

Cavitation - - A Largely Misunderstood Phenomenon

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The vapor bubbles that form in a pot of boiling water will eventually rise to the surface and burst. The energy release (explosion) that occurs upon burst is quite small. But when that same bubble forms in the vanes of an impeller and begins its outward migration, an extremely powerful force can be released.

Cavitation (from cavity) is defined as the rapid formation and collapse of vapor bubbles or pockets in a liquid, due to dynamic action, and resulting in the formation of cavities on the surfaces of solid boundaries. These solid boundaries can exist in any number of structures including hydrofoils, pipes, and fittings but, in our industry, the primary victims are impellers and propellers. Cavitation was first explained in 1917 by the English physicist, Lord Rayleigh, as he was studying a mysterious metal erosion on ship propellers. Although its effects upon the surfaces of an impeller have been witnessed by many of us in the pump industry cavitation, itself, remains a largely misunderstood phenomenon. Actually, this is not too surprising when one considers the complex physical behavior of the relatively, simple water molecule and the dynamic forces it encounters within the centrifugal pump.

The physics and thermodynamics of water vapor bubble formation are quite complex but well understood. The complexities of cavitation have also been well researched and a wealth of data on its causes and effects exist in both printed and on-line literature. Unfortunately most of the articles on cavitation that I have read tend to circumvent what I call the “intuitive approach” to its understanding. The good ones are typically too academic and mathematically complex for the majority of us and, the “not so good” ones just gloss over the phenomenon itself and move on to its rather vague causes and effects. Some even depict cavitation occurring on the wrong side of the vane!

The goal of this tutorial is to help you gain a intuitive understanding of the cavitation process and its causes. I will leave its prevention to the many articles that already exist. Since boiling is the precursor to cavitation, we will begin by taking a look at some of the properties of water and their role in the cavitation process. We will then put NPSH into perspective and review some of the dynamics of centrifugal pump operation that also directly affect the process. We will conclude with a discussion of the different types of centrifugal pump cavitation and the conditions that can cause them to occur.

Properties of Water

If we were to take a look at some of the properties of water, we would find several apparent contradictions. Like many other compounds in nature, it can exist as a solid, liquid, or a gas. There are also indications that its molecules might form a polymer like structure.

At 32°F (0°C) water is happy to exist as either a solid or a liquid - - it will both freeze and thaw. And at 212°F (100°C) it will boil but, it will also condense at that very same temperature. Contrary to normal thinking, boiling is actually a cooling process and, under certain conditions, continued boiling will cause water to freeze! And, on a cold day, hot water will freeze faster than luke-warm water.

Its density, in the liquid state, is far greater than that of its solid state - - exactly the opposite of most other common substances. It is also nearly non-compressible in the liquid state but if you increase the pressure around a ice cube, without changing the temperature, it will melt. Remove that extra pressure and it will freeze again. Water is also a poor conductor of heat and electricity. But, it can store more heat than most other materials and releases it far more slowly. Its attraction to other substances (adhesion) is greater than its attraction to itself (cohesion). Finally, and most importantly, you have to boil rice longer in Denver than you do in Savannah.

Convinced? Could it be that the properties exhibited by this simple little molecule make cavitation difficult to grasp? The best way to unravel some of these contradictions, and understand how they might effect the cavitation process, is to take a look at how the water molecule changes state. By this I mean what is the cause and effect when liquid water changes to vapor and vice versa. I will not spend time on the solid state of water since its change is not important to typical pumping applications.

Change of State

Water in an open container will eventually disappear through a process called **evaporation**. Evaporation is the change in state of a liquid to a gas that occurs only on the surface of the liquid. Often called the "billiard ball effect" it occurs due to the random bumping of the liquid molecules that causes some to be pushed off the surface and into the air above. This results in a loss of energy in the liquid and an increase in energy in the air above. In other words, the water cools and the temperature of the air above increases.

The reverse of this process is called **condensation**. When water vapor molecules are near the water's surface they can be attracted by the liquid molecules. If they strike the

surface, they will again become part of the liquid and transfer the energy they gained from evaporation back into the water. In other words, the water will become warmer and the air above will cool. This is not the case when condensation occurs above the surface of the liquid. When vapor molecules attach to one another in mid air, the resulting liquid is cooled and the surrounding air is warmed.

The rate at which evaporation and condensation occur depends upon the temperature of the water and the air. It is also affected by the atmospheric pressure upon the water's surface. When the water is warmer, more and stronger bumping occurs and the evaporation rate increases. As the air cools the vapor molecules are less lively and more likely to be attracted by the liquid or each other. A change in atmospheric pressure will result in a greater or smaller force on the surface of the water and thus effect the rate at which molecules can leave the surface.

Now, I have to admit that surface evaporation and condensation have absolutely nothing at all to do with cavitation. But we had to start somewhere and it will serve as an introduction to the change of state that is the precursor of cavitation.

Under the right conditions, a type of evaporation can occur beneath the water's surface. A typical example of this is the pot of water I spoke of in the opening paragraph of this tutorial. [Boiling](#), or nucleation, is a change of state that takes place throughout the volume of a liquid. Water vapor bubbles form only when their energy and resulting pressure is great enough to overcome the pressure of the surrounding water and the atmospheric pressure acting on its surface. At sea level, a temperature of 212°F (100°C) will energize water molecules to a point where they will begin to form vapor bubbles. Once boiling, the temperature of the water will remain at 212°F regardless of how much additional heat is applied to the pot. (See - - I told you that boiling is a cooling process.) The "steam" that you see rising from the surface of the water is not really steam at all, it is water vapor that has condensed in the air above.

If you move this same pot to Denver (elevation 5000') you will find that the water boils at about 203°F (95°C). This lower boiling point is due to the higher elevation and the corresponding reduction in atmospheric pressure exerted upon the surface of the water. The formation of vapor bubbles requires less energy, in the form of heat, as the atmospheric pressure decreases because the overall pressure acting against the boiling process is lowered. The reverse is also true - - increase the pressure on the surface to greater than one atmosphere and the boiling point will increase accordingly.

The table on the following page illustrates the relationship between elevation and atmospheric pressure. In our industry, head is typically measured in feet of water so, I have used that same unit of measure. At sea level (0 feet) 34 feet of water pressure is

equal to 14.7 PSI or 760 mm of mercury. The table also shows the atmospheric pressure required to maintain water in its liquid state at various temperatures. This pressure is called Vapor Pressure and is also measured in feet of H₂O. (Please note that these two comparisons are completely independent of one another and are in the same table for purposes of convenience.)

Atmospheric pressure is a positive component of available Net Positive Suction Head (NPSHa), a subject that we will discuss in more detail later. As you can see, it ranges from 34' at sea level to approximately 23.4' at an elevation of 10,000'. When going from Savannah to Denver (sea level to 5000') we lose almost 6' of atmospheric pressure.

Vapor pressure is a negative component of NPSHa. At 50°F just 0.41' of atmospheric pressure is required to keep water in its liquid state. As it rises in temperature, more and more pressure is required to keep it from boiling. Between 200° and 210°F the vapor pressure required reaches that of the atmospheric pressure in Denver and, since it is almost 6 feet lower than that of Savannah, water will boil at a lower temperature (203°F). The reason it takes longer to cook rice in Denver is that the cooking process depends upon the heat content per unit of time, not the mere fact that water is boiling.

Elevation In Feet	Atmospheric Pressure In Feet of H ₂ O	H ₂ O Temperature In °F	Vapor Pressure In Feet of H ₂ O
0	34.0	50	0.41
500	33.3	60	0.59
1000	32.8	70	0.84
1500	32.2	80	1.17
2000	31.6	90	1.62
2500	31.0	100	2.20
3000	30.5	110	2.96
3500	29.8	120	3.95
4000	29.4	130	5.20
4500	28.7	140	6.78
5000	28.2	150	8.74
5500	27.8	160	11.20
6000	27.3	170	14.20
6500	26.6	180	17.85
7000	26.2	190	22.30
7500	25.7	200	27.60
8000	25.2	210	34.00
8500	24.8	220	41.45
9000	24.3	230	50.35
10000	23.4	240	60.75

NPSHa & NPSHr

As we saw earlier, the boiling point of water, in a pot, is a function of atmospheric pressure and the temperature of the water. When a centrifugal pump is involved in the boiling process, three additional components must be factored into the equation.

The **NPSH available** to a centrifugal pump combines the effects of atmospheric pressure, water temperature, supply elevation, and the dynamics of the suction piping. The following equation illustrates this relationship. All values are in feet of water.

$$\text{NPSHa} = H_a \pm H_z - H_f + H_v - H_{vp}$$

Where: **H_a** is the atmospheric pressure

H_z is the vertical distance from the surface of the water to the centerline of the pump's suction (positive or negative)

H_f is the friction formed in the suction piping

H_v is the velocity head at the pump's suction

H_{vp} is the vapor pressure of the water at its ambient temperature

With the possible exception of **H_v**, the components of NPSHa are pretty self explanatory. Unlike **H_z** which represents potential energy of a water column, **H_v** or velocity head is the kinetic energy of a mass of water moving at some velocity **V**. It can be easily calculated by determining the velocity in the suction piping from a velocity table and substituting that value for **V** in the equation " **$h = V^2/2g$** " (where **g** is the force of gravity @ 32 ft/sec²). It is usually small (at a velocity of 7 feet per second, **h = 0.765'**) but can be important when overall NPSHa is small or when suction lift conditions exist.

At first glance, the equation for NPSHa looks pretty cut & dried but, it is actually quite dynamic. All of the variables can be in a continuous state of change. Atmospheric pressure, for example, can vary by several feet depending upon weather conditions. Likewise, water temperature and supply elevation can be seasonal. And, velocity head and suction line friction vary as a function of flow. Usually the "worst case" values for each of its components are used when calculating NPSHa.

A centrifugal pump begins to cavitate when the NPSH available falls below the vapor pressure of the liquid in a pump's flow passages. Most published definitions of the **Net Positive Suction Head required** by a pump (NPSHr) state that it is the head required to prevent cavitation. Recently a knowledgeable engineer, and member of the Hydraulic Institute, told me that the definition has changed over time. It now defines NPSHr as the suction head at which a particular pump's hydraulic performance is degraded by 3%. This tidbit of knowledge is quite alarming because the degradation, itself, is due to

cavitation and, at the 3% level, it is almost certainly damaging cavitation. It is also reasonable to expect that damaging cavitation could occur well before degradation reaches the 3% level. The Hydraulic Institute's standards stipulate that the points on a pump manufacturer's NPSHr curves must reflect these values. This same engineer said that reputable manufacturers often inflate the NPSHr points on published curves in order to keep those of us unfamiliar with this definition out of trouble. Watch for the HI to change the name of NPSHr to NPSH₃.

It is reasonable to expect that a small amount of cavitation, due to turbulence from the impeller, can occur much of the time. In recent years a new term, **NPSHi (inception)**, was developed to define the pressure required at the suction that will suppress all cavitation. The cavitation that occurs between NPSHi and the point where damage occurs is called **incipient** cavitation. This form of cavitation appears to cause little, if any, damage in normal pumping applications, however, there are instances where excessive margins of NPSHa can increase the severity of incipient cavitation to a point that it can cause damage. But, this is the stuff of pump design (pump and suction specific speed) and we will not be going there in this tutorial!

NPSHr cannot be calculated and must be determined by actual testing of each and every pump model. Why does a pump require a positive suction head? Quite simply, it is impossible to design a centrifugal pump that exhibits absolutely no pressure drop between the suction inlet and its minimum pressure point, which normally occurs at the entrance to the impeller vanes. And, even if we could its application would be limited because it would be unable to take water from any source below its inlet. Therefore, all pump systems must maintain a positive suction pressure that is sufficient to overcome this pressure drop. If the pressure is not sufficient, the water will boil.

Cavitation - The Process, Its Types, & Causes

Suction cavitation, the most common and predictable form of cavitation, occurs when the NPSH available at the suction inlet falls below the minimum NPSH required by a particular pump. The areas most sensitive to this type of cavitation are the low pressure sides of the impeller vanes near the inlet and the front shroud, where vane curvature is greatest. When water flows over the surfaces of these convex curvatures, the pressure near the surface is lowered and the flow can separate from the surface. If the pressure is low enough, water vapor pockets or bubbles can form in the separated area and then collapse (or implode) upon entering an area of higher pressure. This process of formation and collapse can occur thousands of times over a very short linear distance of travel. Unlike an air bubble, which simply dissolves into the surrounding water as pressure increases, the vapor bubble actually changes state from gas to liquid. This collapse or implosion of a bubble can be difficult to comprehend, so let's compare its

action to that of a bubble bursting on the surface.

There are two distinct differences between the burst of a vapor bubble on the surface of a boiling pot of water and its implosion or collapse beneath the surface. First, there is a very large difference in the [concentration of energy](#) or the amount of energy released per unit of volume. An exploding bubble releases an extremely small amount of energy (on the order of 1+ atmospheres) while an imploding bubble, releases a very large amount of energy (on the order of 10^4 atmospheres). The reason for the large difference has to do with the change of state we discussed earlier. When water boils and changes state to a vapor bubble, it gains energy in the process. But, it also gains volume - - an increase of about 1,673 times that of its liquid state at 212° F. (When that same vapor bubble forms at 68° F, a typical cavitation temperature, its volume increase is approximately 58,000 times that of its liquid state!) The pressure in the bubble is relatively small - - just slightly more than that of the atmosphere. When that bubble rises to the surface and bursts, its contents remain in the vapor state and its energy is simply dispersed into the air above. But, when that same vapor bubble begins to collapse, it loses volume and the pressure (energy) within increases accordingly. At total collapse, when its volume is almost zero, it changes back to a liquid and all of the energy, gained in the boiling process, is released into the water around it in the form of heat. Additionally, a shock wave is generated as the surrounding water rushes in to fill the void left by the bubble.

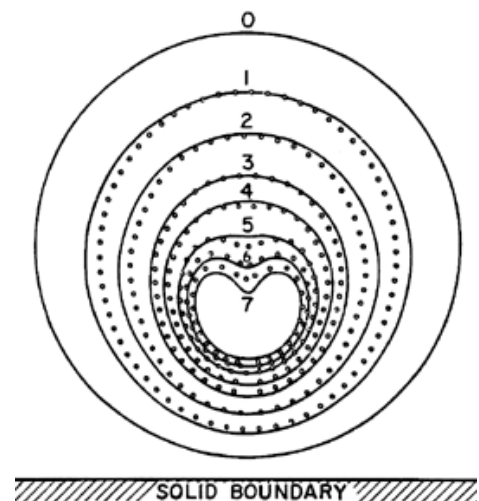
The other difference is the manner in which that [energy is dispersed](#). When a water vapor bubble bursts its energy is dispersed into the atmosphere from a nearly perfect circle on the surface of the water. It is not a violent explosion since its pressure is only slightly greater than that of the atmosphere. In other words a relatively small amount of energy is released over a relatively large area. But when a vapor bubble collapses, all of its energy is released into an extremely small volume due to the shrinkage of the bubble. This energy release can also be directed in a single direction, due to the formation of something known as a re-entrant micro jet. If the implosion is near the impeller surface, it has been shown that the direction of the micro jet will likely be towards its surface. If so, the entire energy content of the bubble (both heat and shock wave) will strike the impeller in an almost microscopic area.

So, it is a combination of the energy concentration and its focused direction, in the form of a micro jet, that differentiates an explosion from an implosion and the potential damage the latter can cause. Remember, a single cavitation bubble will not cause detectable damage. Pitting is an erosion process that occurs, over time, due to the continuous formation and collapse of vapor bubbles over a particular area. Severe cavitation can cause significant damage in just a few days while minor cavitation may not be noticed for years. Research has shown that the life of a cavitation bubble is on

the order of three milliseconds. When translated into “normal speak”, this means that a single bubble can form, collapse, and reform 333 times in a single second. During severe cavitation tens, if not hundreds, of thousands of bubbles may be forming at any point in time!

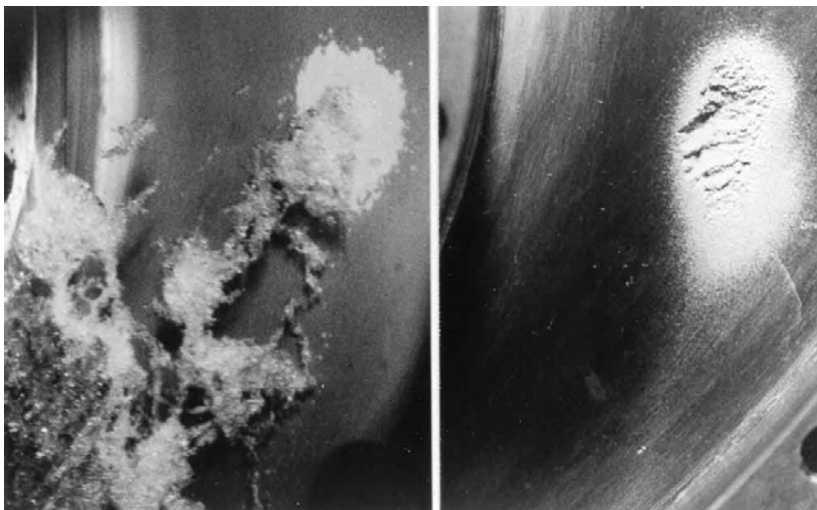
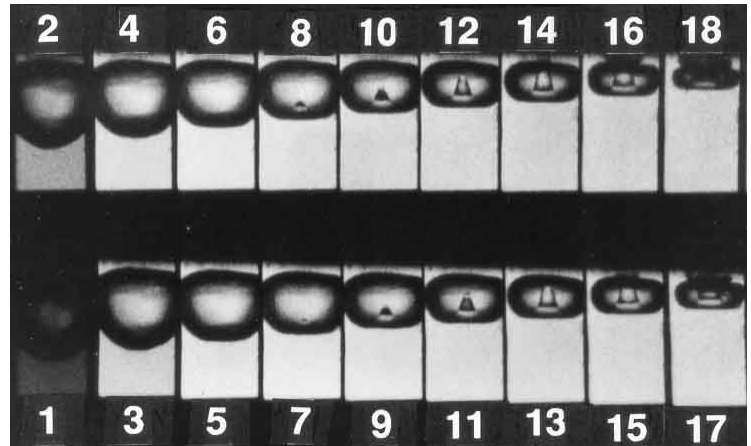
Even if the bubbles implode well above the surface of the impeller and pitting is avoided, vibration and noise are likely to be present. Vibration is also due to the shock waves emitted by the imploding bubbles and can lead to other forms of mechanical or structural damage. The noise created by pump cavitation is a primary indication of its presence and is similar to the sounds emitted by a pot of water just before it reaches the boiling point. This “crackling” sound is caused by vapor bubbles that form at the bottom of the pot, where the temperature is highest, but implode as they reach cooler temperatures just a fraction of an inch above the bottom. (If water boiled in a pot at 68°F instead of 212°F, the bottom of the pot would not last very long. Why? Because the bubble would be almost 35 times larger and so would the shock wave it generates.) Current evidence also points to the presence of extremely high “pin point” temperatures during bubble implosion but their damaging effect, if any, is secondary to the mechanical shock wave that is released.

The drawing to the right is that of a water vapor bubble, in various stages of collapse, near the surface of some solid boundary such as the vane of an impeller. The solid lines are those that were predicted by a model and the dotted lines are those obtained through experimentation. In stages 1 through 3 compression is fairly spherical, but starting in stage 4 there is a small depression on the side of the bubble directly opposite of the solid boundary. This depression becomes more pronounced in the latter stages and the bubble becomes toroidal in its three dimensional shape.



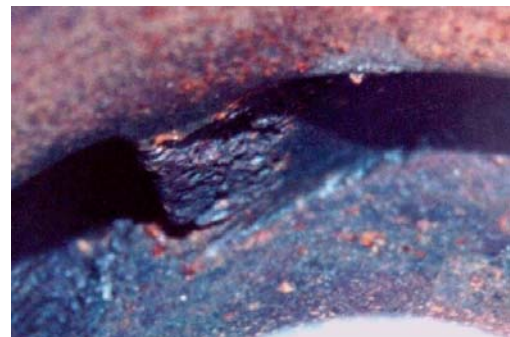
Upon implosion, the re-entrant micro jet would normally form at the bottom of the bubble and direct its energy towards the solid boundary.

The picture to the right is a series of actual photographs of bubble collapse below a solid boundary. It also shows the formation of the re-entrant micro jet. In stage 7 you can see a small dot at the bottom of the bubble. It grows in size in the following stages and appears to penetrate the upper surface in stage 14. Stage 18 is just prior to total collapse and generation of the shock wave. Remember that at 68°F the bubble volume is 56,000X that of the liquid state. (Enlarge the Acrobat page size to 150% for a more detailed view.)



The two pictures on the left are of the same area of a centrifugal pump impeller. The one on the left shows a typical cavitation pattern during flow. Bubbles are forming to the left and imploding at the impeller's surface in the upper right. The picture on the right shows the actual damage caused by continuous implosion of bubbles in the same area.

The picture to the right shows damage at the low pressure side of the leading edge of an impeller vane due to suction cavitation.



I said earlier that [suction cavitation](#) is caused by inadequate NPSHa at the inlet of the pump. This is the most common cause but, other factors can give rise to this form of cavitation even when the calculated or measured NPSHa is adequate for a particular pump. For example, entrained air in the water can, at times, give rise to cavitation. Vortices (both surface and subsurface) can also cause it to occur. And, improper suction piping - - too many elbows too close to the inlet - - is very often a culprit. All of these potential causes have one thing in common - - they can change the manner in which water flows into a pump's suction.

A centrifugal pump is designed for water to enter its suction in a direction that is axial to the impeller eye. Additionally the water should undergo a smooth, laminar flow with streamlines that are parallel to that axis and at a velocity that precludes the onset of turbulence. If these conditions are met, the water will enter the eye of the impeller and contact the vanes at the angle intended by the pump designer. But, if one of the factors mentioned above occurs, axial flow into the suction can be interrupted.

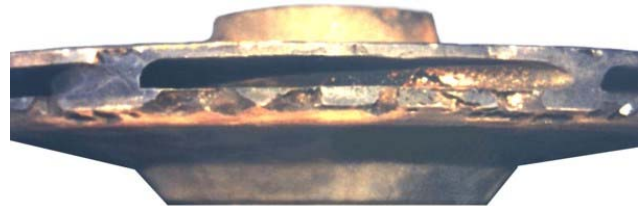
Prerotation is a term that describes a swirling motion of water in the suction piping. In simple language, it means that the water begins to rotate in one direction or the other prior to entering the impeller. In doing so, it can contact the impeller vanes at an unintended angle and its interaction with the impeller surfaces can create low pressure areas where cavitation can occur. In a nutshell, almost any event that causes turbulent flow or prerotation in the suction piping, has the potential to foster the onset of suction cavitation. There are, however, those who would probably disagree with the totality of this statement.

[Recirculation Cavitation](#)

In any centrifugal pump, there is always an extremely small flow from the impeller discharge back to the suction via the clearance between the impeller hub and the front wear ring or through the balancing holes in the rear shroud. Normally this flow has little, if any, effect upon pump performance. But, when certain pumps run at flows well below their design points, water that was intended to exit the discharge can create a secondary flow path and recirculate within the pump itself. There are two different forms of this recirculation that can occur - - suction and discharge. Both types exhibit similar traits and their common thread is two paths of flow, each moving in opposite directions. When this occurs vortices can form between the paths and create pockets of low pressure that can give rise to cavitation. Recirculation cavitation and its potential damage tends to be closely related to pump design. Some designs create higher levels of recirculation than do others.

Suction recirculation occurs when water, that would normally flow towards the periphery, reverses flow and travels back through the impeller eye, near its diameter, and into the inlet of the pump. This backwards flow creates a tumbling or rotating motion that interacts with the incoming axial flow to form vortices which can result in cavitation. A distinctive difference between normal suction cavitation and that of suction recirculation is that most of the damage from the latter tends to occur on the high pressure side of the vane. Thus, it is usually easy to diagnose which form was present at the time the damage occurred. Also, the noise caused by suction recirculation cavitation is generally more intense than that caused by low NPSHa cavitation. Unfortunately, I was unable to find a suitable picture because damage from this form of cavitation is not visible through the eye of an impeller. Instead a mirror, similar to those used by dentists, is required to view damage to the undersides (high pressure side) of the vanes.

Discharge recirculation occurs at the tips of the impeller vanes or in the discharge nozzle of the pump. As with suction recirculation, this bi-directional flow can create vortices that can lead to cavitation. Most of the damage occurs on the high pressure side of the vane tips and shroud periphery but the cutwater and discharge nozzle are also susceptible. The picture to the right shows an example of damage due to discharge recirculation cavitation.



I hope that this short tutorial has helped you gain a better understanding of cavitation. Your comments, corrections, and suggestions are welcome. On the surface, the centrifugal pump appears to be an extremely simple machine. But, as we delve into the dynamics that occur in its impeller, it can become quite complex. Hopefully this tutorial's intuitive approach to understanding these dynamics made them less complex. If you are interested in an in depth, and quite academic, study of cavitation click on the link below.

Credits

The figure on page 8 and the top two pictures on page 9 are from "Cavitation and Bubble Dynamics" by Christopher Earls Brennen, Oxford University Press 1995. Available online at <http://caltechbook.library.caltech.edu/1/00/content.htm>