ME 423: FLUIDS ENGINEERING

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Lecture-26-27 (30/11/2024)

Pressure Required to Transport

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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. A more complex case with gas flow into the pipeline (injection) at various points along its length combined with deliveries at other points is shown in Figure 3.1. In such a pipeline system, the pressure required at the beginning point A will be calculated by considering the pipeline broken into segments AB, BC, etc.

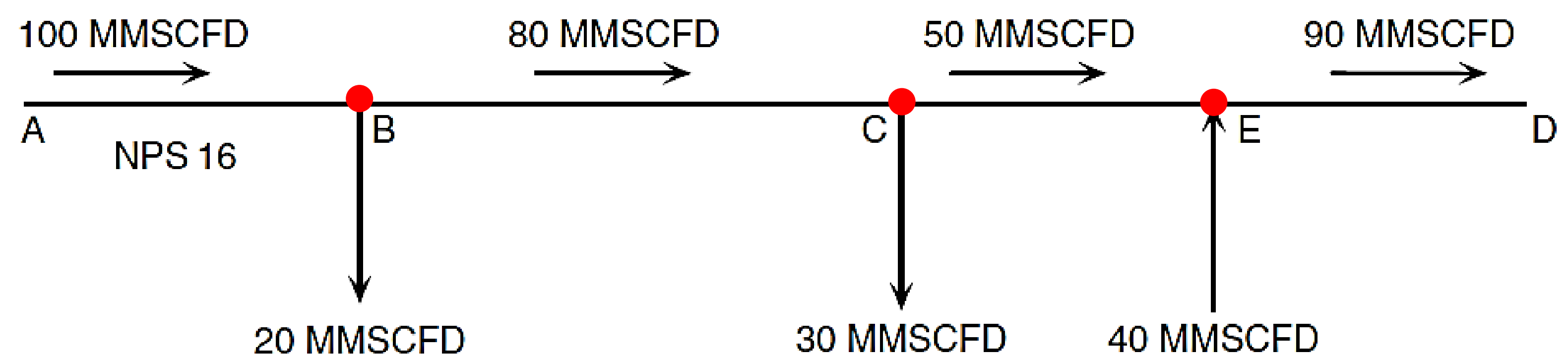


Figure 3.1 Pipeline with injection and deliveries.

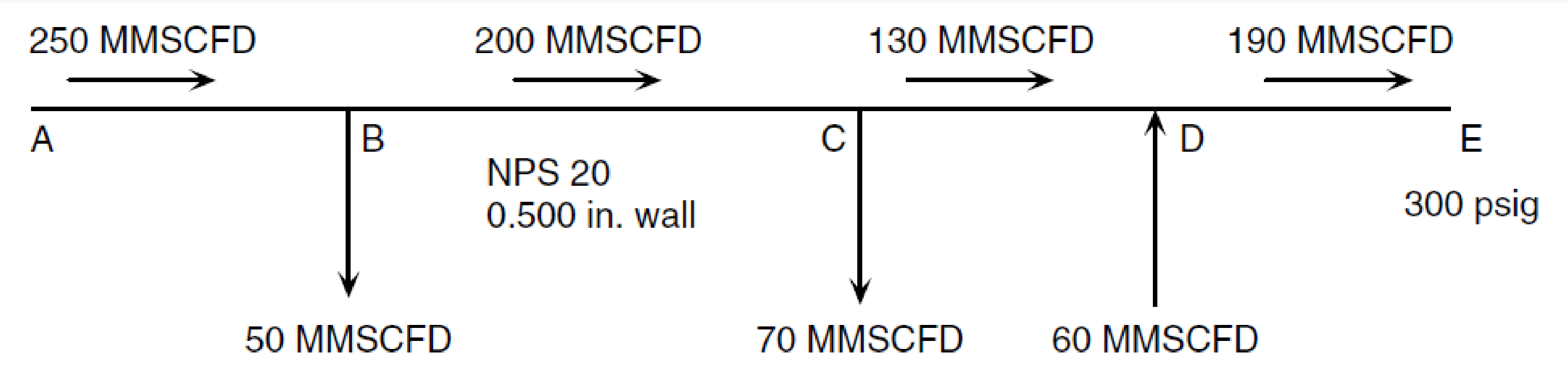
Problem

Example 2

A 150 mi long natural gas pipeline consists of several injections and deliveries as shown in Figure below. The pipeline is NPS 20, has 0.500 in. wall thickness, and has an inlet volume of 250 MMSCFD. At points B (milepost 20) and C (milepost 80), 50 MMSCFD and 70 MMSCFD, respectively, are delivered. At D (milepost 100), gas enters the pipeline at 60 MMSCFD. All streams of gas may be assumed to have a specific gravity of 0.65 and a viscosity of 8.0×10^{-6} lb/ft-s. The pipe is internally coated (to reduce friction), resulting in an absolute roughness of 150 μ in. Assume a constant gas flow temperature of 60°F and base pressure and base temperature of 14.7 psia and 60°F, respectively. Use a constant compressibility factor of 0.85 throughout. Neglect elevation differences along the pipeline.

a) Using the AGA equation, calculate the pressures along the pipeline at points A, B, C, and D for a minimum delivery pressure of 300 psig at the terminus E. Assume a drag factor = 0.96.

b) What diameter pipe will be required for section DE if the required delivery pressure at E is increased to 500 psig? The inlet pressure at A remains the same as calculated above.



Solution:
(a)

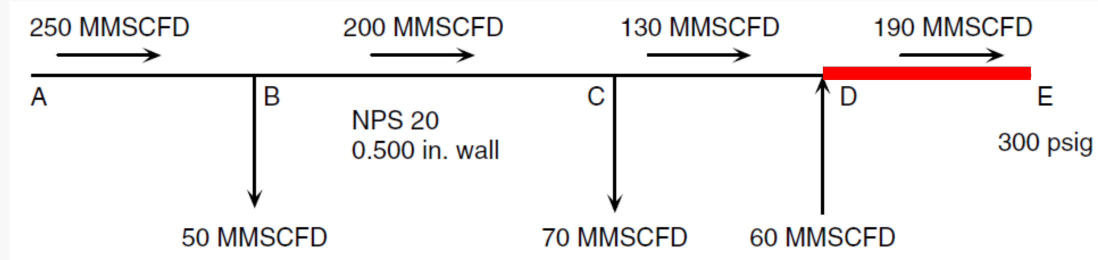
We will start calculations beginning with the last segment DE.

Pipe inside diameter $D = 20 - 2 \times 0.500 = 19.00$ in.

The flow rate in pipe DE is 190 MMSCFD.

Using Equation 2.34, the Reynolds number is

$$R = 0.0004778\left(\frac{14.7}{520}\right)\left(\frac{0.65\times190\times10^{6}}{8\times10^{-6}\times19}\right) = 10{,}974{,}469$$



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

$D = 20 - 2\times0.5 = 19$ in.

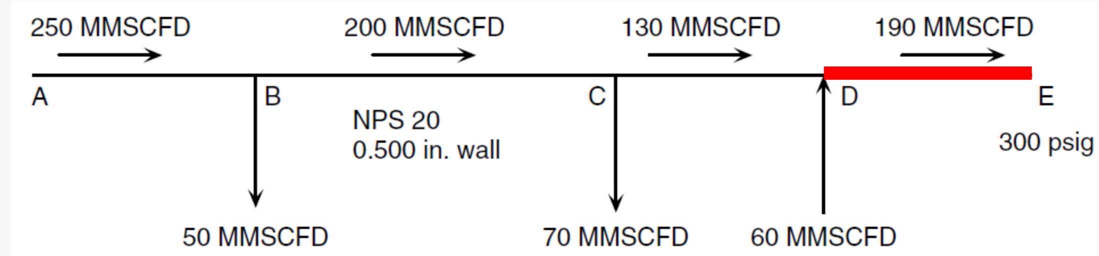
Next, calculate the two transmission factors required per AGA.

1) The fully turbulent transmission factor, using Equation 2.48, is

$$F = 4\text{Log}_{10}\left(\frac{3.7\times19}{150\times10^{-6}}\right) = 22.68$$

For the fully turbulent zone, AGA recommends using the following formula for F, based on relative roughness e/D and independent of the Reynolds number:

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



2) The smooth pipe zone Von Karman transmission factor, using Equation 2.50, is

$$F_t = 4\text{Log}_{10}\left(\frac{10{,}974{,}469}{F_t}\right) - 0.6$$

Solving for F_t by iteration, we get

$$F_t = 22.18$$

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

$$F = 4 \times 0.96\text{Log}_{10}\left(\frac{10{,}974{,}469}{1.4125 \times 22.18}\right) = 21.29$$

For the partially turbulent zone, F 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:

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

and

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

where

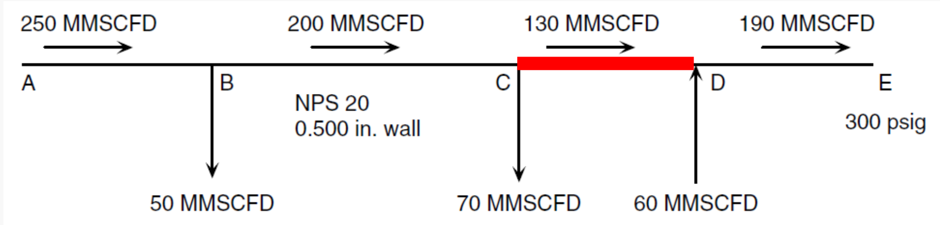
F_t = Von Karman smooth pipe transmission factor

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

Using the smaller of the two values, the AGA transmission factor is

$$F = 21.29$$

(among 22.68 & 21.29)



Next, we use General Flow Equation 2.4 to calculate the upstream pressure P_1 at D, based on a given downstream pressure of 300 psig at E.

$$190 \times 10^6 = 38.77 \times 21.29 \left(\frac{520}{14.7}\right)\left(\frac{P_1^2 - 314.7^2}{0.65 \times 520 \times 50 \times 0.85}\right)^{0.5} 19^{2.5}$$

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

Solving for P_1, we get the pressure at D as

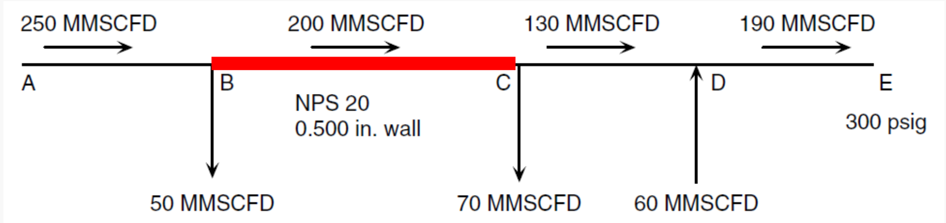
$$P_1 = 587.11 \text{ psia} = 572.41 \text{ psig} \quad (P_D)$$

Next, we consider the pipe segment CD, which has a flow rate of 130 MMSCFD. We calculate the pressure at C using the downstream pressure at D calculated above.

To simplify calculation, we will use the same AGA transmission factor we calculated for segment DE. A more nearly correct solution will be to calculate the Reynolds number and the two transmission factors as we did for the segment DE. However, for simplicity, we will use $F = 21.29$ for all pipe segments.

Applying General Flow Equation 2.4, we calculate the pressure P_1 at C as follows:

$$130\times10^6 = 38.77\times21.29\left(\frac{520}{14.7}\right)\left(\frac{P_1^2-587.11^2}{0.65\times520\times20\times0.85}\right)^{0.5}(19.0)^{2.5}$$



Solving for P_1, we get the pressure at C as

$$P_1 = 625.06 \text{ psia} = 610.36 \text{ psig}$$

(P_C)

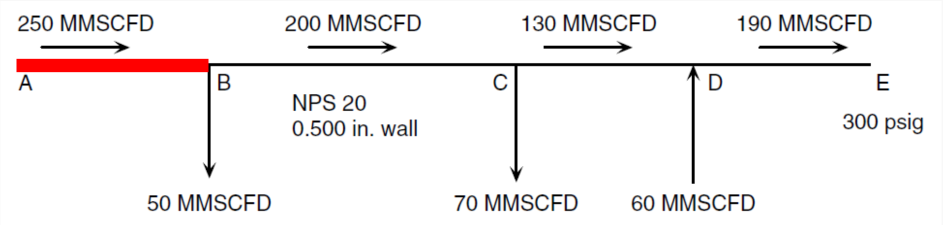
Similarly, we calculate the pressure at B, considering the pipe segment BC that flows 200 MMSCFD.

$$200\times10^6 = 38.77\times21.29\left(\frac{520}{14.7}\right)\left(\frac{P_1^2-625.06^2}{0.65\times520\times60\times0.85}\right)^{0.5}(19.0)^{2.5}$$

Solving for P_1, we get the pressure at B as

$$P_1 = 846.95 \text{ psia} = 832.25 \text{ psig}$$

(P_B)



Finally, for pipe segment AB that flows 250 MMSCFD, we calculate the pressure P_1 at A as follows:

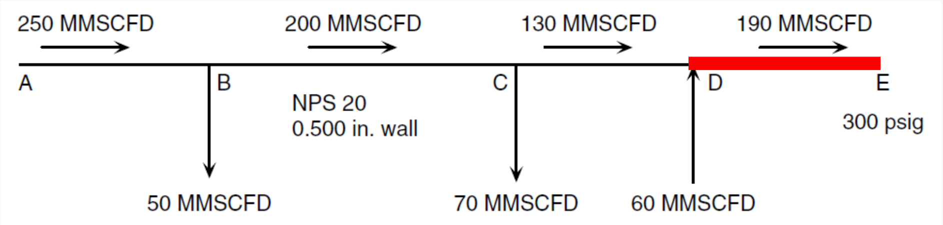
$$250\times10^6 = 38.77\times21.29\left(\frac{520}{14.7}\right)\left(\frac{P_1^2-846.95^2}{0.65\times520\times20\times0.85}\right)^{0.5}(19.0)^{2.5}$$

Solving for P_1, we get the pressure at A as

$$P_1 = 942.04 \text{ psia} = 927.34 \text{ psig}$$

(P_A)

(b)



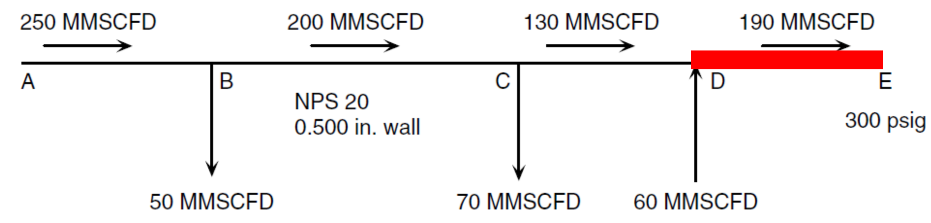
If we maintain the same inlet pressure, 927.34 psig, at A and increase the delivery pressure at E to 500 psig, we can determine the pipe diameter required for section DE by considering the same upstream pressure of 572.41 psig at D, as we calculated before.

Therefore, for segment DE,

$$\text{Upstream pressure } P_1 = 572.41 + 14.7 = 587.11 \text{ psia}$$

$$\text{Downstream pressure } P_2 = 500 + 14.7 = 514.7 \text{ psia}$$

Using General Flow Equation 2.4, with the same AGA transmission factor as before, we get



$$190\times10^{6}=38.77\times21.29\left(\frac{520}{14.7}\right)\left(\frac{587.11^{2}-514.7^{2}}{0.65\times520\times50\times0.85}\right)^{0.5}(D)^{2.5}$$

Solving for the inside diameter D of pipe DE, we get

$$D = 23.79 \text{ in.}$$

The nearest standard pipe size is NPS 26 with 0.500 in. wall thickness. This will give an inside diameter of 25 in., which is slightly more than the required minimum of 23.79 in. calculated above.

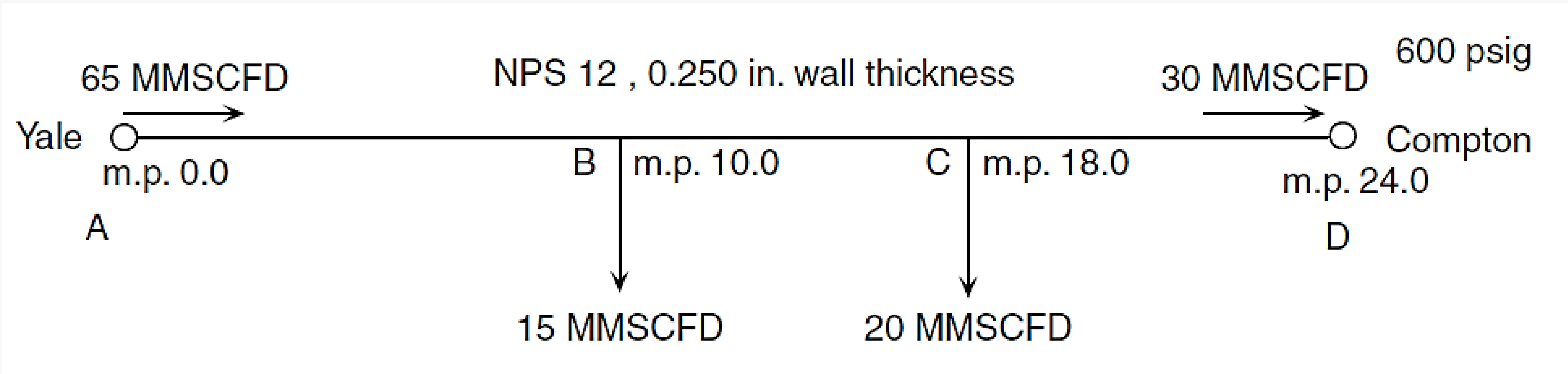
The wall thickness required for this pipe diameter and pressure will be dictated by the pipe material and is the subject of Chapter 6.

Pipeline with intermediate injections and deliveries

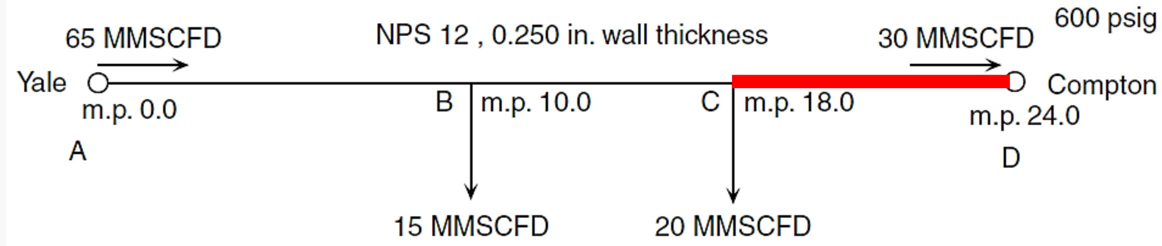
Example 4 (p-102)

A natural gas distribution piping system consists of NPS 12 with 0.250 in. wall thickness, 24 mi long, as shown in Figure below. At *Yale*, an inlet flow rate of 65 MMSCFD of natural gas enters the pipeline at 60°F. At the *Compton terminus*, gas must be supplied at a flow rate of 30 MMSCFD at a minimum pressure of 600 psig. There are intermediate deliveries of 15 MMSCFD at *milepost 10* and 20 MMSCFD at *milepost 18*. **What is the required inlet pressure at *Yale*?** Use a constant friction factor of 0.01 throughout. The compressibility factor can be assumed to be 0.94. The gas gravity and viscosity are 0.6 and 7×10^{-6} lb/ft-s, respectively. Assume isothermal flow at 60°F. The base temperature and base pressure are 60°F and 14.7 psia, respectively.

If the delivery volume at B is increased to 30 MMSCFD and other deliveries remain the same, what increased pressure is required at *Yale* to maintain the same flow rate and delivery pressure at Compton? Neglect elevation differences along the pipeline.



Solution:



Inside diameter of pipe = 12.75 – 2 × 0.250 = 12.25 in.

Friction factor $f = 0.01$

$$F = \frac{2}{\sqrt{0.01}} = 20.00$$

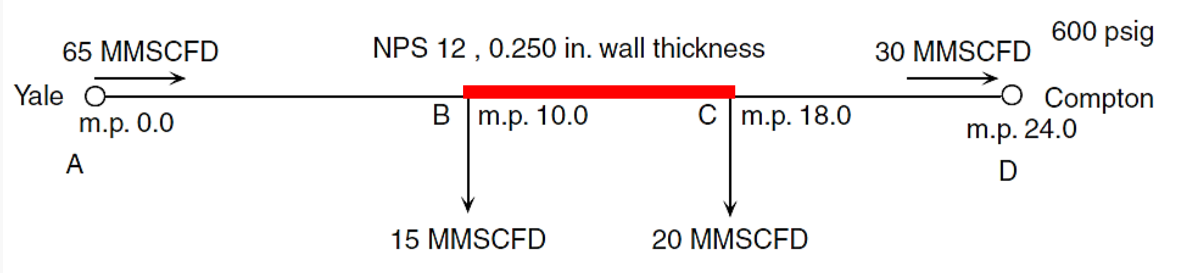
Using General Flow Equation 2.7, for the last pipe segment from milepost 18 to milepost 24, we get

$$30 \times 10^6 = 38.77 \times 20.0 \left(\frac{520}{14.7} \right) \left[\frac{P_C^2 - 614.7^2}{0.6 \times 520 \times 6 \times 0.94} \right]^{0.5} \times (12.25)^{2.5}$$

Solving for the pressure at C,

$$P_C = 620.88 \text{ psia}$$

Next we will use this pressure P_C to calculate the pressure P_B for the 8 mi section of pipe segment BC flowing 50 MMSCFD.

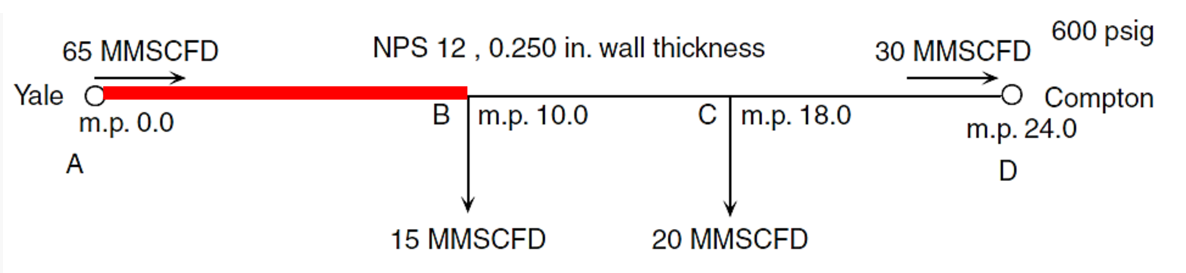


Using General Flow Equation 2.7,

$$50\times10^6 = 38.77\times20\left(\frac{520}{14.7}\right)\left[\frac{P_B^2-620.88^2}{0.6\times520\times8\times0.94}\right]^{0.5}\times(12.25)^{2.5}$$

$$P_B = 643.24 \text{ psia}$$

Finally, we calculate the pressure P_1 at Yale by considering the 10 mi pipe segment from Yale to point B that flows 65 MMSCFD.

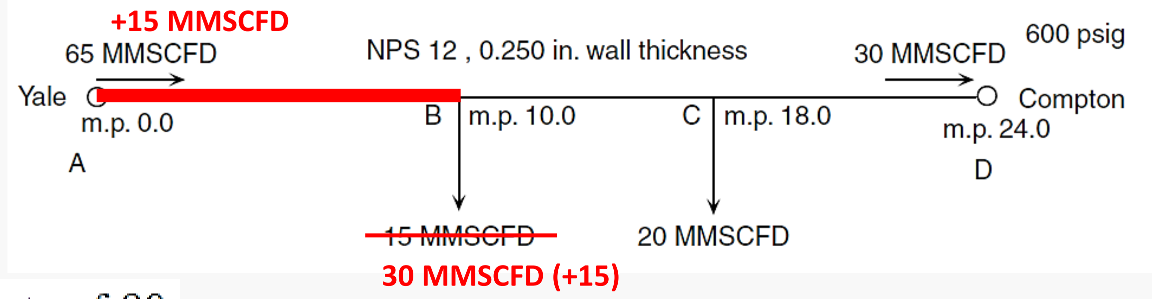


$$65\times10^6 = 38.77\times20\left(\frac{520}{14.7}\right)\left[\frac{P_1^2-643.24^2}{0.6\times520\times10\times0.94}\right]^{0.5}\times(12.25)^{2.5}$$

$$P_1 = 688.09 \text{ psia} = 673.39 \text{ psig}$$

Therefore, the required inlet pressure at Yale is 673.39 psig.

When the delivery volume at B is increased from 15 to 30 MMSCFD and all other delivery volumes remain the same, the inlet flow rate at Yale will increase to 65 + 15 = 80 MMSCFD. If the delivery pressure at Compton is to remain the same as before, the pressures at B and C will also be the same as calculated before, since the flow rate in BC and CD are the same as before. Therefore, we can recalculate the



inlet pressure for the pipe section from Yale to point B considering a flow rate of 80 MMSCFD that causes a pressure of 643.24 psia at B.

Using General Flow Equation 2.7, the pressure P_1 at Yale is

$$80 \times 10^6 = 38.77 \times 20.0 \left(\frac{520}{14.7} \right) \left[\frac{P_1^2 - 643.24^2}{0.6 \times 520 \times 10 \times 0.94} \right]^{0.5} \times (12.25)^{2.5}$$

$$P_1 = 710.07 \text{ psia} = 695.37 \text{ psig}$$

Therefore, increasing the delivery volume at B by 15 MMSCFD causes the pressure at Yale to increase by approximately 22 psig.

Series Piping

In the preceding discussions we assumed the pipeline to have the same diameter throughout its length. There are situations where a gas pipeline can consist of different pipe diameters connected together in a series. This is especially true when the **different pipe segments are required to transport different volumes of gas**, as shown in Figure 3.5.

In Figure 3.5, section AB with a diameter of 16 in. is used to transport a volume of 100 MMSCFD, and after making a delivery of 20 MMSCFD at B, the remainder of 80 MMSCFD flows through the 14 in. diameter pipe BC. At C, a delivery of 30 MMSCFD is made, and the balance volume of 50 MMSCFD is delivered to the terminus D through a 12 in. pipeline CD.

It is clear that the pipe section AB flows the largest volume (100 MMSCFD), whereas the pipe segment CD transports the least volume (50 MMSCFD). Therefore, segments AB and CD, for **reasons of economy, should be of different pipe diameters**, as indicated in Figure 3.5. If we maintained the same pipe diameter of 16 in. from A to D, it would be a waste of pipe material and, therefore, cost.

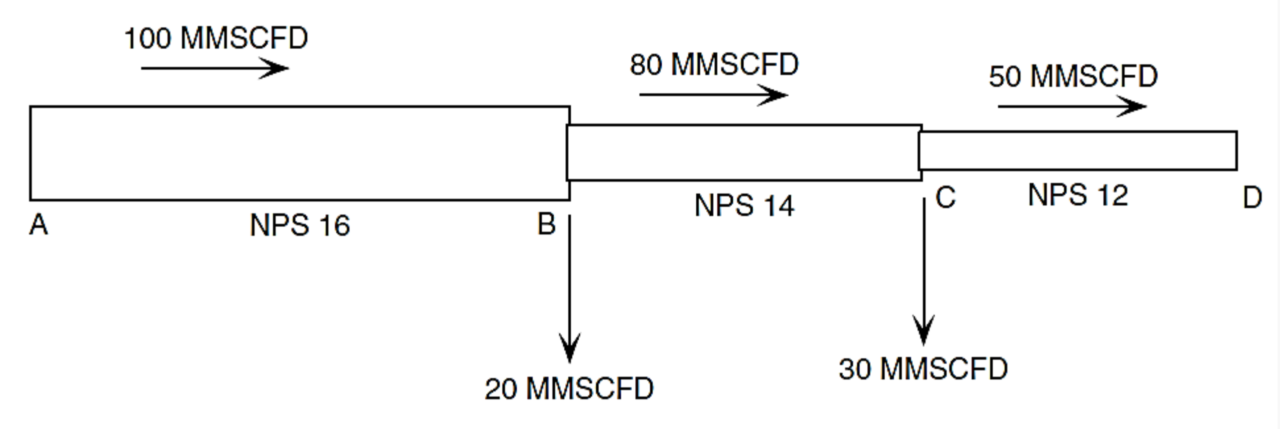


Figure 3.5 Series piping.

Series Piping

The ***equivalent length method*** can be applied when the **same uniform flow exists throughout the pipeline consisting of pipe segments of different diameter, with no intermediate deliveries or injections**.

Consider the same flow rate Q through all pipe segments. The first pipe segment has an inside diameter D_1 and length L_1, followed by the second segment of inside diameter D_2 and length L_2 and so on. We calculate the equivalent length of the second pipe segment based on the diameter D_1 **such that the pressure drop in the equivalent length matches that in the original pipe segment of diameter D_2.** The pressure drop in diameter D_2 and length L_2 equals the pressure drop in diameter D_1 and equivalent length Le_2. Thus, the second segment can be replaced with a piece of pipe of length Le_2 and diameter D_1.

Similarly, the third pipe segment with diameter D_3 and length L_3 will be replaced with a piece of pipe of Le_3 and diameter D_1. Thus, we have converted the three segments of pipe in terms of diameter D_1 as follows:

Segment 1 — diameter D_1 and length L_1
Segment 2 — diameter D_1 and length Le_2
Segment 3 — diameter D_1 and length Le_3

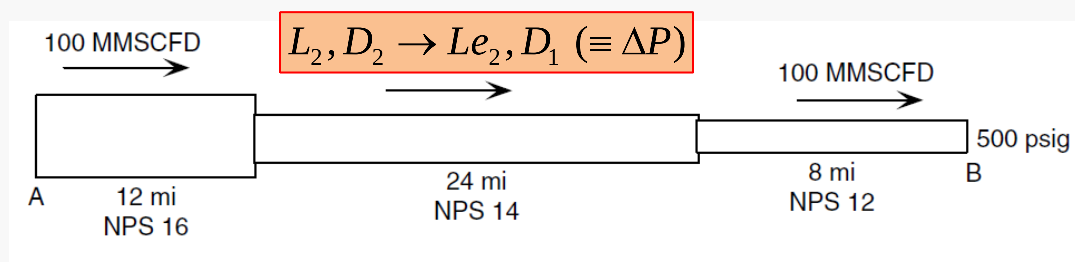


Figure 3.6 Example problem—series piping.

Series Piping

For convenience, we picked the diameter D_1 of segment 1 as the base diameter to use, to convert from the other pipe sizes. We now have the series piping system reduced to one constant-diameter (D_1) pipe of total equivalent length given by

$$Le = L_1 + Le_2 + Le_3 \qquad (3.1)$$

The pressure required at the inlet of this series piping system can then be calculated based on diameter D_1 and length Le. We will now explain how the equivalent length is calculated.

Upon examining General Flow Equation 2.7, we see that for the same flow rate and gas properties, neglecting elevation effects, the pressure difference ($P_1^2 - P_2^2$) is inversely proportional to the fifth power of the pipe diameter and directly proportional to the pipe length. Therefore, we can state that, approximately,

$$Q = 38.77F\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - e^s P_2^2}{GT_f L_e Z}\right)^{0.5} D^{2.5}$$

$$\Delta P_{sq} = \frac{CL}{D^5} \qquad (3.2)$$

where

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

Series Piping

From Equation 3.2 we conclude that the equivalent length for the same pressure drop is proportional to the fifth power of the diameter. Therefore, in the series piping discussed in the foregoing, the equivalent length of the second pipe segment of diameter D_2 and length L_2 is

$$\frac{CL_2}{D_2^5} = \frac{CLe_2}{D_1^5} \qquad (3.3)$$

or

$$Le_2 = L_2\left(\frac{D_1}{D_2}\right)^5 \qquad (3.4)$$

Similarly, for the third pipe segment of diameter D_3 and length L_3 , the equivalent length is

$$Le_3 = L_3\left(\frac{D_1}{D_3}\right)^5 \qquad (3.5)$$

$L_2, D_2 \rightarrow Le_2, D_1 \ (\equiv \Delta P)$

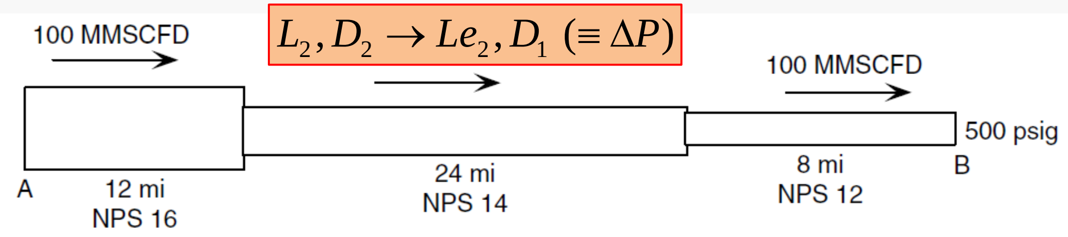


Figure 3.6 Example problem—series piping.

Series Piping

Therefore, the total equivalent length Le for all three pipe segments in terms of diameter D_1 is

$$Le = L_1 + L_2\left(\frac{D_1}{D_2}\right)^5 + L_3\left(\frac{D_1}{D_3}\right)^5 \qquad (3.6)$$

It can be seen from Equation 3.6 that if $D_1 = D_2 = D_3$, the total equivalent length reduces to $(L_1 + L_2 + L_3)$, as expected.

We can now calculate the pressure drop for the series piping system, considering a single pipe of length Le and uniform diameter D_1 flowing a constant volume Q.

Problem

Example 5

A series piping system, shown in Figure 3.6, consists of 12 mi of NPS 16, 0.375 in. wall thickness connected to 24 mi of NPS 14, 0.250 in. wall thickness and 8 miles of NPS 12, 0.250 in. wall thickness pipes. Calculate the inlet pressure required at the origin A of this pipeline system for a gas flow rate of 100 MMSCFD. Gas is delivered to the terminus B at a delivery pressure of 500 psig. The gas gravity and viscosity are 0.6 and 0.000008 lb/ft-s, respectively. The gas temperature is assumed constant at 60°F. Use a compressibility factor of 0.90 and the General Flow equation with Darcy friction factor = 0.02. The base temperature and base pressure are 60°F and 14.7 psia, respectively.

Compare results using the equivalent length method and with the more detailed method of calculating pressure for each pipe segment separately.

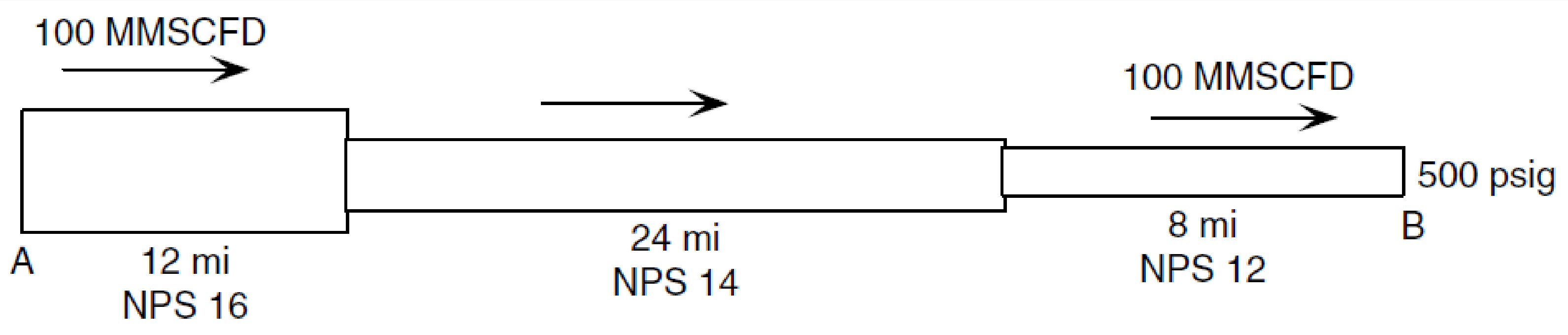


Figure 3.6 Example problem—series piping.

Solution:

Inside diameter of first pipe segment = 16 – 2 × 0.375 = 15.25 in.

Inside diameter of second pipe segment = 14 – 2 × 0.250 = 13.50 in.

Inside diameter of third pipe segment = 12.75 – 2 × 0.250 = 12.25 in.

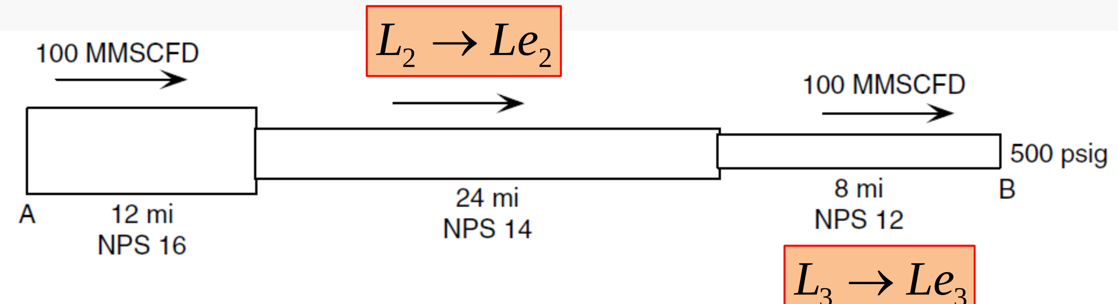


Figure 3.6 Example problem—series piping.

$$Le = L_1 + L_2\left(\frac{D_1}{D_2}\right)^5 + L_3\left(\frac{D_1}{D_3}\right)^5 \quad (3.6)$$

or $$Le = 12 + 24\times\left(\frac{15.25}{13.5}\right)^5 + 8\times\left(\frac{15.25}{12.25}\right)^5$$

or $$Le = 12 + 44.15 + 23.92 = 80.07 \text{ mi}$$

Therefore, we will calculate the inlet pressure P_1 considering a single pipe from A to B having a length of 80.07 mi and inside diameter of 15.25 in.

Outlet pressure = 500 + 14.7 = 514.7 psia

Using General Flow Equation 2.2, neglecting elevation effects and substituting given values, we get

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

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

$$100\times10^6 = 77.54\left(\frac{1}{\sqrt{0.02}}\right)\left(\frac{520}{14.7}\right)\left[\frac{\left(P_1^2 - 514.7^2\right)}{0.6\times520\times80.07\times0.9}\right]^{0.5} 15.25^{2.5}$$

$$P_1 = 994.77 \text{ psia} = 980.07 \text{ psig}$$

Next, we will compare the preceding result, using the equivalent length method, with the more detailed calculation of treating each pipe segment separately and adding the pressure drops.

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

Consider the 8 mi pipe segment 3 first, since we know the outlet pressure at B is 500 psig. Therefore, we can calculate the pressure at the beginning of segment 3 using General Flow Equation 2.2, as follows:

$$100\times10^6 = 77.54\left(\frac{1}{\sqrt{0.02}}\right)\left(\frac{520}{14.7}\right)\left[\frac{(P_1^2 - 514.7^2)}{0.6\times520\times8\times0.9}\right]^{0.5} 12.25^{2.5}$$

$$P_1 = 693.83 \text{ psia} = 679.13 \text{ psig}$$

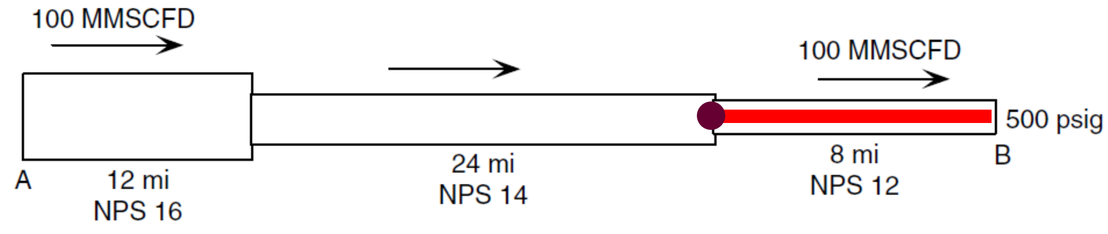


Figure 3.6 Example problem—series piping.

Next, consider pipe segment 2 (24 mi of NPS 14 pipe) and calculate the upstream pressure P_1 required for a downstream pressure of 679.13 psig, calculated in the preceding section. Using General Flow Equation 2.2 for pipe segment 2, we get

$$100\times10^6 = 77.54\left(\frac{1}{\sqrt{0.02}}\right)\left(\frac{520}{14.7}\right)\left[\frac{(P_1^2 - 693.83^2)}{0.6\times520\times24\times0.9}\right]^{0.5} 13.5^{2.5}$$

$$P_1 = 938.58 \text{ psia} = 923.88 \text{ psig}$$

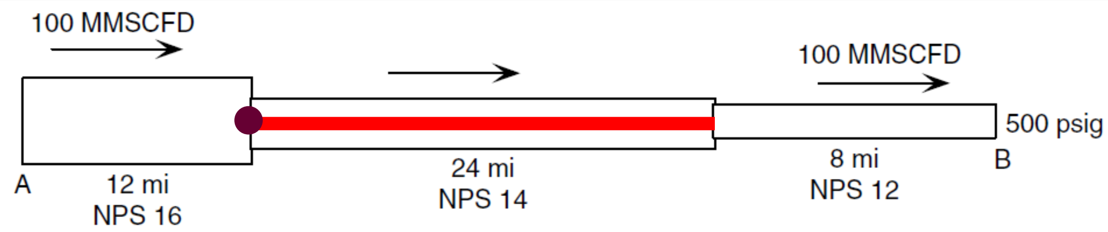


Figure 3.6 Example problem—series piping.

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

Next, we calculate the inlet pressure P_1 of pipe segment 1 (12 mi of NPS 16 pipe) for an outlet pressure of 923.88 psig, just calculated. Using the General Flow equation for pipe segment 1, we get

$$100\times10^6 = 77.54\left(\frac{1}{\sqrt{0.02}}\right)\left(\frac{520}{14.7}\right)\left[\frac{\left(P_1^2 - 938.58^2\right)}{0.6\times520\times12\times0.9}\right]^{0.5} 15.25^{2.5}$$

$$P_1 = 994.75 \text{ psia} = 980.05 \text{ psig}$$

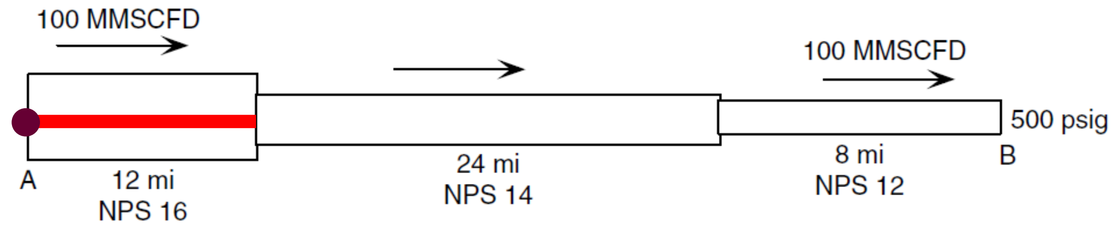


Figure 3.6 Example problem—series piping.

This compares well with the pressure of 980.07 psig we calculated earlier using the equivalent length method.

Parallel Piping

Sometimes two or more pipes are connected such that the gas flow splits among the branch pipes and eventually combines downstream into a single pipe, as illustrated in Figure 3.7. Such a piping system is referred to as ***parallel pipes***. It is also called a **looped piping system**, where each parallel pipe is known as a loop.

The reason for installing parallel pipes or loops is

- to reduce pressure drop in a certain section of the pipeline due to pipe pressure limitation or
- for increasing the flow rate in a bottleneck section.

By installing a pipe loop from B to E, in Figure 3.7 we are effectively reducing the overall pressure drop in the pipeline from A to F, since between B and E the flow is split through two pipes.

In Figure 3.7 we will assume that the entire pipeline system is in the horizontal plane with no changes in pipe elevations. Gas enters the pipeline at A and flows through the pipe segment AB at a flow rate of Q. At the junction B, the gas flow splits into the two parallel pipe branches BCE and BDE at the flow rates of Q_1 and Q_2, respectively.
At E, the gas flows recombine to equal the initial flow rate Q and continue flowing through the single pipe EF.

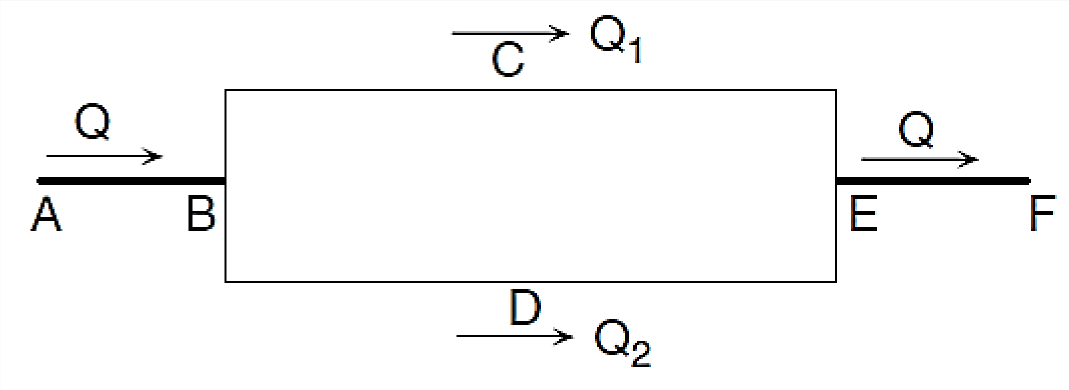


Figure 3.7

Parallel Piping

In order to calculate the pressure drop due to friction in the parallel piping system, we follow two main principles of parallel pipes.

- The first principle is that of ***conservation of flow at any junction point***.
- The second principle is that ***there is a common pressure across each parallel pipe***.

Applying the principle of **flow conservation**, at junction B, the incoming flow into B must exactly equal the total outflow at B through the parallel pipes. Therefore, at junction B,

$$Q = Q_1 + Q_2 \qquad (3.7)$$

where

Q = inlet flow at A

Q_1 = flow through pipe branch BCE

Q_2 = flow through pipe branch BDE

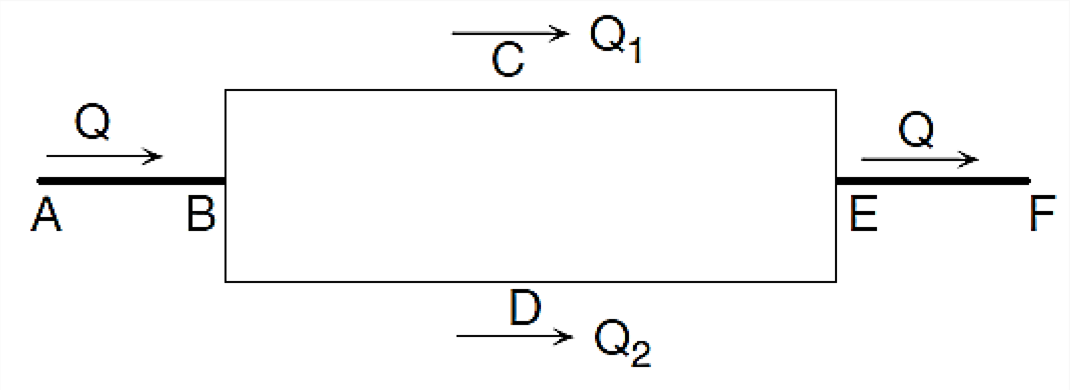


Figure 3.7

Parallel Piping

According to the second principle of parallel pipes, the pressure drop in pipe branch BCE must equal the pressure drop in pipe branch BDE. This is due to the fact that both pipe branches have a common starting point (B) and common ending point (E). Therefore, the pressure drop in the branch pipe BCE and branch pipe BDE are each equal to $(P_B - P_E)$, where P_B and P_E are the pressures at junctions B and E, respectively.

Therefore, we can write

$$\Delta P_{BCE} = \Delta P_{BDE} = P_B - P_E \tag{3.8}$$

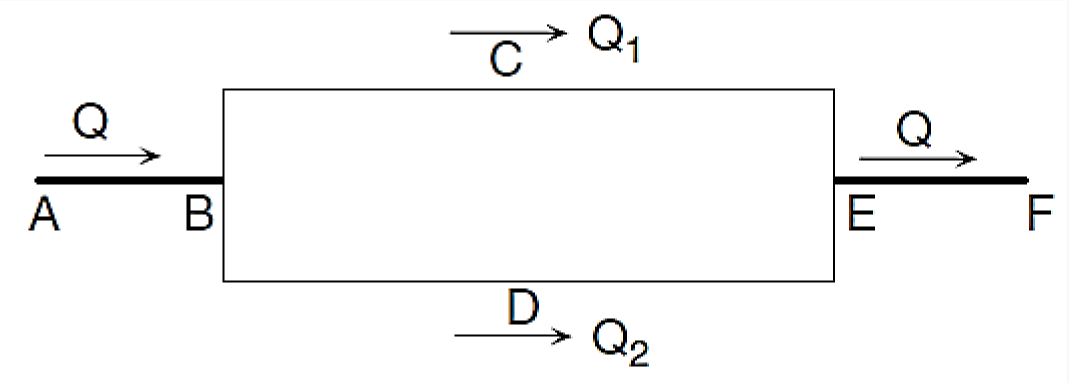


Figure 3.7

ΔP represents pressure drop, and ΔP_{BCE} is a function of the diameter and length of branch BCE and the flow rate Q_1. Similarly, ΔP_{BDE} is a function of the diameter and length of branch BDE and the flow rate Q_2.

Parallel Piping

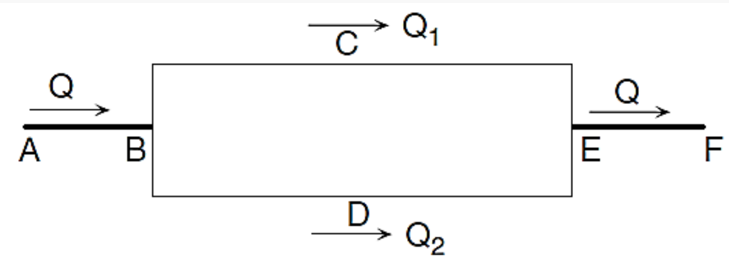
The pressure drop due to friction in branch BCE can be calculated from

$$\left(P_B^2 - P_E^2\right) = \frac{K_1 L_1 Q_1^2}{D_1^5} \qquad (3.10)$$

where

K_1 = a parameter that depends on gas properties, gas temperature, etc.
L_1 = length of pipe branch BCE
D_1 = inside diameter of pipe branch BCE
Q_1 = flow rate through pipe branch BCE

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



Similarly, the pressure drop due to friction in branch BDE is calculated from

$$\left(P_B^2 - P_E^2\right) = \frac{K_2 L_2 Q_2^2}{D_2^5} \qquad (3.11)$$

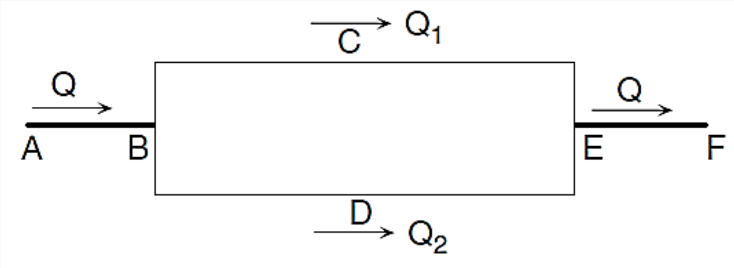
where

K_2 = a constant like K_1
L_2 = length of pipe branch BDE
D_2 = inside diameter of pipe branch BDE
Q_2 = flow rate through pipe branch BDE

Parallel Piping

In Equation 3.10 and Equation 3.11, the constants K_1 and K_2 are equal, since they do not depend on the diameter or length of the branch pipes BCE and BDE. Combining both equations, we can state the following for common pressure drop through each branch:

$$\frac{L_1 Q_1^2}{D_1^5} = \frac{L_2 Q_2^2}{D_2^5} \quad (3.12)$$



Simplifying further, we get the following relationship between the two flow rates Q_1 and Q_2:

$$\frac{Q_1}{Q_2} = \left(\frac{L_2}{L_1}\right)^{0.5} \left(\frac{D_1}{D_2}\right)^{2.5} \quad (3.13)$$

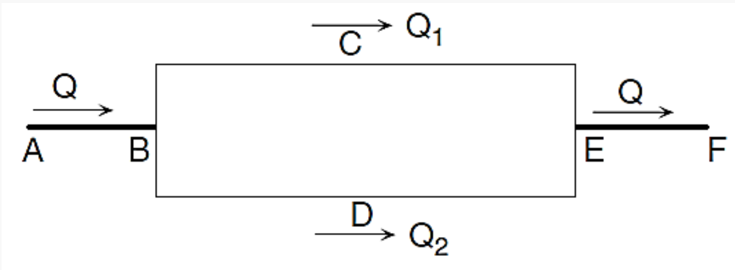
Parallel Piping

Another method of calculating pressure drops in parallel pipes is using the equivalent diameter.

In this method, we replace the pipe loops BCE and BDE with a certain length of an equivalent diameter pipe that has the same pressure drop as one of the branch pipes.

The equivalent diameter pipe can be calculated using the General Flow equation, as explained next. The equivalent pipe with the same ΔP that will replace both branches will have a diameter D_e and a length equal to one of the branch pipes, say L_e.

Since the pressure drop in the equivalent diameter pipe, which flows the full volume Q, is the same as that in any of the branch pipes, from Equation 3.10, we can state the following:



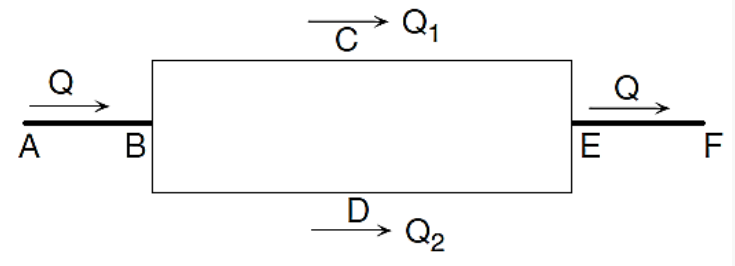
$$\left(P_B^2 - P_E^2\right) = \frac{K_e L_e Q^2}{D_e^5} \quad (3.14)$$

where $Q = Q_1 + Q_2$ from Equation 3.7 and K_e represents the constant for the equivalent diameter pipe of length L_e flowing the full volume Q.

Parallel Piping

Equating the value of $(P_B^2 - P_E^2)$ to the corresponding values, considering each branch separately, we get, using Equation 3.10, Equation 3.11, and Equation 3.14:

$$\frac{K_1 L_1 Q_1^2}{D_1^5} = \frac{K_2 L_2 Q_2^2}{D_2^5} = \frac{K_e L_e Q^2}{D_e^5} \qquad (3.15)$$



Also, setting $K_1 = K_2 = K_e$ and $L_e = L_1$, we simplify Equation 3.15 as follows:

$$\frac{L_1 Q_1^2}{D_1^5} = \frac{L_2 Q_2^2}{D_2^5} = \frac{L_1 Q^2}{D_e^5} \qquad (3.16)$$

Using Equation 3.16 in conjunction with Equation 3.7, we solve for the equivalent diameter D_e as

$$D_e = D_1 \left[\left(\frac{1 + Const1}{Const1} \right)^2 \right]^{1/5} \qquad (3.17)$$

where

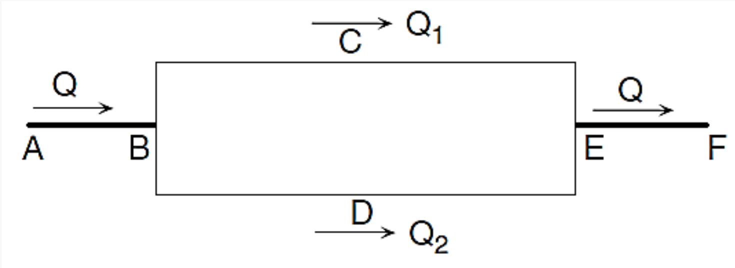
$$Const1 = \sqrt{\left(\frac{D_1}{D_2}\right)^5 \left(\frac{L_2}{L_1}\right)} \qquad (3.18)$$

Parallel Piping

and the individual flow rates Q_1 and Q_2 are calculated from

$$Q_1 = \frac{Q\,Const1}{1 + Const1} \quad (3.19)$$

$$Q_2 = \frac{Q}{1 + Const1} \quad (3.20)$$



Problem

Example 7

A gas pipeline consists of two parallel pipes, as shown in Figure 3.7. It is designed to operate at a flow rate of 100 MMSCFD. The first pipe segment AB is 12 miles long and consists of NPS 16, 0.250 in. wall thickness pipe. The loop BCE is 24 mi long and consists of NPS 14, 0.250 in. wall thickness pipe. The loop BDE is 16 miles long and consists of NPS 12, 0.250 in. wall thickness pipe. The last segment EF is 20 miles long and consists of NPS 16, 0.250 in. wall thickness pipe. Assuming a gas gravity of 0.6, calculate the outlet pressure at F and the pressures at the beginning and the end of the pipe loops and the flow rates through them. The inlet pressure at A = 1200 psig. The gas flowing temperature = 80°F, base temperature = 60°F, and base pressure = 14.73 psia. The compressibility factor $Z = 0.92$. Use the General Flow equation with Colebrook friction factor $f = 0.015$.

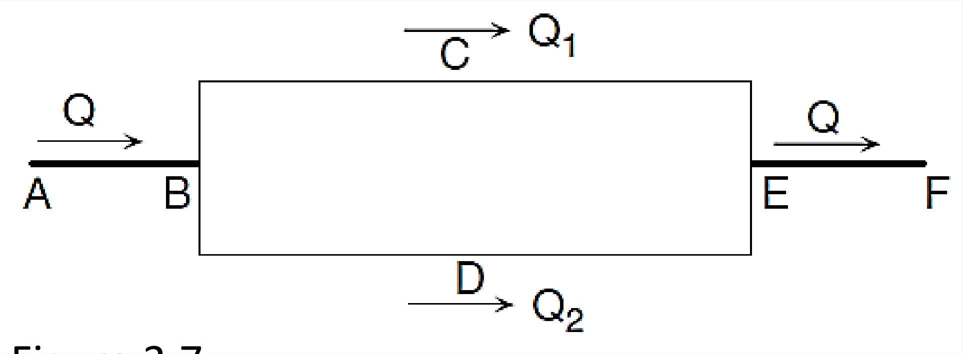


Figure 3.7

Solution:

From Equation 3.13, the ratio of the flow rates through the two pipe loops is given by

$$\frac{Q_1}{Q_2} = \left(\frac{16}{24}\right)^{0.5} \left(\frac{14 - 2 \times 0.25}{12.75 - 2 \times 0.25}\right)^{2.5} = 1.041$$

$$\frac{Q_1}{Q_2} = \left(\frac{L_2}{L_1}\right)^{0.5} \left(\frac{D_1}{D_2}\right)^{2.5} \qquad (3.13)$$

and from Equation 3.7

$$Q_1 + Q_2 = 100$$

Solving for Q_1 and Q_2, we get

$$Q_1 = 51.0\,\text{MMSCFD}$$

$$Q_2 = 49.0\,\text{MMSCFD}$$

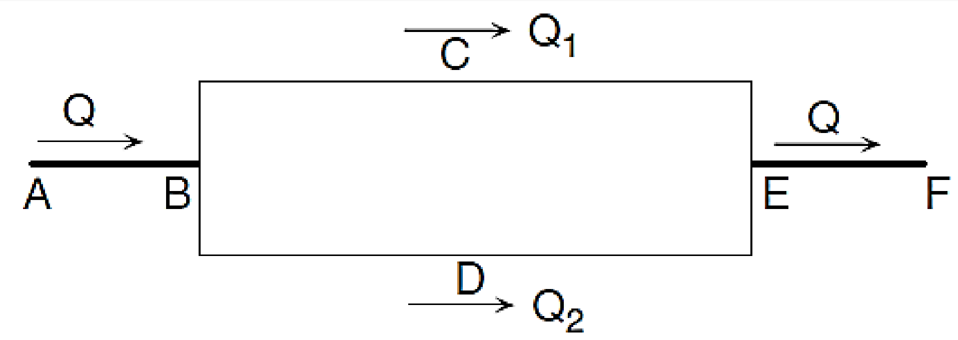


Figure 3.7

Next, considering the first pipe segment AB, we will calculate the pressure at B based upon the inlet pressure of 1200 psig at A, using General Flow Equation 2.2, as follows:

AB:

$$100\times10^{6}=77.54\left(\frac{1}{\sqrt{0.015}}\right)\left(\frac{520}{14.73}\right)\left[\frac{\left(1214.73^{2}-P_{2}^{2}\right)}{0.6\times540\times12\times0.92}\right]^{0.5}15.5^{2.5}$$

Solving for the pressure at B, we get

$$P_2 = 1181.33 \text{ psia} = 1166.6 \text{ psig} \quad (P_B)$$

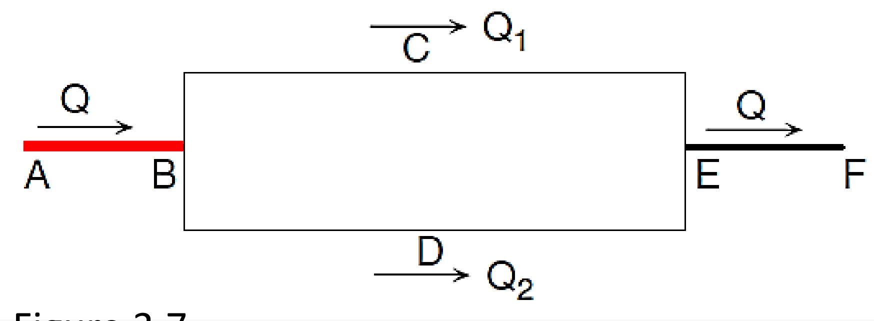


Figure 3.7

This is the pressure at the beginning of the looped section at B. Next we calculate the outlet pressure at E of pipe branch BCE, considering a flow rate of 51 MMSCFD through the NPS 14 pipe, starting at a pressure of 1181.33 psia at B.

Using the General Flow equation, we get

BCE:

$$51\times10^{6}=77.54\left(\frac{1}{\sqrt{0.015}}\right)\left(\frac{520}{14.73}\right)\left[\frac{\left(1181.33^{2}-P_{2}^{2}\right)}{0.6\times540\times24\times0.92}\right]^{0.5}13.5^{2.5}$$

Solving for the pressure at E, we get

$$P_2 = 1145.63 \text{ psia} = 1130.9 \text{ psig} \quad (P_E)$$

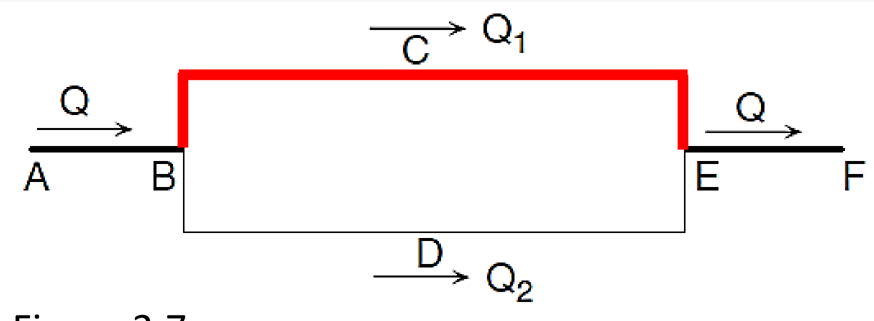


Figure 3.7

Next, we use this pressure as the inlet pressure for the last pipe segment EF and calculate the outlet pressure at F using the General Flow equation, as follows:

EF:

$$100\times10^6 = 77.54\left(\frac{1}{\sqrt{0.015}}\right)\left(\frac{520}{14.73}\right)\left[\frac{\left(1145.63^2 - P_2^{\,2}\right)}{0.6\times540\times20\times0.92}\right]^{0.5} 15.5^{2.5}$$

Solving for the outlet pressure at F, we get

$$P_2 = 1085.85 \text{ psia} = 1071.12 \text{ psig} \quad (P_F)$$

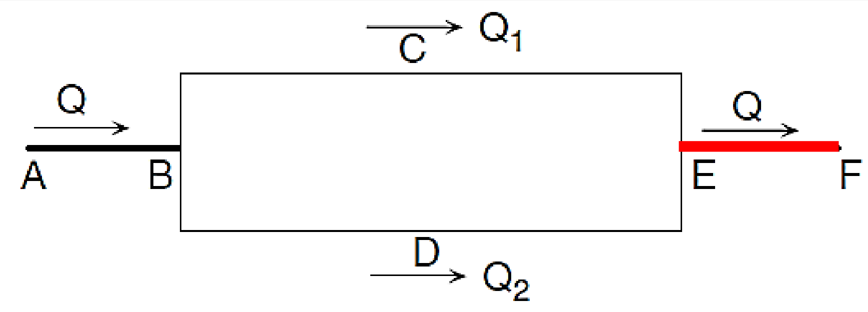


Figure 3.7

Check the solution of the problem using "equivalent pipe" method

(Homework)

Hydraulic Pressure Gradient

The ***hydraulic pressure gradient*** is a graphical representation of the gas pressures along the pipeline, as shown in Figure 3.9. The horizontal axis shows the distance along the pipeline starting at the upstream end. The vertical axis depicts the pipeline pressures.

Since pressure in a gas pipeline is nonlinear compared to liquid pipelines, the hydraulic gradient for a gas pipeline appears to be a slightly ***curved line*** instead of a straight line.

The slope of the hydraulic gradient at any point represents the pressure loss due to friction per unit length of pipe.

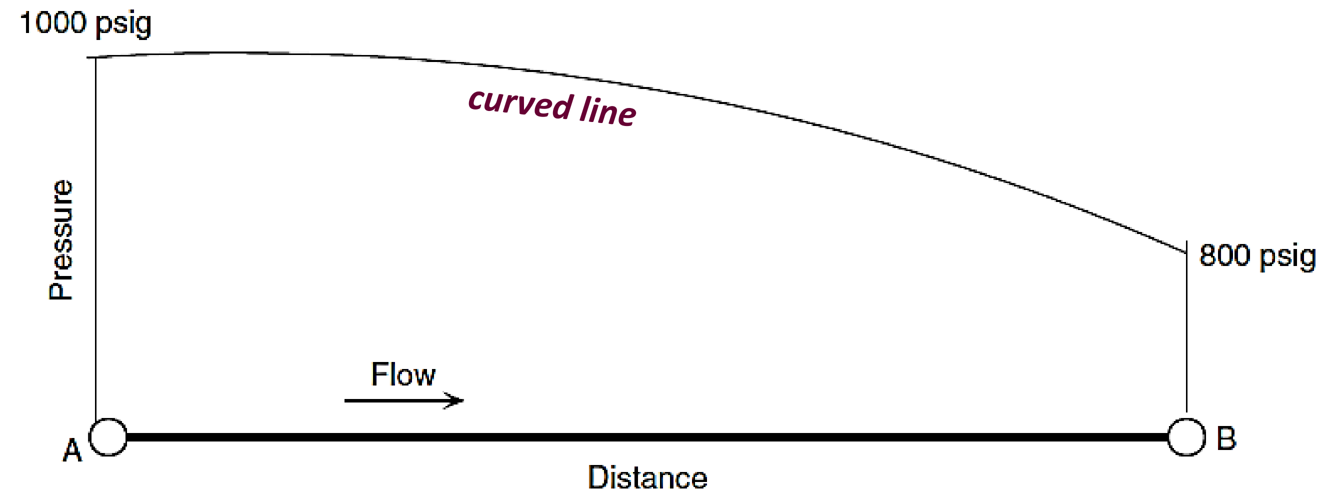


Figure 3.9 Hydraulic pressure gradient for uniform flow.

If the flow rate through the pipeline is a constant value (no intermediate injections or deliveries) and pipe size is uniform throughout, the hydraulic gradient appears to be a slightly curved line, as shown in Figure 3.9, with no appreciable breaks.

Hydraulic Pressure Gradient

If there are ***intermediate deliveries or injections along the pipeline***, the hydraulic gradient will be a **series of broken lines**, as indicated in Figure 3.10.

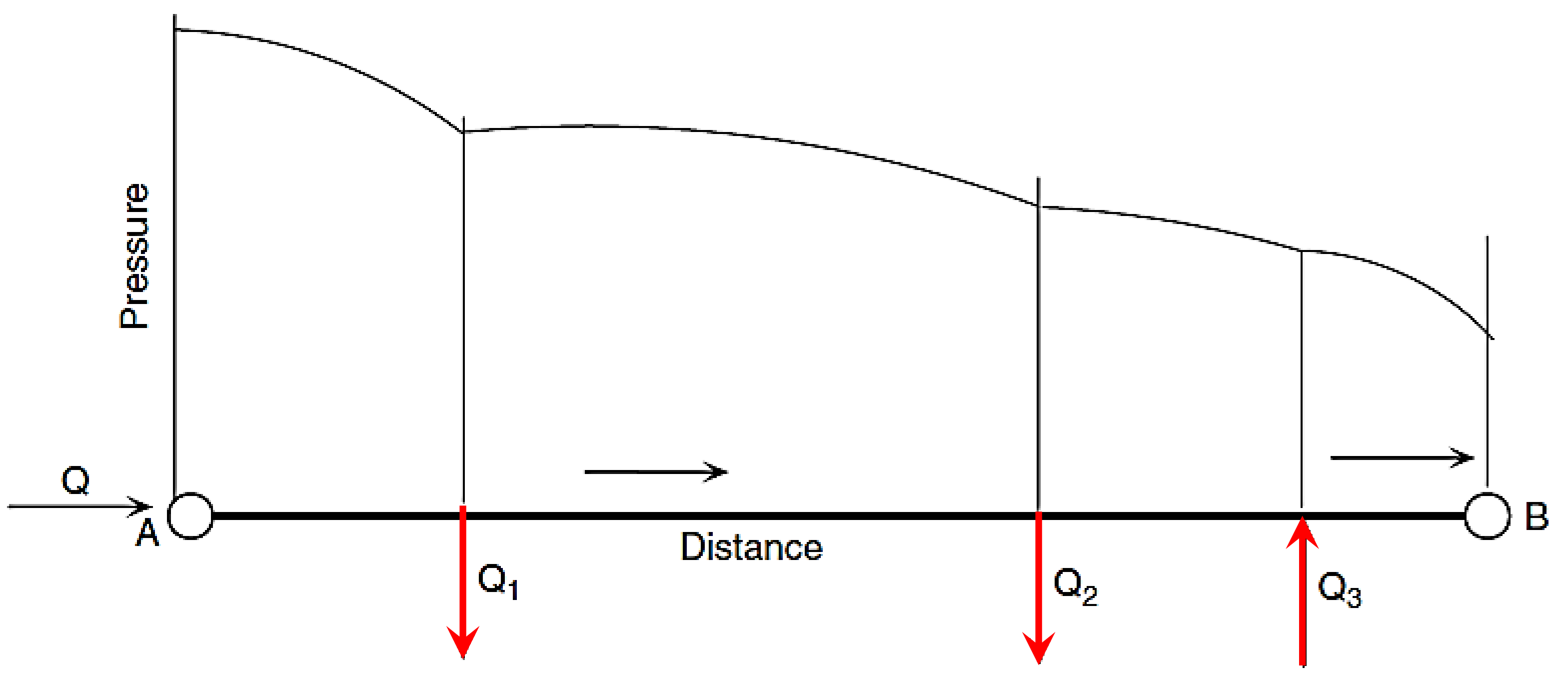


Figure 3.10 Hydraulic pressure gradient for deliveries and injections.

A similar broken hydraulic gradient can also be seen in the case of a pipeline with variable pipe diameters and wall thicknesses, even if the flow rate is constant. Unlike liquid pipelines, the breaks in hydraulic pressure gradient are not as conspicuous in gas pipelines.

In a long-distance gas pipeline, due to limitations of pipe pressure, intermediate **compressor stations** will be installed to **boost the gas pressure** to the required value so the gas can be delivered at the contract delivery pressure at the end of the pipeline.

Pressure Regulators

In a long-distance gas pipeline with intermediate delivery points, there may be a need to regulate the gas pressure at certain delivery points in order to satisfy the customer requirements.

Suppose the pressure at a delivery point is 800 psig, whereas the customer requirement is only 500 psig. Obviously, some means of **reducing the gas pressure** must be provided so that the customer can utilize the gas for his or her requirements at the correct pressure. This is achieved by means of a ***pressure regulator that will ensure a constant pressure downstream of the delivery point***, regardless of the pressure on the upstream side of the pressure regulator.

The flow rate from A to B is 100 MMSCFD, with an inlet pressure of 1200 psig at A. At B, gas is delivered into a branch line BE at the rate of 30 MMSCFD. The remaining volume of 70 MMSCFD is delivered to the pipeline terminus C at a delivery pressure of 600 psig. Based on the delivery pressure requirement of 600 psig at C and a takeoff of 30 MMSCFD at point B, the calculated pressure at B is 900 psig. Starting with 900 psig on the branch line at B, at 30 MMSCFD, gas is delivered to point E at 600 psig. If the actual requirement at E is only 400 psig, a pressure regulator will be installed at E to reduce the delivery pressure by 200 psig.

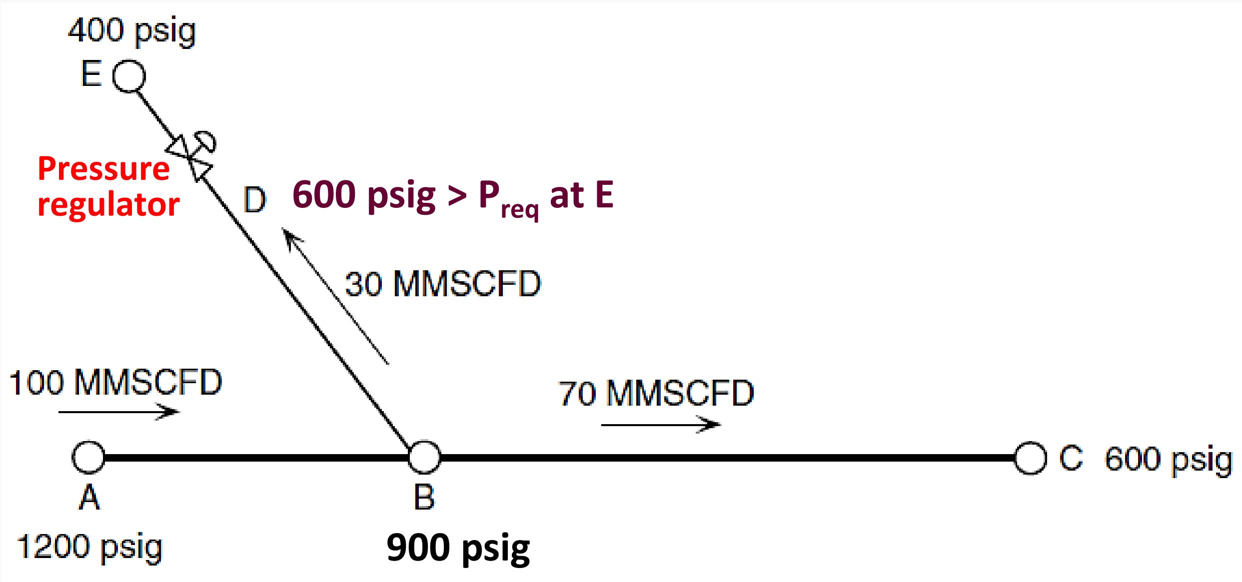


Fig. Pressure regulation

Problem

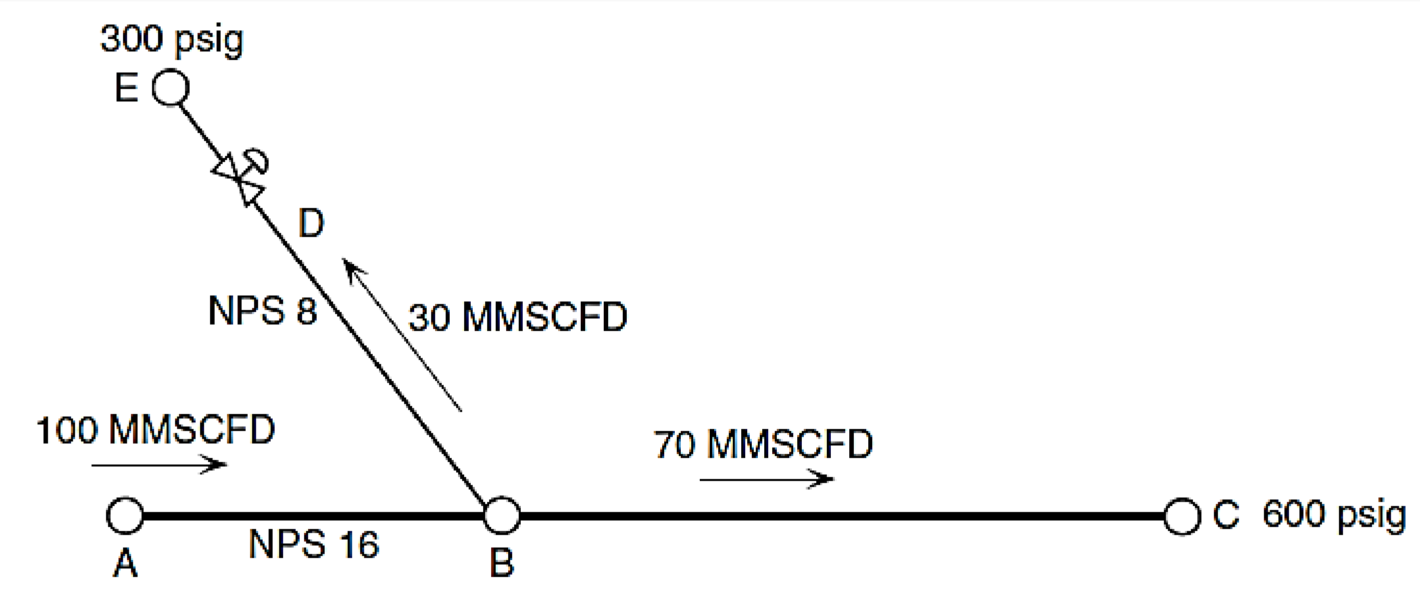
Example 9

A natural gas pipeline, NPS 16, 0.250 in. wall thickness, 50 mi long, with a branch pipe (NPS 8, 0.250 in. wall thickness, 15 mi long), as shown in Figure 3.13, is used to transport 100 MMSCFD gas (gravity = 0.6 and viscosity = 0.000008 lb/ft-s) from A to B. At B (milepost 20), a delivery of 30 MMSCFD occurs into the branch pipe BE. **The delivery pressure at E must be maintained at 300 psig**. The remaining volume of 70 MMSCFD is shipped to the terminus C at a delivery pressure of 600 psig. Assume a constant gas temperature of 60°F and a pipeline efficiency of 0.95. The base temperature and base pressure are 60°F and 14.7 psia, respectively. The compressibility factor $Z = 0.88$.

a) Using the Panhandle A equation, calculate the inlet pressure required at A.

b) Is a pressure regulator required at E?

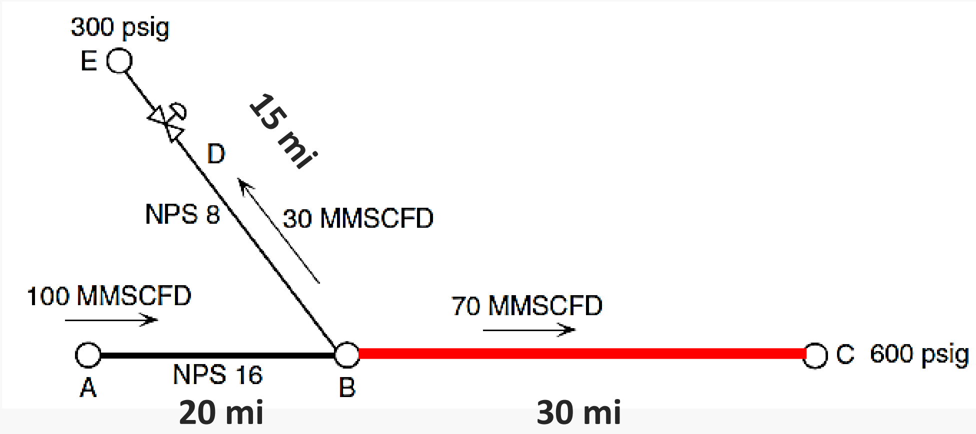
c) If the inlet flow at A drops to 60 MMSCFD, what is the impact in the branch pipeline BE if the flow rate of 30 MMSCFD is maintained?



Solution:

$$D_{AB} = D_{BC} = 16 - 2 \times 0.25 = 15.5 \text{ in.} \qquad \text{(NPS16, 0.25 in. wall thickness)}$$

$$D_{BE} = D_{BD} = 8.625 - 2 \times 0.25 = 8.125 \text{ in.} \qquad \text{(NPS8, 0.25 in. wall thickness)}$$



Panhandle A equation in USCS units (neglecting elevation effects):

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

BC pipeline:

$$70\times10^6 = 435.87(0.95)\left(\frac{60+460}{14.7}\right)^{1.0788}\left(\frac{P_1^2-(600+14.7)^2}{0.6^{0.8539}(60+460)(30)(0.88)}\right)^{0.5394}(15.5)^{2.6182}$$

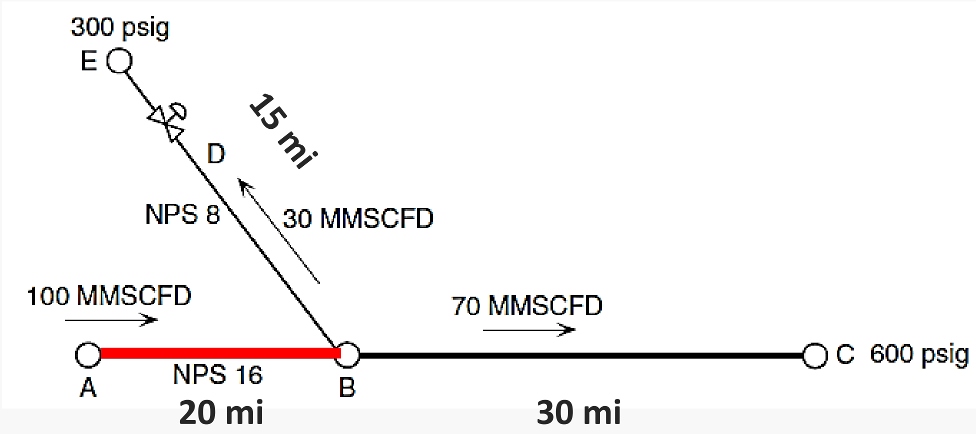
$$\Rightarrow P_1 = 660.39 \text{ psia} = 645.69 \text{ psig} \quad (\equiv P_B)$$

AB pipeline:

$$100\times10^6 = 435.87(0.95)\left(\frac{60+460}{14.7}\right)^{1.0788}\left(\frac{P_1^2-660.39^2}{0.6^{0.8539}(60+460)(20)(0.88)}\right)^{0.5394}(15.5)^{2.6182}$$

$$\Rightarrow P_1 = 715.08 \text{ psia} = 700.38 \text{ psig} \quad (\equiv P_A)$$

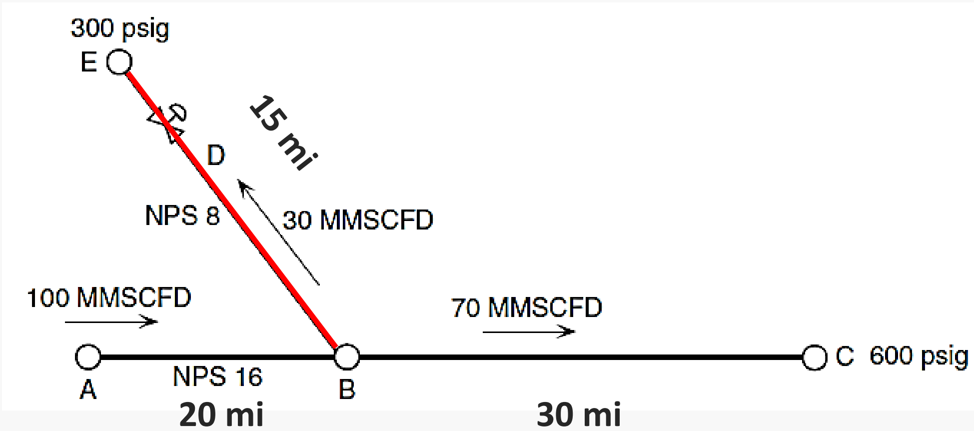
Ans. (a)



BE pipeline:

$$30\times10^6 = 435.87(0.95)\left(\frac{60+460}{14.7}\right)^{1.0788}\left(\frac{660.39^2-P_2^2}{0.6^{0.8539}(60+460)(15)(0.88)}\right)^{0.5394}(8.125)^{2.6182}$$

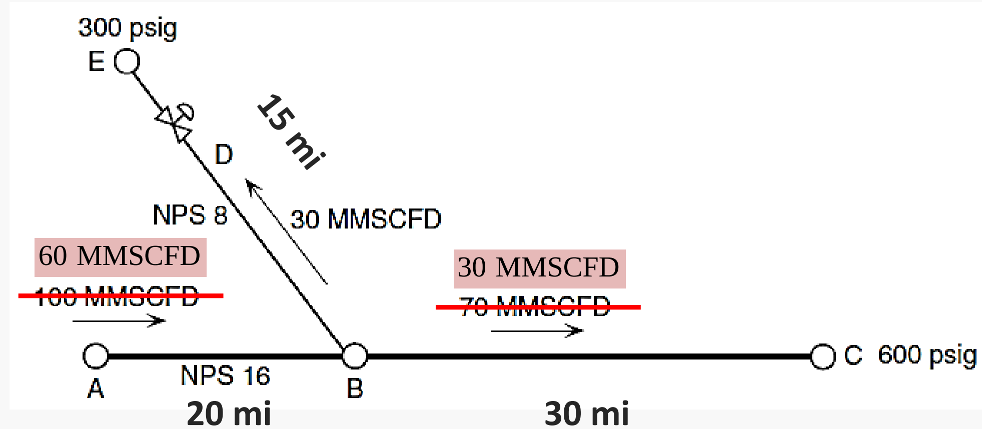
$$\Rightarrow P_2 = 544.90 \text{ psia} = 530.2 \text{ psig} \quad (\equiv P_E) \; > P_{\text{req}} \text{ at E which is 300 psig}$$



Since the required delivery pressure at E is 300 psig, a pressure regulator is required to be installed at E.

Ans. (b)

(c) If the inflow at A drops to 60 MMSCFD, what is the impact in the branch pipeline BE if the flow rate of 30 MMSCFD is maintained?



BC pipeline:

$$30\times10^{6}=435.87(0.95)\left(\frac{60+460}{14.7}\right)^{1.0788}\left(\frac{P_1^2-(600+14.7)^2}{0.6^{0.8539}(60+460)(30)(0.88)}\right)^{0.5394}(15.5)^{2.6182}$$

$$\Rightarrow P_1=624.47\ \text{psia}=609.77\ \text{psig}\ \ (\equiv P_B)$$

BE pipeline:

$$30\times10^{6}=435.87(0.95)\left(\frac{60+460}{14.7}\right)^{1.0788}\left(\frac{624.47^2-P_2^2}{0.6^{0.8539}(60+460)(15)(0.88)}\right)^{0.5394}(15.5)^{2.6182}$$

$$\Rightarrow P_2=500.76\ \text{psia}=486.06\ \text{psig}\ \ (\equiv P_E)\ >P_{\text{req}}\ \text{at E which is 300 psig}$$

Still a pressure regulator will be required to be installed at E at this new flow conditions.

Class Test

07/12/2024 SAT

12:00 noon