

SECTION 17

Fluid Flow and Piping

Few flow problems can be solved with an acceptable degree of accuracy when using equations designed to fit idealized applications. Flow regimes and associated pressure drops are complex phenomena and require complex equations to predict

their relationships. For engineering design purposes, several empirical formulas have been developed to fit particular circumstances in predicting flow capacity and pressure drop.

FIG. 17-1
Nomenclature

A = pipe cross sectional area, ft^2 ($A = \pi D^2/4$)	N_{Lv} = liquid velocity number, from Equation 17-54
c = sum of allowances for corrosion, erosion, etc., in., Fig. 17-22	N_{gv} = gas velocity number, from Equation 17-55
C = design parameter used in Hazen and Williams formula, Equation 17-33	N_d = pipe diameter number, from Equation 17-56
C_1 = discharge factor from Fig. 17-8	N_L = liquid viscosity number, from Equation 17-57
C_2 = size factor from Fig. 17-9	P = pressure, psia
d = internal diameter of pipe, in.	P_1 = inlet pressure, psia
d_o = outside pipe diameter, in.	P_2 = outlet pressure, psia
D = internal diameter of pipe, feet	P_{avg} = average pressure, psia, from Equation 17-16
E = pipeline efficiency factor (fraction)	P_b = base absolute pressure, psia (ANSI 2530 specification: $P_b = 14.73$ psia)
E' = longitudinal weld joint factor from ANSI B31.3, Fig. 17-22	P_i = internal design pressure, psig
E'' = longitudinal joint factor from ANSI B31.8, Fig. 17-23	ΔP_{100} = pressure drop, psi/100 ft equivalent pipe length
f_f = Fanning friction factor	ΔP_e = elevation component of pressure drop, psi
f_m = Moody friction factor ($f_m = 4.0 f_f$)	ΔP_f = frictional component of pressure drop, psi
f_n = single phase friction factor for Dukler calculation, from Equation 17-45	ΔP_t = total pressure drop, psi
f_{tpr} = friction factor ratio for Dukler calculation, Fig. 17-17	ΔP_{wh} = pressure increase due to water hammer, psi
F'' = construction type design factor used in ANSI B31.8, Fig. 17-23	q = flow rate, gal./min
F_{pv} = volume correction for a non-ideal fluid due to compressibility from Equation 17-13	Q = flow rate of gas, cubic feet per day at base conditions
$\sqrt{1/f_f}$ = transmission factor	Q_L = liquid volumetric flow rate at flowing conditions, ft^3/sec
g = acceleration due to gravity, $32.2 \text{ ft}/\text{sec}^2$	Q_g = gas volumetric flow rate at flowing conditions, ft^3/sec
g_c = gravitational constant, $32.2 (\text{ft} \cdot \text{lbm})/(\text{lb}_f \cdot \text{sec}^2)$	Re = Reynolds number
h_L = loss of static pressure head due to fluid flow, feet of fluid	Re_y = mixture Reynolds number for Dukler calculation, from Equation 17-46
H = total energy of a fluid at a point above a datum, from Equation 17-1	S = specific gravity of flowing gas (air = 1.0)
H_{Ld} = liquid holdup fraction (Dukler), Fig. 17-18	S' = allowable stress, psi, Fig. 17-22
H_{Le} = liquid holdup fraction (Eaton), Fig. 17-20	S'' = specified minimum yield strength, psi, Fig. 17-23
H_{Lf} = liquid holdup fraction (Flanigan), Fig. 17-19	t = thickness, in., Figs. 17-22, 17-23
I_L = liquid inventory in pipe, ft^3 , from Equation 17-58	t_m = minimum required wall thickness, in., Fig. 17-22
L = length of line, feet	T = absolute temperature of flowing gas, $^{\circ}\text{R}$
L_m = length of line, miles	T'' = temperature derating factor used in ANSI B31.8, Fig. 17-23
MW = molecular weight	T_{avg} = average temperature, $^{\circ}\text{R}$, [$T_{avg} = 1/2 (T_{in} + T_{out})$]
N_x = Fig. 17-16 horizontal coordinate, ft/sec	T_b = base absolute temperature, $^{\circ}\text{R}$ (ANSI 2530 specification: $T_b = 520$ $^{\circ}\text{R}$)
N_y = Fig. 17-16 vertical coordinate, ft/sec	V = single phase fluid velocity, ft/sec
N_E = abscissa of Eaton correlation, Fig. 17-20	V_a = acoustic velocity of fluid, ft/sec
	V_{sg} = superficial gas velocity, ft/sec , from Equation 17-37
	V_{sL} = superficial liquid velocity, ft/sec , from Equation 17-36
	V_m = mixture velocity, ft/sec , from Equation 17-47
	W = mass flow, lb/hr

FIG. 17-1 (Cont'd)
Nomenclature

X_A = Aziz fluid property correction factor (horizontal axis, Fig. 17-16)	μ_L = liquid viscosity, cp
Y_A = Aziz fluid property correction factor (vertical axis, Fig. 17-16)	μ_n = mixture viscosity for Dukler calculation, cp
Y' = coefficient found in Table 304.1.1, ANSI B31.3, Fig. 17-22	ρ = single phase fluid density, lb/ft ³
Z_{avg} = average compressibility factor	ρ_{avg} = average density, lb/ft ³ [$\rho_{avg} = 1/2 (\rho_{in} + \rho_{out})$]
Z_e = pipeline vertical elevation rise, ft	ρ_a = air density at 60 °F and 14.7 psia, 0.0764 lb/ft ³
ε = absolute roughness, ft	ρ_w = water density at 60 °F and 14.7 psia, 62.4 lb/ft ³
λ = flowing liquid volume fraction	ρ_g = gas density, lb/ft ³
μ_e = single phase fluid viscosity, lb _m /(ft · sec)	ρ_L = liquid density, lb/ft ³
μ = single phase fluid viscosity, cp	ρ_k = two phase mixture density for Dukler calculation, lb/ft ³
μ_g = gas viscosity, cp	σ = interfacial tension at flowing conditions, dyne/cm
	σ_{wa} = interfacial tension of air and water at 60 °F and 14.7 psia, 72.4 dyne/cm

Bernoulli's Theorem

The Bernoulli Theorem¹ is a mathematical derivation based on the law of conservation of energy. This theorem states that the total energy of a fluid at any particular point above a datum plane is the sum of the elevation head, the pressure head, and the velocity head. Stated mathematically:

$$H = Z_e + \frac{144 P}{\rho} + \frac{V^2}{2g} \quad \text{Eq 17-1}$$

If there are no friction losses and no energy is added to or taken from the system, H is constant for any point in the fluid. In reality, whenever fluid is moving there is friction loss (h_L). This loss describes the difference in total energy at two points in the system. Expressing the energy levels at Point 1 versus Point 2 then becomes:

$$Z_{e1} + \frac{144 P_1}{\rho_1} + \frac{V_1^2}{2g} = Z_{e2} + \frac{144 P_2}{\rho_2} + \frac{V_2^2}{2g} + h_L \quad \text{Eq 17-2}$$

All practical formulas for fluid flow are derived from the above. Modifications to Equation 17-2 have been proposed by many investigators to account for the friction losses.

Fluid Physical Properties

The physical properties of a flowing fluid must be known to predict pressure drop in piping. The two properties entering into the solution of most fluid flow problems are viscosity and density.

Viscosity expresses the readiness with which a fluid flows when it is acted upon by an external force. Two types of viscosity measurements are used, absolute and kinematic. Absolute viscosity is a measure of a fluid's internal resistance to deformation or shear. Kinematic viscosity is the ratio of absolute viscosity to mass density. The absolute viscosity will be used for all calculations in this section.

Viscosity is temperature dependent. The viscosity of most liquids decreases with an increase in temperature, whereas that of gases increases. Pressure has almost no effect on the viscosity of liquids or near perfect gases. On the other hand, the viscosity of saturated or slightly superheated vapors is changed appreciably by pressure changes. The viscosity of steam is readily available, but the viscosity of other vapors may not be known.

Specific volume is the inverse of density. Specific gravity of a liquid is the ratio of the density of the liquid at a specified temperature to the density of water at 60 °F. The specific gravity of gas is defined as the ratio of the molecular weight of the gas to the molecular mass of air.

$$S = \frac{MW(\text{gas})}{MW(\text{air})} \quad \text{Eq 17-3}$$

Flow in Pipes and Reynolds Number

At low velocities, fluid molecules or particles carried by the fluid move in a reasonably straight line. Velocity of the fluid is maximum at the center of the pipe and zero at the pipe wall. This flow pattern is referred to as laminar. If the velocity is increased it will reach a critical point where fluid particles begin to show a random motion transverse to the direction of flow. This is the critical velocity. This random motion is typical of what is referred to as turbulent flow. Above the critical velocity the flow is considered to be completely turbulent even though there is always a boundary layer at the pipe wall where flow is laminar. In the turbulent zone the velocity profile is more nearly straight across the face of the pipe.

Reynolds developed a dimensionless number that may be considered as the ratio of the dynamic forces of mass flow to the shear stress due to viscosity. The Reynolds number is:

$$Re = \frac{DV\rho}{\mu_e} \quad \text{Eq 17-4}$$

If the Reynolds number is less than 2000, flow may be considered laminar. If it is above 4000, the flow is turbulent. In the zone between 2000 and 4000 the flow could be either turbulent or laminar, but cannot be predicted by the Reynolds number.

If a non-circular conduit is encountered, the Reynolds number can be approximated by using an equivalent diameter for D. The equivalent diameter would equal four (4) times the hydraulic radius. The hydraulic radius is defined as:

$$\text{Hydraulic Radius} = \frac{\text{Area of Flowing Fluid}}{\text{Wetted Perimeter}} \quad \text{Eq 17-5}$$

This conversion would not apply to extremely narrow shapes where the width is small relative to the length. In such cases an

approximation may be used wherein one-half the width of the passage is equal to the hydraulic radius.

Pressure Loss Due to Friction

Flow is always accompanied by friction. This friction results in a loss of energy available for work. A general equation for pressure drop due to friction is the Darcy-Weisbach² (often referred to as simply the Darcy) equation. This equation can be rationally derived by dimensional analysis, with the exception of the friction factor, f_m , which must be determined experimentally. Expressed in feet of fluid this equation is:

$$h_L = \frac{f_m L V^2}{2 g D} \quad \text{Eq 17-6}$$

Converting to pounds per square inch, the equation becomes:

$$\Delta P_f = \frac{\rho f_m L V^2}{(144) D (2g)} \quad \text{Eq 17-7}$$

It should be noted that the Moody friction factor,³ f_m , is used in the equations above. Some equations are shown in terms of the Fanning friction factor, ff , which is one fourth of f_m ($f_m = 4.0 ff$). A graph of both Fanning and Moody friction factors as a function of Reynolds number appears in Fig. 17-2.

The Darcy-Weisbach equation is valid for both laminar and turbulent flow of any liquid, and may also be used for gases with certain restrictions. When using this equation, changes in elevation, velocity, or density must be accounted for by applying

Bernoulli's theorem. The Darcy-Weisbach equation must be applied to line segments sufficiently short such that fluid density is essentially constant over that segment. The overall pressure drop is the sum of the ΔP_f values calculated for the individual segments. For gas applications the segmental length may be relatively short, as compared to liquid applications, since many gas applications involve compressible gases where gas densities vary with pressure.

Friction Factor and Effect of Pipe Roughness

When the fluid flow is laminar ($Re < 2000$), the friction factor has a direct relationship to the Reynolds number, such that:

$$f_m = 64/Re \text{ or } f_f = 16/Re \quad \text{Eq 17-8}$$

Pipe roughness has no effect on the friction factor in laminar flow.

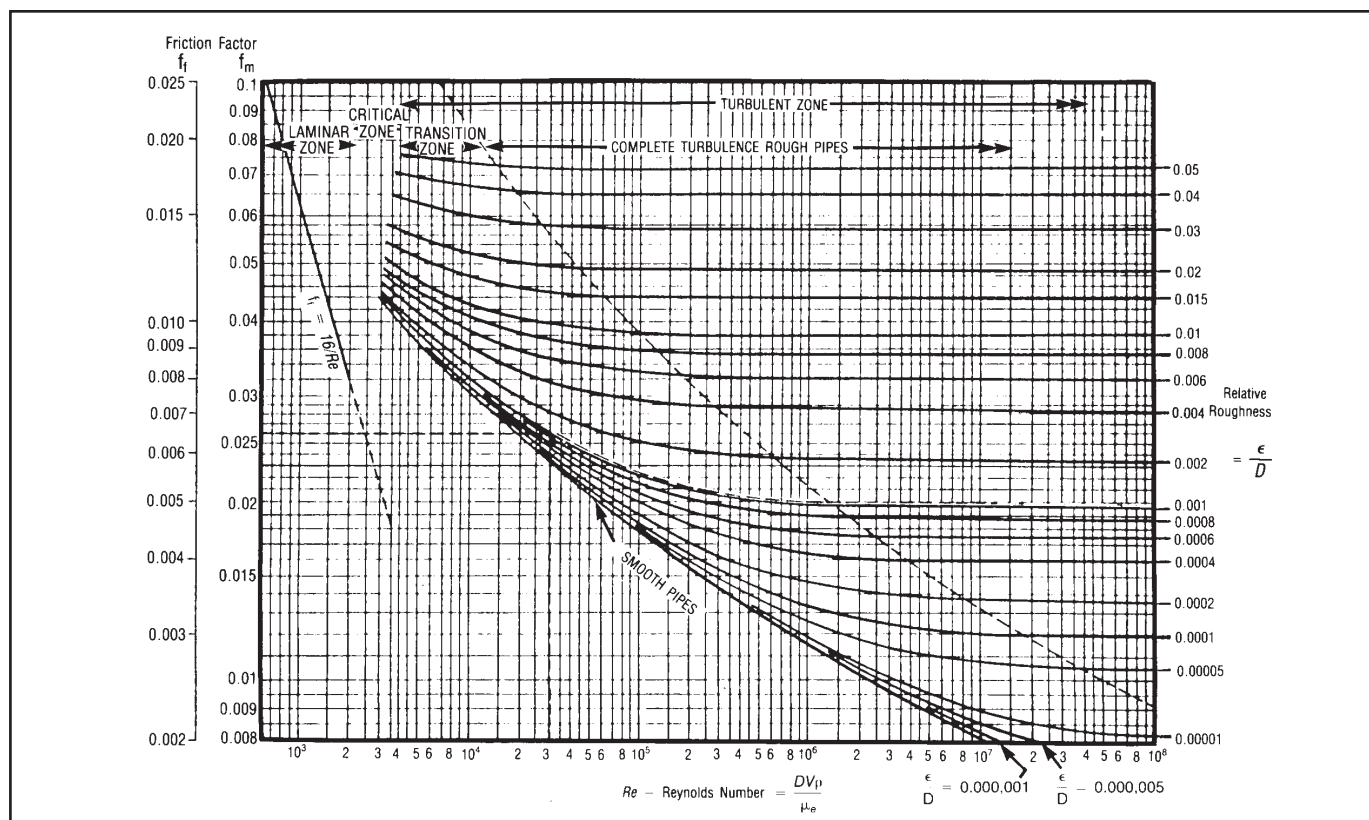
Substitution of the formula for Reynolds number, Equation 17-4, into Equation 17-8, yields the following:

$$f_m = \frac{64 \mu_e}{DV\rho} = \left(\frac{64}{V\rho} \right) \left(\frac{\mu}{1488} \right) \left(\frac{12}{d} \right) \quad \text{Eq 17-9}$$

This expression can then be substituted for the friction factor in Equation 17-7, resulting in the following formula for pressure loss in pounds per square inch:

$$\Delta P_f = 0.000668 \frac{\mu L_m V}{d^2} \text{ or } \frac{1.27 \cdot 10^{-7} \mu L V}{d^2} \quad \text{Eq 17-10}$$

FIG. 17-2
Friction Factors⁵



Equation 17-10 is commonly known as Poiseuille's law for laminar flow.

When the flow is turbulent, the friction factor depends on the Reynolds number and the relative roughness of the pipe, ε/D , which is the roughness of the pipe, ε , over the pipe diameter, D . Fig. 17-2 incorporates the relative roughness of the pipe into the determination of the friction factor. Fig. 17-3 indicates relative roughness and friction factors for various piping materials.

$$\frac{1}{\sqrt{f_m}} = -2 \log_{10} \left(\frac{\varepsilon}{3.7 D} + \frac{2.51}{\text{Re} \sqrt{f_m}} \right) \quad \text{Eq 17-11}$$

Various explicit equations have been presented which provide a direct solution for the friction factor. The equation below was proposed by Chen³¹ and is accurate and is almost identical to the Colebrook equation over Reynolds Numbers (4000 to $4(10)^8$) and roughness factors (ε/D) from 0.05 to $5(10)^{-7}$.

$$A = \log \left[\frac{\left(\frac{\varepsilon}{D} \right)^{1.1098}}{2.8257} + \left(\frac{5.8506}{\text{Re}^{0.8981}} \right) \right] \quad \text{Eq 17-11a}$$

$$f_m = \left(\frac{1}{-2 \cdot \log \left(\frac{\varepsilon}{3.7065 D} - \frac{5.0452 \cdot A}{\text{Re}} \right)} \right)^2 \quad \text{Eq 17-11b}$$

Equivalent Length of Valves and Fittings

The pressure drop effects of valves and fittings can be accounted for by addition of the "equivalent lengths" of the fittings to the actual piping lengths. This augmented pipe length is then used in any of the following pressure drop calculation techniques. A table of equivalent lengths for a number of representative valves and fittings appears in Fig. 17-4.

Compressibility of Gases

For more accurate values of Z , refer to Section 23. For more approximate calculations, the value of the average compressibility factor, Z_{avg} , may be calculated from the following equations:

$$Z_{\text{avg}} = \frac{1}{(F_{\text{pv}})^2} \quad \text{Eq 17-12}$$

and

$$F_{\text{pv}} = \left(1 + \left[\frac{(P_{\text{avg}}) (3.444) (10^5) (10^{(1.785) (S)})}{T_{\text{avg}}^{3.825}} \right] \right)^{0.5} \quad \text{Eq 17-13}$$

Fig. 17-5 contains a plot of the deviation factor, F_{pv} .

An estimate for Z_{avg} at pressures below 100 psi is:

$$Z_{\text{avg}} = \frac{1}{1 + 0.0002 P_{\text{avg}}} \quad \text{Eq 17-14}$$

SINGLE PHASE FLOW

Transmission Line Gas Flow

Isothermal flow — The steady-state, isothermal flow behavior of gas in pipelines is defined by a general energy equation of the form:

$$Q = 38.77 \left(\frac{T_b}{P_b} \right) E \sqrt{\frac{1}{f_f}} \left[\frac{P_1^2 - P_2^2}{S L_m T_{\text{avg}} Z_{\text{avg}}} \right]^{0.5} d^{2.5} \quad \text{Eq 17-15}$$

This equation is completely general for steady-state flow, and adequately accounts for variations in compressibility factor, kinetic energy, pressure, and temperature for any typical line section. However, the equation as derived involves an unspecified value of the transmission factor, $\sqrt{1/f_f}$. The correct representation of this friction factor is necessary to the validity of the equation.

The friction factor is fundamentally related to the energy lost due to friction. In the derivation of the general energy equation, all irreversibilities and non-idealities, except for those covered by the real gas law, have been collected into the friction loss term.

Empirical methods historically and currently used to calculate or predict the flow of gas in a pipeline are the result of various correlations of the transmission factor substituted into the general energy equation.

Examination of the relationships presented by various authors shows that their forms differ primarily in the inherent or specified representation of the transmission factor which defines the energy lost in resistance to flow for various pipe sizes, roughnesses, flow conditions, and gases.

To obtain Equation 17-15, which is convenient for general calculations, a number of simplifying assumptions have been made. For other than pipeline sections with a very high pressure gradient, the change in the kinetic energy of the gas is not significant, and is assumed equal to zero. It is also assumed that the gas temperature is constant at an average value for the section considered; the compressibility factor is constant at the value characterized by the average gas temperature and pressure; and in the term giving the effect of elevation change, the pressure is constant at the average value. In the range of conditions to which pipeline flow equations are ordinarily applied, averages are usually sufficiently accurate. Average temperatures are calculated as indicated in Fig. 17-1.

The average pressure in the line can be computed by:

$$P_{\text{avg}} = \frac{2}{3} \left(P_1 + P_2 - \frac{P_1 P_2}{P_1 + P_2} \right) \quad \text{Eq 17-16}$$

In the absence of field data indicating otherwise, an efficiency factor, E , of 1.0 is usually assumed.

The AGA equations — The AGA Equations were developed to approximate partially and fully turbulent flow using two different transmission factors. The fully turbulent flow equation accounts for the relative pipe roughness, ε/D , based on the rough-pipe law.⁴ This equation uses the following transmission factor:

$$\sqrt{1/f_f} = 4 \log_{10} \left(\frac{3.7 D}{\varepsilon} \right) \quad \text{Eq 17-17}$$

When the transmission factor for fully turbulent flow is substituted in the general energy equation (Equation 17-15), the AGA Equation for fully turbulent flow becomes:

$$Q = 38.77 \left(\frac{T_b}{P_b} \right) E \left[4 \log_{10} \left(\frac{3.7 D}{\varepsilon} \right) \right] \left[\frac{P_1^2 - P_2^2}{S L_m T_{\text{avg}} Z_{\text{avg}}} \right]^{0.5} d^{2.5} \quad \text{Eq 17-18}$$

FIG. 17-3
Relative Roughness of Pipe Materials and Friction Factors for Complete Turbulence⁵

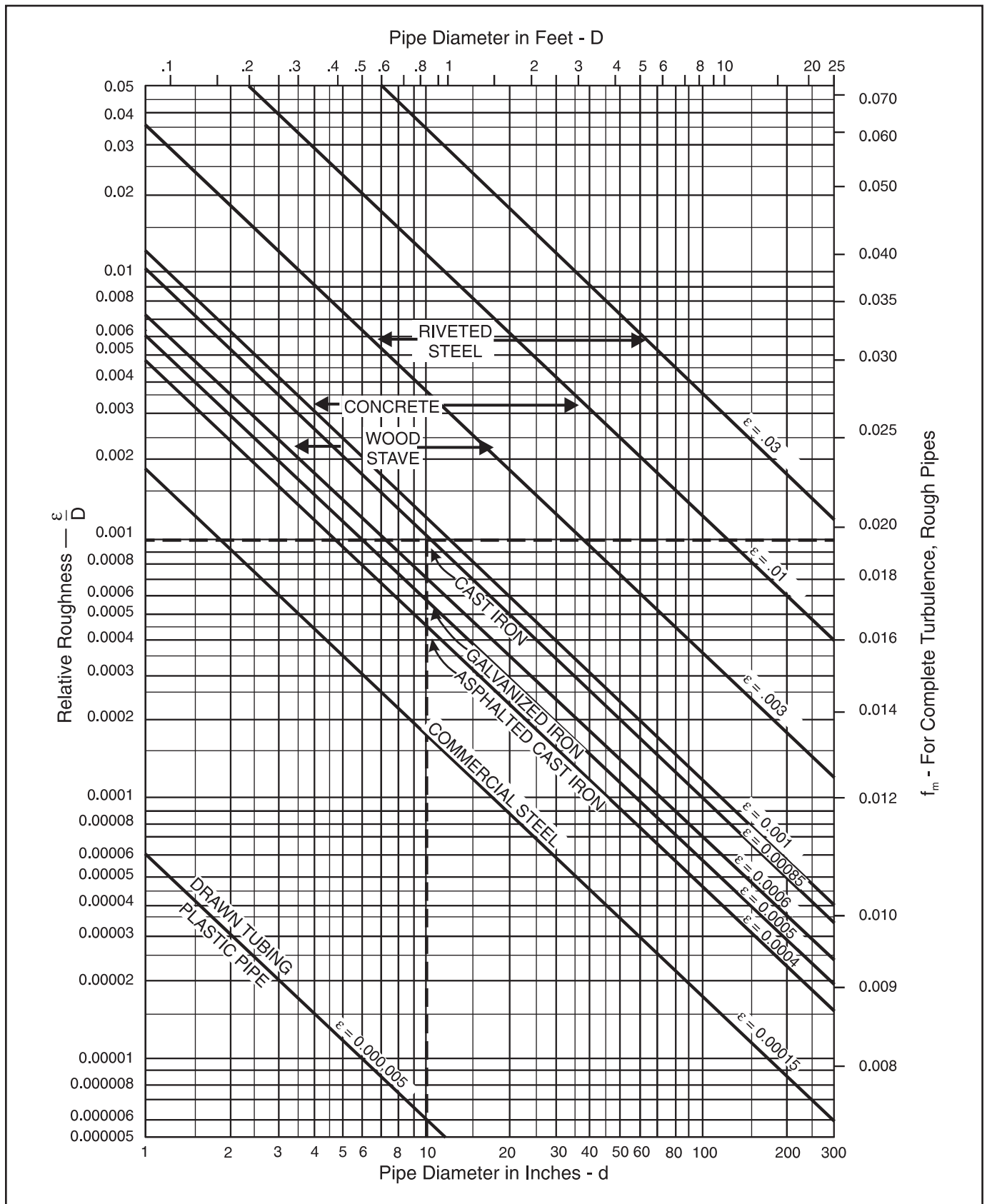


FIG. 17-4
Equivalent Length of Valves and Fittings in Feet

Nominal Pipe size in.	Globe valve or ball check valve	Angle valve	Swing check valve	Plug cock	Gate or ball valve	45° ell		Short rad. ell		Long rad. ell		Hard T		Soft T		90° miter bends			Enlargement			Contraction													
						Welded	Threaded	Welded	Threaded	Welded	Threaded	Welded	Threaded	Welded	Threaded	2 miter	3 miter	4 miter	Sudden		Std. red.	Sudden		Std. red.											
																			Equiv. L in terms of small d																
																			d/D = 1/4	d/D = 1/2	d/D = 3/4	d/D = 1/2	d/D = 3/4	d/D = 1/4	d/D = 1/2	d/D = 3/4	d/D = 1/2	d/D = 3/4	d/D = 1/2	d/D = 3/4	d/D = 1/2	d/D = 3/4			
1½	55	26	13	7	1	1	2	3	5	2	3	8	9	2	3				5	3	1	4	1	3	2	1	1	—							
2	70	33	17	14	2	2	3	4	5	3	4	10	11	3	4				7	4	1	5	1	3	3	1	1	—							
2½	80	40	20	11	2	2	—	5	—	3	—	12	—	3	—				8	5	2	6	2	4	3	2	2	—							
3	100	50	25	17	2	2		6		4		14		4					10	6	2	8	2	5	4	2	2	—							
4	130	65	32	30	3	3		7		5		19		5					12	8	3	10	3	6	5	3	3	—							
6	200	100	48	70	4	4		11		8		28		8					18	12	4	14	4	9	7	4	4	1							
8	260	125	64	120	6	6		15		9		37		9					25	16	5	19	5	12	9	5	5	2							
10	330	160	80	170	7	7		18		12		47		12					31	20	7	24	7	15	12	6	6	2							
12	400	190	95	170	9	9		22		14		55		14		28	21	20	37	24	8	28	8	18	14	7	7	2							
14	450	210	105	80	10	10		26		16		62		16		32	24	22	42	26	9	—	—	20	16	8	—	—							
16	500	240	120	145	11	11		29		18		72		18		38	27	24	47	30	10	—	—	24	18	9	—	—							
18	550	280	140	160	12	12		33		20		82		20		42	30	28	53	35	11	—	—	26	20	10	—	—							
20	650	300	155	210	14	14		36		23		90		23		46	33	32	60	38	13	—	—	30	23	11	—	—							
22	688	335	170	225	15	15		40		25		100		25		52	36	34	65	42	14	—	—	32	25	12	—	—							
24	750	370	185	254	16	16		44		27		110		27		56	39	36	70	46	15	—	—	35	27	13	—	—							
30	—	—	—	312	21	21		55		40		140		40		70	51	44																	
36	—	—	—		25	25		66		47		170		47		84	60	52																	
42	—	—	—		30	30		77		55		200		55		98	69	64																	
48	—	—	—		35	35		88		65		220		65		112	81	72																	
54	—	—	—		40	40		99		70		250		70		126	90	80																	
60	—	—	—		45	45		110		80		260		80		190	99	92																	

The partially turbulent flow equation is based on the smooth-pipe law⁴ and is modified to account for drag-inducing elements. The transmission factor for this equation is:

$$\sqrt{1/f_f} = 4 \log_{10} \frac{Re}{\sqrt{1/f_f}} - 0.6 \quad \text{Eq 17-19}$$

Substituting $\sqrt{1/f_f}$ from Equation 17-19 into Equation 17-15 does not provide an equation which can be solved directly. For partially turbulent flow a frictional drag factor must also be applied to account for the effects of pipe bends and irregularities. These calculations are beyond the scope of this book and the AGA "Steady Flow in Gas Pipelines"⁶ should be consulted for a detailed treatment of partially turbulent flow.

The Weymouth equation — The Weymouth Equation, published in 1912,⁷ evaluated the coefficient of friction as a function of the diameter.

$$f_f = \frac{0.008}{d^{1/3}} \quad \text{Eq 17-20}$$

$$\sqrt{1/f_f} = 11.18 d^{1/6} \quad \text{Eq 17-21}$$

When the friction factor, f_f , is substituted in the general energy equation, Weymouth's equation becomes:

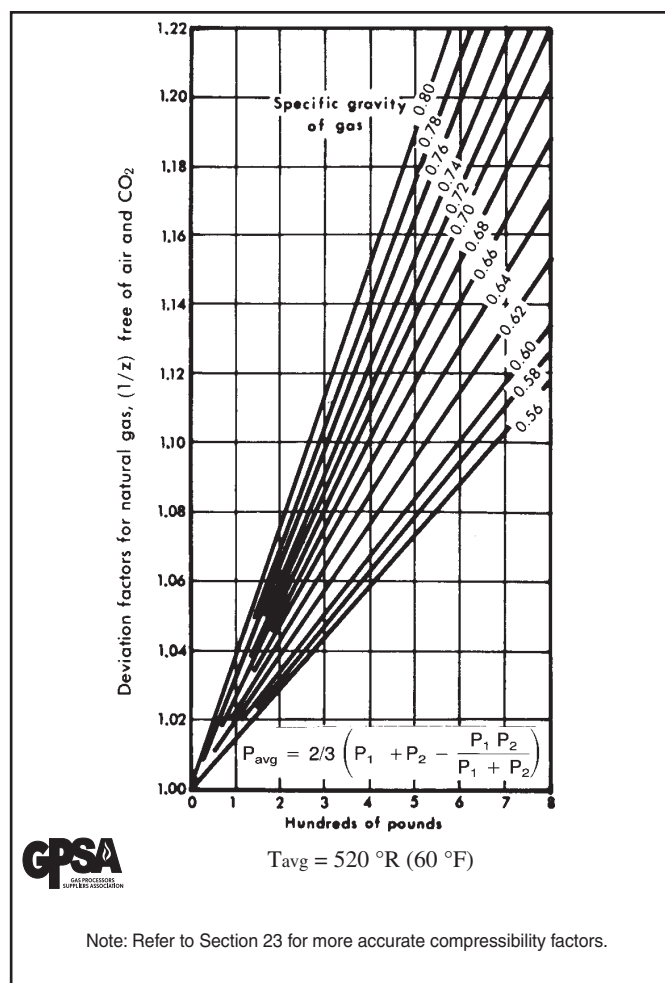
$$Q = (433.5) \left(\frac{T_b}{P_b} \right) E \left[\frac{P_1^2 - P_2^2}{S L_m T_{avg} Z_{avg}} \right]^{0.5} d^{2.667} \quad \text{Eq 17-22}$$

The Weymouth formula for short pipelines and gathering systems agrees more closely with metered rates than those calculated by most other formulae. However, the degree of error increases with pressure. If the Q calculated from the Weymouth formula is multiplied by $\sqrt{1/Z}$, where Z is the compressibility factor of the gas, the corrected Q will closely approximate the metered flow. Fig. 17-5 shows a plot of the deviation factor, $\sqrt{1/Z}$, of a common gas and can be used safely if exact data is not available.

The equation cannot be generally applied to any variety of diameters and roughness, and in the flow region of partially developed turbulence, it is not valid. The Weymouth Equation may be used to approximate fully turbulent flow by applying correction factors determined from the system to which it is to be applied. Graphs showing gas flow calculations based on the Weymouth equation are shown in Fig. 17-6a and 17-6b.

Panhandle A equation — In the early 1940s Panhandle Eastern Pipe Line Company developed a formula for calculation of gas flow in transmission lines which has become known as the Panhandle A equation. This equation uses the following expressions of Reynolds number and transmission factor.

FIG. 17-5
Deviation Factors⁸



$$Re = 1.934 \frac{QS}{d} \quad \text{Eq 17-23}$$

$$\sqrt{1/f_f} = 7.211 \left(\frac{QS}{d} \right)^{0.07305} = 6.872 (Re)^{0.07305} \quad \text{Eq 17-24}$$

The transmission factor assumes a Reynolds number value from 5 to 11 million based on actual metered experience.

Substituting Equation 17-24 for $\sqrt{1/f_f}$ in the general energy equation (Equation 17-15), the Panhandle A equation becomes:

$$Q = 435.87 \left(\frac{T_b}{P_b} \right)^{1.0788} E \left[\frac{P_1^2 - P_2^2}{S^{0.853} L_m T_{avg} Z_{avg}} \right]^{0.5392} d^{2.6182} \quad \text{Eq 17-25}$$

This equation was intended to reflect the flow of gas through smooth pipes. When “adjusted” with an efficiency factor, E, of about 0.90, the equation is a reasonable approximation of the partially turbulent flow equation. The equation becomes less accurate as flow rate increases. Many users of the Panhandle A Equation assume an efficiency factor of 0.92.

Panhandle B equation — A new or revised Panhandle equation was published in 1956. This revised equation is known as the Panhandle B equation and is only slightly Reynolds number dependent. Therefore, it more nearly approximates fully turbulent flow behavior. The transmission factor used here is:

$$\sqrt{1/f_f} = 16.70 \left(\frac{QS}{d} \right)^{0.01961} = 16.49 (Re)^{0.01961} \quad \text{Eq 17-26}$$

Substituting Equation 17-23 for $\sqrt{1/f_f}$ in the general energy equation (Equation 17-15), the Panhandle B equation becomes:

$$Q = 737 \left(\frac{T_b}{P_b} \right)^{1.02} E \left[\frac{P_1^2 - P_2^2}{S^{0.961} L_m T_{avg} Z_{avg}} \right]^{0.51} d^{2.53} \quad \text{Eq 17-27}$$

The equation can be adjusted through the use of an efficiency term that makes it applicable across a relatively limited range of Reynolds numbers. Other than this, however, there are no means for adjustment of the equation to correct it for variations in pipe surface. Adjusted to an average flowing Reynolds number, the equation will predict low flow rates at low Reynolds numbers, and high flow rates at high Reynolds numbers, as compared to a fully turbulent flow equation. Efficiencies based on the Panhandle B equation decrease with increasing flow rate for fully turbulent flow. The efficiency factor, E, used in the Panhandle B equation generally varies between about 0.88 and 0.94.

Conclusions — The successful application of these transmission line flow equations in the past has largely involved compensation for discrepancies through the use of adjustment factors, usually termed “efficiencies.” These efficiencies are frequently found in practice by determining the constant required to cause predicted gas equation behavior to agree with flow data. As a result, the values of these factors are specific to particular gas flow equations and field conditions and, under many circumstances, vary with flow rate in a fashion that obscures the real nature of flow behavior in the pipe.

The Reynolds number dependent equations, such as the Panhandle equations, utilize a friction factor expression which yields an approximation to partially turbulent flow behavior in the case of the Panhandle A equation, and an approximation to fully turbulent behavior in the case of the Panhandle B.

These equations suffer from the substitution of a fixed gas viscosity value into the Reynolds number expression, which, in turn, substituted into the flow equation, results in an expression with a preconditioned bias.

Regardless of the merits of various gas flow equations, past practices may dictate the use of a particular equation to maintain continuity of comparative capacities through application of consistent operating policy. A summary of comparisons between transmission factors used in the above gas equations are shown in Fig. 17-7.

Reference should be made to “Steady Flow in Gas Pipelines,”⁶ published by American Gas Association, for a complete analysis of steady flow in gas pipelines.

Low Pressure Gas Flow

Gas gathering often involves operating pressures below 100 psi. Some systems flow under vacuum conditions. For these low

FIG. 17-6a
Gas Flow Based on Weymouth Formula

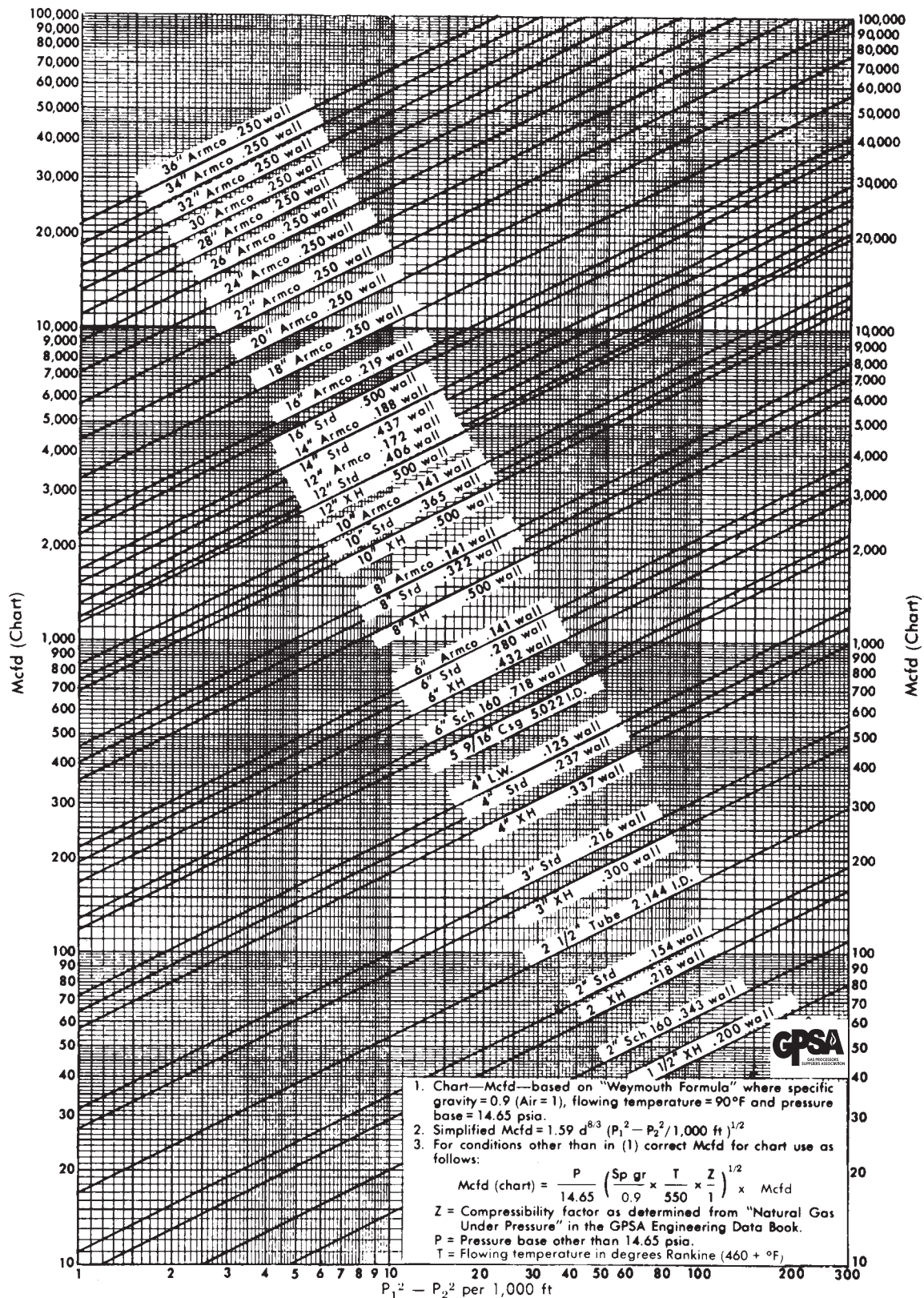


FIG. 17-6b
Gas Flow Based on Weymouth Formula

