Oil and Gas Pipeline Design, Maintenance and Repair

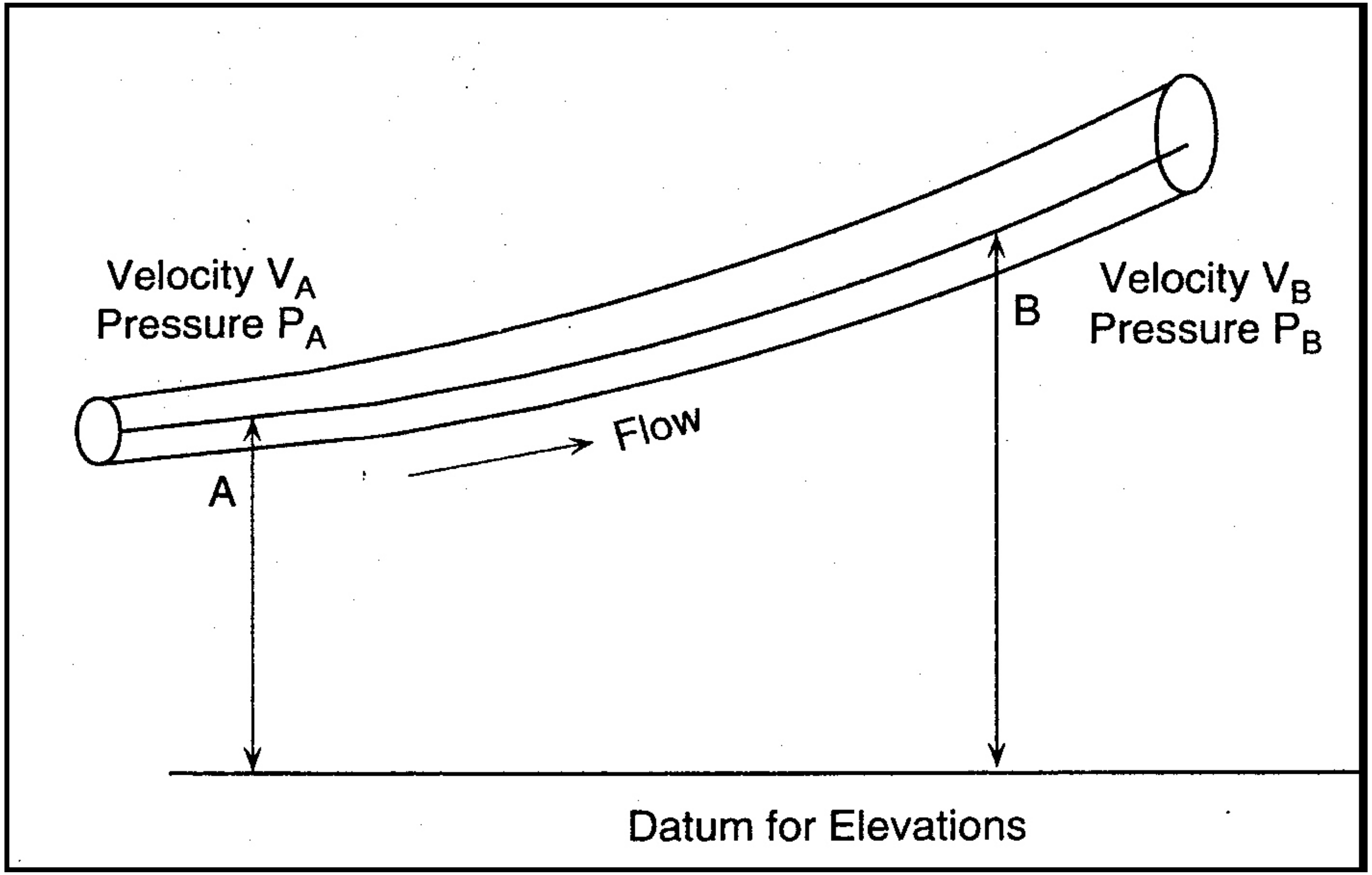
Dr. Abdel-Alim Hashem
Professor of Petroleum Engineering
Mining, Petroleum & Metallurgical Eng. Dept.
Faculty of Engineering – Cairo University
aelsayed@mail.eng.cu.edu.eg
ahshem2000@yahoo.com

Part 2: Steady-State Flow of Gas through Pipes

INTRODUCTION

- Pipes provide an economic means of producing and transporting fluids in large volumes over great distances
- The flow of gases through piping systems involves flow in horizontal, inclined, and vertical orientations, and through constrictions such as chokes for flow control

ENERGY OF FLOW OF A FLUID



BERNOULLI'S EQUATION

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

- P = the pressure
- V = the velocity
- Z = the height
- H_p = the equivalent head added to the fluid by a compressor at A
- h_f = represents the total frictional pressure loss between points A and B.

VELOCITY OF GAS IN A PIPELINE

$$Q = VA$$

$$V_1 \rho_1 = V_1 \rho$$

$$M_1 = q_1 \rho_1 = q_2 \rho_2 = q_b \rho_b$$

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

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

$$M_1 = q_1 \rho_1 = M_2 = q_2 \rho_2$$

$$q_1 = V_1 A_1$$

$$q_1 = q_b \left(\frac{\rho_b}{\rho_1} \right)$$

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

$$q_1 = q_b \left(\frac{P_b}{T_b} \right) \left(\frac{T_1}{P_1} \right) \left(\frac{Z_1}{Z_b} \right)$$

VELOCITY OF GAS IN A PIPELINE

$$q_1 = q_b \left(\frac{P_b}{T_b}\right)\left(\frac{T_1}{P_1}\right) Z_1 \quad \text{since } Z_b = 1.0$$

$$V_1 = \frac{q_b Z_1}{A}\left(\frac{P_b}{T_b}\right)\left(\frac{T_1}{P_1}\right) = \frac{4x144 q_b Z_1}{\pi d^2}\left(\frac{P_b}{T_b}\right)\left(\frac{T_1}{P_1}\right)$$

$$V_1 = 0.002122 \frac{q_b}{d^2}\left(\frac{P_b}{T_b}\right)\left(\frac{Z_1 T_1}{P_1}\right) \quad (USCS)$$

- V_1 = upstream gas velocity, ft/s
- q_b = gas flow rate, measured at standard conditions, ft^3/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)

VELOCITY OF GAS IN A PIPELINE

- Gas velocity at section 2 is given by

$$V_2 = 0.002122 \frac{q_b}{d^2} \left(\frac{P_b}{T_b} \right) \left(\frac{Z_2 T_2}{P_2} \right)$$

- Gas velocity at any point in a pipeline is given by

$$V = 0.002122 \frac{q_b}{d^2} \left(\frac{P_b}{T_b} \right) \left(\frac{ZT}{P} \right) \quad (USCS)$$

$$V = 14.739 \frac{q_b}{d^2} \left(\frac{P_b}{T_b} \right) \left(\frac{ZT}{P} \right) \quad (SI)$$

EROSIONAL VELOCITY

$$V_{max} = \frac{100}{\sqrt{\rho}}$$

- V_{max} = maximum or erosional velocity, ft/s
- ρ = gas density at flowing temperature, lb/ft^3

$$V_{max} = 100\sqrt{\frac{ZRT}{29\gamma_g P}}$$

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

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?

Solution

- For compressibility factor Z = 1.00, the velocity of gas at the inlet pressure of 1000 psig is

$$V_1 = 0.002122\left(\frac{250x\,10^5}{19.0^2}\right)\left(\frac{14.7}{60+460}\right)\left(\frac{60+460}{1014.7}\right) = 21.29 \text{ ft/s}$$

- Gas velocity at the outlet is

$$V_2 = 21.29\left(\frac{1014.7}{864.7}\right) = 24.89 \text{ ft/s}$$

- The erosional velocity is found for Z = 0.90,

$$V_{max} = 100\sqrt{\frac{0.9x\,1014.7x\,250}{29x\,0.6x\,1014.7}} = 53.33 \text{ ft/s}$$

REYNOLD'S NUMBER OF FLOW

$$R_e = \frac{\rho V d}{\mu} \quad (USCS)$$

- R_e = Reynolds number, dimensionless
- V = 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

REYNOLD'S NUMBER OF FLOW

$$R_e = \frac{\rho V d}{\mu} \quad (USCS)$$

- USCS or SI
- R_e = Reynolds number, dimensionless
- V = average velocity of gas in pipe, ft/s or m/s
- d = inside diameter of pipe, ft or m
- ρ = gas density, lb/ft^3 or kg/m^3
- μ = gas viscosity, lb/ft.s or kg/m.s

REYNOLD'S NUMBER OF FLOW IN CUSTOMARY UNITS

$$R_e = 0.0004778\left(\frac{P_b}{T_b}\right)\left(\frac{\gamma_g q}{\mu d}\right) \quad (USCS)$$

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

REYNOLD'S NUMBER OF FLOW IN CUSTOMARY UNITS

$$R_e = 0.5134\left(\frac{P_b}{T_b}\right)\left(\frac{\gamma_g q}{\mu d}\right) \quad (SI)$$

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

Flow Regime

- Re ≤ 2000 Laminar flow,
- 2000 > Re ≤ 4000 Critical flow
- Re > 4000 Turbulent flow

Example

- 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.

Solution

- Pipe inside diameter = 20 - 2 x 0.5 = 19.0 in.
- The base temperature = 60 + 460 = 520 °R
- Using Equation we get

$$R_e = 0.0004778\left(\frac{14.7}{520}\right)\left(\frac{0.6x\,100x\,10^6}{0.000008x\,19}\right) = 5,331,726$$

- Since Re is greater than 4000, the flow is in the turbulent region.

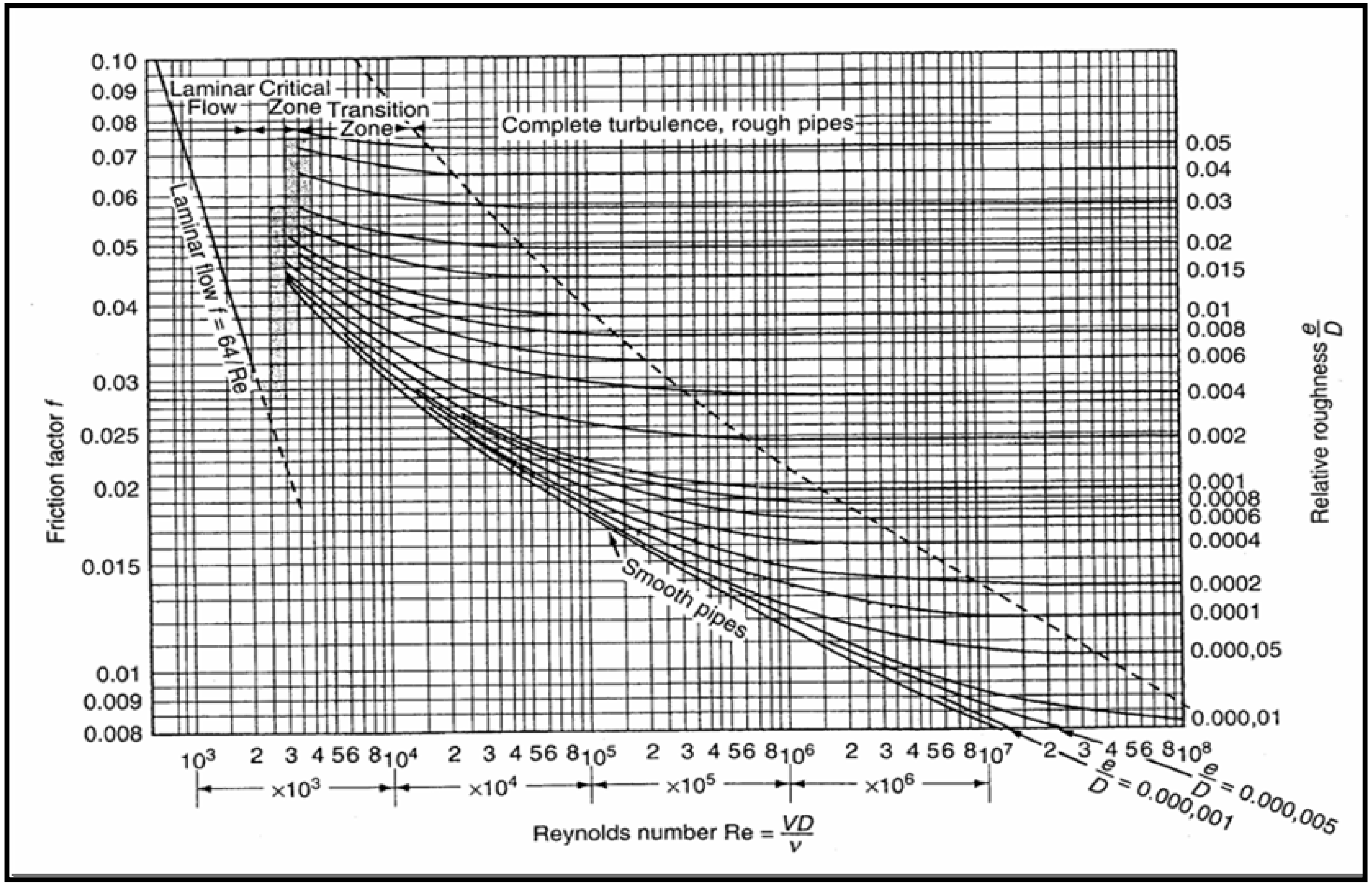
FRICTION FACTOR

$$f_f = \frac{f_d}{4}$$

- f_f = Fanning friction factor
- f_d = Darcy friction factor
- For laminar flow

$$f = \frac{64}{R_e}$$

FRICTION FACTOR FOR TURBULENT FLOW



INTERNAL ROUGHNESS

Type of pipe	e, in	e,mm
Drawn tubing (brass, lead, glass)	0.00006	0.001524
Aluminum pipe	0.0002	0.000508
Plastic-lined or sand blasted	0.0002-0.0003	0.00508-0.00762
Commercial steel or wrought iron	0.0018	0.04572
Asphalted cast iron	0.0048	0.1292
Galvanized iron	0.006	0.01524
Cast iron	0.0102	0.25908
Cement-lined	0.012-0.12	0.3048-3.048
Riveted steel	0.036-0.36	0.9144-9.144
PVC, drawn tubing, glass	0.000059	0.0015
Concrete	0.0118-0.118	0.3-3.0
Wrought iron	0.0018	0.045
Commonly used well tubing and line pipe:		
New pipe	0.0005-0.0007	0.0127-.01778
12-months old	0.00150	0.381
24-months old	0.00175	0.04445

TRANSMISSION FACTOR

- The transmission factor F is related to the friction factor *f* as follows

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

$$f = \frac{4}{F^2}$$

Relative Roughness

$$\text{Relative roughness} = \frac{e}{d}$$

- e = absolute or internal roughness of pipe, in.
- d = pipe inside diameter, in.

FLOW EQUATIONS FOR HIGH PRESSURE SYSTEM

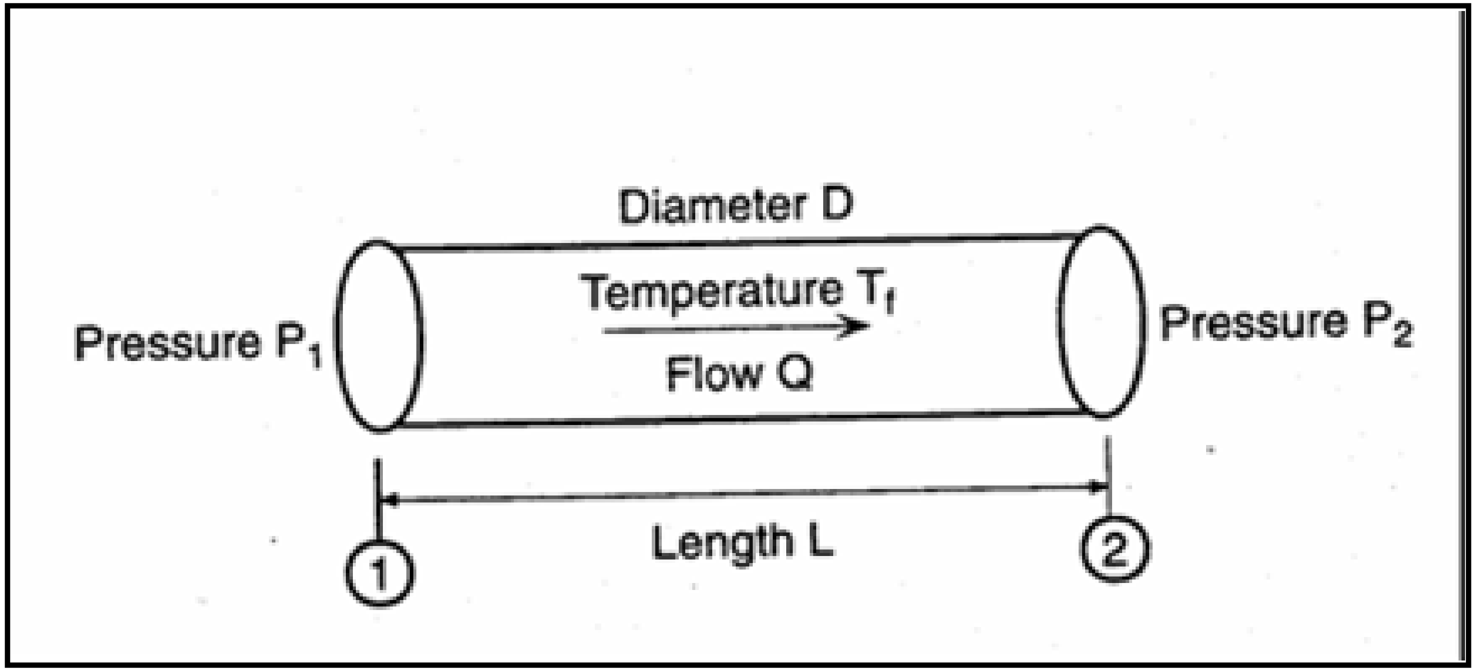
- General Flow equation
- Colebrook-White equation
- Modified Colebrook-White equation
- AGA equation
- Weymouth equation
- Panhandle A equation
- Panhandle B equation
- IGT equation
- Spitzglass equation
- Mueller equation
- Fritzsche equation

GENERAL FLOW EQUATION (USCS)

$$q_{sc} = 77.54\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - P_2^2\right)d^5}{\gamma_g Z_{av} T_{av} f L}\right)^{0.5} \quad (USCS)$$

- q_{sc} = 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
- γ_g = gas gravity (air = 1.00)
- T_{av} = average gas flowing temperature, °R (460 + °F)
- L = pipe segment length, mi
- Z_{av} = gas compressibility factor at the flowing temperature, dimensionless
- d = pipe inside diameter, in.

Steady flow in a gas pipeline



GENERAL FLOW EQUATION (SI)

$$q_{sc} = 1.1494x\,10^{-3}\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^{\,2} - P_2^{\,2}\right)d^{\,5}}{\gamma_g Z_{av} T_{av} f L}\right)^{0.5} \quad (SI)$$

- q_{sc} = 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)
- P1 = upstream pressure, kPa
- P2 = downstream pressure, kPa
- γ_g = gas gravity (air = 1.00)
- T_{av} = average gas flowing temperature, °K (273 + °C)
- L = pipe segment length, km
- Z_{av} = gas compressibility factor at the flowing temperature, dimensionless
- d = pipe inside diameter, mm

General flow equation in terms of the transmission factor F

$$q_{sc} = 38.77F\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - P_2^2\right)d^5}{\gamma_g Z_{av} T_{av} L}\right)^{0.5} \quad (USCS)$$

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

$$q_{sc} = 5.747x\,10^{-4}F\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - P_2^2\right)d^5}{\gamma_g Z_{av} T_{av} L}\right)^{0.5} \quad (SI)$$

- F = transmission factor

EFFECT OF PIPE ELEVATIONS

$$q_{sc} = 38.77F\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - e^s P_2^2\right)d^5}{\gamma_g Z_{av} T_{av} L_e}\right)^{0.5} \quad (USCS)$$

$$q_{sc} = 5.747x\,10^{-4}F\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - e^s P_2^2\right)d^5}{\gamma_g Z_{av} T_{av} L_e}\right)^{0.5} \quad (SI)$$

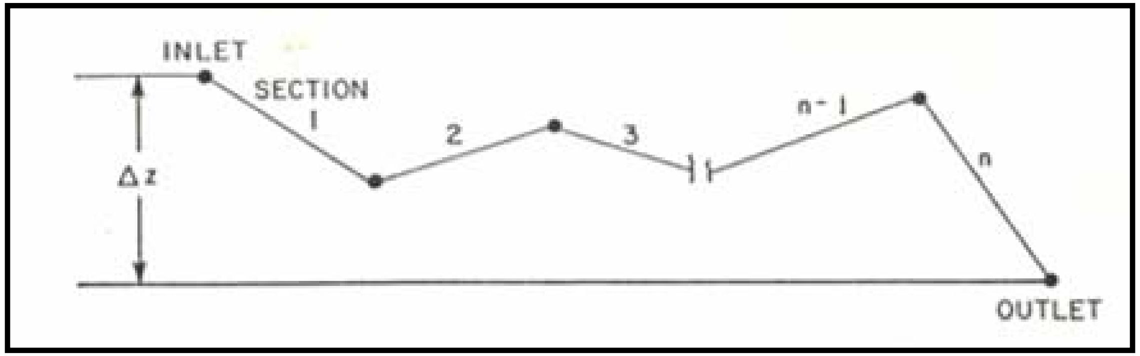
$$L_e = \frac{(e^s - 1)}{s} L$$

$$s = (0.0375)\gamma_g(\Delta z)/(Z_{av}T_{av}) \quad (USCS)$$

$$s = (0.0684)\gamma_g(\Delta z)/(Z_{av}T_{av}) \quad (SI)$$

- s = elevation adjustment parameter, dimensionless
- ΔZ = elevation difference
- e = base of natural logarithms (e = 2.718...)

Gas flow through different elevations



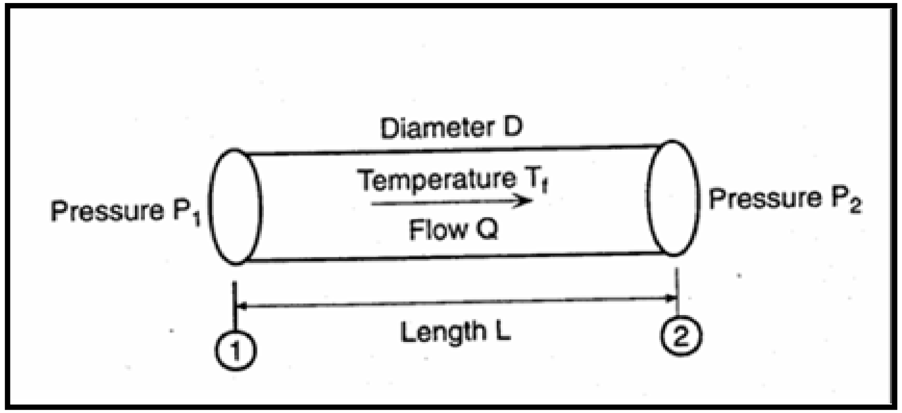
$$L_e = \frac{(e^{s_1} - 1)}{s_1} L_1 + \frac{e^{s_1}(e^{s_2} - 1)}{s_2} L_2 + \frac{e^{s_1 + s_2}(e^{s_3} - 1)}{s_3} L_3 + \ldots\ldots + \frac{e^{\sum s_{n-1}}(e^{s_n} - 1)}{s_n} L_n \qquad s_i \neq 0$$

$$j = \frac{(e^{s} - 1)}{s}$$

$$L_e = j_1 L_1 + j_2 L_2 e^{s_1} + j_3 L_3 e^{s_3} + \ldots\ldots + j_n L_n e^{s_{n-1}} \qquad s_i \neq 0$$

AVERAGE PRESSURE IN PIPE SEGMENT

$$P_{av} = \frac{2}{3}\left(P_1 + P_2 + \frac{P_1 P_2}{P_1 + P_2}\right)$$



- Or

$$P_{av} = \frac{2}{3}\left(\frac{P_1^{\,3} - P_2^{\,3}}{P_1^{\,2} - P_2^{\,2}}\right)$$

COLEBROOK-WHITE EQUATION

- A relationship between the friction factor and the Reynolds number, pipe roughness, and inside diameter of pipe.
- Generally 3 to 4 iterations are sufficient to converge on a reasonably good value of the friction factor

$$\frac{1}{\sqrt{f}} = -2\log\left[\left(\frac{e}{3.7d}\right) + \left(\frac{2.51}{R_e\sqrt{f}}\right)\right] \quad \text{Turbulent flow}$$

- f = friction factor, dimensionless
- d = pipe inside diameter, in.
- e = absolute pipe roughness, in.
- R_e = Reynolds number of flow, dimensionless

COLEBROOK-WHITE EQUATION

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{2.51}{R_e\sqrt{f}}\right)$$ Turbulent flow in smooth pipe

$$\frac{1}{\sqrt{f}} = -2\log\left({e}/{3.7d}\right)$$ turbulent flow in fully rough pipes

Example

- 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.

Solution

- Pipe inside diameter = 20 - 2 x 0.5 = 19.0 in.
- Absolute pipe roughness = 600 ~ in. = 0.0006 in.
- First, we calculate the Reynolds number
- Re = 0.0004778(14.7/(60+460))x((0.6 x 200 x 106) /(0.000008x 19)) = 10,663,452
- This equation will be solved by successive iteration.
- Assume *f* = 0.01 initially; substituting above, we get a better approximation as *f* = 0.0101. Repeating the iteration, we get the final value as *f* = 0.0101. Therefore, the friction factor is 0.0101.

MODIFIED COLEBROOK-WHITE EQUATION

$$\frac{1}{\sqrt{f}} = -2\log\left[\left(e/3.7d\right) + \left(\frac{2.825}{R_e\sqrt{f}}\right)\right] \quad \text{turbulent flow}$$

$$F = -2\log\left[\left(e/3.7d\right) + \left(\frac{1.4125F}{R_e}\right)\right] \quad \text{with transmission factor}$$

AMERICAN GAS ASSOCIATION (AGA) EQUATION

$$F = 4\log\left(\frac{3.7d}{e}\right) \quad \text{Von Karman, for rough pipe}$$

$$F = 4D_f \log\left(\frac{R_e}{1.412F_t}\right) \quad \text{Von Karman, smooth pipe}$$

- D_f known as the pipe drag factor depend on bend index, Its value ranges from 0.90 to 0.99
- F_t = Von Karman smooth pipe transmission factor

$$F_t = 4\log\left(\frac{R_e}{F_t}\right) - 0.6$$

Bend Index

- Bend index is the sum of all the angles and bends in the pipe segment, divided by the total length of the pipe section under consideration

$$BI = \frac{\text{total degrees of all bends in pipe section}}{\text{total length of pipe section}}$$

Material	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

WEYMOUTH EQUATION

$$q_{sc} = 38.77E\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^{\,2} - e^{s}P_2^{\,2}\right)d^{16/3}}{\gamma_g Z_{av} T_{av} L_e}\right)^{0.5} \quad (USCS)$$

- q_{sc} = gas flow rate, measured at standard conditions, ft³/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
- γ_g = gas gravity (air = 1.00)
- T_{av} = average gas flowing temperature, °R (460 + °F)
- L_e = equivalent pipe segment length, mi
- Z_{av} = gas compressibility factor at the flowing temperature, dimensionless
- d = pipe inside diameter, in.

$$F = 11.18d^{1/6} \quad (USCS)$$

WEYMOUTH EQUATION

$$q_{sc} = 3.7435x\,10^{-3}xE\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - e^s P_2^2\right)d^{16/3}}{\gamma_g Z_{av} T_{av} L_e}\right)^{0.5} \quad (SI)$$

- q_{sc} = gas flow rate, measured at standard conditions,m³/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
- γ_g = gas gravity (air = 1.00)
- T_{av} = average gas flowing temperature, °K (272 + °C)
- L_e = equivalent pipe segment length, km
- Z_{av} = gas compressibility factor at the flowing temperature, dimensionless
- d = pipe inside diameter, mm

$$F = 6.521 d^{1/6} \quad (SI)$$

PANHANDLE A EQUATION

$$q_{sc} = 435.87E\left(\frac{T_b}{P_b}\right)^{1.0788}\left(\frac{\left(P_1^{\,2} - e^s P_2^{\,2}\right)}{\gamma_g^{0.8539} x T_{av} x L_e x Z}\right)^{0.5394} d^{\,2.6182} \quad (USCS)$$

$$q_{sc} = 4.5965x\,10^{-3}E\left(\frac{T_b}{P_b}\right)^{1.0788}\left(\frac{\left(P_1^{\,2} - e^s P_2^{\,2}\right)}{\gamma_g^{0.8539} x T_{av} x L_e x Z}\right)^{0.5394} d^{\,2.6182} \quad (SI)$$

- E = pipeline efficiency, a decimal value less than 1.0

PANHANDLE A EQUATION
Transmission Factor

$$F = 7.2111 E \left(\frac{q \gamma_g}{d} \right)^{0.07305} \qquad (USCS)$$

$$F = 11.85 E \left(\frac{q \gamma_g}{d} \right)^{0.07305} \qquad (SI)$$

PANHANDLE B EQUATION

$$q_{sc} = 737E\left(\frac{T_b}{P_b}\right)^{1.02}\left(\frac{\left(P_1^{\,2} - e^{s}P_2^{\,2}\right)}{\gamma_g^{0.961} x T_{av} x L_e x Z}\right)^{0.51} d^{\,2.53} \quad (USCS)$$

$$q_{sc} = 1.002x10^{-2}E\left(\frac{T_b}{P_b}\right)^{1.02}\left(\frac{\left(P_1^{\,2} - e^{s}P_2^{\,2}\right)}{\gamma_g^{0.961} x T_{av} x L_e x Z}\right)^{0.51} d^{\,2.53} \quad (SI)$$

- E = pipeline efficiency, a decimal value less than 1.0

PANHANDLE A EQUATION
Transmission Factor

$$F = 16.7E\left(\frac{q\gamma_g}{d}\right)^{0.01961} \qquad (USCS)$$

$$F = 19.08E\left(\frac{q\gamma_g}{d}\right)^{0.01961} \qquad (SI)$$

INSTITUTE OF GAS TECHNOLOGY (IGT) EQUATION

$$q_{sc} = 136.9E\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - e^s P_2^2\right)}{\gamma_g^{0.8} x T_{av} x L_e x Z x \mu^{0.2}}\right)^{0.555} d^{2.667} \quad (USCS)$$

- μ = gas viscosity, lb/ft.s

$$q_{sc} = 1.2822 x 10^{-3} E\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - e^s P_2^2\right)}{\gamma_g^{0.8} x T_{av} x L_e x Z x \mu^{0.2}}\right)^{0.555} d^{2.667} \quad (SI)$$

- μ = gas viscosity, Poise

SPITZGLASS EQUATION
Low Pressure

$$q_{sc} = 3.839x\,10^{3} E \left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1 - e^{s} P_2\right)}{\gamma_g x T_{av} x L_e x Z_{av}\,(1+3.6/d\;+0.03d\,)}\right)^{0.5} d^{\,2.5} \quad (USCS\,)$$

- Pressure less than or equal 1.0 psi

$$q_{sc} = 5.69x\,10^{-2} E \left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1 - e^{s} P_2\right)}{\gamma_g x T_{av} x L_e x Z_{av}\,(1+91.44/d\;+0.03d\,)}\right)^{0.5} d^{\,2.5} \quad (SI\,)$$

- Pressure less than or equal 6.9 kPa

SPITZGLASS EQUATION
High Pressure

$$q_{sc} = 729.608E\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1 - e^s P_2\right)}{\gamma_g x T_{av} x L_e x Z_{av}\,(1+3.6/d + 0.03d)}\right)^{0.5} d^{2.5} \quad (USCS)$$

- Pressure more than 1.0 psi

$$q_{sc} = 1.0815x10^{-2}E\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1 - e^s P_2\right)}{\gamma_g x T_{av} x L_e x Z_{av}\,(1+91.44/d + 0.0012d)}\right)^{0.5} d^{2.5} \quad (SI)$$

- Pressure more than 6.9 kPa

MUELLER EQUATION

$$q_{sc} = 85.7368E\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - e^s P_2^2\right)}{\gamma_g^{0.7391} x T_{av} x L_e x\, \mu^{0.2609}}\right)^{0.575} d^{2.725} \quad (USCS)$$

- μ = gas viscosity, lb/ft.s

$$q_{sc} = 3.0398x\,10^{-2} xE\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - e^s P_2^2\right)}{\gamma_g^{0.7391} x T_{av} x L_e x\, \mu^{0.2609}}\right)^{0.575} d^{2.725} \quad (SI)$$

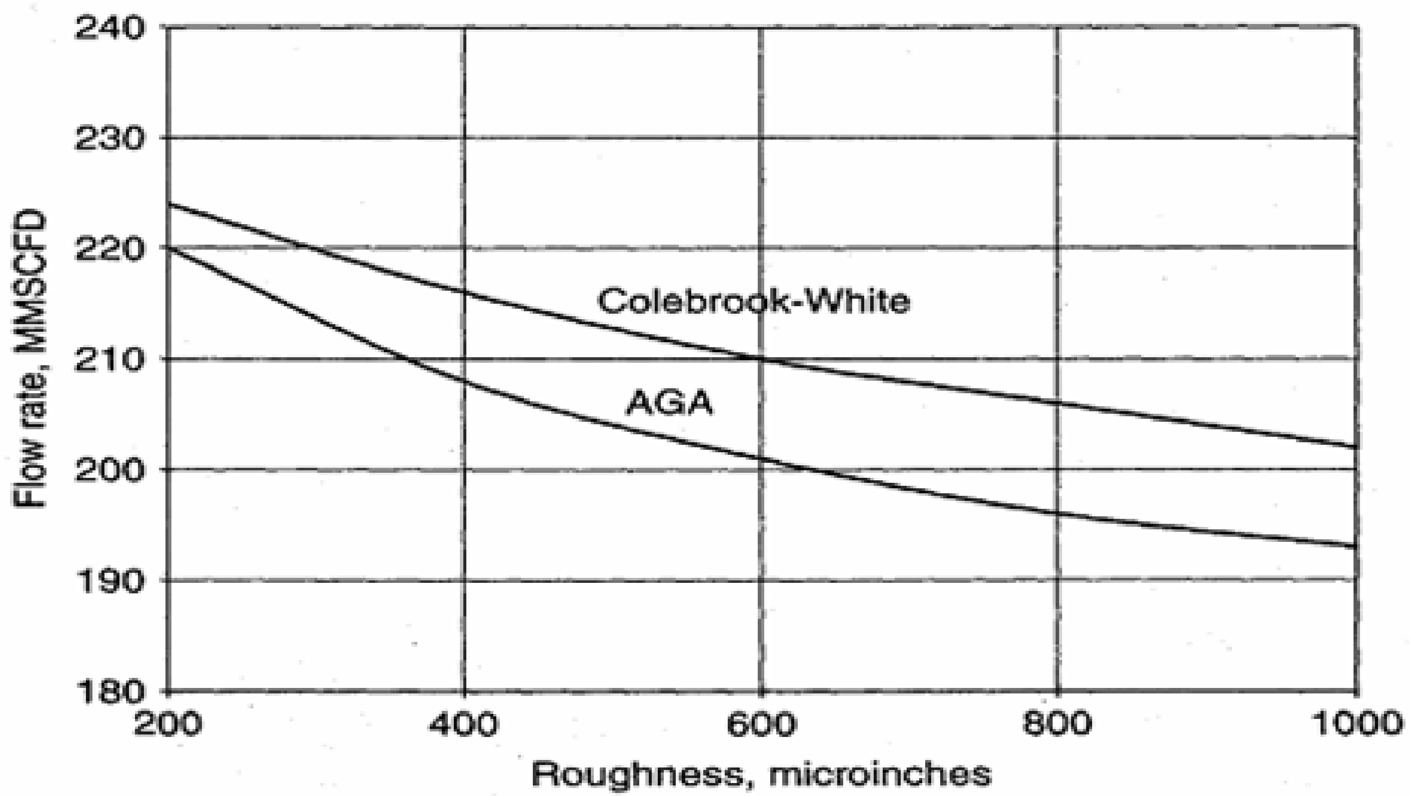
- μ = gas viscosity, cP

FRITZSCHE EQUATION

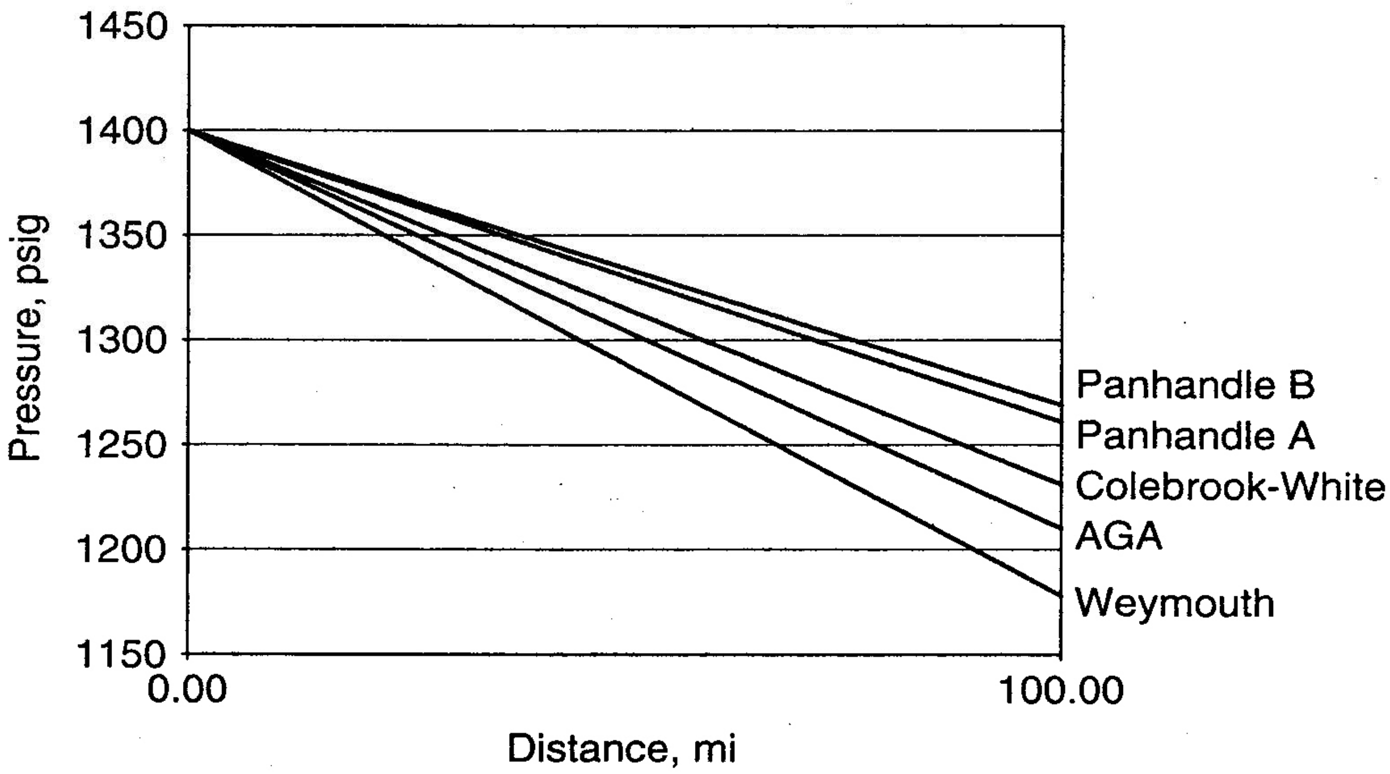
$$q_{sc} = 410.1688E\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - e^s P_2^2\right)}{\gamma_g^{0.8587} x T_{av} x L_e}\right)^{0.538} d^{2.69} \quad (USCS)$$

$$q_{sc} = 2.827E\left(\frac{T_b}{P_b}\right)\left(\frac{\left(P_1^2 - e^s P_2^2\right)}{\gamma_g^{0.8587} x T_{av} x L_e}\right)^{0.538} d^{2.69} \quad (SI)$$

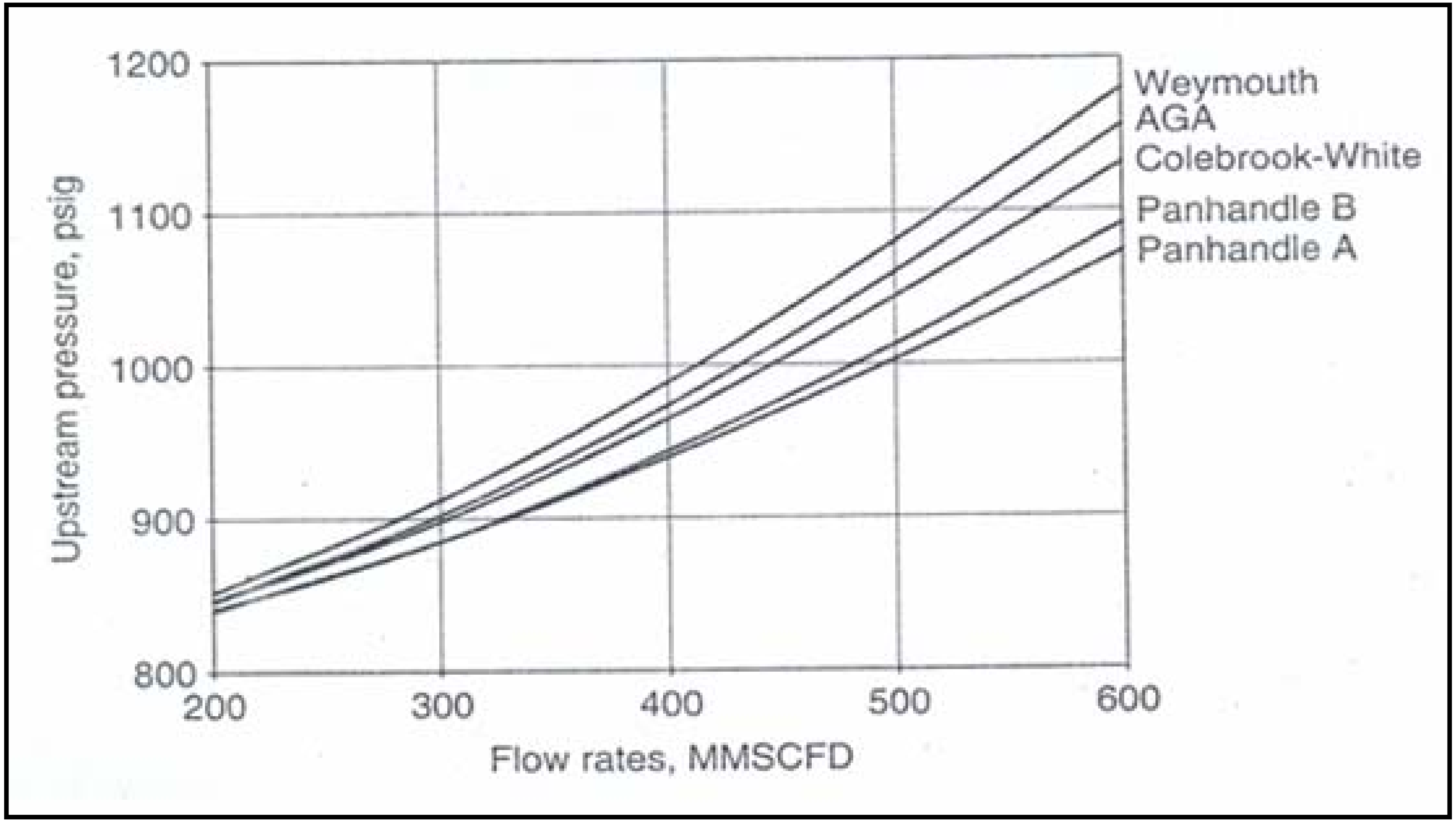
EFFECT OF PIPE ROUGHNESS



COMPARISON OF FLOW EQUATIONS



COMPARISON OF FLOW EQUATIONS



Flow Characteristics of Low-Pressure Services

$$ft^3/hr = \left[\frac{\text{total pressure drop in service, in } H_2O}{\left(K_p\right)\left(\gamma/\gamma'\right)\left(L + L_{ef}\right)}\right]^{0.54}$$

- K_p = pipe constant
- γ = sp gr of gas
- γ' = sp gr 0.60
- L = length of service, ft
- L_{ef} = equivalent length of fittings given below

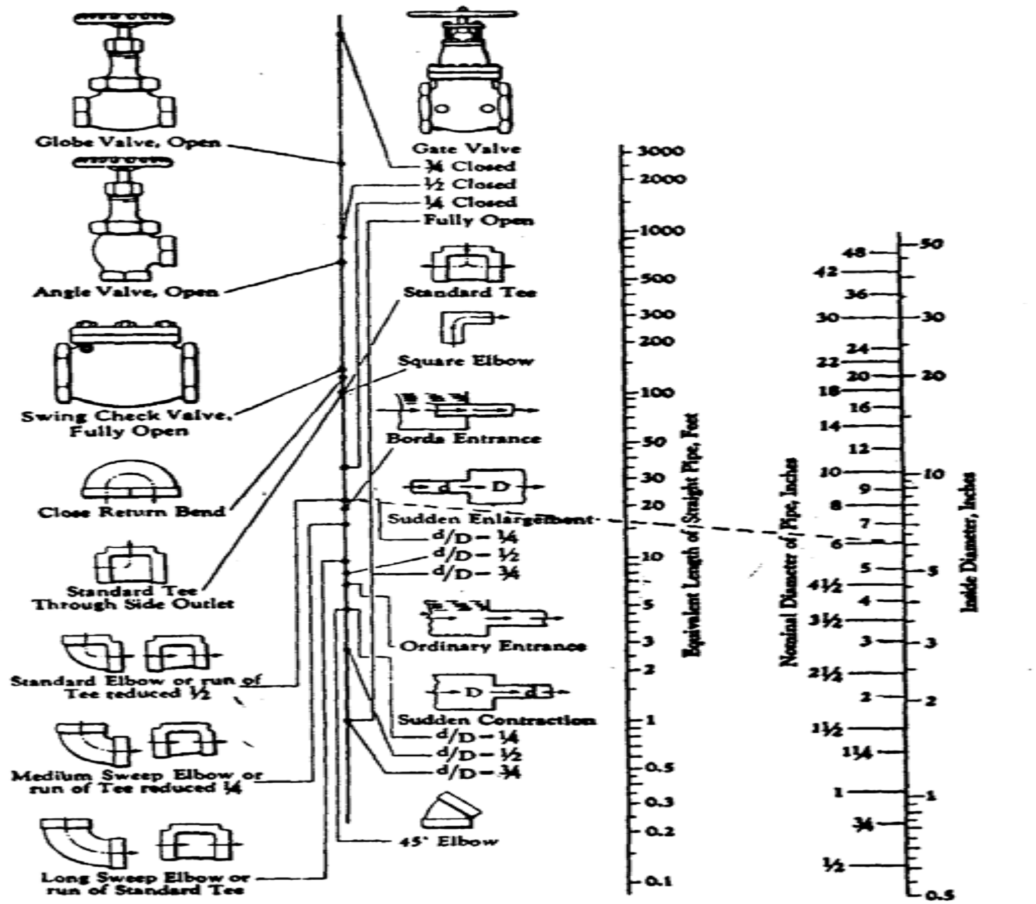
Values of K_p

Pipe size and type	K_p
3/4-in CTS copper	1.622×10^{-6}
1-in ID plastic	0.279×10^{-6}
1-in CTS copper	0.383×10^{-6}
1¼-in CTS copper	0.124×10^{-6}
1¼-in NS steel	0.080×10^{-6}
1½-in NS steel	0.037×10^{-6}

Equivalent lengths of pipe fittings

Fitting	Equivalent length, ft
• 1-in or 1¼-in Curb cock for copper service	3.5
• 1¼-in curb cock for 1¼-in steel service	13.5
• 1½-in curb cock for 1½-in steel service	12.0
• 1½-in street elbow for 1¼-in steel service	7.5
• 1½-in street elbow for 1½--in steel service	7.5
• 1¼-in street tee for 1¼-in steel service	10.5
• 1½-in street tee on sleeve or 1¼-in hole in main	15.0
• 1¼ x 1 x 1¼-in street tee	23.0
• 1½ x 1¼ x 1½-in street tee	19.0
• Combined outlet fittings	
• ¾-in copper	2.0
• 1-in copper or plastic	6.0
• 1¼-in steel	8.0
• 1½-in steel	22.0

Equivalent lengths of pipe fittings



Flowing Temperature in (Horizontal]) Pipelines

$$T_{L_x} = \frac{\left[T_s + C_4/C_2 - \left(C_1C_5\right)/\left(C_2\left(C_2+C_3\right)\right)\right]C_1^{C_2/C_3}}{\left(C_1 + C_2L_x\right)^{C_2/C_3}} - \frac{C_4 + C_5L_x}{C_2} + \frac{C_5\left(C_1 + C_3L_x\right)}{C_2\left(C_2+C_3\right)}$$

$$C_1 = z_{v1}c_pL + \left(1 - z_{v1}\right)c_p$$

$$C_2 = k/m$$

$$C_3 = \left(z_{v2} - z_{v1}\right)\left(c_{pL} - c_{pv}\right)/L$$

$$C_4 = \frac{P_1 - P_2}{L}\left[z_{v1}c_{pL}\mu_{dL} + \left(1 - z_{v1}\right)c_{pv}\mu_{dv}\right] + \frac{z_{v2} - z_{v1}}{L}Q + \frac{v_2 - v_1}{L}v_1 + gh/L - \frac{k\pi d_0}{m}T_1$$

$$C_5 = \frac{\left(z_{v2} - z_{v1}\right)\left(P_1 - P_2\right)}{L^2}\left[c_{pL}\mu_{dL} + c_{pv}\mu_{dv}\right] + \frac{v_2 - v_1}{L}$$

Flowing Temperature in (Horizontal]) Pipelines

- z_v = mole fraction of vapor (gas) in the gas-liquid flowstream
- P = pressure, lbf/ft^2
- L = pipeline length, ft
- v = fluid velocity, ft/sec
- c_p = fluid specific heat at constant pressure, Btu/lbm.ºF
- μ_d = Joule-Thomson coefficient, ft^2.ºF/lbf
- m = mass flow rate, lbm/sec
- Q = phase-transition heat, Btu/lbm
- k = thermal conductivity, Btu/ft.sec.ºf
- g = gravitational acceleration, equal to 32.17 ft/sec^2
- h = elevation difference between the inlet and outlet, ft
- d_o = outside pipe diameter, ft
- Ts = temperature of the soil or surroundings, of

SUMMARY OF PRESSURE DROP EQUATIONS

Equation	Application
General Flow	Fundamental flow equation using friction or transmission factor; used with Colebrook-White friction factor or AGA transmission factor
Colebrook-White	Friction factor calculated for pipe roughness and Reynolds number; most popular equation for general gas transmission pipelines
Modified Colebrook-White	Modified equation based on U.S. Bureau of Mines experiments; gives higher pressure drop compared to original Colebrook equation
AGA	Transmission factor calculated for partially turbulent and fully turbulent flow considering roughness, bend index, and Reynolds number

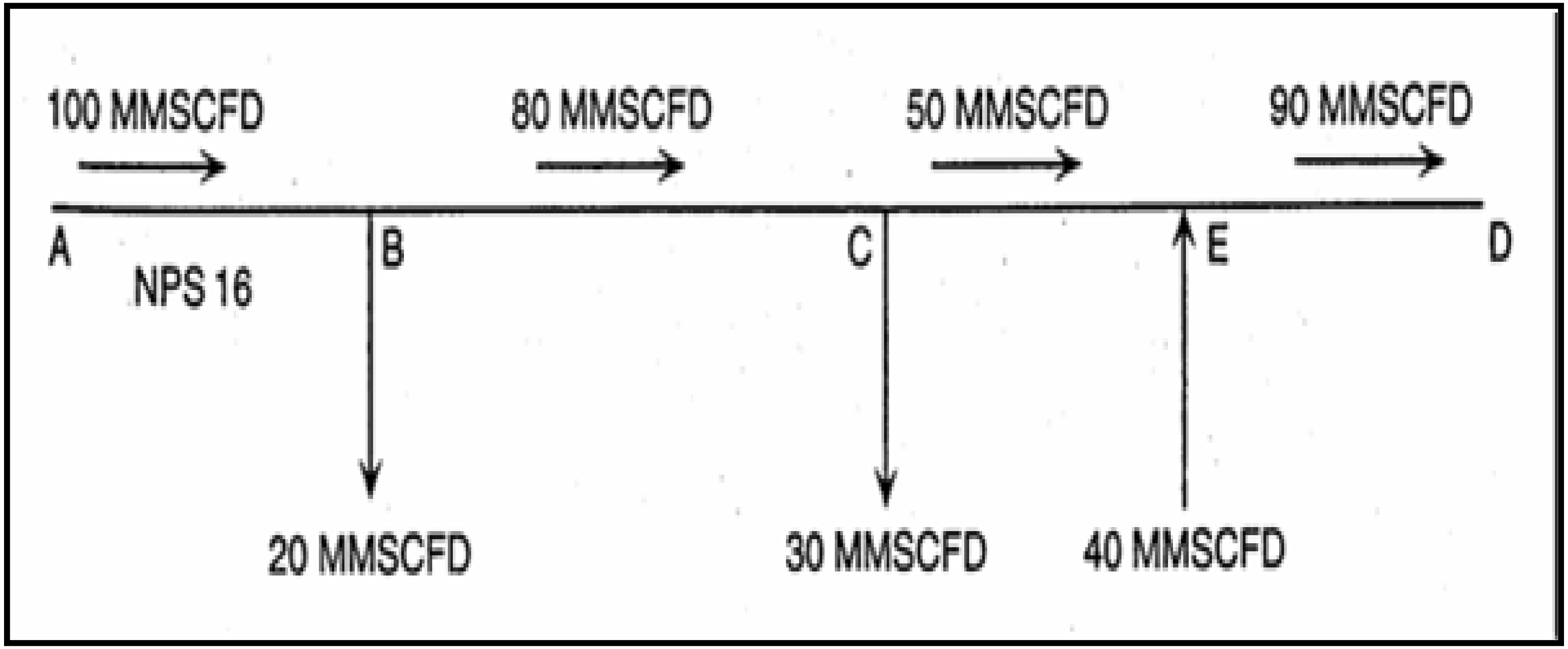
SUMMARY OF PRESSURE DROP EQUATIONS

Equation	Application
Panhandle A Panhandle B	Panhandle equations do not consider pipe roughness; instead. an efficiency factor is used; less conservative than Colebrook or AGA
Weymouth	Does not consider pipe roughness; uses an efficiency factor used for high-pressure gas gathering systems; most conservative equation that gives highest pressure drop for given flow rate
IGT	Does not consider pipe roughness; uses an efficiency factor used on gas distribution piping

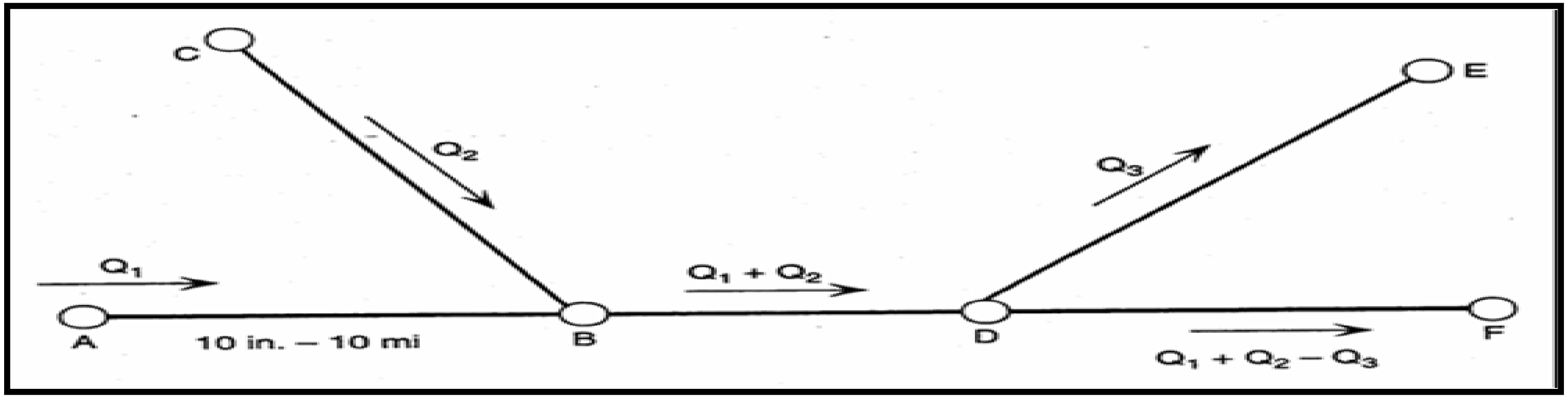
PIPELINE WITH INTERMEDIATE INJECTIONS AND DELIVERIES

- A pipeline in which gas enters at the beginning of the pipeline and the same volume exits at the end of the pipeline is a pipeline with no intermediate injection or deliveries
- When portions of the inlet volume are delivered at various points along the pipeline and the remaining volume is delivered at the end of the pipeline, we call this system a pipeline with intermediate delivery points.

PIPELINE WITH INTERMEDIATE INJECTIONS AND DELIVERIES

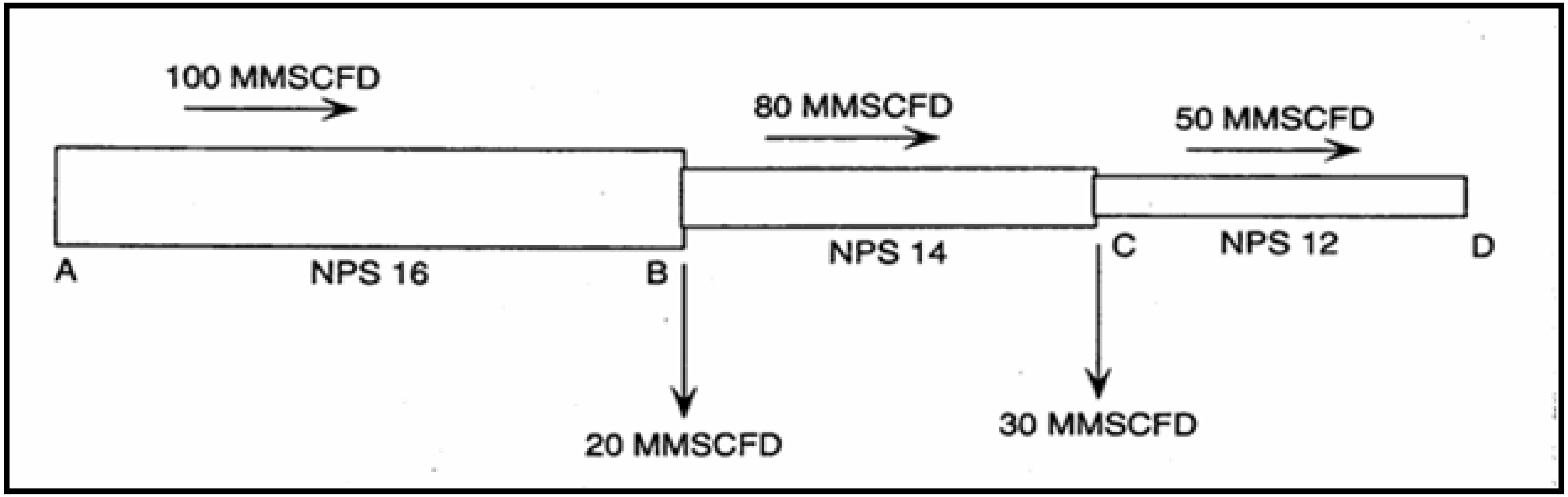


PIPELINE WITH INTERMEDIATE INJECTIONS AND DELIVERIES



- Pipe AB has a certain volume, Q1, flowing through it.
- At point B, another pipeline, CB, brings in additional volumes resulting in a volume of (Q_1 + Q_2) flowing through section BD.
- At D, a branch pipe, DE, delivers a volume of Q_3 to a customer location, E.
- The remaining volume (Q_1 + Q_2 - Q_3) flows from D to F through pipe segment DF to a customer location at F.

SERIES PIPING



- Segment 1 - diameter d_1 and length Le_1
- Segment 2 - diameter d_2 and length Le_2
- Segment 3 - diameter d_3 and length Le_3

$$L_e = L_{e1} + L_{e2} + L_{e3}$$

SERIES PIPING

$$\Delta P_{sq} = \frac{CL}{d^5}$$

- ΔP_{sq} = difference in the square of pressures ($P_1^2 - P_2^2$) for the pipe segment
- C = constant
- L = pipe length
- d = pipe inside diameter

SERIES PIPING

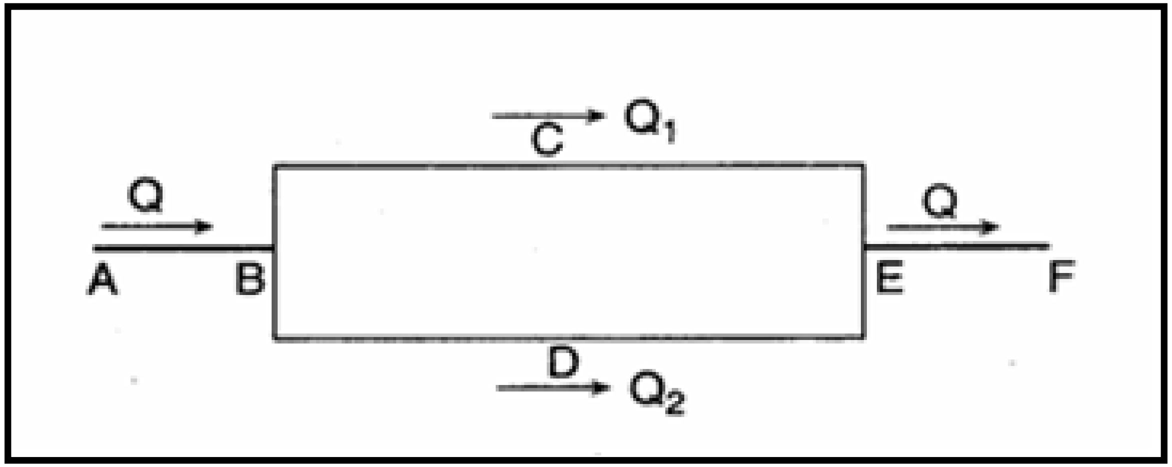
$$\frac{CL_1}{d_1^5} = \frac{CL_{e2}}{d_2^5}$$

$$L_{e2} = L_2 \left(\frac{d_1}{d_2} \right)^5$$

$$L_{e3} = L_3 \left(\frac{d_1}{d_3} \right)^5$$

$$L_e = L_1 + L_2 \left(\frac{d_1}{d_2} \right)^5 + L_3 \left(\frac{d_1}{d_3} \right)^5$$

PARALLEL PIPING



$Q = Q_1 + Q_2$

where

Q = inlet flow at A

Q_1 = flow through pipe branch BCE

Q_2 = flow through pipe branch BDE

PARALLEL PIPING

$$\left(P_B^2 - P_E^2\right) = \frac{K_1 L_1 Q_1^2}{d_1^5} \qquad \left(P_B^2 - P_E^2\right) = \frac{K_2 L_2 Q_2^2}{d_2^5}$$

$$\frac{Q_1}{Q_2} = \left(\frac{L_2}{L_1}\right)^{0.5} \left(\frac{d_1}{d_2}\right)^{2.5}$$

where

- K_1, K_2 = a parameter that depends on gas properties, gas temperature, etc.
- L_1 , L_2 = length of pipe branch BCE, BDE
- d_1, d_2 = inside diameter of pipe branch BCE, BDE
- Q_1 , Q_2 = flow rate through pipe branch BCE, BDE

PARALLEL PIPING

$$\left(P_B^2 - P_E^2\right) = \frac{K_e L_e Q^2}{d_e^5}$$

$$\frac{K_1 L_1 Q_1^2}{d_1^5} = \frac{K_2 L_2 Q_2^2}{d_2^5} = \frac{K_e L_e Q^2}{d_e^5}$$

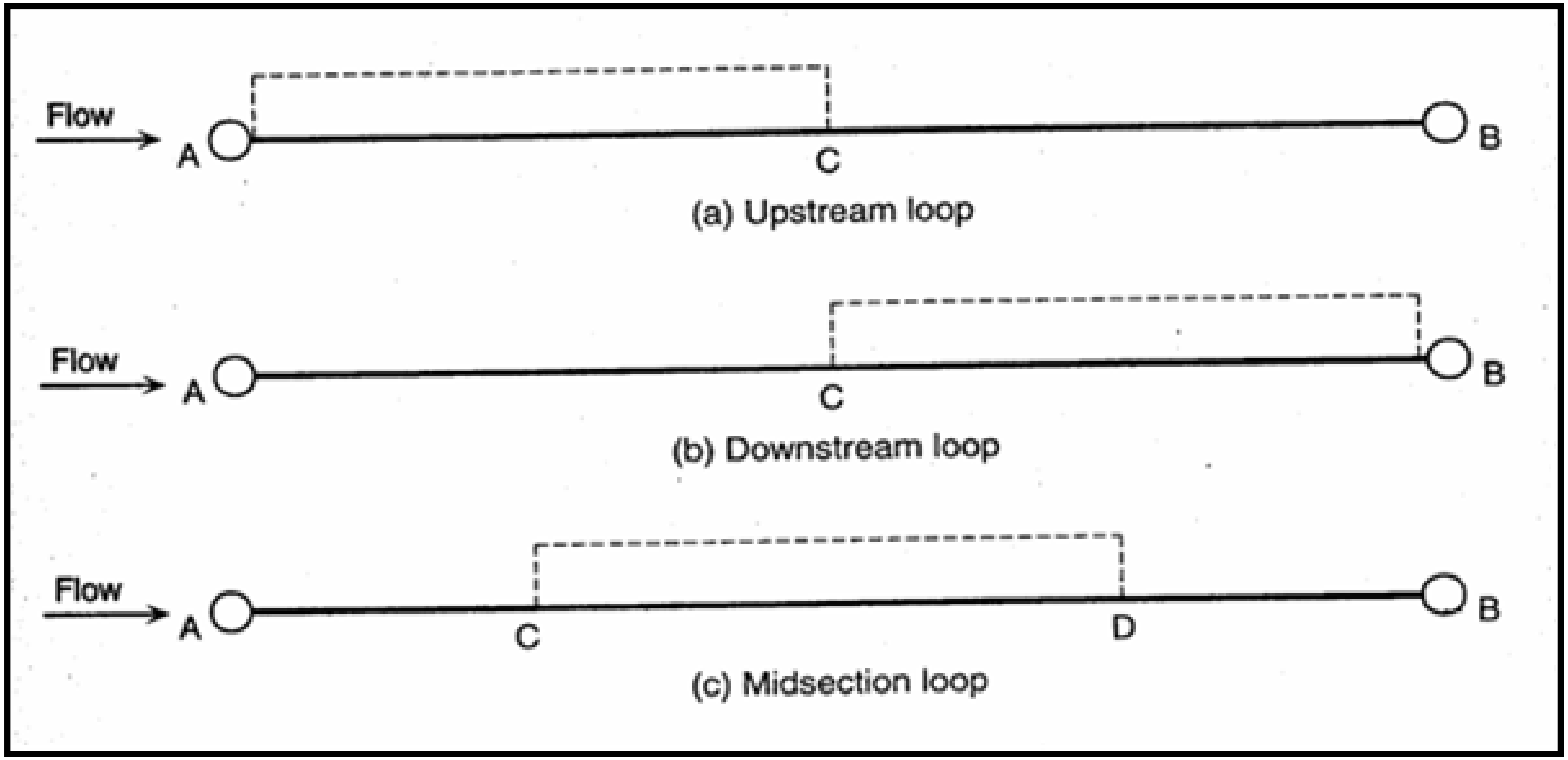
$$\frac{L_1 Q_1^2}{d_1^5} = \frac{L_2 Q_2^2}{d_2^5} = \frac{L_e Q^2}{d_e^5}$$

$$d_e = d_1 \left[\left(\frac{1 + const_1}{const_1}\right)^2\right]^{1/5}$$

$$const_1 = \sqrt{\left(\frac{d_1}{d_2}\right)^5 \left(\frac{L_1}{L_2}\right)}$$

$Q_1 = Q\ const_1/(1 + const_1)$

LOCATING PIPE LOOP



Different looping scenarios

Summary

- This part introduced the various methods of calculating the pressure drop in a pipeline transporting gas and gas mixtures.
- The more commonly used equations for pressure drop vs. flow rate and pipe size
- The effect of elevation changes and the concepts of the Reynolds number, friction factor, and transmission factor were introduced.
- The importance of the Moody diagram and how to calculate the friction factor for laminar and turbulent flow were explained.
- Comparison of the more commonly used pressure drop equations, such as AGA, Colebrook-White, Weymouth, and Panhandle equations.
- The use of a pipeline efficiency in comparing various equations
- The average velocity of gas flow and the limiting value of erosional velocity was discussed.

Summary

- Several piping configurations, such as pipes in series, pipes in parallel, and gas pipelines with injections and deliveries
- The concepts of equivalent length in series piping and equivalent diameter in pipe loops were explained and illustrated using example problems.
- The hydraulic pressure gradient and the need for intermediate compressor stations to transport given volumes of gas without exceeding allowable pipeline pressures were also covered.
- The importance of temperature variation in gas pipelines and how it is taken into account in calculating pipeline pressures were introduced with reference to commercial hydraulic simulation models..