Number 7

Pressure Drop of Valves and Tubes from 1 to 1000 mL/min

Abstract. The flow resistance of injectors, switching valves, detectors, and connecting tubes can cause problems under some conditions. The high flow rates of preparative LC cause large pressure drops in components designed for analytical LC, using up available pump pressure. The rapid intake strokes of some pumps cause pressures to fall below one atmosphere in inlet tubes, producing air bubbles. This Technical Note describes how flow resistance depends on passage diameter, length, and flow rate, by covering the theory of laminar and turbulent flow. It compares the pressure drop of Rheodyne small-bore and large-bore valves and provides guidelines for selecting proper tubing.

Flow passage diameters in analytical LC components are small in order to reduce dispersion. Connecting tube diameters are typically 0.1 to 0.25 mm (0.004 to 0.010 inch). Valves, sample injectors, and sample loops are rarely larger than 0.8 mm (0.030 inch). The resistance to flow caused by such passages is low at flow rates below 100 mL/min. In analytical and small-scale preparative chromatographs the extra pump pressure required to overcome the resistance is usually negligible.

At higher flow rates the pressure drop of extra-column components must be considered. Large-bore components are sometimes necessary to avoid using up too much of the available pump pressure. However, since large diameters cause more dispersion, a judicious choice should be made to avoid excessively compromising either resolution or pressure drop.

Likewise, the pressure drop across pump inlet tubes can be significant at higher intake flow rates, such as with pumps that have a rapid intake stroke. This causes the inlet line pressure to fall below one atmosphere. If dissolved gas comes out of solution it can cause erratic pump performance. However, tube diameter should be small enough to prevent excessive flush-out volume during solvent changeover.

The tables and graphs in this Technical Note show the pressure drop caused by tubes, valves, injectors, and sample loops as a function of flow rate. The text discusses the theory of flow resistance. Readers not interested in the theory, but who want to use the graphs and tables for selecting appropriate products, can skim the text and read only the summary.

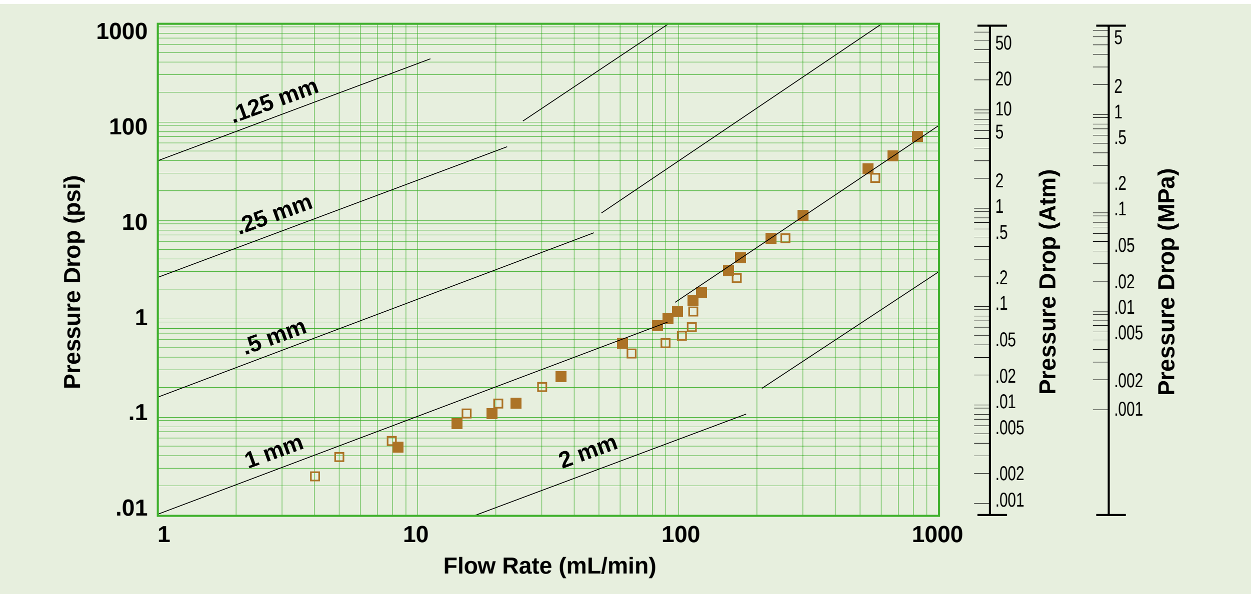

Figure 1. Pressure drop vs. flow rate per 10 cm of smooth-walled straight tubing of circular cross section with water at 20° C. At low flow rates the flow pattern is laminar; pressure drop is proportional to flow rate and inversely proportional to the fourth power of diameter. At high flow rates, above a Reynolds number of 2000, the flow pattern is turbulent; pressure drop is proportional to the square of flow rate and inversely proportional to about the fifth power of diameter. The solid lines are calculated values from equations (1) and (7) in the test. The solid squares are experimental measurements for a 10 cm long tube. The open squares are experimental measurements for a 200 cm long tube, the DP values being divided by 20 to give a per 10 cm basis. The different shapes of these curves are explained in the text.

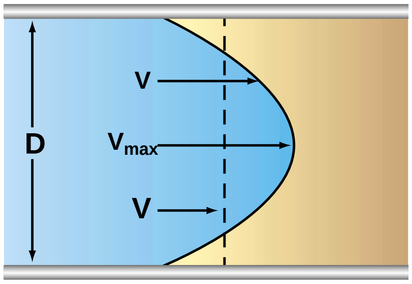

Figure 2. Longitudinal section through tubing showing laminar flow pattern. The parabola is the envelope of flow velocity vectors. Velocity at the wall is zero. The direct proportionality of pressure drop to viscosity, flow rate and tube length is intuitively agreeable. Note the inverse fourth power dependence on diameter. A 0.5 mm tube has sixteen times the pressure drop of a 1 mm tube, when the flow is laminar.

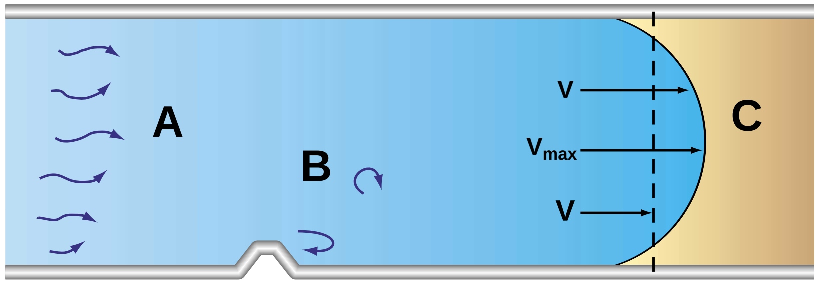

Figure 3. Turbulent flow pattern in tubing. A) shows flow not always parallel to the tube axis. B) shows the shedding of an eddy, a type of turbulence, into the flow from behind a rough spot on the wall. C) shows the time-averaged velocity profile, which has been flattened compared to the laminar profile.

The pressure required to produce a certain flow rate through a passageway depends on the resistance. This is analagous to Ohm's law relating voltage, current, and resistance in an electrical conductor, E = IR. However, the resistance of fluid passageways is not a constant, but depends on whether the flow is laminar or turbulent. The presence of turbulence in turn depends on the flow rate, passage diameter, and fluid viscosity. The following discussion shows how pressure, flow rate, viscosity, passage diameter, and passage length are related in both laminar and turbulent flow. It shows how to determine which type of flow is present and how to calculate the pressure drop, ΔP.

Laminar Flow Pressure Drop

At low flow rates the movement of fluid through straight tubes of circular cross section has a completely orderly flow pattern. The velocity at all points is parallel to the tube axis. There is no radial mixing except for molecular diffusion, and the velocity at a point is unchanging with respect to time. This is called laminar or Poiseuille flow. The fluid velocity at the wall is zero and increases progressively until, at the tube axis, it is maximum and equal to twice the average. (The average velocity is the flow rate divided by the area, $V = cm^3\ sec^{-1}/cm^2$.) The longitudinal section through a tube diagrammed in Figure 2 shows the velocity at selected points as vectors. The envelope of all velocity vectors is a parabola.

Thus, there is a telescopic sliding of adjacent concentric layers of fluid. The energy needed to overcome the friction is supplied by the fluid pressure. As the fluid travels through the tube the pressure decreases, the energy loss being converted to heat. The pressure difference between the two ends of the tube is the pressure drop, ΔP, or the head loss, h_f. In this discussion we ignore the relatively insignificant pressure losses due to elevation changes: a 100 cm head of water = .01 MPa = .1 Atm = 1.5 psi.

The relationship between pressure drop and laminar flow in a tube is

$$\Delta P = 32\mu LV/D^2 = 128\mu LF/\pi D^4 \qquad (1)$$

where, in International System (SI) units

- ΔP = pressure drop $N\ m^{-2}$ = Pa, Pascal
- μ = dynamic (absolute) viscosity in $N\ sec\ m^{-2}$ = 10 poise = 1000 centipoise
- L = length m
- V = average linear velocity $m\ sec^{-1}$
- D = diameter m
- F = flow rate $m^3\ sec^{-1}$

The right hand expression of equation (1) is in terms of flow rate. The version of it below (2) allows direct calculation of pressure drop in psi using units common in chromatography instead of SI units.

$$\Delta P = 9.849 \times 10^{-8}\ \mu FL/D^4 \text{ psi} \qquad (2)$$

where

- μ = dynamic viscosity centipoise (1 for water at 20° C)
- F = flow rate mL/min
- L = length cm
- D = diameter cm

Conversion to other units is

$$1 \text{ MPa} = 106 \text{ Pa} = 10^6 \text{ N m}^{-2} = 9.864 \text{ Atm} = 145.03 \text{ psi} \qquad (3)$$

The direct proportionality of pressure drop to viscosity, flow rate, and tube length is intuitively agreeable. But note the inverse fourth power dependence on diameter. A 0.5 mm tube has sixteen times the pressure drop of a 1 mm tube, when the flow is laminar.

Reynolds Number

As flow rate increases, the orderly laminar flow pattern changes into chaotic motion. There is radial mixing, and the velocity at a point fluctuates due to inherent instabilities. This is called turbulent flow. Velocity at the wall is zero, as a laminar flow, but the parabolic velocity profile is flattened to a logarithmic one. Figure 3 shows A) flow not always parallel to the axis, B) the shedding of an eddy – a type of turbulence – into the flow from behind a rough spot on the wall, and C) the time-averaged velocity profile.

Turbulent flow has more friction than laminar flow, and equations (1) and (2) do not apply. Calculating the pressure drop through a tube requires knowing whether the flow is laminar or turbulent.

The flow becomes turbulent when inertial forces (that perpetuate flow instabilities) dominate viscous forces (that dampen instabilities). The Reynolds number is a dimensionless ratio of these forces.

$$Re = \frac{\rho VD}{\mu} = \frac{\text{inertial}}{\text{viscous}} \qquad (4)$$

Turbulence usually starts when the Reynolds number reaches the 2000 to 4000 range. Increasing any of the three variables in the numerator promotes turbulence. Increasing density, and average linear velocity, V, increases the inertia of instabilities. Increasing diameter, D, allows eddies to be larger and makes the suppressing effects of the wall farther from eddies. Increasing dynamic viscosity, μ, discourages turbulence because it increases friction. (Re can also be expressed in terms of the kinematic viscosity, thus Re = VD/n.)

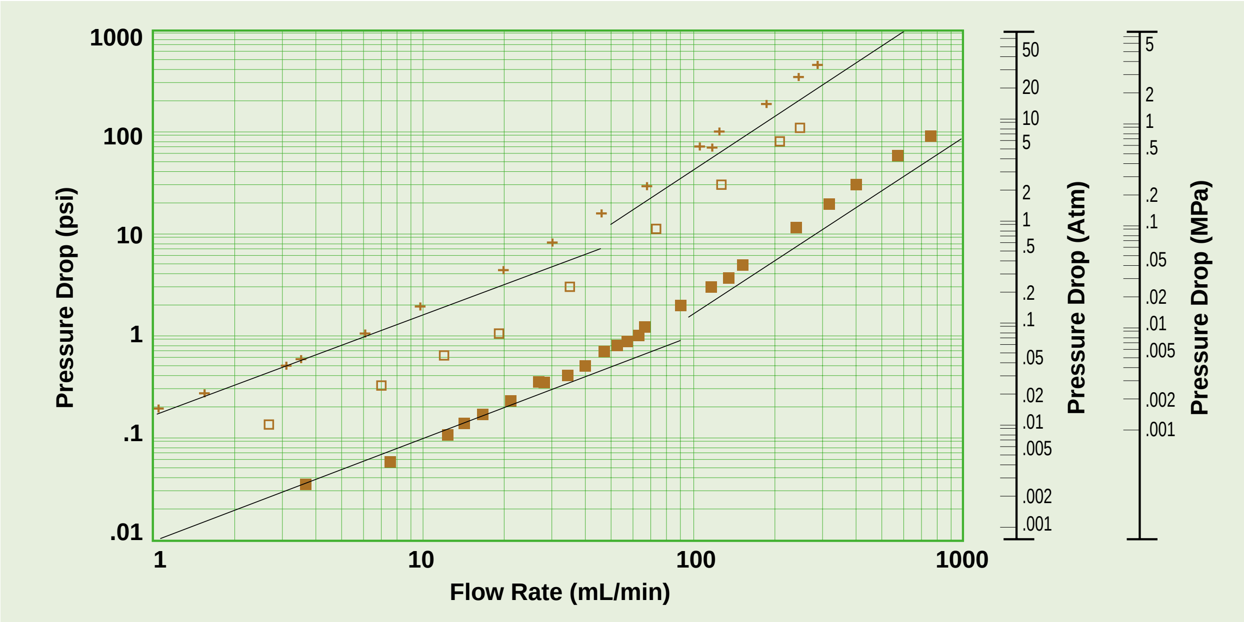

Fig. 4. Pressure drop vs. flow rate for Rheodyne standard bore Model 7000 and large bore Model 7000L high pressure switching valves with water at 20° C. The curves for other Type 70 valves are similar. The pressure drop includes that caused by one rotor seal channel, one stator inlet port, one stator outlet port, one inlet connecting tube and one outlet connecting tube. The experimental measurements are: solid squares = (1 mm 7000L valve) + (two 1 mm x 5 cm tubes). Open squares = (0.6 mm 7000 valve) + (two 1 mm x 5 cm tubes). Cross mark = (0.6 mm 7000 valve) + (two 0.5 cm tubes). The solid lines are calculated values for 10 cm long tubes of 1 mm and 0.5 mm I.D., as shown in Figure 1. The contribution of the internal passages of the valve are seen to be small, since the experimental points are close to curves for the tubes alone, especially in the laminar region. The transition from laminar to turbulent flow is gradual due to flow disturbances caused by directional changes within the valve and inexact mating of flow passages in the various parts.

Equation (4) must be dimensionally homogeneous: ρ in g cm^{-3}, V in cm sec^{-1}, D in cm and m in g cm^{-1} sec^{-1} = poise. The equation below is more convenient since it does not require linear velocity and can be used with familiar flow rate and viscosity units, instead of SI units.

$$Re = 2.112\, \rho F/D\mu \qquad (5)$$

where

ρ = density g/cm^3
(1 for water at 20° C)
F = flow rate mL/min
D = diameter cm
μ = dynamic viscosity centipoise
(1 for water at 20° C)

Note that the diameter is now in the denominator. In contrast to equation (4), the Reynolds number decreases as the diameter increases. This is not inconsistent with the previous discussion, because at a fixed flow rate, F, increasing the diameter causes the linear velocity, V, to decrease by the inverse of the diameter squared.

Some Reynolds numbers for water at 20° C calculated from (5) are in Table I. Recalling that the onset of turbulence is not until Re ≥ 2000, the table shows that flow in conventional tubing is laminar under typical analytical HPLC conditions.

Turbulent Flow Pressure Drop

The relationship between pressure drop and turbulent flow in a tube is an expression in the same variables discussed previously, but it includes a friction factor, f. This factor depends on the Reynolds number and the relative roughness of the tube wall. In practice, the friction factor is usually determined from published graphs, such as the Moody resistance diagram, which is in mechanical engineering handbooks and fluid mechanics texts.[1] With smooth-walled tubes, in the range 4000 < Re < 10^5, the friction factor is approximated by equation (6), which we will use for all subsequent calculations.

$$f = 0.316/(Re^{0.25}) \qquad (6)$$

The pressure drop with turbulent flow can be calculated by using equation (5) for the Reynolds number, equation (6) for the friction factor, and equation (7) below for the pressure drop.

$$\Delta P = f\,\frac{L}{D} \bullet \frac{\rho V^2}{2} = f\,\frac{8}{\pi^2} \bullet \frac{\rho L F^2}{D^5} \qquad (7)$$

where, in SI units

ΔP = pressure drop N m^{-2} = Pa
f = friction factor
L = length m
D = diameter m
ρ = density kg m^{-3}
V = average linear velocity m sec^{-1}
F = flow rate m^3 sec^{-1}

The right hand expression of equation (7) is in terms of flow rate. The version of it below allows direct calculation of pressure drop in psi using units common in chromatography instead of SI units.

$$\Delta P = 3.266 \times 10^{-9}\, f \rho L F^2/D^5 \text{ psi} \qquad (8)$$

where

f = friction factor
ρ = density g/cm^3
(1 for water at 20° C)
L = length cm
F = flow rate mL/min
D = diameter cm

Table I. Reynolds Number for Tubing.

ID	mL/Min	Re	Flow
1 mm	10	211	laminar
	100	2112	transition
.25 mm	10	845	laminar
	100	8448	turbulent
.1 mm	10	2112	transition
	100	21120	turbulent

Pressure Drop Graph for Tubes

Figure 1 is a plot of pressure drop vs. flow rate of water for 10 cm tube lengths with various inside diameters. The solid lines are calculated values. Equation (1) was used at Re < 2000. Equation (7) was used at Re > 2000. The log-log plot permits the display of data over a wide range of flow rates and tube diameters.

The discontinuity of each line is at a Reynolds number of 2000. As the tube diameter becomes smaller, the flow rate at which turbulence begins becomes proportionately smaller. This follows directly from equation (5). In the transition region between laminar and turbulent flow, the pressure increases rapidly with increasing flow rate. The curve in this region has not been plotted.

Pressure drop is proportional to F when laminar and approximately F^2 when turbulent. The F^2 dependence is manifested by a higher slope, and would be a curve on a linear-linear plot.

Pressure drop is inversely proportional to D^4 when laminar and approximately D^5 when turbulent. At 20 mL/min, the change from 1 mm to 0.5 mm diameter increases the laminar ΔP 16-fold, from 0.2 psi to 3.2 psi. At 200 mL/min, the change from 1-mm to 0.5 mm diameter increases the turbulent ΔP 32-fold, from 4.3 psi to 138 psi.

The pressure drop across stainless steel tubing of 0.040 inch (1 mm) bore was measured experimentally. The solid squares plot the results with a 10 cm long tube. The open squares plot the results with a 200 cm long tube, where the pressures were divided by 20 to obtain a per 10 cm value. The 10 cm tube has a higher pressure drop per 10 cm than does the 200 cm tube. This is because there is resistance to flow caused by the tube entrance, due to local non-uniform flow. It becomes an insignificant part of the total pressure drop in the 200 cm tube. A discussion of pressure drops caused by tube entrances and abrupt changes in diameter are beyond the scope of this article.[2] The reader should realize that the pressure drops per 10 cm of length plotted in Figure 1 are approximate. The actual values will depend on the tube length and wall roughness.

Pressure Drop Graphs for Valves

Figure 4 is a plot of experimentally-measured pressure drop vs. flow rate of water for two typical Rheodyne high pressure valves. The flow through the valves goes through only one rotor seal channel. In each case the pressure drops include that caused by an inlet connecting tube and an outlet connecting tube. In most cases each tube had dimensions of 0.040 inch (1 mm) bore x 1/16 inch OD x 5 cm length. Since connections to the valve ports must be made via 1/16 inch OD tubing, and since tubing wall thickness less than 0.010 inch has a low burst pressure rating[3], this tubing represents the largest practical bore for connections. 5 cm is a convenient minimum length, allowing reducing unions to be attached for connection to larger bore tubing.[4]

Table II shows the dimensions of internal flow passages of the standard valves and the larger bore "L" models used in this study.

The graph shows that there is a significant difference in the pressure drops caused by the standard Model 7000 and the larger bore Model 7000L, when both are connected using 0.040 inch (1 mm) bore tubing. When the Model 7000 is used with 0.020 inch (0.5 mm) bore tubing, the pressure drop is predictably higher.

Table II. Effective Diameter of Internal Valve Passages.

	Standard Bore Model 7000	Large Bore Model 7000L
Stator Holes	0.6 mm (0.024 inch)	1 mm (0.040 inch)
Rotor Seal Groove	0.5 mm (0.018 inch)	1 mm (0.040 inch)
Total Volume*	2 µL	6.5 µL

*** Includes two stator holes and one rotor seal groove.**

Figure 4 can be used as a guideline for pressure drops across Rheodyne valves with similar passageways. Keep in mind that the pressure drops are for passages through two 5 cm x 1 mm bore connecting tubes, two stator holes, and one rotor groove. When flowing through additional ports the pressure drops will be proportionally higher.

The pressure drop through sample injectors must take into account the resistance of the sample loop when in the INJECT position. Table III shows approximate pressure drops of typical Rheodyne sample loops. When using these loops on large bore "L" models, most of the pressure drop will be caused by the loop. Loops with lower pressure drops can be made by using tubing with a larger bore. For example, equations (5), (6) and (8) show that if a 1 mL loop is made from tubing of 1 mm ID instead of 0.76 mm, the pressure drop at 300 mL/min would decrease from about 800 psi to about 130 psi.

Increasing sample loop diameter in order to reduce the flow resistance can cause loss of resolution. The dispersion is inversely proportional to the fourth power of diameter.[5] Doubling passage diameter increased the dispersion caused by the passages, in terms of mL^2 of variance, by a factor of 16. Often, however, the total dispersion of the injector will remain a very small contribution to the total system variance.

Figure 5 is a plot of experimentally measured pressure drop vs. flow rate for two typical Rheodyne low pressure Teflon® valves. The flow goes through only one rotor channel. The pressure drop includes the two connecting tubes that are an integral part of the valves. The length of each tube is 7.2 cm.

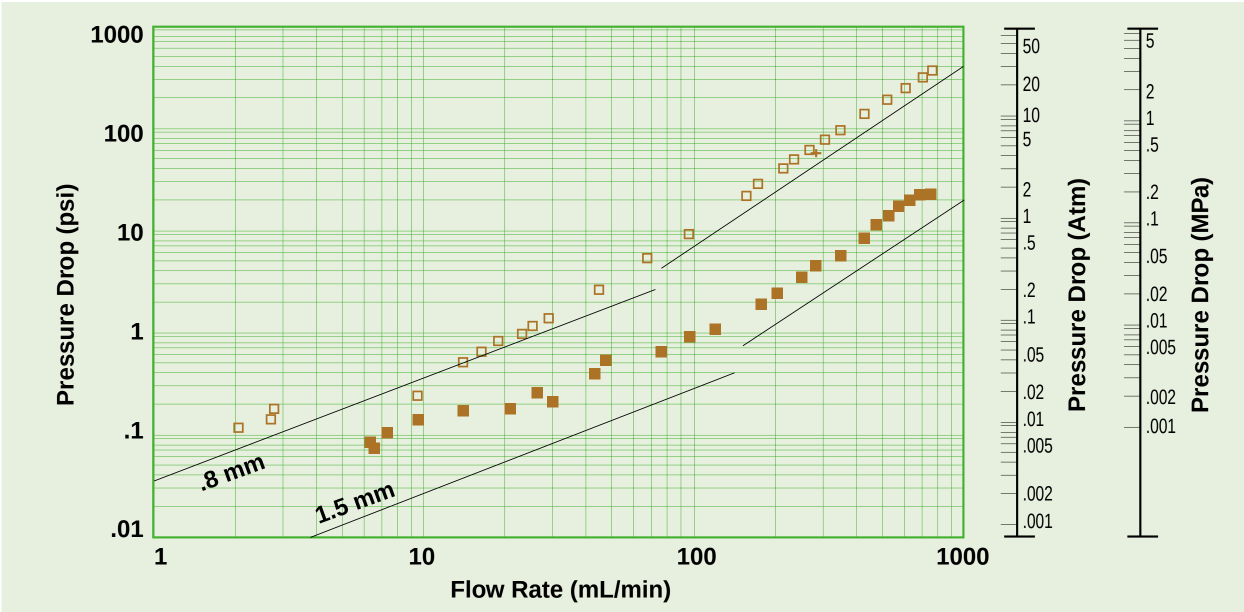

Fig. 5. Pressure drop vs. flow rate for two Rheodyne low pressure Type 50 Teflon valves with water at 20° C. The pressure drop includes that caused by one rotor seal channel, one inlet tube, and one outlet tube. The tubes, an integral part of the valve, are each 7.2 cm long. The experimental measurements are: solid squares = Model 5032 valve, which has tubing and passages of 1.5 mm (0.06 inch). Open squares = Model 5031 valve, which has tubing and passages of 0.8 mm (0.03 inch). The solid lines are calculated values for 14.4 cm long tubes of 1.5 mm and 0.8 mm bore. The slope of the Model 5032 valve does not match theory in the laminar region. This may be due to gas bubbles forming along the tube and valve passage walls, which would change the flow resistance. The water was not degassed.

Table III. Approximate Pressure Drop of Rheodyne Sample Loops for Water at 20° C.

P/N	Nominal Volume	mm ID x cm	Pressure Drop (psi) at 20 mL/Min	100 mL/Min	300 mL/Min
7020	5mL	.18 x 9	300	> 1000	> 1000
7021	10mL	.30 x 11.6	4	80	500
7022	20mL	.51 x 9	3	50	250
7023	50mL	.51 x 23.9	7	100	600
7024	100mL	.51 x 48.6	15	220	> 1000
7025	200mL	.76 x 43.5	3	40	150
7026	500mL	.76 x 109	7	70	400
7027	1mL	.76 x 219	14	130	800
7028	2mL	1.00 x 246	5	50	250
7029	5mL	1.00 x 617	11	100	600

Summary

Figures 1, 4 and 5 are plots of pressure drop vs. flow rates for tubing, high pressure valves, and low pressure valves respectively. The pressure drop is the difference in pressure measured between each end of the tube or valve. It represents the conversion of potential energy to heat due to the resistance of the flow passages. The resistance at low flow rates is described by equation (2), which is for laminar flow. At high flow rates, above a Reynolds number of 2000, the flow is turbulent. Here the resistance is described by equation (8). The steps in using the equations are: a) Use equation (5) to find the Reynolds number; b) If Re is < 2000 use equation (2) to calculate the pressure drop; c) If Re > 2000 use equation (8) to calculate the pressure drop. The friction factor, f, in this equation is determined by using equation (6).

The pressure drops determined using these equations or the figures are approximate, because the actual values depend on the roughness of the tubing wall, the inlet effects at the tube entrance, and the actual passage diameters (all dimensions have tolerances).

Footnotes

1. In a smooth walled tube, even under turbulent flow conditions, there is a region very near the wall where the flow is laminar because of the low velocity. This is called the laminar sub-layer. When the tube wall is rough it breaks up the sub-layer and changes the flow resistance. The roughness of the tube is described as the relative roughness, the height of the surface features divided by the tube diameter. For example, the relative roughness of a 0.04 inch ID tube with a 40 micro-inch finish would be 0.00004/0.04 = 0.001. The Moody resistance diagram plots resistance coefficient, f, vs. Reynolds number, Re. At Re > 2000 the straight line breaks into a family of curves, each being for a different relative roughness. From the diagram, for a tube with relative roughness of 0.001, the resistance coefficient is .040 at Re = 4000, .032 at Re = 10^4, .022 at Re = 10^5, .20 at Re ≥ 10^6. By comparison, a tube with a relative roughness of 0.01 has a resistance coefficient of .043 at Re = 10^4. That is, the ΔP would be .043/.032 = 1.34 times larger for the rougher tube.

2. That there is a flow disturbance at the tube entrance is also evidenced by the shape of the curves at the transition point. The onset of turbulence starts earlier and is more gradual in the 10 cm tube, where the inlet geometry influences downstream flow for an appreciable length of the tube. In the 200 cm tube the inlet is a negligible factor, and the transition to turbulence is abrupt, as predicted for laminar flow.

3. One way of estimating working pressure of tubing is the Barlow formula. It uses yield strength, S, which for 316 stainless steel is often considered 20,000 psi. Thus, with dimensions in inches:

$$P_{working} = (2 \times S \times \text{min.wall}) / OD$$

$$= (2 \times 20{,}000 \times .01) / .063 = 6349 \text{ psi}$$

Working pressure is considered safe day-in and day-out. Burst pressure is that at which the tube is expected to burst. Using the same formula, but substituting tensile strength (70,000 psi for 316 stainless steel) produces 22,000 psi burst pressure.

4. The minimum length of tube that can be used to connect a Rheodyne Type 70 valve to another fitting is about 32 mm. This is used up as follows: A standard male nut (Rheodyne bushing, P/N 7010-009) and ferrule require 20 mm. A union with a female nut requires about 10 mm. A 2 mm space is needed between the nuts. Such a tube cannot be bent without the nuts interfering, 5 cm is a more practical length.

5. The classic expression for dispersion in a tube in terms of the plate height, radius, linear velocity and diffusion coefficient is H = $r^2v/24D$. In these equations D stands for diffusion coefficient, not diameter. Using the relationships H = σ2/L and v = flow rate/area, and converting from length units to volume units, we have the expression for variance in terms of radius, length and flow rate, in units of volume squared:

$$\sigma^2 = \frac{\pi r^4 LF}{24D}$$