Tech Sheet #CVR 403

Laminar Flow Valve Sizing Made Easy

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NOMENCLATURE

C_v	Flow coefficient, gpm/(PSI) $^{.5}$
C_{VL}	Flow coefficient calculated assuming laminar flow, gpm/(PSI) $^{.5}$
C_{VT}	Valve flow coefficient measured under fully turbulent conditions, (rated C_v in valve manufacturer's catalog), gpm/(PSI) $^{.5}$
D	Valve Diameter, in.
D_o	Equivalent Orifice diameter, in.
F_d	Valve style modifier, D_H/D_o, dimensionless
F_L	Liquid Pressure Recovery Factor, dimensionless
F_R	Valve Reynolds number factor, dimensionless
K	Velocity head loss coefficient of valve, dimensionless
L	Length of valve flow path, in
P	Pressure, psi
q	Gas flow rate, ACFH (SCFH * SG)
Q	Liquid flow rate, gal/min
Re_O	Orifice Reynolds number, dimensionless
Re_V	Valve Reynolds number, dimensionless
β	D_o/D, *dimensionless*
ρ	Density, lb/ft^3
ν	Kinematic viscosity, centistokes, 10^{-6} m^2/s

Subscripts:

F	Full Trim, $10<C_{VT}/D_o^2<30$
H	Hydraulic
L	Laminar flow regime
P	Pipe
R	Reduced Trim, $C_{VT}/D_o^2<10$
T	Turbulent flow regime

Equations to calculate control valve C_v values in the laminar and transitional flow regimes have been derived from fundamental principles. These equations are simpler and more accurate to use than the ISA standard 75.01.

Most valve sizing is done using Cv equations which are only good for turbulent flow when the Reynolds Number is greater than 10,000. The Reynolds number for liquids in the turbulent regime is[1]:

$$\mathrm{Re}_P = \frac{3160 * Q}{D_P * \nu} \qquad (1)$$

This equation shows that a low Re_P is generally found with high viscosities or low flow rates. To understand why viscosity would effect a valve's flow capacity, assume a ½" valve has a C_v of 5, which means it can flow 5 gpm of water with a 1 PSI pressure drop (Re = 31600). To flow 5 gpm of syrup (ν=1000) with the same 1 PSI pressure drop (Re=31.6) would require a valve with a capacity larger than 5. The ratio of these two factors is defined:

(2) $$F_R = \frac{C_V}{C_{VT}}$$

The laminar Cv is therefore defined as the Valve Reynolds Number Factor multiplied by the turbulent Cv.:

(3) $$C_V = F_R * C_{VT}$$

An equation for F_R can be derived if you first model a control valve in the transitional regime as two valves in series as shown in Figure #1. In this case the flow moves slowly through the test piping and body piping and very quickly through the throttling orifice. Therefore in this model the first valve is the body Cv with a laminar Re_V (C_{VL}) and the second valve is the Cv from the orifice with a turbulent Re_o (C_{VT}) as shown in Figure #1.

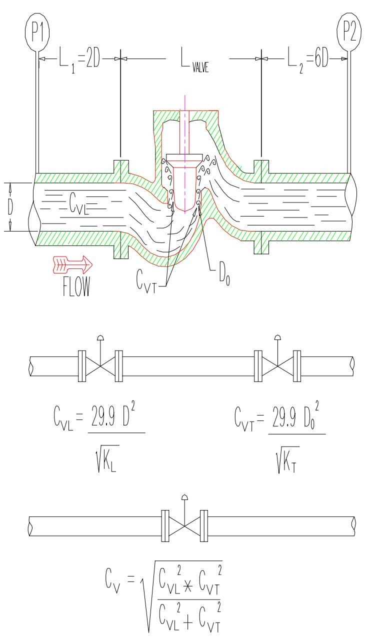


Figure # 1 – Flow Modeled as Two Valves in Series

The combined liquid C_v for two C_V values in series can be calculated by substituting $C_{VL}=A/(P_1-P_2)^{.5}$ and $C_{VT} = A/(P_2-P_3)^{.5}$ into the equation $C_V = A/(P_1-P_3)^{.5}$ where $A=Q(G)^{.5}$ for subcritical flow or $Q(G)^{.5}/F_L$ for critical flow. The combined liquid C_V is:

(4) $$C_V = \sqrt{\frac{C_{VL}^2 * C_{VT}^2}{C_{VL}^2 + C_{VT}^2}}$$

For a valve under turbulent flow C_{VT},the rated maximum Cv of the valve, is[1]:

(5)

$$C_{VT} := \frac{29.9 \cdot D_o^2}{\sqrt{K_T}}$$

Before continuing with the derivation of F_R, an explanation of D_o and D must be made. D_o is generally thought to be the orifice which is typically equal to the pipe size. For a pipe $D_o = D_P$, and $C_{VT}/D_O^2 = 29.9$ since $K_T = 1$. In a valve D_o is an equivalent diameter which gives the same circular area as the actual valve opening. For instance when a control valve is throttling, the plug is moved partially into the seat which creates an annular orifice as shown in Figure #2.

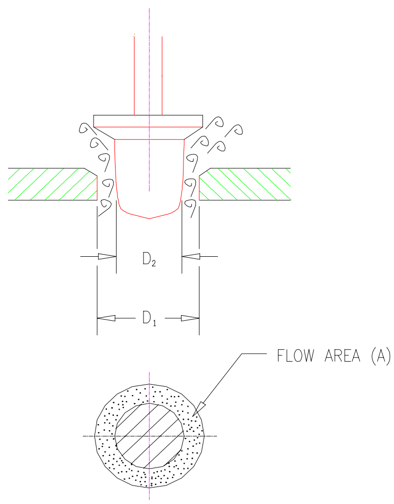


Figure # 2 – Determination of D_O

If the seat diameter is D_1 and the plug diameter is D_2 then the area of this orifice would be $Pi*(D_1^2-D_2^2)/4$. The orifice diameter for this application would therefore be:

$$D_O = \sqrt{D_1^2 - D_2^2}$$

The equation for C_{VL} is similar to equation #5 for the laminar flow regime. However in the laminar regime the hydraulic diameter must be substituted for the diameter. The hydraulic diameter is defined as D_O*Fd. In this case since we are talking about a circular pipe as being the flow path, the Fd = 1 and $D_H = D_P$. Therefore :

(6) $$C_{VL} = \frac{29.9 * D_P^2}{\sqrt{K_L}}$$

Substituting equations 4, 5,and 6 into 2 and simplifying yields:

(7) $$F_R = \frac{1}{\sqrt{1+\frac{K_L}{K_T}}}$$

The Crane Handbook[1] defines K as fL/D, and for laminar flow when Re <2100 Poiseuille's law is applicable so f = 64/Re and:

(8) $$K_L = \frac{64*L}{\mathrm{Re}_P * D_P}$$

Substituting Equations 8 and 1 into Equation 7 yields an equation for F_R which is valid for the laminar, transitional and turbulent flow regimes:

(9) $$F_R = \frac{1}{\sqrt{1+\frac{v*L*C_{VT}^2}{44142*Q*D_O^4}}}$$

This equation indicates that the F_R factor is a function of the viscosity, the flow rate Q, the orifice diameter D_O and the length of the flow path L, and is independent of D_P, F_L and Fd. The length of the flow path L is the distance between the pressure taps used to calculate the Cv. This is shown in Figure 1 to be approximately equal to eight times the valve size added to the face-to-face dimension of the valve.

Derived Equation #9 is remarkably close to the current ISA Equation if D_o=1. Test data proves this method to be extremely accurate. Figure #3 shows data for a Spence ½" J control valve. The Spence valve has a face-to-face dimension of 7.625" and a standard tapered plug in a .125 orifice. This valve has a C_{VT} of .051and a D_o of .057. Test data was taken by leaving the valve wide open and reducing the flow rate and Reynolds number by gradually reducing the pressure drop.

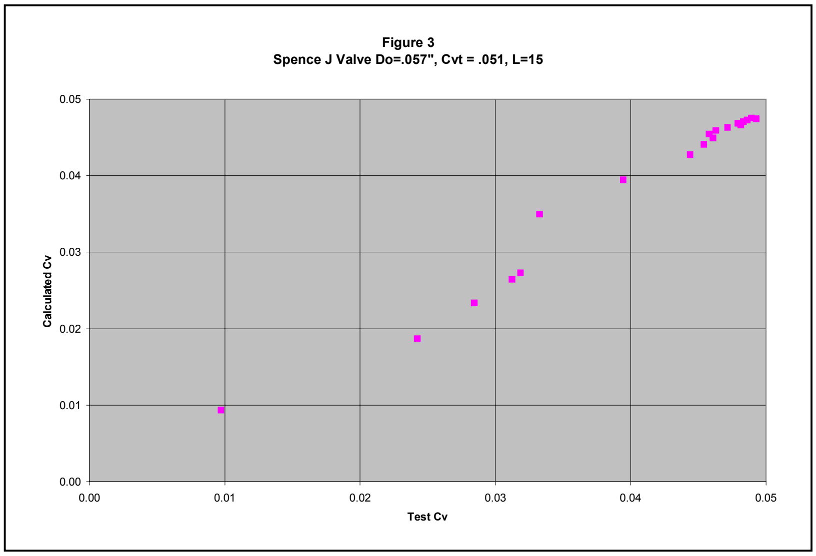
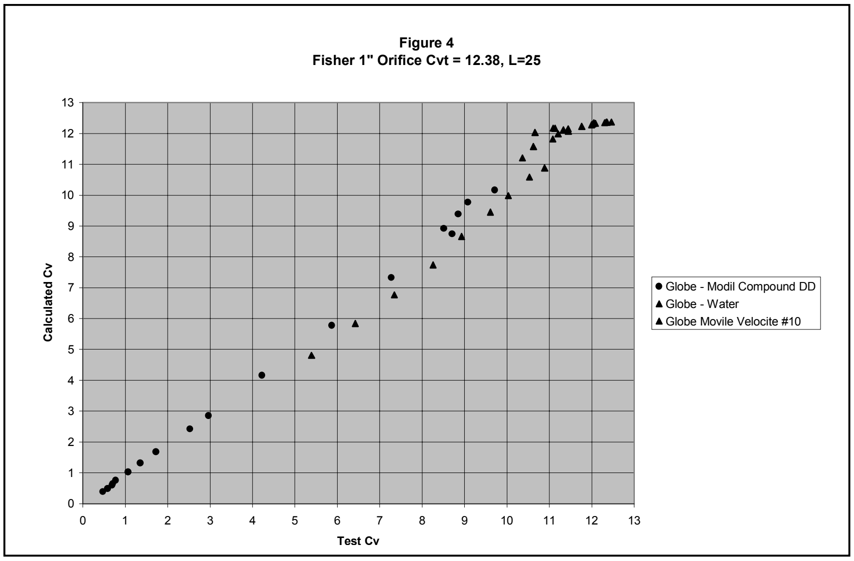


Figure #4 shows test data for a 1" Fisher Globe valve and Figure #5 shows test data for a V-Port Globe valve for a variety of fluids.



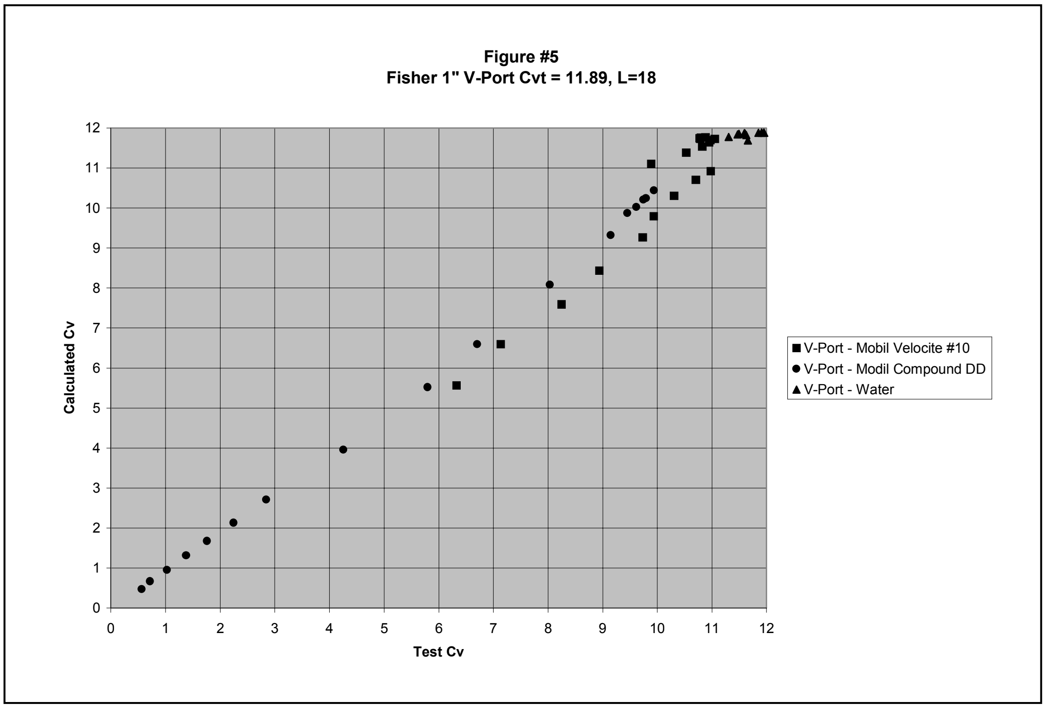


Figure #6 shows data for a Neles Controls 2" Finetrol valve flowing a fluid with a viscosity of 31729 cs. In this case the data shows F_R values as the valve is gradually closed to about 10% of its wide open C_{VT}. The orifice diameter values (Do) are calculated assuming C_{VT}/D_O remains constant as the valve is closed (constant K_T = 4.91). Again the derived equations give a remarkably good fit considering the difficulty in getting reliable test data in the Re_V range of only 1. An L of 22" was used for this data.

Figure #6 – Neles Controls 2" Finetrol, C_{VT} = 53.95

Travel	Do	Cvt	GPM	Cv_L Test	Calc F_R	Cv_L Calc	Calc/Test
10%	0.68	6.27	0.172	0.05	0.0077	0.05	1.00
30%	1.10	16.45	1.327	0.43	0.0215	0.35	0.82
50%	1.41	26.82	2.382	0.88	0.0288	0.77	0.87
75%	1.76	41.80	3.046	1.23	0.0325	1.36	1.11
100%	2.00	53.95	3.717	1.46	0.0359	1.94	1.32

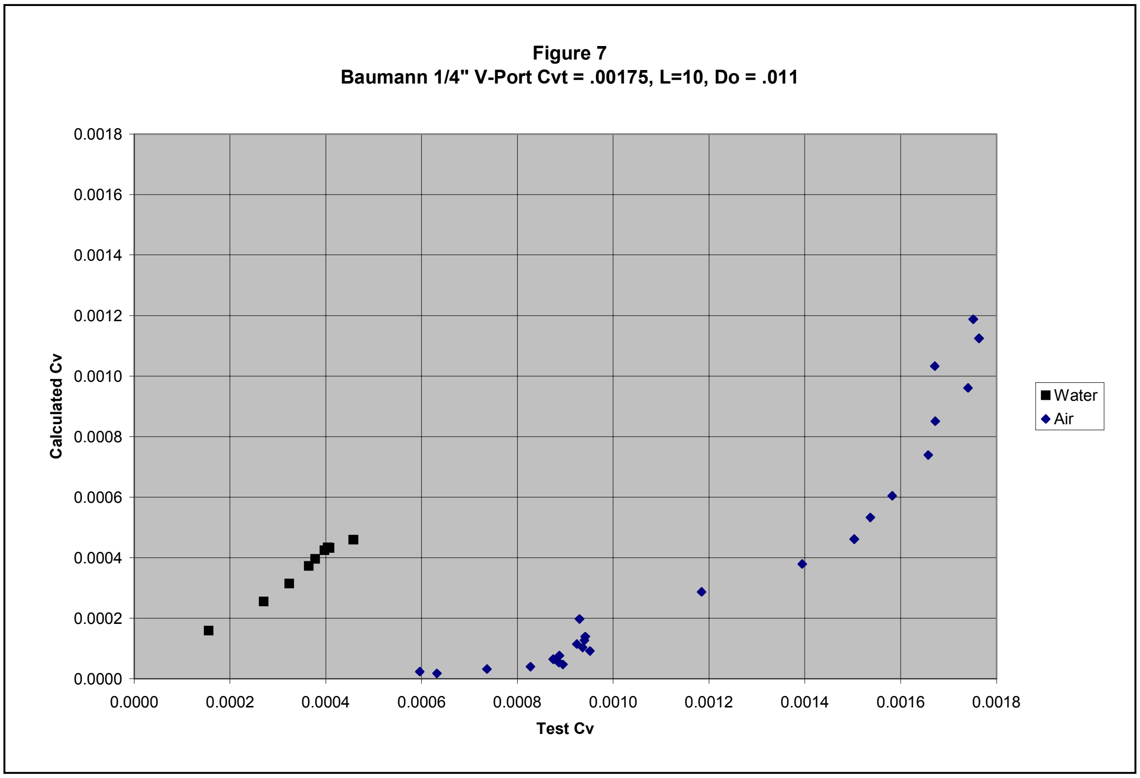
The *FR* value for a gas can be calculated starting with the gas Reynolds Number:

$$\text{Re}_P = \frac{.482 * q}{D_P * \nu} \qquad (12)$$

By substituting Equation # 8 and #12 into Equation #7, an FR value is obtained which is valid for the laminar, transitional and turbulent flow regimes:

$$F_R = \frac{1}{\sqrt{1 + \dfrac{\nu * L * C_{VT}^2}{6.7 * q * D_O^4}}} \qquad (13)$$

Figure #7 shows liquid and air data[3] for a ¼" Baumann small flow trim valve with a C_{VT} of 0.00175, and D_O of .011. a show Equations #9 and #13 are amazingly accurate.



Acknowledgement

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References

1. Crane Co., "Flow of Fluids Through Valves, Fittings, and Pipe", Technical Paper No. 410.
2. Page, George, "Simplified Valve Sizing for Laminar Flows", Chemical Engineering, October 1998.