Pump cavitation and how to avoid it
Best practices in pump system design

Presented by: Xylem Applied Water Systems

Cavitation is not a new phenomenon that can impact a pump system, but it is an issue that is growing. While no official figures exist, it is not misleading to say that in the last five years, cases of pump cavitation have increased markedly.

Often the pump itself is unfairly blamed. Pumping system problems, including cavitation, often manifest themselves at the pump but are rarely caused by it. In fact, nine out of 10 pump problems are not caused by the pump itself but by issues such as cavitation, poor system design and lack of maintenance.

Additional issues caused by cavitation, such as vibration, can be severe and may lead to mechanical damage to the pump. Cavitation related problems also have the potential to reduce pump life from 10-15 years, down to just two years in extreme cases.

Why is cavitation on the increase when 20 years ago it was a more isolated occurrence? One of the causes may lie in the fact that design engineers in the water industry are now expected to understand a wide range of different technologies. It is impractical for these professionals to be experts in several areas. Cavitation is primarily due to poor pump system design and a lack of awareness about how cavitation is caused.

This paper investigates the causes and effects of cavitation and the process to be followed during the design stage. Potential solutions for installations with cavitation issues are discussed; some of these can be expensive and disruptive. The good news is that cavitation and the downstream impact on maintenance and repair costs can be avoided.

What is cavitation?
Cavitation can have a serious negative impact on pump operation and lifespan. It can affect many aspects of a pump, but it is often the pump impeller that is most severely impacted. A relatively new impeller that has suffered from cavitation typically looks like it has been in use for many years; the impeller material may be eroded and it can be damaged beyond repair.

Cavitation occurs when the liquid in a pump turns to a vapor at low pressure. It occurs because there is not enough pressure at the suction end of the pump, or insufficient Net Positive Suction Head available (NPSHa).

When cavitation takes place, air bubbles are created at low pressure. As the liquid passes from the suction side of the impeller to the delivery side, the bubbles implode. This creates a shockwave that hits the impeller and creates pump vibration and mechanical damage, possibly leading to complete failure of the pump at some stage.

What is vapor pressure?
At a specific combination of pressure and temperature, which is different for different liquids, the liquid molecules turn to vapor. An everyday example is a pot of water on the kitchen stove. When boiled to 100o Celsius, atmospheric pressure bubbles form on the bottom of the pan and steam rises. This indicates vapor pressure and temperature have been reached and the water will begin boiling.

Vapor pressure is defined as the pressure at which liquid molecules will turn into vapor (see **Figure 1.0**). It should be noted that the vapor pressure for all liquids varies with temperature. It is also important to understand that vapor pressure and temperature are linked. A half full bottle of water subjected to a partial vacuum will begin to boil without the addition of any heat whatsoever.

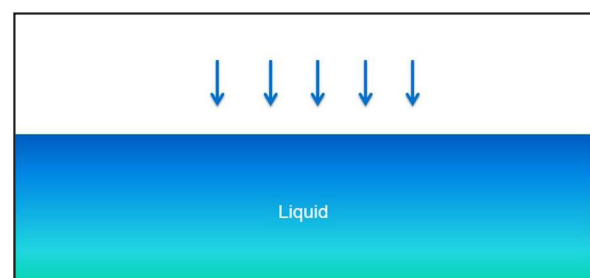**Constant pressure acting on liquid (atmospheric pressure)**

Liquid

Figure 1.0

Properties of water at different temperatures

By regulating the pressure at which water is subjected its vapor pressure can be changed and it will eventually boil at room temperature. **Figure 2.0** illustrates a tabulation of temperatures from 5 to 100oC with variations in vapor pressure, density and specific gravity for water.

Temperature Degrees C	Vapour Pressure N/m^2	Density kg/m^3	Specific Gravity
5	871.9	999.9	0.9999
10	1227	999.7	0.9997
15	1704	999	0.999
20	2337	998.2	0.9982
25	3166	997	0.997
30	4242	995.6	0.9956
35	5622	994	0.994
40	7375	992.2	0.9922
45	9582	990.2	0.9912
50	12330	988.1	0.9881
55	15740	985.2	0.9852
60	19920	983.3	0.9833
65	25010	980.4	0.9804
70	31160	977.5	0.9775
75	38550	974.7	0.9747
80	47360	971.8	0.9718
85	57800	969	0.969
90	70110	965.3	0.9653
95	84530	961.5	0.9615
100	101325	957.9	0.9579

Figure 2.0

At 5°C, the density is 999.9, which an engineer will round to 1000. The specific gravity is 0.9999, or 1. At the bottom of the table one can see that at 100°C the density has changed to approximately 958, a significant but not a big change. If one looks at the specific gravity, it has changed from 1 to approximately 0.96.

The variability of vapor pressure

At 5°C, water vapor pressure is 872 in round figures, but at 100°C it is 101,000 which is a major change in pressure. This means that for any combination of pressure and temperature in the table, the water will begin boiling and turn into vapor (see **Figure 3.0**). For example, a glass of water subjected to a pressure of 2337 N/m2 at 20°C will begin boiling.
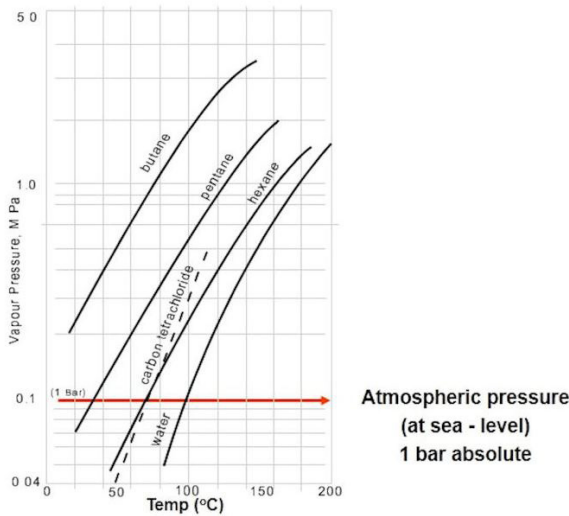

Figure 3.0

At 100°C the vapor pressure is 101325 N/m2, which is atmospheric pressure. With cavitation one must deal with absolute pressures, not gauge pressures. By regulating the temperature and pressure, it is possible to boil water at different points. Other liquids have similar charts, but the values will be different.

The influence of atmospheric pressure

Outlined in **Figure 3.1**, water will start to boil at 100°C atmospheric pressure (1 bar) at sea level. Other liquids such as hexane, carbon tetrachloride, pentane and butane are very different and will boil off at much lower temperatures than water. Butane, for example, will start to boil at negative temperatures.
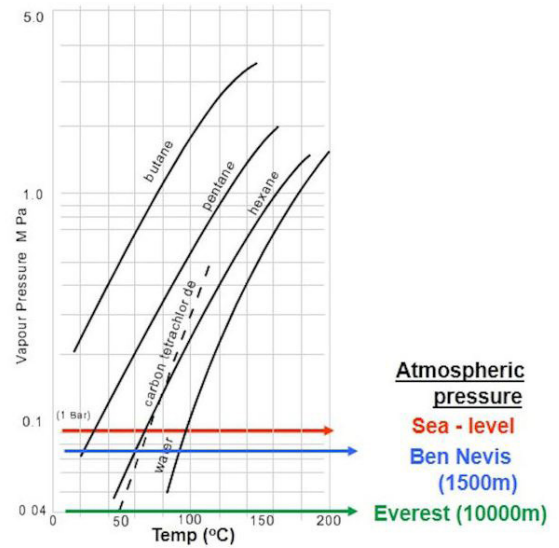

Figure 3.1

Pressure is dependent on altitude. In **Figure 3.1** a line is plotted for the top of Ben Nevis, the highest mountain in the United Kingdom at 1,344 meters, and a line for Mount Everest in Nepal at 8,848 meters. The table demonstrates that at the top of Ben Nevis the vapor pressure of water has dropped sufficiently to allow it to start to boil at 80°C. While it is unlikely that pumps will be installed on the top of these mountains, it is the case that pumps will be used in various locations around the world with similar altitudes, including Johannesburg, South Africa, which is approximately 1,700 meters above sea level. In such places it is important to determine the change in vapor pressure for that location.

The impact of cavitation on a pump

Cavitation causes pump performance deterioration, mechanical damage, noise and vibration which can ultimately lead to pump failure. Vibration is a common symptom of cavitation, and many times the first sign of an issue. Vibration causes problems for many pump components, including the shaft, bearings and seals.
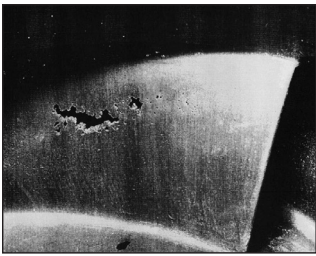
Hole in pump impeller vane.
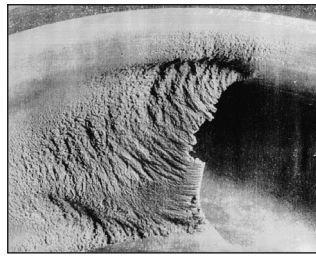
Impeller damage.

These photographs show cavitation damage to an impeller with segments chipped away and severe mechanical damage.

How to avoid cavitation

Assuming no changes to the suction conditions or liquid properties during operation, cavitation can be avoided most easily during the design stage. The key is to understand Net Positive Suction Head (NPSH) and take
it into account throughout the design process. In order to understand this term more easily it is helpful to break it down:

• Net refers to that which is remaining after all deductions have been made
• Positive is obvious
• Suction Head refers to the pressure at the pump inlet flange.

NPSH is defined as the difference between the pressure available at the pump inlet and the vapor pressure of the liquid. Vapor pressure is different for different liquids and varies with pressure and temperature.

The pressure available at the pump inlet is what remains after friction loss, velocity head loss and inlet and outlet losses have been taken into account within the suction pipework of the pumping system. Because of this, during the design phase, it is necessary to calculate these losses and process unit losses in the suction pipework and then deduct those losses from the suction head available to the pump. By doing this, at the point where the pump is installed, one is left with net pressure remaining and available for the pump.

Net Positive Suction Head Available (NPSHa)

Net Positive Suction Head available (NPSHa) has nothing to do with the pump; it is a system value specific to the system design being considered. NPSHa is the head available at the pump suction flange pipework connection for the pumping system in question, and is completely independent of the pump to be installed there. It is the actual difference between the pressure at the pump inlet flange and the vapor pressure of the liquid for the installation and is determined by the design, configuration and relative levels for the suction side of a particular system.

$$\text{NPSHa = P pump inlet ¬- vapor pressure (m)}$$

Pressure available at the pump inlet is that which remains after allowances have been made for all the losses as described above.

Net Positive Suction Head Required (NPSHr)

Net positive suction head required (NPSHr) is a pump characteristic that is not related to the system. All pump NPSHr's are different and the values can be obtained from the pump manufacturer.

What causes cavitation?

Cavitation occurs in a pump when the temperature and pressure of the liquid at the suction of the impeller equals the vapor pressure. It can happen at low pressures and normal operating temperatures. Locally, it results in the liquid turning to a vapor and creating very high temperatures and pressures, which can reach circa 10,000K and 1GN/m2.

Bubbles form during cavitation. As the pressure in the pump increases, those bubbles collapse in the form of an implosion – equally as violent as an explosion. The implosion causes shockwaves to travel through the liquid and hit the impeller causing mechanical damage.

Impeller damage.

NPSHr is defined as the difference between the pressure at the pump inlet and the vapor pressure required for the pump in question. This value should not be taken as sufficient to ensure that cavitation will not occur, because it is measured at during testing when the pump is just starting to cavitate. The onset of cavitation is measured as being the point at which the delivery head on the pump drops by 3 percent.

It is therefore necessary to ensure that NPSHa is greater than NPSHr, and for that, a margin must be built in to the equation.

NPSHa ≥ NPSHr + margin

The golden rule is to ensure that there is always sufficient margin to avoid cavitation. The value of the margin is often specified in-house by design consultants, but pump manufacturers will always offer advice. Typically, a margin of approximately 1.5 meters will be sufficient.

NPSHa is a characteristic of the system design that can be controlled. Every effort should be made at the design stage to ensure that there is sufficient NPSHa within a system. The consequences of not doing so may prove to be costly and disruptive.

Understanding Cavitation

Figure 4.0 illustrates a cross section of a piece of suction pipe and the impeller in the pump. It identifies five positions. Considering liquid flows through the pump from positions 1 to 5, it is obvious that this is equivalent to a continuous pipe flow system, and the flow rate at every position from 1 to 5 must be constant.
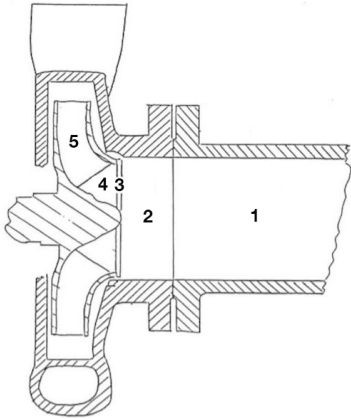

Figure 4.0

By definition, because there is a large cross section at position 1, going down to a very small cross section area, the velocity is much higher at the eye of the impeller than in the suction pipe.

As the velocity in a pipe system increases, the pressure is reduced, and as the velocity decreases, the pressure increases. The reason for this is that a higher velocity creates head, which is wasteful energy. Ideally, pressure is desired – not velocity head. The effect is similar to squeezing a garden hose. The flow rate of the water is the same, but the velocity can be increased by squeezing the end of the hose. The water leaving the hose has high velocity head but is at atmospheric pressure.

Figure 4.1 shows the pressure at different positions within the pump. It demonstrates that the pressure through the impeller drops and then recovers as it leaves the pump. This is due to the fact that the diameter of the eye of the impeller is small compared to the suction pipe, and the pump impeller is adding energy to the liquid, thereby increasing its pressure.
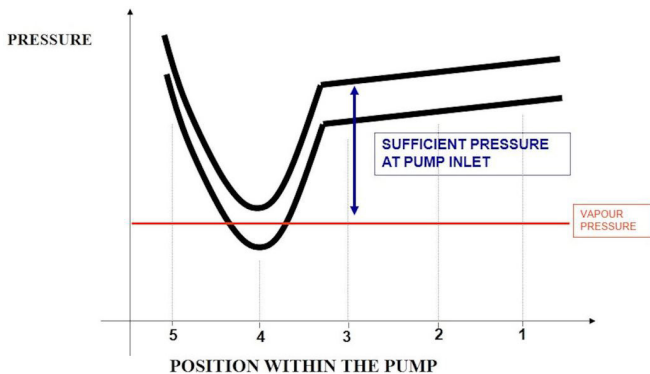

Figure 4.1

Good and bad pumping system graphs

Figure 5.0 illustrates the pressure variation through an impeller with two lines drawn, one red and one green, to represent the vapor pressure of different liquids being pumped.
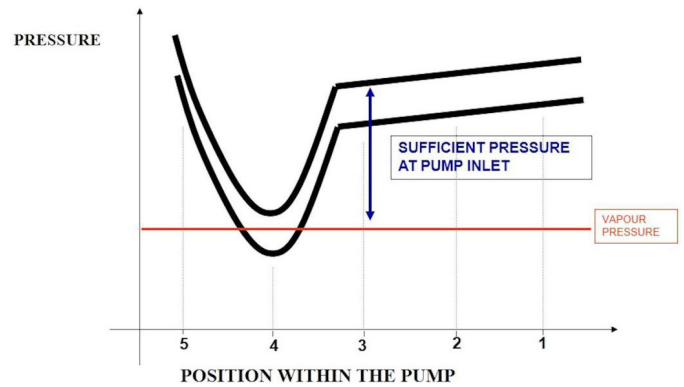

Figure 5.0

In the case of the red vapor pressure line, the curve cuts across the line signifying that at the position shown, the pressure will be lower than the vapor pressure of the liquid. This means that the system, in which the pump is installed, is not providing sufficient NPSHa, and by definition, cavitation will occur.

For the green vapor pressure line, the curve does not cut across the line at any point. This shows that there is sufficient NPSHa and the pressure will not drop below the vapor pressure of the liquid. This system has been correctly designed, and cavitation will not occur.

Avoiding cavitation

As discussed above, it is critical to ensure sufficient NPSHa is available so that the liquid remains above vapor pressure.

The pump cavitation test carried out by the manufacturer determines the NPSHr for each pump. During the design phase, the manufacturer will be able to supply the NPSHr for any pumps being considered.

Per **Figure 6.0**, the pump NPSHr curve is obtained through a test by starting the pump and running it at a given head and flow. The delivery head and flow are measured and the suction pressure is also measured. The suction to the pump is then throttled, simulating a reduction in NPSHa until the pump delivery head drops by 3 percent. At this point, the suction head is recorded along with the flow rate, and this becomes one point on the NPSHr Q-H curve. The test is repeated for different flow rates and heads until sufficient measurements have been taken to plot an NPSHr curve.
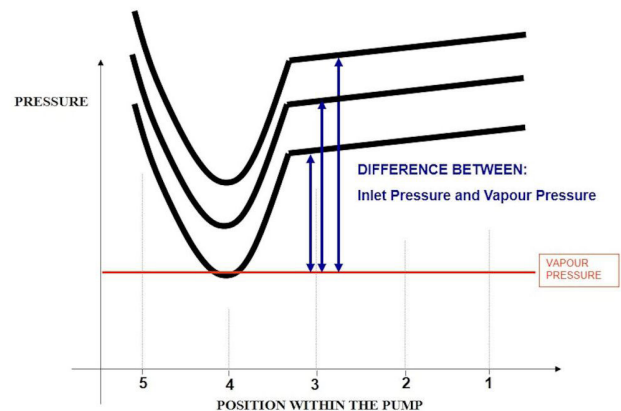

Figure 6.0

Conclusion

There is no alternative to getting pump system design right in order to avoid cavitation. During design, the value of NPSHa (which is independent of the pump to be selected) can easily be determined. The NPSHa can then be compared to the NPSHr for the types of pumps being considered. If there is insufficient NPSHa, it is much easier to make changes to the system design, rather than after construction and installation. It is strongly recommended that any changes necessary are made at the design stage as any additional costs incurred will be much lower compared to the costs of rectifying an installation with cavitation problems.

In the event that pump cavitation is a problem on an existing installation, there are essentially only two routes that can be followed to resolve the issue. The first is to increase the NPSHa to the pump or decrease NPSHr by the pump.

Options available to increase the NPSHa will depend upon the nature of the system in question. This can include increasing the pressure on the suction end of the pump, or reducing the friction losses in the pipework to make more pressure available to the pump. Increasing supply pressure can be achieved by raising the static head of the supply, applying pressure to the supply vessel, using a booster pump, or reducing friction losses in the pipework by using larger diameter pipes, or fewer components and fittings. Pressure could be supplied to the supply vessel with the use of a booster pump.

However, these are rarely viable options for an existing installation and are nearly always impractical due to space issues, cost and potential disruption. Similarly, it is rarely practical to replace the suction system pipework with a larger diameter.

The second option for resolving pump cavitation in an existing installation is to replace the damaged pumps with pumps that have a lower NPSHr, or install parallel pumping using multiple pumps.

In many cases the above options may not be viable, and in all cases they may involve considerable cost and disruption.

Good design to avoid cavitation is always the best option.