Control Valve Cavitation, Damage Control

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Introduction

In typical industrial process plants there are hundreds of process control loops. Most of these loops include a control valve as the final control element. Therefore, reliable system performance is directly associated with the control valve reliability. Because of the throttling process a control valve can be subjected to more severe conditions than other system components. In severe applications, control valves play a crucial role in safely controlling high process fluid energy levels to avoid valve and piping damage from acoustic noise, vibration, cavitation, and erosion. Designing valves to resist the deleterious effects of the throttling process fluid is only as effective as the valve sizing and selection process itself. A control valve designed with hardened trim material could last almost indefinitely on low pressure drop service conditions. This same valve used on a high pressure liquid letdown application could fail in a matter of hours. This paper outlines the application methods used by leading control valve manufacturers to avoid the damaging effect of cavitation on control valve performance and reliability.

Overview of Cavitation

Associated with liquid pressure drop across a control valve is the pressure recovery downstream of the throttling area. If the high velocity in the throttling area results in a localized pressure less than the overall fluid vapor pressure, vapor bubbles form. If the pressure recovery after the throttling area is higher than the vapor pressure the vapor bubbles collapse back into a liquid. It is the violent collapse of these vapor bubbles near valve component surfaces which cause cavitation damage and subsequent performance degradation. In control valves, this process typically occurs near or at the exit of the valve trim (Figure 1, page 6).

The shock waves and pressure fluctuations resulting from these high velocity collapses can also cause vibrations, noise, accelerated corrosion, as well as limited valve capacity [1]. Although the cavitation is generated 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. This can result in not only component damage but also pipe wall vibration (noise) and system vibrations. This can affect the reliability of the control valve accessories and other system components. However, it is the erosion of the valve controlling surfaces and valve and/or piping pressure vessel walls that is most dangerous. If cavitation levels are reduced below damaging levels the associated vibration and noise levels will also be reduced to an acceptable level.

Cavitation Erosion Damage

The two main mechanisms posited for cavitation erosion damage are: high pressure shock waves created by the collapsing vapor [2], which can result in material fatigue and plastic deformation and micro-jet impingement resulting from asymmetrical collapse of the vapor bubbles (Figure 2, page 6) near the material surfaces. The typical appearance of a surface exposed to damaging cavitation is a crater-like, pitted appearance (Figure 3, page 7).

Valve Selection Methods

Cavitation itself is relatively easy to predict in simple geometries because it generally follows fluid dynamic principles. Cavitation and its resultant damage are more difficult to consistently predict, particularly in complex valve geometries. Along with service pressures and temperatures, there are other fluid and material properties which can affect the intensity and damage potential of cavitation. Fluid surface tension can enhance the damage potential due to higher implosion stresses. As water is one of the fluids with high surface tension, particularly cold water, testing for cavitation damage is less problematic. The valve component surface material also plays a key roll in determining the rate of cavitation damage. Generally once cavitation begins near a surface; it will eventually damage the surface. Although tougher metals (i.e. Stellite) can dramatically slow the damage rate, they too will eventually yield [3]

Until recent years, most Control Valve Manufacturers used a cavitation index based of the standard control valve pressure recovery test curve (Figure 4, page 7). This curve represents capacity limitations as a result of bubble formation in the throttling vena contracta area. Choked flow (F_L) is achieved when further decrease in pressure drop no longer results in an increase in capacity [4]. The cavitation index (Kc) was defined as the point of initial departure from a proportional relationship between pressure drop and capacity [5]. Some manufacturers describe this point as incipient cavitation. However, again this represents the beginning of vapor bubble formation in the min. vena contracta area only. Most manufacturers established an allowable application cavitation index between F_L and Kc, which has to vary with valve type. For some valve trim designs F_L was used as the cavitation index. The point of allowable cavitation index was usually based on testing and significant field experience. Accordingly, the user was required to use a myriad of indexes depending on the individual manufacturer’s rules and type valves and materials being selected. None of these indexes vary (for a particular geometry) based on pressure and size of the collapsing bubbles, both of which can dramatically effect the type and extend of the cavitation damage.

The problem with using an index on the pressure recovery curve is that it represents a cavitation level which affects capacity only, and not the point were damage, noise and vibrations begin to occur. For instance a valve with more than one flow path (i.e. a double seated or butterfly valve) can exhibit cavitation in one flow path only, without significantly affecting overall valve capacity. Such a valve used at a point lower than its FL limit can exhibit significant cavitation damage, depending on the severity of the service conditions. Therefore a very conservative index would be required for these types of valves (Figure 5, page 8). Also some control valve throttling geometries can develop flow vortices outside of the vena-contracta (Figure 6, page 8). These vortices created by flow shedding action can result in high velocity locations for cavitation bubble formations. If capacity is not affected, this type of cavitation may not be apparent in the pressure recovery curve but still damaging. In these cases the application of a single pressure recovery index would have to vary significantly depending on flow geometries, materials of construction, application pressures, flow velocities and manufacturer’s field experience.

Because of the wide range of variables (service and valve types) influencing cavitation damage potential, there is no simple universal index and calculation method that can be used for all manufactures and valve types. To help improve this situation the Instrumentation, Systems and Automation Society (ISA) set out to develop a more reliable method for accessing control valve cavitation damage potential. In 1995 ISA released a Recommended Practice [6] which included a method to predict control valve cavitation damage potential for any type of control valve.

Sigma Method

The method uses a parameter (Sigma, σ) which reflects a valve's propensity for cavitation inception and damage, based on measuring collapsing bubbles energy. These energy levels are determined by measurement of down stream pipe wall vibration acceleration levels due to the pressure fluctuations caused by the collapsing bubbles.

$$\sigma = \frac{(P_1 - P_v)}{(P_1 - P_2)}$$

P1 and P2 represent the pressures upstream and downstream of the valve, and Pv the vapor pressure of the process fluid at process temperature. The smaller the σ value the greater the cavitation potential for an application. The form of this factor was chosen to distinguish it from all the existing cavitation indexes used in both industry and academia. The sigma value is calculated for the service conditions and compared to a valve's allowable sigma which has been scaled to those same service conditions. This allowable sigma level is determined by testing in accordance with the test section 8 of the Recommended Practice [6]. The Recommended Practice requires the testing of an orifice plate of specific geometry in order to qualify a laboratory's ability to run sigma testing. The testing laboratory must be able to attain the results specified for this calibration test.

The procedure requires the development of tested sigma curves (Figure 7, page 9) for each product and travel position. The sigma curves are developed by recording down stream pipe wall vibration levels while flowing from fully choked flow to non-cavitating pressure drop conditions. Figure 7 is a sigma test curve for an eccentric plug control valve, tested at 200 psig, at 15% travel opening, in the flow to open direction. This curve has three distinct cavitation regimes. The incipient cavitation index σ_i ,represents the conditions at which cavitation can first be detected via an accelerometer with high-frequency sensitivity (5-50 KHz). Incipient cavitation found by this method represents infrequent bubble formation and collapse events, likely caused by turbulent and unsteady pressure fluctuations. This level of cavitation is extremely mild and not damaging to the valve or system. As cavitation frequency and intensity increases, low-frequency cavitation events become more common as flow enters the constant cavitation regime, σ_c. Again for most control valves, the point of σ_c generally has no undesirable damage associated with it. However, as process conditions continue to increase, the cavitation and vibration intensity increases until the maximum vibration index, σ_{mv} is reached. Most control valves will begin to exhibit cavitation damage at a point between σ_c and σ_{mv} (Figure 8, page 9).

Multiple valve sizes and up stream pressures are tested in order to develop size and pressure scaling factors (SEE & PSE) for a particular geometry. Along with the allowable sigma rating, the valve manufacture provides the reference size valve and reference P1-Pv used in the testing program. These scaling factors are defined as:

$$SSE = \left[\frac{d}{d_R}\right]^b \qquad PSE = \left[\frac{(P_1 - P_v)}{(P_1 - P_v)_R}\right]^a$$

- d is the application valve size
- d_R is the reference valve size
- $(P_1 - P_v)$ is for the application conditions
- $(P_1 - P_v)_R$ is for the reference conditions

It should be pointed out that if a valve line has same relative Cv/d2 for all sizes, b can also be calculated as follows:

$$b = 0.068\left(\frac{Cv}{d^2}\right)^{0.25}$$

With the scaling factors developed during testing and the reference size and pressures as well as σ_{mr} (manufacturer's recommended) rating known, a valve's sigma limit can be scaled for those conditions.

$$\sigma_v = (\sigma_{mr} * SSE - 1) * PSE + 1$$

To determine the allowable sigma rating σ_{mr} , for each valve travel position an aluminum model of the valve throttling geometry is also tested though a range of cavitating conditions. After each run the aluminum model is inspected for damage. The onset of visible damage on the model is considered incipient damage, σ_{id}. This is usually applied as the valve allowable σ_{mr} for that travel, referenced valve size and pressure drop (P1-Pv). For a particular application the service σ is calculated. Then the valve sigma rating at required travel position is scaled to the service pressures and valve size. The resultant valve sigma rating is compared to the service sigma. If larger than the service sigma, the valve will operate beyond the incipient damage point. If less than the service sigma the application is acceptable. This means that the level of cavitation will be lower than the energy required to cause incipient damage in the aluminum material for this geometry. The information required from a control valve supplier are the min. recommended sigma at each travel position, the reference size (d_R), capacity (Cv_R), pressure ($(P_1-P_v)_R$), and the 'a' and 'b' exponents for a product line. The application process is outlined in Figure 9 (page 10).

If aluminum model damage testing is not possible, past successful cavitation application envelopes can be used to determine the σ_{mr} for a product geometry. This allowable application envelop should contain pressure and size limitations if applicable. This method would be useful for very low pressure recovery valves such as multi-stage anti-cavitation designs because of the difficulty of achieving the caviation conditions for damage testing.

Summation

This author advocates the use of the sigma method for all products including multi-staged designs. The application of anti-cavitation control valve designs is as important as the individual designs themselves. The sigma method of applying a cavitation index to a control valve is an improvement over past more simplified indexes. The sigma method actually uses the cavitation testing performance of a product to develop a cavitation index and applies an incipient damage limitation. In contrast, past indices were based on product choked flow performance not actual cavitation damage potential. The sigma method has been successfully incorporated into some control valve manufacturer valve sizing and selection software programs. Although it is agreed that more work in this area is needed, for the present, the best technology for determining control valve cavitation damage potential is the sigma method. Using the sigma method will help reduce the cavitation related problems and provide reliable, cost effective control valve solutions.

References

[1] NRC Publication NUREG/CR-6031, "Cavitation Guide for Control Valves", U.S. Nuclear Regulatory Commission, Washington, D.C. 1993

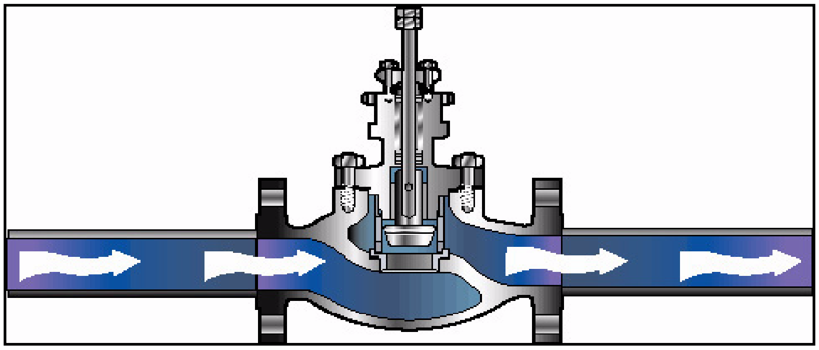
[2] Knapp, R.T., Daily, J.W., and Hammitt, F.G., "Cavitation", McGraw-Hill, New York, 1970

[3] Stares, J.A., Roth, K.W., "Avoiding Control Valve Application Problems with Physics-Based Models", Hydrocarbon Processing, August 2001

[4] ANSI/ISA – SP75.02, 1996, "Control Valve Capacity Test Procedure", October 1996

[5] Hutchison, J.W., "ISA Handbook of Control Valves", ISA, 1976

[6] ISA- RP75.23 – 1995, "Considerations for Evaluating Control Valve Cavitation", Recommended Practice, June 1995



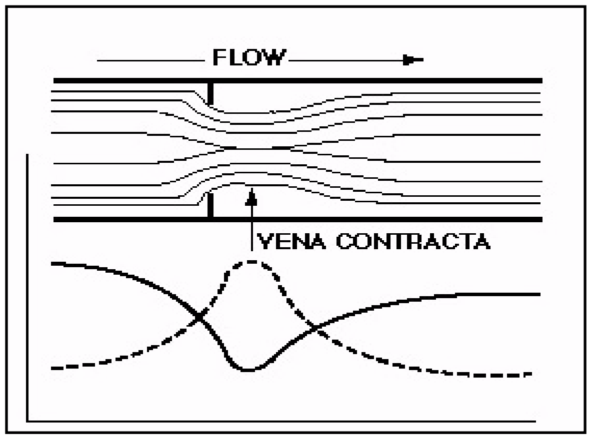


Figure 1

Collapsing Bubble Micro-jet Impingement

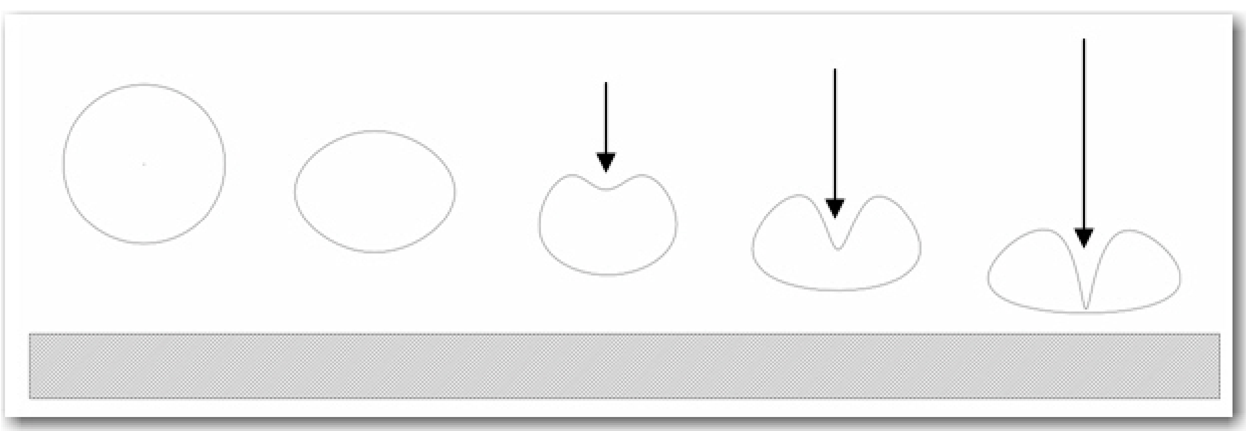


Figure 2

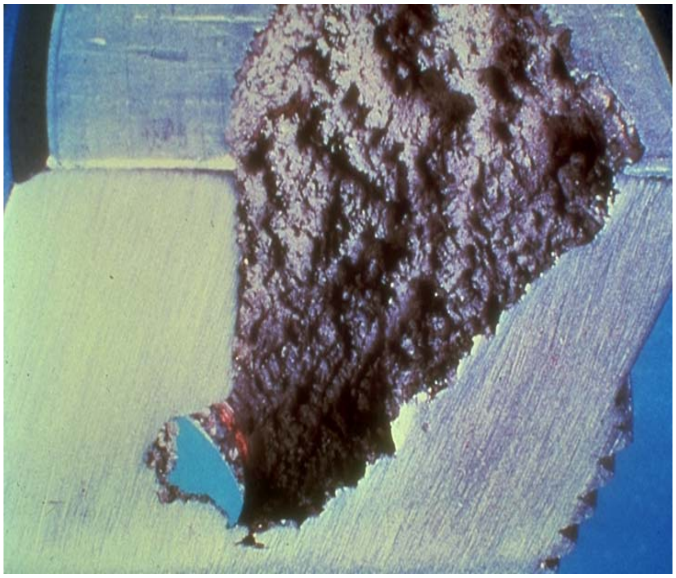


Figure 3

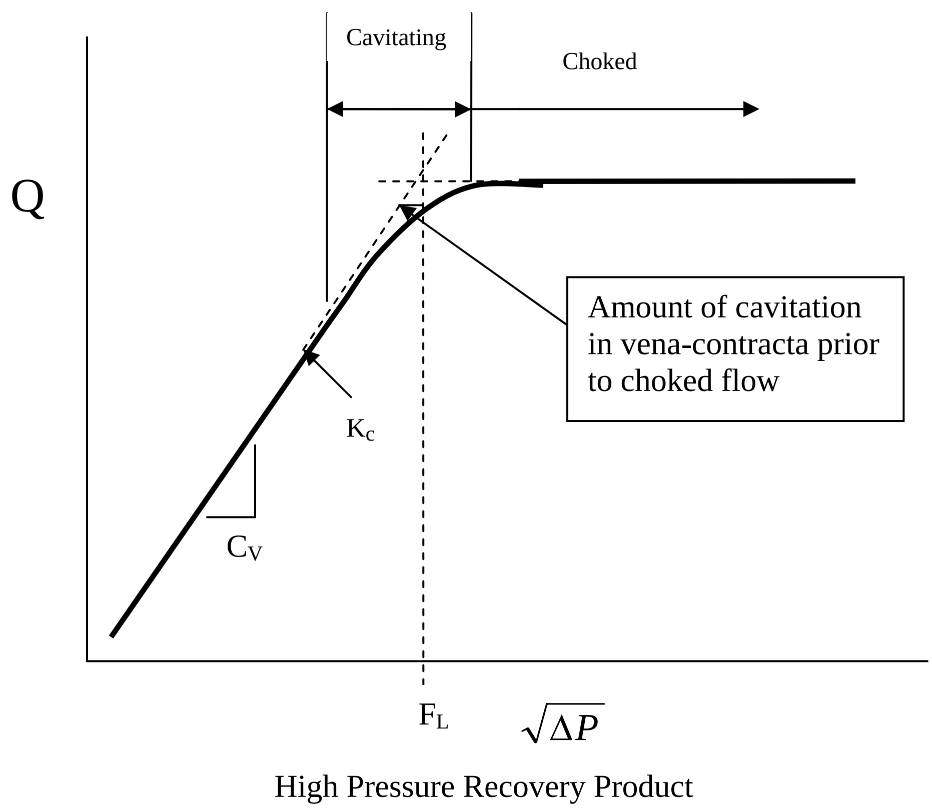


Figure 4

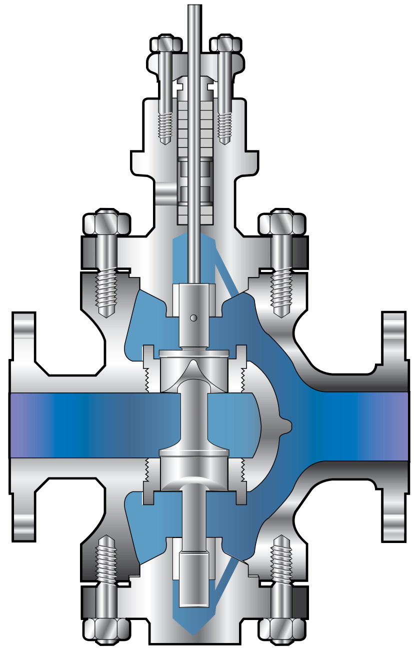


Figure 5

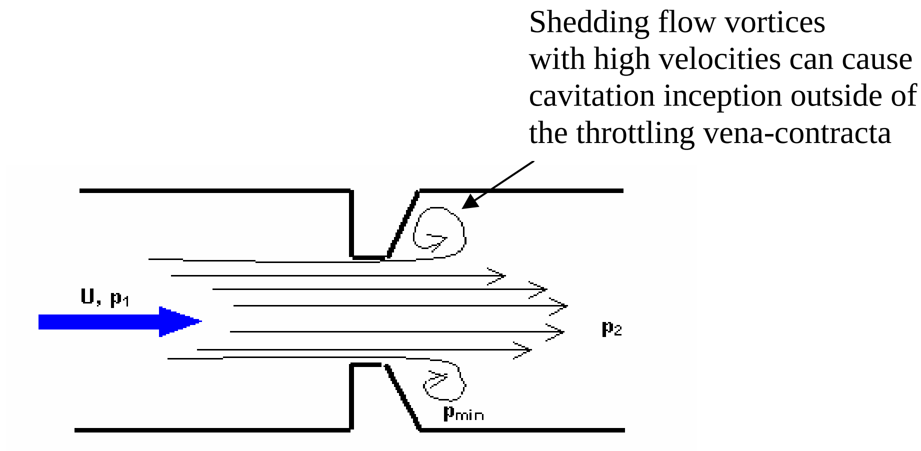


Figure 6

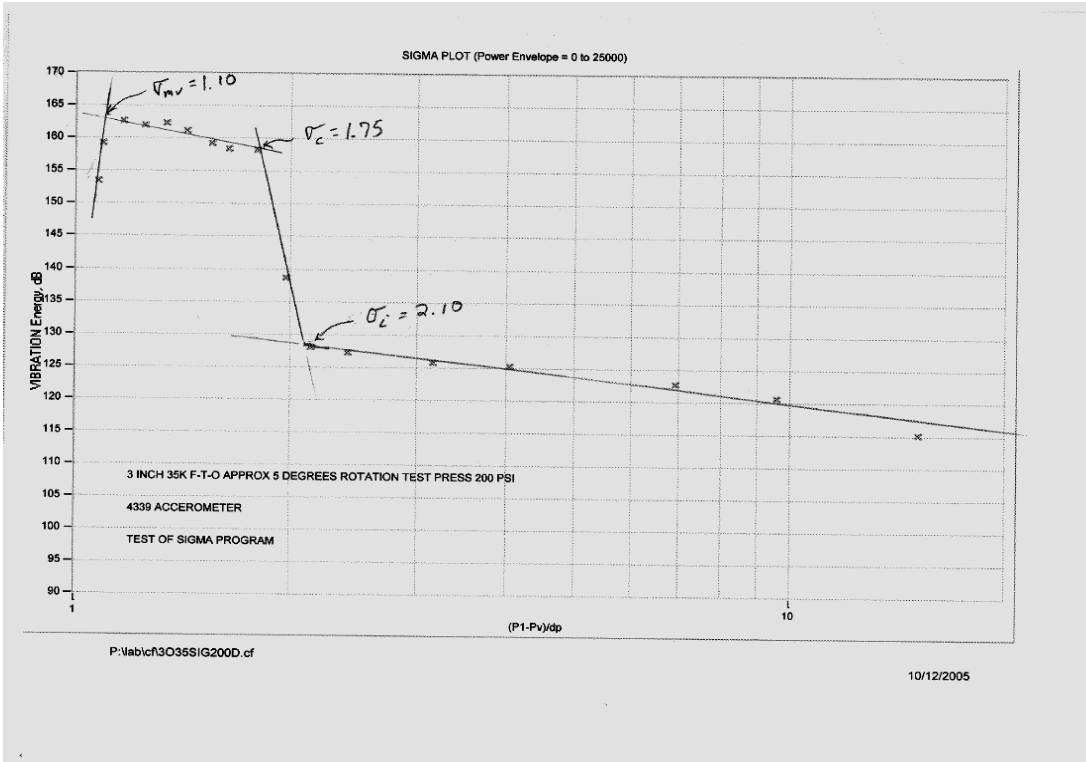


Figure 7

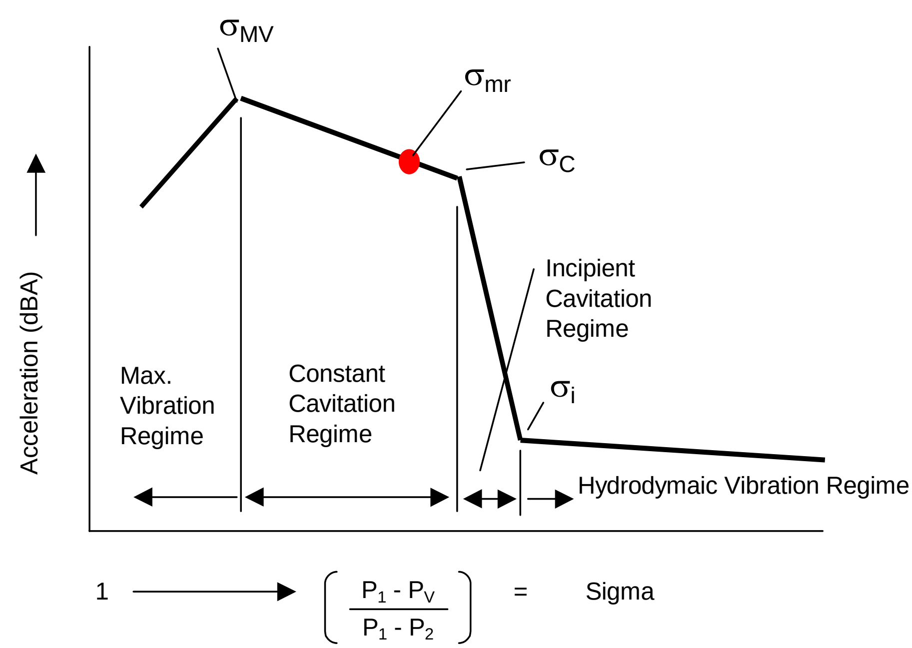


Figure 8

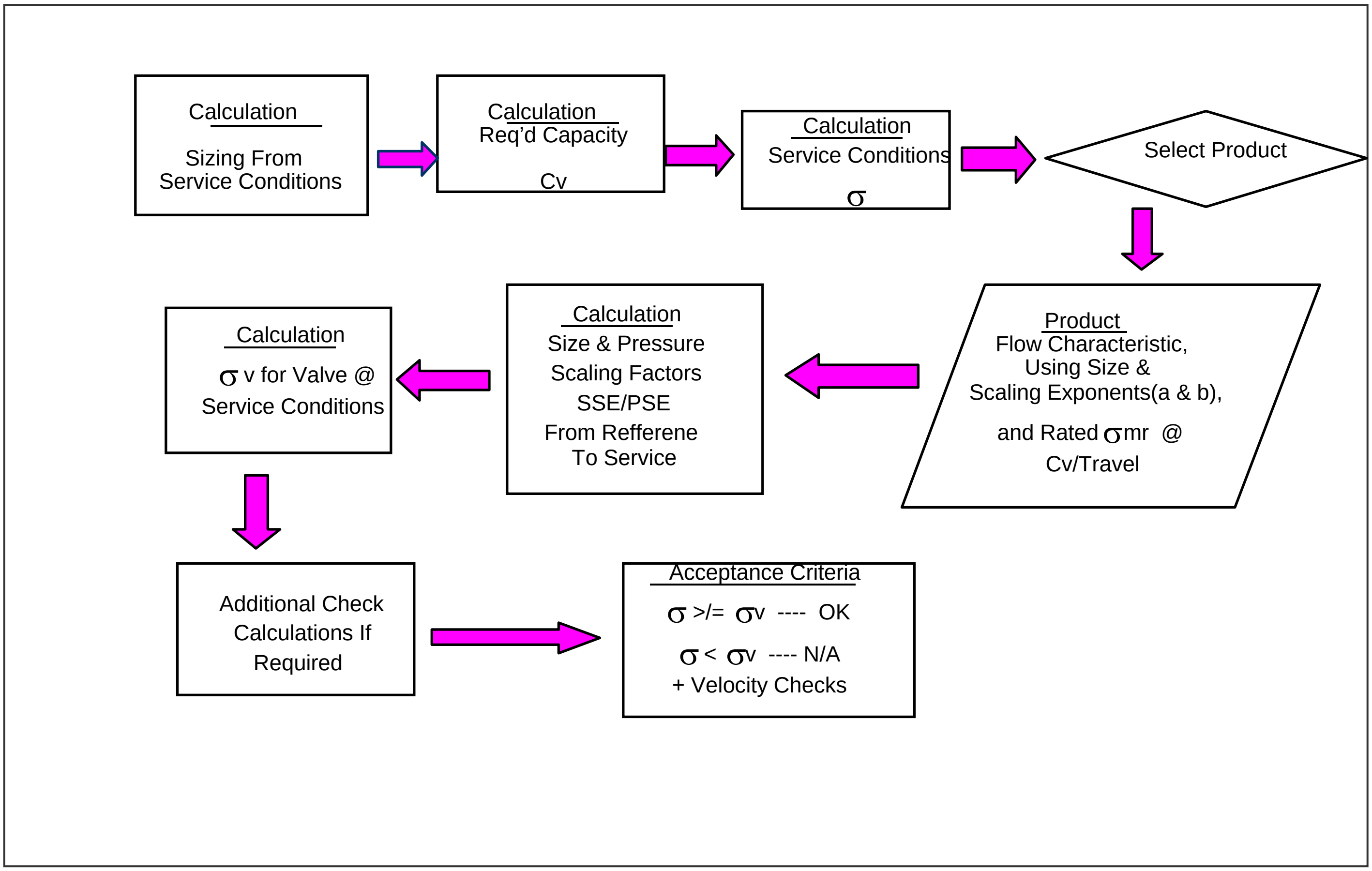

Calculation
Sizing From
Service Conditions
Calculation
Req'd Capacity
Cv
Calculation
Service Conditions
σ
Select Product
Product
Flow Characteristic,
Using Size &
Scaling Exponents(a & b),
and Rated σmr @
Cv/Travel
Calculation
Size & Pressure
Scaling Factors
SSE/PSE
From Refferene
To Service
Calculation
σ v for Valve @
Service Conditions
Additional Check
Calculations If
Required
Acceptance Criteria
σ >/= σv ---- OK
σ < σv ---- N/A
+ Velocity Checks

Figure 9