Size Control Valves for Lab-Scale Laminar Flow

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Existing equations used to size control valves are inadequate for laboratory- and pilot-scale work. Use the simple equation introduced in this article to accurately size needle control valves for laminar and transitional flow.

Sizing valves for laboratory- or pilot-scale use must account for flow in the laminar and transitional regimes. Conventional equations for calculating the flow coefficient (C_V) — the essential parameter for sizing control valves — work only for turbulent flow (Re > 10,000).

This article provides an overview of the available equation to calculate C_V and discusses its applicability to turbulent flow. It then offers a new way to size valves for flow in laminar and transitional regimes. The discussion focuses on the needle valve (Figure 1), which is the most accurate among the various types of control valves and is most often used for lab- and pilot-scale work.

Laminar and transitional flow

The flow coefficient (C_V) is the volumetric flowrate (gpm) of water that can pass through a valve with a 1-psi pressure drop across the valve at standard temperature. Valve manufacturers provide flow capacities expressed in terms of C_V for their valves of varying sizes and types.

The conventional equation used to calculate C_V is:

$$C_V = Q\left(\sqrt{\frac{SG}{P_1 - P_2}}\right) \quad (1)$$

where Q is the volumetric flowrate (gpm), SG is the specific gravity of the fluid relative to water (dimensionless), P_1 is the inlet pressure (psi), and P_2 is the outlet pressure (psi). This equation is valid only for turbulent flow.

In the small valves used in the lab or pilot plant, however, the flow of liquids is often not turbulent, despite what many may believe.

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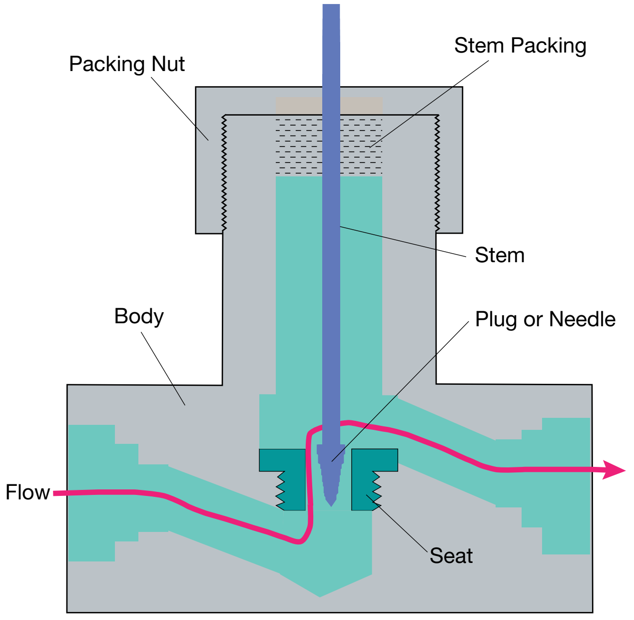
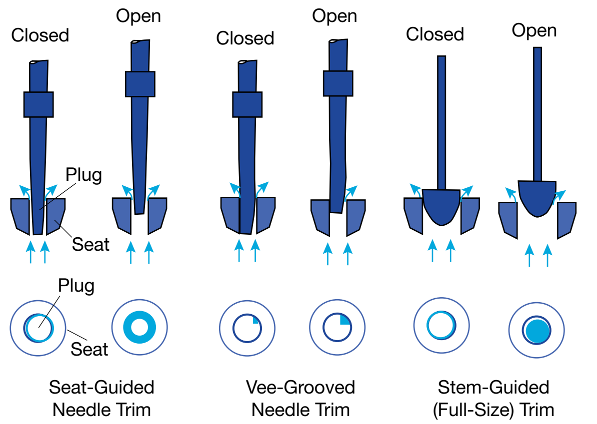
Consider the flow of a fluid through a needle control valve sized for a lab or pilot plant. The valve's trim, which consists of the seat and the plug, defines the flow path. (Figure 2 shows three types of trims commonly found in needle control valves.) The annulus formed between the seat hole (on the order of 0.060 in. dia.) and the needle or plug (on the order of perhaps 0.0595 in. dia.) is very small,



▲ **Figure 1.** A typical needle control valve consists of a body, stem and plug, seat, and packing. The body encases the valve parts and includes the fluid flow path and the inlet and outlet connections. An actuator moves the stem up and down through the packing in the body. The plug (or needle) is a machined part on the end of the stem that fits into the seat of the valve. The internal parts of the valve are collectively referred to as the valve's trim.



▲ **Figure 2.** Three common types of needle valve trims are seat-guided, vee-grooved, and stem-guided trims. The trim type determines the fluid flow path through the valve. In a seat-guided valve (left), the flow path is a circular annulus that varies in both length and inner diameter with the travel of the valve, and the plug is never completely removed from the seat, even when the valve is 100% open. In a vee-grooved valve (center), vee-shaped grooves are milled into the plug and the fluid flows along these grooves. In the stem-guided trim (right), which is also referred to as full-size trim, opening the valve raises the plug and creates a circular hole that the fluid passes through when the valve is 100% open.

so the velocity of the fluid moving through this valve will be very high. But high fluid velocity alone does not mean that the flow is turbulent ($Re > 10{,}000$), because the Reynolds number depends on more than just the velocity. In these small needle valves, the surface area (or wetted perimeter) of the annulus is large enough to stabilize laminar flow, even at very high velocities. Thus, Eq. 1 is not applicable to pilot-scale needle valves.

Applying Eq. 1 to a system operating at laminar or transitional flow conditions will result in valves that are significantly undersized, sometimes by many trim sizes.

Methods to correct for laminar flow

Rely on vendor expertise. Some manufacturers of lab- and pilot-scale control valves are aware of the consequences of laminar flow on sizing and have developed their own methods to correct for this phenomenon. However, we have found that vendors' sizing predictions for viscous liquids do not match measurements; frequently, the predictions and the measurements can differ by 200–500%. Therefore, we do not recommend relying solely on vendor sizing for laminar flow conditions.

Use the ISA method. The International Society of Automation (ISA) has developed a rather complex and cumbersome method to size valves in the laminar and transitional flow regimes *(1)*. This iterative method is often simplified to nomographs that can be used to determine an effective valve Reynolds number and the associated valve sizing correction factor (F_R). F_R is a "fudge factor" and is expressed as:

$$F_R = \frac{C_{VL}}{C_{VT}} \tag{2}$$

where C_{VL} is the flow coefficient for laminar or transitional flow (gpm/psi$^{0.5}$) and C_{VT} is the flow coefficient for turbulent flow (gpm/psi$^{0.5}$). F_R approaches 1 as flow approaches fully developed turbulent conditions, and becomes significantly less than 1 as flow becomes laminar.

For laminar conditions, ISA defines F_R as:

$$F_R = aRe^b \tag{3}$$

where a and b are constants that depend on whether the goal is to size a valve for a particular flowrate and pressure drop, to calculate the flowrate given the C_{VT} and the pressure drop, or to predict the pressure drop required to obtain a given flowrate through a valve of known C_{VT}. For transitional flow, F_R simply transitions smoothly between the two equations $F_R = aRe^b$ and $F_R = 1$, and is generally given in tabular or graphical format.

Unfortunately, determining the valve-trim Reynolds number (Re in the annulus between the plug and the seat) in valve trims of the size used in lab and pilot plant equipment ($C_V < 1$) is not straightforward. The ISA method does not clearly specify how to determine or select the appropriate variables (velocity, diameter, etc.) to use in the equations. And, valve manufacturers consider the geometric dimensions of their trims a proprietary part of their design and seldom publish that information.

Apply Page's equation. George W. Page described a simpler and more elegant method of sizing valves in the laminar and transitional flow regimes *(2)*. This method models a control valve in the transitional flow regime as two valves in series: one valve in purely laminar flow (representing flow through the body piping), and one in turbulent flow (representing flow through the throttling orifice). Applying the simple equations in Crane *(3)* for each of the two conditions, Page arrives at a new equation for the laminar/transitional flow sizing correction factor, F_R:

$$F_R = \frac{1}{\sqrt{\left(1+\left(\frac{\nu L}{44{,}142Q}\right)\left(\frac{C_{VT}}{D_O^2}\right)^2\right)}} \tag{4}$$

where ν is the fluid kinematic viscosity (cSt), L is the length of pipe between the upstream and downstream pressure-measurement taps (in.), and D_O is the diameter of a circle that has the same area as the valve opening (in.):

$$D_O = \sqrt{\frac{4A}{\pi}} \tag{5}$$

where A is the area of the annulus between the plug and the seat (in.^{2}).

Page demonstrated good agreement between the results of Eq. 4 and experimental data. However, this equation is not easy to use because D_O is not always known. D_O is calculated from the valve geometry, and is equal to the valve size only for full-sized globe-type trims.

For a lab- or pilot-scale valve, frictional loss in the inlet and outlet tubing is not the controlling resistance to flow and seldom contributes detectably to the overall pressure drop, so L is meaningless in the laminar flow situation. Thus, Eq. 4 is not valid for nonturbulent conditions in reduced-port valves.

Use Zeton's K-factor method. Rearranging Page's equation (Eq. 4) reveals that L/D_O^2 is an adjustable parameter with little practical physical meaning. Indeed, it is essentially a parameter of fit for the Fanning/Darcy equation *(4)*.

When flow is purely laminar, Page's equation (Eq. 4) *(2)* reduces to:

$$F_R = 210\left(\frac{D_O^2}{C_{VT}\sqrt{\dfrac{Q}{\nu L}}}\right) \tag{6}$$

Upon rearrangement of this equation, it appears that a new parameter, K, can be constructed to account for the contributions of the lumped parameter L/D_O^2, the fluid density (ρ, kg/m^3), and a unit conversion factor. K can be obtained from a plot of flow versus $\Delta P/\mu$, where ΔP is the pressure difference across the valve (psi) and μ is dynamic viscosity (cP). This plot is a straight line through the origin for a valve in fully laminar flow (Figure 3). Accordingly, the value of K for any particular valve can be determined through a single experiment with a Newtonian fluid viscous enough and at a flowrate low enough to ensure fully laminar flow through the valve trim. (The flow must be fully laminar such that the flowrate varies linearly with $\Delta P/\mu$.)

Thus, for fully laminar flow:

$$Q = \frac{\Delta P}{K\mu} \tag{7}$$

Page's equation then reduces to:

$$F_R = \frac{1}{\sqrt{1+\dfrac{\mu K C_{VT}^2}{Q}}} \tag{8}$$

Separate experiments for each trim size are required to determine the value of K, which varies with the C_{VT} of the valve.

Zeton's new laminar flow sizing parameter

An equation relating K and C_{VT} could reduce the number of experiments needed to determine K for a series of trims that have similar geometry but different C_{VT} values. We hypothesized that families of trims of similar geometry would need only a single parameter to describe their laminar flow performance relative to that observed in turbulent flow, since the same underlying geometric factors define pressure drop for a particular trim type under any flow regime.

The ISA *(1, 5)* provides the relationship $F_R = aRe^b$, with the exponent b set to 0.5, 0.67, or 1, depending on the intended use. We tested the relationship for $b = 0.5$.

Consider a valve of a particular geometry with a particular fluid flowing through it at a constant valve opening (%). The Reynolds number, $Re = DV\rho/\mu$ (where D is the diameter of the opening in meters and V is the velocity in m/sec) varies directly with the volumetric flowrate. Taking the definitions of K (Eq. 7) and F_R (Eq. 3), and then grouping all of the proportionality constants together as a_v, we obtain the following relationship:

$$C_{VT} = \frac{a_v}{\sqrt{K}} \tag{9}$$

where a_v and K are both lumped parameters of best fit (without a clear physical interpretation). Substituting the laminar flow geometric parameter a_v into Page's equation (Eq. 8) gives the following simple relationship:

$$F_R = \frac{1}{\sqrt{1+\dfrac{\mu a_v^2}{Q\times SG}}} \tag{10}$$

Next, the equations that define C_V (Eq. 1) and F_R (Eq. 2) can be combined with Eq. 10 to derive a new sizing equation:

$$C_{VT\text{-}Req} = Q\sqrt{\frac{SG}{\Delta P}}\left(\sqrt{1+\frac{\mu a_v^2}{Q\times SG}}\right) \tag{11}$$

Solving for Q yields a somewhat more complex equation:

$$Q = \frac{-\mu a_v^2 + \sqrt{\left(\mu a_v^2\right)^2 + 4(SG\times C_{VT}^2\times \Delta P)}}{2(SG)} \tag{12}$$

Equation 12 reduces to Eq. 1, which is the definition of C_V for turbulent flow, when $a_v = 0$ or when the product μa_v^2 is sufficiently small. A high a_v value for a particular trim geometry indicates that the trim has a tendency to stabilize laminar flow to a greater extent than trims with a lower a_v value, perhaps due to the higher ratio of wetted perimeter to cross-sectional area in the flow path.

This model uses a single parameter to correct for the laminar flow behavior of a series of geometrically similar trims, across a wide range of C_{VT} values. For two popular trim brands, we found that a_v values of 0.135–0.14 provide an excellent fit.

This simple, one-parameter model given in Eqs. 11 and 12 may be cautiously extended to use with other seat-guided annular needle-type valves. In this case, the model equations should not be trusted completely and should be verified with experiments. However, it will surely give better results than either the turbulent sizing equation, or the ISA sizing equations without values for F_d and D validated by real testing on viscous liquids.

Equations 11 and 12 with a conservative value of a_v (*e.g.*, 0.18) can be used for the approximate sizing of annular needle-type trims in the absence of other data. Equation 11 with $a_v = 0.18$ can also be used as a test of whether laminar-flow correction is necessary. If the calculated F_R is significantly less than 1, it would be prudent to either perform validation experiments with your particular trim and fluid, or to have your valve supplier do so for you.

Model verification for seat-guided needle trims

The model (Eqs. 11 and 12) was verified for a pneumatically actuated needle control valve (Brand A). The valve's trim, which is a type widely used in lab- and pilot-scale work, has a proprietary design, the dimensions of which are not published. In general, however, the trim involves a small-bore circular seat with a tapered needle plug that is never completely removed from the seat even when the valve is fully open (*i.e.*, the plug is seat guided).

The testing apparatus consisted of a reservoir of liquid that could be pressurized with air or nitrogen, a filter to remove fine particulate matter, an accurate differential-pressure transmitter with tubing tees mounted immediately upstream and downstream of the valve body to connect the pressure-measurement impulse lines, a bucket or vial, and an accurate scale. Data on weight and time were collected and used with the liquid density to calculate volumetric flowrate.

Data were collected over a range of applied pressures (5–500 psig) for several trim sizes. Brand A's manufacturer sells valves with trim sizes designated by letters ranging from A (largest) to P and micro-flow trims designated as P1 (largest of the micro trims) to P14. The verification tests evaluated trim sizes M, P1, P3, and P5.

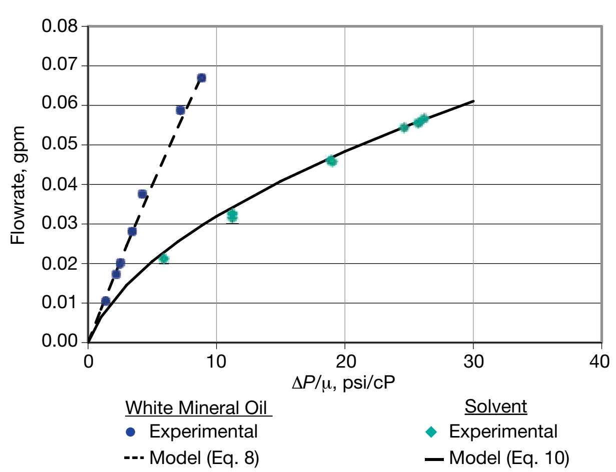
Gas flow measurements were taken to verify the actual C_{VT} of the valves. A rotameter and thermal mass flowmeter were used to measure the flowrate of bottled nitrogen, with measurements made in choked flow (*i.e.*, $P_1 > 2P_2$).

Figure 3 presents the results of the first set of tests, which used two fluids — Liquid 1 (a kerosene-like solvent with $\mu = 0.8$ cP and $\rho = 788$ kg/m^3 at 20°C) and Liquid 2 (a paraffin white mineral oil with $\mu \sim 29$ cP and $\rho = 846$ kg/m^3 at 20°C) — flowing through a 0.25-in. Brand A control valve with an M trim size. The vendor specifies this valve's C_{VT} to be 0.01 nominal; the measured C_{VT} based on nitrogen flow measurements is 0.012.

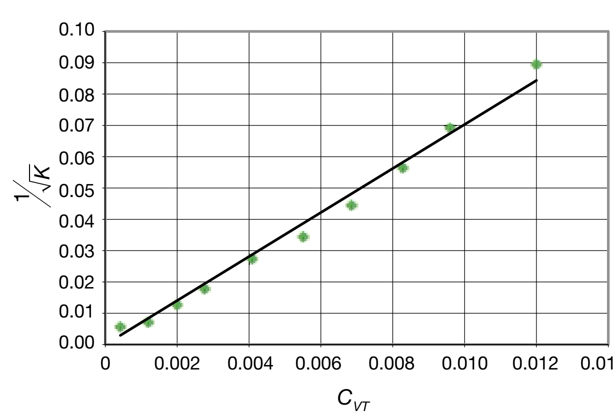
As shown in the Q vs. $\Delta P/\mu$ plot in Figure 3, the model of Eq. 8 is in excellent agreement with the experimental data for Liquid 2 in purely laminar flow in this trim, with F_R under these conditions ranging between 0.25 and 0.6. The more-general model of Eq. 10 does a good job of predicting the experimental data for the much-less-viscous Liquid 1 (F_R ranging from 0.93 to about 1) in transitional to turbulent flow.

The next set of tests used more-viscous fluids, Liquid 3 ($\mu \sim 90$ cP) and Liquid 4 ($\mu \sim 296$ cP), and Brand A valves with the smaller trims of P1 ($C_{VT} \sim 0.002$), P3 ($C_{VT} \sim 0.001$), and P5 ($C_{VT} \sim 0.0004$). The unique K values obtained for each trim size were in excellent agreement with Eqs. 8 and 10.

Figure 4 is a plot of $K^{-0.5}$ vs. measured C_{VT} for all of the valve trims of Brand A that were tested, including the M trim at varying stem positions. The slope of this plot is the laminar flow sizing coefficient, a_v, which for this brand and



▲ **Figure 3.** The volumetric flowrate as a function of $\Delta P/\mu$ is plotted for two liquids. The model of Eq. 8 fits well for Liquid 2 (mineral oil) in purely laminar flow (F_R under these conditions ranges between 0.25 and 0.6), while the more-general model of Eq. 10 does a good job of predicting the experimental data for transitional to turbulent flow for the much-less-viscous Liquid 1 (solvent) (F_R ranges from 0.93 to about 1).



▲ **Figure 4.** $K^{-0.5}$ vs. measured C_{VT} for all of the Brand A valve trims. The slope of this plot is the laminar-flow sizing coefficient, a_v.

these trims had a value of about 0.135. The graph demonstrates the excellent fit of the new model (Eqs. 11 and 12) to the entire set of measured data for the entire family of trims.

Subsequent testing used a different brand of control valves with similar seat-guided needle-type trims in a similar trim size range (C_{VT} = 0.01–0.0001). In these tests, a_v had similar values, in the range of 0.12–0.14. The value of a_v did not change much with trim travel, similar to what was observed for Brand A.

Low-flow control valves manufactured by other vendors with similar seat-guided needle-type valve trims were found to have a_v values of similar magnitude. An experiment on a single valve from a third manufacturer also demonstrated that the a_v value was constant as the valve's open area changed.

Vee-grooved needle trims

The new equations were also demonstrated for a vee-grooved needle valve. This valve has a trim consisting of a cylindrical plug with one or more triangular grooves of varying depth machined into the plug. The triangular groove trim design has a smaller ratio of wetted perimeter to cross-sectional area than a trim with a purely annular cross section, which translates into a higher Reynolds number at a given flowrate and viscosity than a circular annular trim of the same C_{VT}. Thus, this type of valve would be expected to have a smaller a_v value.

Using the same setup as for the seat-guided valves, a_v values were measured for the vee-grooved needle valve in the range of 0.05–0.065. The a_v values decreased as the valve's open area decreased, falling to 0.02 in some of the trims. Even at a_v values in the range of 0.02–0.06, the F_R values for these valves were significantly less than one with liquids of even modest viscosity. Assuming that flow in these valves is turbulent, therefore, will lead to the selection of valves far too small for the duty.

Stem-guided trims

Based on our observations, we would not expect a_v to remain constant with varying stem position for valves with full-size trims. These valves are fully stem guided rather than seat guided, and the trim becomes an unrestricted circular orifice when the valve is fully open. Such valves include some of the fine-metering manual needle valves offered by several tube-fitting manufacturers. Individual sizing experiments using the K factor previously discussed would be required for accurate sizing of this type of valve in laminar flow. CEP

Nomenclature

A	= area of the annulus between the plug and the seat of the valve, in.^{2}
a_v	= trim family valve-sizing factor for laminar flow, (gpm/cP)$^{0.5}$
C_{VL}	= flow coefficient for laminar and transitional flow, gpm/psi$^{0.5}$
C_{VT}	= flow coefficient for turbulent flow, gpm/psi$^{0.5}$
D_O	= diameter of a circle with the same area as the valve opening, in.
F_R	= laminar flow adjustment ratio (dimensionless)
K	= single trim valve-sizing factor for laminar flow, psi/gpm-cP
L	= length of pipe between upstream and downstream pressure measurement taps, in.
P_1	= valve inlet pressure, psi
P_2	= valve outlet pressure, psi
ΔP	= pressure difference across valve, psi
Q	= volumetric flowrate, gal/min
Re	= Reynolds number (dimensionless)

Greek Letters

ρ	= density, kg/m^3
μ	= dynamic viscosity, cP
υ	= fluid kinematic viscosity, cSt

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