to roughly its original size the surface tension becomes increasingly important and this will further increase the rate of collapse. In the end the bubble walls will hit each other , as all vapor disappears. The energy of collapse is then converted in a very high local pressure. In the last stage of collapse the velocity of the bubble wall will exceed the velocity of sound and shock waves are also radiated.

An example of the growth and collapse of a bubble is given in Fig. 4.4[15]. The vapor bubble is created by a spark from the left hand electrode. The bubble collapses on the wall above the electrode. The first bang is the generation of the cavity. After reaching its maximum size the bubble collapses on the wall, and it is clear that the impact is high. After the first collapse a rebound is visible. Note the time scale: the pictures were taken with a frame rate of 40.000 Hz and the whole sequence is 120 pictures or 3 milliseconds.

In the very last stage of collapse any gas in the bubble will act as a buffer and slow down the rate of collapse. The maximum pressure is decreased by the gas, but, depending on the gas, the temperature increases rapidly. The temperature may increase so much that light emission takes place (sonoluminiscence) . The energy, stored in the gas, makes the bubble to rebound once or twice.After rebound the single bubble is often fractured into many smaller ones.

At this point we are interested in inception only. At the critical pressure the nucleus is not visible yet, and the question is when is it? What time does it take to grow to a visible size? This can be estimated from an asymptotic solution of eq. 4.6. With a constant under-pressure in region l[3,4] of Fig. 4.3 the acceleration term $\frac{\partial^2 R}{\partial t^2}$ will vanish. With increasing radius the gas pressure p_g and the surface tension term $\frac{2s}{R}$ will become small, leaving only

$$\frac{3}{2}(\frac{\partial R}{\partial t})^2 = p - p_v \tag{4.7}$$

This estimation can be used to estimate the time dt in Fig. 4.3 between the time the critical pressure is reached and the time the bubble becomes visible. Take e.g. the nucleus with $K = 5 * 10^{-10}$ from Fig. 4.1. It reaches the critical pressure at a radius of 100 microns and the critical pressure is 700 Pa. When this is also the minimum pressure in the fluid the pressure difference $p - p_v = 1000$ Pa, assuming that the vapor pressure is 1700 Pa. The bubble still has to grow 400 microns in radius to become visible, so $dr = 4 * 10^{-4} m$. From eq. 4.7 it is found that this requires a time $dt = 1.5 * 10^{-5}$ sec. Even at a very high flow velocity of 40 m/sec the bubble will thus be detected at a position which is 0.6 mm downstream of the minimum pressure location. So except for very short low pressure pulses the critical pressure is a useful inception criterion.

The Raleigh- Plesset equation is often used in numerical calculations to provide a model for the phase change of water into vapor when cavitation occurs.

4.4 Bubble Resonance

When the duration of a pressure change is too short the response of the bubble will decrease. A measure for this time scale is the resonance frequency of a gas bubble. The resonance frequency of a spherical gas-vapor bubble with radius R at a pressure p is [51][14]

$$f_0 = \frac{1}{2\pi R\sqrt{\rho_w}}[3\gamma(p + \frac{2s}{\rho_w} - p_v) - \frac{2s}{R} - \frac{4\mu^2}{R^2\rho}]^{\frac{1}{2}} \tag{4.8}$$

in which γ is the ratio of specific heats (its value is value approximately 1.4) and μ is the dynamic viscosity of water. The effect of viscosity in water is mall. For bubbles larger than 10 microns in radius the surface tension becomes small and can be neglected and eq. 4.8 can be simplified to

$$f_0 = \frac{1}{2\pi R\sqrt{\rho_w}}[3\gamma(p - p_v)]^{\frac{1}{2}} \tag{4.9}$$

In most cases the vapor pressure is small relative to the pressure p. Then eq.4.9 is reduced to

$$f_0 = \frac{1}{2\pi R\sqrt{\rho_w}}(3\gamma p)^{\frac{1}{2}} \tag{4.10}$$

The assumptions are mentioned here, because eq. 4.10 is often used without noticing the restrictions.

When e.g. the pressure in the test section of a cavitation tunnel is 0.3 at or 33.000 Pa, the resonance frequency of a nucleus of 100 microns radius is 18.7 kHz. The relevant length scale can be estimated as half the wave length, so at $2.7 * 10^{-5} m$. At a tunnel speed of 10 m/sec the length of a low pressure region which is of the order of the resonance frequency is $2.7 * 10^{-4} m$. When the length of the low pressure region is 10 times higher, so 2.7 mm, the bubble will remain close to equilibrium. This may require attention sometimes, because on thin foils as used in ship propellers, the length of the low pressure peak at the leading edge is only a few percent of the chord. With a chord length of 10 cm the low pressure peak may become so short that the nucleus has no time to react to the pressure drop at the leading edge.

4.5 Thermal effects

Evaporation of water requires energy. Evaporation of water lowers the temperature of the surroundings, as is well known by everybody who is sweating. The amount of required energy is the evaporation heat (2270 kJ/kg). To get an impression of the thermal effects of evaporation, consider a cubical vapor volume of $1m^3$. Creation of a vapor volume of $1m^3$ requires the evaporation of $10^-5 * 1000kg$ of water, or 10 g of water. When the evaporated water comes from the six sides of $1m^2$ each, the evaporated water thickness is only 0.0017 millimeter! The amount of heat involved to evaporate 10 g of water is is $22.7kJ$. The specific heat of water can be taken as $4.2kJ/kgK$. Now assume that the water temperature is affected over $1mm$ of water depth. This is an amount of 6 kg. The drop in temperature of that amount of water is then $22.7/4.2/6 = 0.9$ degrees K (or Celcius). Its main effect is the temporary change of the equilibrium vapor pressure by 100 Pa.

In the above example the critical assumption is the thickness of the layer which is cooled by the evaporation. There will be a temperature gradient and the minimum temperature will be at the evaporating surface. For a short time the temperature can therefore be much lower than the average temperature in a thin fluid layer. This is especially important when the time scale is small, such as in acoustic cavitation. In water the thermal effects are often small, but in other fluids they can be important.

The main reason for the limited effect of thermal effects is that the mass of the vapor needed to influence the flow pattern is limited. Cavitation in water occurs at a low pressure and at this pressure the amount of water to generate the vapor is very small. Much smaller than when e.g. evaporation is used for cooling (sweating) at atmospheric pressure. In some cases, where the evaporation is very strong, thermal effects can become more important [62]

4.6 Scale Effects

The inception criterion developed until now has been the unsteady growth of gas nuclei and the definition of the inception pressure is the critical pressure. This means that in theory cavitation inception is determined by the largest nuclei in the flow. When the density of the largest nuclei is low, it may take time to encounter a nucleus. On a propeller in uniform flow this time is available, but in non-uniform inflow the time in which the propeller blade can reach inception is limited. So the *encounter frequency* or the *nuclei density* is also becoming a parameter in inception. It is generally assumed that in inception tests the density of the relevant nuclei is high enough to make the encounter frequency much higher than the blade passing frequency. So the definition of the inception pressure is the critical pressure of the largest nuclei which become unstable and which are available in sufficient quantity.//

Cavitation tests on ship propellers are generally done at model scale. That means that scaling rules have to be maintained. These rules can be defined as non-dimensional parameters which have to be maintained at model and at full scale. Examples are the Reynolds number, the Froude number, the cavitation index and the Weber number.

Visible cavitation bubbles have an internal pressure which is close to the vapor pressure, since the gas content has become negligible So the parameter which has to be maintained for proper scaling of cavitation is the cavitation index (equation 4.4). Cavitation inception is not determined by the vapor pressure, but by the critical pressure of the largest nuclei, or by the pressure difference $p_{crit} - p_v$ (eq. 4.3). In non dimensional terms this means that a new scaling parameter $\Delta\sigma$ is introduced, which has to be maintained at model scale and full scale:

$$\Delta\sigma = \frac{p_{crit} - p_v}{1/2\rho V^2} \tag{4.11}$$

Using eq.4.3 it can be derived that when eq.4.11 is the same at model and ship, this means that

$$\frac{R_{crit}(model)}{R_{crit}(ship)} = \frac{V_s^2}{V_m^2}$$

When the Froude number is maintained in case of a free surface this ratio is equal to the scale ratio, which in model testing generally is between 10 and 30. It means that the critical radius of nuclei at model scale have to be larger than at full scale by approximately the scale ratio.

Apart from this requirement also the geometrical distribution of the nuclei should be scaled properly at model scale. That means that at model scale there should be the same amount of bubbles on the model propeller blade as on the ship. This means that the number density of the nuclei at model scale has to be increased by the third power of the scale ratio!

The combination of both requirements would lead to a very high free air content, a "soda pop tunnel".The transparency would be such that visual observations were impossible and the fluid would not be incompressible anymore. So it is impossible to maintain the scaling laws of bubble cavitation inception.

To evaluate this problem consider the value of $\Delta\sigma$ at full scale. There are generally ample small nuclei of the order of R=0.1 mm present in sea water (Fig. 3.3)at about atmospheric pressure. The critical radius of such nuclei will be much larger than the initial radius at atmospheric pressure, because at full scale the difference between the vapor pressure and the initial pressure is large (which is of the order of 10^5 Pa.). From eqs.4.1 and 4.2 it can be found that the critical radius of such nuclei is larger than 0.1 mm. The value of $p_{crit} - p_v$ from eq.4.3 is then 100 Pa. From Fig. 4.1 it can be seen that this is relatively close to the vapor pressure (about 1700 Pa at 15 degrees Celcius). So at full scale the inception pressure is always close to the vapor pressure.

To maintain $\Delta\sigma$ at model scale at a scale ratio of say 25, this requires nuclei with a critical radius larger than $25 * 0.1mm$ or 2.5 mm. Such nuclei will rise relatively fast and will obscure visibility when present in sufficient numbers. In practice the largest nuclei in a model tt will be smaller. But from Fig. 4.1 it can also be seen that when the critical pressure approaches the vapor pressure, the curve of critical pressures approaches the vapor pressure asymptotically. This means that deviations of the critical radius have little effect on the inception pressure. So when at model scale the required nuclei size is not reached, the error in inception pressure will be small, provided that the inception pressure is close to the vapor pressure.

The conclusion therefore is that proper scaling of bubble inception at model scale is not possible. To obtain a good approximation of full scale inception at model scale the nuclei size should be such that the inception pressure (critical pressure) is close to the vapor pressure. So the nuclei should be as large as possible without harming visibility. On the other hand the maximum size of the nuclei at model scale should not be so large that the nuclei become visible before the vapor pressure is reached. In that case gaseous cavitation will be observed, and the inception pressure at full

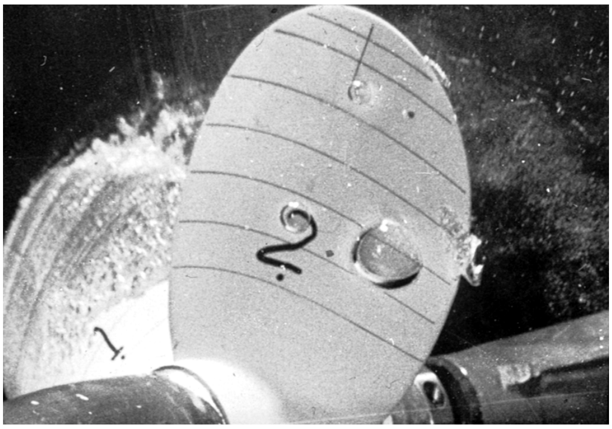

Figure 4.5: Bubble cavitation due to a single nucleus

scale will not be predicted correctly.

Note that for proper scaling of cavitation and its dynamics the cavitation index is still the proper index, because the pressure inside the cavitation is the vapor pressure. It is not correct to base the cavitation properties on σ/σ_i, as is sometimes done in literature. When inception has occurred the inception pressure does no longer affect the cavity size or dynamics, except for the very short time the cavity grows from inception to its dynamic equilibrium (see section 4.3).

At model scale the nuclei density of the largest nuclei will be smaller than at full scale,which has an effect on the appearance of bubble cavitation. When very few nuclei are available which can reach the critical size, inception will occur only incidentally, depending on the passage of an incidental nucleus. Such a single nucleus will grow rapidly because it is unstable and the minimum pressure is far below the vapor pressure. Since no other nuclei are growing around it,its surrounding pressure will not be affected until it has grown to a substantial size. An example is shown in Fig. 4.5.

Such large incidental bubble cavities indicate that the critical radius is only reached incidentally and that the number density of the nuclei is not sufficient. The inception pressure is much lower than during the observation in Fig 4.5.

4.7 Acoustic Inception

Up to now e have focussed on visual detection of cavitation inception. As indicated in Fig. 4.3 the collapse of a cavitation bubble is not symmetrical with its inception. After becoming unstable the nucleus grows and reaches a maximum value, after which it collapses. This collapse generates noise, dominated by one or several pressure spikes. In the frequency domain this means a significant increase of the high frequencies. The spike or the increase in high frequency noise can be used to detect cavitation. In that case it is called acoustic inception.

There may be differences between acoustic inception and visual inception. When the nuclei are small and the low pressure peak is narrow, the nuclei may become unstable but may remain invisible. In that case acoustic inception is detected first. In a cavitation tunnel this is the dominant situation. However, from Fig. 4.2 it was observed that larger nuclei can grow to a visible size without becoming unstable. In such a situation the bubble returns to its approximate original size without a violent collapse and thus without being detected acoustically. Stricly speaking this is gaseous cavitation.

The response of a nucleus to a pressure change has also been investigated extensively when the pressure change is periodical. The pressure field is then defined by an acoustic pressure field: a mean pressure p_{mean}, a pressure amplitude p_a and a frequency f. Vaporous bubble growth (inception) of nuclei may occur when the minimum pressure $p_{mean} - p_a$ is lower than the vapor pressure, even when the mean pressure is higher than the vapor pressure. However, when the minimum pressure is only slightly lower than the vapor pressure the nuclei will respond by a periodical motion. In that case there is no implosion and no acoustical cavitation will be detected. When the minimum pressure decreases below a certain limit value below the vapor pressure the response of the nuclei changes and the nuclei will collapse periodically. From experiments and calculations it is found that the critical pressure from eq. 4.1 can also be used with good accuracy for inception of acoustic cavitation [[51],[14]].

4.8 Inception measurements

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The definition of cavitation inception as given until now is from the instability of a single bubble. Even then the distinction between gaseous cavitation and inception cannot be made without knowledge of the nuclei content in the flow. When a nuclei distribution is involved, the nuclei density distribution is another factor, determining the frequency of cavitation inception. Also the accuracy of observation (what is defined as a visible bubble) is a factor in cavitation inception. The determination of cavitation inception is therefore difficult and the accuracy of the observed inception pressure of a propeller is not high.

4.8.1 Inception speed on Navy ships

The inception pressure is only important for Navy ships, where the acoustical detection of the ship depends on the occurrence of the first small cavitation event. The noise level of such an event can be such that it exceeds the flow noise or machinery noise considerably. A criterion for Navy ship is therefore the inception speed, which is the speed at which the first cavitation occurs. Inception measurements on Navy ships are therefore always done acoustically. The determination of the inception speed of a Navy ship at full scale is still difficult and is often not very repeatable. It may also change considerably in time and certainly with seastate, wind and fouling. At model scale the determination of cavitation inception exhibits a lot of scatter due to flow parameters such as nuclei, but also because visual inception is difficult to see. Acoustic inception is not well defined either, because cavitation inception starts with a single incidental implosion and the frequency of the implosions increases gradually and a certain criterion has to be used.

4.8.2 Inception measurements for comparative purposes

Cavitation inception is not very important for commercial propellers, except in some specific cases where a very low noise level is required (research vessels), which does not allow any cavitation. The noise level generated by a small amount of cavitation (incipient cavitation) is not high and in most cases can be ignored. Cavitation inception is still often measured at model scale, as a criterion for the operational conditions or for comparison between different propellers. This is only because there is no other more repeatable criterion available. It should be kept in mind, however, that cavitation inception curves are more inaccurate than is often suggested. Inception conditions will be discussed with the various types of cavitation.

4.9 The inception bucket

The inception properties of a propeller are expressed in an "inception diagram". This di-

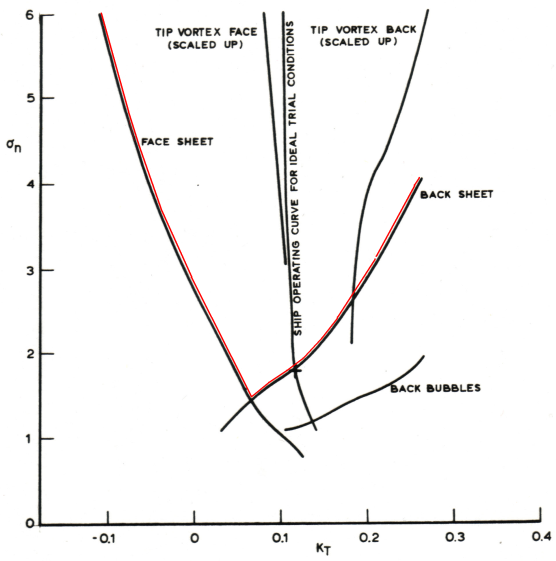

Figure 4.6: Example of an inception diagram of a propeller

agram gives the inception pressures at various loadings of the propeller. The loading is generally expressed in the non-dimensional thrust coefficient K_t, or in the non-dimensional advance ratio J. An example of such a diagram is given in Fig. 4.6.

The corresponding curves of sheet cavitation have been marked red in Fig. 4.6. Conditions outside the V-shaped curves will have sheet cavitation. Conditions inside the V-shaped curve will be free of sheet cavitation. Because the shape of the curves generally is V- or U-shaped, such an inception curve is called an inception *bucket*. To be free of any type of cavitation the conditions must be inside the innermost bucket.