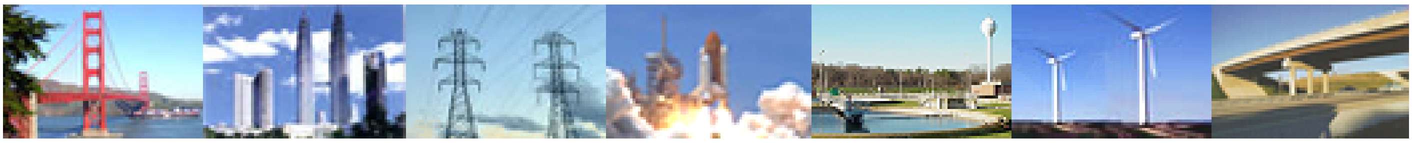

PDHonline Course M225 (6 PDH)

Interesting Facts (and Myths) about Cavitation

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2012

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Interesting Facts (and Myths) about Cavitation

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Introduction

Classical Gas

The word cavity, from which the term cavitation derives, comes from the Latin word *cavus*, which means hollow. Cavities result when a liquid partially *vaporizes*. Although the term cavitation can mean the formation of cavities of gas in a liquid, when classified correctly in fluidics, the cavitation process consists of both liquid cavity formation, and liquid cavity deformation. It is therefore a reversible, double change of state phenomenon. Note that the terms *boiling* and *flashing* are special categories of vaporization. Boiling is defined as the specific vaporization point of a liquid in the presence of local atmospheric pressure. The process known as flashing involves a fluid's rapid phase change from liquid to vapor without the return of the fluid to the liquid phase.

MYTH NUMBER 1

The terms *cavitating, boiling,* and *flashing* all mean the same thing and therefore can be used interchangeably.

Although not meeting the technical definition of cavitation, there are also occurrences in which relative flow arrangement, entrainment/dissolution, or chemical reaction can lead to cavity formation and later collapse in what is known as *pseudo-cavitation*.

Cavitation can, and often does, occur in any situation where fluid is moving in relation to a solid surface. Usually associated with powered, rotating equipment, cavitation also occurs in stationary hydraulic structures involving both small and large scale flows. Normally considered detrimental, the cavitation process is actually desirous in some special situations. These could be subsurface drilling or process mixing applications where the associated turbulence is advantageous. A recent development in mixing microtechnology called cavitation microstreaming, whereby a gas bubble inside a liquid is made to oscillate at a various frequencies, greatly enhances the mixing of blood samples with reagents.

MYTH NUMBER 2

Cavitation is always problematic and deleterious and therefore always should be eliminated or at least minimized.

It's All About Pressure

The process of cavitation begins when the pressure on portions of the liquid decrease to a point low enough for the fluid to change states, from a liquid to a gas. This occurs at the vapor pressure of the liquid.

The classical chemistry definition of vapor pressure goes something like: *The pressure of a confined vapor in equilibrium with its liquid at a specified temperature and, thus, a measure of a substance's propensity to evaporate.* Whitesides[1] has offered the following alternative descriptions of vapor pressure:

- Vapor pressure is defined as that pressure exerted by the gaseous state of a fluid, that is in equilibrium with its liquid phase.
- Vapor pressure is that pressure at which a liquid begins to vaporize.

The vapor pressures of liquids depend directly on their temperatures. Figure 1 shows the relationship between temperature and vapor pressure (and the boiling point) for four liquids. High temperatures increase the pressure at which a liquid will vaporize. One major source of cavitation trouble can be high liquid temperature, particularly if the process temperature is approaching its vapor pressure.

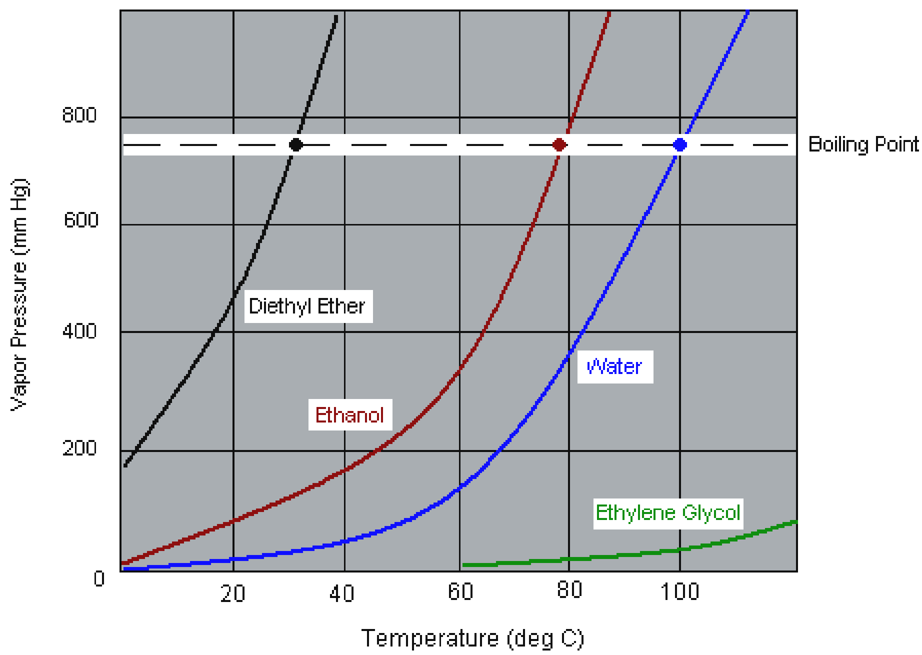


Figure 1- Vapor Pressures of Four Common Liquids

When liquids change state from liquid to gas, their volumes increase by orders of magnitude and bubbles (or cavities) can be formed. As this two-phase fluid moves to an area of greater external pressure, the bubbles rapidly collapse, changing state back into a liquid, imploding as the volume decreases immensely.

Incipient cavitation has become the accepted term for the threshold formation of vapor phase bubbles. Sheet cavitation is a steady state type of cavitation in which a bounded region of cavities forms on a solid surface and, in appearance at least, remains attached. In reality, a continual, on-going process of cavity formation and deformation is occurring.

Research History

A discussion of liquid cavitation should not be undertaken without giving credit to the pioneers and present day experts in the field of cavitation research. Initial scientific inquiry began in the early 20th century with Rayleigh[2] and has continued with extensive work by Brennen[3,4], among others.

Historically, cavitation noise and damage were considered on the basis of the collapse of individual bubbles. The importance of the interactions between bubbles is a relatively recent revelation. In 1997, research shed light on the effects of flow on a single cavitation *event*. The progression of events is a rich complexity of micro-fluid mechanics of bubble cavitation, much of which remains to be understood.[3]

The classic Rayleigh-Plesset[5] analysis of a spherical bubble which follows, could not reproduce some of the phenomena which were observed in actual laboratory settings. Both Knapp - Hollander and Parkin observed that almost all cavitation bubbles are closer to hemispherical rather than spherical.[3] Whatever the deviations from the spherical shape, the fact remains that their collapse is a violent process that produces noise and the potential for material damage to nearby surfaces.[4] Much attention is given to this point in this course.

Bubble Theory

The Models

Two fundamental models for cavitation are spherical bubble and free streamline theory which consists of attached cavities (*clouds*) or vapor-filled wakes.

Spherical bubble models are based on the Rayleigh-Plesset equation that defines the relation between the radius of a spherical bubble, *R*, and the far field pressure over time, *t*, the simplified version of which is:

$$\frac{\Delta P}{\rho} = R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2$$

where ΔP = local and far field pressure differential
ρ = the liquid density
dR/dt = bubble growth rate

Numerical calculations using the full Rayleigh-Plesset equation (which adds liquid kinematic viscosity and surface tension terms) confirms that the optimum time for growth is the time for which the bubble experiences a local pressure below the vapor pressure of the liquid.

Explosive Process[3]

Cavitation growth is an explosive process that corresponds to a volume that is increasing on the order of

$$dR = t^3\,dt$$

to be contrasted with the thermally inhibited boiling growth that occurs in water in a kettle on the stove in which *dR/dt* typically behaves like

$$dR = \frac{1}{\sqrt{t}}\,dt$$

Implosive Process

Cavitation intensity can be thought of as the product of bubble collapse (or implosion) pressure times the number of bubbles collapsing. When a cavitation bubble implodes, it emits a pressure pulse resulting in the generation of noise. The noise level increases with the number of implosions and the pressure from individual bubbles. Blake[6] and Brennen[3] have shown that the radiated acoustic pressure, p_a, at a distance of ζ, from the center of a bubble volume, V, is a function of the second derivative of the volume differential,

$$p_a = \frac{\rho}{4\pi\zeta}\frac{d^2V}{dt^2}$$

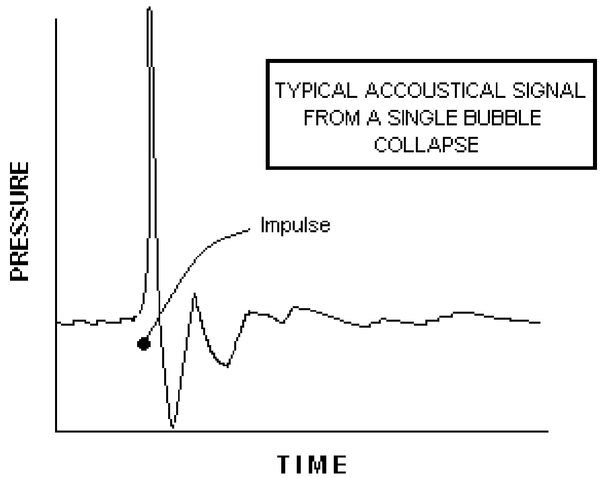
The noise pulse generated at bubble collapse results from large values of the d^2V/dt^2 term.

Values for bubble implosion pressure, P_i, ranging from 20,000 to 100,000 psi have been reported in the open literature. Calculations of kinematic bubble collapse by Rayleigh in 1917 provided that this pressure is described by

$$P_i = c\sqrt{\tfrac{2}{3}P_o\,\rho\left(\frac{R_i^{\,3}}{R_f^{\,3}} - 1\right)}$$

where, c = sonic velocity in fluid
P_o = far field pressure
R_i = initial bubble radius
R_f = final bubble radius

A good measure of the magnitude of the collapse pulse is the acoustic impulse, *I*, defined as the area under the acoustic impulse curve, or the change in the radiated acoustic pressure during a differential time increment,



$$I = \int_{t_1}^{t_2} p_a \, dt$$

where t_1 corresponds to the time just before the pulse and t_2 is that time when $p_a \rightarrow 0$. Impulse spikes like the one depicted here last between several microseconds and several milliseconds.[7]

Partly Cloudy[3]

When the density of cavitation events increases in space or time, bubbles begin to interact hydrodynamically, forming *clouds* of cavitation bubbles which periodically form and then collapse possibly because of flow disturbance. The dynamics and acoustics of finite clouds of cavitation bubbles, because of their very destructive effects, have received much interest. In many cases, collapse of the cloud can cause more intense noise and more potential for damage than in a similar non-fluctuating flow. Research efforts have focussed on the dynamics of cavitation clouds but the basic explanation for the increase in the noise and damage potential is still not completely clear.[4] As in the single bubble model, a finite cloud of nuclei is subjected to an episode of low pressure which causes the cloud to cavitate; the pressure then returns to the original level causing the cloud to collapse. Collapse occurs first on the surface of the cloud. The inward propagating collapse front becomes a bubbly shock wave which grows in magnitude. Very large pressures and radiated impulses occur when the shock reaches the center of the cloud. As with the single bubble, actual clouds have been observed to be far from spherical.

Warfare with Micro Depth Charges

The intense disturbances that are caused by cavitation bubble collapse have two separate origins: (1) fluid reentrant microjet and (2) remnant cloud secondary shock. The first derives from the fact that the collapsing bubble experiences shape instability. The resulting spherical asymmetry forms a rapidly accelerating jet of fluid, entering the bubble from the boundary most distant from the proximate solid surface which receives damage. This reentrant vector (microjet) achieves very high speeds, so that its impact on the opposing side of the bubble generates a shock wave, and a highly localized shock loading of the solid surface (see Figure 2).

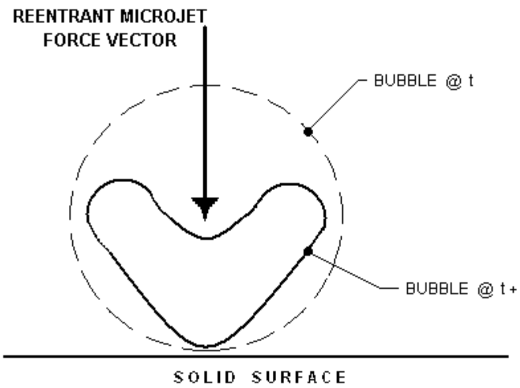


Figure 2 – Asymmetrical Bubble Collapse with Reentrant Mircrojet

This was originally theorized by Plesset-Chapman[8] and more recently visualized by He [9] using a volume of fluid (VOF) method which computationally simulated the cavitation bubble collapse near the solid free surfaces of mechanical heart valves. The visualization of Dr. He's simulation is shown in Figure 3 on page 9.

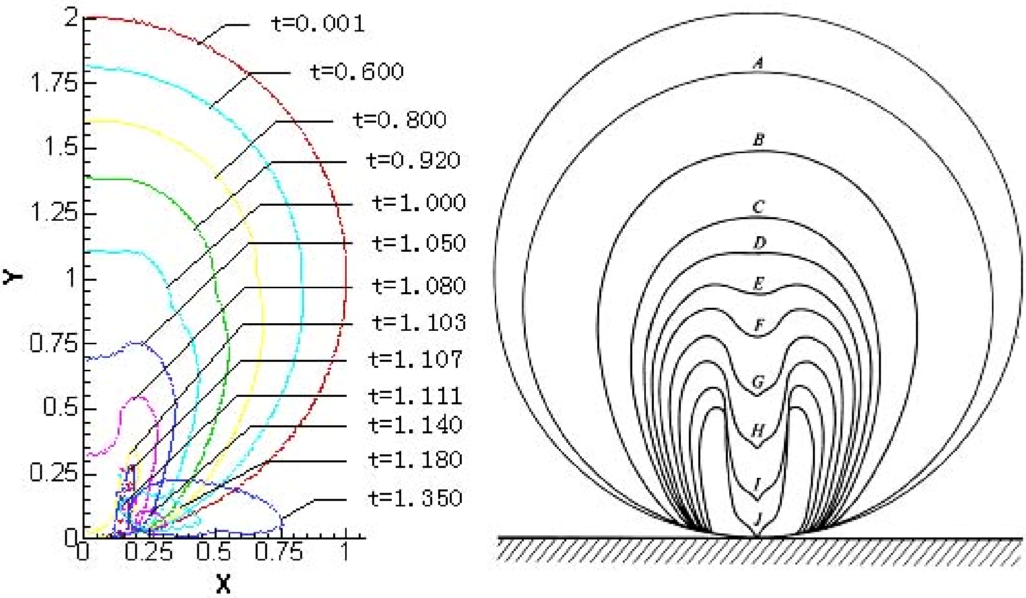
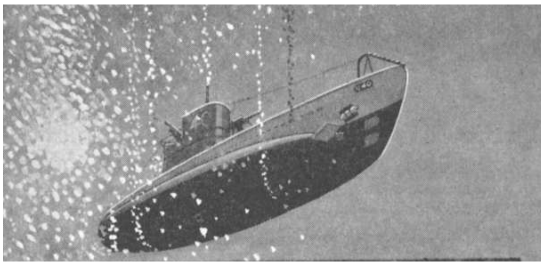


Figure 3 – Bubble collapse simulation by VOF method (left) v. Plesset-Chapman graphic (right)[9]

Brennen[4] has noted that the reentrant jet force vector can be likened to the principle upon which the



now dated conventional antisubmarine warfare depth charge weapon was based. To wit, the proximate explosion generally created little damage to the target vessel. However, it did produce a very large subsurface cavity, which upon collapse, generated a greatly damaging reentrant jet directed toward any solid surface, such as the submarine's hull.

A second shock wave that impinges on any proximate solid surface is generated by the collapse of a remnant cloud of bubbles which remains after the microjet disruption. Kimoto[10] showed that this remnant cloud secondary shock wave as well as the microjet force vector created stress waves in the solid, with the former producing surface loading 2X to 3X that of the latter.

Please refer to References 3 and 4 for a theoretical discussion of cavitation bubble dynamics, damage, and noise generation.

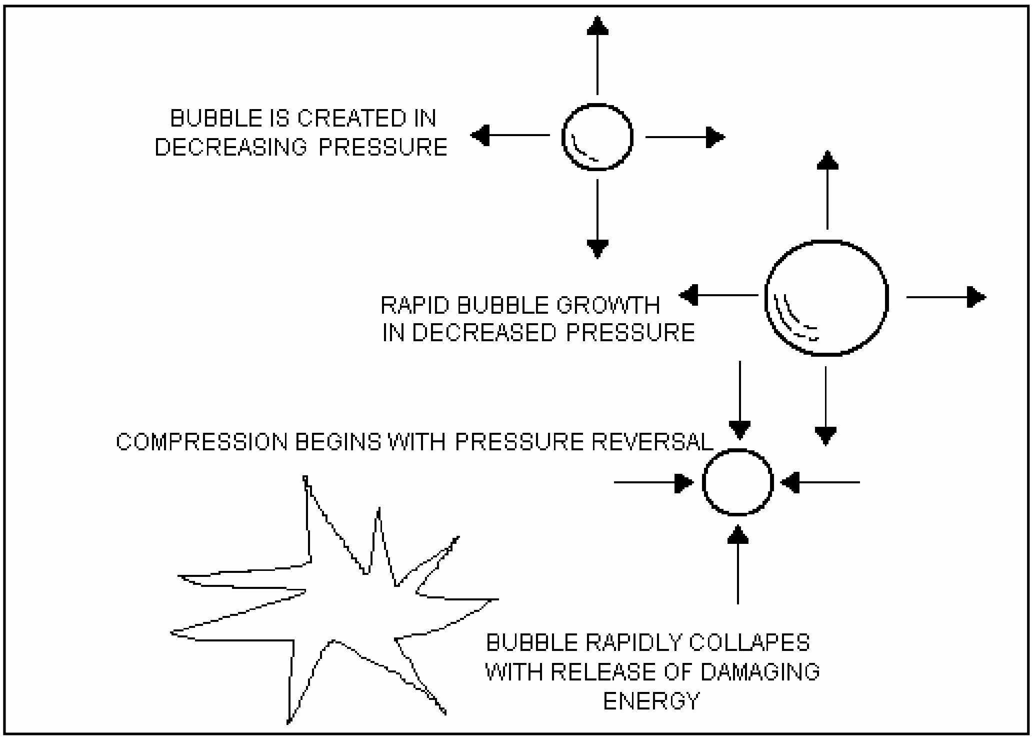


Figure 4 – Bubble Lifecycle (a rarefaction and compression process)

Cavitation Damage

Erosion and Corrosion

Cavitation has detrimental effects such as surface material erosion, destructive vibration, and noise radiation. If erosion were not enough, studies show that cavitation can remove oxide passivation layers and thereby enhance corrosion effects by constantly exposing new metal to oxidation. When cavitation occurs, chemical alterations in the fluid can take place. For instance, cavitation in water causes the formation of free radicals which can increase oxidation (corrosion) reactivity.

Multiple Variables Inhibit Simple Predictions

Cavitation bubble collapse is a violent process that generates highly localized, large amplitude disturbances and shocks in the fluid at the point of collapse. Bubbles collapse in the free stream as well as on the surface of objects moving through the fluid stream. Three conditions must exist in order to have erosion: (1) cavities must form in the fluid; (2) cavities must implode on or very near the material surface; and (3) the cavitation intensity must exceed the cavitation resistance of the material. Highly localized and transient surface stresses in the solid surface are generated from these intense disturbances that occur close to the surface. Local surface fatigue failure can result from repetitive bubble collapse loading. Cavitation damage can have the crystalline and jagged appearance of fatigue failure, see Figure 5, which contrasts with erosion damage derived from larger solid flowing particles, which has a smoothly worn appearance with scratches.[3] The development of solid surface material damage derived from proximity cavitation bubble collapse is complex because it involves the details of a complicated unsteady flow combined with the reaction of the particular

Figure 5 – Localized damage has the appearance of fatigue failure (Source: Ref. 3, Fig. 6.3)[11]

material of which the solid surface is made.[3] Because of the number of interrelated variables, the quantitative prediction of cavitation damage is a complex problem which is neither easily solved by exact theoretical analysis nor by experimental means. After all, cavitation erosion is a three dimensional, two phase, thermohydraulic process within a four component system of a binary pure fluid; possible dissolved or entrained gas; metal; and metal oxide. The failure mechanism depends on the ratio of the intensity to the material resistance. To complicate matters, the mechanism for failure changes over time; more will be presented on this topic immediately below.

Damage is Dependent on Liquid Viscosity

An increase in liquid viscosity causes, with all other fluid properties being held constant, a reduction in the number and size of cavitation bubbles. Moreover, the kinematic impulse of the previously mentioned microjet is smaller with greater viscosity. Given the infinitesimal physical extent of the reentrant microjet, researchers have been confident in assuming a laminar flow regime is appropriate, which infers that the microjet velocity is inversely proportional to the viscosity. This supports observations of reduced damage with increased viscosity.

Erosion Severity is Directly Related to Fluid Density

According to the equation for P_i on page 6, the pressure occurring when cavitation bubbles implode is directly proportional to the square root of the liquid density. Consequently, and most logically, damage increases with increased density. As can be imagined, the erosion rate for a liquefied metal, such as mercury, is particularly high.

Instantaneous Damage Rates Vary Over Time

The rate at which the cavitation erosion process is carried out is generally subdivided into three distinct time periods, with the duration of each very dependent on the nature of the material under assault. In the first, termed the incubation period, damage begins but has yet to fully manifest. The second period, which varies greatly with material resilience, is characterized by an almost constant, but not necessarily linear, erosion rate; areas and depths of material erosion increase with time. Finally, a period ensues in which the solid surface is damaged to the extent that the resulting profile can actually reduce the probability for a surface proximity implosion. The material erodes at a much slower rate during this period because of this interference to implosion.

Restrictions May Apply

Fluids which undergo sudden contractions experience turbulence and have pressure drops associated with accelerated flow. For instance, in heat exchanger tubes, internal tube cavitation erosion can occur in the area of sudden contraction at the tube sheet (See Figure 6). As mentioned earlier,

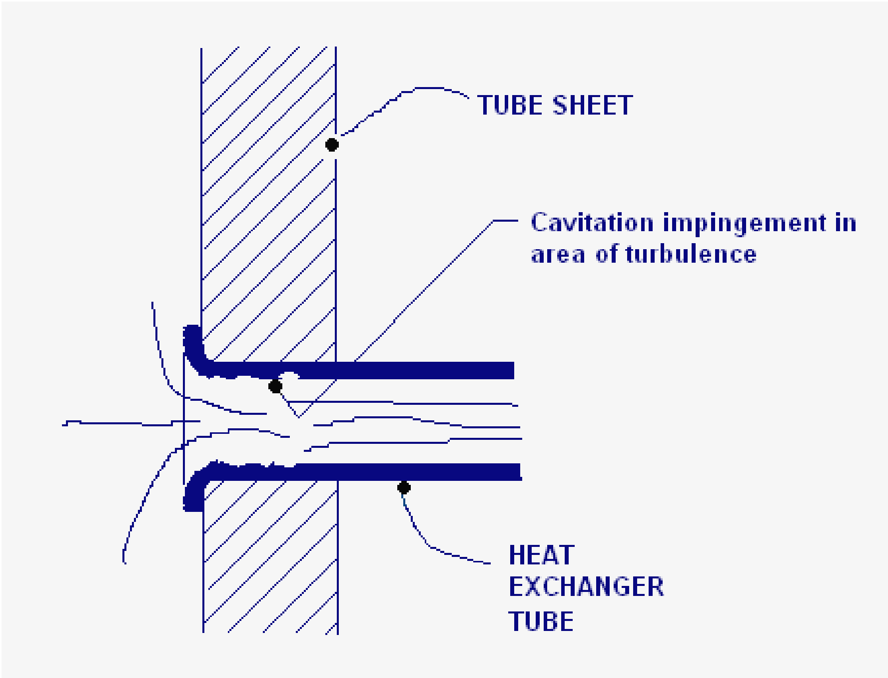


Figure 6 – Flow restriction cavitation damage

fluid microjets are formed due to asymmetrical bubble collapse. The combination of the high intensity pressure waves and microjet impingement on solid surfaces causes severe damage. Cavitation impingement attack can be thought of as a process which is very similar to erosion in the natural environment. Erosion damage can take on the appearance of a solid that has been blasted at high pressure with small hard *shot* almost like sandblasting.

MYTH NUMBER 3

Cavitation erosion damage only occurs when a solid surface is in motion through a fluid.

Water over the Dam

Cavitation damage can also occur in much larger scale flows. Figure 7 is a photograph of cavitation damage in the concrete wall of a 50 foot diameter Hoover Dam spillway. While somewhat difficult to discern from the photograph, the damaged area is 4½ feet deep, 30 feet wide, and 115 feet long.

Figure 7 – Axial View of damage in Hoover Dam Spillway (Source: Ref. 3, Fig. 6.5)[11]

Local Forecast

In pump impellers or marine propellers, cavitation damage is often observed to take place in quite localized areas of the surface. Coherent, periodic cloud cavitation bubble collapse is frequently the cause and the damage is logically most severe on the solid surface in the vicinity of the cloud collapse (see Figure 8 on page 15). Erosion increases as the peripheral speed of the impeller, the head developed per stage, and the number of hours of operation at off-design conditions increase. The more brittle the impeller material, the greater the pitting damage.

Depending on flow rate and pump impeller inlet design, flow will separate from the suction side of the vane and backflow or recirculation occurs. In this case, damage can occur on both the pressure and suction side of the impeller vane. Experiments by Gulich *et.al.*[12] generated an empirical correlation[13] which expresses damage rate as a function of the $NPSH_A$ (described in a special section later) and the length of the suction-side cavity springing from the leading edge of the impeller blade:

$$\textbf{Damage rate} \propto NPSH_A^{\,3}\,\lambda^{2.38}$$

In addition to causing severe mechanical damage, cavitation causes a loss of head and reduced hydraulic efficiency.

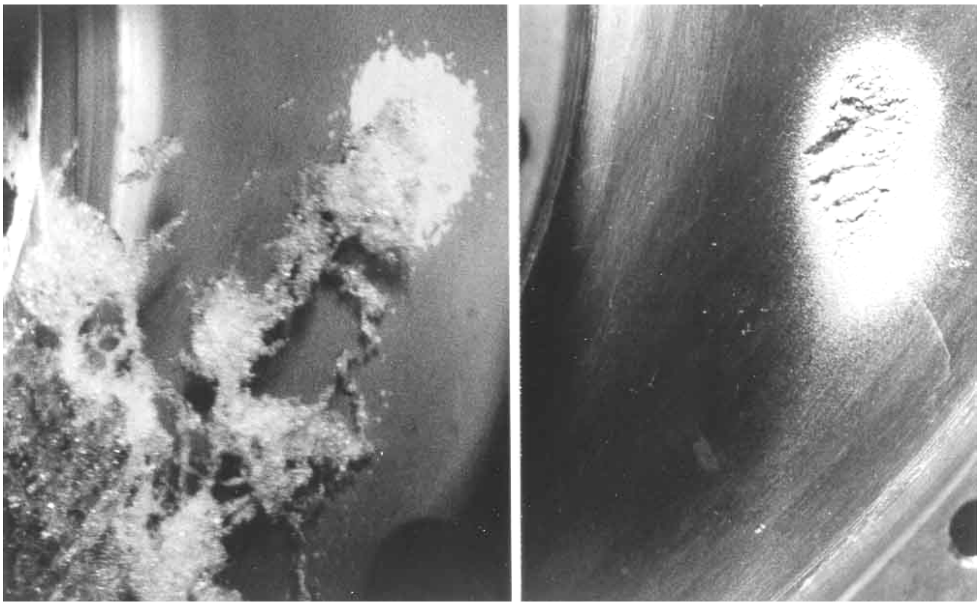


Figure 8 – Cavitation damage on a pump impeller. The two photographs are of the same area. Typical cavitation pattern during flow(left); Typical cavitation damage (right). (Source: Ref. 3, Fig. 6.6)[11]

Broad Impacts – Extended Damage

In marine applications cavitation has detrimental effects such as surface material erosion, destructive vibration, and noise radiation. Collapsing cavitation bubbles generate broad band noise which is not only radiated into the surrounding marine environment but is also transferred into the ship structure. There are several types of propeller cavitation which exist (see Figure 9).

Not surprisingly, damage in rotating equipment is not limited to the pitting of motive components that are normally depicted in damage photographs. Moreover, cavitation can be most problematic

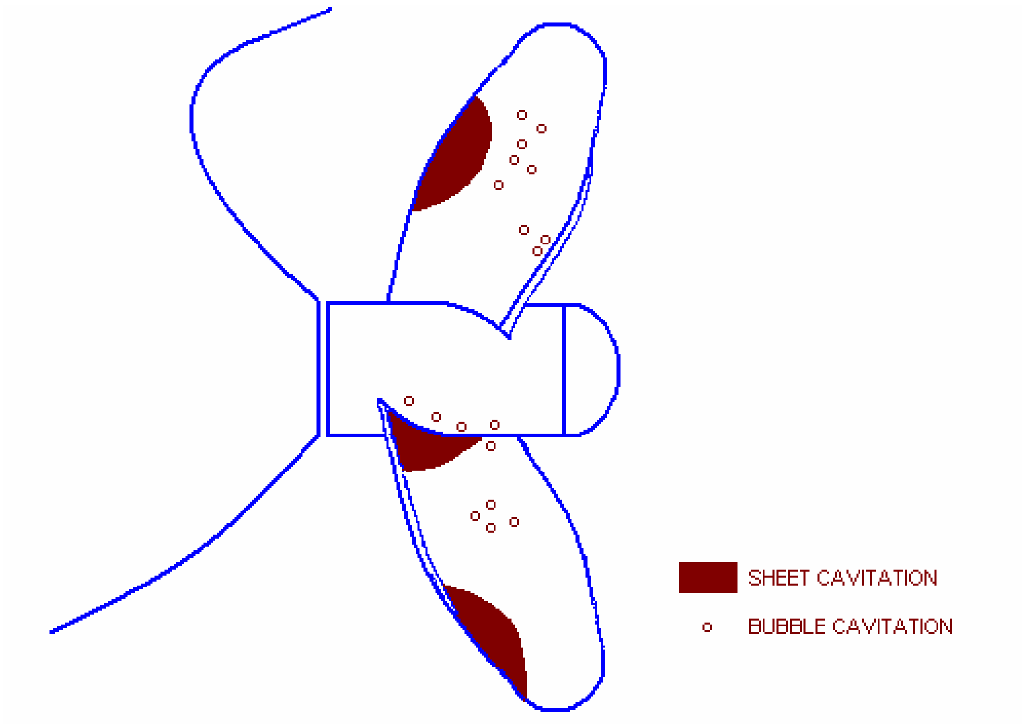


Figure 9 – Types and locations of propeller cavitation (adapted from Kinnas 1996 http://cavity.ce.utexas.edu)

on bearings and seals. This stems from that fact that operation without cavitation results in pressures (thrusts) acting uniformly, both axially and radially. Cavitation rapidly and violently alters the pressure field acting on the rotating segment. Because both the cavity formation and collapse are random, so are the pressure fields. Consequently, axial and radial thrusts become random, reaching high peaks at unpredictable frequencies. Bearings and seals subjected to these elevated random forces wear unevenly and rapidly, supplying an additional source for equipment vibration.

Let's Not Forget the Liquid

It many instances, the fluid medium itself can be harmed through the subjection to high loading when cavitation bubbles implode. This has been documented with regard to blood platelet degradation during mechanical heart valve cavitation. Dissolved air and oil vapor contained in fluid power system liquids such as lubricating and hydraulic oils, can actually be ignited by elevated temperatures generated from bubble collapse. Research has shown that this phenomenon, known as micro-dieseling, contributes to the accelerated aging of hydraulic fluids.

MYTH NUMBER 4

Cavitation damage is limited to directly impacted hydraulic solid surfaces.

Where, When, and Why

Going with the Flow

Liquid cavity formation occurs in valves, sudden contractions, and sudden directional flow changes if the static pressure of the flowing liquid decreases to a value less than the fluid's vapor pressure. Continuity of flow is broken by the formation of these vapor bubbles.

It is well documented that valves and orifices exhibit degrees of pressure recovery because the final downstream pressure is generally higher that the throttling static pressure. When this recovery pressure value is higher than the vapor pressure of the fluid, vapor cavities that have formed revert to liquid. Pressure recovery is a function of the particular internal throttling geometry of the flow element. Ironically, the more streamlined the post-throttling flow altering geometry, the greater the pressure recovery experienced, and the increased possibility of cavitation if the upstream pressure drop is significant.

A phenomenon known as *recirculation cavitation* occurs when flow is restricted to the extent that a portion of the liquid will swirl in a circular fashion, forming small vortices. The eye of each vortex can have an area of low pressure sufficient to support liquid vaporization.

Pseudo Cavitation

Liquids exposed to air or other gases can absorb a portion of that gas. Liquids often therefore become a solution of the parent liquid and a dissolved gas, with a different vapor pressure from that of the pure liquid. The mixture of liquid and vapor is now a compressible fluid. The density of the vapor is orders of magnitude less than that of the liquid fluid density. On pressure increase, the mixture passes through its vapor pressure level and the vapor pockets instantly collapse like tiny balloons. Dissolved air or gases coming out of solution and imploding has been referred to as *pseudo-cavitation.* Even in closed fluid power circulating systems, an elevated oil viscosity can cause a significant oil static pressure drop as it is drawn into the circulator's inlet. The pressure reduction causes air normally dissolved in the oil to be desorbed and become entrained as air bubbles. When the oil reaches the circulating pump, this "bubbly" oil is compressed on the high pressure side, the bubbles violently implode.

Additives in liquids tend to be more volatile than the parent liquid and therefore will vaporize first. Additives in liquids which increase vapor pressure can increase cavitation damage. A good example is cooling tower water treatment agents.

System design that encourages the introduction of entrained gas or liquid voids likewise will result in pseudo-cavitation. Ideally, systems intended to be purely liquid in nature would not promote the internal creation of compressible flow constitutes, *i.e.* air, vapor, or gas. Even small amounts of entrained air or gas can be problematic to powered, liquid handling equipment, reducing their liquid output capacity and efficiency.

Aeration is the unintentional, and sometimes unavoidable, conditional introduction of compressible constituents into a process. Aeration can be caused by the entrance of air into the vacuum condition of a suction line, or it can be created by excessive agitation or turbulence in a vessel. Pipe lines to sumps or tanks that allow the liquid to free-fall and impact on the suction reservoir's liquid surface can aerate the vessel's contents. In an optimum system design, entering liquids would not be allowed to cascade, but rather terminate below the liquid level in order to minimize turbulence, agitation, and the creation of entrained gas. In a similar fashion, entrance lines would not terminate in close proximity to the suction outlet of process reservoirs that feed fluid conveying equipment.

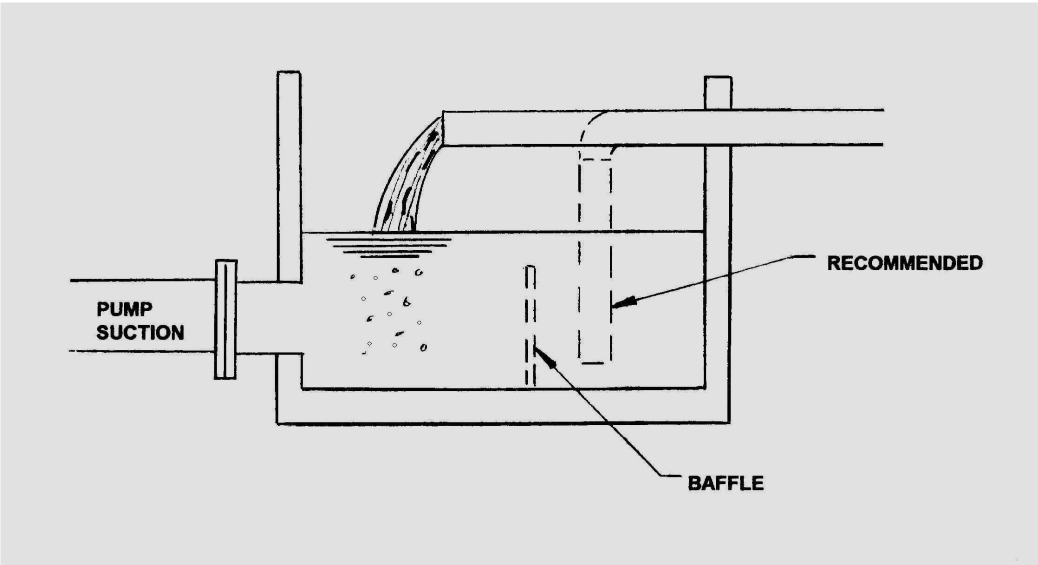


Figure 10 – Close, cascading introduction of liquids can lead to aeration

Ideally, feed lines that could possibly introduce gas-entrained liquid to sumps or suction tanks are positioned physically distant from the suction point to alleviate the possibility of hydraulic short-circuiting. Doing so allows the freshly entering liquid important residence time in the suction vessel to dissipate gas. If this arrangement is not feasible, baffles are installed in the sump to cause the liquid to have hold-up time before making its way to the pump outlet.

While generally not air, many pharmaceutical and beverage fermentations are inherently plagued with entrained (and sometimes dissolved) gas as a result of normal chemical reaction products such as CO_2. This also is true of many petroleum liquids which naturally exist in binary phases of liquid/hydrocarbon gases and which exhibit very high vapor pressures. In many cases, these entrained and dissolved gases are carried into high pressure regions of the process where they collapse, or implode, releasing large amounts of energy which is dissipated with resultant destructive force and sometimes high temperature.

MYTH NUMBER 5

Entrained gas is always problematic with regards to cavitation. Well, yes and no. Small amounts of entrained gas (1 to 2%) can actually cushion the forces from the collapsing cavitation bubbles, and can reduce the resulting noise, vibration and erosion damage. Ironically, the lack of any entrained gas can have the opposite effect.

To learn more on the subject of aeration, as well as other problematic suction conditions such as vortices and unbalanced flows, view or download PDHcenter.com course number M134, *Practical Considerations in Pump Suction Arrangements.*

It's All About Pressure (Revisited)

A common source of cavitation is the frictional loss incurred in the suction line between the suction source and a pump . A long suction line, or one with numerous turns or restrictions, can cause sufficient pressure drop to result in cavitation as the liquid enters the pump. In a centrifugal pump, the liquid is most likely to vaporize in the eye of the impeller, near the vane tips. In a reciprocating pump, the liquid is most likely to vaporize in the pumping chamber between the suction and discharge valves at the face of plunger or piston during the suction stroke.

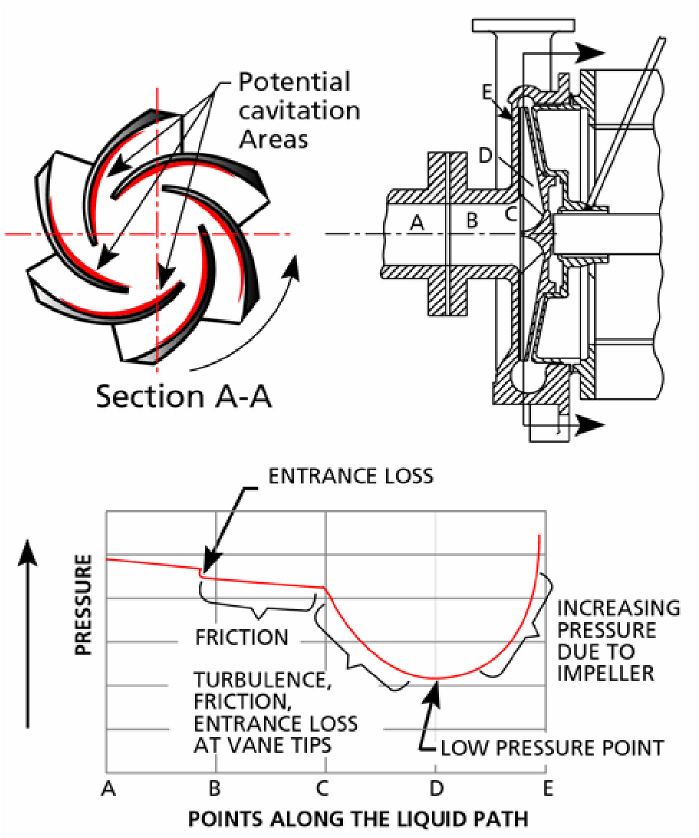


Figure 11- Source: The Duriron Co. Inc., Pump Engineering Manual, 5th edition, ©1980, Fig. 5.1, page 64

Cavitation in Mechanical Heart Valves[8]

The human heart can be thought of as connected, twin positive displacement (PD) pumps, working in tandem. Mechanical heart valves (MHVs) are prosthetics designed to replicate the function of the natural valves in the human heart. Cavitation on the mechanical heart valve has been found to be traumatic to both blood and the nearby valve structure. Early studies revealed that valve leaflet surface pitting was due to cavitation. Cavitation manifests as transient bubbles on the MHV surface on valve closure. The cavitation bubbles occur due to abrupt pressure changes in the vicinity of the valve on valve closing. The most contributive factor to MHV cavitation is apparently a phenomenon called *squeeze jets.* Squeeze jets are formed when the valve is closing and the blood between the occluder, or disk, and the valve housing is "squeezed" out to form a high speed jet. This results in intense vortices with very low pressure that support cavitation.

Because of the smaller energy scale, cavitation that causes valve failure is extremely rare in mechanical heart valve patients. However, the energies appear to be sufficient to cause blood platelet activation or even platelet destruction and can thereby result in increased risk of thromboembolic complications.

Valves

Throttle Me Up Scotty

As mentioned earlier, sudden contractions or restrictions of the flowing liquid can give rise to the cavitation process. Valves can be thought of as variable or flow modulating contractions. As the liquid passes the point of greatest restriction inside a valve, its velocity reaches a maximum and its pressure falls to a minimum. If the pressure falls below the liquid's vapor pressure, vapor bubbles form within the valve. The static pressure at the throttling point, even at moderate operating conditions, can reach levels sufficient for liquid cavitation to begin.

Pressure Recovery Leads to Cavitation

Due to the pressure recovery inevitable in valves and other flow restrictions, such as orifices, cavitation bubbles ultimately reach zones of higher pressure where they implode.

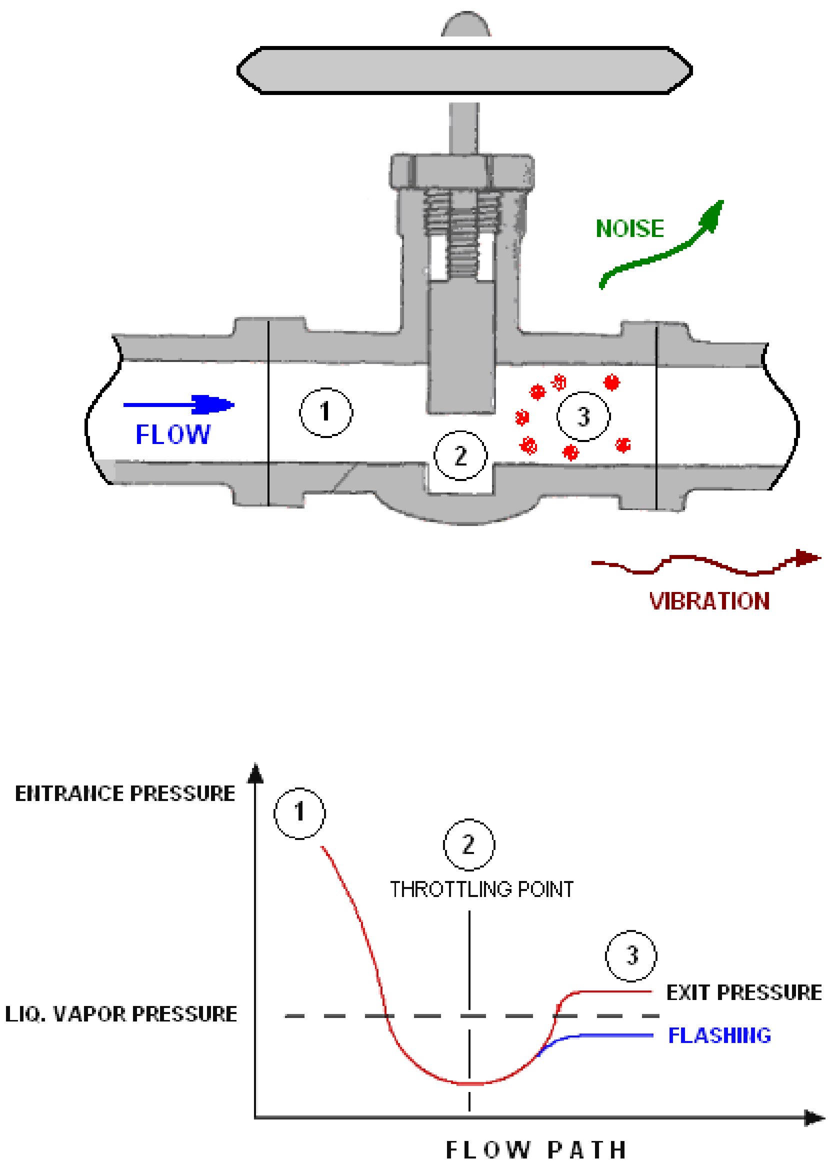
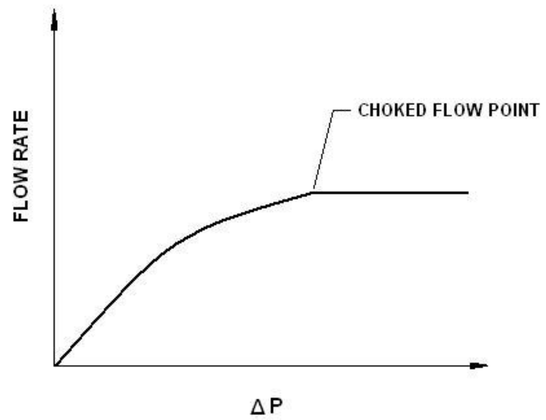


Figure 12 – Valve Liquid Vaporization

The valve trim depicted in Figure 12 is not the recommended style for a prolonged throttling application. It is shown solely to illustrate the pressure regions along the flow path. Globe, not gate valves, are better suited to modulate flow rate.

All Choked Up

Normally a valve's flow capacity can be augmented by increasing the differential pressure. Increasing the pressure drop across a cavitating valve by reducing the downstream pressure beyond the point where vapor bubbles form does not result in a corresponding flow increase. This flow condition is said to be *choked*, a term that it is semantically misleading because the flow with this condition is far from being totally obstructed.



Choked flow is a result of either flashing or cavitation. If the pressure downstream of the valve is below the liquid's vapor pressure, the vapor bubbles persist in the liquid. This is valve flashing (see Figure 12). Because the velocity of the flashing vapor-liquid stream is much higher that the inlet liquid velocity, the flashing stream often erodes valve internals or downstream piping. If, under choked-flow, the downstream pressure is above the liquid's vapor pressure, the vapor bubbles will collapse as they leave the point of greatest restriction in the valve. This is valve cavitation. The shock waves and noise caused by the collapsing bubbles cause rapid and severe damage to the valve and piping.

MYTH NUMBER 6

Increasing the pressure differential across a valve, which is choked, will not increase the flow rate through the valve. Not exactly. Choked flow simply means that the flow rate becomes independent of the downstream pressure. Increasing the up-stream pressure will result in increased flow. Changing the choking conditions, *e.g.* increasing the valve opening, can also increase the flow.

Why is the Flow Choked?

Cavitation makes the compressibility of the fluid increase locally and the density of the fluid is drastically reduced by the bubble volume in the area of the restriction as the pressure ratio rises. The continuity of the fluid phase is therefore interrupted and the dynamic interaction between flow and its restriction is affected. These effects limit the flow rate when a critical pressure differential is exceeded.

What is the Outcome of Valve Cavitation?

- Loud noise emission;
- Strong mechanical vibrations in the valve and connected piping;
- Choked (restricted) flow caused by vapor formation;
- Erosion of internal valve components;
- Alteration of the valve hydraulic flow coefficient (C_V);
- Potential physical modification of the fluid properties.

The Marine Environment

In the Beginning

In 1917 the British admiralty commissioned physicist Lord Rayleigh to investigate the probable cause of accelerated deterioration to ship propellers with the advent of higher rotational speeds. The search for the cause of this ship propeller destruction led to the discovery of the damage source as cavitation. Rayleigh's research led to the discovery of the effects of cavitation, and confirmed the existence of cavitation that was previously established in 1894 by the renowned Irish engineer and physicist named Osbourne Reynolds. Reynolds is the individual whose observations resulted in the now famous dimensionless quantity which bears his name, the Reynolds number.

It's Universal

Virtually all propellers of modern marine craft operate with some amount of cavitation – some with tremendous amounts. It occurs in vessels ranging from small pleasure boats to large cargo and tanker ships. Cavitation can be so minimal that water flow and total thrust is not affected. Many rudders as well as shaft brackets and other fairwaters operating in the slipstream of the propeller will also exhibit cavitation. The extent of cavitation varies during the course of a complete revolution of the propeller blade. The cavitation volume peaks when the blade comes closest to the hull, producing a higher local velocity and consequently a lower local pressure. All types of ships and boats and all types of propellers are affected.

Propeller Thrust is Horizontal Lift

Hydrofoils, in this case the propeller blades, produce differential pressure or lift as they rotate through the water. This "lift" is produced by both the suction and pressure faces of the blade. Propellers supply thrust to a marine craft by transferring this lift from the blades, through the hub, and on through the propeller shaft. When the magnitude of the suction (negative) pressure exceeds the surrounding water's vapor pressure, cavitation occurs. Figure 13 is a graphical representation of the induced pressures along the two surfaces of a single propeller blade. The graph represents an instant in time during the complete revolutionary cycle of the blade. During this cycle the suction pressure increases and decreases thereby causing the blade surface impacted by the cavitation process to change accordingly. An animated graphic of this process can be seen at http://cavity.ce.utexas.edu/kinnas/movies.html.

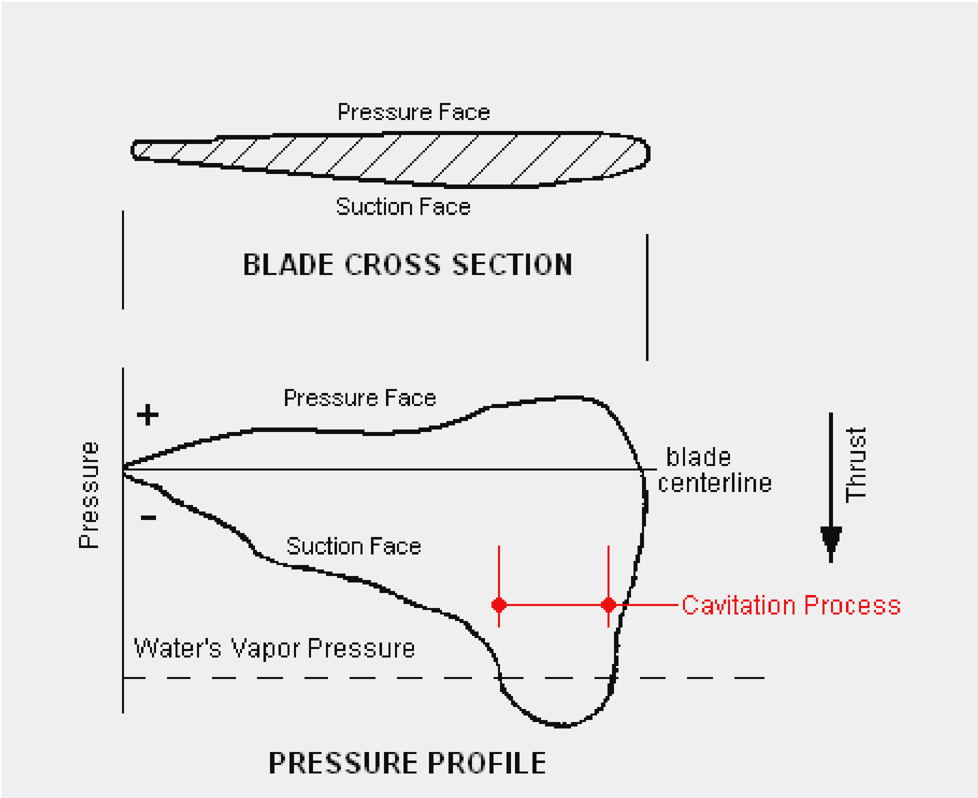


Figure 13 – Pressure distribution along propeller blade (adapted from Reference 14)

When Does It Begin?

Propellers begin to cavitate when there is excessive thrust for the propeller to transmit. Commander Irish[15] published data derived from his observation of cavitating propellers. The table[16] of data correlates peripheral velocity to a critical unit thrust (force per projected blade area) at which incipient cavitation occurs. As the amount of cavitation increases, a portion of the transmitted reactive thrust is lost.

Propeller peripheral velocity, ft/min	2,000	4,000	6,000	8,000	10,000	12,000	14,000
Critical unit thrust, lb/in²	1.2	5.6	12.0	18.2	23.6	28.5	33.0

Elevated cavitation results in full water flow separation from the propeller suction face and a reduction in the amount of torque necessary to keep the propeller rotating. This is similar to the reduction in load that occurs when the inlet to a centrifugal fan is blocked, thus decreasing the mass flow rate of compressible fluid handled. When full flow separation occurs, effective thrust and hydraulic efficiency are reduced.

Net Positive Suction Head

Net Positive Suction Head is an important element in the proper selection of both centrifugal and positive displacement type pumps. Net Positive Suction Head exists in two forms; the numerical comparison of these forms is a useful tool in the prediction of potential liquid cavitation conditions. Pressure head is always expressed in height (feet or meters) to make it independent of any specific fluid. Whitesides[1] has offered the following definition of Net Positive Suction Head:

> *Net positive suction head is a pressure, associated with the intake of a pump, expressed in feet of pumped liquid, resulting from the algebraic evaluation of both the accretive and depletive aspects of that suction system.*

For a complete treatment of the subject of Net Positive Suction Head and its computation, view or download PDHcenter.com course number M124, *Understanding Net Positive Suction Head.* Net Positive Suction Head is almost universally denoted by the term:

NPSH

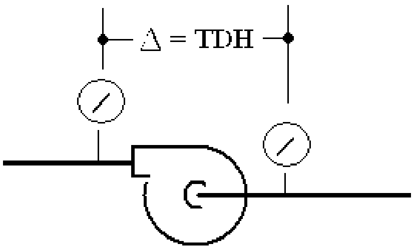
and this abbreviation will be utilized in this course content when it is appropriate. This term should not be confused as the product of separate variables as is customary in mathematical notation. Net Positive Suction Head available ($NPSH_A$) is the absolute pressure in feet of liquid at pumping temperature available at the pump suction flange, above vapor pressure. Mathematically this looks like,

$$NPSH_A = \pm h_S - h_L + h_A - h_V$$

Where,

h_S = Static suction head (+) or lift (-), feet
h_L = Suction line losses (friction, entrance and fittings), feet
h_A = Absolute pressure at the liquid's free surface, in feet of liquid pumped
h_V = Vapor pressure of liquid at pumping temperature, converted to ft. of liquid

The technical definition of Net Positive Suction Head required ($NPSH_R$) is: *The reduction in total head as the liquid enters the pump.* $NPSH_R$ is experimentally determined by several methodologies. One procedure is the operation of the pump under study, with clear water while incrementally reducing $NPSH_A$ by throttling a valve. The on-set of cavitation is then observed and recorded at controlled flow rates. How is the on-set of cavitation accurately determined? It is an approximation at best, but has been officially defined as corresponding to a 3% drop in total dynamic head (TDH). Obviously there is sufficient cavitation that is already occurring to produce this 3% reduction in pressure.



The only true definition of $NPSH_R$ can be: The observed value of $NPSH_A$ which, for a given pump, at a given flow rate of 60º F clean water, produces an abrupt decline in total dynamic head due to cavitation. Put more simply, $NPSH_R$ is no more than the observed flow conditions during a pump test, which results in the onset of abrupt reduced performance.

MYTH NUMBER 7

Conventional wisdom holds that $NPSH_R$ values can be used as the demarcation point to completely avoid cavitation. This is not altogether true. Pump manufacturers establish $NPSH_R$ values by reducing the suction pressure at predetermined flows until cavitation reduces the total dynamic head by 3%. Consequently, plots of $NPSH_R$ values merely depict operating conditions where the cavitation has reached an arbitrarily predetermined, assumed acceptable value (see Figure 14).

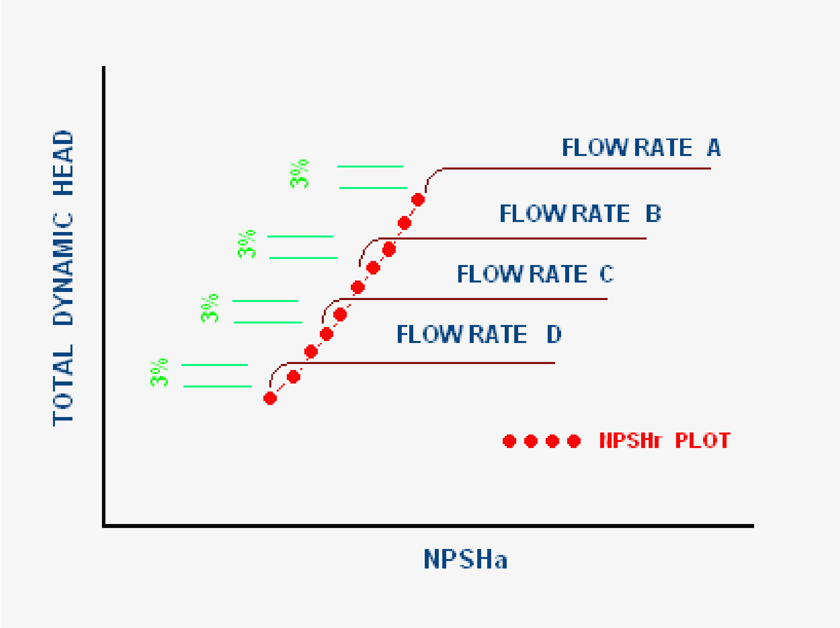


Figure 14 – Generation of $NPSH_R$ values via "TDH breakdown"

A variant of the plot in Figure 14, which essentially arrives at the same result, is one in which a concept called *pump cavitation coefficient*, ***σ***, is introduced. Its value is substituted for the abscissa in Figure 14 and the total dynamic head produced as a percent of the more or less steady state head observed, is substituted for the ordinate axis (see Figure 15).

The pump cavitation coefficient is nothing more that the ratio of the $NPSH_A$ to that of the total pump head per stage:

$$\sigma = \frac{NPSH_A}{H}$$

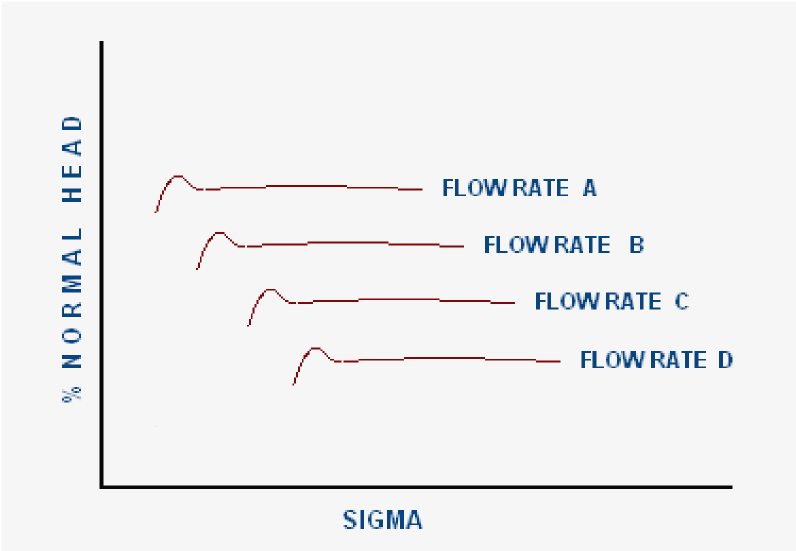


Figure 15 – Pump flow test using the concept of pump cavitation coefficient

For a given pump, the larger values of σ (higher values of $NPSH_A$) produce values of total dynamic head, efficiency, and brake horsepower that are relatively constant, or flat on a graphic plot. As σ is reduced, a juncture is reached where these values drop off distinctively, signaling incipient cavitation. Obviously, the pump should be operated above the value of σ where "drop-off" occurs if the noise, vibration, and damage associated with cavitation are to be avoided. Realistic values of σ range from small fractional positive values to unity, and above. Figure 16 is a curve showing a hypothetical pump's relationship between its pump cavitation coefficient and suction specific speed. A full explanation and detailed treatment of suction specific speed, denoted by N_{SS},, is beyond the scope of this course. For a detailed treatment of the subject, view or download PDHcenter.com course number M136, *Understanding Pump and Suction Specific Speeds.* Limited coverage of the concept will be provided in a later section of this course.

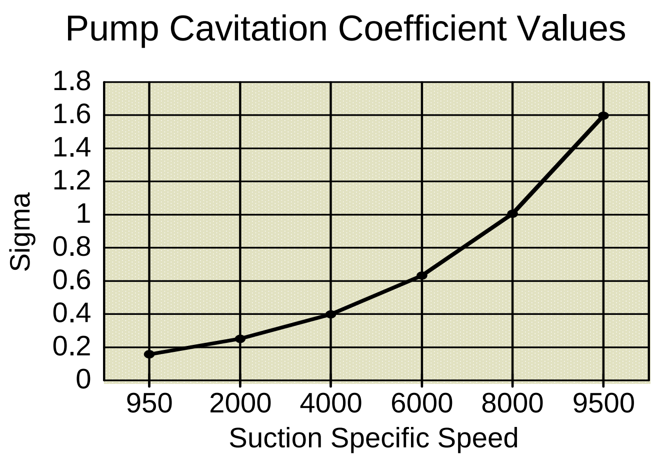


Figure 16

Pumping from the Same Page

An important consideration with respect to the evaluation of $NPSH_R$ is that of the liquid's vapor pressure. Standard pump performance curves plot $NPSH_R$ versus flow; these data points are experimentally determined by conducting tests utilizing water. If the fluid being pumped exhibits a vapor pressure differing from that of water, it should be intuitively obvious that $NPSH_R$ values provided on the pump manufacturer's standard performance curve cannot be considered reliable for the water dissimilar liquid being pumped. The $NPSH_R$ data becomes even less meaningful for liquids whose physical properties do not approximate those of the test liquid. Even elevated water temperature can introduce inaccuracy and enormous variability. In order to be exact, special charts must be used to determine the potential reduction in $NPSH_R$ when pumping at elevated temperatures or pumping highly volatile fluids such as light hydrocarbons. Permissible reductions from cold water $NPSH_R$ values for specific liquids are available in log-log straight line plots of NPSH versus temperature.[20] A schematic of such a chart is shown in Figure 17.

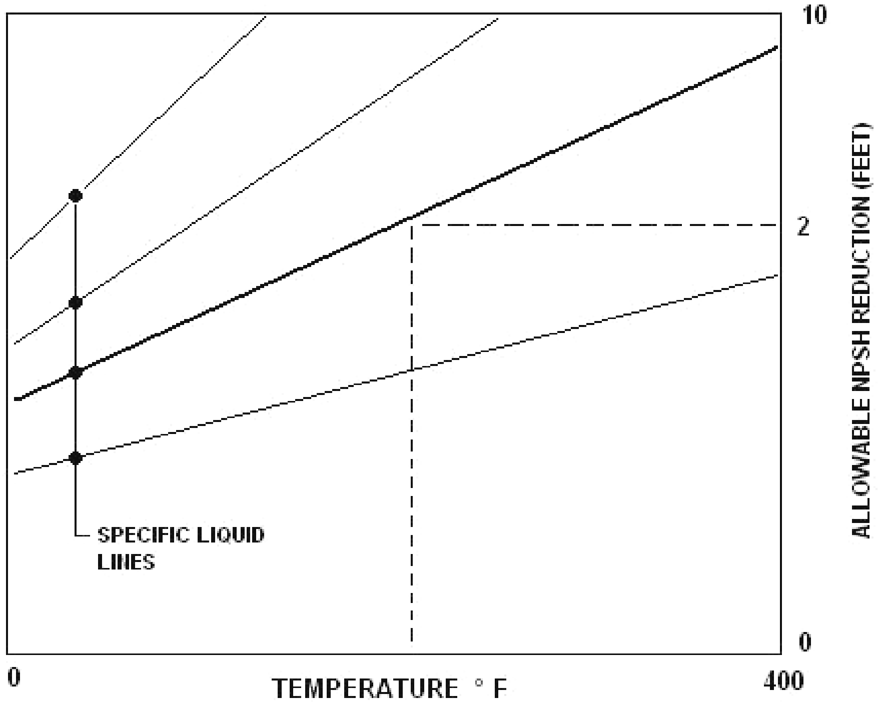


Figure 17- Schematic of $NPSH_R$ reduction chart

As an example, in the above chart a reduction in $NPSH_R$ of 2 feet is allowed for methyl alcohol at 190° F. The Hydraulic Institute recommends that under no circumstance should $NPSH_R$ reductions greater than 10 feet be credited nor should reductions exceed 50% of the cold water $NPSH_R$ value.

System Dynamics

Up until this point we have limited our discussion to single component, pure liquids. What consideration should be given to a fluid which is not a pure liquid? Let's suppose that a process uses a fluid which is an amalgamation of three non-miscible liquids, each exhibiting different vapor pressures. A recommended, conservative rule of thumb, is to calculate the system's $NPSH_A$ based on the component with the highest vapor pressure. Were the constituents to combine to form a true solution, then the vapor pressure of this "new" liquid would have to be determined possibly through laboratory testing.

Normal system operating transients are often overlooked. The accurate assessment of $NPSH_A$ would consider the full range of system conditions, such as temperatures, over the entire operating realm.

The Desired Inequality of $NPSH_A$ and $NPSH_R$

Theoretically, to preclude liquid cavitation,

$$NPSH_A \geq NPSH_R$$

Practically, in order to compensate for system variations and incorrect analytical assumptions,

$$NPSH_A >> NPSH_R$$

It has been recommended in some technical circles that a differential of 1 to 2 feet between the two net positive suction heads be considered as a minimum to introduce a margin of safety against liquid cavitation when pumping water and water-similar liquids. Margins of 20% to 30% are not uncommon when the properties of the liquid being pumped are doubtful or unknown. Margin is often indicated by a factor or multiple derived from the ratio $NPSH_A \div NPSH_R$. The American National Standards Institute (ANSI) and the Hydraulic Institute have collaborated to produce a guidance document entitled *Centrifugal and Vertical Pump NPSH Margin*, standard 9.6.1 (Reference 17), that addresses the subject of margin. The document is available from the Hydraulic Institute at www.pumps.org.

Now, Let's Really Burst a Bubble

Now that the standard margin values and accepted NPSH inequalities have been stated, ponder the following:

M Y T H N U M B E R 8

As just stated, conventional wisdom holds that when $NPSH_A$ is equal to or greater than $NPSH_R$, cavitation will not occur. **THIS IS NOT ENTIRELY CORRECT**. The NPSH margin matrix presented in the table below is a summarization of this customary thinking.

CONVENTIONAL WISDOM NPSH MARGIN TABLE		
MARGIN RELATIONSHIP	**CAVITATION STATUS**	**OPERATIONAL QUALITY**
$NPSH_A < NPSH_R$	YES	POOR
$NPSH_A = NPSH_R$	NO	ACCEPTABLE
$NPSH_A > NPSH_R$	NO	GOOD
$NPSH_A >> NPSH_R$	NO	BEST

The table essentially incorrectly states as long as a negative margin does not exist, cavitation is eliminated. As it turns out, margin is an inexact science which sometimes is misunderstood. We know from our previous discussion of the origin of $NPSH_R$ values that this table of conditions is an oversimplification. Fact is, some degree of cavitation is usually occurring in each of the four margin relationships listed above. There are studies that show that the maximum cavitation damage can actually occur at $NPSH_A$ values 2X or more of the $NPSH_R$ value for very high suction energy pumps.

So What is a High Suction Energy Pump? Suction energy equates to energy available for cavitation damage. Pumps are referred to as low, moderate, or high suction energy even though there are only general classification guidelines.[17] The suction energy level of a pump varies directly with, among other variables, the impeller eye diameter, the suction specific speed, and the specific gravity of the pumped liquid. Broadly, high suction energy pumps are those that exhibit impeller eye peripheral velocities greater than ≈ 50 feet per second and/or suction specific speeds that exceed ≈ 20,000. (The subject of suction specific speed will be taken up momentarily). Inlet piping configurations which promote turbulence at the pump suction and the extent of operational departure from the best efficiency point (BEP) are also contributing factors.

Other studies indicated that clouds of millions of bubbles formed and collapsed at 1.3 to 1.5X the 3% $NPSH_R$ value. Still other studies have indicated that the highest rate of damage to typical impeller blades appeared to occur at an NPSH significantly greater that the NPSH corresponding to the 3% breakdown value; maximum suction pressure pulsations from cavitation occurred at a NPSH margin ratios ranging from 1.4 to 2.3. Research is showing that $NPSH_A$ values at or near $NPSH_R$ correspond to less cavitation damage than that occurring at margin ratios of 1.2 to 2.5 (for high suction energy pumps anyway). This gives rise to Figure 18 on the next page, which is a purely hypothetical plot of possible cavitation activity for a pump at various margin multiples. It is hypothesized on tests[14] which have shown that the damage rate is maximum in regions between the $NPSH_R$ corresponding to the 3% total dynamic head drop $NPSH_R$ and the incipient cavitation $NPSH_A$. Consequently, supplying more $NPSH_A$ than the manufacturer's test $NPSH_R$ values can, in some instances, advance the damage rate. The Hydraulic Institute standard[17] for NPSH margin states that the $NPSH_A$ at incipient cavitation can be from 2 to 20 times the 3% total dynamic head drop $NPSH_R$.

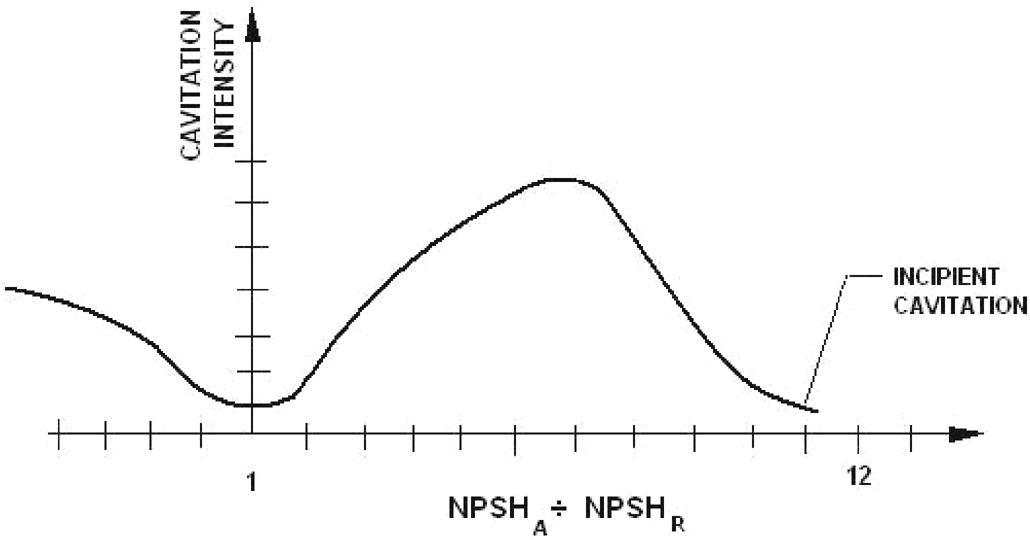


Figure 18 – Hypothetical cavitation activity curve for a given pump at various margin ratios

Increasing the margin until the incipient cavitation point is surpassed, *i.e.* where zero cavitation exists, may result in a cavitation-free pump whose cost is economically less attractive compared to that cost associated with the higher maintenance caused by cavitation.

MYTH NUMBER 9

Because the maintenance and replacement costs generated by cavitation damage have such a negative impact, no expense should be spared in order to completely eliminate its occurrence.

So let's look at the previously presented table with revised values which more closely reflect real world conditions for high suction energy pumps, which are quite commonplace.

NPSH MARGIN versus REAL WORLD CAVITATION		
MARGIN RELATIONSHIP	**CAVITATION STATUS**	**OPERATIONAL QUALITY**
$NPSH_A < NPSH_R$	YES	POOR
$NPSH_A = NPSH_R$	MINIMAL	(PROBABLY) BEST
$NPSH_A > NPSH_R$	YES	ACCEPTABLE
$NPSH_A >> NPSH_R$	MINIMAL	GOOD (BUT EXPENSIVE)

Conclusion: Unless a system can economically provide $NPSH_A$ to achieve incipient cavitation, it is best to provide NPSH at or only a few percent above the $NPSH_R$ corresponding to the 3% breakdown value. These findings bring this author to the formulation of two basic, while maybe somewhat exaggerated, maxims of pump cavitation:

WHITESIDES' AXOIM OF PUMP CAVITATION

ALL PUMPS CAVITATE, ALL THE TIME

WHITESIDES' COROLLARY OF PUMP CAVITATION

THE PUMP THAT IS NOT CAVITATING IS
THE PUMP THAT IS NOT OPERATIONAL

Finally, and very briefly, the $NPSH_R$ can significantly be reduced by the use of slower rotational speeds as a result of a concept that was developed in 1937-8 known as **suction specific speed**. Suction specific speed is defined as,

$$N_{ss} = \frac{N\sqrt{Q}}{\mathrm{NPSH}_R^{\,3/4}}$$

Where, N = pump rotational speed, rpm
Q = pump capacity, gallons per minute

all variables being those corresponding to those at the pump's best hydraulic efficiency point (BEP). Much that is known about pumps has been determined largely by experience; it is fairly well known among pump designers that cavitation usually occurs beyond N_{SS} = 10,000 (based on cold water)[14]. Special pump designs can accommodate suction specific speeds of 12,000. Occasionally, cavitation can be experienced even when the value of N_{SS} is well below the 12,000 limit.

Predicting and Troubleshooting

How can Pump Cavitation be Detected?

In a centrifugal pump, if cool water is cavitating, a crackling sound will be emitted from the pump – as though it were pumping gravel. Cavitation in a reciprocating pump causes a knocking sound. In a power pump, this knocking is transmitted to, and emits from, the power end, often being confused with a loose rod.

> **MYTH NUMBER 10**
>
> Pump cavitation always results in noise which sounds like solids being pumped. CAUTION: Cavitation can, and often does, exist without the generation of perceptible airborne noise.

> **DIAGNOSTIC TIP**
>
> If noise is present, cavitation in pumps is often mistaken for a mechanical problem, such as a faulty bearing. The noise source can be isolated by running the pump briefly without liquid flowing. If the noise ceases, then cavitation is the likely cause.

MYTH NUMBER 11

Submersible pumps, line shaft turbines, sump pumps, and pumps which have flooded suctions or, pumps which are completely submerged or immersed, cannot cavitate.

In radial impeller pumps, which exhibit low suction specific speeds, cavitation may be detected as a drop in power consumption. This stems from the fact that radials generally have horsepower curves which rise with increasing flow. In axial flow pumps, which have high suction specific speeds, cavitation may be detected as an increase in power consumption. This is because the horsepower curve for axials rise with decreasing flow.

Because cavitation limits the discharge flow of the pump, the first (and most reliable) indication of cavitation is a drop in efficiency, even before other signs are present, such as airborne noise. A good diagnostic technique is to determine accurately the flow and head developed, and back calculate the actual pump efficiency. This value can then be compared with that of the manufacturer's predicted efficiency.

Determining the Actual Efficiency

The operating pump hydraulic efficiency can be back-calculated through the following formula after determining the actual flow and head,

$$E = \frac{QHS}{3960\,HP}$$

Where, E = actual hydraulic efficiency, expressed as a decimal fraction
Q = actual flow rate (capacity), gpm
H = actual head, feet of liquid
S = liquid specific gravity, dimensionless
HP = input (brake) horsepower

Actual input horsepower is determined by any number of means. These include transmission and torsion dynamometers, strain gauge type torque measuring devices, and calibrated drivers.

Corrective Actions

As has been previously mentioned, pump cavitation can be caused by any of a number of reasons; however, the primary one is the vaporization of the pumped liquid caused by insufficient $NPSH_A$. It is one thing to identify a potential cavitation problem because of inadequate $NPSH_A$, and then quite another to identify measures that can be taken to rectify the problematic situation. To get an answer or develop a list of solutions, let's first list the causes of inadequate $NPSH_A$. We have already mentioned most of them. We only have to look at the right side of the classical $NPSH_A$ equation to begin an understanding of contributing factors to inadequate $NPSH_A$.

$$NPSH_A = \pm h_S - h_L + h_A - h_V$$

If one or more of the negative terms, *i.e.*, static suction lift (h_S), suction line loss (h_L), or liquid vapor pressure (h_V) are excessive, the resulting $NPSH_A$ will be reduced.

Obvious physical system changes than might be possible, before a complete pump replacement for a badly cavitating pump is undertaken are:

- Raise the suction liquid level or, alternatively, lower the pump's elevation;
- Decrease the operating temperature, *i.e.*, vapor pressure of the liquid;
- If applicable, increase the superimposed pressure in the suction vessel's vapor space;
- Increase the suction line size or shorten its length, thereby lowering the frictional losses;
- Install a separate low speed booster pump upstream of the main pump.

The Significance of Specific Speed

References to suction specific speed have been made in previous sections. Through empirical methods, milestone values of specific speeds have been identified and are utilized to back-calculate estimated rotational speeds that promote optimum suction conditions for a given set of pump parameters. Historically, a knowledge base has been developed that indicates that cavitation usually occurs when values of N_{SS} exceed $\approx 10{,}000$ and that for a given application, a pump that results in a lower calculated suction specific speed should be considered over that of higher value, all other conditions being equal. Through extensive pump industry experience, it has been determined that the optimum suction conditions exist at suction specific speeds less than 8,500.[12,13] Armed with this fact and the fact that the evaluation of $NPSH_A$ is easy accomplished for a given hydraulic system, the previously presented suction specific speed equation based on $NPSH_R$ can be rewritten and rearranged to appear as,

$$N = \frac{8500\,(\mathrm{NPSH_A})^{3/4}}{\sqrt{Q}}$$

Available suction specific speed can therefore be used through the above equation to determine the optimum rotational speed of the pump that will hopefully minimize cavitation.

Predicting Valve Cavitation

Like other hardware-specific rheologies, the field of restrictive flow, for valves in particular, has its own special terminologies. In order to analyze and predict valve cavitation, three separate pressures must be mathematically evaluated, and proportionally compared, through the quantities known as *valve pressure ratio* and *valve cavitation coefficient.* Predicting valve cavitation can be problematic because direct measurement of internal pressure at critical points in the valve is difficult to accomplish. Very often this is performed in an indirect manner through noise generation measurement.

Figure 19 shows the internal pressure profile of a cavitation-free valve. Note that the lowest pressure encountered in the throttling area, designated P_{min}, is greater than the local liquid vapor pressure.

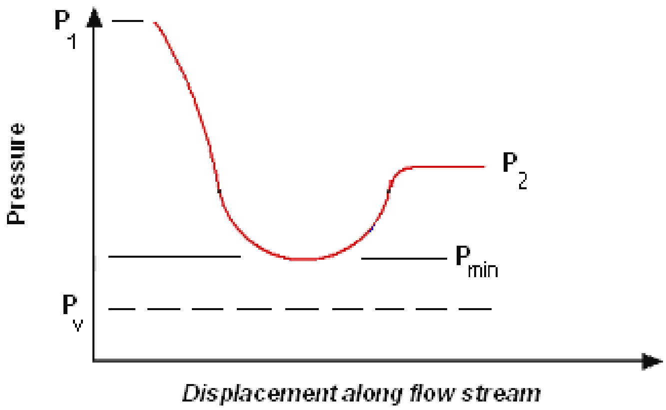


Figure 19 – Pressure profile of a non-cavitation valve

A valve's cavitation coefficient is given by,

$$\sigma_V = \frac{P_1 - P_2}{P_1 - P_{\min}}$$

From Figure 19 it logically follows that the cavitation process occurs when a valve's pressure ratio,

$$P_C = \frac{P_1 - P_2}{P_1 - P_V}$$

is greater than the valve's cavitation coefficient,

$$P_C > \sigma_C \quad \text{or} \quad \frac{P_1 - P_2}{P_1 - P_V} > \frac{P_1 - P_2}{P_1 - P_{\min}}$$

and that the extent of cavitation damage increases as

$$(P_1 - P_2)\uparrow \text{ and as } P_2 \rightarrow P_V$$

If a valve's σ_C values can be determined over the complete operating travel range of the throttling element, then cavitation can be predicted for those regions where the operating pressure ratio exceeds the valve cavitation coefficient.

In Summary

In cases where $P_c < \sigma_C$ there is little or no danger of cavitation occurring; when operating conditions indicate $P_c = \sigma_C$, an incipient cavitation signal is given. When $P_c \geq \sigma_C$ a stationary cavitation zone builds up in the vicinity of the throttling element whose growth, according to Reference 7, is approximately proportional to the quantity

$$P_C - \sigma_C$$

The cavitation area extends and the number of cavitation bubbles grows as the difference between the pressure ratio σ_C and the valve coefficient P_c for incipient cavitation increase.

Combating Valve Cavitation[7]

One method of preventing cavitation is to divide the required differential pressure into smaller incremental steps by installing two or more valves in series. The same pressure drop can be obtained with the sum of the separate valve cavitation coefficients being less than that for a single valve. Anti-cavitation (multi-stage) valve trim is also available for control valves. Valve manufacturers often assume, for initial rough assessment, that the cavitation coefficient for each stage, designated σ_{Ci}, is the same in a valve with a multi-stage plug. Consequently, the σ_C value is obtained for an n^{th} stage control valve according to

$$\sigma_C = 1-(1-\sigma_{C_i})^n$$

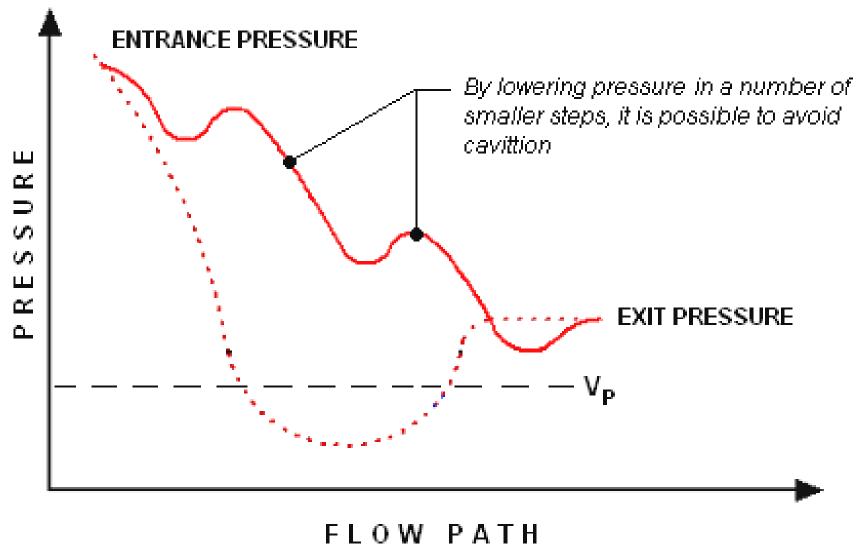


Figure 20 – Pressure profile in a valve with multi-stage trim

Determining Propeller Critical Thrust

Incipient cavitation begins at the critical unit thrust pressure of a propeller's blade. A statistical analysis by Whitesides of the previously mentioned Commander Irish experimental data for cavitating marine propellers, resulted in the following linear relationship which approximates the empirical data of the published laboratory findings:

$$P_T = eV_P - 4.2$$

where P_T = critical unit thrust, lb/in^2 (based on projected blade area)
e = base of natural logarithm, dimensionless
V_P = propeller peripheral velocity, in 000's ft/min

A plot of this equation is shown in Figure 21. In order to avoid cavitation, Baumeister and Marks[10] have recommended that the actual unit thrust should be 10 percent less than the critical value, P_T.

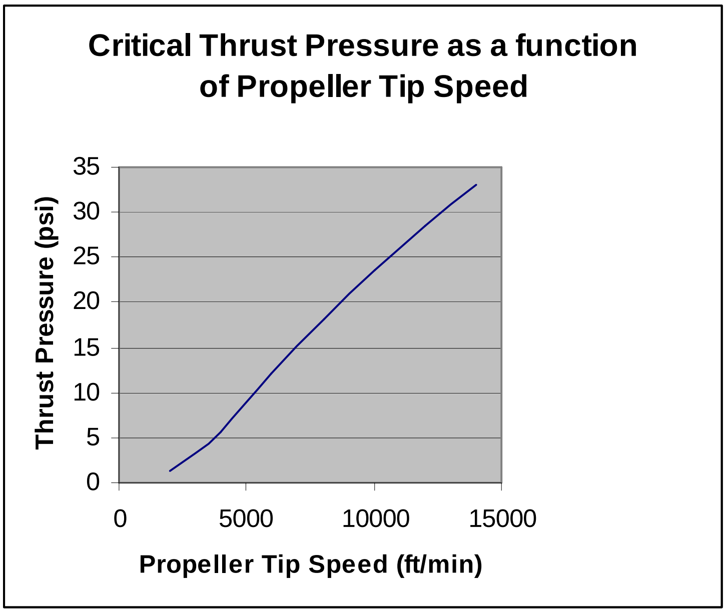


Figure 21

Course Summary

1. Cavitation describes the formation, and subsequent collapse, of vapor in a liquid, in regions where the local hydrostatic pressure becomes lower that the liquid's vapor pressure.
2. Cavitation, boiling, and flashing are terms that denote different forms of liquid vaporization.
3. Cavitation can, and often does, occur in any situation where fluid is moving in relation to a solid surface.
4. Vapor pressure is that pressure exerted by the gaseous state of a liquid, that is in equilibrium with its liquid phase. A thorough knowledge of a liquid's vapor pressure is extremely important toward the understanding of its cavitation.
5. Extensive cavitation research has been conducted; it started with ship propellers. Much is known about the cavitation process; much is still to be understood.

6. Cavitation is both an explosive and implosive process, the latter having detrimental effects such as erosion of surface materials, vibration, and noise radiation.
7. Damage emanates primarily from collapsing bubble spherical asymmetry microjets which generate highly localized shock waves which produce stresses in the proximate solid.
8. Cavitation not only causes erosion damage but also can exacerbate metal corrosion by the removal of protective passivation layers.
9. Cavitation damage often has the crystalline and jagged appearance of fatigue failure. Quantitative damage prediction is made difficult by the number of interrelated variables involved.
10. Damage rate and erosion severity is dependent on liquid properties and the time period over which it occurs.
11. Cavitation damage is not limited to solid surfaces in motion. Large scale flow cavitation in stationary structures is common place as is damage to bearings and seals in rotating equipment. Liquid properties can be physically altered by cavitation.
12. Pseudo cavitation stems from liquid aeration, additives, and absorbed gases.
13. Valve cavitation results in noise, vibration, choked flow, and internal damage.
14. Propeller cavitation begins at critical unit thrust values which have been derived empirically.
15. Net positive suction head is an important element in predicting pump cavitation.
16. The concept and philosophy of NPSH margin is varied, is often oversimplified and therefore, often misunderstood.
17. Pump suction specific speed can be used as a tool to optimize suction conditions and minimize cavitation.
18. Valve cavitation can be understood by carefully examining internal pressures along the flow path.

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