ME 423: FLUIDS ENGINEERING

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Pressure Drop

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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

Panhandle A Equation

The **Panhandle A Equation** was developed for use in natural gas pipelines, incorporating an **efficiency factor, *E*** for Reynolds numbers in the range of 5 to 11 million ($5x10^6$ - $11x10^6$).

In this equation, the pipe roughness is not used. The general form of the Panhandle A equation is expressed in USCS units as follows:

$$Q = 435.87E\left(\frac{T_b}{P_b}\right)^{1.0788}\left(\frac{P_1^2 - e^s P_2^2}{G^{0.8539} T_f L_e Z}\right)^{0.5394} D^{2.6182} \quad \text{(USCS units)} \qquad (2.55)$$

where

- Q = volume flow rate, standard ft³/day (SCFD)
- E = pipeline efficiency, a decimal value less than 1.0
- 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 flow temperature, °R (460 + °F)
- L_e = equivalent length of pipe segment, mi → $L_e = \dfrac{L(e^s - 1)}{s}$ (2.9)
- Z = gas compressibility factor, dimensionless
- D = pipe inside diameter, in.

$$s = \text{elevation adjustment parameter} = 0.0375G\left(\frac{H_2 - H_1}{T_f Z}\right) \qquad (2.10)$$

Panhandle A Equation

Since the gas gravity is several orders of magnitude lower that the liquid, the influence of elevation is generally insignificant in a pipeline that transports gas. And hence, in calculation of flow rate/pressure drop, elevation difference in not being considered (in general).

Accordingly, the **Panhandle A** equation takes the following form:

$$Q = 435.87E\left(\frac{T_b}{P_b}\right)^{1.0788}\left(\frac{P_1^2 - P_2^2}{G^{0.8539}T_f LZ}\right)^{0.5394} D^{2.6182} \qquad \text{(USCS units)}$$

where

Q = volume flow rate, standard ft³/day (SCFD)
E = pipeline efficiency, a decimal value less than 1.0
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 flow temperature, °R (460 + °F)
L = length of pipe segment, mi
Z = gas compressibility factor, dimensionless
D = pipe inside diameter, in.

$$L_e = \frac{L(e^s - 1)}{s} \Rightarrow \frac{L_e}{L} = \lim_{s \to 0}\frac{e^s - 1}{s}$$

$$\Rightarrow \frac{L_e}{L} = \lim_{s \to 0}\frac{e^s}{1} = 1 \qquad \text{(L'Hospital rule)}$$

$$\therefore L_e = L$$

Panhandle A Equation

By comparing the **Panhandle A equation** with **General Flow equation**, an equivalent transmission factor in USCS units can be calculated as follows:

$$F = 7.2111E\left(\frac{QG}{D}\right)^{0.07305} \quad \text{(USCS)} \qquad (2.57)$$

$$Q = 435.87E\left(\frac{T_b}{P_b}\right)^{1.0788}\left(\frac{P_1^2 - P_2^2}{G^{0.8539}T_f LZ}\right)^{0.5394} D^{2.6182} \quad \text{(USCS units)}$$

Panhandle A Eq.

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

General Flow Eq.

Panhandle B Equation

The **Panhandle B equation**, also known as the revised Panhandle equation, is used in large diameter, high pressure transmission lines. In fully turbulent flow, it is found to be accurate for values of **Reynolds number in the range of 4 to 40 million** (4×10^6 - 40×10^6).

This equation in USCS units is as follows:

$$Q = 737E\left(\frac{T_b}{P_b}\right)^{1.02}\left(\frac{P_1^2 - e^s P_2^2}{G^{0.961} T_f L_e Z}\right)^{0.51} D^{2.53} \qquad \text{(USCS units)} \qquad (2.59)$$

Neglecting the elevation difference, **Panhandle B equation** takes the following form:

$$Q = 737E\left(\frac{T_b}{P_b}\right)^{1.02}\left(\frac{P_1^2 - P_2^2}{G^{0.961} T_f L Z}\right)^{0.51} D^{2.53} \qquad \text{(USCS units)}$$

Panhandle B Equation

In **SI units**, **Panhandle equation** takes the following form:

$$Q = 4.5965 \times 10^{-3} E \left(\frac{T_b}{P_b}\right)^{1.0788} \left(\frac{P_1^2 - e^s P_2^2}{G^{0.8539} T_f L_e Z}\right)^{0.5394} D^{2.6182} \quad \text{(SI units)} \qquad (2.56)$$

Panhandle A Eq.

$$Q = 1.002 \times 10^{-2} E \left(\frac{T_b}{P_b}\right)^{1.02} \left(\frac{P_1^2 - e^s P_2^2}{G^{0.961} T_f L_e Z}\right)^{0.51} D^{2.53} \quad \text{(SI units)} \qquad (2.60)$$

Panhandle B Eq.

where

Q = gas flow rate, standard m^3/day
E = pipeline efficiency, a decimal value less than 1.0
T_b = base temperature, K (273 + °C)
P_b = base pressure, kPa
T_f = average gas flow temperature, K (273 + °C)
P_1 = upstream pressure, kPa (absolute)
P_2 = downstream pressure, kPa (absolute)
L_e = equivalent length of pipe segment, km
Z = gas compressibility factor at the flowing temperature, dimensionless

Other symbols are as defined previously.

Problem

Example 15

Using the Panhandle A equation, calculate the outlet pressure in a natural gas pipeline, NPS 16 with 0.250 in. wall thickness, 15 miles long. The gas flow rate is 100 MMSCFD at an inlet pressure of 1000 psia. The gas gravity = 0.6 and viscosity = 0.000008 lb/ft-sec. The average gas temperature is 80°F. Assume base pressure = 14.73 psia and base temperature = 60°F. For compressibility factor Z, use the CNGA method. Assume pipeline efficiency of 0.92.

Solution:

The average pressure, P_{avg}, needs to be calculated before the compressibility factor Z can be determined. Since the inlet pressure P_1 = 1,000 psia, and the outlet pressure P_2 is unknown, we will have to assume a value of P_2 (such as 800 psia) and calculate P_{avg} and then calculate the value of Z. Once Z is known, from the Panhandle A equation we can calculate the outlet pressure P_2. Using this value of P_2, a better approximation for Z is calculated from a new P_{avg}. This process is repeated until successive values of P_2 are within allowable limits, such as 0.5 psia.

Assume P_2 = 800 psia. The average pressure comes as:

$$P_{avg} = \frac{2}{3}\left(1000 + 800 - \frac{1000 \times 800}{1000 + 800}\right) = 903.7 \text{ psia}$$

Problem

Now, calculate the compressibility factor, Z using the CNGA method;

$$Z = \frac{1}{\left[1 + \left(\frac{P_{avg} \times 344400(10)^{1.785G}}{T_f^{\ 3.825}}\right)\right]} \; ; \; P_{avg} \text{ in Psig} \qquad (1.34)$$

$$\Rightarrow Z = \frac{1}{\left[1 + \frac{(903.7 - 14.73) \times 344400(10)^{1.785 \times 0.6}}{(80+460)^{3.825}}\right]} = 0.8869$$

Use Panhandle A equation & neglecting elevation difference

$$Q = 435.87E\left(\frac{T_b}{P_b}\right)^{1.0788}\left(\frac{P_1^2 - P_2^2}{G^{0.8539}T_f LZ}\right)^{0.5394} D^{2.6182} \qquad \text{(USCS units)}$$

$$\Rightarrow 100 \times 10^6 = 435.87 \times 0.92\left(\frac{60+460}{14.73}\right)^{1.0788}\left(\frac{1000^2 - P_2^2}{(0.6)^{0.8539}(80+460)(15)(0.8869)}\right)^{0.5394}(16 - 0.25 \times 2)^{2.6182} \qquad \text{(USCS units)}$$

→ $P_2 = 968.02 \text{ psia}$ $\quad P_2\big|_{\text{assumed}} = 800 \text{ psia}$ $\quad \Delta P_2 = 168.02 \text{ psia, too big!!}$

Problem

Use this new P_2 for next iteration;

$$P_{avg} = \frac{2}{3}\left(1000 + 968.02 - \frac{1000 \times 968.02}{1000 + 968.02}\right) = 984.10\,\text{psia}$$

$$\therefore\ Z = \frac{1}{\left[1 + \dfrac{(984.10 - 14.73) \times 344400(10)^{1.785\times 0.6}}{(80+460)^{3.825}}\right]} = 0.8780$$

Use Panhandle A equation & neglecting elevation difference

$$Q = 435.87E\left(\frac{T_b}{P_b}\right)^{1.0788}\left(\frac{P_1^2 - P_2^2}{G^{0.8539}T_f LZ}\right)^{0.5394} D^{2.6182} \qquad \text{(USCS units)}$$

$$\Rightarrow 100\times 10^6 = 435.87\times 0.92\left(\frac{60+460}{14.73}\right)^{1.0788}\left(\frac{1000^2 - P_2^2}{(0.6)^{0.8539}(80+460)(15)(0.8780)}\right)^{0.5394}(16 - 0.25\times 2)^{2.6182} \qquad \text{(USCS units)}$$

→ $P_2 = 968.35$ psia

$P_2\big|_{\text{last iter}} = 968.02$ psia

$\Delta P_2 = 0.33$ psia < 0.5 psia (no further iteration)

$\therefore P_2 = 968.35$ psia Ans.

Problem

Using the **Panhandle B equation**, calculate the outlet pressure in a natural gas pipeline, NPS 16 with 0.250 in. wall thickness, 15 miles long. The gas flow rate is 100 MMSCFD at an inlet pressure of 1000 psia. The gas gravity = 0.6 and viscosity = 0.000008 lb/ft-sec. The average gas temperature is 80°F. Assume base pressure = 14.73 psia and base temperature = 60°F. For compressibility factor *Z*, use the CNGA method. Assume pipeline efficiency of 0.92.

Compare the result with that obtained from **Panhandle A equation**.

(Homework)

Summary table

DESCRIPTION	PANHANDLE A EQUATION	PANHANDLE B EQUATION
Published	Early 1940s	1956
Reynolds number range	5 – 11 Million	4 – 40 Million
Efficiency factor (E)	less than 1 and normally assumed as 0.92	less than 1 and generally varies between 0.88 – 0.94
Pipeline diameters	generally 12 – 60 inch (305 – 1524 mm)	generally used for larger pipelines > 36 inch (> 914 mm)
Pressure	around 800 – 1500 psia (5516 – 10342 kPa)	> 1000 psia (> 6895 kPa)

Other Flow Equations for Gas Transport in Pipeline

$$Q = 433.5E\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - e^s P_2^2}{GT_f L_e Z}\right)^{0.5} D^{2.667} \qquad (2.52)$$

Weymouth eq.

$$Q = 136.9E\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - e^s P_2^2}{G^{0.8} T_f L_e \mu^{0.2}}\right)^{0.555} D^{2.667} \quad \text{(USCS units)} \qquad (2.63)$$

Institute of Gas Technology (IGT) eq.

μ = gas viscosity, lb/ft-s

$$Q = 85.7368E\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - e^s P_2^2}{G^{0.7391} T_f L_e \mu^{0.2609}}\right)^{0.575} D^{2.725} \quad \text{(USCS units)} \qquad (2.69)$$

Mueller eq.

$$Q = 410.1688E\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - P_2^2}{G^{0.8587} T_f L_e}\right)^{0.538} D^{2.69} \quad \text{(USCS units)} \qquad (2.71)$$

Fritzsche eq.