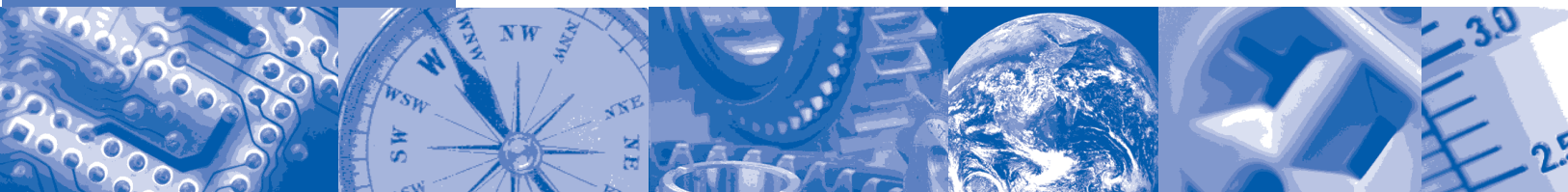


ISA-RP75.23-1995



Considerations for Evaluating Control Valve Cavitation



**ISA—The Instrumentation,
Systems, and
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Approved 2 June 1995



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ISA-RP75.23-1995, Considerations for Evaluating Control Valve Cavitation

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1 Scope

This recommended practice is intended for control valves used in the control of process fluids and is not intended to apply to fluid power components. The reader and user should be familiar with fluid mechanics fundamentals and ISA standards ANSI/ISA S75.01 and ANSI/ISA S75.02 on valve sizing and testing. Definitions of terms in this document are intended for general understanding; more rigorous definitions are found in the references.

Noise measurement and prediction methods are beyond the current scope of this document. Methods of liquid flow noise measurement and prediction may be found in standards of the International Electrotechnical Commission, CEI/IEC documents 534-8-2 and 534-8-4. The relationship between cavitation parameters used in this recommended practice and those of the IEC documents is discussed in [Annex B](#).

2 Purpose

Cavitation as an applied science has not evolved to the highly refined level of that supporting the more traditional control valve sizing calculations. However, there is a great need by users and manufacturers alike for practical information in this area. The purpose of this document is to supply that information, and to that end it is necessarily broad in scope. It embodies several objectives:

- a) to provide educational material in a background section that condenses the literature and educates the reader in state-of-the-art valve cavitation knowledge and practice;
- b) to establish a basis for communication by defining cavitation parameters and nomenclature;
- c) to propose methods for evaluating the cavitation characteristics of individual control valves through testing procedures and application experience; and
- d) to offer guidelines for selecting control valves for given applications.

ISA Subcommittee SP75.16 recognizes that the science of cavitation is in its infancy in terms of defining the behavior of cavitation in complex valve geometry. The final objective of this recommended practice is to promote additional research and testing. Subsequently, this practice can serve as a starting point for those seeking to advance the state of the art.

3 Definition of terms

Terms used are per ISA-S75.05 and additional terms as follows:

3.1 cavitation: A two-stage process associated with the flow of liquids. The first stage involves the formation of vapor cavities or bubbles in the flow stream as a result of the local static pressure in the flow stream dropping below the liquid vapor pressure. The second stage of the process is the subsequent collapse or implosion of the vapor cavities back to the liquid state when the local static pressure again becomes greater than the fluid vapor pressure. (The evaluation of "gaseous" cavitation, i.e. the sudden dissolution of dissolved gases in a liquid, is not currently within the scope of this document.)

3.2 cavitation coefficient: A characteristic number for σ (e.g., σ_i , σ_c , σ_{mv} , σ_{id} , σ_{ch}), determined for a given valve, valve opening, and pressure conditions, which corresponds to the numerical value of the cavitation index at which the levels of incipient cavitation, constant cavitation, maximum vibration cavitation, incipient damage, and choking cavitation occur.

3.3 cavitation index: The value for the operating service conditions of a valve, expressed as σ and numerically equal to $(P_1 - P_v)/(P_1 - P_2)$.

3.4 cavitation level: The degree to which cavitation is occurring, i.e., incipient, constant, incipient damage, choking, or maximum vibration. Levels can be determined by testing for vibration, pitting or metal loss, and changes in valve capacity (C_v).

3.5 choking cavitation: A limiting flow condition in which vapor formation is enough to limit the rate of flow through the valve to some maximum value. Further increases in flow rate through the valve are only possible by increasing the valve inlet pressure, because reducing downstream pressure will no longer increase flow rate.

3.6 constant cavitation: An early level of cavitation characterized by mild, steady popping or crackling sounds that may be audible or detected by vibration measurements. It is the next higher inflection point on the cavitation profile above the point of incipient cavitation. (See Figure 1.) This level is represented by the constant cavitation coefficient σ_c .

3.7 duty cycle: The ratio of the amount of time a valve spends performing one particular function to the valve's total installed time period. It may be expressed as a percentage of total time (service time vs. installed time).

3.8 flashing: A flow condition in which vapor pockets formed inside a valve persist downstream of the valve because the valve outlet pressure is at or below the fluid vapor pressure.

3.9 flow separation: A flow condition in which the fluid boundary layer flows away from the boundary wall instead of flowing along the wall. A turbulent wake exists downstream of the point of flow separation that is characterized by the presence of vortices. These vortices contain regions of high local fluid velocities and hence low, local pressures. The areas of low pressure are potential sites for vapor formation.

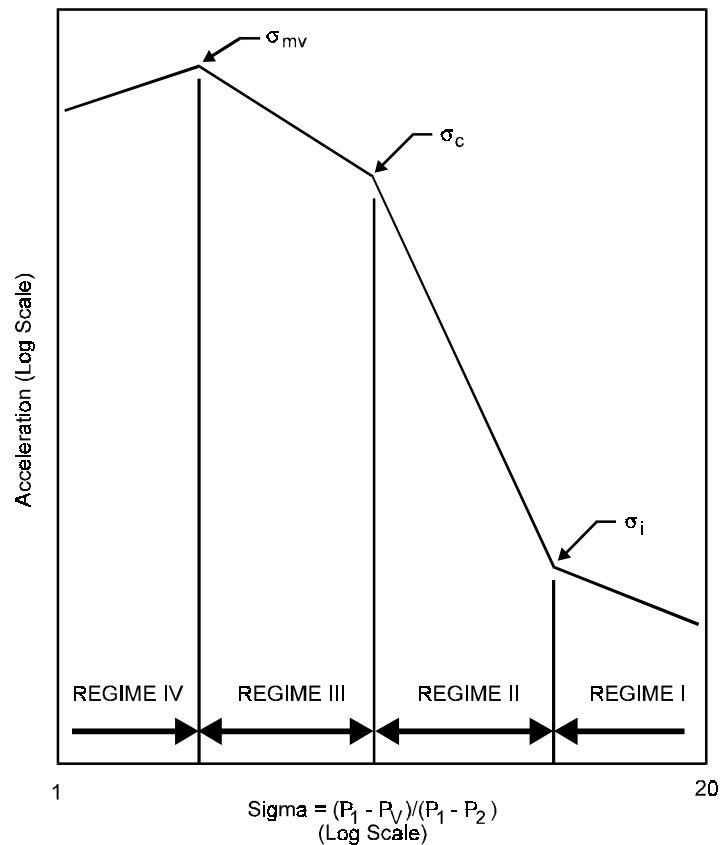


Figure 1 — Cavitation parameter plot

NOTE — This is a classical curve illustrating acceleration versus sigma. Tested valves may not result in this specific configuration or exhibit all the inflection points or coefficients shown above. Test data are subject to expert interpretation.

3.10 incipient cavitation: The onset of cavitation, where only small vapor bubbles are formed in the flow stream. (See Figure 1.) This level is represented by the incipient cavitation coefficient σ_i or $1/x_{FZ}$.

3.11 incipient damage: A cavitation level sufficient to begin minor, observable indications of pitting damage. (This is not to be confused with incipient cavitation. See 3.10.)

3.12 influences: Factors or effects that change the damage rate or extent of damage but do not change the numerical value of cavitation coefficients. See Figure B.2.

3.13 manufacturer's recommended cavitation limit: An operational limit expressed as a cavitation coefficient σ_{mr} supplied by the valve manufacturer for a given valve type, size, opening, and reference upstream pressure. Application of the limit may require scale effect and influence factors if the service conditions and valve size are different than for the reference pressure and size.

3.14 maximum vibration cavitation: The level of cavitation associated with peak vibration measurements and determined from a cavitation level plot at the peak separating Regime III and Regime IV. The test conditions at this point define the conditions for calculating the valve cavitation coefficient σ_{mv} . See Figure 1.

3.15 pressure recovery: The increase in fluid static pressure that occurs as fluid moves through a valve from the vena contracta to the valve's outlet and downstream piping. The recovery, which may be expressed as the difference $P_2 - P_{VC}$, is caused by the velocity-reducing, diffusing action of the downstream geometry.

3.16 scale effects: Differences in cavitation coefficients occurring between the flow test conditions and actual valve operating conditions. These scale effects result from differences in valve size and operating pressures. Scaling equations are used to modify the reference values of cavitation coefficients supplied by valve manufacturers in order to evaluate equipment at other than reference conditions. See Figure B.1.

3.17 vapor pressure: The pressure, for a specified fluid temperature, at which both the liquid and vapor phases of a fluid exist in equilibrium. The vapor pressure is more commonly thought of as the thermodynamic saturation pressure.

3.18 vena contracta: The minimum area of a flow stream. It is smaller than the area causing the flow constriction, because the streamlines continue to converge for a short distance beyond the constriction. Average flow velocity is highest and mean static pressure is lowest in the vena contracta. However, local vortex pressures in separation regions and turbulent boundary layers can be lower than the vena contracta pressure.

4 Nomenclature

Nomenclature used is per ANSI/ISA S75.01 and additionally as follows:

- a* Empirical characteristic exponent for calculating PSE
- b* A characteristic exponent for calculating SSE; determined from reference valve data for geometrically similar valves.

C_V	Valve flow coefficient*, $C_V = q(G_f/\Delta P)^{1/2}$
C_{VR}	Valve flow coefficient of a reference valve
d	Valve inlet inside diameter, inches (mm)
d_R	Valve inlet inside diameter of tested reference valve, inches (mm)
D_1	Internal diameter of upstream pipe, inches (mm)
D_2	Internal diameter of downstream pipe, inches (mm)
e	Napierian base, $e = 2.71828...$ (for natural logarithms)
F_{DC}	Duty cycle factor for modifying the intensity index
F_F	Liquid critical pressure ratio factor*
F_L	Liquid pressure recovery factor*
F_p	Piping factor for ISA valve sizing*
F_T	Temperature factor for modifying the intensity index
F_U	Velocity factor for modifying the intensity index
G_f	Specific gravity of the liquid at inlet flowing conditions
I	Intensity index
K_{B1}	Bernoulli coefficient for upstream pipe reducer*
K_{B2}	Bernoulli coefficient for downstream pipe expansion*
K_1	Head loss coefficient for upstream pipe reducer*
K_2	Head loss coefficient for downstream pipe increaser*
N_{1-4}	Numerical constants for units of measure used in equations. See Table 1.
P_a	Atmospheric pressure, psia (kPa)
P_1	Valve inlet static pressure, psia (kPa)
P_2	Valve outlet static pressure, psia (kPa)
PSE	Pressure scale effect
P_v	Absolute fluid vapor pressure of liquid at inlet temperature, psia (kPa)
P_{vc}	Fluid static pressure in valve vena contracta*, psia (kPa)
q	Volumetric flow rate, gpm (m^3/h)
SSE	Size scale effect
SPL	Sound Pressure Level referenced to 20×10^{-6} Pascal ($2.0 \times 10^{-5} N/m^2$)
T	Fluid Temperature, °F (°C)
T_{ave}	Average temperature between a liquid's freezing and boiling temperatures for a specified pressure, T_{ave} is equal to $(T_F + T_B)/2$, °F (°C)
T_B	Boiling temperature of a liquid for specified pressure, °F (°C)
T_F	Freezing temperature of a liquid, °F (°C)
U	Average velocity at the valve inlet, ft/s (m/s)

*More completely defined in ANSI/ISA S75.01 and ANSI/ISA S75.02



U_0	Pitting threshold velocity determined at the valve inlet, ft/s (m/s)
x_{Fz}	Coefficient of incipient cavitation per IEC-534-8-2; $x_{Fz} \approx 1/\sigma_i$
ΔP	Measured valve differential pressure, psi (kPa)
ΔP_{ch}	Pressure drop at choking, psi (kPa)
σ	Cavitation index equal to $(P_1 - P_v)/(P_1 - P_2)$ at service conditions, i.e., $\sigma(\text{service})$
σ_2	Alternate cavitation index equal to $(P_2 - P_v)/(P_1 - P_2)$ at service conditions. See B.5.6.
σ_c	Coefficient for constant cavitation; σ_c is equal to $(P_1 - P_v)/\Delta P$ at the conditions causing mild, steady cavitation
σ_{ch}	Coefficient for choking cavitation; σ_{ch} is equal to $(P_1 - P_v)/[F_L^2(P_1 - F_F P_v)]$ at the point associated with choking in the valve
σ_i	Coefficient of incipient cavitation; σ_i is equal to $(P_1 - P_v)/\Delta P$ at the point where incipient cavitation begins to occur
σ_{id}	Coefficient of incipient damage for cavitation; σ_{id} is equal to $(P_1 - P_v)/\Delta P$ at the conditions causing onset of damage by cavitation
σ_{mr}	Coefficient of manufacturer's recommended minimum limit of the cavitation index for a specified valve; σ_{mr} is equal to minimum recommended value of $(P_1 - P_v)/(P_1 - P_2)$
σ_{mv}	Coefficient of cavitation causing maximum vibration as measured on a cavitation parameter plot (See Figure 1.)
σ_p	Cavitation coefficient σ_v that has been adjusted for the effects of installing a smaller-than-line-size valve with reducers in the pipeline.
σ_R	A reference value of a cavitation coefficient.
σ_{ss}	Cavitation index scaled for service pressure and size effects for use in intensity index calculations; σ_{ss} is equal to $[(\sigma/SSE-1)/PSE] + 1$
σ_v	Cavitation coefficient for a valve, scaled for a valve size and pressure other than the originally tested size and pressure, that has geometric similarity to the tested valve. It does not include the effect of reducers.

Table 1 — Numerical constants for cavitation equations

Constant		Units Used in Equation	
	N	d, D	U, U_0
N_{c1}	1.00	in	-
	0.00155	mm	-
N_{c2}	890	in	-
	0.00214	mm	-
N_{c3}	1.00	in	-
	25.4	mm	-
N_{c4}	0.078	-	ft/s
	0.256	-	m/s

5 Overview

5.1 Cavitation is a phenomenon that can accompany the flow of liquids through control valves. Failure to account for cavitation can result in potentially costly performance problems. To prevent this situation, it is important that personnel responsible for control valve specifications understand the nature of cavitation and fundamental abatement technology. The purpose of this section is to provide the reader with a brief introduction to the subject. For a more comprehensive treatment of the same subject, the reader is directed to [Annex B](#). Familiarity with this material is encouraged. Successful solutions to cavitation problems still rely heavily on engineering judgments stemming from insight into cavitation basics.

5.2 Simply viewed, cavitation consists of the formation, growth and rapid collapse of cavities in a liquid. These vapor cavities (bubbles) are formed whenever the prevailing fluid pressure falls below the vapor pressure of the liquid. They subsequently collapse if the pressure again rises above the vapor pressure.

5.3 Different specific sources of pressure changes cause cavitation, but they all arise from the flow of the liquid through the control valve. Cavitation usually begins in the low pressure regions associated with boundary layer separation. This may occur even though the mean pressure is greater than the vapor pressure. Mean pressure (the average static pressure in the plane perpendicular to the flow path) will decrease as the liquid passes through the various restrictions in the valve trim. The degree and extent of cavitation escalates when the mean pressure falls below the vapor pressure in these regions.

5.4 Unacceptable noise levels, excessive vibrations, and physical damage to the valve and adjacent hardware are the foremost problems associated with cavitation. These problems all arise from the collapse of the vapor cavities. Material damage results from shock waves and micro-jets, established during cavity collapse, impinging on the boundary surfaces. Corrosion further aggravates these mechanical attack mechanisms. The physical appearance of cavitation damage varies from a "frosted glass" appearance to a rough, cinder-like surface texture.

5.5 Another "side effect" of cavitation is an apparent decrease in the efficiency of the valve. The compressibility introduced to the fluid when a portion of the liquid vaporizes can ultimately lead to a choked flow condition similar to a flashing fluid.

5.6 While treated simply in this section, cavitation is a very complex sequence of events. Not all cavitation necessarily results in the problems mentioned above. However, attempts to model the behavior of the cavitating liquid have not met with universal success. Distinguishing "problem causing" cavitation from acceptable behavior presents some very real challenges.

5.7 Historically, the control valve industry has adopted the practice of describing cavitation applications in terms of a single, unadjusted parameter. In this approach, the suitability of a given control valve is determined by comparing the value of this parameter evaluated at operating conditions to an "operating limit" for that control valve.

5.8 While appealing from a user standpoint, the approach described above suffers from some major drawbacks. First, the definition of the parameter and the manner in which it is used have varied significantly from manufacturer to manufacturer. While the principle underlying the method is basically the same, the differences in appearance lead to much confusion. Furthermore, the complexity of cavitation renders it difficult to predict the exact behavior in any given service on the basis of a single, unadjusted parameter. Many service factors can affect the apparent level of

cavitation. Unfortunately, no currently known model fully describes the intensity or extent of cavitation under universally varying conditions regardless of the number of parameters employed.

5.9 The operating limit used as the basis for comparison has, in many instances, been equal to the value of the pressure recovery factor, F_L . If a valve is operated at the limit defined by the pressure recovery factor, the valve is at or near choked flow conditions. Substantial vapor has been formed in the flow stream, and significant levels of cavitation can exist. As discussed elsewhere, using F_L in this manner is not a universally correct solution and is, in general, valid only for specially designed valve trims. The vast majority of valves cannot operate problem free under this condition.

5.10 A modified single parameter will be adopted for use in this document. A specific parameter, as defined in Equation 1, is recommended. Adjustments to this parameter are supplied wherever they are known to account for the variations associated with different application conditions. While it is recognized that even this technique may have limitations, it is believed that it will provide a justifiable blend of ease of use and meaningful predictions.

5.11 The parameter chosen for use in this document is the cavitation index

$$\sigma = (P_1 - P_v)/(P_1 - P_2) \quad (1)$$

where P_1 is the absolute pressure upstream of the valve, P_2 is the absolute pressure downstream of the valve, and P_v is the absolute vapor pressure of the fluid at the inlet temperature.

5.12 As noted above, other parameters have been used and probably will continue to be used in the future for essentially the same purpose. In many instances, well defined mathematical relationships exist between these parameters and the index defined in Equation 1. Several other parameters, relationships to σ , and the associated advantages or disadvantages are discussed in [Annex B](#).

5.13 The σ index, in effect, quantifies only the service conditions. By itself it does not convey any information about the performance of a particular valve in that particular application. Different valves can tolerate different levels of cavitation, and different applications are concerned about different aspects of cavitation (for instance, noise versus damage). Therefore, σ must be evaluated at the service conditions and then compared to some benchmark.

5.14 The benchmark σ value for any specific application obviously will depend on both the problem of concern (e.g., noise) as well as the valve style selected. Various limits have been suggested and used in the control valve industry in the past. The following benchmarks, hereafter referred to as levels, are used throughout this document:

- a) incipient cavitation;
- b) constant cavitation;
- c) incipient damage;
- d) choking cavitation; and
- e) maximum vibration cavitation.

Definitions of these various levels are given in [Section 3](#). More complete descriptions of their significance are provided in [Annex B](#). A discussion of the methods of determination is presented in [Section 8](#).

5.15 The different levels of cavitation listed in 5.14 merely define different significant cavitation conditions that exist. No specific levels can be universally recommended. The appropriate level

to use for a given application is not always self-evident and will usually embrace a degree of subjectivity. In addition to the service conditions, factors such as valve style and opening, duty cycle, location, desired life, and past experience should be considered. The valve manufacturer always should be consulted. A manufacturer may recommend an application dependent valve operating limit called "manufacturer's recommended limit" or σ_{mr} . Additional discussion may be found in [Section 7](#) and [Annex B](#) of this document.

5.16 These various levels are a strong function of the internal geometry of the control valve. It can be expected that different values of any given cavitation coefficient will be associated with different valve styles or even different openings of the same valve.

5.17 Furthermore, the numerical values of these cavitation coefficients must be adjusted if a reduced scale model was used to determine them. Any factor that changes the numerical value of a cavitation coefficient as that factor is varied is known as a "scale effect." The numerical values of σ coefficients can be corrected for "size scale effect" (SSE) through the use of scaling equations presented in [Section 6](#).

5.18 Research has shown that many factors contribute to the total nature of cavitation and to the resulting problems. Some of these factors are associated with the valve geometry as noted in 5.16. Others are associated with the service environment. The foremost service condition scale effect is the "pressure scale effect" (PSE). The numerical values of the various cavitation coefficients for a particular valve will change as a function of the pressures at which they are evaluated. Consequently, an adjustment in the values is necessary if the service pressures are different from the test pressures. Equations to calculate these adjustments are presented in [Section 6](#).

5.19 At this point it is helpful to introduce another category of effects other than "scale effects" as defined in 5.17. Application "influences" include factors that do not change the numerical value of cavitation coefficients as in scale effects, but that do affect the intensity of the cavitation. The list of influences is long, but for engineering purposes can be pared down to the following primary effects (Knapp, ref. 1; Barnes and Cain, ref. 13):

- a) viscosity;
- b) velocity;
- c) dissolved and undissolved gases in the liquid;
- d) thermal properties of the liquid; and
- e) duty cycle.

More detailed discussion regarding the nature of these effects and methods of accounting for them are presented in Annexes B and C.

5.20 The pressure drop, ΔP , measured in testing valves for cavitation is the pressure difference between upstream and downstream pressure taps of the test manifold. For higher recovery valves ($C_v/N_1 d^2 > 20$) and critical applications, it may be necessary to adjust this pressure drop to account for actual piping configuration in evaluating C_v , ΔP , valve opening, and σ . [Annex D](#) discusses this in more detail.

5.21 Cavitation will continue to be a major problem in industrial process control. An understanding of the nature of the subject and utilization of current quantitative information will aid in formulating effective problem abatement. However, the ultimate benefit of analyzing valves and service conditions for cavitation depends upon the quality and completeness of service and valve information available. Valve users and manufacturers should make every reasonable effort to share clear and accurate data (see ISA-RP75.21, Process Data Presentation). The data will make possible the comparisons between the service conditions and valve capabilities.

5.22 The procedures contained in this document are intended to provide the best practical knowledge currently available on the subject. However, practitioners always should avail themselves of proven new technology as it becomes available.

6 Cavitation index and valve scale effects

6.1 Application dependencies

6.1.1 The cavitation index σ (Equation 1) is based on the assumption that the size of the valve and the process fluid properties (other than vapor pressure) would have little effect on the value of the index. (Knapp et. al., ref. 1). In actuality, the cavitation behavior and cavitation coefficients are not independent or constant with either different upstream pressures or valve size. The change in the value of a cavitation coefficient associated with change in pressure is known as the "pressure scale effect" (PSE) (Tullis, refs. 2, 4; Rahmeyer, ref. 3; Stripling, ref. 6). Likewise, the change in the value of a cavitation coefficient associated with valve size is known as the "size scale effect" (SSE) (Tullis, refs. 2, 4; Rahmeyer, ref. 3; Stripling, ref. 6). In addition to direct valve size changes, the presence of pipe reducers or increasers can also affect the value of a coefficient.

6.1.2 Methods are presented in this section to account for these effects. Equations are available that adjust the value of the coefficients for the difference between the actual size or pressure (operating conditions) and the test size or pressure (reference conditions) (Tullis, ref. 2). Modifications to the coefficients for pipe fittings are also provided. It is important to note that the equations for scale effect adjustments were developed using water as the test fluid. They are assumed valid for fluids other than water.

6.1.3 Other factors besides pressure and valve size also can influence the nature of the cavitation. Fluid properties such as viscosity, density, and surface tension are recognized effects (Knapp, et al., ref. 1; Barnes and Cain, ref. 13). Effects such as these do not tend to change the value of the coefficients, but can change the degree of cavitation associated with any particular cavitation level. These are referred to as "influences", which are further discussed in [Annex B](#).

6.2 Equations for scaling the cavitation coefficients

6.2.1 Scaling equations and exponents have been derived to adjust or extrapolate cavitation coefficients from one system pressure and size to another. Equation 2 gives the relationship by which a coefficient for the valve, σ_v , can be calculated from a reference coefficient, σ_R . The value of σ_R may be chosen as the value of a cavitation coefficient or a manufacturer's limit σ_{mr} . Equation 2 reflects the correlation of published data (Rahmeyer, ref. 3 and Tullis, ref. 4).

$$\sigma_v = (\sigma_R \text{SSE} - 1)\text{PSE} + 1 \quad (2)$$

After σ_v has been calculated, it can be compared to σ (service) calculated by Equation 1. If σ (service) is greater than σ_v , the valve will operate at a level of cavitation less severe than that for which the valve's σ_R was determined by the manufacturer. If the valve will be installed in a larger diameter pipe, σ_p must be calculated from σ_v by Equation 7. The piping adjusted σ_p is then compared to σ (service).