ME 423: FLUIDS ENGINEERING

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Pressure Drop Due to Friction

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The gas pipeline throughput (flow rate) will depend upon

- the gas properties,
- pipe diameter and length,
- initial gas pressure and temperature, and
- the pressure drop due to friction.

Energy Equation (Bernoulli Equation)

As gas flows through a pipeline, the total energy of the gas at various points consists of energy due to pressure, energy due to velocity, and energy due to position or elevation above an established datum. Bernoulli's equation simply connects these components of the energy of the flowing fluid to form an energy conservation equation. Bernoulli's equation is stated as follows, considering two points, 1 and 2, as shown in Figure 2.1.

$$Z_A + \frac{P_A}{\gamma} + \frac{V_A^{\ 2}}{2g} + H_p = Z_B + \frac{P_B}{\gamma} + \frac{V_B^2}{2g} + h_f \qquad (2.1)$$

where H_p is the equivalent head added to the fluid by a compressor at A and h_f represents the total frictional pressure loss between points A and B.

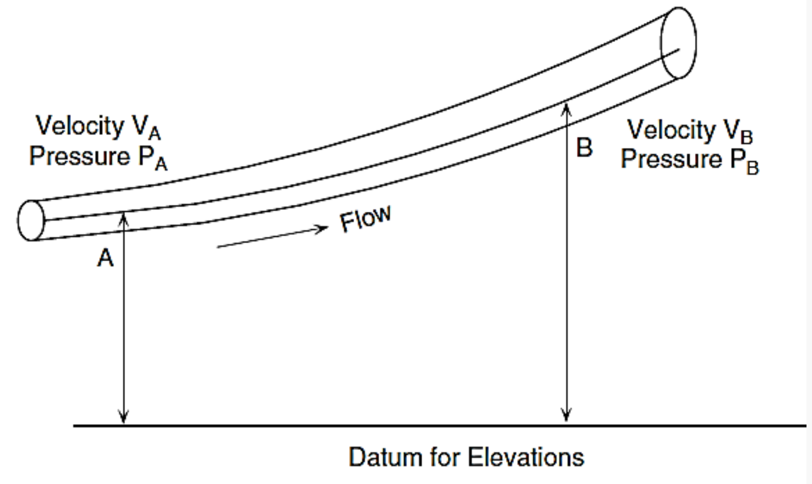


Figure 2.1 Energy of flow of a fluid.

Starting with the basic energy Equation 2.1, applying gas laws, and after some simplification, various formulas were developed over the years to predict the performance of a pipeline transporting gas. These formulas are intended to show the relationship between the gas properties, such as gravity and compressibility factor, with the flow rate, pipe diameter and length, and the pressures along the pipeline.

Flow Equations

Several equations are available that relate the gas flow rate with gas properties, pipe diameter and length, and upstream and downstream pressures. These equations are listed as follows:

1. General Flow equation
2. Colebrook-White equation
3. Modified Colebrook-White equation
4. AGA equation
5. Weymouth equation
6. Panhandle A equation
7. Panhandle B equation
8. IGT equation
9. Spitzglass equation
10. Mueller equation
11. Fritzsche equation

General Flow Equation

The General Flow equation, also called the **Fundamental Flow equation**, for the **steady-state isothermal flow in a gas pipeline** is the basic equation for relating the pressure drop with flow rate. The most common form of this equation in the U.S. Customary System (USCS) of units is given in terms of the pipe diameter, gas properties, pressures, temperatures, and flow rate as follows.

Refer to Figure 2.2 for an explanation of symbols used.

$$Q = 77.54\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - P_2^2}{GT_f LZf}\right)^{0.5} D^{2.5} \quad \text{(USCS units)} \qquad (2.2)$$

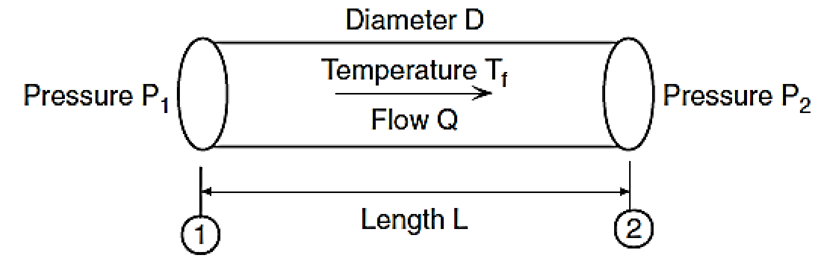


Figure 2.2 Steady flow in gas pipeline.

where

Q = gas flow rate, measured at standard conditions, ft^3/day (SCFD)
f = friction factor, dimensionless
P_b = base pressure, psia
T_b = base temperature, °R(460 + °F)
P_1 = upstream pressure, psia
P_2 = downstream pressure, psia
G = gas gravity (air = 1.00)
T_f = average gas flowing temperature, °R (460 + °F)
L = pipe segment length, mi
Z = gas compressibility factor at the flowing temperature, dimensionless
D = pipe inside diameter, in.

It must be noted that for the pipe segment from section 1 to section 2, the gas temperature T_f is assumed to be constant (isothermal flow).

General Flow Equation

In SI units, the General Flow equation is stated as follows:

$$Q = 1.1494 \times 10^{-3} \left(\frac{T_b}{P_b}\right) \left[\frac{\left(P_1^2 - P_2^2\right)}{G T_f L Z f}\right]^{0.5} D^{2.5} \quad \text{(SI units)} \qquad (2.3)$$

where

- Q = gas flow rate, measured at standard conditions, m^3/day
- f = friction factor, dimensionless
- P_b = base pressure, kPa
- T_b = base temperature, K (273 + °C)
- P_1 = upstream pressure, kPa
- P_2 = downstream pressure, kPa
- G = gas gravity (air = 1.00)
- T_f = average gas flowing temperature, K (273 + °C)
- L = pipe segment length, km
- Z = gas compressibility factor at the flowing temperature, dimensionless
- D = pipe inside diameter, mm

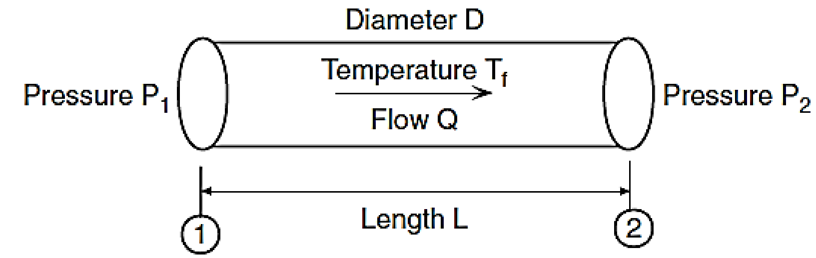


Figure 2.2 Steady flow in gas pipeline.

General Flow Equation

Sometimes the General Flow equation is represented in terms of the **transmission factor, *F*** instead of the **friction factor, *f***. This form of the equation is as follows.

$$Q = 38.77F\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - P_2^2}{GT_fLZ}\right)^{0.5} D^{2.5} \quad \text{(USCS units)} \qquad (2.4)$$

where the transmission factor F and friction factor f are related by

$$F = \frac{2}{\sqrt{f}} \qquad (2.5)$$

and **in SI units**

$$Q = 5.747 \times 10^{-4} F\left(\frac{T_b}{P_b}\right)\left[\frac{\left(P_1^2 - P_2^2\right)}{GT_fLZ}\right]^{0.5} D^{2.5} \quad \text{(SI units)} \qquad (2.6)$$

Average Pipe Segment Pressure

In the General Flow equation, the compressibility factor *Z* is used. This must be calculated at the gas flowing temperature and average pressure in the pipe segment. Therefore, it is important to first calculate the average pressure in a pipe segment, described in Figure 2.2.

Consider a pipe segment with upstream pressure P_1 and downstream pressure P_2, as in Fig. 2.2, the **average pressure** is calculated more accurately as:

$$P_{avg} = \frac{2}{3}\left(P_1 + P_2 - \frac{P_1 P_2}{P_1 + P_2}\right) \quad (2.14)$$

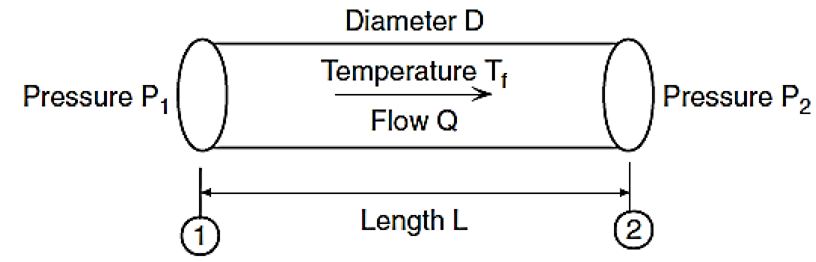


Figure 2.2 Steady flow in gas pipeline.

Another form of the average pressure in a pipe segment is

$$P_{avg} = \frac{2}{3}\left(\frac{P_1^3 - P_2^3}{P_1^2 - P_2^2}\right) \quad (2.15)$$

Velocity of Gas in a Pipeline

Unlike a liquid pipeline, due to compressibility, the gas velocity depends upon the pressure and, hence, will vary along the pipeline even if the pipe diameter is constant. The highest velocity will be at the downstream end, where the pressure is the least. Correspondingly, the least velocity will be at the upstream end, where the pressure is higher.

Consider a pipe transporting gas from point A to point B as shown in Figure 2.2. Under steady state flow, at A, the mass flow rate of gas is designated as M and will be the same as the mass flow rate at point B, if between A and B there is no injection or delivery of gas. The mass being the product of volume and density, we can write the following relationship for point A:

$$M = Q\rho \tag{2.16}$$

The volume rate Q can be expressed in terms of the flow velocity u and pipe cross sectional area A as follows:

$$Q = uA \tag{2.17}$$

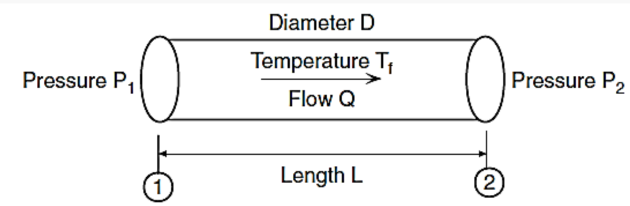


Figure 2.2 Steady flow in gas pipeline.

Velocity of Gas in a Pipeline

Therefore, combining Equation 2.16 and Equation 2.17 and applying the conservation of mass to points A and B, we get

$$M_1 = u_1 A_1 \rho_1 = M_2 = u_2 A_2 \rho_2 \quad (2.18)$$

where subscripts 1 and 2 refer to points A and B, respectively. If the pipe is of uniform cross section between A and B, then $A_1 = A_2 = A$.

Therefore, the area term in Equation 2.18 can be dropped, and the velocities at A and B are related by the following equation:

$$u_1 \rho_1 = u_2 \rho_2 \quad (2.19)$$

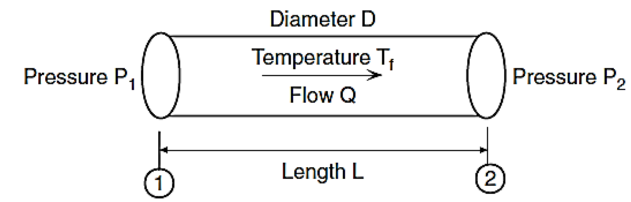


Figure 2.2 Steady flow in gas pipeline.

Since the flow of gas in a pipe can result in variation of temperature from point A to point B, the gas density will also vary with temperature and pressure. If the density and velocity at one point are known, the corresponding velocity at the other point can be calculated using Equation 2.19.

If inlet conditions are represented by point A and the volume flow rate Q at standard conditions of 60°F and 14.7 psia are known, we can calculate the velocity at any point along the pipeline at which the pressure and temperature of the gas are P and T, respectively.

Velocity of Gas in a Pipeline

The velocity of gas at section 1 is related to the flow rate Q_1 at section 1 and pipe cross-sectional area A as follows from Equation 2.17:

$$Q_1 = u_1 A$$

The mass flow rate M at section 1 and 2 is the same for steady-state flow. Therefore,

$$M = Q_1\rho_1 = Q_2\rho_2 = Q_b\rho_b \tag{2.20}$$

where Q_b is the gas flow rate at standard conditions and ρ_b is the corresponding gas density.

Therefore, simplifying Equation 2.20,

$$Q_1 = Q_b\left(\frac{\rho_b}{\rho_1}\right) \tag{2.21}$$

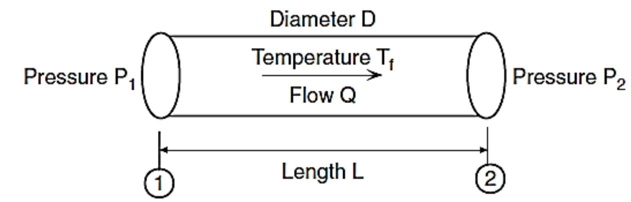


Figure 2.2 Steady flow in gas pipeline.

Velocity of Gas in a Pipeline

Applying the gas law Equation 1.9, we get

$$\frac{P_1}{\rho_1} = Z_1 R T_1$$

or

$$\rho_1 = \frac{P_1}{Z_1 R T_1} \tag{2.22}$$

where P_1 and T_1 are the pressure and temperature at pipe section 1.

Similarly, at standard conditions,

$$\rho_b = \frac{P_b}{Z_b R T_b} \tag{2.23}$$

From Equation 2.21, Equation 2.22, and Equation 2.23, we get

$$Q_1 = Q_b \left(\frac{P_b}{T_b}\right)\left(\frac{T_1}{P_1}\right)\left(\frac{Z_1}{Z_b}\right) \tag{2.24}$$

Since $Z_b = 1.00$, approximately, we can simplify this to

$$Q_1 = Q_b \left(\frac{P_b}{T_b}\right)\left(\frac{T_1}{P_1}\right) Z_1 \tag{2.25}$$

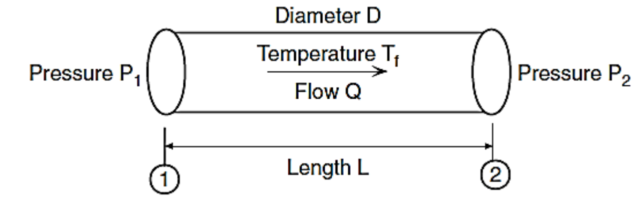


Figure 2.2 Steady flow in gas pipeline.

Velocity of Gas in a Pipeline

Therefore, the gas velocity at section 1 is, using Equation 2.17 and Equation 2.25,

$$u_1 = \frac{Q_b Z_1}{A}\left(\frac{P_b}{T_b}\right)\left(\frac{T_1}{P_1}\right) = \frac{4 \times 144}{\pi D^2} Q_b Z_1 \left(\frac{P_b}{T_b}\right)\left(\frac{T_1}{P_1}\right)$$

$$u_1 = 0.002122\left(\frac{Q_b}{D^2}\right)\left(\frac{P_b}{T_b}\right)\left(\frac{Z_1 T_1}{P_1}\right) \quad \text{(USCS units)} \qquad (2.26)$$

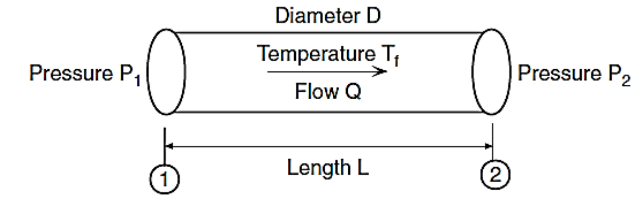


Figure 2.2 Steady flow in gas pipeline.

where

u_1 = upstream gas velocity, ft/s
Q_b = gas flow rate, measured at standard conditions, ft³/day (SCFD)
D = pipe inside diameter, in.
P_b = base pressure, psia
T_b = base temperature, °R (460 + °F)
P_1 = upstream pressure, psia
T_1 = upstream gas temperature, °R (460 + °F)
Z_1 = gas compressibility factor at upstream conditions, dimensionless

Velocity of Gas in a Pipeline

Similarly, the gas velocity at section 2 is given by

$$u_2 = 0.002122\left(\frac{Q_b}{D^2}\right)\left(\frac{P_b}{T_b}\right)\left(\frac{Z_2T_2}{P_2}\right) \quad \text{(USCS units)} \qquad (2.27)$$

In general, the gas velocity at any point in a pipeline is given by

$$u = 0.002122\left(\frac{Q_b}{D^2}\right)\left(\frac{P_b}{T_b}\right)\left(\frac{ZT}{P}\right) \qquad (2.28)$$

In SI units, the gas velocity at any point in a gas pipeline is given by

$$u = 14.7349\left(\frac{Q_b}{D^2}\right)\left(\frac{P_b}{T_b}\right)\left(\frac{ZT}{P}\right) \quad \text{(SI units)} \qquad (2.29)$$

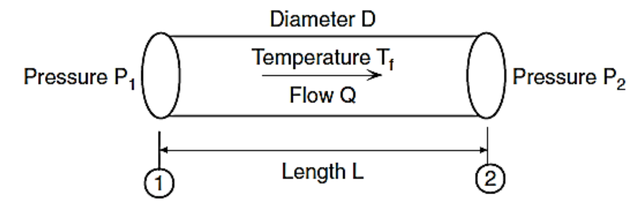


Figure 2.2 Steady flow in gas pipeline.

where

u = gas velocity, m/s
Q_b = gas flow rate, measured at standard conditions, m³/day
D = pipe inside diameter, mm
P_b = base pressure, kPa
T_b = base temperature, K(273 + °C)
P = pressure, kPa
T = average gas flowing temperature, K(273 + °C)
Z = gas compressibility factor at the flowing temperature, dimensionless

Erosional Velocity

We have seen from the preceding section that the gas velocity is directly related to the flow rate. As flow rate increases, so does the gas velocity. How high can the gas velocity be in a pipeline? As the velocity increases, vibration and noise are evident. In addition, higher velocities will cause erosion of the pipe interior over a long period of time. The upper limit of the gas velocity is usually calculated approximately from the following equation:

$$u_{max} = \frac{100}{\sqrt{\rho}} \tag{2.30}$$

where

u_{max} = maximum or erosional velocity, ft/s

ρ = gas density at flowing temperature, lb/ft^3

Erosional Velocity

Since the gas density ρ may be expressed in terms of pressure and temperature, using the gas law Equation 1.8, the maximum velocity Equation 2.30 can be rewritten as

$$u_{max} = 100\sqrt{\frac{ZRT}{29GP}} \quad \text{(USCS units)} \tag{2.31}$$

where

Z = compressibility factor of gas, dimensionless
R = gas constant = 10.73 ft^3 psia/lb-moleR
T = gas temperature, °R
G = gas gravity (air = 1.00)
P = gas pressure, psia

Usually, an acceptable operational velocity is 50% of the above.

Problem

Example 1

A gas pipeline, NPS 20 with 0.500 in. wall thickness, transports natural gas (specific gravity = 0.6) at a flow rate of 250 MMSCFD at an inlet temperature of 60°F. Assuming isothermal flow, calculate the velocity of gas at the inlet and outlet of the pipe if the inlet pressure is 1000 psig and the outlet pressure is 850 psig. The base pressure and base temperature are 14.7 psia and 60°F, respectively. Assume compressibility factor Z = 1.00. What is the erosional velocity for this pipeline based on the above data and a compressibility factor Z = 0.90?

$$u = 0.002122\left(\frac{Q_b}{D^2}\right)\left(\frac{P_b}{T_b}\right)\left(\frac{ZT}{P}\right) \qquad (2.28)$$

gas velocity at inlet ($p_1 = 1000\text{psig}$); $u_1 = 0.002122\left(\frac{250\times10^6}{19.0^2}\right)\left(\frac{14.7}{60+460}\right)\left(\frac{1.0\times(60+460)}{(1000+14.7)}\right) = 21.3\,\text{ft/s} \qquad (Z=1.0)$

gas velocity at outlet ($p_2 = 850\text{psig}$); $u_2 = 0.002122\left(\frac{250\times10^6}{19.0^2}\right)\left(\frac{14.7}{60+460}\right)\left(\frac{1.0\times(60+460)}{(850+14.7)}\right) = 25.0\,\text{ft/s} \qquad (Z=1.0)$

erosional velocity; $u_{\max} = 100\sqrt{\frac{ZRT}{29GP}} = 100\sqrt{\frac{1.0\times10.73\times(60+460)}{29(0.6)(1014.7)}} \qquad (Z=1.0)\,(R=10.73\,\text{ft}^3\text{psia/lb-moleR})$

$= 56.2\,\text{ft/s} \qquad (Z=1.0)$

$= 53.3\,\text{ft/s} \qquad (Z=0.9)$

$u_{gas} \approx 50\%\, u_{\max}$

Problem

Example 2:

A gas pipeline, NPS 20 with 0.500 in. wall thickness, transports natural gas (specific gravity = 0.6) at a flow rate of 250 MMSCFD at an inlet temperature of 60°F. Assuming isothermal flow, calculate the velocity of gas at the inlet and outlet of the pipe if the inlet pressure is 1000 psig and the outlet pressure is 850 psig. The base pressure and base temperature are 14.7 psia and 60°F, respectively.

The compressibility factor, Z can be calculated based on **CNGA** or **Standing-Katz method**.

CNGA:

$$Z = \frac{1}{\left[1 + \left(\frac{P_{avg} 344{,}400 (10)^{1.785G}}{T_f^{3.825}}\right)\right]} \qquad (1.34)$$

where

P_{avg} = average gas pressure, psig

T_f = average gas temperature, °R

G = gas gravity (air = 1.00)

Problem

$$\text{At inlet (1000 psig)}: \quad Z_1 = \frac{1}{\left[1 + \frac{1000 \times 344400(10)^{1.785 \times 0.6}}{(60+460)^{3.825}}\right]} = 0.8578$$

$$\text{At outlet (850 psig)}: \quad Z_2 = \frac{1}{\left[1 + \frac{850 \times 344400(10)^{1.785 \times 0.6}}{(60+460)^{3.825}}\right]} = 0.8765$$

Gas velocity:

$$u = 0.002122\left(\frac{Q_b}{D^2}\right)\left(\frac{P_b}{T_b}\right)\left(\frac{ZT}{P}\right) \qquad (2.28)$$

$$\text{gas velocity at inlet } (p_1 = 1000\text{psig});\ u_1 = 0.002122\left(\frac{250 \times 10^6}{19.0^2}\right)\left(\frac{14.7}{60+460}\right)\left(\frac{0.8578 \times (60+460)}{(1000+14.7)}\right) = 18.3\,\text{ft/s} \qquad (Z_1 = 0.8578)$$

$$\text{gas velocity at outlet } (p_2 = 850\text{psig});\ u_2 = 0.002122\left(\frac{250 \times 10^6}{19.0^2}\right)\left(\frac{14.7}{60+460}\right)\left(\frac{0.8765 \times (60+460)}{(850+14.7)}\right) = 21.9\,\text{ft/s} \qquad (Z_2 = 0.8765)$$

Problem

Solution with Standing-Katz method is remained as homework

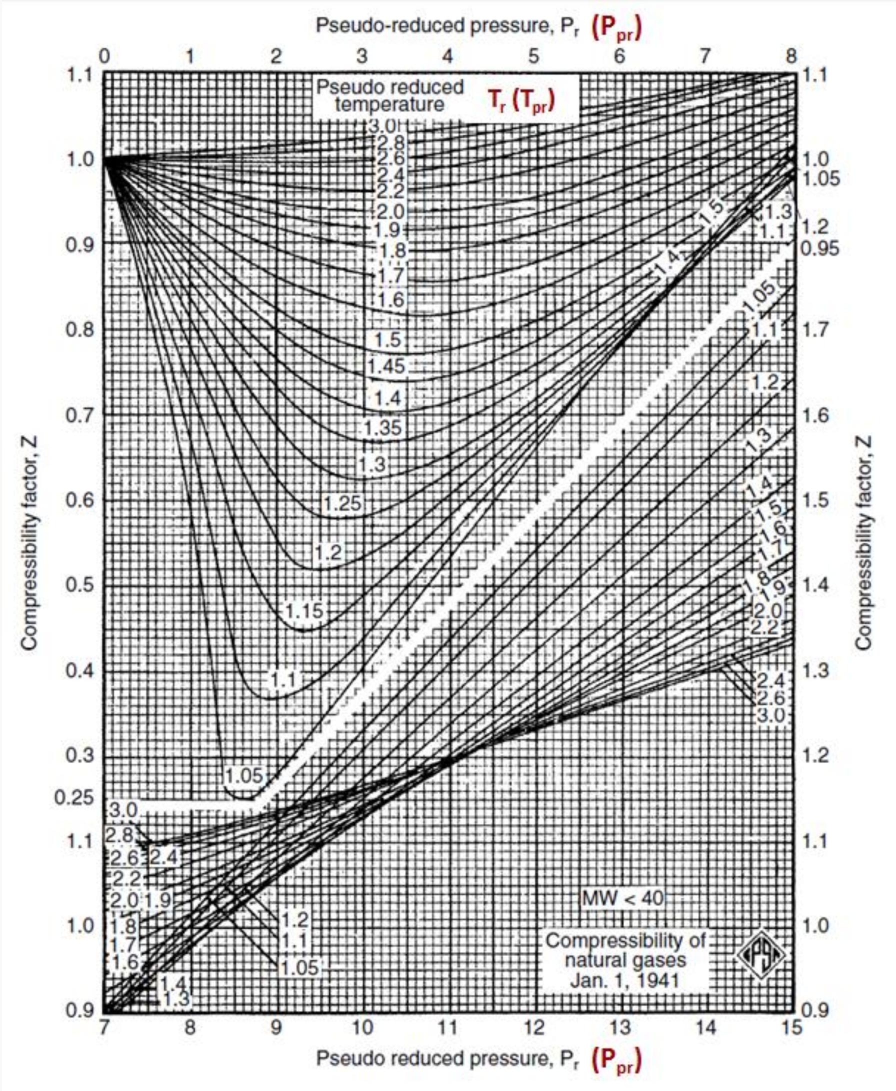
Given

$p_c = 666\,\text{psia}$

$T_c = 343°\text{R}$

$$p_r = \frac{p}{p_c} \quad \left(p_{r1} = \frac{p_1}{p_c}; \quad p_{r2} = \frac{p_2}{p_c} \right)$$

$$T_r = \frac{T}{T_c} \quad \left(T_{r1} = \frac{T_1}{T_c}; \quad T_{r2} = \frac{T_2}{T_c} \;\; ; \; T_1 = T_2 = 60°\text{F} = (60+460)°\text{R} \right)$$



Reynolds Number

An important parameter in flow of fluids in a pipe is the nondimensional term *Reynolds number.* The Reynolds number is used to characterize the type of flow in a pipe, such as laminar, turbulent, or critical flow. It is also used to calculate the friction factor in pipe flow. We will first outline the calculation of the Reynolds number based upon the properties of the gas and pipe diameter and then discuss the range of Reynolds number for the various types of flow and how to calculate the friction factor. The Reynolds number is a function of the gas flow rate, pipe inside diameter, and the gas density and viscosity and is calculated from the following equation:

$$Re = \frac{uD\rho}{\mu} \quad \text{(USCS units)} \qquad (2.32)$$

where

Re = Reynolds number, dimensionless
u = average velocity of gas in pipe, ft/s
D = inside diameter of pipe, ft
ρ = gas density, lb/ft^3
μ = gas viscosity, lb/ft-s

Reynolds Number

In gas pipeline hydraulics, using customary units, a more suitable equation for the Reynolds number is as follows:

$$Re = 0.0004778\left(\frac{P_b}{T_b}\right)\left(\frac{GQ}{\mu D}\right) \quad \text{(USCS units)} \qquad (2.34)$$

where

P_b = base pressure, psia
T_b = base temperature, °R (460 + °F)
G = specific gravity of gas (air = 1.0)
Q = gas flow rate, standard ft^3/day (SCFD)
D = pipe inside diameter, in.
μ = viscosity of gas, lb/ft-s

In SI units, the Reynolds number is

$$Re = 0.5134\left(\frac{P_b}{T_b}\right)\left(\frac{GQ}{\mu D}\right) \quad \text{(SI units)} \qquad (2.35)$$

where

P_b = base pressure, kPa
T_b = base temperature, °K (273 + °C)
G = specific gravity of gas (air = 1.0)
Q = gas flow rate, m^3/day (standard conditions)
D = pipe inside diameter, mm
μ = viscosity of gas, Poise

Reynolds Number

Example 3

A natural gas pipeline, NPS 20 with 0.500 in. wall thickness, transports 100 MMSCFD. The specific gravity of gas is 0.6 and viscosity is 0.000008 lb/ft-s. Calculate the value of the Reynolds number of flow. Assume the base temperature and base pressure are 60°F and 14.7 psia, respectively.

Friction Factor

In order to calculate the pressure drop in a pipeline at a given flow rate, we must first understand the concept of **friction factor**. The term ***friction factor*** is a dimensionless parameter that depends upon the Reynolds number of flow. In engineering literature, we find two different friction factors mentioned (***Darcy & Fanning friction factor***). However, the **Darcy friction factor, *f* is more common** and will be used throughout this course.

For turbulent flow, the friction factor is a function of the Reynolds number, pipe inside diameter, and internal roughness of the pipe. Many empirical relationships for calculating *f* have been put forth by researchers. The more popular correlations include the **Colebrook-White** and **AGA equations**.

$$\frac{1}{\sqrt{f}} = -2\,\text{Log}_{10}\left(\frac{e}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \quad \text{for } Re > 4000 \qquad (2.39)$$

where

f = friction factor, dimensionless
D = pipe inside diameter, in.
e = absolute pipe roughness, in.
Re = Reynolds number of flow, dimensionless

It can be seen from Equation 2.39 that in order to **calculate the friction factor *f*, we must use a trial-and-error approach**. It is an implicit equation in *f*, since *f* appears on both sides of the equation. We first assume a value of *f* (such as 0.01) and substitute it in the right-hand side of the equation. This will yield a second approximation for *f*, and continue until the convergence criteria.

Friction Factor

Table 2.1 Pipe Internal Roughness

Pipe Material	Roughness, in.	Roughness, mm
Riveted steel	0.0354 to 0.354	0.9 to 9.0
Commercial steel/welded steel	0.0018	0.045
Cast iron	0.0102	0.26
Galvanized iron	0.0059	0.15
Asphalted cast iron	0.0047	0.12
Wrought iron	0.0018	0.045
PVC, drawn tubing, glass	0.000059	0.0015
Concrete	0.0118 to 0.118	0.3 to 3.0

Example 5

A natural gas pipeline, NPS 20 with 0.500 in. wall thickness, transports 200 MMSCFD. The specific gravity of gas is 0.6 and viscosity is 0.000008 lb/ft-s. Calculate the friction factor using the Colebrook equation. Assume absolute pipe roughness = 600 μ in.

The base temperature and base pressure are 60°F and 14.7 psia, respectively.

Friction Factor

Modified Colebrook-White Equation

The U.S. Bureau of Mines in 1956 introduced a modified Colebrook-White equation which results a higher friction factor (and hence a ***smaller transmission factor, F***) so that a conservative estimation of gas flow rate can be achieved.

$$\frac{1}{\sqrt{f}} = -2\,\text{Log}_{10}\left(\frac{e}{3.7D} + \frac{2.825}{Re\sqrt{f}}\right) \qquad (2.46)$$

(Modified Colebrook-White Equation)

$$\frac{1}{\sqrt{f}} = -2\,\text{Log}_{10}\left(\frac{e}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \quad \text{for } Re > 4000 \qquad (2.39)$$

(Original Colebrook-White Equation)

Transmission Factor, F

The **transmission factor, *F*** is considered the **opposite of the friction factor, *f***.

Whereas the friction factor indicates how difficult it is to move a certain quantity of gas through a pipeline, the transmission factor is a direct measure of how much gas can be transported through the pipeline.

As the friction factor increases, the transmission factor decreases and, therefore, the gas flow rate also decreases. Conversely, the higher the transmission factor, the lower the friction factor and, therefore, the higher the flow rate will be.

$$F = \frac{2}{\sqrt{f}} \tag{2.42}$$

where

f = friction factor

F = transmission factor

Transmission Factor, F

Accordingly, modified Colebrook-White equation take the following form in terms of transmission factor, *F*:

$$F = -4\,\mathrm{Log}_{10}\left(\frac{e}{3.7D} + \frac{1.4125F}{Re}\right) \quad \text{(USCS and SI units)} \qquad (2.47)$$

using

$$F = \frac{2}{\sqrt{f}} \qquad (2.42)$$

American Gas Association (AGA) Equation

In 1964 and 1965, the **American Gas Association (AGA)** published a report on how to calculate the transmission factor for gas pipelines to be used in the General Flow equation.

According to AGA, the **transmission factor, *F*** is calculated using two different equations.

- First, *F* is calculated for the rough pipe law (referred to as the fully turbulent zone).
- Next, *F* is calculated based on the smooth pipe law (referred to as the partially turbulent zone).
- Finally, the **smaller of the two values of the transmission factor** is used in the General Flow equation for pressure drop calculation.

First, F_1 **for fully turbulent zone**:

$$\approx 0 \quad (\text{Re} \uparrow\uparrow)$$

$$F = -4\,\text{Log}_{10}\left(\frac{e}{3.7D} + \frac{1.4125F}{Re}\right) \quad \text{(USCS and SI units)} \qquad (2.47)$$

$$\approx F = -4\text{Log}_{10}\left(\frac{e}{3.7D}\right)$$

$$F = 4\,\text{Log}_{10}\left(\frac{3.7D}{e}\right) \qquad (2.48) \longrightarrow F_1$$

American Gas Association (AGA) Equation

For the partially turbulent zone, ***F* (F_2)** is calculated from the following equations using the Reynolds number, a parameter D_f known as the **pipe drag factor**, and the Von Karman smooth pipe transmission factor F_t:

$$F = 4D_f \,\mathrm{Log}_{10}\left(\frac{Re}{1.4125F_t}\right) \quad (2.49)$$

and

$$F_t = 4\,\mathrm{Log}_{10}\left(\frac{Re}{F_t}\right) - 0.6 \quad (2.50)$$

(implicit)

→ F_2

where

F_t = Von Karman smooth pipe transmission factor

D_f = pipe drag factor that depends on the Bend Index (BI) of the pipe

AGA: *F* = smaller of F_1 & F_2

Table 2.2 Bend Index and Drag Factor D_f

	Bend Index		
	Extremely Low 5° to 10°	Average 60° to 80°	Extremely High 200° to 300°
Bare steel	0.975–0.973	0.960–0.956	0.930–0.900
Plastic lined	0.979–0.976	0.964–0.960	0.936–0.910
Pig burnished	0.982–0.980	0.968–0.965	0.944–0.920
Sand blasted	0.985–0.983	0.976–0.970	0.951–0.930

Note: The drag factors above are based on 40-ft joints of pipelines and mainline valves at 10-mile spacing.

Problem

Example 11

Using the AGA method, calculate the transmission factor and friction factor for gas flow in an NPS 20 pipeline with 0.500 in. wall thickness. The flow rate is 200 MMSCFD, gas gravity = 0.6, and viscosity = 0.000008 lb/ft-sec. The absolute pipe roughness is 700 μ in. Assume a bend index of 60°, base pressure of 14.73 psia, and base temperature of 60°F.

$$F = 4\,\mathrm{Log}_{10}\left(\frac{3.7D}{e}\right) \qquad (2.48)$$

$$F = 4D_f\,\mathrm{Log}_{10}\left(\frac{Re}{1.4125F_t}\right) \qquad (2.49)$$

and

$$F_t = 4\,\mathrm{Log}_{10}\left(\frac{Re}{F_t}\right) - 0.6 \qquad (2.50)$$

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Sand blasted	0.985–0.983	0.976–0.970	0.951–0.930

Note: The drag factors above are based on 40-ft joints of pipelines and mainline valves at 10-mile spacing.

Solution

Inside diameter of pipe = 20 – 2 × 0.5 = 19.0 in.

The base temperature = 60 + 460 = 520°R

We will first calculate the Reynolds number using Equation 2.34.

$$Re = \frac{0.0004778 \times 200 \times 10^6 \times 0.6 \times 14.73}{19 \times 0.000008 \times 520} = 10{,}685{,}214$$

Next, calculate the two transmission factors.

The fully turbulent transmission factor, using Equation 2.48, is

$$F = 4\,\text{Log}_{10}\left(\frac{3.7 \times 19}{0.0007}\right) = 20.01$$

For the smooth pipe zone, using Equation 2.50, the Von Karman transmission factor is

$$F_t = 4\,\text{Log}_{10}\left(\frac{10{,}685{,}214}{F_t}\right) - 0.6$$

Solving this equation by trial and error, we get $F_t = 22.13$.

From Table 2.2, for a bend index of 60°, the drag factor D_f is 0.96.

Therefore, for the partially turbulent flow zone, using Equation 2.49, the transmission factor is

$$F = 4 \times 0.96\,\text{Log}_{10}\left(\frac{10{,}685{,}214}{1.4125 \times 22.13}\right) = 21.25$$

From the above two values of F, using the smaller number, we get the AGA transmission factor as

$$F = 20.01$$

Therefore, the corresponding friction factor f is found from Equation 2.42 as

$$\frac{2}{\sqrt{f}} = 20.01$$

or

$$f = 0.0100$$