



Taking the Mystery out of Cavitation
Pilot-Operated Automatic Control Valves

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Abstract

Cavitation can be an extremely damaging force as related to the application of pilot-operated automatic control valves. The consequences of cavitation are numerous and can include: loud noise, extreme vibrations, choked flow, destruction or erosion of control valves and their components resulting in disruption of water distribution or plant shutdown.

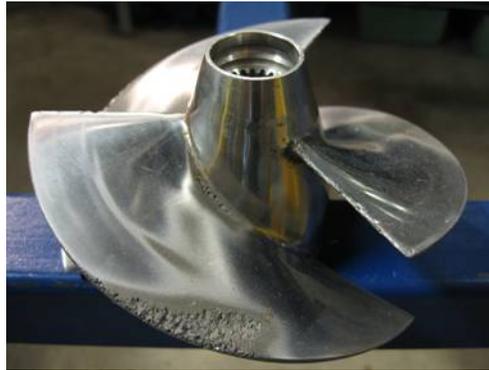
This white paper will deal with cavitation solutions as they relate to valves and specifically pilot-operated automatic control valves. A high level description of what causes cavitation and the associated impacts will be covered. Typical occurrences of cavitation and consequences will also be discussed in some detail. A brief history of cavitation solutions will be explored so an understanding of past practices will be fully understood. An overview of products addressing cavitation (anti-cavitation trim) will be explored and will cover body design and understanding C_v^1 values as applied to full port and reduced port valves. The benefits of anti-cavitation trim are explored in some detail with sub-topics such as noise reduction. Finally numerous typical applications will be covered to explain where anti-cavitation trim will eliminate or substantially reduce the normal impacts of cavitation.

This white paper is primarily written for municipal planners, engineers, and consultants who are involved with the process of selecting the appropriate solution for solving high pressure drop problems.

¹ C_v is defined as flow coefficient
v

Introduction

Most of us are familiar with cavitation and the impact that cavitation can have on boat propellers as depicted below.



In the late 19th century Lord Rayleigh, a prominent British physicist explored the question of why fast rotating propellers eroded so quickly. Through the results of his research, he was able to associate cavitation on boat propellers with previous experiments by Osbourne Reynolds in 1894 which proved the theory of cavitation. It is amazing that over the last century, numerous experiments and investigations on the subject of cavitation have failed to fully explain the many accompanying effects of cavitation. The complexity of cavitation covers numerous scientific arenas including optics, acoustics, thermodynamics, hydrodynamics, plasma physics and chemistry. Control valves are often exposed to this problem since the static pressure at the “vena contracta²”, even at medium operating conditions, can reach levels sufficient for cavitation to commence in liquids.



John William Strutt, Lord Rayleigh

² Vena Contracta is the point in a fluid stream where the diameter of the stream is the lowest.

Cavitation Explained

There are infinite studies and resource materials available on cavitation and its effects and causes so it is not the intent of this paper to elaborate on the very complicated process of cavitation but rather to give a simplistic summary of this process along with key relative points as they relate to control valves.

Cavitation consists of rapid vaporization and condensation within a liquid. When local pressure falls to vapor pressure (approximately 0.25 psi / 0.018 bar absolute for cold water), vapor bubbles are formed and when these bubbles travel to an area of higher pressure, the bubbles collapse with phenomenal force and great localized stress. It is the violent collapse of these vapor bubbles near valve components or downstream piping surfaces which cause cavitation damage and subsequent performance degradation. Typically, the reason for low pressure is that the pressure drop across a control valve has created very high velocity in the seat area and corresponding low pressure because potential (pressure) energy is reduced to compensate for the increase in kinetic energy. This principle, known as Bernoulli's Principle was named after the mathematician Daniel Bernoulli and was first published in 1798 in his book, *Hydrodynamica*. The principle can be applied to various types of fluid flow and simply states that when there is an increase in the velocity of fluids then it must be accompanied by a decrease in the fluid's pressure, the total energy associated with the flow must remain constant. And as summarized above, in scenarios where the pressure drops to vapour pressure, cavitation will occur.

In control valves, the pressure drop typically occurs at or near the seat area or just downstream. The shock waves and pressure fluctuations resulting from these high velocity bubble collapses can also cause noise, vibrations, accelerated corrosion, as well as limited valve flow. Typically the cavitation is formed in the valve throttling area, the pressure fluctuations radiate into the downstream pipe as noise. As the cavitation increases the magnitude of these pressure fluctuations also increase. System vibrations, pipe wall vibration, and component damage will increase accordingly. The associated results can negatively impact the reliability of control valve accessories and other system components.

The most dangerous outcome of cavitation is likely the erosion of either the control valve components or alternately the downstream piping in the vicinity of the control valve. When the cavitation levels are reduced below damaging levels, the associated vibration and noise will also be reduced.

As mentioned in the introduction, cavitation is often difficult to predict. One factor worth noting is that cavitation will increase with increasing fluid temperatures. This is but one example of the many inputs and factors that makes predicting when cavitation will occur, so difficult. Cavitation can also manifest when liquid at a high velocity is trying to make a sharp bend. Flow separation from the solid boundary creates low pressure and cavitation. Cavitation is most frequently found in control valves and pumps, the topic of this paper being specifically control valves.

Illustration 1 below demonstrates how a standard pilot-operated automatic control valve incurs cavitation when extreme pressure differential occurs through the valve flow path. Please note the highest velocity lowest pressure “vena contracta” within the actual valve and the subsequent outlet pressure and flashing (which is a combination of fluid and vapor) demonstrating the destructive forces of cavitation at work. The cavitation process will occur regardless of coatings such as two-part epoxy or heat fusion epoxy. Valve metallurgy also has an impact on cavitation and the valves referenced in this paper are typically made from ductile iron or cast iron. Other materials such as stainless steel generally have much superior tolerances to the effects of cavitation. Numerous studies have been conducted on metallurgy and cavitation so the intent of this paper is not to elaborate on this subject but to advise the reader that there are some insightful resources available on this topic.

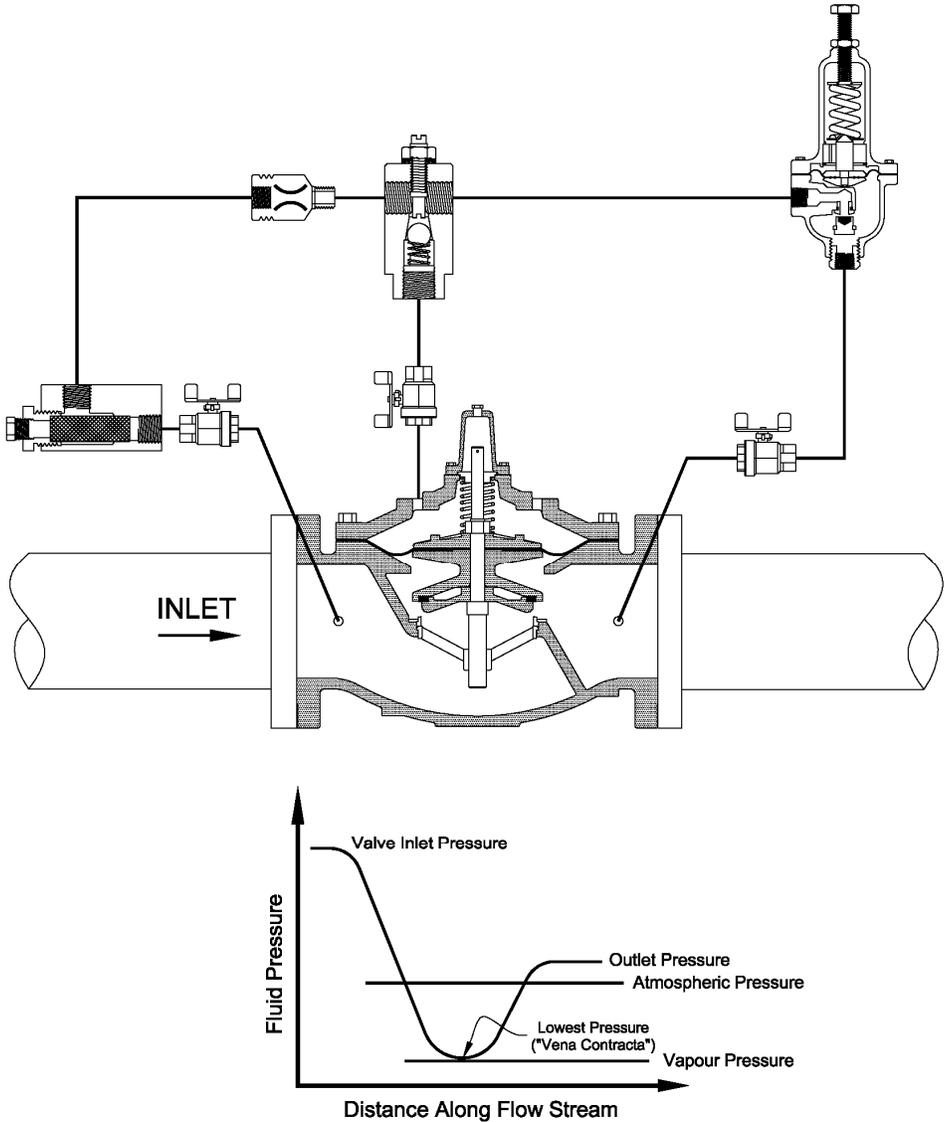


Illustration 1 – Pressure Differentials with a Standard Automatic Control Valve

Impacts of Cavitation

1. Strong vibrations – The shock waves generated by collapsing vapor bubbles produce pressure fluctuations and cause vibration. As cavitation increases, the magnitude of the vibrations increases by several orders. Even systems with large valves that are properly secured will exhibit pipe and valve movement during severe levels of cavitation. Such vibrations can loosen bolts, cause fatigue of connections, loosen or break restraining devices and ultimately lead to structural damage or failure.
2. Loud noise – In its least violent form, cavitation produces only a light crackling sound, about the same intensity as popcorn popping. However, at more advanced stages cavitation noise becomes objectionable and safety concerns may increase. For example, cavitation in certain types of valves sounds like gravel rumbling through the pipeline. In extreme cases in a large valve the noise can even resemble the sound of dynamite exploding. The noise intensity can exceed 100 dB, a level that constitutes a risk of hearing damage.
3. Choked flow caused by vapor formation – Less flow capacity for flow due to presence of vapour.
4. Erosion of valve components.



5. Destruction of the control valve.



6. Erosion and destruction of downstream piping in close proximity to the valve.
7. Plant or distribution system shut down due to catastrophic failure.

Predicting Cavitation

Many manufacturers of pilot-operated valves have the ability to assist in predicting cavitation and defining what conditions should be of concern. Often this information can be found in technical product catalogues. The cold water cavitation coefficient (σ)³ is an approximation that many manufacturers use for reference. In the case of globe style valves, damage can occur when the cold water coefficient is less than the 0.7. This roughly translates to a 3 to 1 ratio indicator which is a rule of thumb that Singer Valve uses to flag applications that require careful consideration for implementing a variety of techniques to overcome or contain cavitation.

³ Cold water coefficient (σ) = (Downstream Pressure (P_2) + 14.4) / Differential Pressure (ΔP)

As an example, in pressure management if your inlet pressure was 90 psi / 6.2 bar and your preferred outlet pressure was 30 psi / 2.07 bar or less, then it would be advisable that you carefully evaluate your cavitation options. It is recommended that you consult with a local engineering firm that has experience with cavitation issues on control valves or consult with an experienced control valve manufacturer for assistance.

When discharging from a pressurized supply line to atmosphere (such as filling a reservoir) it has been our experience that when pressures in the supply line are 25 psi / 1.7 bar or less cavitation is not a concern. If pressures are greater, then some form of cavitation protection should be considered. Please note that the above mentioned rule of thumb is a guideline only and it is always advisable to get the assistance of a qualified engineer due to the many factors and inputs that are required to fully evaluate a potential cavitation application.

Cavitation Solutions from the Past

Before the introduction of anti-cavitation trim and anti-cavitation chambers in the pilot-operated control valve industry 25 – 30 years ago it was common practice to utilize two or more control valves in a series. Manufacturers that do not provide anti-cavitation trim will often still recommend this approach. The concept behind this practice is to break the pressure into multiple stages using two or more control valves.

Illustration 2 below shows two pressure reducing valves being utilized with the first valve reducing pressure from 110 psi / 7.6 bar to 50 psi / 3.5 bar while the second valve reduces pressure from 50 psi / 3.5 bar to 20 psi / 1.3 bar. It is common practice and most efficient to design for approximately 2/3 of the pressure drop through the first pressure reducing valve and the remaining 1/3 of the pressure drop through the second pressure reducing valve. This approach can be very effective in eliminating cavitation, providing the pressure settings of the pressure reducing valves have been well thought out. The primary disadvantage of this approach is economics. Instead of one pressure reducing valve, two isolation valves, bypass control, pressure gages concrete chamber and associated equipment as well as labor for installation, you would be doubling the cost of the complete installation in this example if you were to provide two standard pressure reducing valves.

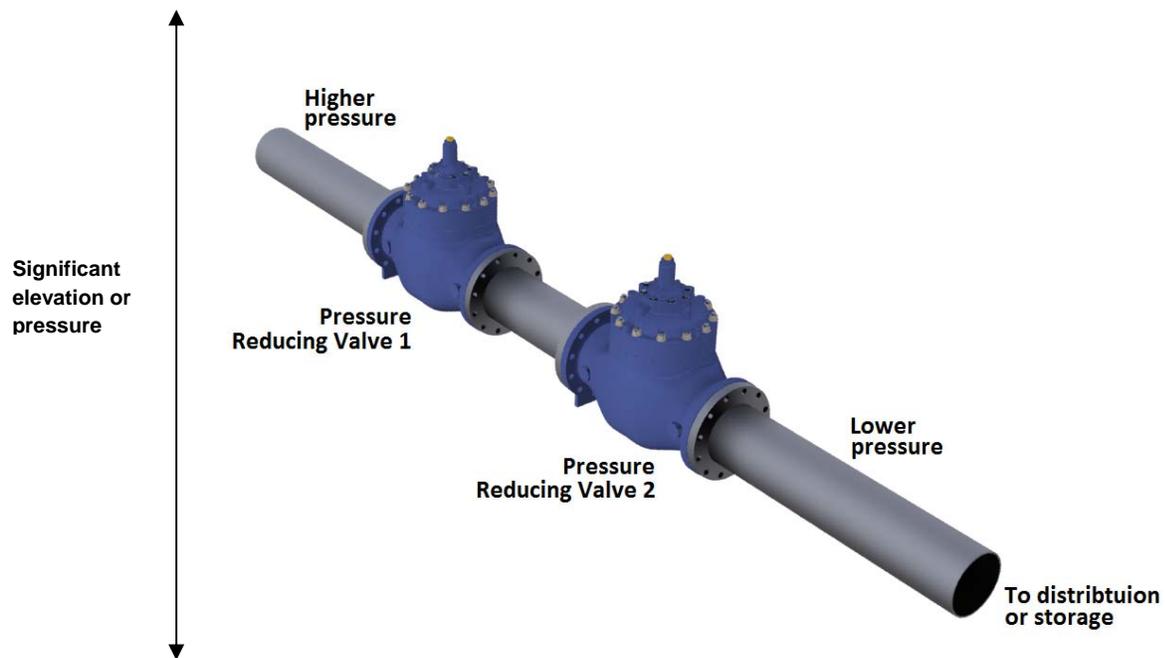


Illustration 2 – Two Pressure Reducing Valves

Additionally, the extra space required to house the second pressure reducing valve station may be an issue. Note, should an operator divide the pressure drop equally between the two valves, its second valve would operate 65 psi / 4.5 bar to 20 psi / 1.3 bar and risk cavitation damage.

The second example of managing cavitation is by utilizing a properly sized orifice plate to the downstream side of a single pressure reducing valve as shown in illustration 3. This means of controlling cavitation is only truly effective if you have unchanging flow rates. This is not a good practice if flow rates are not constant. Great care needs to be given in sizing the orifice plate as the first stage reduction is achieved in the standard pressure reducing valve while the second stage reduction is achieved through the use of the orifice plate. If the pressure differential across the orifice plate exceeds the rule of thumb (3 to 1 ratio) or if the valve and orifice plate is discharging to atmosphere at more than 25 psi / 1.7 bar then cavitation will occur and will migrate downstream creating possible consequences as listed previously. Most water utility distribution systems, irrigation systems and high rise applications have changing flow rates so this orifice plate solution is not suitable for most systems.

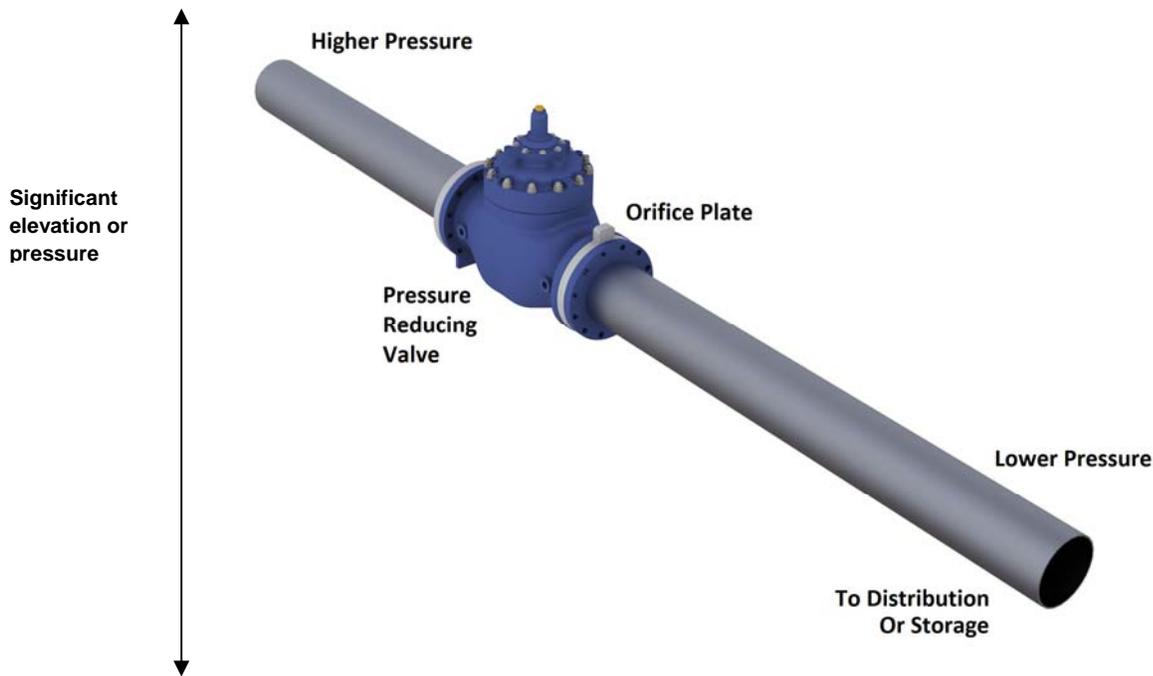


Illustration 3 – Pressure Reducing Valve With Downstream Orifice

Today's Cavitation Solutions

Numerous approaches to cavitation and the control thereof have been applied by a variety of pilot-operated automatic control valve manufacturers with varying degrees of success. Each methodology may be applied successfully, however, it is the authors opinion that a “one size fits all” approach is not always practical as each cavitation event has different characteristics and each application requires a study to evaluate the preferred outcome. Most manufacturers to date have taken advantage of stainless steel cages with preference for grade 316 stainless over 303 / 304 stainless steel due to superior corrosion characteristics. It's recommended that material specifications are checked in detail. Some of the approaches complete with comments are listed below to give the reader a cross section of possible options.

Dual Cages with Pre-Set Elongated Slots

This approach has been used for years in the control valve industry, often as a sound suppressor rather than cavitation fighter and is an off-the-shelf solution and not typically engineered for a specific application. In this approach, each size of control valve has a standard cage offering with pre-set elongated slots, which means a single size must be used for all applications, refer to illustration 4. There are often published limitations for this

approach such as “For atmospheric discharge, the maximum inlet pressure cannot exceed 150 psi / 10.3 bar” amongst others. When selecting this type of anti-cavitation solution full attention must be given to “Notes on Operating Differential” as if this is exceeded the pre-determined size of the discharge slots (large by comparison) may allow vapor bubbles to migrate downstream without collapsing within the cage.



Illustration 4 – Dual Cages With Elongated Slots

Illustration 5 depicts the elongated slots in three simulated flow positions: closed, half open, fully open. When reviewing manufacturer’s literature exercise caution when statements like “Virtually Cavitation Free Operation” is used. If an inadequate solution is implemented often the only recourse is to add a second pressure reducing valve or retrofit an orifice plate downstream of the suspect valve (which is not the best choice as previously discussed if flows vary). Another concern is the size of the actual cage and the resulting C_v difference (see sizing considerations in upcoming section). In order for the cage to be received by a given body of the main valve, the cages of the elongated slotted version tend to be substantially smaller than an equivalent sized version of an engineered orifice style cage. Always check C_v values and maximum flow required when choosing a valve size, never select a valve solely on the existing pipeline size.

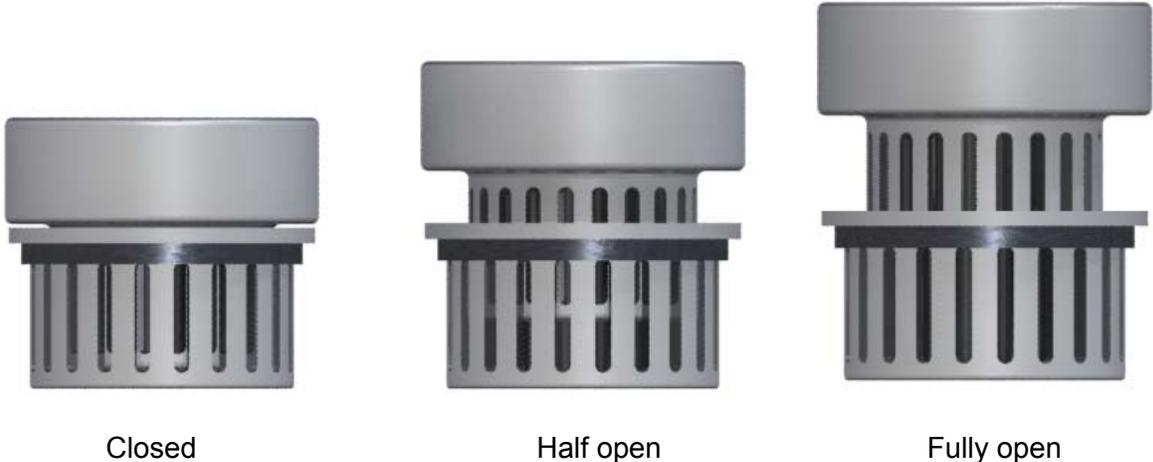


Illustration 5 – Simulated Anti-Cavitation Cage Positions

Dual Cages with Pre-Set Orifices

The second approach to addressing cavitation effects has also been in market for a number of years and utilizes dual stainless steel cages. This approach is very similar to the dual cages with the pre-set elongated slots, with the only difference being that the water flows through orifices and not slots, see illustration 6. With this design the cages are engineered with orifices that follow a pre-set pattern and does not take into account the specific flow and pressure data of a particular application. The outer cage modulates with changing flow and should supply the maximum catalogued flow rates. As this is not an engineered solution specifically for each application, great care should be taken in ensuring that the given application falls well within the manufacturer's catalogued data.

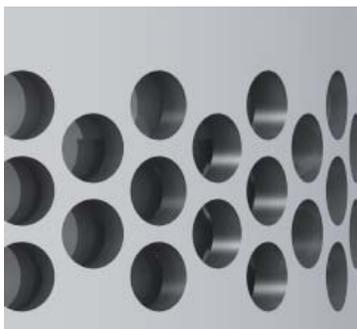


Illustration 6 – Pre-Set Engineered Orifices

Dual Cages with Engineered Orifices

The third approach is an approach which has worked successfully and consistently for over 25 years. It is an engineered solution for each application, so specific flow ranges, inlet pressure ranges and outlet pressure requirements must be supplied. The above mentioned data is then entered into proprietary engineering software which calculates the size and placement of the orifices on both inlet and outlet cages. Illustration 7 depicts the double cages with engineered orifices. The outlet cage modulates with changing flow and will supply the requested maximum flow rates.

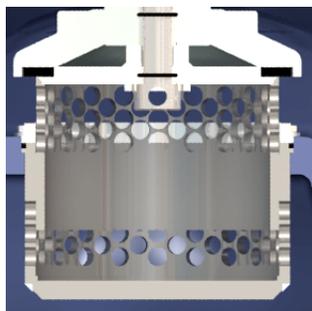


Illustration 7 – Dual Cages With Engineered Orifices

In illustration 8, the cage is depicted in three positions: closed, half open, fully open. Since this is an engineered solution the limitations that other styles of cages demonstrate are not a factor. Extreme pressure drops, even to atmosphere can easily be handled with this technology. There are numerous advantages of the engineered orifice approach such as:

1. Multiple engineered orifices have quicker recovery and cavitation. Collapse occurs close to the orifices, inside the cages with reduced risk of carry over downstream of the cage
2. Adjusting the number and size of orifices allows the control of pressure inside the cages and therefore cage to downstream to prevent secondary cavitation
3. Customizing the orifices ensures sufficient pressure inside the cage to open the valve (e.g. bonnet pressure is greater than or equal to downstream so downstream pressure is of no help in opening)
4. Customizing the orifices can reduce the rate of change of flow when partly open to reduce closing surges
5. Larger diameter cages given flow velocity provides more dwell time to collapse – contain recovery which if carries over downstream is damaging.

The dependability of this technology is only limited to the accuracy of the engineering data supplied for each application.



Illustration 8 – Simulated Flow Anti-Cavitation Cage Positions

In illustration 9 note the large separation between the wall of the valve and the anti-cavitation cage. The bodies of the engineered orifice design are specifically designed to fit a larger cage allowing higher C_v values (increased flow) while the body is also specifically designed to allow reasonable space between the anti-cavitation trim and the body wall. This separation allows for even, uniform entry around the cage area ensuring the vapor bubbles collapse symmetrically towards the center of the anti-cavitation cage.

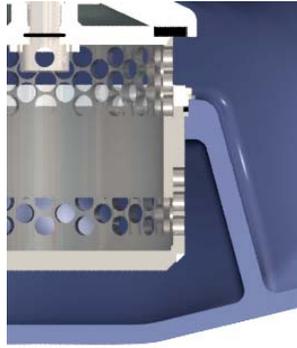


Illustration 9 – Cage & Valve Wall

If there is not sufficient space between the cage and the wall of the valve, flow into the cage area may be restricted offsetting the central collapse of the vapor bubbles (refer to illustration 10) and forcing the vapor bubbles to the extremity of the upper cage potentially encouraging the escape of these vapor bubbles downstream.

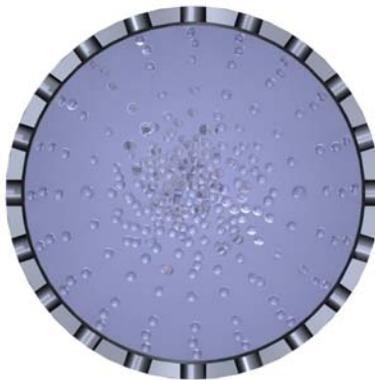
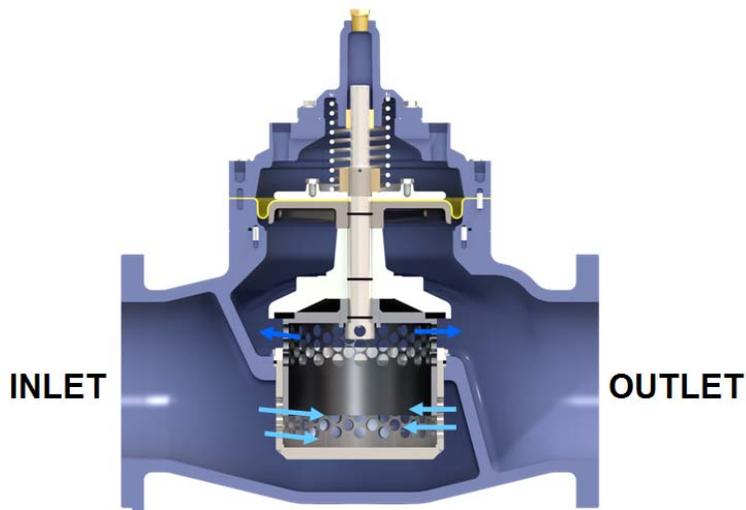


Illustration 10 – Vapor Bubbles Contained In Cage (Topview)

Illustration 11 depicts the flow of water and stages of pressure reducing and illustration 12 shows a picture of a piloted pressure reducing valve with this type of engineered anti-cavitation trim.



First stage:

Flow into the cage. Severe cavitation may be present but the vapour bubbles collapse inside the cage, away from metal.

Second stage:

Flow from cage to downstream. Pressure drop is controlled to assure no cavitation.

Illustration 11 – Stages Of Pressure Reduction

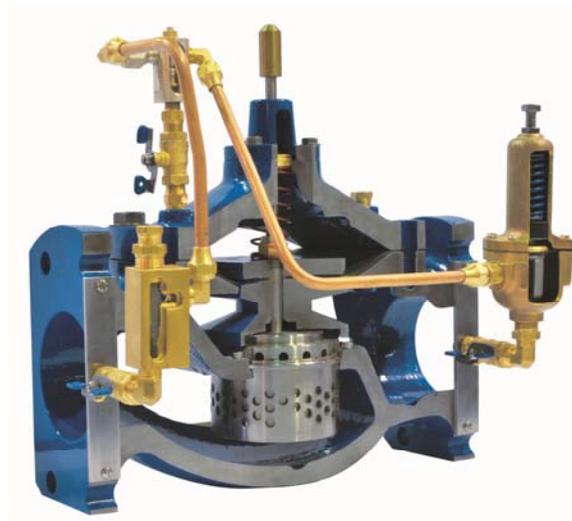
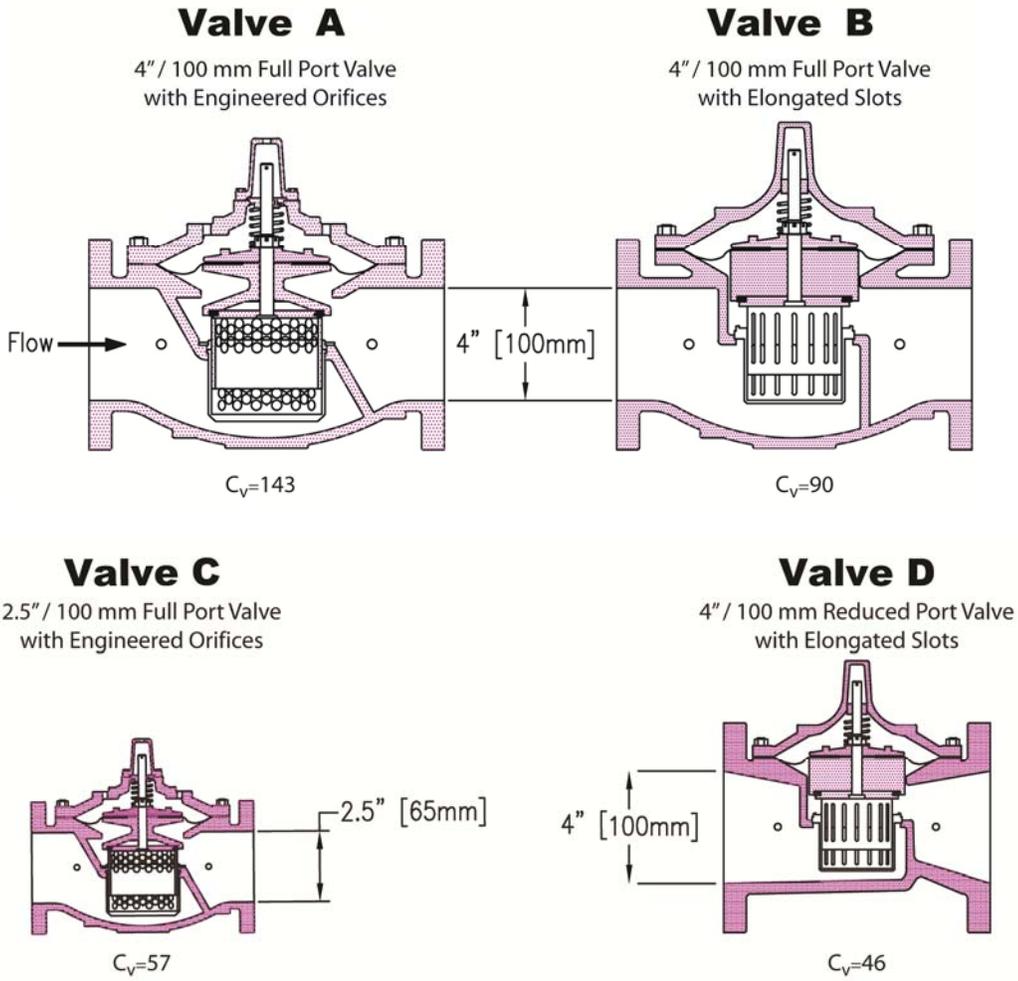


Illustration 12 – Cut-Away Of Valve With Anti-Cavitation Trim And Pilot System

Valve Sizing Considerations

When considering sizing options on pilot-operated automatic control valves with anti-cavitation cages / trim, be very aware that each manufacturer has different sized stainless steel cages, orifices, slots and in fact very different C_v values which dictate maximum flow you can get through a valve. A valve should never be sized according to existing pipeline sizes but should

always have maximum flow as a prime consideration. Illustration 13 below demonstrates a selection process where 4" / 100 mm full port and reduced port valves are being considered. In this example if a C_v were required of 46, the elongated slot version would likely be sized at 4" / 100 mm reduced port or if an engineered orifice version were selected a 2.5" / 65 mm version would easily cover this application. When economics are considered the 2.5" / 65mm choice would make the most sense the valve would be less expensive and easily handle the maximum flow. Note also the large difference on C_v 's comparing similar models of 4" / 100 mm full port valves with engineered orifices versus elongated slots. This is due to very different sized cage designs to adapt and fit into the valve body.



Note: Value outlines are for illustration purposes only. C_v 's are expressed in imperial units.

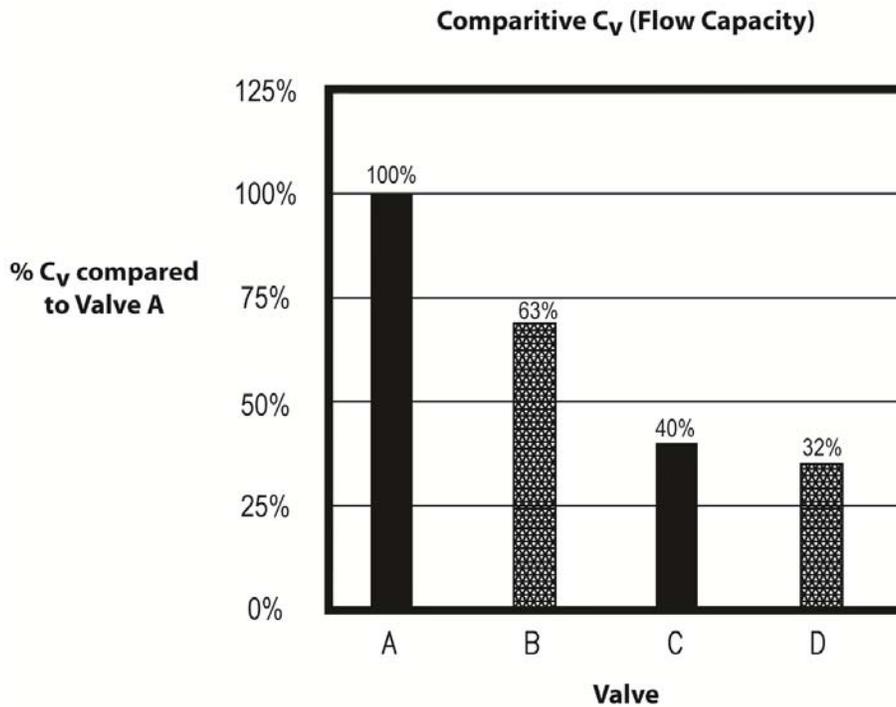


Illustration 13 – Valve Sizing Selection Process

Sub-Atmospheric Considerations

Regardless of the cavitation solution you select, caution should always be utilized when dealing with sub-atmospheric applications. In the application illustration 14 shown below, note that it is always preferred to avoid submerging a discharge line if possible. If the discharge line is to be submerged it is recommended that the length of the vertical discharge line not exceed 6 ft / 1.8 m as this would render the anti-cavitation option useless, and cavitation would occur. If the vertical discharge line exceeds 6 ft / 1.8 m some consideration may be given to supplying an optional small diameter riser pipe vented to atmosphere off the horizontal pipe as shown on the drawing. It is suggested that if this application is considered, an engineering firm with experience in cavitation effects be consulted.

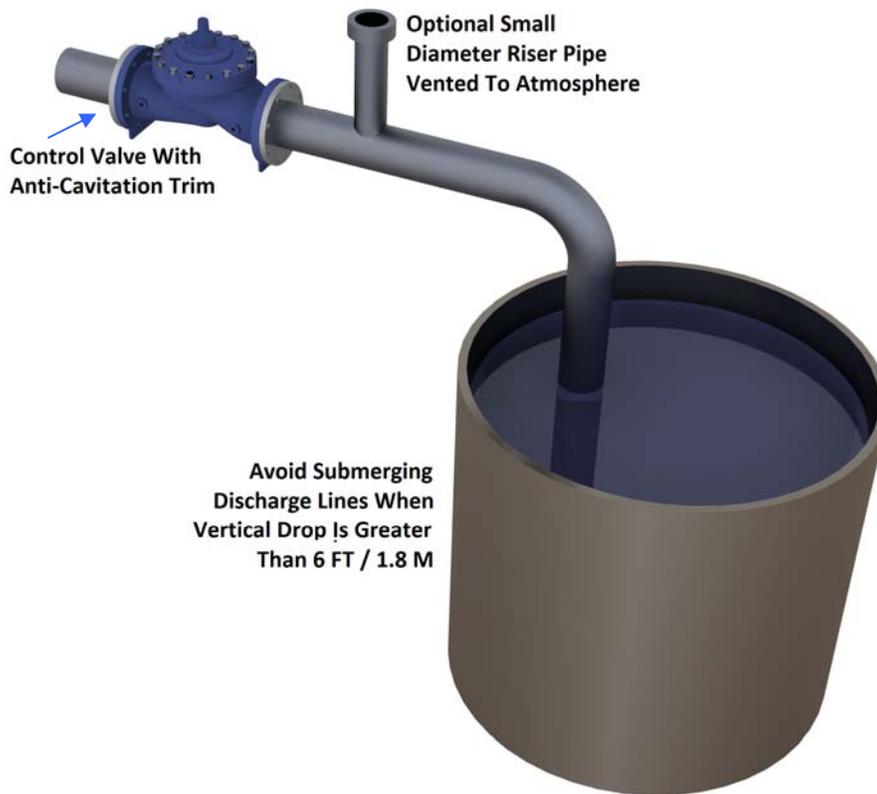


Illustration 14 – Sub-Atmospheric Considerations

Noise Considerations

In-house field studies at a pilot-operated automatic control valve manufacturer have shown reductions of up to 10 dB (100 dB to 90 dB) may be experienced when comparing standard pressure reducing valves to pressure reducing valves utilizing anti-cavitation trim when operating within the cavitation zone. Noise evaluations are very difficult to conduct as the test locations selected can be quite different whether employed at an outdoor site or in an enclosed concrete vault. Be cautious of noise data supplied on control valves. With this said there is no question that there is a substantial noise reduction effect when employing anti-cavitation cages / trim. This can be a very large benefit if supplying distribution valves in an above ground residential location or supplying valves in a high rise building with residential suites or a hotel where noise can be an irritant when valves are in the cavitation zone. Anti-cavitation cages / trim have been employed on applications where the valves may not be in the cavitation zone but due to high velocity and large flows have increased noise impacts. The selection of anti-cavitation trim while not eliminating the problem, did help reduce the effect.

Typical Applications

Here are some typical applications to explain where anti-cavitation trim will eliminate or substantially reduce the normal impacts of cavitation.

Distribution Systems

Often in water utility distribution systems, there can be significant pressure differential or drop which may necessitate the use of anti-cavitation cages / trim. The most common use for this type of technology can be where there is a requirement to reduce pressure significantly from high pressure transmission lines to a lower pressure distribution system. Another common application is where there are significant elevation changes within a transmission system or distribution system where lower elevations can be prone to significant pressures. Remember the 3 to1 ratio rule applies but always verify the use of anti-cavitation with an engineering consultant versed in this field. The use of this technology requires that only one valve has anti-cavitation trim and therefore is ideal for space constraints (Illustration 15). Sizing consideration is very important and again maximum flows (fire flows if relevant) should be considered when selecting the appropriate sized valve. Also keep in mind that different manufacturers have different sized anti-cavitation trim with different C_v values so make sure the valve is sized correctly and if more than one manufacturer is being considered it is not unusual for different sizes being selected based on manufacturers C_v values.

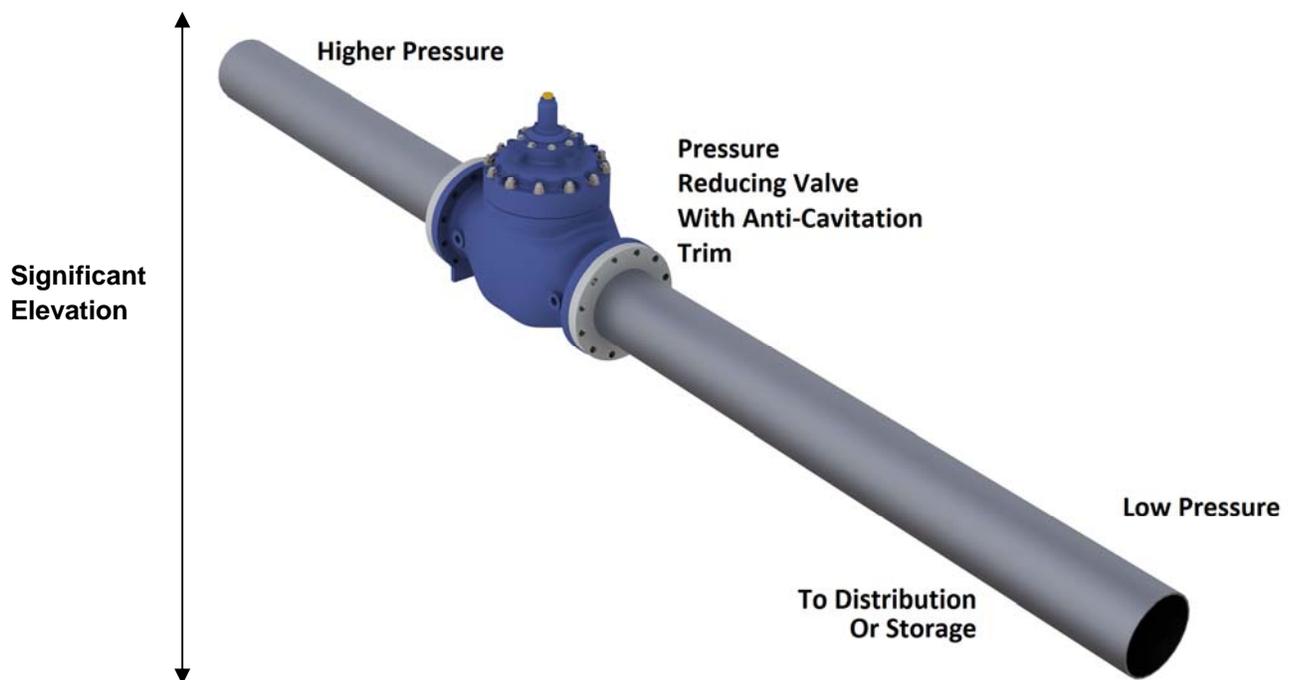


Illustration 15 – Single Pressure Reducing Valve with Anti-Cavitation Trim

High Rise Buildings

Often in high rise buildings standard pilot-operated automatic control valves (standard pressure reducing valves) are utilized to control pressures. While there are numerous approaches to pressure management in high rise buildings, often water is pumped to the top of a building, stored in an elevated tank and then gravity fed to the floors below. It is typical for one pressure reducing valve to supply 4 – 5 floors which requires that several valves be installed to service the entire high rise. (Example: A 40 story high rise building would require approximately 7 pressure reducing valves, one every 5 floors, see illustration 16). But often the highest floors rely purely on gravity and may require a small booster pump to supply sufficient pressure to the top 2 or 3 floors. The higher the building is the greater the pressure on the lower floors. Taking into consideration the 3 to 1 ratio rule, it makes sense that in the lower portions of the building anti-cavitation trim could be very beneficial not only to protect the valves and downstream piping from the destructive forces of the vapor bubbles collapsing but also reducing the severe noise associated with cavitation. The noise issue becomes even more important if the high rise has a residential or hotel focus.

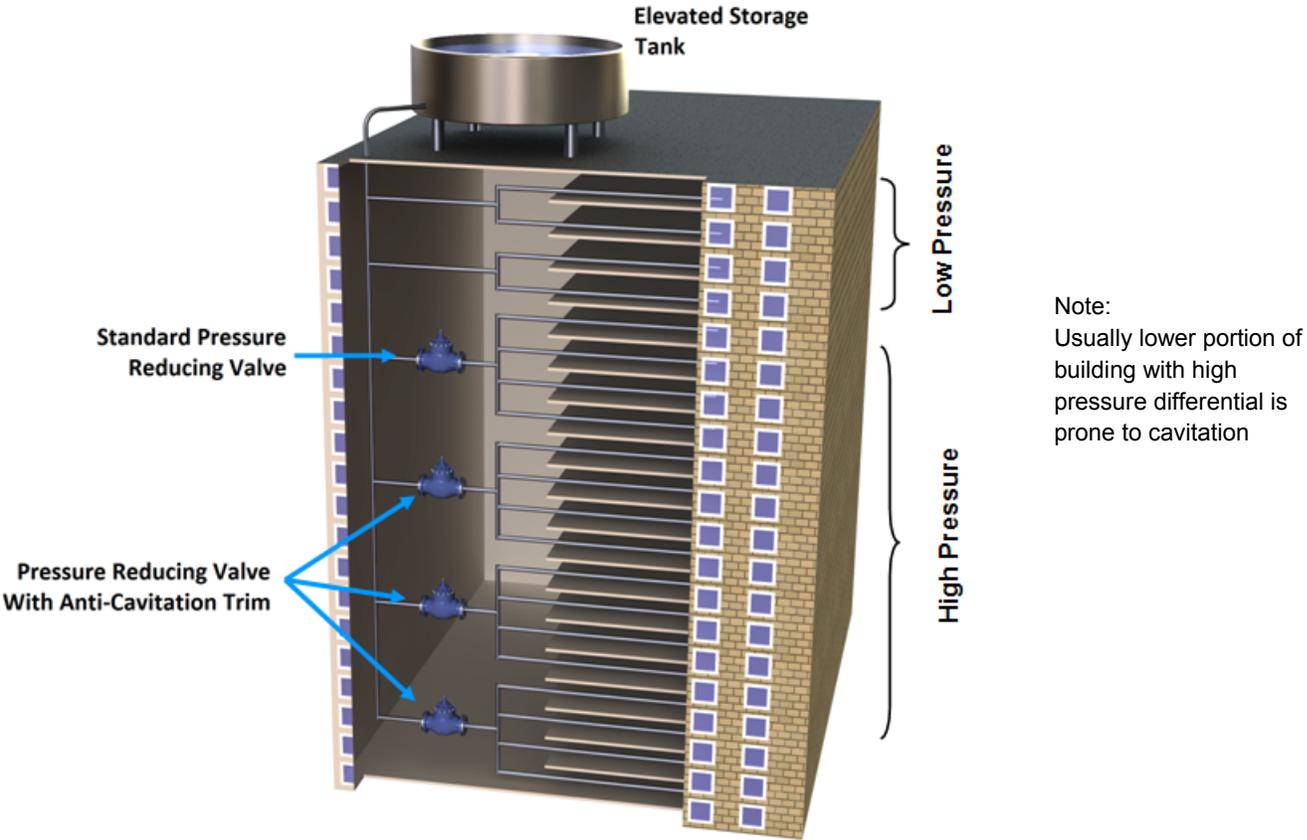


Illustration 16 – High Rise Building

Reservoir Filling

At times elevated storage tanks may be supplied with high pressure with the downstream pressure being dictated by the static level of the tank, as seen in illustration 17. Pilot-operated automatic control valves utilizing altitude pilots or solenoid valves reacting to level switches can often be used in these applications. If the high pressure on the upstream side of the control valve exceeds a 3 to 1 ratio when comparing the static head of the tank, then this would be another application where anti-cavitation trim can reduce noise and eliminate damage downstream.

Characterizing Opening

Employment of double cage design with engineered orifices provides an opportunity to characterize the C_v versus lift curve to limit maximum flow and / or to effect “soft” closing to reduce or eliminate closing surges in applications such as Solenoid Valves, Altitude Valves, and some Float Valves.

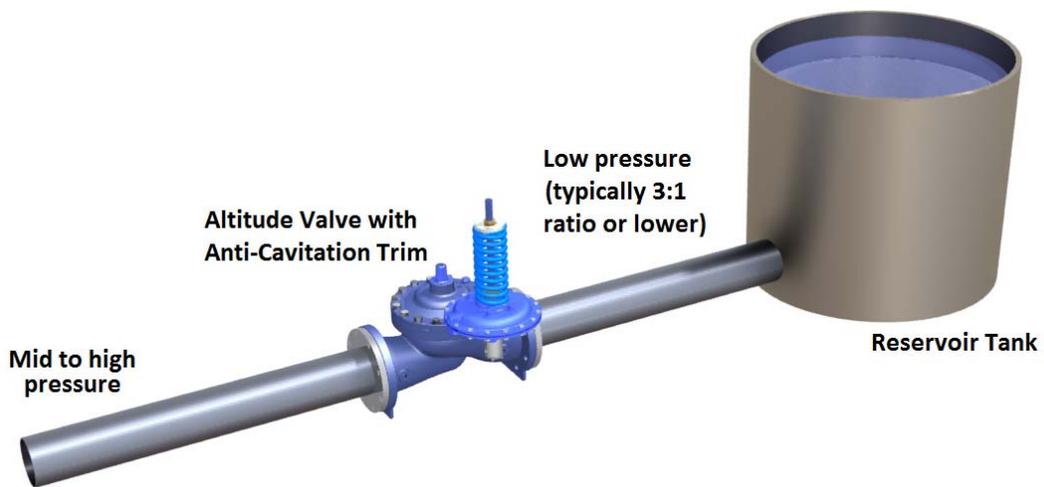


Illustration 17 – Reservoir Filling

Reservoir Fill to Atmosphere

If pilot-operated automatic control valves are used to fill a reservoir and the water is being discharged to atmosphere there is a strong possibility that cavitation may occur depending on the upstream pressure. Often a float or solenoid style pilot system may be used in these applications, as seen in illustration 18. Another rule of thumb based on the authors experience is, if the upstream pressure is at or below 25 psi / 1.6 bar it should negate the requirements for anti-cavitation trim and damage to the valve would be unlikely. For pressures exceeding the above stated figures it is strongly recommended that some form of protection against cavitation is considered. With an engineered solution utilizing engineered orifices much higher pressures may be considered than other options such as the elongated slots which may be limited to 150 psi / 10 bar to atmosphere.

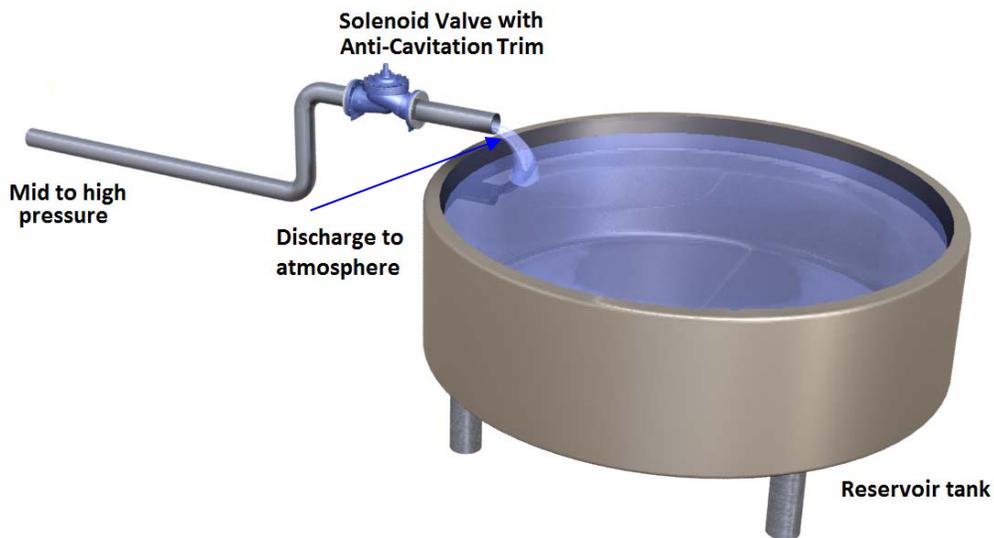


Illustration 18 – Reservoir Fill to Atmosphere

Continuous Pressure Relief

A very effective way of controlling outlet pressure of a pump is to relieve the excess flow back into the clear well, as seen in illustration 19. Obviously, this ends up being deep in the cavitation zone. A valve with properly engineered anti-cavitation cages / trim can do an excellent job in this application with pressure in excess of 300 psi / 20 bar relieving to atmosphere.

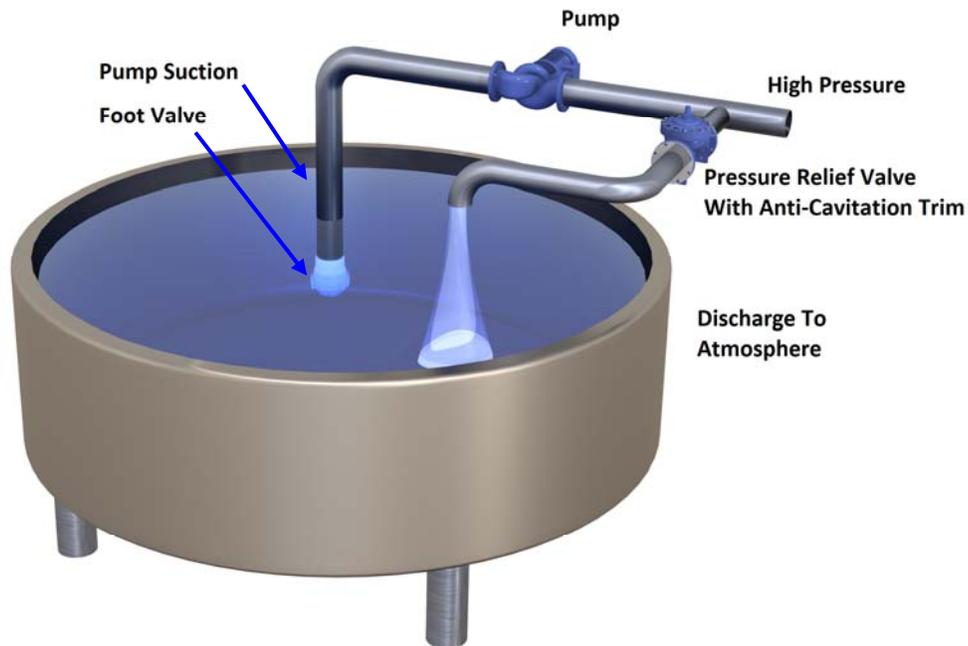


Illustration 19 – Continuous Pressure Relief

Traditional pressure relief valve applications are usually designed for infrequent momentary operation when over pressures occur (surge, power loss, etc). While these types of valves do cavitate each and every time they operate, due to very infrequent overpressures, it would take many, many years for these valves to actually incur any damage. If you are using pressure relief valves, surge anticipating valves or rate of rise relief valves it is very uncommon to specify anti-cavitation trim due to limited or infrequent opening of these types of valves. You need only be concerned if relief valves are designed for frequent or continuous use.

Conclusions

Cavitation and its associated effects can be extremely damaging and noisy in respect to pilot-operated automatic control valves. While its effects can be basically understood, addressing cavitation is an extremely complicated process and advice / consultation from a qualified engineer should always be solicited. The consequences of cavitation can be strong vibrations, loud noise, choked flow, erosion of valve components, destruction of the actual valve, erosion and destruction of downstream piping and finally plant or distribution system shutdown. There are numerous methods of controlling cavitation, some have stood the test of time and others are still relatively new. It's recommended that you research the solutions carefully and if selecting cavitation cages / trim approaches, give careful consideration to limitations of dual cages with pre-set elongated slots or pre-set orifices style designs and also very careful consideration on sizing based on maximum flow. Engineered solutions which address specific applications can often be the most successful approach. Cavitation is prevalent in water utility distribution systems, high rise buildings, tank filling reservoirs, reservoir fill to atmosphere and continuous relief to mention a few of the more common applications. Always consult an expert when soliciting advice and recommendations on cavitation and selection of anti-cavitation devices.

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Pumps, Valves, Cavitation, Transients

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Control Valve cavitation, Damage Control

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