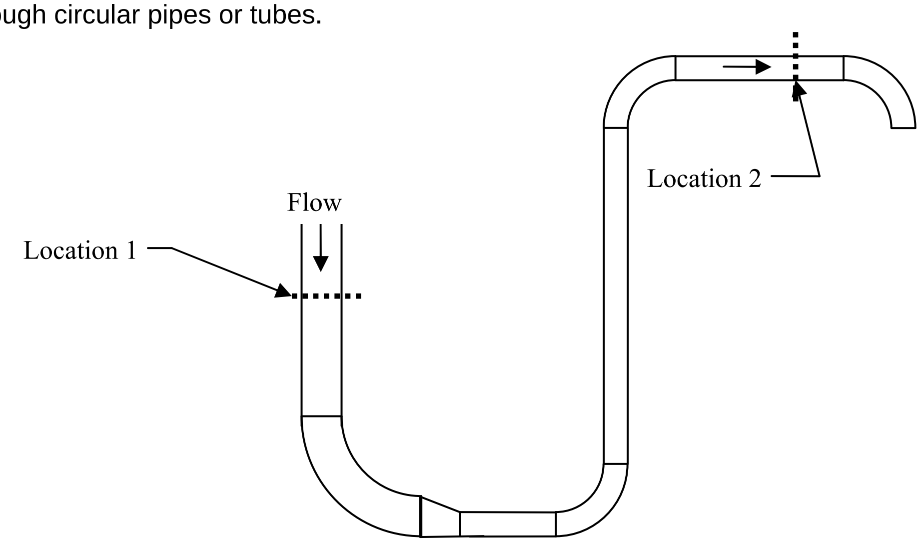
Hydraulic Design of Liquid or Water Piping System

Circular pipe is the usual means moving liquids in process plants, utility systems, or pipelines. We will, therefore, emphasize here the design of piping system for liquids of constant viscosity flowing through circular pipes or tubes.



Material Balance

The mass flow rate in a piping system will not change if no addition or diversion of flow occurs between two flow locations (Location 1 and Location 2 in the above sketch):

$$W_{lb/hr} = (\rho_{lb/CF})_1 (A_{ft^2})_1 (\upsilon_{ft/\sec})_1 = (\rho_{lb/CF})_2 (A_{ft^2})_2 (\upsilon_{ft/\sec})_2 \qquad (1)$$

where W =flow rate in pounds per hour, lb/hr

ρ = flowing density, pounds per cubic foot, lb/CF;

A_{ft^2} = pipe cross-sectional area in square feet, ft^2

$$A_{ft^2} = \frac{\pi}{4}\left(\frac{d_{inch}}{12}\right)^2 \text{ for a circular pipe.} \qquad (2)$$

d = inside diameter of the pipe, inches.

υ = flowing velocity in pipe in feet per second, fps.

$$\upsilon_{fps} = \frac{W_{lb/hr}}{(\rho_{lb/CF})(3600\frac{\sec}{hr})(A_{ft^2})} = \frac{(0.4085)(Q_{gpm})}{(d_{inch})^2} \qquad (3)$$

Q_{gpm} = volumetric flow rate in gallon per minute in flowing conditions, gpm

Furthermore, if the flowing densities and the cross-sectional areas of the pipe are the same at Location 1 and Location 2, then the velocities are the same at both locations.

Overall Energy Balance

The Bernoulli's theorem overall energy balance equation for each flow segment of constant inside diameter flowing an incompressible fluid is

$$\Delta P + \Delta P_s + \Delta P_p = \Delta P_f + \Delta P_{acc} \tag{4}$$

or

$$P_{in} - P_{out} + [\frac{(\rho)(h)}{144}]_{in} - [\frac{(\rho)(h)}{144}]_{out} + \Delta P_p = \Delta P_f + \Delta P_{acc} \tag{5}$$

where

P_{in} = pressure at the inlet of the segment, psig

P_{out} = pressure at the outlet of the segment, psig

ΔP = system total pressure drop = $P_{in} - P_{out}$, psi

ΔP_s = segment static pressure change due to change in elevation , psi

$$\Delta P_{s\ psi} = [\frac{(\rho_{lb/CF})(h_{ft})}{144}]_{in} - [\frac{(\rho_{lb/CF})(h_{ft})}{144}]_{out}$$

ΔP_p = pressure increase due to pump, psi

ΔP_f = segment frictional pressure drop, psi

ΔP_{acc} = segment pressure drop due to fluid acceleration, psi

ρ = flowing density, pounds per cubic foot, lb/CF;

h = elevation, ft

Acceleration pressure drop, ΔP_{acc} , typically involves fluid flashing. Flashing in liquid or water piping system is normally treated separately and, therefore, not considered here. Furthermore, we will not address the pump flow in this study guide. Consequently, $\Delta P_p = 0$.

The overall energy balance equation for a non-flashing liquid flowing through a series of pipes becomes:

$$P_{in} - P_{out} + \sum[\frac{(\rho)(h_{in} - h_{out})}{144}]_{upflow} + \sum[\frac{(\rho)(h_{in} - h_{out})}{144}]_{downflow} = \sum \Delta P_f \tag{6}$$

Some frequently used terminologies relating to the word "head" (for pressure) are introduced below:

- **Liquid Flowing Specific Gravity G**

G = specific gravity of fluid at flowing condition relative to water at 60°F,

$$= \frac{\rho_{lb/CF} \text{ @flowing temperature}}{62.3688_{\text{lb/CF}}}$$

- **Pressure, Pressure Head**

Pressure is the force exerted by fluid that acts to pipe or container and can be expressed as force per square unit surface area. This pressure typically can be measured directly by a pressure gage in a unit such as pounds per square inch, psig.

Parallel to the principle of a mercury barometer, the same pressure that is exerted by the fluid also can cause a measuring fluid to rise in a column to a height of H_{ft} until its weight balances out the pressure in the pipe or container. In other words, a column of liquid will exert a local **Pressure** that is proportional to the height of that liquid:

$$P_{psia} = \frac{(\rho_{lb/CF})(H_{ft})}{144} \tag{7}$$

Thus, the pressure in the pipe or container can be expressed by the height of the column of a measuring liquid, such as mercury, water or the same fluid itself, and is called **Pressure Head**:

$$H_{ft} = \frac{(144)(P_{psia})}{\rho_{lb/CF}} \tag{8}$$

For example, normal atmospheric pressure at 0 psig or 14.6959 psia and 60°F is equivalent to a head of mercury of 29.92 (=14.69X144/848.7X12) inches or a head of water of 33.93 (=14.6959X144/62.3688) feet. Therefore, the pressure will increase by 2.036 psi per inch of mercury column rise or 0.433 psi per foot of water column height:

14.6959 psi = 29.92" Hg = 760 mmHg
1 psi = 2.036"Hg
0.433 psi = 1' WC (60°F, density = 62.3688 lb/CF)
1 psi = 2.31' WC (60°F, density = 62.3688 lb/CF)

- **Static Pressure, Static Head**

Static head is a measurement of pressure due to the weight of column of fluid at a given height. Thus, a fluid at a level of H feet above a reference point (a difference in elevation) is said to have a static head of $H_{s,\ ft}$. This **Static Head** of H feet also can be expressed in terms of a local pressure at the base of the column if the density of the fluid is known, for example,

$$H_{s,\ psi} = \frac{(\rho_{lb/CF})(H_{s,\ ft})}{144}$$ in pounds per square inch of area.

Static head $H_{s,\ psi}$ also can be called **Static Pressure** simply because it measures the pressure head and is expressed in a pressure unit.

$$H_{s,\ psi} = \frac{(62.3688_{\ lb/CF})(H_{s,\ ft})}{144} = \frac{(H_{s,\ ft})}{2.31} \text{ for water at } 60^{o}\text{F}$$

- **<u>Velocity Head</u>**

  We will use the following simplified concept for the purposes of introducing the term velocity head. When an object falls, it will lose its potential energy. It will, in turn, gain the kinetic energy at the expense of potential energy. Thus, when a fluid falls from a stationary state for H feet, its velocity will increase from zero to υ ft/sec at a kinetic energy of $\rho v^{2} / 2g_{c}$ in ft-lb per cubic feet. We say that the static head $H_{s,\ ft}$ produces a **Velocity Head**

$$H_{v,\ ft} = \frac{(\upsilon_{ft/\sec})^{2}}{(2)(g_{c})} \quad \text{in feet,} \qquad (9)$$

where

g_c = gravitational constant, 32.18 ft/sec^2.

Thus, Eq. (9) defines the concept of velocity head.

Eq. (9) can be converted to a pressure unit such as

$$H_{v,\ psi} = \frac{(\rho_{lb/CF})(\upsilon_{ft/\sec})^{2}}{(2)(g_{c})(144)} \quad \text{in unit of pounds per square inch, psi} \qquad (10)$$

Again, velocity head $H_{v,\ psi}$ also can be called **Velocity Pressure** because of it unit.

Note that in a pipe segment of constant inside diameter flowing liquid or water, the velocity, and hence the velocity head, do not change throughout the segment.

One of the utilities of velocity head in pipe flow hydraulics is to help to express the frictional pressure drop of equipment, such as a flow nozzle, heat exchanger, etc. in terms of number of velocity heads (see Eq. 24).

- **<u>Static Head-Loss</u>**

When a pipe segment runs inclined or vertical, there will be a difference in elevation between the start and the end of that pipe segment. This difference in elevation Δh (=inlet elevation - outlet elevation) will result in a pressure difference due to weight of fluid regardless fluid is flowing or not. **Static Head-Change** can be expressed either in pressure unit:

$$\Delta H_{s,\ psi} = \Delta P_{s,\ psi} = \frac{(\rho_{lb/CF})(\Delta h_{ft})}{144} = \frac{(\Delta h_{ft})(G)}{2.31} \qquad (11)$$

$$\Delta H_{s,\ psi} = \Delta P_{s,\ psi} = \frac{\Delta h_{ft}}{2.31} \text{ for water at } 60^{o}F \qquad (11a)$$

or in head unit:

$$\Delta H_{s,\ ft} = h_{in,ft} - h_{out,ft} = \Delta h_{ft} = \frac{(144)(\Delta P_{s,\ psi})}{\rho_{lb/CF}} = \frac{(\Delta P_{s,\ psi})(2.31)}{G} . \qquad (12)$$

$$\Delta H_{s,\ ft} = h_{in,ft} - h_{out,ft} = \Delta h_{ft} = (2.31)(\Delta P_{s,\ psi}) \text{ for water at } 60^{o}F \qquad (12a)$$

In down flow where ΔP_s or ΔH_s is positive, we say that there is a **Static Head Gain**.

In up flow where ΔP_s or ΔH_s is negative, we say that there is a **Static Head Loss**.

Since we take static head loss as a positive quantity, Static Head Loss = $-\Delta H_s = -\Delta P_s$.
When an overall piping circuit involves several pipe segments which has its own elevation change, these individual elevation changes can be added together to arrive at the overall elevation change. In other words, the static head change is additive and the net static head change for the overall system of constant density depends on only the elevation at the start and the end of that piping circuit.

Note

Cautions should be exercised that you should evaluate the pressure at the highest point of the entire circuit to ensure the origin has sufficient pressure to deliver liquid to that point before the liquid can continue to flow subsequently to the delivery point.

- **Dynamic Head-Loss**
  The term **Dynamic Head-Loss** or **Dynamic Pressure Drop** refers to the frictional pressure drop associated with piping (pipe and flow elements) plus equipment:

$$\Delta H_{f,\ psi} = \Delta P_{f,\ psi} \qquad (13)$$

$$\Delta H_{f,\ ft} = \frac{(144)(\Delta P_{f,\ psi})}{\rho_{lb/CF}} = \frac{(2.31)(\Delta P_{f,\ psi})}{G} \qquad (14)$$

$$\Delta H_{f,\ ft} = (2.31)(\Delta P_{f,\ psi})\ \text{ for water at } 60^{o}F \tag{14a}$$

The formula for $\Delta P_{f,\ psi}$ will be presented later.

- **Total Head-Loss**

$$\text{Total Head Loss} = \text{Dynamic Head Loss} + \text{Static Head Loss} \tag{15}$$

Total head loss is also called **System Pressure Drop**.

Finally, the overall energy balance equation, Eq. 6, for a non-flashing liquid flowing through a series of pipes can be written in terms of heads:

$$\left(\frac{(P_{in,psia})(144)}{\rho_{lb/CF}} - \frac{(P_{out,psia})(144)}{\rho_{lb/CF}}\right)_{ft} + \sum[h_{in,ft} - h_{out,ft}]_{upflow} + \sum[h_{in,ft} - h_{out,ft}]_{downflow} = \sum\left(\frac{(\Delta P_{f,psi})(144)}{\rho_{lb/CF}}\right)_{ft}$$

Total Head Loss — - Static Head Loss — Dynamics Head Loss

(16)

Reynolds number Re

This is the parameter used to establish the flow regimes in a pipe. The value of friction factor, which is used to correlate the dynamics head loss, depends on the Reynolds number

Reynolds number	Flow Regime
< 2,000	Laminar
2,000 to 4,000	Transition
> 4,000	Turbulent

$$Re = \frac{(\rho_{lb/CF})(D_{ft})(\upsilon_{ft/sec})}{(\mu e_{lb/ft/sec})} = 6.31\frac{W_{lb/hr}}{(d_{inch})(\mu_{cP})} = 50.6\frac{(Q_{gpm})(\rho_{lb/CF})}{(d_{inch})(\mu_{cP})} \tag{17}$$

Re = Reynolds number
μ_e = absolute viscosity, lb/ft/sec
μ = viscosity, centipoise, cP
D = inside diameter of the pipe, ft

To calculate the Reynolds number, all the parameters related to the fluid shall be evaluated at the flowing temperature and pressure, rather than a standard condition such as 60^{o}F and 1 atmosphere.

Most fluid flowing in the in-plant piping or pipelines are in the turbulent flow regime.

Friction Factor f

Darcy friction factor is more commonly used in the engineering calculations.

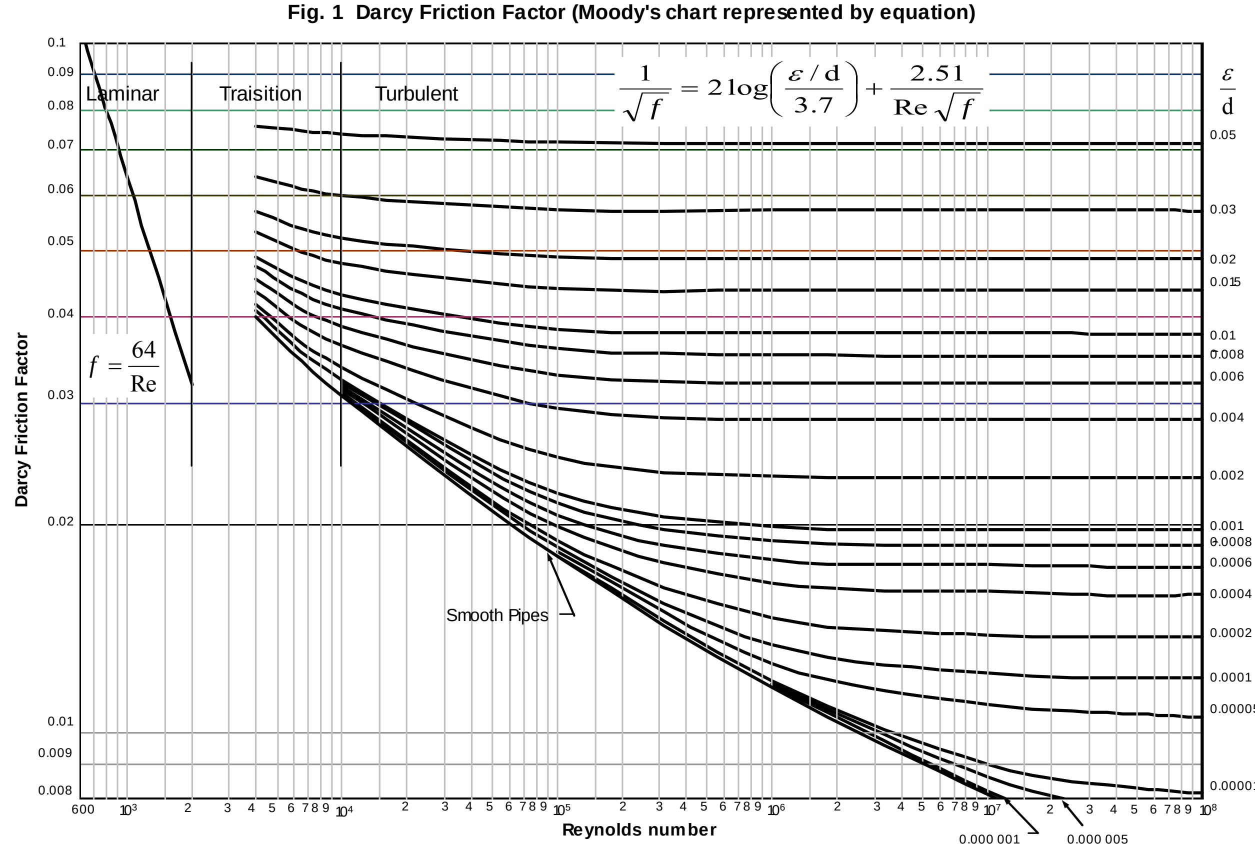
For **laminar** flow: $$f = \frac{64}{\text{Re}}.\qquad (18)$$

For **turbulent** flow, Moody's chart is generally accepted for the friction factor calculation. The Colebrook-White equation is an analytical form for the Moody's friction factor:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left[\frac{\varepsilon/\text{d}}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}}\right] \qquad (19)$$

The Cole Brook-White equation representation of Moody's friction factor is plotted in Fig. 1.

Fig. 1 Darcy Friction Factor (Moody's chart represented by equation)



Absolute Roughness of Pipe ε

For turbulent flow, Moody's friction is correlated with both Reynolds number and the pipe's absolute roughness. Typical values are listed below for new pipes:

Table 1

	Recommended	Absolute Roughness ε
Pipe or Tubing Material	feet	*inches*
Drawn Tubing	0.000 005 [1]	*0.000 06*
Teflon, PTFE; PFA-PTFE	0.000 005	*0.000 06*
High Density Polyethylene, PVDF; PVC; etc	0.000 07	*0.000 84*
Epoxy Coated Steel	0.000 025	*0.000 3*
New API Line Pipe	0.000 0582	*0.000 7*
Commercial Steel	0.000 15 [1]	*0.001 8*
Stainless Steel	0.000 15	*0.001 8*
Asphalt Coated Cast Iron	0.000 4 [1]	*0.004 8*
Galvanized Iron	0.000 5 [1]	*0.006*
Cast Iron	0.000 85 [1]	*0.010 2*
Wood Stave	0.003 to 0.000 6 [1]	*0.036 to 0.0072*
Concrete	0.01 to 0.001 [1]	*0.12 to 0.012*
Riveted Steel	0.03 to 0.003 [1]	*0.36 to 0.036*

PTFE= poly(tetrafluoroethylene)
PFA=poly(fluoroalkoxy)
PVC=poly(vinyl chloride)
PVDF=poly(vinylidene fluoride)

Absolute roughness can increase over time after initial service, resulting in higher frictional pressure drop. For example, it can double in 10 to 15 years for petroleum residues and in 25 to 35 years for light distillates. Whenever possible, a back calculated absolute roughness from actual pipe pressure drop data would be preferred.

Darcy Friction Factor for a commercial pipe at Complete Turbulence[(1)] :

Table 2

Pipe Size	**1"**	**1.5"**	**2"**	**3"**	**4"**	**6"**	**8" to 10"**	**12" to 16"**	**18" to 24"**
Darcy Friction Factor	0.023	0.021	0.019	0.018	0.017	0.015	0.014	0.013	0.012

<u>Frictional Pressure Drop in Pipes</u>

Use the Darcy formula for pipe frictional pressure drop for liquids:

$$\Delta P_{f\ psi} = \left(f\ \frac{L_{ft}}{D_{ft}} \right) \frac{(\rho_{lb/CF})(\upsilon_{ft/\sec})^2}{(2)(g_c)(144)} \quad (20)$$

where

L = Pipe straight length, ft

Frictional pressure drop can be also expressed as psi per 100 feet of pipe run length:

$$\frac{psi}{100\ ft} = \left(f\ \frac{100}{D_{ft}} \right) \frac{(\rho_{lb/CF})(\upsilon_{ft/\sec})^2}{(2)(g_c)(144)} \quad (21)$$

Use the appropriate Darcy frictional factor depending upon the flow regime per Reynolds number as discussed previously. Note that substituting the laminar flow Darcy friction factor to the above equation will result in the Hagen-Poiseuille formula for laminar flow of liquids.

Note also that the operating parameters that lend themselves to the frictional pressure drop calculation for liquid or water in pipes involve the flowing density, velocity, and viscosity (for Reynolds number and friction factor) only, the pressure in pipe is not involved. The liquid or water density is a function of pressure but, practically, can be considered as a constant in most application for hydraulics purposes. Thus, Darcy formula will calculate the same pressure drop for liquids or water independent of the pipe pressures.

Some More Turbulent Flow Equations:

Since most industrial piping hydraulic design practically end up fluid flowing in a turbulent flow, we will derive more useful turbulent-flow equations as tools in piping hydraulic design.

The velocity and density terms can be replaced by the mass flow rate or the volumetric flow rate term using the mass balance equation. With appropriate unit conversions, one can write the pipe frictional pressure drop in terms of the flow rate for turbulent flows:

$$\Delta P_{f\ psi} = (0.000\ 003\ 36) \frac{(f)(L_{ft})(W_{lb/hr})^2}{(\rho_{lb/CF})(d_{inch})^5} \quad (22)$$

$$\Delta P_{f\ psi} = (0.000\ 216) \frac{(f)(L_{ft})(\rho_{lb/CF})(Q_{gpm})^2}{(d_{inch})^5} \quad (23)$$

$$\frac{\Delta P_{f\ psi}}{100\ ft} = (0.000\,336) \frac{(f)(W_{lb/hr})^2}{(\rho_{lb/CF})(d_{inch})^5} \quad (22a)$$

$$\frac{\Delta P_{f\ psi}}{100\ ft} = (0.0216) \frac{(f)(\rho_{lb/CF})(Q_{gpm})^2}{(d_{inch})^5} \quad (23a)$$

At this point it is important to recognize several simple and useful **approximations** that will aid in your analysis of turbulent flow piping hydraulics:

$\Delta P \propto \upsilon^2$

In a pipe line of constant diameter and constant flowing density, the pressure drop is proportional to the square of flowing velocity. Conversely, at constant flowing density, the fluid's flowing velocity is proportional to the square root of the pipe's frictional pressure drop.

For example, for a given pipe, if a velocity of fluid in pipe is doubled, the pipe frictional pressure drop would be quadrupled.

$\Delta P \propto W^2$

In a pipe line of constant diameter and constant flowing density, the pressure drop is proportional to the square of flowing mass flow rate. Or, at constant flowing density, the fluid's flow rate is proportional to the square root of the pipe frictional pressure drop.

This relationship is similar to the previous one. The frictional pressure drop is proportional to the square of velocity or flow rate.

$\Delta P \propto \frac{1}{d^5}$

For a pipe line to flow a target flow rate at constant flowing density, its frictional pressure drop is approximately inversely proportional to the fifth power of the pipe inside diameter.

The use of this approximation can be illustrated in this design scenario: Suppose you want to deliver water at a given flow rate between two points in a given piping run of a known pipe diameter and yet the frictional pressure too high (either by your calculation or actual measurement), you can increase the pipe size in order to reduce the frictional pressure drop. If you are to increase the pipe diameter one size from 2 inches to 3 inches, for example, the resulting frictional pressure drop at 3"-dia case can be reduced to approximately $\left(\frac{2}{3}\right)^5$ = 0.13 or 13% of the 2"-dia. case.

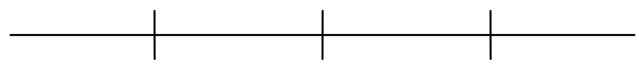
$L \propto d^5$

The trade-off between the length and the diameter for flowing at a target flow rate and at a given head. This relationship also provide the concept of **equivalent length**. The equivalent length of a pipe of size d can be referenced to a base size d_o and length L_o, is $L_{eq} = L_o\left(\frac{d}{d_o}\right)^5$.

If you find that you need to increase the pipe run 4 times the original length as a result of a revamping the existing piping system at the constant carrying capacity and the head, you can consider increasing the diameter by $\left(\frac{4}{1}\right)^{1/5} = 1.32$ times in

order to maintain the original flow rate. For example, a 4"-dia. pipe can have a run length equivalent to 4 times that of a 3"-dia. pipe flowing the same rate of flow at a given head: $L_{eq\,4"\text{-dia}} = L_{3"\text{-dia}}\left(\frac{4"}{3"}\right)^5 = L_{3"\text{-dia}}(4)$.

$$\Delta P = \Delta P_o$$
$$W = W_o$$
$$L = L_o$$
$$d = d_o = 3"$$



$$\Delta P = \Delta P_o$$
$$W = W_o$$
$$L = 4L_o$$
$$d = ? = 4"$$

$W \propto d^{5/2}$ At constant head and density, the ratio of resulting flow rates between two pipes is proportionally to the ratio of 5/2 power of ratio of corresponding inside diameters. This relationship can be used to give indication of **Pipe's Relative Carrying Capacity.**

For example, a pipe of 3" inside diameter can carry $\left(\frac{3}{2}\right)^{5/2} = 2.75$ times more water than a pipe of 2" inside diameter at a constant length. Thus, one 3" inside diameter pipe is worth approximately three 2" inside diameter pipes of the same length in parallel to flow the same amount of water.

Note

Use the above approximations as a quick guide within a few pipe sizes so that the effect of friction factor f due to the change in parameters such as flow rate or pipe ID can be practically eliminated. Otherwise, you can always factor the friction factor into the analysis.

Flow Resistance Coefficient K for Flow Elements or Equipment

Resistance Coefficient K is generally given to indicate dynamic head-loss through a flow element (i. e., valve or fitting, etc.) or a piece of equipment (i.e., heat exchanger) as **number of velocity heads**, $\rho v^2 / 2g_c$.

$$\Delta P_{f,\ psi} = K \frac{(\rho_{lb/CF})(\upsilon_{ft/\sec})^2}{(2)(g_c)(144)} \tag{24}$$

The velocity head is to be calculated on basis of inside diameter of the pipe leading to the flow element or a representative header leading to that piece equipment.

Similarly, the dynamic head loss for flow elements or equipment can also be expressed in terms of flow rates as follows for the turbulent flows:

$$\Delta P_{f\ \ psi} = (0.000\ 000\ 280) \frac{(K)(W_{lb/hr})^2}{(\rho_{lb/CF})(d_{inch})^4} \tag{25}$$

$$\Delta P_{f\ \ psi} = (0.000\ 018) \frac{(K)(\rho_{lb/CF})(Q_{gpm})^2}{(d_{inch})^4} \tag{26}$$

The K normally shall come from the equipment vendor. Some references[1,2] have published the estimated K value for common flow elements. Some vendor may provide hydraulic data (such as flow rate versus the corresponding pressure drop) for their specific equipment. In the latter situation you can back-calculate the K from Eq. (24). Remember though once the K has been developed based on certain characteristic diameter of pipe or header that you pick, that K value shall always refer to that characteristic diameter for consistency.

The dynamic head losses calculated by the K coefficient for several pieces of equipment in a row can be added directly together to arrive at the total head loss due to these pieces of equipment:

$$\Delta P_{f,\ psi} = \left[\sum_i K_i\right]\left[\frac{(\rho_{lb/CF})(\upsilon_{ft/\sec})^2}{(2)(g_c)(144)}\right] \text{ for one pipe} \tag{27}$$

Or

$$\Delta P_{f,\ psi} = \left[\sum_i K_i\right]_{pipe1}\left[\frac{(\rho_{1\ \ lb/CF})(\upsilon_{1\ \ ft/\sec})^2}{(2)(g_c)(144)}\right] + \left[\sum_i K_i\right]_{pipe2}\left[\frac{(\rho_{2\ \ lb/CF})(\upsilon_{2\ \ ft/\sec})^2}{(2)(g_c)(144)}\right] \tag{28}$$

for two pipes, etc.

Flow Coefficient for Valves C_v

Flow Coefficient C_v for valves is sometimes preferred in certain industries or by valve professionals. When Eq. 26 is written for the flow rate as:

$$Q_{gpm} = C_v \sqrt{\frac{\Delta P_{psi}}{G}} \tag{29}$$

where G = specific gravity of fluid at flowing condition relative to water at 60°F, then C_v can be found to be related to K as follows:

$$C_v = (29.9)\frac{(d_{inch})^2}{\sqrt{K}} \qquad (30)$$

As for K, the C_v is therefore also determined experimentally for each style and size of valve. C_v is numerically equal to the number of gpm of water at 60°F will flow through the valve in 1 minute when the pressure differential across the valve is 1 psi. Thus, C_v provides an index for comparing liquid capacities of different valves under a standard set of conditions. Eq. (29) is also called **liquid valve sizing equation**.

Equivalent Length of Flow Elements and Equipment L_{eq}

Relating Eq. (21) to Eq. (17), the equivalent length of flow elements or equipments can be expressed in terms of the K coefficient, the inside diameter, and friction factor of the pipe that they are on:

$$L_{eq,\ ft} = (K)\left(\frac{D_{ft}}{f}\right) \qquad (31)$$

The equivalent length for the liquid flow system at constant flowing density is additive and can also be added to the straight length of the pipe run (L_{ft}) to obtain a combined equivalent length ($L = L_{ft} + \sum L_{eq,ft}$) as a system parameter of length (L) with respect to a common diameter you have chosen. Accordingly, the system frictional pressure drop can be conveniently calculated from the pressure drop-per-100ft data:

$$\Delta P_{f,\ psi} = \left(\frac{L_{ft} + \sum L_{eq,ft}}{100}\right)\left(\frac{psi}{100ft}\right). \qquad (32)$$

Equivalent Length of A Pipe of Different Diameter

If a piping circuit is made up of lines of different sizes (d_1, d_2, d_3, etc.), they can be resolved to a common size (say, d_1) with their respective **Equivalent Length** ($L_{eq\ 2}$, $L_{eq\ 3}$, etc.) and then solve the hydraulics only once.

$$L_{eq\ 2} = L_2\left(\frac{f_2}{f_1}\right)\left(\frac{d_1}{d_2}\right)^5, \quad L_{eq\ 3} = L_3\left(\frac{f_3}{f_1}\right)\left(\frac{d_1}{d_3}\right)^5, \quad \text{etc.} \qquad (33)$$

The simplified piping system has a diameter d_1 and a total length of $L_1 + L_{eq\ 2} + L_{eq\ 2} + ...$
If their diameters are within a few sizes, the friction factor can be cancelled out as a simplification.

Overall Frictional Pressure Drop

Finally, Darcy formula for a line that consists of pine and i number of flow elements can be written as follows in terms of velocity head:

$$\Delta P_{f\ psi} = \left(f \frac{L_{ft}}{D_{ft}} + \sum_i K_i \right) \frac{(\rho_{lb/CF})(\upsilon_{ft/\sec})^2}{(2)(g_c)(144)} \quad (34)$$

Selection of Line Size

Experience indicates that frequently in line sizing, pressure drop may not be the limiting factor. There are considerations dictating the use of certain minimum pipe sizes, avoiding the use of excessive high pipe velocities or using certain minimum velocity in design. They are listed below as reference examples and shall not be considered as absolute limit. Always consult local application experts and historical experience or design procedures.

- Structural Consideration –Typically, pipe sizes 2" in diameter or larger can span 20 feet without needing an intermediate support. Thus, a minimum pipe size of 2"-dia would be considered for design if this line would go up to a pipe rack of 20 feet in spacing between pipe supports.

- Vibration – Flowing velocity in equipment such as the shell side of the shell-&-tube heat exchangers normally kept below certain velocity head in order to minimize equipment vibration.

- Solid precipitation or growth – Systems, for example, such as de-ionized (DI) water circulation system normally would need to maintain a flowing velocity above certain level in order to prevent flow stagnation. Stagnation may favor bacteria growth which is undesirable in DI water circulation system..

- Corrosion – Caustic (such as soda ash, caustic, glycol) or acid solutions (such as amine solutions or wet H_2S & CO_2-saturated solutions) normally will limit its pipe velocity to minimize the cause of corrosion to pipe material. In general, corrosive lines should have lower velocity than the non-corrosive counterpart for the same service.

- Smooth equipment operation – Centrifugal pump suction piping typically is one size larger than the discharge piping to have a smooth flow through pump. Avoid installing elbows in the suction piping to mitigate uneven flow to the impeller, which produces turbulence and may result in pump vibration and impeller damage. Outlet pipe of a control valve shall be size to avoid cavitation in pipe.

In addition, optimal line size is seldom realized due to unknown factors such as

- actual pressure drop through an existing process equipment,
- future expansion allowance,
- anticipated piping or equipment frictional pressure drop increase over time, etc.

Thus, It is also wise to design for future frictional loss. Otherwise, the piping system may be overloaded in the future before revamping.

Hazen-Williams Formula for Water Piping Design

While Darcy formula is generally accepted in estimating the frictional pressure drop for liquid and water, empirical formula, such as the Hazen-Williams expression for water pipe frictional loss, has been preferred by the water hydraulics professionals. This generally accepted formula is of the form:

$$h_L = (R)(Q^{1.85}) \qquad (35)$$

where,

h_L = frictional pressure drop or head loss, psi

Q = water flow rate, gpm

$R = \text{resistance coefficient} = \dfrac{(K_1)(L)}{(C_{HW}^{\ 1.85})(d^{4.87})}$

K_1 = a constants depending on units of measure

= 4.52 for the conventional units

= 10.59 for the SI units

L = pipe length, ft

C_{HW} = the Hazen-Williams parameter depending on the pipe inside roughness

d = pipe inside diameter, inches

From Eq. (35) and (14), the frictional pressure drop and head loss can be written as:

$$\Delta P_{psi} = \frac{(4.52)(L_{ft})}{d^{4.87}}\left(\frac{Q_{gpm}}{C_{HW}}\right)^{1.85} \qquad (36)$$

$$h_{L,ft} = \frac{144(\Delta P_{psi})}{\rho_{lb/CF}} = \frac{144}{\rho_{lb/CF}}\frac{(4.52)(L_{ft})}{d^{4.87}}\left(\frac{Q_{gpm}}{C_{HW}}\right)^{1.85} \qquad (37)$$

where

ρ = flowing density of water.

Since the Hazen-Williams parameter C_{HW} is the only parameter in the Hazen-Williams formula that relates the fluid and pipe in estimating the water frictional loss, the value varies with pipe roughness (pipe type plus the internal pipe conditions). Due to the corrosion or fouling in the water service over time, the parameter C_{HW} for a given pipe is expected to vary (i. e., decrease) with age. Degradation of C_{HW} can be of the following[3]:

Hazen-Williams C	Conditions
140	new steel pipe
100	average
60 to 75	moderately or severely corrosive water for 15-year old pipe

Lined or non-metallic piping exhibits less decrease over time.

From Eq. (36) the Hazen-Williams frictional pressure drop per 100 feet of water pipe run is:

$$\frac{\Delta P_{psi}}{100 \quad ft} = \frac{(452)}{d^{4.87}}\left(\frac{Q_{gpm}}{C_{HW}}\right)^{1.85} \qquad (38)$$

Eq. (38) is resembling to the Darcy counterpart, Eq. (23a), in that they are formerly similar with differences in the actual power for the Q and d terms plus the account of flow resistance for pipe via Hazen-Williams coefficient C_{HW}, instead of via the friction factor.

<u>Calculation of C_{HW} from the actual data</u>:

The value of C_{HW} can be back calculated from the measurement data. For example, a cement pipe 6" in inside diameter flowing 488 gpm of water for 1,000 feet at 8 psi pressure drop. What is the Hazen-Williams C?

Answer: Rearranging Eq. 36, we have

$$C_{HW} = \left[\frac{(4.52)(L_{ft})}{(d^{4.87})(\Delta P_{psi})}\right]^{\frac{1}{1.85}} Q_{gpm} = \left[\frac{(4.52)(1000)}{(6^{4.87})(8)}\right]^{\frac{1}{1.85}}(488) = 134\,.$$

References

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3. "Piping Handbook", Nayyar, Mohinder L., Editor in Chief, Sixth Ed., McGraw-Hill, Inc., New York, 1992.
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