The Inbal Valve Sizing

What is Valve Sizing for?

Simply specifying an **Inbal** Valve size to match an existing pipeline size leaves much to chance and will probably create an impractical situation in terms of initial investment and adequacy of control. Obviously, an **Inbal** Valve that is too small will not pass the required amount of flow.
Undoubtedly, the tendency is to make the valve too large to be on the "safe" side. Besides an unnecessary and expensive investment, too large of a valve may create instability problems, particularly in low rates of the flow.

However, this article offers a method of selection of a correct **Inbal** Valve size based on the assumption of full knowledge of the actual flowing conditions. Frequently, one or more of these conditions is arbitrarily assumed. Therefore, being aware that there is no substitute for good engineering judgement, it is recommended that the final **Inbal** Valve sizing is determined by good common sense combined with experience.

Pressure Drop Across the Inbal Valve

In the interest of economy, the engineer tries to keep the control valve pressure drop as low as possible. However, a valve can only regulate flow by absorbing and giving up pressure drop to the system.
As will be discussed later, there must be a correlation between the pressure differential absorbed by the **Inbal** Valve and the system characteristics.
The choice of pressure drop is a complex problem which cannot be defined by a set of numerical rules. On a simple pressure reducing or pressure sustaining application, the drop across the valve may be known quite accurately. If the pressure difference is relatively small, some allowance may be necessary for line friction. On the other hand, in a large percentage of all control applications, the pressure drop across the valve must be chosen arbitrarily. The guidelines should thus be used more as benchmarks than design criteria.
In a pump circuit, the pressure drop allocated to the control valve should be equal to 33% of the dynamic loss in the system at the rated flow.
For **Inbal** Valves installed in extremely long or high pressure drop lines, the percentage of drop across the valve may be somewhat lower but at least 15% of the system drop should be taken.

Inherent Flow Characteristics

Inherent Flow Characteristics is the relationship between fractional control space volume and the relative flow through the valve. Inherent Flow Characteristics are shown by plotting the flow through the **Inbal** Valve at various openings versus control space volume, and at constant pressure drop.
The **Inbal** Valve sensitivity is defined as the ratio between the change in flow and the change in the control space volume. It is evident that the slope of the flow characteristic curve is the **Inbal** Valve sensitivity [see Figure (1) for **Inbal** Valve series 700].
The **Inbal** Valve provides a high rate of sensitivity at the relevant % K_v/C_v range (say 50% maximum): a larger volume of water is needed to be modified at the control space to change the valve position.

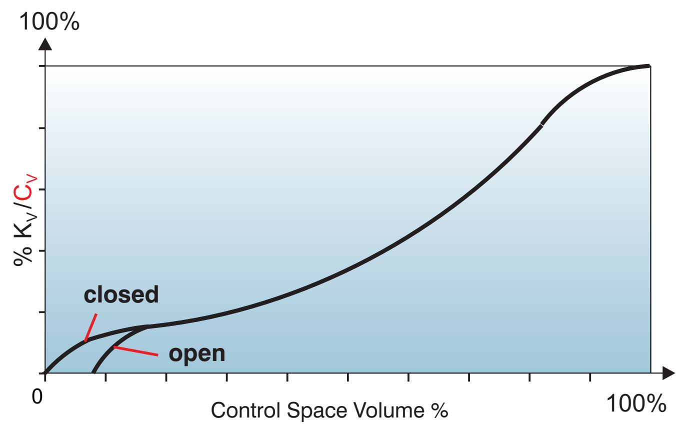


Figure (1)
Inbal *Valve series 700 Inherent Flow Characteristics*

Nomenclature

*C_v - **Inbal** Valve flow factor (English units).*

*K_v - **Inbal** Valve flow factor (Metric units).*

Installed Flow Characteristics

Obviously, the flow through the **Inbal** Valve is affected by the pressure drop across the valve (more specifically by the variation in pressure drop across the valve). Thus, pressure drop must be specified as a part of the flow characteristic. However, the **Inbal** Valve Inherent Flow Characteristics in the previous chapter are shown at a constant pressure drop throughout the opening of the valve. The Inherent Flow Characteristic is valuable in describing the **Inbal** Valve as supplied by Mil. However, it is immediately evident that few valves actually operate at a constant pressure drop. Thus, the flow characteristic of the **Inbal** Valve installed in the pipeline provides the basis for proper application of the valve. However, there is a distortion of the inherent **Inbal** Valve flow characteristics which is unique for each valve installation. The relationship between fractional control space volume and the relative flow through the valve at various pressure drops is called the Installed Flow Characteristics.

If the ratio of the **Inbal** Valve pressure drop to the total system dynamic loss is defined as DP_T, then:

$$\Delta P_T = \frac{\Delta P_n}{\Delta P_n + \Delta P_s} \qquad (2\text{-}1)$$

Figure (2) shows the distortion of the inherent **Inbal** Valve characteristics as it relates to the installed characteristics with a varying valve pressure drop ratio.

Notice that the distortion increases with a decreasing ratio. As stated in the "pressure drop" chapter, the ratio of 0,15 should be the limit for acceptable performance.

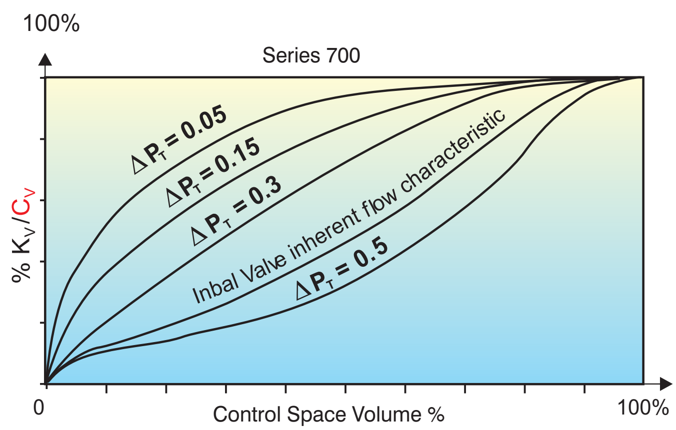


Figure (2)

Inbal *Valve Installed Flow Characteristics*

For a better demonstration of the **Inbal** Valve Installed Flow Characteristics we may analyze a simple installation which consists of a pipe between two reservoirs at an altitude differential H [See figure (3)].

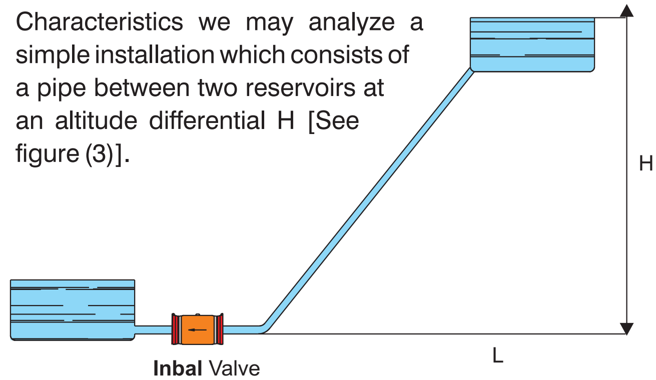


Figure (3)

Inbal *Valve between two reservoirs*

The head differential is determined by the following equation:

$$H = f\,\frac{L}{D}\cdot\frac{V^2}{2g}$$

If $f\frac{L}{D}$ is substituted by Z, then:

$$H = Z\cdot\frac{V^2}{2g}$$

The velocity is:

$$V = \left(\frac{2gH}{Z}\right)^{1/2}$$

If an **Inbal** Control Valve is installed , the pressure drop through the valve is:

$$\Delta P_n = K_n\cdot\frac{V_n^2}{2g}$$

The total pressure drop through the installation now is:

$$\Delta H = H - \Delta P_n = Z\cdot\frac{V_n^2}{2g}$$

$$Z\cdot\frac{V_n^2}{2g} = Z\cdot\frac{V^2}{2g} - K_n\cdot\frac{V_n^2}{2g}$$

$$V_n = \left(\frac{2gH}{Z}\right)^{1/2}\cdot\left(\frac{1}{1+K_n/Z}\right)^{1/2} \qquad (2\text{-}2)$$

Nomenclature

D - *Internal pipe diameter (mm ; inches).*
f - *Pipe friction coefficient.*
g - *Local acceleration of gravity (m/sec²; feet/sec²).*
H - *Total system head (m H_2o ; ft H_2O).*
ΔH - *Total dynamic pressure loss through the system (m H_2o ; ft H_2O).*
K_v/C_v - **Inbal** *Valve flow factor (Metric / English units).*
K_n - *Valve velocity coefficient at n opening degree.*
L - *Total pipe length (meter ; feet).*
ΔP_n - *Valve pressure drop at n opening degree (m H_2o ; ft H_2O).*
ΔP_s - *Dynamic pressure loss of the system except the installed valve (m H_2o ; ft H_2O).*
ΔP_T - *Ratio of valve pressure drop to the total system dynamic loss (dimensionless).*
V - *Fluid Velocity (m/sec ; feet / sec).*
V_n - *Fluid velocity across the valve at n% opening degree (m/sec ; feet / sec).*
$Z = f\frac{L}{D}$ - *Pipe head loss coefficient (dimensionless).*

In the equation (2-2) the expression $(\frac{2gH}{Z})^{1/2}$ represents the velocity as if the **Inbal** Valve is not installed. The expression $\frac{1}{(1+K_n/Z)^{1/2}}$ represents the "correction factor" at the velocity due to the certain opening degree (n) of the **Inbal** Valve. It is evident that the Installed Flow Characteristic is the ratio of the Inherent Flow Characteristics and the Installation resistance coefficient.

If too large of an **Inbal** Valve is installed, when in fully open position the ratio K_n/Z is very small and practically negligible. In order to reduce the velocity (flow rate) by 30% only, the valve should develop a pressure drop equal to the installation pressure loss $K_n = Z$. That means that the **Inbal** Control Valve performs on the lower range of the throttling degree only, which may result in unstable regulating performance and in extreme conditions even in hunting. The performance of a correctly sized **Inbal** Valve compared to a too large valve may be demonstrated in a graph [see Figure (4)].

In order to reduce the velocity from *Va* to *Vb*, the "correct" size **Inbal** Valve would reduce the velocity while changing its opening degree from *n 1* to *n 2*. The "too large" **Inbal** Valve would reduce the same velocity by traveling from *n3* to *n4*. It is obvious that the "correct" size **Inbal** Valve affects the installation flow quite effectively through all its travel. The "too large" **Inbal** Valve affects the rate of flow only at the low opening degree. Consequently, when a "too large" **Inbal** Valve is activated from fully open position to closed position, a pressure surge might be developed.

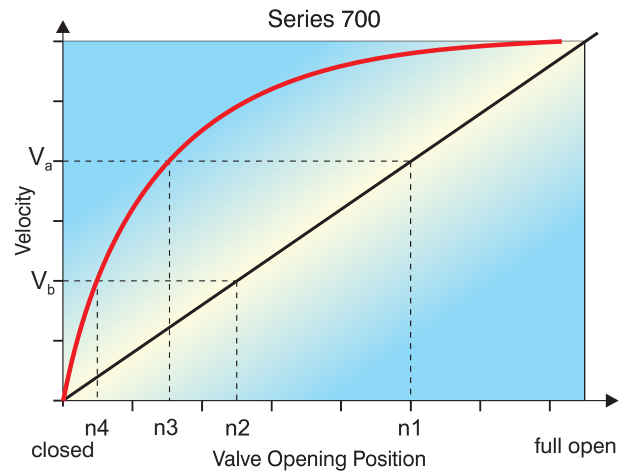


Figure (4)

*"Too Large" and "correct" size **Inbal** Valve*

Determining Liquid Flow Pattern

Flow through a valve is classified as either vaporizing (critical) or non-vaporizing (subcritical). If the liquid does not vaporize [see Curve A in Figure (6)], the flow rate through the **Inbal** Valve at a given opening degree is a function of the differential pressure between the inlet and outlet of the valve. At subcritical flowing conditions a linear relationship exists between the flow rate and the square root of the pressure differential across the valve. The constant of this proportionality is the valve Flow Factor K_v or C_v [See Figure (5)] .

While the basic liquid sizing equation implies that there is no limit to the amount of flow through a valve as long as the differential pressure across the valve increases, the realities of flashing and cavitation prove otherwise. If vapor bubbles form either temporarily (cavitation) or permanently (flashing) this relationship may no longer hold. Increasing the pressure drop beyond a certain range while holding a constant inlet pressure will ultimately result in a point where the calculated K_v; C_v values will begin to decrease. This apparent decrease in the Flow Factor has been shown to be an indication of cavitation within the valve. The point of initial departure from the proportional relationship between the flow rate and the square root of the pressure differential indicates incipient cavitation K_C of the main flow stream. After cavitation has begun, further increases in the pressure differential result in increased vaporization and cavitation intensity [see curve B

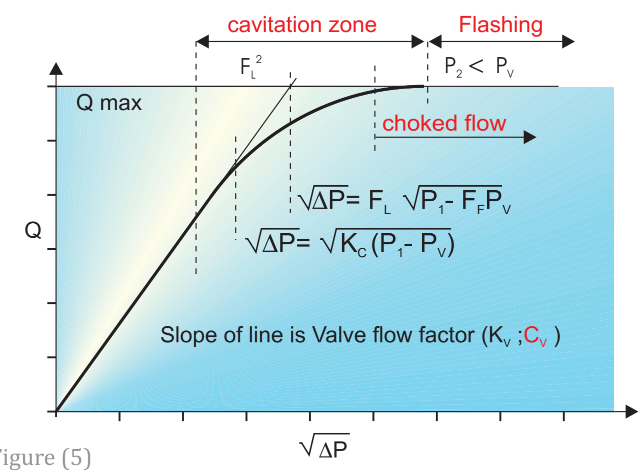


Figure (5)

*Liquid flow rate versus pressure drop for **Inbal** Valve (constant upstream pressure and vapor pressure)*

Nomenclature

- F_F - *Liquid critical pressure ratio factor (dimensionless).*
- F_L - *Liquid pressure recovery factor of valve without attached fittings (dimensionless).*
- g - *Local acceleration of gravity (m / sec^2 ; feet / sec^2).*
- H - *Total system head (meter / feet).*
- K_C - *Incipient cavitation coefficient.*
- K_v / C_v - ***Inbal** Valve flow factor (Metric / English units).*
- K_n - *Valve velocity coefficient at n opening degree.*
- n - ***Inbal** Valve opening degree (%).*
- P_1 - *Upstream absolute pressure (bar absolute ; psia).*
- P_2 - *Downstream absolute pressure (bar absolute ; psia).*
- ΔP - *Pressure differential (bar ; psi).*
- P_V - *Absolute vapor pressure of liquid at flowing temperature (bar absolute ; psia) .*
- Q max - *Maximum flow rate (m^3/h ; U.S. gpm).*
- V - *Fluid Velocity (m / sec ; feet / sec).*
- Z - *pipe head loss coefficient (dimensionless).*

in Figure (6)] and further decreases in the apparent valve Flow Factor. Referring to Figure (5), it is noted that with sufficient pressure drop the flow becomes fully choked so that increasing the pressure drop results in no increase in flow rate. At this point a condition of critical flow exists. Increasing the pressure drop further at choked flow reduces the downstream pressure to be equal to, or less, than the vapor pressure of the liquid and flashing occurs [see curve C in Figure (6)].

To determine whether a critical or subcritical flow condition exists, the following equations are used:

Subcritical Flow exists when:

$$DP < F_L^2 (P_1 - F_F'' P_V) \quad (3\text{-}1)$$

Critical Flow exists when:

$$DP \geq F_L^2 (P_1 - F_F'' P_V) \quad (3\text{-}2)$$

or for simplicity if the vapor pressure is less than one half the upstream pressure $P_v < 0.5\ P_1$ then, Subcritical Flow exists when:

$$\Delta P < F_L^2 (P_1 - P_V) \quad (3\text{-}3)$$

Critical Flow exists when:

$$\Delta P \geq F_L^2 (P_1 - P_V) \quad (3\text{-}4)$$

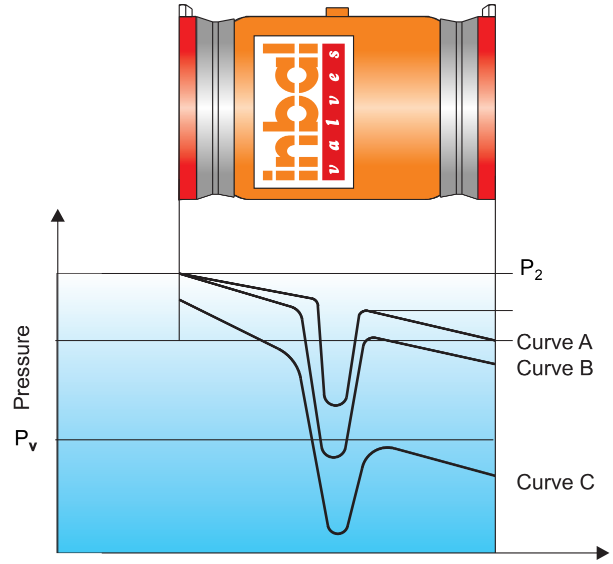


Figure (6)
Pressure profiles at subcritical and critical flows

Liquid Pressure Recovery Factor - F_L

The Liquid Pressure Recovery Factor accounts for the influence of the internal construction of the **Inbal** Valve on its capacity at choked flow. Under non-vaporizing flow conditions it is defined as follows:

$$F_L = \sqrt{\frac{P_1 - P_2}{P_1 - P_{VC}}} \quad (4\text{-}1)$$

The Liquid Pressure Recovery Factor is related to the pressure which is recovered downstream of the vena contracta. If $(P_1 - P_{VC})$ is the maximum pressure drop across the orifice, the fraction of this pressure drop which is recovered is $(1-F_L^2)$. The unrecoverable fraction or permanent loss is F_L^2: If cavitation or flashing exists, this relationship no longer exists since pressure recovery may be diminished or reduced to zero.

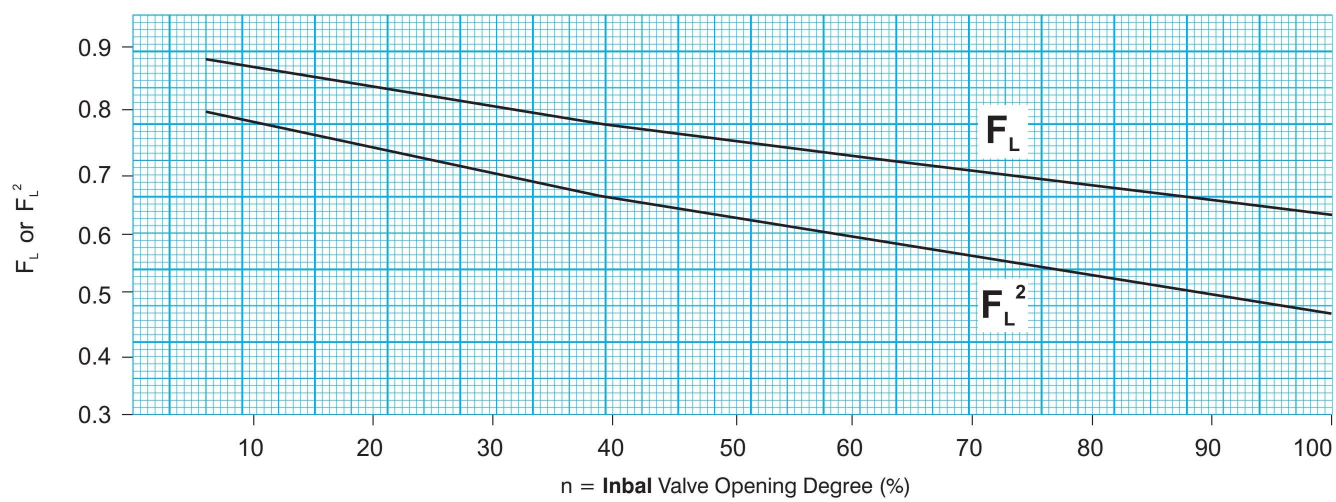


Figure (7)
*F_L and F_L^2 curves for **Inbal** Valve series 700*

Nomenclature

F_F - Liquid critical pressure ratio factor (dimensionless).
F_L - Liquid pressure recovery factor of valve without attached fittings(dimensionless).
*n - **Inbal** Valve opening degree (%).*
P_1 - Upstream absolute pressure (bar absolute ; psia).
P_2 - Downstream absolute pressure (bar absolute ; psia).
P_V - Absolute vapor pressure of liquid at flowing temperature (bar absolute ; psia).
P_{VC} - Absolute pressure at the vena contracta (bar absolute ; psia).
ΔP - Pressure differential (bar ; psi).

Although there are some small variations in F_L values along the sizes of each of the **Inbal** Valve series, for the sake of simplicity only one averaged value is shown for each series. These values are determined by flow test as specified in ISA S39.02 using cold water as the test fluid. The values of the **Inbal** Valve Pressure Recovery Factor at various opening degrees (n) are shown graphically in Figure (7). It shows F_L and F_L^2 versus *n*, then the value may be calculated as follows:

$$n = 100\frac{K_{VR}}{K_V} = 100\frac{Q}{K_V}\sqrt{\frac{G_f}{\Delta P}} \quad \text{or:} \qquad (4\text{-}2)$$

$$n = 100\frac{C_{VR}}{C_V} = 100\frac{Q}{C_V}\sqrt{\frac{G_f}{DP}}$$

Liquid Sizing Equations for Subcritical Flow

Based on the principle of energy conservation, when a liquid flows through an orifice, the square of the fluid velocity is directly proportional to the pressure differential across the orifice and inversely proportional to the specific gravity of the fluid. The basic liquid sizing equation is written as follows:

$$Q = K_V\sqrt{\frac{\Delta P}{G_f}} \quad \text{or:} \quad Q = C_V\sqrt{\frac{\Delta P}{G_f}} \qquad (5\text{-}1)$$

The maximum flowing quantity that could be handled by the valve should be 15-40% above the maximum flow required by the process.

In order to determine the **Inbal** Valve size, thefollowing equation is used:

$$K_V \geq 1.15 \div 1.4\ Q\ max \cdot \sqrt{\frac{G_f}{\Delta P}} \quad \text{or:} \qquad (5\text{-}2)$$

$$C_V \geq 1.15 \div 1.4\ Q\ max \cdot \sqrt{\frac{G_f}{\Delta P}}$$

The **Inbal** Valve size selected should have a higher flow factor than the flow factor valve calculated by the above equation (for **Inbal** Valves flow factor values, see Table A).

Table A:

Inbal *Valve series 700 flow factors*

Inbal Valve Size		Flow Factors	
mm	inch	K_V	C_V
40	1½	60	70
50	2	90	105
80	3	140	162
100	4	330	383
150	6	610	708
200	8	1150	1334
250	10	1630	1891
300	12	2365	2743

Minimum Flow Rate

The core (sealing disc) shape of the **Inbal** Valve is designed to fit the sleeve's contoured outer lining at various positions and to establish a defined sleeve-disc clearance orifice. However, when the sleeve is first cracked open, a close clearance flow path is formed, temporarily causing a choked flow. Thus characterized flow should begin only after the sleeve makes a slight additional lift.

On many systems, a reduction in flow means an increase in pressure drop; e.g. in pressure reducing service when the demand is reduced, downstream pressure remains constant and upstream pressure is increased. In these conditions the **Inbal** Valve port area range may be much greater than might be expected. For example, the maximum operating conditions for a pressure reducing **Inbal** Valve are 880 gpm (200 m^3/h) at 29 psi (2 bar) drop and the minimum conditions are 110 gpm (25 m^3/h) at 115 psi (8 bar) drop. The **Inbal** Valve port area range is the product of the ratio of the Flow Factor at maximum conditions to the Flow Factor at minimum conditions and is calculated as follows:

$$\frac{K_{VR}\,max}{K_{VR}\,min} = \frac{Q_R\,max}{Q_R\,min} \cdot \frac{\sqrt{\Delta P\,min}}{\sqrt{\Delta P\,max}} \qquad (6\text{-}1)$$

and in our case:

$$\text{port area range} = \frac{200 \times \sqrt{8}}{25 \times \sqrt{2}} = \frac{880 \times \sqrt{115}}{110 \times \sqrt{29}} = \frac{16}{1}$$

Therefore, it is imperative to verify that the **Inbal** Valve size selected is capable of handling the minimum flow rate required by the process.

Nomenclature

- F_L - *Liquid pressure recovery factor of valve without attached fittings (dimensionless).*
- G_f - *Liquid specific gravity at flowing temperature (water = 1@ 15°C / 60°F).*
- K_V / C_V - ***Inbal** Valve flow factor (Metric / English units).*
- K_{VR} *min* / C_{VR} *min* - *Required Valve flow factor at minimum condition of the process (metric / English units).*
- K_{VR} *max* / C_{VR} *max* - *Required Valve flow factor at maximum condition of the process (metric / English units).*
- *n* - ***Inbal** Valve opening degree (%).*
- ΔP - *Pressure differential across the **Inbal** Valve (bar ; psi)*
- ΔP *min* - *Minimum Pressure differential across the valve (bar ; psi).*
- ΔP *max* - *Maximum Pressure differential across the valve (bar ; psi).*
- *Q* - *Liquid flow rate (m^3/h ; U.S. gpm).*
- Q_R *max* - *Maximum flow rate required by the process (m^3/h ; U.S. gpm).*
- Q_R *min* - *Minimum flow rate required by the process (m^3/h ; U.S. gpm).*

"Minimum" flow factors are given in Table B below:

Table B:
Inbal *Valve series 700 "minimum flow factors"*

Inbal Valve Size		Minimum Flow Factors	
mm	inch	K_v	C_v
40	1½	1.5	1.8
50	2	1.5	1.8
80	3	1.5	1.8
100	4	3.0	3.5
150	6	10.0	11.6
200	8	15.0	17.4
250	10	20.0	23.0
300	12	25.0	29.0

Initially the flow pattern should be determined at the minimum flow rate conditions:

If $\Delta P < F_L^2 (P_1 - F_F \cdot P_V)$ subcritical flow condition exists:

$$Q\ min > K_v min \sqrt{\frac{\Delta P}{G_f}} \quad \text{or:} \qquad (6\text{-}2)$$

$$Q\ min \geq C_v min \sqrt{\frac{\Delta P}{G_f}}$$

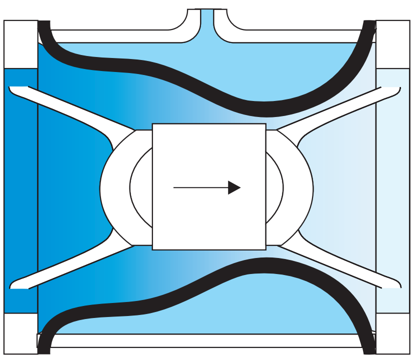
The flow rate in m^3/h or U.S. gpm should be equal or greater than the right wing equation.

If $\Delta P \geq F_L^2 (P_1 - F_F \cdot P_v)$ critical flow conditions exist:

$$Q\ min \geq K_v min \cdot F_L \sqrt{\frac{P_1 - F_F\ P_V}{G_f}} \quad \text{or:} \qquad (6\text{-}3)$$

$$Q\ min \geq C_v min \cdot F_L \sqrt{\frac{P_1 - F_F\ P_V}{G_f}}$$

The Flow Rate in m^3/h or U.S. gpm should be equal to or greater than the right portion of the equation.



Figure(8)
The core contour doesn't form a sleeve-disc clearance orifice for low rates of flow.

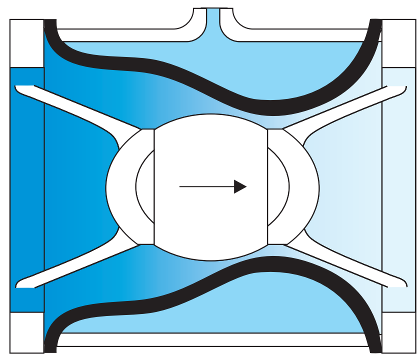


Figure (9)
The core contour for ideal low flow characteristics.

Cavitation and Flashing

The occurrence of cavitation within a control valve can have a significant effect on the valve sizing procedure. Cavitation, briefly, is a two-stage phenomenon which is encountered in liquid flow. In the first stage, the static pressure of the flowing liquid decreases to a value less than the liquid vapor pressure. When this occurs, continuity of flow is broken by the formation of vapor bubbles. In the second stage the bubbles move into a higher pressure region where they cannot exist as a vapor and collapse back into the liquid. It is the collapse of these bubbles which can cause damage. As the bubbles implode, high velocity water jets cause shock waves and extreme temperatures in the locality. The process known as "flashing" is when the cavitation process is halted before completion of the second stage so that vapor persists downstream of the region where the collapsing of bubbles normally takes place. Obviously, since flashing is directly related to the first stage of cavitation, the statements regarding the inception of cavitation also apply to flashing.
For the sake of later statements for cavitation (and flashing) conditions, the pressure and velocity changes caused by a restriction in a line are visualized in Figure (10).
The orifice may be considered analogous to the **Inbal** Valve at some fixed opening. The total energy level should remain constant at every point along a given datum plant in the

Nomenclature

- F_F - *Liquid critical pressure ratio factor (dimensionless).*
- F_L - *Liquid pressure recovery factor of valve without attached fittings (dimensionless).*
- G_f - *Liquid specific gravity at flowing temperature (water = 1@ 15°C / 60°F).*
- $K_v\ min$ / $C_v min$ - *Inbal Valve minimum flow factor (Metric / English units).*
- K_v / C_v - **Inbal** *Valve flow factor (Metric / English units).*
- P_1 - *Upstream absolute pressure (bar absolute ; psia).*
- P_v - *Absolute vapor pressure of liquid at flowing temperature (bar absolute ; psia).*
- ΔP - *Pressure differential (bar ; psi).*
- *Q min* - *The minimum flow rate the* **Inbal** *Valve is capable to handle at given conditions (m^3/h ; U.S. gpm).*

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system. As the fluid stream approaches the restriction in the line, its cross-sectional area must decrease in order to pass through the orifice. The velocity is inversely proportional to the stream area, and therefore, must increase. Since the total energy remains constant, an energy interchange must take place with the pressure head losing what the velocity head gains.

Immediately downstream of the orifice, the stream will reach its minimum cross section, and thus its maximum velocity and minimum pressure. This point is called the "vena contracta" (P_{VC}). If velocity is increased sufficiently, the pressure will fall to the vapor pressure thus permitting the formation of voids in the stream which is the first stage of cavitation.

Downstream from the vena contracta there is a reversal of the energy interchange between the velocity and the pressure heads. This reversal is called "pressure recovery" and plays an important role in **Inbal** Valve sizing. Vapor bubbles, formed as a result of reducing the pressure at the vena contract to the vapor pressure, cannot exist at the increased pressure downstream and are forced to collapse or implode back into the liquid stage. This is the second stage of cavitation.

If pressure at the valve outlet remains below the vapor pressure of the liquid, the bubbles will remain in the downstream system and the process is said to have "flashed". The pressure recovery in the valve is a function of its particular internal geometry. The more turbulence the valve introduces into the flow stream, the less pressure recovery is experienced. Obviously, high recovery valves tend to be more likely to rise above the liquid's vapor pressure [see Figure (11)].

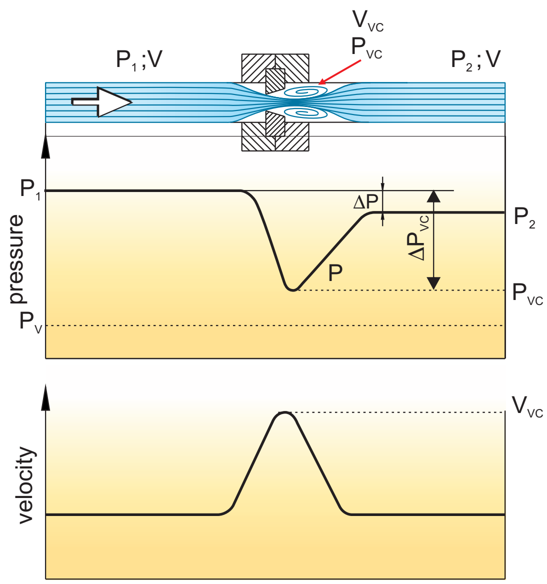


Figure (10)

Pressure and velocity profiles through restriction Orifices.

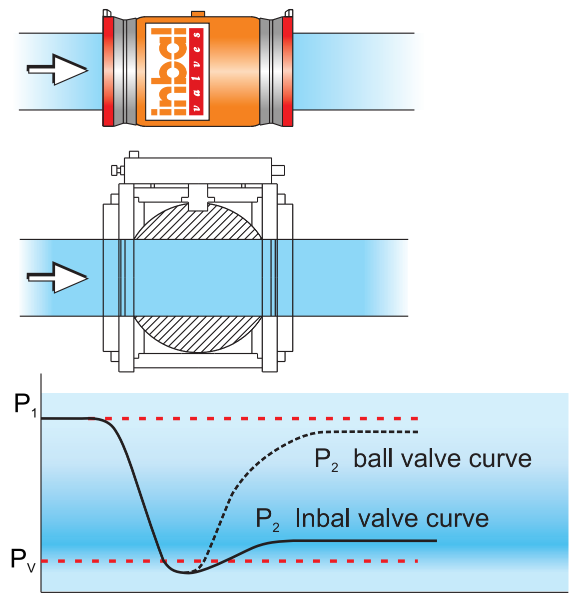


Figure (11)

*Comparison of pressure profiles for high (ball) and low (**Inbal**) recovery values.*

Incipient Cavitation Coefficient - K_c

When vapor bubbles begin to form, they displace the liquid, thereby chocking the flow and reducing the efficiency of the valve. The early stage of bubble formation is called incipient cavitation. It is designated by the symbol Kc and is defined as follows:

$$K_C = \frac{P_1 - P_2}{P_1 - P_V} = \frac{\Delta P}{P_I - P_V} \qquad (8\text{-}1)$$

The K_c is a dimensionless ratio.

Figure (5) is used to describe the point in which the relationship of the flow to the square root of the pressure differential begins to deviate from linear. Inspection of the K_C relationship indicates that it represents the fraction of the total pressure drop from the inlet pressure to vapor pressure which may be taken as the pressure drop across the valve before cavitation begins within the main fluid stream. The K_C should be used in the applications where absolutely no cavitation can be tolerated.

Nomenclature

K_C - Incipient cavitation coefficient (dimensionless).
P_1 - Valve inlet pressure (bar absolute ; psia).
P_2 - Valve outlet pressure (bar absolute ; psia).
P_V - Absolute vapor pressure of liquid at flowing temperature (bar absolute ; psia).
P_{VC} - Absolute pressure at the vena contracta (bar absolute ; psia).
ΔP - Pressure differential (bar ; psi).
ΔP_{VC} - Pressure differential between inlet pressure and the vena contracta pressure (bar ; psi).
V - Fluid Velocity (m/sec ; feet / sec).
V_{VC} - Fluid velocity at vena contracta (m/sec ; feet / sec).

In Such cases the Incipient Cavitation Coefficient (K_c) should be employed in place of F_L^2. Values of K_C for various valve opening degrees (*n*) are demonstrated in Figure (12), (For calculation of *n*, review Liquid Pressure Recovery Factor, page 004). When reducers are used, the same K_c value may be safely used. To find the pressure differential for incipient cavitation the following formula is used:

$$\Delta P_I = K_C \ (P_1 - P_V) \qquad (8\text{-}2)$$

If the actual differential pressure required by the process is found to be greater than the allowable pressure differential DP (calculated from 5-2), cavitation will occur. If this cannot be tolerated, the following condition should exist:

$$\Delta P < K_C \ (P_1 - P_V) \qquad (8\text{-}3)$$

In such conditions equations for subcritical flow are applied.

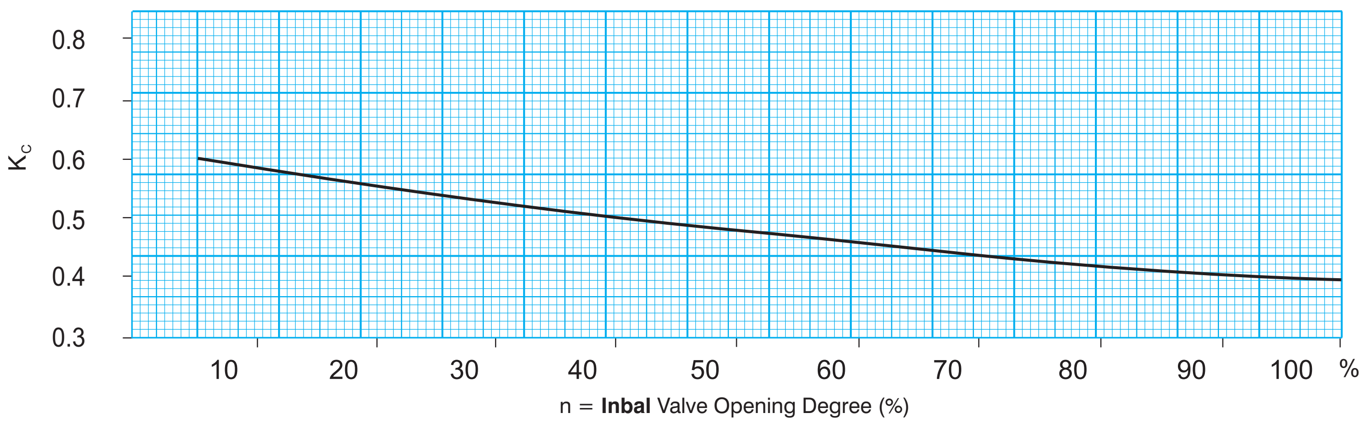


Figure (12)

*K_C curve for **Inbal** Valve series 700*

Liquid Critical Pressure Ratio Factor - F_F

When the ratio of pressure differential to the upstream absolute pressure less vapor pressure [DP/(P_1 - P_V)] increases beyond the stage of incipient cavitation, a choked flow condition is developed. Fully choked conditions are developed when downstream pressure is further decreased and upstream pressure remains constant, while not producing an increase of flow through the valve. While incipient cavitation occurs when vena contracta pressure (P_{VC}) equals that of the vapor pressure, at choked flow conditions the pressure at the vena contracta must be lower than the vapor pressure since more flow is realized at choked flow point than at incipient cavitation point [see Figure (5)].

The flow rate is a function of the pressure drop from the valve inlet to the vena contacta. Under non-vaporizing liquid flow condition, the pressure recovery is a consistent fraction of the pressure drop to the vena contracta, thus the vena contracta pressure can be predicted from the downstream pressure (P_2).

Under choked flow conditions there is no relationship between P_2 and P_{VC} because vaporization affects pressure recovery. The Liquid Critical Ratio Factor, designated by the symbol F_F , is the ratio of the vena contracta pressure, at choked flow condition to the vapor pressure of the liquid as its inlet temperature is called.

The F_F equation is based on the assumption that the fluid is always in the thermodynamic equilibrium and is defined as follows:

$$F_F = \frac{P_{VC}}{P_V} = 0.96 - 0.28\sqrt{\frac{P_V}{P_C}} \qquad (9\text{-}1)$$

For simplicity, if $P_V < 0.5\ P_1$ then the F_F value equal to 1 could be used within reasonable accuracy.

Nomenclature

- *F_F - Liquid critical pressure ratio factor (dimensionless).*
- *F_L - Liquid pressure recovery factor of Inbal Valve without attached fittings (dimensionless).*
- *K_C - Incipient cavitation coefficient (dimensionless).*
- *n - Inbal Valve opening degree (%).*
- *P_1 - Valve inlet pressure (bar absolute ; psia).*
- *P_2 - Valve outlet pressure (bar absolute ; psia).*
- *P_C - Absolute thermodynamic critical pressure (221.06 bar absolute ; 3206.2 psia) - see Table C.*
- *P_V - Absolute vapor pressure of liquid at flowing temperature (bar absolute ; psia) - see Table C.*
- *P_{VC} - Absolute pressure at the vena contracta (bar absolute ; psia).*
- *ΔP - Pressure differential (bar ; psi).*
- *ΔP_I - Pressure differential across the valve at incipient cavitation (bar ; psi).*

Liquid Sizing for Critical Flow

The pressure drop in a valve in which cavitation is experienced is termed as critical pressure drop (DP_{crit}). Full cavitation will therefore exist if actual pressure drop is greater than critical pressure drop and if the downstream pressure is higher than the fluid vapor pressure.
The critical pressure drop is defined as follows:

$$DP_{crit} = F_L^2 (P_1 - F_F \cdot P_V) \quad (10\text{-}1)$$

The actual valve Flow Factor under choked conditions is defined as follows:

$$K_v = \frac{Q}{F_L}\sqrt{\frac{G_f}{P_1 - F_F \cdot P_V}} \quad \text{or:} \quad (10\text{-}2)$$

$$C_v = \frac{Q}{F_L}\sqrt{\frac{G_f}{P_1 - F_F \cdot P_V}}$$

The flow rate under choked conditions is determined as follows:

$$Q = K_V \cdot F_L \sqrt{\frac{P_1 - F_F \cdot P_V}{G_f}} \quad \text{or:} \quad (10\text{-}3)$$

$$Q = C_V \cdot F_L \sqrt{\frac{P_1 - F_F \cdot P_V}{G_f}}$$

For P_v and P_c values refer to Table C

Table C:
Physical Properties of Water

Temperature of Water T C^0	Vapor Pressure P_v Bar Absolute	Temperature of Water T F^0	Vapor Pressure P_v Psia
0.01	0.006112	32	0.08859
5	0.008719	40	0.12163
10	0.012271	50	0.17796
15	0.017041	60	0.25611
20	0.023368		
		70	0.36292
25	0.031663	80	0.50683
30	0.042418	90	0.69813
35	0.056217	100	0.94924
40	0.073750		
		110	1.2750
45	0.09582	120	1.6927
50	0.12335	130	2.2230
55	0.15740	140	2.8892
60	0.19919		
		150	3.7184
65	0.25008	160	4.7414
70	0.31160	170	5.9926
75	0.38547	180	7.5110
80	0.47359	190	9.340
85	0.57803	200	11.526
90	0.70109	210	14.123
95	0.84526	212	14.696
100	1.01325	220	17.186
110	1.4326	240	24.968
120	1.9853	260	35.427
130	2.7012	280	49.200
140	3.6136	300	67.005

P_c = 221.06 [bar (A)] P_c = 3206.2 [psia]

Piping Effects

If the **Inbal** Valve is installed between reducers, the C_v of the entire assembly is different from that of the **Inbal** Valve alone. If the inlet and outlet reducers are the same size, the only effect is the added resistance of the fittings, which creates an additional pressure drop. If there is only one reducer or if there are reducers of different sizes, there will be an additional effect on the pressure due to the difference in velocity between the inlet and outlet stream.

Nomenclature

- F_F - *Liquid critical pressure ratio factor (dimensionless).*
- F_L - *Liquid pressure recovery factor of valve without attached fittings (dimensionless).*
- G_f - *Liquid specific gravity at flowing temperature (water = 1@ 15°C / 60°F).*
- K_v/C_v - ***Inbal** Valve minimum flow factor (Metric / English units).*
- P_1 - *Upstream absolute pressure (bar absolute ; psia).*
- P_c - *Pressure at thermodynamic critical point (bar absolute ; psia) - see Table C.*
- P_v - *Absolute vapor pressure of liquid at flowing temperature (bar absolute ; psia) - see Table C.*
- ΔP_{crit} - *Pressure differential across the valve at which cavitation is experienced (bar ; psi).*
- Q - *Flow rate (m^3/h ; U.S.gpm).*
- T - *Temperature of water (Celsius ; Fahrenheit).*

Piping Geometry Factor - F_P

The Piping Geometry Factor F_P accounts for fittings attached to either the valve inlet or outlet. F_P is actually the ratio of the valve Flow Factor (K_V or C_V) published as standard (refer to **Inbal** Valve installed in a straight pipe of the same size as the valve).The piping geometry factor (F_P) is calculated as follows:

$$F_P = \left[\frac{629K \cdot K_V}{d^4} + 1\right]^{-1/2} \qquad \text{or:} \qquad (11\text{-}1)$$

$$F_P = \left[\frac{K \cdot C_V}{890\, d^4} + 1\right]^{-1/2}$$

The K Factor values are calculated as follows:

For inlet reducer only:

$$K = 1.5 - \left(\frac{d}{D_1}\right)^2 \left[1 + 0.5\left(\frac{d}{D_1}\right)^2\right] \qquad (11\text{-}2)$$

For outlet increaser only:

$$K = 2\left(\frac{d}{D_2}\right)^2 \left[\left(\frac{d}{D_2}\right)^2 - 1\right] \qquad (11\text{-}3)$$

For inlet reducer and outlet increaser of the same size:

$$K = 1.5\left[1-\left(\frac{d}{D_{1;2}}\right)^2\right]^2 \qquad (11\text{-}4)$$

The inlet reducer and outlet increaser of different sizes:

$$K = 1.5 - \left(\frac{d}{D_1}\right)^2 \left[1 + 0.5\left(\frac{d}{D_1}\right)^2\right] + 2\left(\frac{d}{D_2}\right)^2 \left[\left(\frac{d}{D_2}\right)^2 - 1\right] \qquad (11\text{-}5)$$

Values of the K Factor calculated for several ratios of d/D are given in Table D.

Table D:
Reducers at ***Inbal*** *Valve, K Factors*

$\frac{d}{D}$		0.25	0.30	0.44	0.50	0.60	0.67	0.75	0.8
$D_1 = D_2 > d$	$K = 1.5[1-(\frac{d}{D})^2]^2$	1.32	1.19	1.06	0.84	0.61	0.46	0.29	0.19
$D_1 > d = D_2$	$K = K_I = 1.5-(\frac{d}{D})^2[1+0.5(\frac{d}{D})^2]$	1.44	1.38	1.33	1.22	1.08	0.96	0.78	0.66
$D_1 = d < D_2$	$K = K_D = 2(\frac{d}{D})^2[(\frac{d}{D})^2 - 1]$	-0.12	-0.20	-0.27	-0.38	-0.46	-0.49	-0.49	-0.46
$D_1 = D_2 > d$**	$K = K_I + K_D$	$K_I + K_D$	$K_I + K_D$	$K_I + K_D$	$K_I + K_D$	$K_I + K_D$	$K_I + K_D$	$K_I + K_D$	$K_I + K_D$

* *D_1 = Inlet reducer; D_2 = Outlet increaser; d =* ***Inbal*** *valve size.*

** *The values of K for the case of the last row are the sum of the K values derived from the second and third rows in the table, where K_I is for the inlet reducer and K_D is for the outlet increaser.*

Piping Effects in Subcritical Flow

The equations for determining the flow rate of a liquid across the **Inbal** Valve when it is installed with reducers and under turbulent non-vaporizing flow conditions are:

$$Q = F_P \cdot K_V \sqrt{\frac{P_1 - P_2}{G_f}} \qquad \text{or:} \qquad (11\text{-}6)$$

$$Q = F_P \cdot C_V \sqrt{\frac{P_1 - P_2}{G_f}}$$

$$K_V = \frac{Q}{F_P}\sqrt{\frac{G_f}{P_1 - P_2}} \qquad \text{or:} \qquad (11\text{-}7)$$

$$C_V = \frac{Q}{F_P}\sqrt{\frac{G_f}{P_1 - P_2}}$$

The Inbal Valve selected should be of flow factor greater by 15-40% of the flow factor calculated above.

Piping Effects in Critical Flow

The flow capacity of the **Inbal** Valve under choked flow conditions is also reduced. The liquid pressure recovery of the valve-fitting combination is not the same as that for the valve alone. For calculations, it is convenient to treat the Piping

Nomenclature

- d - **Inbal** *Valve size (mm ; inches).*
- D_1 - *Inlet internal pipe diameter (mm ; inches).*
- D_2 - *Outlet internal pipe diameter (mm ; inches).*
- F_p - *Piping geometry factor (dimensionless).*
- G_f - *Liquid specific gravity at flowing temperature (water = 1@15°C / 60°F).*
- K - *Head loss coefficient of a device (dimensionless).*
- K_D - *Velocity head factors for an outlet fitting (dimensionless).*
- K_I - *Velocity head factors for an inlet fitting (dimensionless).*
- K_V / C_V - **Inbal** *Valve flow factor (Metric / English Units).*
- P_1 - *Upstream absolute pressure (bar absolute ; psia).*
- P_2 - *Downstream absolute pressure (bar absolute ; psia).*
- Q - *Flow rate (m^3/h ; U.S.gpm).*

Geometry Factor (F_p) and the F_L Factor for the valve-fitting combination as a single factor designated F_P. The value of F_L for the combination is then the ratio F_{LP} / F_P.

The following equation should be used only when inlet reducer is used, since outlet reducer does not influence the flow.

The F_L of valve-fitting combination is designated as $(F_L)_P$:

$$(F_L)_P = \frac{F_{LP}}{F_P}\sqrt{\frac{P_1 - P_2}{P_1 - P_{VC}}} \qquad (11\text{-}8)$$

The following equation is used to determine F_{LP} :

$$F_{LP} = F_L\left[\frac{629 F_L^2 \cdot K_V^2 \cdot K_I}{d^4} + 1\right]^{-1/2} \quad \text{or:} \qquad (11\text{-}9)$$

$$F_{LP} = F_L\left[\frac{F_L^2 \cdot C_V^2 \cdot K_I}{890 d^4} + 1\right]^{-1/2}$$

Where K_I is the inlet fitting coefficient and is determined by the following equation:

$$K_I = 1.5 - \left(\frac{d}{D_1}\right)^2\left[1 + 0.5\left(\frac{d}{D_1}\right)^2\right] \qquad (11\text{-}10)$$

The pressure differential across the **Inbal** Valve with reducers in choked flow conditions are:

$$DP_{crit} = \left(\frac{F_{LP}}{F_P}\right)^2 (P_1 - F_F \cdot P_V) \qquad (11\text{-}11)$$

The flow rate across the **Inbal** Valve with reducers in choked flow conditions are:

$$Q = (F_L)_P \cdot K_V \sqrt{\frac{P_1 - F_F \cdot P_V}{G_f}} \quad \text{or:} \qquad (11\text{-}12)$$

$$Q = (F_L)_P \cdot C_V \sqrt{\frac{P_1 - F_F \cdot P_V}{G_f}}$$

Hydrodynamic Noise Calculation

Noise through the **Inbal** Control Valve is produced by two main hydraulic phenomena:

A. Flow noise - produced by the flow velocity and turbulence in the control valve. At low pipe velocity, the flow noise phenomenon is almost negligible, but in deluge and other fire protection applications, where flow is very high (more than 16.4 ft/sec or 5 m/sec), this phenomenon creates damage to the valve and equipment. Therefore, it is recommended to limit the velocity to less than 33 ft/sec (10 m/sec) and to limit the noise level to 82 dBA.

Flow Noise Calculation:

If $\Delta P < P_I$ where $\Delta P_I = K_C (P_1 - P_V)$, then

$$dBA = 10 \log \frac{K_V \cdot \Delta P^2}{t^3} + 70.5 \quad \text{or:} \qquad (12\text{-}1)$$

$$dBA = 10 \log \frac{C_V \cdot \Delta P^2}{t^3} + 5$$

B. Cavitation noise - caused by the collapsing of vapor bubbles at the downstream of the valve restriction area. Cavitation noise is accompanied by damage to the valve, pipe, and equipment. It is recommended to take immediate action against cavitation if cavitation exceeds the critical point and noise level is more than 82 dBA. For more details regarding cavitation, refer to the relevant sections of this bulletin.

Incipient Cavitation Noise Calculation:

$$N = \frac{5(\Delta P - \Delta P_I)}{\Delta P_{crit} - \Delta P_I}$$

If $\Delta P_I < \Delta P_{crit}$ where $\Delta P_{crit} = F_L^2 (P_1 - P_V)$, then:

$$dBA = 10 \log \frac{K_V \cdot \Delta P^2}{t^3} + N \log 14.5 (P_2 + 0.07 - P_V) + 70.5 \qquad (12\text{-}2)$$

or:

$$dBA = 10 \log \frac{C_V \cdot \Delta P^2}{t^3} + N \log (P_2 + 1 - P_V) + 5$$

Critical Cavitation Noise Calculation:

If $\Delta P > \Delta P_{crit}$ and $P_2 > Pv$ where $\Delta P_{crit} = F_L^2 (P_1 - P_V)$, then:

$$dBA = 10 \log \frac{K_V \cdot \Delta P^2}{t^3} + \log \frac{[14.5 (P_2 + 0.07 - P_V)]^N}{(\Delta P + 0.07 - \Delta P_C)^5} + 64.5 \qquad (12\text{-}3)$$

or:

$$dBA = 10 \log \frac{C_V \cdot \Delta P^2}{t^3} + \log \frac{(P_2 + 1 - P_V)^N}{(\Delta P + 1 - \Delta P_C)^5} + 5$$

Nomenclature

- *d* - ***Inbal** Valve size (mm ; inches).*
- D_1 - *Inlet internal pipe diameter (mm ; inches).*
- F_F - *Liquid critical pressure ratio factor (dimensionless).*
- F_L - *Liquid pressure recovery factor of **Inbal** Valve without attached fittings (dimensionless).*
- F_{LP} - *Product of the liquid pressure recovery factor of the **Inbal** Valve with attached fittings [F_{LP}], and the piping geometry factor (F_P) (dimensionless).*
- $(F_L)_P$ - *Liquid pressure recovery factor of the **Inbal** Valve with attached fittings (dimensionless).*
- F_P - *Piping geometry factor (dimensionless).*
- G_f - *Liquid specific gravity at flowing temperature (water = 1@ 15°C / 60°F).*
- K_C - *Incipient cavitation coefficient.*
- K_I - *Velocity head factors for an inlet fitting (dimensionless).*
- K_V/C_V - ***Inbal** Valve flow factor (Metric / English units).*
- P_1 - *Upstream absolute pressure (bar absolute ; psia).*
- P_2 - *Downstream absolute pressure (bar absolute ; psia).*
- P_V - *Absolute vapor pressure of liquid at flowing temperature (bar absolute ; psia).*
- P_{vc} - *Absolute pressure at vena contracta (bar absolute ; psia).*
- ΔP - *Pressure differential (bar ; psi).*
- ΔP_{crit} - *Pressure differential across the valve at which cavitation is experienced (bar absolute ; psia).*
- ΔP_I - *Pressure differential across the valve at incipient cavitation (bar ; psi).*
- *Q* - *Flow rate (m^3/h ; US gpm)*
- *t* - *Pipe wall thickness (mm ; inches).*

How to Avoid Cavitation

Referring to the relationship $DP_{crit} = F_L^2 (P_1 - F_F P_V)$, the obvious remedy is to reduce the pressure drop across the **Inbal** Valve to below DP_{crit}. This can be done by increasing P_2. For example, to install an orifice plate at the **Inbal** Control Valve outlet [see figure (13)], part of the total required pressure differential is absorbed by the orifice plate. Therefore, the pressure differential across the **Inbal** Valve is reduced and the P_{vc} pressure increases above the P_V pressure.

This orifice is quite effective in eliminating the cavitation at the high rates of flow (colored lines). When the flow rate is reduced, the head loss through the orifice plate is also reduced (by square root) and the **Inbal** Valve should "break" more pressure now. Consequently, cavitation conditions occur. [See Figure (14)].

It is advisable to calculate the maximum flow which can be released through the selected orifice plate. The orifice pressure recovery factor is:

$$F_{LO} = \sqrt{0.970 - 0.925 \frac{d_O^2}{D^2}} \qquad (12\text{-}1)$$

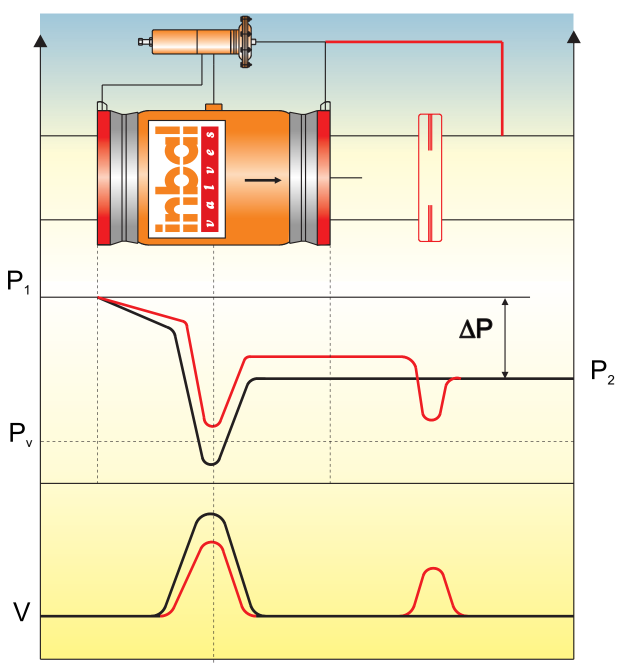
The orifice plate is in cavitation whether the result of $F_{LO}^2(P_1 - F_F P_V)$ is equal to or greater than the actual DP through the orifice plate.

$$DP_{O\ crit} = F_{LO}^2 (P_1 - F_F \cdot P_V) \qquad (12\text{-}2)$$

The maximum flow that can be handled by the orifice plate then is:

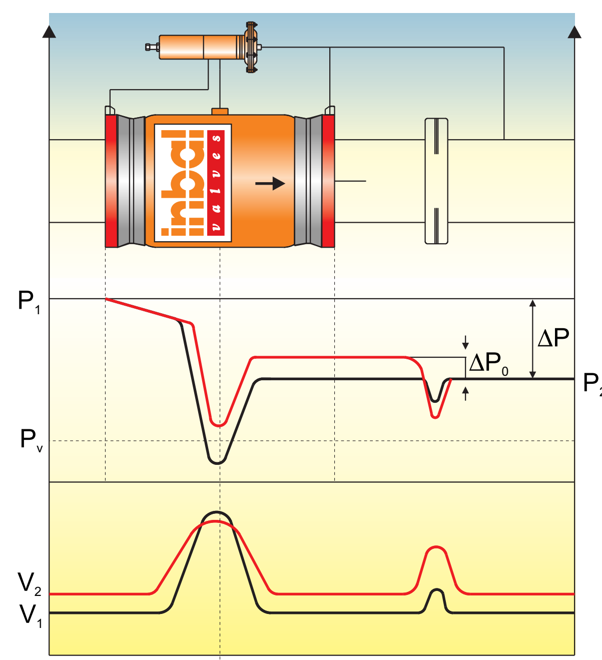
$$Q = K_{VO} \cdot F_{LO} \sqrt{\frac{P_1 - F_F \cdot P_V}{G_f}} \quad \text{or:} \qquad (12\text{-}3)$$

$$Q = C_{VO} \cdot F_{LO} \sqrt{\frac{P_1 - F_F \cdot P_V}{G_f}}$$



— Without orifice plate, cavitation occurs.
— With an orifice plate, cavitation is avoided

Figure (13)
Orifice plate to avoid cavitation.



— Low flow rate, cavitation occurs.
— High flow rate, orifice prevents cavitation.

Figure (14)
Orifice plate to avoid cavitation at high and low flow rates.

Nomenclature

- d_o - Diameter of orifice bore (mm / inches).
- D - Internal pipe diameter (mm / inches).
- F_F - Liquid critical pressure ratio factor (dimensionless).
- F_L - Liquid pressure recovery factor without attached orifice plate (dimensionless).
- F_{LO} - Orifice plate pressure recovery ratio (dimensionless).
- G_F - Liquid specific gravity at flowing temperature (water = 1@ 15°C / 60°F).
- K_{VO}/C_{VO} - Orifice plate flow factor (metric / English units).
- P_1 - Upstream absolute pressure (bar absolute ; psia).
- P_V - Absolute vapor pressure of liquid at flowing temperature (bar absolute ; psia).
- P_{vc} - Absolute pressure at vena contracta (bar absolute ; psia).
- $\Delta P_{O\ crit}$ - Pressure differential across the orifice plate at which cavitation is experienced (bar absolute ; psia).