Pump cavitation and how to avoid it

Cavitation is not a new phenomenon, but it is a growing phenomenon. Whilst no official figures exist, it is not misleading to say that in the last five years, cases of pump cavitation have increased markedly in the UK.

All too 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 ten pump problems are not caused by the pump itself but by issues such as cavitation, poor system design and lack of maintenance.

Pump problems 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 circa 10-15 years, down to just two years in extreme cases.
But why is cavitation on the increase when 20 years ago it was a more isolated occurrence? I believe one of the causes may lie in the fact that design engineers in some industries, such as the water industry, are now expected to deal with a very wide range of different technologies. It is therefore impractical for them to be expert in all areas such as system design and cavitation problems. The truth of the matter is that 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 at design stage. Potential solutions for installations with cavitation issues are discussed but some of these can be very expensive and disruptive.

The good news is that cavitation and the downstream impact on maintenance and repair costs can be avoided. I hope this paper will increase awareness of the cavitation issue and offer some solutions for pump users.

What is cavitation?

Cavitation can have a serious effect on pump operation and lifespan. Cavitation can affect many aspects of a pump, but it is often the pump impeller which bears the brunt of its impact.

A relatively new impeller which has suffered from cavitation will often look 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 vapour at low pressure. It occurs because there is insufficient pressure at the suction end of the pump, in other words, there is insufficient Net Positive Suction Head available (NPSHa).

When cavitation occurs, 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 creating pump vibration and mechanical damage, possibly leading to complete failure of the pump at some stage.

What is vapour pressure?

At a specific combination of pressure and temperature, which is different for different liquids, the liquid molecules turn to vapour. An everyday example is a pot of water on the kitchen hob at home. When boiled to 100°C at atmospheric pressure bubbles form on the bottom of the pan and steam rises. This indicates we have achieved vapour pressure and temperature, and hence the water will begin boiling.

Vapour pressure is defined as the pressure at which liquid molecules will turn to a vapour. It should be noted that the vapour pressure for all liquids varies with temperature.

It is important to understand that vapour 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.

Properties of water at different temperatures

By regulating the pressure to which water is subjected you can change its vapour pressure and eventually boil it at room temperature. Figure one illustrates a tabulation of temperatures from 5 to 100°C with variations in vapour pressure, density and specific gravity for water.

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

| 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

Fig.1 The properties of water at different temperatures

The variability of vapour pressure

Let's have a look at vapour pressure. At 5°C water vapour pressure is 872 in round figures, but at 100°C it is 101,000 which is a huge change in pressure. This means that for any combination of pressure and temperature in the table, the liquid (water in this case) will turn into vapour and will begin boiling. For example, a glass of water subjected to a pressure of 2337 N/m2 at 20°C will begin boiling.

At 100°C the vapour pressure is 101325 N/m2, which is atmospheric pressure. It's important to note that with cavitation we must deal with absolute pressures, not gauge pressures.

By regulating the temperature and pressure it is possible to start water boiling at different points. Other liquids have similar charts, but the values will be different.


Constant pressure acting on liquid (atmospheric pressure)

Liquid

Vapour Pressure

Atmospheric pressure (at sea - level) 1 bar absolute
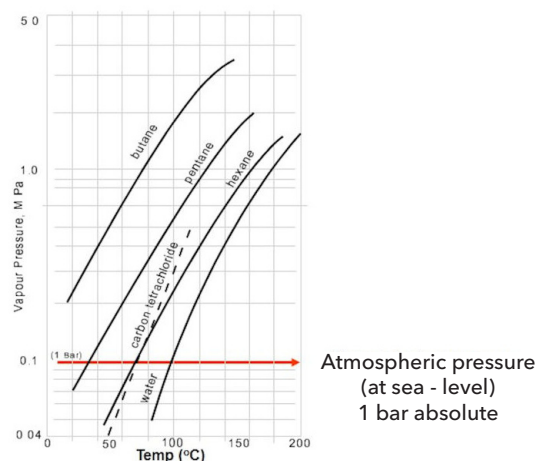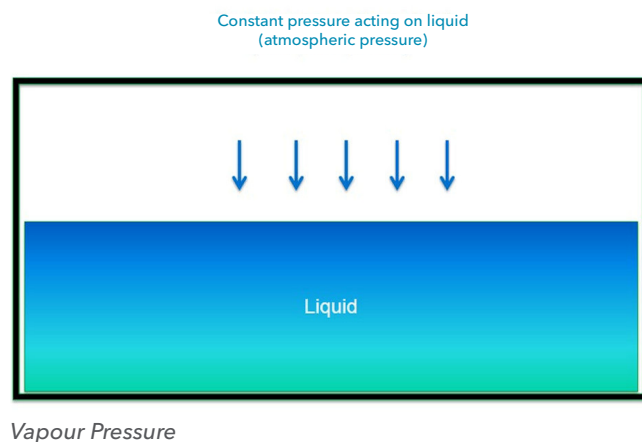
Atmospheric pressure

The influence of atmospheric pressure

Water will start to boil at 100°C and atmospheric pressure (1 bar) when measured 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.

It should be noted that pressure is dependent on altitude. The chart below has a plotted line for the top of Ben Nevis at 1500 metres and Everest at 10,000 metres, which demonstrates that at the top of Ben Nevis the vapour pressure of water has dropped sufficiently to allow it to start to boil at approximately 80°C. Whilst it may be unlikely that pumps will be installed on the top of Ben Nevis, it is definitely the case that pumps will be used in various locations around the world with similar altitudes, such as Johannesburg, which is approximately 1700 m above sea level. In such places it is very important to determine the change in vapour pressure for that location.
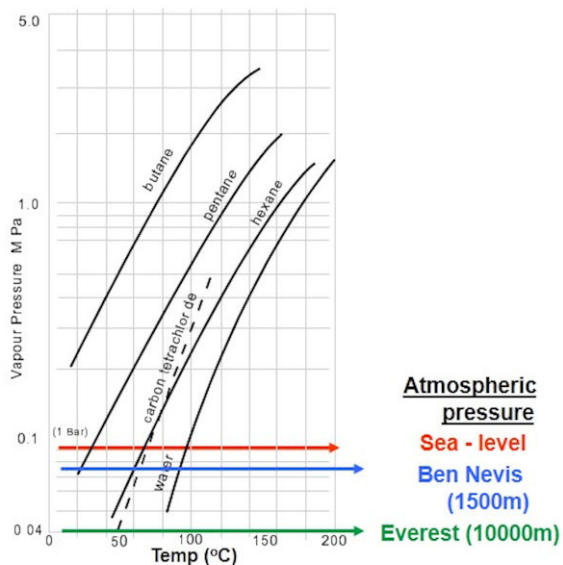
Vapour pressure vs. Atmospheric pressure

What causes cavitation?

Cavitation occurs in a pump when the temperature and pressure of the liquid at the suction of the impeller equals the vapour pressure. Cavitation can occur at low pressures and normal operating temperatures. Locally it results in the liquid turning to a vapour and creating very high temperatures and pressures, which can reach circa 10,000K and 1GN/M².

When cavitation occurs bubbles are formed. As the pressure in the pump increases, those bubbles collapse in the form of an implosion, which is equally as violent as an explosion. The implosion causes shockwaves to travel through the liquid and hit the impeller causing mechanical damage.

The impact of cavitation on a pump

Cavitation causes pump performance deterioration, mechanical damage, noise and vibration which can ultimately lead to the complete failure of the pump. Often the first sign of a pump problem is a symptom such as vibration. It should be noted that vibration also causes problems for many pump components including the shaft, bearings and seals.

The image below illustrates cavitation damage to an impeller with segments chipped away, illustrating 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 or NPSH and take this into account during design. In order to understand this term more easily it is helpful to break it down into its constituent parts. Net refers to that which is remaining after all deductions have been made, Positive is obvious and 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 vapour pressure of the liquid. It is important to bear in mind that vapour pressure is different for different liquids and varies with pressure and temperature.

It is also important to remember that the pressure available at the pump inlet is that which remains after account has been taken of all the friction losses, velocity head losses and inlet and outlet losses in the suction pipework of the pumping system.

During design it is therefore necessary to calculate all the friction losses, inlet and outlet losses and process unit losses in the suction pipework to determine the suction head available to the pump. Therefore, at the point where the pump is installed, we are left with a net pressure remaining and available for the pump.
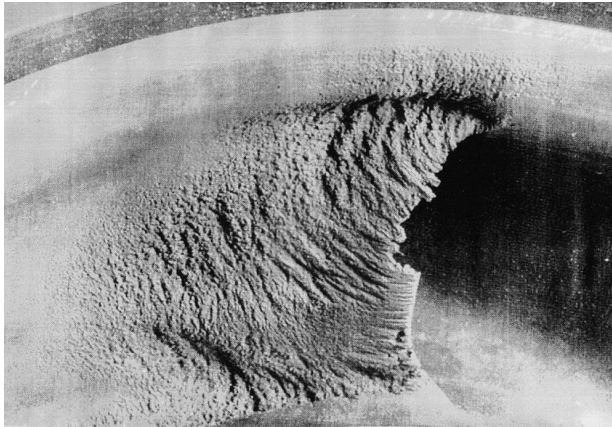
Effects of Pump Cavitation

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 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 vapour pressure of the liquid for the installation in question and will be determined by the design, configuration and relative levels for the suction side of a the system.

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

NPSHa is specific to the site in question and determined by the design of the system. It is important to note that 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 and has nothing to do with the system. All pump NPSHr's are different and the values can be obtained from the pump manufacturer.

NPSHr is defined as the minimum suction pressure required at the pump inlet 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 works test 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%.

It is therefore necessary to ensure that NPSHa is greater than NPSHr, and for that we must build in a margin.

$$NPSHa \geq NPSHr + \text{margin}$$

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 standards, but pump manufacturers will always offer advice. Typically a margin of approximately 1.5 metres will be sufficient.

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

Understanding Cavitation

The illustration below is a cross section of a piece of suction pipe and the impeller in the pump.

The illustration identifies five positions. Considering liquid flow through the pump from positions 1 to 5 it is obvious that this is equivalent to a continuous pipe flow system, and hence the flow rate at every position from 1 to 5 must be constant.

By definition, because there is a large cross sectional area at position 1 going down to a very small cross section area, the velocity is much higher through 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 velocity head, which is wasteful energy. Ideally we want pressure, not velocity head. This is a similar effect 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.
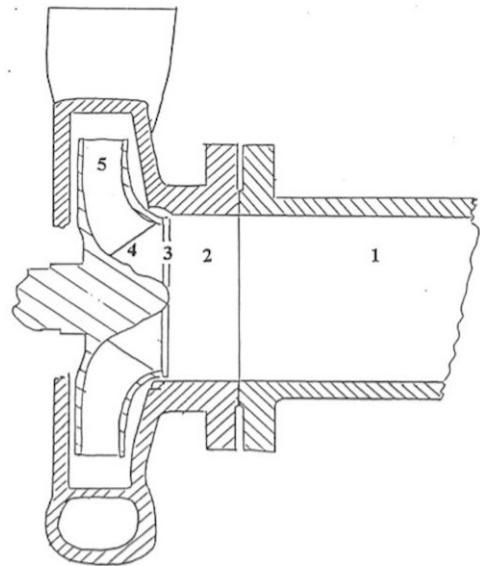
Pressure varies with position as the liquid flows through the impeller

When the pressure at different positions through the pump is plotted on a graph the illustration below is created. The graph 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.
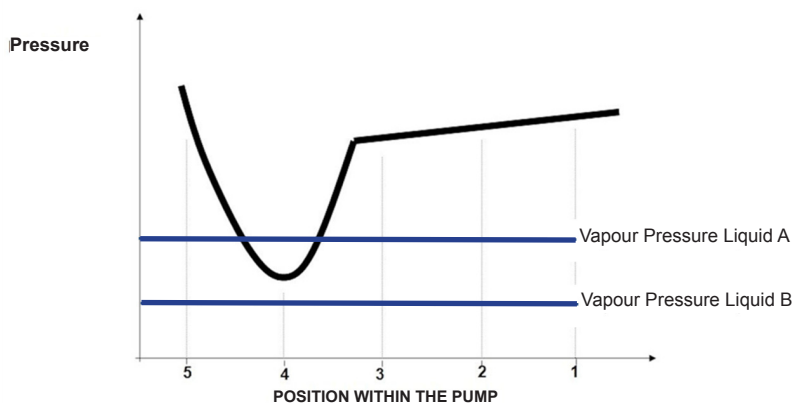
Pressure

POSITION WITHIN THE PUMP
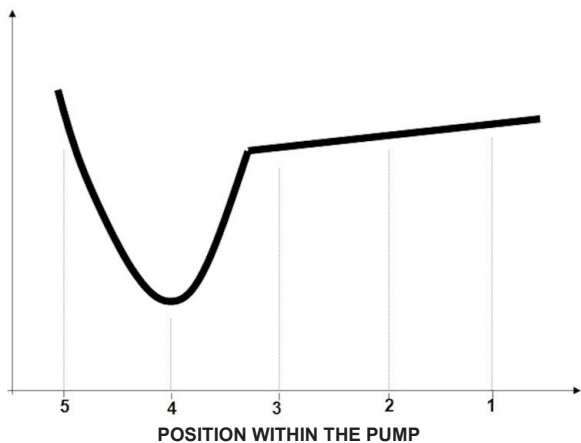
Pressure at different positions through the pump

Good and bad pumping system graphs

This graph below shows the pressure variation through an impeller with two lines drawn to represent the vapour pressure of different liquids being pumped.

In the case of the upper vapour pressure line it will be noted that the curve cuts across the line. This signifies that at the position shown the pressure will be lower than the vapour 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.

In the case of the lower vapour pressure line it will be noted that 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 vapour pressure of the liquid. The system has therefore been correctly designed, and cavitation will not occur.


Pressure

Vapour Pressure Liquid A

Vapour Pressure Liquid B

POSITION WITHIN THE PUMP

Sufficient and Insufficient pressure at pump inlet

How to avoid cavitation

It is therefore critical to ensure that there is always sufficient NPSHa available to ensure that the liquid remains above vapour pressure. The pump cavitation test carried out by the manufacturer is the means by which the NPSHr for each pump is determined. At design stage the manufacturer will be able to supply the NPSHr for any pumps being considered.

The pump NPSHr curve is obtained on a pump works 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, thereby simulating a reduction in NPSHa, until the pump delivery head drops by 3%. At this point the suction head is recorded along with the flow rate, and this becomes one point on the NPSHr H/Q curve. The test is repeated for different flow rates and heads until sufficient measurements have been taken to plot an NPSHr curve.
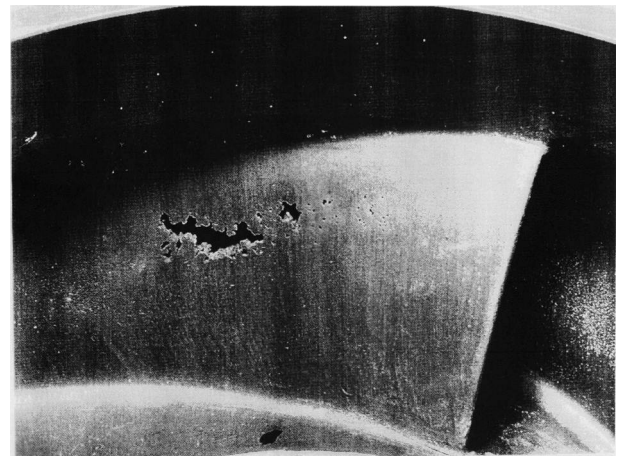
Impeller vane hole caused by cavitation

Conclusion

There is no alternative to getting pump system design right at the design stage. During design the value of NPSHa (which is independent of the pump to be selected) can be determined quite easily. Having determined the NPSHa it 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 at design stage rather than after construction and installation. It is strongly recommended that any changes necessary are made at design stage as any additional costs incurred may pale into insignificance 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 rectify the problem. 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, thereby making 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 less 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 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.

A second option is to replace the existing 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.

There is no alternative to getting it right at design stage, regardless of the pressure to reduce costs. If it is necessary to take out two metres of concrete in order to lower the pump suction connection and achieve the correct NPSHa, then my strong advice is to do it or look for an alternative pump location. Good design to avoid cavitation is always the best option.

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