Book 2: Chapter 4 - Fluid Flow

Piping systems are specifically designed to transport a fluid from one location to another. Fluids may be gaseous or liquid, or may be a slurry of solid particles in a liquid.

Application Limitations

Polyethylene pipes are suitable for many applications, but there are a few applications where polyethylene should not be considered or may be applicable only with appropriate precautions.

Steam service is not recommended for obvious service temperature reasons.

Dry pneumatic transport of combustible materials such as coal or food grains is not recommended, and can be extremely dangerous. Polyethylene is non-conductive. Dry, sliding friction will cause a static electric charge to build on the pipe surface. ***Static electric discharge can ignite combustible dust and cause an explosion, property damage, or possible personal injury.***

Pneumatic transport of non-combustible solids is not recommended. Particles sliding on the surface will heat and may melt the surface, and will cause static electric charges to build. ***Static electric discharge can be dangerous to property or persons.***

Above grade compressed gas lines are a possible safety concern. When installed on or above grade, polyethylene may be subject to external mechanical damage. Severe damage could cause rupture and possible uncontrolled whipping. If used for compressed gas service, polyethylene pipe should be completely restrained by burial, encased in shatter-resistant materials, or otherwise protected against external mechanical damage.

Frozen Pipes

Water can be frozen solid in polyethylene pipe without damaging the pipe, but an ice plug in the pipe will stop flow. ***Do not apply pressure to a frozen line that has an ice plug because it can move the plug down the line at significant velocity. If the plug stops suddenly at an obstruction, water hammer will result, which can burst or shatter the line.***

Severe water hammer (such as from an ice plug stopping suddenly at an obstruction) in a frozen, surface or above grade pipeline can shatter the pipeline and flying fragments can cause death, injury or property damage. Allow an ice plug to thaw before applying pressure to the line.

Pipe Internal Diameter

When a fluid is transported inside a pipe, the pipe's inside diameter determines the flow rate. DriscoPlex™ 2000 SPIROLITE® pipes are sized by the inside diameter, so the nominal diameter is the diameter used for flow calculations.

DriscoPlex™ OD-controlled pipe is nominally sized by the outside diameter. Several sizing systems are used including IPS, which is the same as IPS steel pipe, DIPS, which is the same as ductile iron pipe, CTS, which is the same as copper tubing, and international metric sizes. Pipe wall thickness determines the inside diameter. For OD-controlled pipe, the wall thickness is increased as applied stress (internal pressure or external load) requirements increase, thus the inside diameter of the pipe is reduced.

For the purposes of fluid flow design[1], Formula 4-1 provides an approximate inside diameter for DriscoPlex™ OD-controlled polyethylene pipe.

$$d = OD - 2.12\left(\frac{OD}{DR}\right) \quad \textbf{(4-1)}$$

where:

d = pipe inside diameter for flow design, in
OD = pipe outside diameter, in
DR = OD controlled pipe dimension ratio (Formula 3-3)

Consult Performance Pipe product literature, and specifications published by ASTM, AWWA, API, etc., for polyethylene pipe dimensions and tolerances.

Pressure Flow of Liquids

Darcy-Weisbach/Colebrook/Moody

Liquids in a pipe resist flowing due to viscous shear stresses within the liquid, and friction along the pipe walls. Flow resistance in a pipe results in a pressure drop, or loss of head in the piping system.

The Darcy-Weisbach or Fanning formula, Formula 4-2, and the Colebrook formula, Formula 4-5, are generally accepted methods for calculating friction losses due to liquids flowing in full pipes. These formulas recognize dependence on pipe bore and pipe surface characteristics, liquid viscosity and flow velocity.

The Darcy-Weisbach formula is:

$$h_f = f\,\frac{L\,V^2}{D\,2g} \quad \textbf{(4-2)}$$

where:

h_f = friction (head) loss, ft. of liquid
L = pipe length, ft.
D = pipe bore, ft.
V = flow velocity, ft./sec.

$$V = \frac{0.4085\,Q}{d^2} \quad \textbf{(4-3)}$$

g = gravitational constant (32.174 ft./sec^2)
Q = flow, gal/min
d = pipe bore, in
f = friction factor (dimensionless, but dependent upon pipe surface roughness and Reynolds number

Liquid flow in pipes may be laminar or turbulent, or may be in transition between laminar and turbulent. For laminar flow (Reynolds number, R, below 2000), the pipe's surface roughness has

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[1] Formula 4-1 provides an approximate inside diameter for flow calculations. It should not be used to determine diameters for devices that are to be fitted in the pipe bore. Consult Performance Pipe product literature and applicable ASTM, AWWA, API, etc., pipe standards for information about actual pipe inside diameter.

no effect, and the friction factor, f, is calculated using Formula 4-4.

$$f = \frac{64}{R} \tag{4-4}$$

For turbulent flow (Reynolds number, R, above 4000), the friction factor, f, is dependent on both the Reynolds number and the pipe's surface roughness. The friction factor may be determined from Figure 4-1, the Moody Diagram, which can be used for various pipe materials and sizes. In the Moody Diagram, relative roughness, e/D, is used. The friction factor may also be determined from the Colebrook formula.

The Colebrook formula is:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left\{\frac{e}{3.7D} + \frac{2.51}{R\sqrt{f}}\right\} \tag{4-5}$$

For Formulas 4-4 and 4-5, terms are as previously defined, and:

e = absolute roughness, ft.
R = Reynolds number, dimensionless

$$R = \frac{VD}{u} = \frac{VDr}{mg} \tag{4-6}$$

$$R = \frac{3126\,Q}{d\,k} \tag{4-7}$$

ν = kinematic viscosity, ft^2/sec

$$n = \frac{mg}{r} \tag{4-8}$$

ρ = fluid density, lb/ft^2
μ = dynamic viscosity, lb-sec/ft^2
k = kinematic viscosity, centistokes

$$k = \frac{z}{s} \tag{4-9}$$

z = dynamic viscosity, centipoises
s = liquid density, gm/cm^3

When the friction loss through one size pipe is known, the friction loss through another pipe of different diameter may be found by:

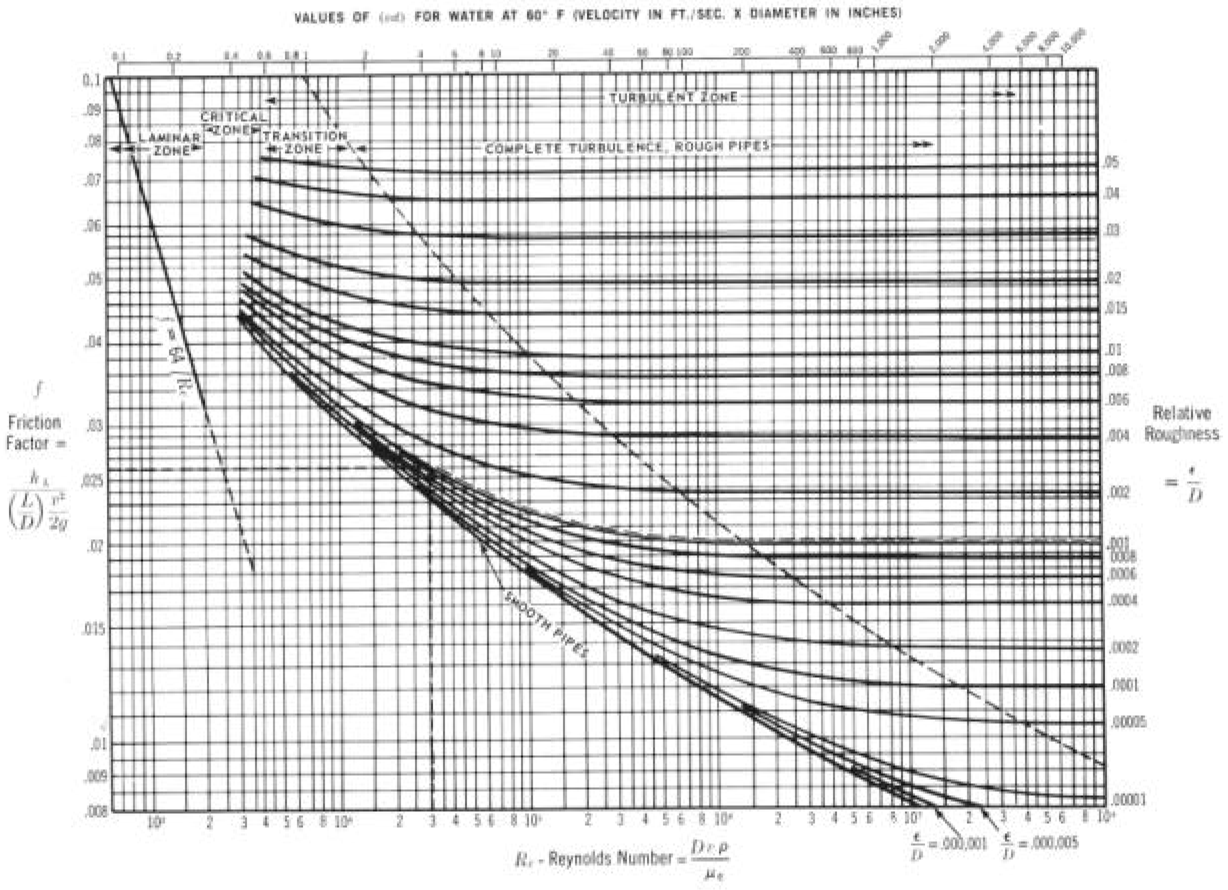
$$h_{f1} = h_{f2}\left(\frac{D_1}{D_2}\right)^5 \tag{4-10}$$

Both pipes must have the same surface roughness, and the fluid must be the same viscosity and flowing at the same rate. Subscripts 1 and 2 refer to the known and unknown pipes.

Table 4-1 Absolute Roughness for Commercial Pipe Materials

Pipe Type (New, clean condition)	*Absolute Roughness (ε, ft.)*
Polyethylene, drawn glass, brass tubing or pipe	0.00007
Steel pipe	0.00015
Cast or ductile iron pipe – asphalt dipped	0.0004
Galvanized iron pipe	0.0005
Cast or ductile iron – uncoated	0.00085
Wood stave pipe	0.0006 – 0.0003
Concrete pipe	0.001 – 0.01
Riveted steel pipe	0.003 – 0.03

Figure 4-1 Moody Diagram



Fitting and Valve Friction Losses

The friction loss through fittings and valves is commonly expressed in terms of an equivalent length of pipe. The equivalent length is found by multiplying the typical resistance coefficient for the fitting times the nominal fitting diameter.

$$L = K' D \tag{4-13}$$

Table 4-2 presents K´ factors for various fittings.

Table 4-2 Fitting Coefficient K'

Fitting	*K'*	*Fitting*	*K'*
90° molded elbow	30	60° fabricated elbow	16
45° molded elbow	16		
		90° fabricated elbow	24
30° fabricated elbow	8	Equal outlet tee, run/branch	60
45° fabricated elbow	12	Equal outlet tee, run/run	20

Where a pipeline contains a large number of fittings in close proximity to each other, this simplified method of predicting fitting flow loss may not be adequate due to the cumulative systems effect. Where this is a design consideration, the designer should consider an additional friction loss allowance, or a more thorough treatment of the fluid mechanics.

Hazen-Williams

The Darcy-Weisbach/Colebrook/Moody method applies to non-plastic liquids, but it is complex. For some applications, empirical formulas are available, and when used within their limitations, reliable results can be obtained with greater convenience. Hazen and Williams developed an empirical formula for water.

The Hazen-Williams formula for water at 60° F can be applied to liquids having the same kinematic viscosity of 1.130 centistokes (0.00001211 ft^2/sec), or 31.5 SSU. Water's viscosity varies with temperature, so some error can occur at other temperatures.

Hazen-Williams formula for friction (head) loss in feet:

$$h_f = \frac{0.002083\, L}{d^{4.8655}} \left(\frac{100\, Q}{C} \right)^{1.85} \tag{4-14}$$

Hazen-Williams formula for friction (head) loss in psi:

$$p_f = \frac{0.0009015\, L}{d^{4.8655}} \left(\frac{100\, Q}{C} \right)^{1.85} \tag{4-15}$$

Terms are as previously defined, and:

C = Hazen-Williams Friction Factor, dimensionless (not related to Darcy-Weisbach friction factor, f)

p_f = friction (head) loss for water, psi

Table 4-3 Properties of Water

Temperature, °F/°C	*Specific Weight, lb/ft^3*	*Kinematic Viscosity, centistokes*
32 / 0	62.414	1.79
60 / 15.6	62.37	1.13
75 / 23.9	62.27	0.90
100 / 37.8	62.00	0.69
120 / 48.9	61.71	0.57
140 / 60	61.38	0.47

Table 4-4 Hazen-Williams Friction Factor, C

Pipe Material	*Values for C*		
	Range High / Low	*Average Value*	*Typical Design Value*
Polyethylene pipe or tubing	160 / 150	150-155	150
Cement or mastic lined iron or steel pipe	160 / 130	148	140
Copper, brass, lead, tin or glass pipe or tubing	150 / 120	140	130
Wood stave	145 / 110	120	110
Welded and seamless steel	150 / 80	130	100
Cast and ductile iron	150 / 80	130	100
Concrete	152 / 85	120	100
Corrugated steel	–	60	60

Pipes of different materials and diameters may be compared using the following formula. The subscripts 1 and 2 refer to the known pipe and the unknown pipe.

$$\%\,flow = 100\,\frac{d_2}{d_1}\left(\frac{C_2}{C_1}\right)^{0.3806} \qquad \textbf{(4-16)}$$

Losses Due to Elevation Change

Line pressure may be lost or gained by a change in elevation. For liquids, the pressure loss for a given elevation change is given by:

$$h_E = h_2 - h_1 \qquad \textbf{(4-17)}$$

where

h_E = Elevation head loss, ft of liquid
h_1 = Pipeline elevation at point 1, ft
h_2 = Pipeline elevation at point 2, ft

If a pipeline is subject to a uniform elevation change along its length, the two points may be the elevations at each end of the line. However, some pipelines may have several elevation changes as they traverse rolling or mountainous terrain. These pipelines may be evaluated by choosing points where the pipeline slope changes, then summing the individual elevation heads for an overall pipeline elevation head.

Air Binding and Vacuum Release

In rolling or mountainous country, additional drag due to air binding must be avoided. Air binding occurs when air in the system accumulates at local high spots. This reduces the effective pipe bore, and restricts flow. Vents such as standpipes or air release valves may be installed at high points to avoid air binding. If the pipeline has a high point above that of either end, vacuum venting may be required to prevent vacuum collapse, siphoning, or to allow drainage.

Water Hammer and Pressure Surge Considerations

Effects on Pressure Piping Systems

Water hammer in a liquid piping system is a high velocity pressure wave caused by a sudden change in liquid flow velocity. A sudden valve opening or closing, a piping failure, or a pump starting or stopping may cause an instantaneous flow change. The sudden liquid velocity change causes a momentum change resulting in a pressure surge. Compressible fluids (gasses) are not subject to water hammer.

The magnitude of the pressure change, P, and the wave velocity, S, of a pressure surge may be determined by the following:

$$\pm P = \frac{-\left(\frac{w}{g}\right)S\left(\pm V\right)}{144} \qquad \textbf{(4-18)}$$

$$S = \sqrt{\frac{144\ E\,E_B}{\left(\frac{w}{g}\right)\left(144\,E + \frac{E_B\,D}{t'}\right)}} \qquad \textbf{(4-19)}$$

where

$\pm P$ = pressure change, psi
w = liquid weight, lb/ft^3
g = acceleration of gravity, ft/sec^2
S = wave velocity, ft/sec
$\pm V$ = liquid velocity change, ft/sec
E = short-term pipe elastic modulus, psi
E_B = liquid bulk modulus, lb/ft^2
D = pipe inside diameter, ft
t' = pipe wall thickness, ft

The pressure wave is superimposed on the system, and may be negative or positive. Water hammer analysis of piping systems is complex and depends on pumping characteristics, elevation changes, valve actuation, system geometry, dissolved gasses, and other factors. For a detailed analysis of hydraulic surge in piping systems, a professional design engineer or consultant who is experienced with hydraulic surge in piping systems should be consulted.

Equation 4-18 gives the maximum surge pressure for a given velocity change. Typically for a rapid valve closure the velocity change equals the flow velocity in the line. However, events such as cavitation or water column separation can occur during which the water velocity can exceed the average flow velocity.

Surge Allowance

Flexibility and short-term mechanical strength in DriscoPlex™ polyethylene pressure pipe provide exceptional surge tolerance. The low elastic modulus provides a quick dampening mechanism for shock loads. These properties result in lower surge pressures compared to more rigid systems such as steel, ductile iron, or PVC. For the same liquid and velocity change, surge pressures in polyethylene pipe are about 86% less than in steel pipe, about 80% less than in ductile iron pipe, and about 50% less than in PVC pipe.

Surges affect systems differently depending upon the system design, surge pressure magnitude and surge frequency. Allowable surge pressures may be limited by the pressure ratings of pumps, valves, fittings, partially restrained or non-restrained connections, or other appurtenances.

Water systems may be subject to surge pressures when there is a sudden increase or decrease in flow velocity. Recurrent pressure surges, P_{RS}, are repetitive surge events that occur frequently such as during pump start-stop operation. Occasional pressure surges, P_{OS}, are irregularly occurring surges such as a sudden flow change due to firefighting or check valve operation. Surge pressure corresponds directly to velocity change, that is, greater velocity change produces greater surge pressure.

With its unique ductile elastic properties and superb fatigue resistance, DriscoPlex™ polyethylene pipe is especially tolerant of pressure surges. Unlike other plastic and metal pipes, the allowance for pressure surge is applied *above* the pressure rating of the pipe. In Table 4-5, pressure rating, P, is determined using Formula 3-1.

Table 4-5 Pressure Surge Allowance

Type of Pressure Surge	*Allowance for Surge*
Recurrent Surge, P_{RS}	$P_{RS} = 0.5\ (P)$
Occasional Surge, P_{OS}	$P_{OS} = 1.0\ (P)$

Working Pressure Rating (WPR)

Working pressure rating, WPR, combines the elements of pressure rating, P (Formula 3-1), and surge pressure.

For recurrent pressure surge applications:

$$WPR = 1.5\ (P) - P_{RS} \tag{4-20}$$

For occasional pressure surge applications:

$$WPR = 2.0\ (P) - P_{OS} \tag{4-21}$$

When flow velocity is at or below the value in Table 4-6 for the surge condition, pressure surge will not exceed the surge pressure allowance. Under these flow conditions; the working pressure rating, WPR, equals the pressure rating, P. Table 4-6 shows surge allowance and corresponding sudden velocity change for DR's typically used for water distribution pipe.

Surge allowance is available only for surge events. Surge allowance is applied above the working pressure; therefore, it cannot be used to increase continuous internal pressure capacity above that permitted by the working pressure.

Table 4-6 Surge Allowance?

DR	WPR, psi	Recurring Surge Events		Occasional Surge Events	
		Surge Allowance P_{RS}, psi	Corresponding Sudden Velocity Change, fps	Surge allowance P_{OS}, psi	Corresponding Sudden Velocity Change, fps
21	80	40.0	4.0	80	8.0
17	100	50.0	4.4	100	8.9
13.5	130	64.0	5.0	130	10.1
11	160	80.0	5.6	160	11.1

? Pressure and velocity ratings are for water at 80°F (27°C) or less, and can vary for other fluids and temperatures.

When flow velocity exceeds the corresponding sudden velocity change in Table 4-6, the surge allowance must increase, and to compensate, the Working Pressure Rating must be reduced. Formulas 4-20 and 4-21 may be used to determine surge pressure allowance and WPR in these cases.

Effects of Cyclic Stressing

When pressure surges are frequent or continuous, the fatigue endurance of the material must be considered. As with all materials, repeated stressing and straining can result in a long-term strength reduction. Although Performance Pipe polyethylene materials are typically more fatigue resistant than other thermoplastic piping materials, they may eventually be affected by continuous, long-term exposure to highly repetitive cyclical surges.

Controlling Water Hammer

Reducing the suddenness of a velocity change can help control water hammer effects. Velocity change rate may be controlled with starting and stopping speed controls on pumps, valve closure and opening speed controls, surge suppressors, and by controlling flow velocity, or flow rate.

To prevent subsequent surges from superimposing on the prior surge, the second surge should be delayed from the first by at least the surge delay interval in Table 4-8. Delay times are for 1000 feet of uninterrupted pipeline upstream from a valve or pump. If surge pressures are within allowable limits, the delay intervals will allow the first surge to die out before the next surge is introduced.

Table 4-7 Surge Delay Interval

Pipe DR	Time Delay Interval Between Surges for 1000 ft of Pipe, sec	Pipe DR	Time Delay Interval Between Surges for 1000 ft of Pipe, sec
7.3	13.3	17.0	21.9
9.0	15.2	21.0	24.5
11.0	17.1	26.0	27.6
13.5	19.3	32.5	31.1

In hilly regions, a liquid flow may separate at high points, and cause surge pressures when the flow rejoins. Reducing the downhill, downstream pipeline bore may help keep the pipeline full by reducing the flow rate. Flow separation is more likely to occur with oversize pipelines. Vacuum breakers and flow control valves can also be effective.

Recommended Flow Velocities

The limiting flow velocity in DriscoPlex™ polyethylene pipe depends on the specific details of the system. For water systems operating at rated pressures, limiting velocities based on surge capacities for some pipe sizes are indicated in Tables 4-7 and 4-8. Where surge effects are not possible, velocities exceeding 25 feet per second may be acceptable.

Velocity may be limited by the capability of pumps or elevation head to overcome friction (head) loss and deliver the flow and pressure through the pipeline required for the application.

Gravity Flow of Liquids

In a pressure pipeline, a prime mover, such as a pump, provides the energy required to move the fluid through the pipeline. Such pipelines can transport fluids across a level surface, uphill, or downhill. However, when the pipeline discharge is below the inlet, a gravity flow can be established.

In operation, gravity flow pipelines require only that the discharge be below the inlet. Like pressure flow pipelines, friction loss in a gravity flow pipeline is dependent upon viscous shear stresses within the liquid, and friction along the pipe walls.

Some gravity flow piping systems may become very complex, especially if the pipeline grade varies, because friction loss will vary along the run. With a varying grade, parts of the line may develop internal pressure, or vacuum, and may have varying liquid levels in the bore.

Manning

For open channel water flow under conditions of constant grade, and uniform channel cross section, the Manning equation may be used. Open channel flow exists in a pipe when it runs partially full. Like the Hazen-Williams formula, the Manning equation is limited to water or liquids with a kinematic viscosity equal to water.

Manning Equation

$$V = \frac{1.486}{n} r^{2/3} S^{1/2} \qquad \textbf{(4-22)}$$

where

V = flow velocity, ft/sec
n = roughness coefficient, dimensionless
r = hydraulic radius, ft

$$r = \frac{A}{P} \qquad \textbf{(4-23)}$$

A = channel cross section area, ft^2
P = perimeter wetted by flow, ft
S = hydraulic slope, ft/ft

$$S = \frac{h_1 - h_2}{L} = \frac{h_f}{L} \qquad \textbf{(4-24)}$$

h_1 = upstream pipe elevation, ft
h_2 = downstream pipe elevation, ft
h_f = friction (head) loss, ft of liquid

It is convenient to combine the Manning equation with

$$Q = AV \tag{4-25}$$

to obtain

$$Q = \frac{1.486\ A}{n} r^{2/3} S^{1/2} \tag{4-26}$$

where terms are as defined above, and

Q = flow, ft^3/sec

When a circular pipe is running full or half-full,

$$r = \frac{D}{4} = \frac{d}{48} \tag{4-27}$$

where

D = pipe bore, ft
d = pipe bore, in

Full pipe flow in ft^3 per second may be estimated using:

$$Q = \left(6.136 \times 10^{-4}\right) \frac{d^{8/3} S^{1/2}}{n} \tag{4-28}$$

Full pipe flow in gallons per minute may be estimated using:

$$Q' = 0.275 \frac{d^{8/3} S^{1/2}}{n} \tag{4-29}$$

Nearly full circular pipes will carry more liquid than a completely full pipe. When slightly less than full, the hydraulic radius is significantly reduced, but the actual flow area is only slightly lessened. Maximum flow is achieved at about 93% of full pipe flow, and maximum velocity at about 78% of full pipe flow.

Table 4-8 Values of n for use with Manning Equation

Surface	*n, range*	*n, typical design*
Polyethylene pipe	0.008 – 0.011	0.009
Uncoated cast or ductile iron pipe	0.012 – 0.015	0.013
Corrugated steel pipe	0.021 – 0.030	0.024
Concrete pipe	0.012 – 0.016	0.015
Vitrified clay pipe	0.011 – 0.017	0.013
Brick and cement mortar sewers	0.012 – 0.017	0.015
Wood stave	0.010 – 0.013	0.011
Rubble masonry	0.017 – 0.030	0.021

Comparative Flows for Slipliners

Sliplining rehabilitation of deteriorated gravity flow sewers involves installing a polyethylene liner inside of the original pipe. For conventional sliplining, clearance between the liner outside diameter, and the existing pipe bore is required to install the liner. So after rehabilitation, the flow channel is smaller than the original pipe. However, DriscoPlex™ polyethylene pipe has a smooth surface that resists aging and deposition. It may be possible to slipline, and maintain all or most of the original flow capacity. See Table 4-10.

Comparative flow capacities of circular pipes may be determined by the following:

$$\%\,flow = 100\,\frac{Q_1}{Q_2} = 100\,\frac{\left(\dfrac{d_1^{8/3}}{n_1}\right)}{\left(\dfrac{d_2^{8/3}}{n_2}\right)} \qquad \textbf{(4-30)}$$

Table 4-10 was developed using Formula 4-30 where d_1 = the liner ID, and d_2 = the existing sewer ID.

Table 4-9 Comparative Flows for Slipliners

Existing Sewer ID, in	Liner OD, in.	Liner DR 32.5			Liner DR 26			Liner DR 21			Liner DR 17		
		Liner ID, in.†	% flow vs. concrete	% flow vs. clay	Liner ID, in.†	% flow vs. concrete	% flow vs. clay	Liner ID, in.†	% flow vs. concrete	% flow vs. clay	Liner ID, in.†	% flow vs. concrete	% flow vs. clay
4	3.500	3.272	97.5%	84.5%	3.215	93.0%	80.6%	3.147	87.9%	76.2%	3.064	81.8%	70.9%
6	4.500	4.206	64.6%	56.0%	4.133	61.7%	53.5%	4.046	58.3%	50.5%	3.939	54.3%	47.0%
6	5.375	5.024	103.8%	90.0%	4.937	99.1%	85.9%	4.832	93.6%	81.1%	4.705	87.1%	75.5%
8	6.625	6.193	84.2%	73.0%	6.085	80.3%	69.6%	5.956	75.9%	65.8%	5.799	70.7%	61.2%
8	7.125	6.660	102.2%	88.6%	6.544	97.5%	84.5%	6.406	92.1%	79.9%	6.236	85.8%	74.4%
10	8.625	8.062	93.8%	81.3%	7.922	89.5%	77.6%	7.754	84.6%	73.3%	7.549	78.8%	68.3%
12	10.750	10.049	103.8%	90.0%	9.873	99.1%	85.9%	9.665	93.6%	81.1%	9.409	87.1%	75.5%
15	12.750	11.918	90.3%	78.2%	11.710	86.1%	74.6%	11.463	81.4%	70.5%	11.160	75.7%	65.6%
15	13.375	12.503	102.5%	88.9%	12.284	97.8%	84.8%	12.025	92.4%	80.1%	11.707	86.1%	74.6%
16	14.000	13.087	97.5%	84.5%	12.858	93.0%	80.6%	12.587	87.9%	76.2%	12.254	81.8%	70.9%
18	16.000	14.956	101.7%	88.1%	14.695	97.0%	84.1%	14.385	91.7%	79.4%	14.005	85.3%	74.0%
21	18.000	16.826	92.3%	80.0%	16.532	88.1%	76.3%	16.183	83.2%	72.1%	15.755	77.5%	67.1%
24	20.000	18.695	85.6%	74.2%	18.369	81.7%	70.8%	17.981	77.2%	66.9%	17.506	71.9%	62.3%
24	22.000	20.565	110.4%	95.7%	20.206	105.3%	91.3%	19.779	99.5%	86.2%	19.256	92.6%	80.3%
27	24.000	22.434	101.7%	88.1%	22.043	97.0%	84.1%	21.577	91.7%	79.4%	21.007	85.3%	74.0%
30	28.000	26.174	115.8%	100.4%	25.717	110.5%	95.8%	25.173	104.4%	90.5%	24.508	97.2%	84.2%
33	30.000	28.043	108.0%	93.6%	27.554	103.0%	89.3%	26.971	97.3%	84.3%	26.259	90.6%	78.5%
36	32.000	29.913	101.7%	88.1%	29.391	97.0%	84.1%	28.770	91.7%	79.4%	28.009	85.3%	74.0%
36	34.000	31.782	119.5%	103.6%	31.228	114.1%	98.9%	30.568	107.7%	93.4%	29.760	100.3%	86.9%
42	36.000	33.652	92.3%	80.0%	33.065	88.1%	76.3%	32.366	83.2%	72.1%	31.511	77.5%	67.1%
48	42.000	39.260	97.5%	84.5%	38.575	93.0%	80.6%	37.760	87.9%	76.2%	36.762	81.8%	70.9%
54	48.000	44.869	101.7%	88.1%	44.086	97.0%	84.1%	43.154	91.7%	79.4%	42.014	85.3%	74.0%
60	54.000	50.478	105.1%	91.1%	49.597	100.3%	86.9%	48.549	94.8%	82.1%	47.266	88.2%	76.5%
† Liner ID calculated per Formula 4-1.													

Pipe Surface Condition, Aging

Aging acts to increase pipe surface roughness in most piping systems. This in turn increases flow resistance.

DriscoPlex™ polyethylene pipe resists aging effects because polyethylene does not rust, rot, corrode or tuberculate, does not support biological growth, and it resists the adherence of scale and deposits. In some cases, moderate flow velocities are sufficient to prevent deposition, and where low velocities predominate, occasional high velocity flows will help to remove deposits.

DriscoPlex™ polyethylene pipes may be cleaned with high-pressure water or by running "soft" (plastic foam) pigs through the pipe. Bucket, wire or finger type scraper pigs should not be used.

Slurry Flow

This discussion is restricted to liquid slurries, and does not address pneumatic transport of solids. Please see "Application Limitations" at the beginning of this chapter.

Liquid slurry piping systems are designed to transport solids entrained in a liquid carrier. Of primary concern in design are the solid material, particle size, and the carrier liquid.

DriscoPlex™ polyethylene pipes are produced from materials with high molecular weight, and low elastic modulus. These materials are well suited for turbulent flow slurry applications.

Turbulent flow is recommended because particles suspended in the carrier liquid will bounce off the pipe inside surface, using the pipe's elasticity and high molecular weight toughness to provide service life significantly greater than many metal piping materials. However, if flow velocity is too low to maintain fully turbulent flow for a given particle size, solids can drift to the bottom of the pipe and slide along the surface. Compared to metals, polyethylene is a softer material, so under sliding solids conditions, polyethylene may wear appreciably.

Particle Size

As a general recommendation, particle size should not exceed about 0.2 in (5 mm); however, larger particles are occasionally acceptable if they are a small percentage of the solids in the slurry.

With relatively large, uniformly sized particles in the slurry, the viscosity of the mixture will be approximately that of the carrying liquid. However, if particle size is very small, about 15 microns or less, the slurry viscosity will increase above that of the carrying liquid alone. Fine particle slurries should be analyzed in a laboratory for viscosity and specific gravity before determining flow friction losses. Inaccurate assumptions of a fluid's rheological properties can lead to significant errors in flow resistance analysis. Examples of fine particle slurries are water slurries of fine silt, clay, and kaolin clay.

Slurries frequently do not have uniform particle size. Some size non-uniformity can aid in transporting larger particles. In a slurry having a proportion of fine particles, the fine particle mixture will act as a more viscous carrying fluid, and help suspend larger particles in the slurry. Flow analysis of non-uniform particle size slurries should include a rheological investigation of the fine particle mixture.

Solids Concentration and Specific Gravity

The following formulas are useful in determining solids concentrations and mixture specific gravity.

$$C_V = \frac{S_M - S_L}{S_S - S_L} \tag{4-31}$$

$$C_W = \frac{C_V S_S}{S_M} \tag{4-32}$$

$$S_M = C_V \left(S_S - S_L \right) + S_L \tag{4-33}$$

$$S_M = \frac{S_L}{1 - \frac{C_W \left(S_S - S_L \right)}{S_S}} \tag{4-34}$$

where

S_L = carrier liquid specific gravity
S_S = solids specific gravity
S_M = slurry mixture specific gravity
C_V = percent solids concentration by volume
C_W = percent solids concentration by weight

Critical Velocity

As presented above, turbulent flow is recommended to keep particles in suspension. Turbulent flow avoids the formation of a sliding bed of solids, excessive pipeline wear, and possible clogging. Generally, Reynolds numbers above 4000 will insure turbulent flow. See "Pressure Flow of Liquids" at the beginning of this chapter.

A general recommendation is to maintain flow velocity at about 30% above the critical settlement velocity. A study performed by Durand on sand-water slurries provides the following formula for determining critical velocity:

$$V_C = F_L \sqrt{2gd \left(S_S - 1 \right)} \tag{4-35}$$

where terms are as previously defined and

V_C = critical carrying velocity, ft/sec
F_L = coefficient dependent upon grain size and concentration. (Table 4-13 and Table 4-14.)

A guideline minimum velocity recommendation for fine particle slurries (below 50 microns, 0.05 mm) is 4 to 7 ft/sec, so long as turbulent flow is maintained. A guideline minimum velocity for larger particle slurries (over 150 microns, 0.15 mm) is

$$V_M = 14\sqrt{D} \tag{4-36}$$

where

V_M = approximate minimum velocity, ft/sec

Another useful relationship is that critical velocity changes with the pipe bore, that is, for the same carrying liquid, particle size and solids concentration, critical velocity increases with increasing pipe bore. Analysis of Formula 4-2, the Darcy-Weisbach formula shows the following relationship:

$$V_2 = \frac{\sqrt{D_2}}{\sqrt{D_1}} V_1 \tag{4-37}$$

where the subscripts 1 and 2 are for the two pipe diameters.

Table 4-10 Scale of Particle Sizes

Tyler Screen Mesh	*U.S. Standard Mesh*	*Inches*	*Microns*	*Class*
		1.3 – 2.5	33,000 – 63,500	Very coarse gravel
		0.6 – 1.3	15,200 – 32,000	Coarse gravel
2.5		0.321	8,000	Medium gravel
5	5	0.157	4,000	Fine gravel
9	10	0.079	2,000	Very fine gravel
16	18	0.039	1,000	Very coarse sand
32	35	0.0197	500	Coarse sand
60	60	0.0098	250	Medium sand
115	120	0.0049	125	Fine sand
250	230	0.0024	62	Very fine sand
400		0.0015	37	Coarse silt
		0.0006 – 0.0012	16 – 31	Medium silt
			8 – 13	Fine silt
			4 – 8	Very fine silt
			2 – 4	Coarse clay
			1 – 2	Medium clay
			0.5 - 1	Fine clay

Table 4-11 Specific Gravity and Slurry Solids Concentration

Material	*Specific Gravity*	*Typical Solids Concentration*	
		% by Weight	*% by Volume*
Gilsonite	1.05	40 – 45	39 – 44
Coal	1.40	45 – 55	37 – 47
Sand	2.65	43 – 43	23 – 30
Limestone	2.70	60 – 65	36 – 41
Copper Concentrate	4.30	60 – 65	26 – 30
Iron Ore	4.90		
Iron Sands	1.90		
Magnetite	4.90	60 - 65	23 - 27

Table 4-12 Water-Base Slurry Specific Gravities

C_W	*Solid Specific Gravity, S_S*									
	1.4	*1.8*	*2.2*	*2.6*	*3.0*	*3.4*	*3.8*	*4.2*	*4.6*	*5.0*
5	1.01	1.02	1.03	1.03	1.03	1.04	1.04	1.04	1.04	1.04
10	1.03	1.05	1.06	1.07	1.07	1.08	1.08	1.08	1.08	1.09
15	1.04	1.07	1.09	1.10	1.11	1.12	1.12	1.13	1.13	1.14
20	1.05	1.10	1.12	1.14	1.15	1.16	1.17	1.18	1.19	1.19
25	1.08	1.13	1.16	1.18	1.20	1.21	1.23	1.24	1.24	1.25
30	1.09	1.15	1.20	1.23	1.25	1.27	1.28	1.30	1.31	1.32
35	1.11	1.18	1.24	1.27	1.30	1.33	1.35	1.36	1.38	1.39
40	1.13	1.22	1.28	1.33	1.36	1.39	1.42	1.44	1.46	1.47
45	1.15	1.25	1.33	1.38	1.43	1.47	1.50	1.52	1.54	1.56
50	1.17	1.29	1.38	1.44	1.50	1.55	1.58	1.62	1.64	1.67
55	1.19	1.32	1.43	1.51	1.58	1.63	1.69	1.72	1.76	1.79
60	1.21	1.36	1.49	1.59	1.67	1.73	1.79	1.84	1.89	1.92
65	1.23	1.41	1.55	1.67	1.76	1.85	1.92	1.98	2.04	2.08
70	1.25	1.45	1.62	1.76	1.88	1.98	2.07	2.14	2.21	2.27

Table 4-13 Velocity Coefficient, F_L (Uniform Particle Size)

Particle Size, mm	*Velocity Coefficient, F_L*			
	C_V = 2%	*C_V = 5%*	*C_V = 10%*	*C_V = 15%*
.1	.76	0.92	0.94	0.96
.2	0.94	1.08	1.20	1.28
.4	1.08	1.26	1.41	1.46
.6	1.15	1.35	1.46	1.50
.8	1.21	1.39	1.45	1.48
1.0	1.24	1.04	1.42	1.44
1.2	1.27	1.38	1.40	1.40
1.4	1.29	1.36	1.67	1.37
1.6	1.30	1.35	1.35	1.35
1.8	1.32	1.34	1.34	1.34
2.0	1.33	1.34	1.34	1.34
2.2	1.34	1.34	1.34	1.34
2.4	1.34	1.34	1.34	1.34
2.6	1.35	1.35	1.35	1.35
2.8	1.36	1.36	1.36	1.36
= 3.0	1.36	1.36	1.36	1.36

Table 4-14 Velocity Coefficient, F_L (50% Passing Particle Size)

Particle Size, mm	*Velocity Coefficient, F_L*			
	C_V = 5%	*C_V = 10%*	*C_V = 20%*	*C_V = 30%*
0.01	0.48	0.48	0.48	0.48
0.02	0.58	0.59	1.60	0.61
0.04	0.70	0.72	0.74	0.76
0.06	0.77	0.79	0.81	0.83
0.08	0.83	0.86	0.86	0.91
0.10	0.85	0.88	0.92	0.95
0.20	0.97	1.00	1.05	0.18
0.40	1.09	1.13	1.18	1.23
0.60	1.15	1.21	1.26	1.30
0.80	1.21	1.25	1.31	1.33
1.0	1.24	1.29	1.33	1.35
2.0	1.33	1.36	1.38	1.40
3.0	1.36	1.38	1.39	1.40

Head Loss

The same formulas used for pressure liquid flows, Darcy-Weisbach (Formula 4-2), and Hazen-Williams (Formulas 4-14 and 4-15) may be used to determine head loss for slurry systems, provided the viscosity limitations of the formulas, are taken into account.

Elevation head loss is increased by the mixture specific gravity.

$$h_E = S_M \left(h_2 - h_1\right) \qquad \textbf{(4-38)}$$

Compressible Gas Flow

Flow formulas for smooth pipe may be used to estimate gas flow rates through DriscoPlex™ polyethylene pipe.

High Pressure Formulas

For pressures greater than 1 psig, the equations presented below are used in the industry. Due to assumptions made for each equation, there may be slight differences in the calculated result for one equation compared to that from another.

Mueller Equation

$$Q_h = \frac{2826\, d^{2.725}}{S_g^{\ 0.425}} \left(\frac{p_1^{\ 2} - p_2^{\ 2}}{L} \right)^{0.575} \qquad \textbf{(4-39)}$$

Weymouth Equation

$$Q_h = \frac{2034\, d^{2.667}}{S_g^{\ 0.5}} \left(\frac{p_1^{\ 2} - p_2^{\ 2}}{L} \right)^{0.5} \qquad \textbf{(4-40)}$$

IGT Distribution Equation

$$Q_h = \frac{2679\, d^{2.667}}{S_g^{\,0.444}} \left(\frac{p_1^{\,2} - p_2^{\,2}}{L} \right)^{0.555} \tag{4-41}$$

Spitzglass Equation

$$Q_h = \frac{3410}{S_g^{\,0.5}} \left(\frac{p_1^{\,2} - p_2^{\,2}}{L} \right)^{0.5} \left(\frac{d^5}{1 + \frac{3.6}{d} + 0.03\, d} \right)^{0.5} \tag{4-42}$$

where

Q_h = flow, standard ft^3/hour
S_g = gas specific gravity
p_1 = inlet pressure, lb/in^2 absolute
p_2 = outlet pressure, lb/in^2 absolute
L = length, ft
d = pipe bore, in

Low Pressure Formulas

For applications where less than 1 psig is encountered, such as landfill gas gathering or wastewater odor control, the following equations may be used.

Mueller Equation

$$Q_h = \frac{2971\, d^{2.725}}{S_g^{\,0.425}} \left(\frac{h_1 - h_2}{L} \right)^{0.575} \tag{4-43}$$

Spitzglass Equation

$$Q_h = \frac{3350}{S_g^{\,0.5}} \left(\frac{h_1 - h_2}{L} \right)^{0.5} \left(\frac{d^5}{1 + \frac{3.6}{d} + 0.03\, d} \right)^{0.5} \tag{4-44}$$

where terms are as defined above, and

h_1 = inlet pressure, in H_2O
h_2 = outlet pressure, in H_2O

Gas Permeation

Long distance pipelines carrying compressed gasses may deliver slightly less gas due to permeation through the pipe wall. Usually, such losses are small, however, it may be necessary to distinguish between permeation losses and possible leakage.

The volume of a gas that will permeate through polyethylene pipe of a given wall thickness is determined by the following formula:

$$q_P = \frac{K A_P \Theta P_A}{t'} \tag{4-45}$$

where

q_P = volume of gas permeated, cm^3 (gas at standard temperature and pressure)
K = permeability constant (Table 4-16)
A_P = area of the outside wall of the pipe, 100 in^2
P_A = pipe internal pressure, atmospheres (1 atmosphere = 14.7 lb/in^2)
T = elapsed time, days
t' = wall thickness, mils

Table 4-15 Permeability Constants

Gas	*K*
Methane	85
Carbon Monoxide	80
Hydrogen	425

Table 4-16 Physical Properties of Gases (Approximate Values at 14.7 psi and 68°F)

Gas	*Chemical Formula*	*Molecular Weight*	*Weight Density, lb/ft^3, s*	*Specific Gravity, S_g*
Acetylene (ethylene)	C_2H_2	26.0	0.0682	0.907
Air	–	29.0	0.0752	1.000
Ammonia	NH_3	17.0	0.0448	0.596
Argon	A	39.9	0.1037	1.379
Butane	C_4H_{10}	58.1	0.1554	2.067
Carbon Dioxide	CO_2	44.0	0.1150	1.529
Carbon Monoxide	CO	28.0	0.0727	0.967
Ethane	C_2H_6	30.0	0.0789	1.049
Ethylene	C_2H_4	28.0	0.0733	0.975
Helium	He	4.0	0.0104	0.138
Hydrogen Chloride	HCl	36.5	0.0954	1.286
Hydrogen	H	2.0	0.0052	0.070
Hydrogen Sulphide	H_2S	34.1	0.0895	1.190
Methane	CH_4	16.0	0.0417	0.554
Methyl Chloride	CH_3Cl	50.5	0.1342	1.785
Natural Gas	–	19.5	0.0502	0.667
Nitric Oxide	NO	30.0	0.0708	1.037
Nitrogen	N_2	28.0	0.0727	0.967
Nitrous Oxide	N_2O	44.0	0.1151	1.530
Oxygen	O_2	32.0	0.0831	1.105
Propane	C_3H_8	44.1	0.1175	1.562
Propene (Propylene)	C_3H_6	42.1	0.1091	1.451
Sulfur Dioxide	SO_2	64.1	0.1703	2.264
Landfill Gas (approx. value)	–	–	–	1.00
Carbureted Water Gas	–	–	–	0.63
Coal Gas	–	–	–	0.42
Coke-Oven Gas	–	–	–	0.44
Refinery Oil Gas	–	–	–	0.99
Oil Gas (Pacific Coast)	–	–	–	0.47
“Wet” Gas (approximate value)	–	–	–	0.75