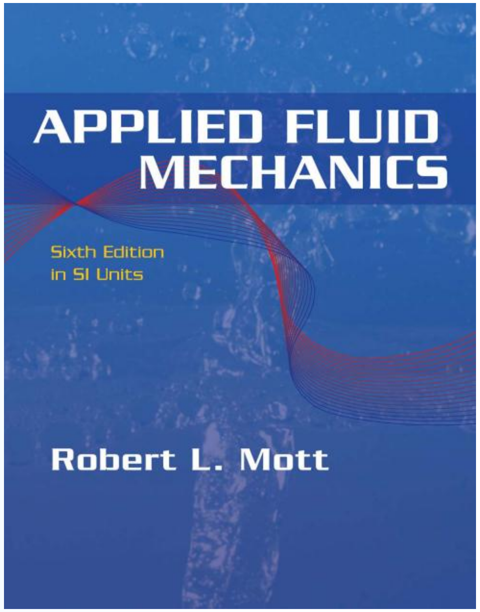
Applied Fluid Mechanics



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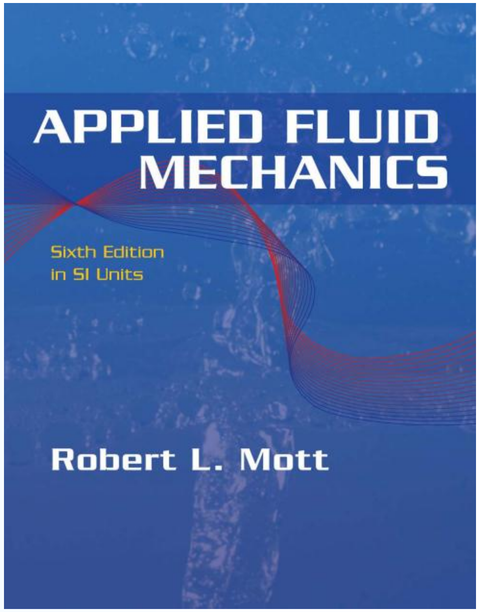

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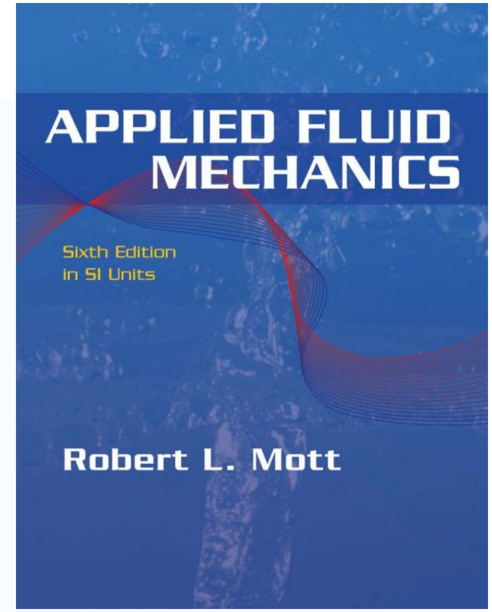

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Chapter Objectives

- Identify series pipeline systems.
- Determine whether a given system is Class I, Class II, or Class III.
- Compute the total energy loss, elevation differences, or pressure differences for Class I systems with any combination of pipes, minor losses, pumps, or reservoirs when the system carries a given flow rate.
- Determine for Class II systems the velocity or volume flow rate through the system with known pressure differences and elevation heads.
- Determine for Class III systems the size of pipe required to carry a given fluid flow rate with a specified limiting pressure drop or for a given elevation difference.

11. Series Pipeline System

Chapter Outline

1. Introductory Concepts
2. Class I Systems
3. Spreadsheet Aid for Class I Problems
4. Class II Systems
5. Class III Systems
6. Pipeline Design for Structural Integrity

11.1 Introductory Concepts

- System analysis and design problems can be classified into three classes as follows:

  Class I The system is completely defined in terms of the size of pipes, the types of minor losses that are present, and the volume flow rate of fluid in the system. The typical objective is to compute the pressure at some point of interest, to compute the total head on a pump, or to compute the elevation of a source of fluid to produce a desired flow rate or pressure at selected points in the system.

11. Series Pipeline System

11.1 Introductory Concepts

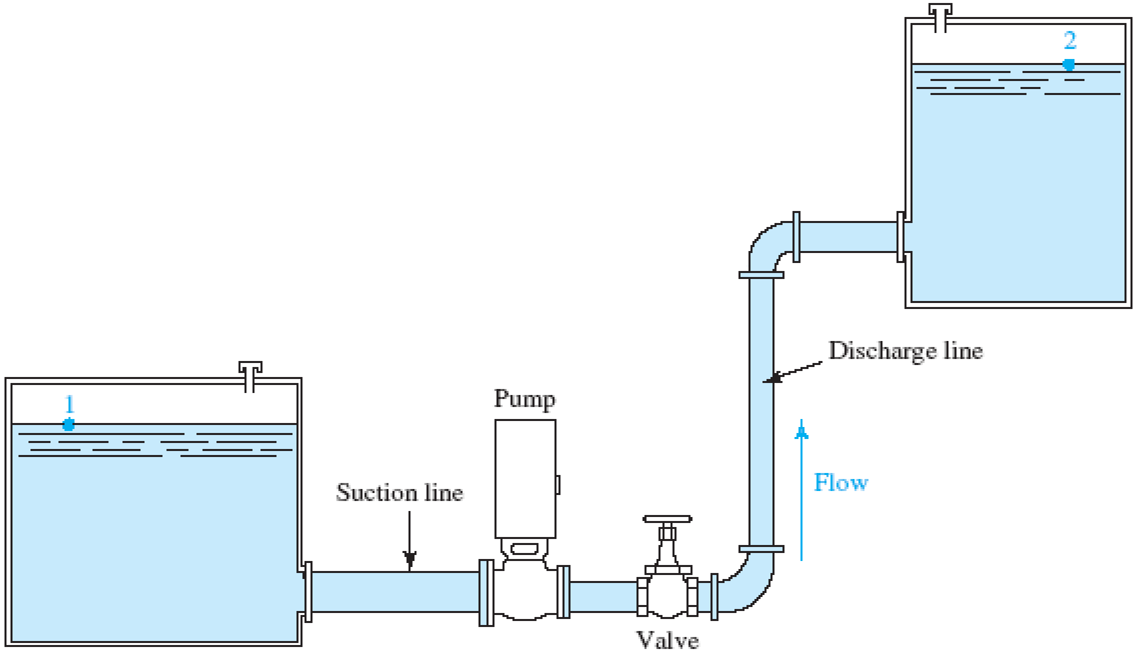
Class II The system is completely described in terms of its elevations, pipe sizes, valves and fittings, and allowable pressure drop at key points in the system. You desire to know the volume flow rate of the fluid that could be delivered by a given system.

Class III The general layout of the system is known along with the desired volume flow rate. The size of the pipe required to carry a given volume flow rate of a given fluid is to be determined.

11. Series Pipeline System

11.1 Class I Systems

- Fig 11.1 shows the series pipeline system.



11. Series Pipeline System

11.1 Class I Systems

- The energy equation for this system, using the surface of each reservoir as the reference points, is

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} + h_A - h_L = \frac{p_2}{\gamma} + z_2 + \frac{v_2^2}{2g} \qquad (11\text{–}1)$$

- The term h_A is the energy added to the fluid by a pump. A common name for this energy is *total head on the pump*, and it is used as one of the primary parameters in selecting a pump and in determining its performance.

11. Series Pipeline System

11.1 Class I Systems

- The term h_L denotes the total energy lost from the system anywhere between reference points 1 and 2.
- There are typically several factors that contribute to the total energy loss.
- Six different factors apply in this problem:

$$h_L = h_1 + h_2 + h_3 + h_4 + h_5 + h_6 \qquad (11\text{–}2)$$

h_L = Total energy loss per unit weight of fluid flowing
h_1 = Entrance loss
h_2 = Friction loss in the suction line
h_3 = Energy loss in the valve
h_4 = Energy loss in the two 90° elbows
h_5 = Friction loss in the discharge line
h_6 = Exit loss

Example 11.1

Calculate the power supplied to the pump shown in Fig. 11.2 if its efficiency is 76 percent. Methyl alcohol at 25°C is flowing at the rate of $54 m^3/s$. The suction line is a standard 4-in Schedule 40 steel pipe, 15 m long. The total length of 2-in Schedule 40 steel pipe in the discharge line is 200 m. Assume that the entrance from reservoir 1 is through a square-edged inlet and that the elbows are standard. The valve is a fully open globe valve.

Example 11.1

Using the surfaces of the reservoirs as the reference points, you should have

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} + h_A - h_L = \frac{p_2}{\gamma} + z_2 + \frac{v_2^2}{2g}$$

The equation can be simplified to

$$z_1 + h_A - h_L = z_2$$

The total head is

$$h_A = z_2 - z_1 + h_L$$

Example 11.1

Your list should include the following items. The subscript *s* indicates the suction line and the subscript *d* indicates the discharge line:

$$h_1 = K(v_s^2/2g) \qquad \text{(entrance loss)}$$

$$h_2 = f_s(L/D)(v_s^2/2g) \qquad \text{(friction loss in suction line)}$$

$$h_3 = f_{dT}(L_e/D)(v_d^2/2g) \qquad \text{(valve)}$$

$$h_4 = f_{dT}(L_e/D)(v_d^2/2g) \qquad \text{(two 90° elbows)}$$

$$h_5 = f_d(L/D)(v_d^2/2g) \qquad \text{(friction loss in discharge line)}$$

$$h_6 = 1.0(v_d^2/2g) \qquad \text{(exit loss)}$$

Example 11.1

Because the velocity head in the suction or discharge line is required for each energy loss, calculate these values now.

$$Q = \frac{54.0\ \mathrm{m}^3}{\mathrm{hr}} \times \frac{1\ \mathrm{hr}}{3600\ \mathrm{s}} = 0.015\ \mathrm{m}^3/\mathrm{s}$$

$$v_s = \frac{Q}{A_s} = \frac{0.015\ \mathrm{m}^3}{\mathrm{s}} \times \frac{1}{8.213 \times 10^{-3}\ \mathrm{m}^2} = 1.83\ \mathrm{m/s}$$

$$\frac{v_s^2}{2g} = \frac{(1.83)^2}{2(9.81)}\mathrm{m} = 0.17\ \mathrm{m}$$

$$v_d = \frac{Q}{A_d} = \frac{0.015\ \mathrm{m}^3}{\mathrm{s}} \times \frac{1}{2.168 \times 10^{-3}\ \mathrm{m}^2} = 6.92\ \mathrm{m/s}$$

$$\frac{v_d^2}{2g} = \frac{(6.92)^2}{2(9.81)}\mathrm{m} = 2.44\ \mathrm{m}$$

Example 11.1

To determine the friction losses in the suction line and the discharge line and the minor losses in the discharge line, we need the Reynolds number, relative roughness, and friction factor for each pipe and the friction factor in the zone of complete turbulence for the discharge line that contains a valve and pipe fittings. Find these values now.

11. Series Pipeline System

Example 11.1

For methyl alcohol at 25°C,

$$N_R = \frac{vD\rho}{\mu} = \frac{(1.83)(0.1023)(789)}{5.60 \times 10^{-4}} = 2.64 \times 10^5$$

For steel pipe, $\epsilon = 4.6 \times 10^{-5}$ m.

$$D/\epsilon = 0.1023/(4.6 \times 10^{-5}) = 2224$$
$$N_R = 2.64 \times 10^5$$

From moody diagram, $f_s = 0.018$

Example 11.1

In the discharge line, we have

$$N_R = \frac{vD\rho}{\mu} = \frac{(6.92)(0.0525)(789)}{5.60 \times 10^{-4}} = 5.12 \times 10^5$$

and

$$D/\epsilon = 0.0525/(4.6 \times 10^{-5}) = 1141$$
$$N_R = 5.12 \times 10^5$$
$$f_d = 0.020$$

Example 11.1

We can find from Table 10.5 that f_{Dt} = 0.019 for the 2-in discharge pipe in the zone of complete turbulence. Returning now to the energy loss calculations, evaluate h_1, the entrance loss, in Nm or m.

The result is h_1 = 0.09m. For a square-edged inlet, *K* = 0.5 and

$$h_1 = 0.5(v_s^2/2g) = (0.5)(0.17\text{ m}) = 0.09\text{ m}$$

$$h_2 = f_s \times \frac{L}{D} \times \frac{v_s^2}{2g} = f_s\left(\frac{15}{0.1023}\right)(0.17)\text{ m}$$

$$h_2 = (0.018)\left(\frac{15}{0.1023}\right)(0.17)\text{ m} = 0.45\text{ m}$$

Example 11.1

From the data in Chapter 10, the equivalent-length ratio L_e/D for a fully open globe valve is 340. The friction factor is 0.019. Then we have

$$h_3 = f_{dT} \times \frac{L_e}{D} \times \frac{v_d^2}{2g} = (0.019)(340)(2.44)\,\text{m} = 15.76\,\text{m}$$

For standard 90° elbows, $L_e/D = 30$. The value of f_{dt} is 0.019, the same as that used in the preceding panel. Then we have

$$h_4 = 2f_{dT} \times \frac{L_e}{D} \times \frac{v_d^2}{2g} = (2)(0.019)(30)(2.44)\,\text{m} = 2.78\,\text{m}$$

Example 11.1

The discharge-line friction loss is

$$h_5 = f_d \times \frac{L}{D} \times \frac{v_d^2}{2g} = (0.020)\left(\frac{200}{0.0525}\right)(2.44)\text{ m} = 185.9\text{ m}$$

The exit loss is

$$h_6 = 1.0(v_d^2/2g) = 2.44\text{ m}$$

The total loss is

$$h_L = h_1 + h_2 + h_3 + h_4 + h_5 + h_6$$

$$h_L = (0.09 + 0.45 + 15.76 + 2.78 + 185.9 + 2.44)\text{ m}$$

$$h_L = 207.4\text{ m}$$

Example 11.1

From the energy equation the expression for the total head on the pump is

$$h_A = z_2 - z_1 + h_L$$

Then we have

$$h_A = 10\,\text{m} + 207.4\,\text{m} = 217.4\,\text{m}$$

The required power is

$$\text{Power} = \frac{h_A \gamma Q}{e_M} = \frac{(217.4\,\text{m})(7.74 \times 10^3\,\text{N/m}^3)(0.015\,\text{m}^3/\text{s})}{0.76}$$

$$P_A = 33.2 \times 10^3\,\text{N}\cdot\text{m/s} = 33.2\,\text{kW}$$

11.2 Spreadsheet Aid for Class I Problems

- The use of a spreadsheet can improve the procedure dramatically by doing most of the calculations for you after you enter the basic data.
- Figure 11.3 shows one approach.
- The data shown are from Example Problem 11.1, where the objective was to compute the power required to drive the pump.

11.2 Spreadsheet Aid for Class I Problems

APPLIED FLUID MECHANICS	CLASS I SERIES SYSTEMS
Objective: *Pump Power*	*Reference points for the energy equation:*
Example Problem 11.1	Point 1: At surface of lower reservoir
Figure 11.2	Point 2: At surface of upper reservoir

System Data:	SI Metric Units		
Volume flow rate: Q =	*0.015 m³/s*	*Elevation at point 1 =*	*0 m*
Pressure at point 1 =	*0 kPa*	*Elevation at point 2 =*	*10 m*
Pressure at point 2 =	*0 kPa*	*If Ref. pt. is in pipe: Set v1 "= B20" OR Set v2 "= E20"*	
Velocity at point 1 =	*0 m/s* →	Vel head at point 1 =	*0 m*
Velocity at point 2 =	*0 m/s* →	Vel head at point 2 =	*0 m*

Fluid Properties:		May need to compute $\nu = \eta/\rho$
Specific weight =	*7.74 kN/m³*	*Kinematic viscosity = 7.10E-07 m²/s*

Pipe 1:		*Pipe 2:*		
Diameter: D =	*0.1023 m*	*Diameter: D =*	*0.0525 m*	
Wall roughness: ε =	*4.60E-05 m*	*Wall roughness: ε =*	*4.60E-05 m*	*[See Table 8.2]*
Length: L =	*15 m*	*Length: L =*	*200 m*	
Area: *A* =	8.22E-03 m²	Area: *A* =	2.16E-03 m²	[A = πD²/4]
D/ε =	2224	*D/ε* =	1141	Relative roughness
L/D =	147	*L/D* =	3810	
Flow velocity =	1.82 m/s	Flow velocity =	6.93 m/s	[*v* = *Q/A*]
Velocity head =	0.170 m	Velocity head =	2.447 m	[*v*²/2*g*]
Reynolds No. =	2.63E+05	Reynolds No. =	5.13E+05	[$N_R = vD/\nu$]
Friction factor: *f* =	0.0182	Friction factor: *f* =	0.0198	Using Eq. 8–7

Energy Losses in Pipe 1:		Qty.			
Pipe: $K_1 = f(L/D)$ =	*2.67*	*1*	Energy loss h_{L1} =	0.453 m	Friction
Entrance loss: K_2 =	*0.50*	*1*	Energy loss h_{L2} =	0.085 m	
Element 3: K_3 =	*0.00*	*1*	Energy loss h_{L3} =	0.000 m	
Element 4: K_4 =	*0.00*	*1*	Energy loss h_{L4} =	0.000 m	
Element 5: K_5 =	*0.00*	*1*	Energy loss h_{L5} =	0.000 m	
Element 6: K_6 =	*0.00*	*1*	Energy loss h_{L6} =	0.000 m	
Element 7: K_7 =	*0.00*	*1*	Energy loss h_{L7} =	0.000 m	
Element 8: K_8 =	*0.00*	*1*	Energy loss h_{L8} =	0.000 m	

Energy Losses in Pipe 2:		Qty.			
Pipe: $K_1 = f(L/D)$ =	75.35	1	Energy loss h_{L1} =	184.40 m	Friction
Globe valve: K_2 =	*6.46*	*1*	Energy loss h_{L2} =	15.81 m	
2 std elbows: K_3 =	*0.57*	*2*	Energy loss h_{L3} =	2.79 m	
Exit loss: K_4 =	*1.00*	*1*	Energy loss h_{L4} =	2.45 m	
Element 5: K_5 =	*0.00*	*1*	Energy loss h_{L5} =	0.00 m	
Element 6: K_6 =	*0.00*	*1*	Energy loss h_{L6} =	0.00 m	
Element 7: K_7 =	*0.00*	*1*	Energy loss h_{L7} =	0.00 m	
Element 8: K_8 =	*0.00*	*1*	Energy loss h_{L8} =	0.00 m	

	Total energy loss h_{Ltot} =	205.98 m
Results:	Total head on pump: h_A =	216.0 m
	Power added to fluid: P_A =	25.08 kW
	Pump efficiency =	*76.00 %*
	Power input to pump: P_I =	32.99 kW

11. Series Pipeline System

11.3 Class II Systems

- A Class II series pipeline system is one for which you desire to know the volume flow rate of the fluid that could be delivered by a given system.
- The system is completely described in terms of its elevations, pipe sizes, valves and fittings, and allowable pressure drop at key points in the system.
- We will suggest three different approaches to designing Class II systems.
- They vary in their complexity and the degree of precision of the final result.

11.3.1 Method II-A

- Used for a series system in which only pipe friction losses are considered, this direct solution process uses an equation, based on the work of Swamee and Jain (Reference 13), that includes the direct computation of the friction factor.

11.3.2 Method II-B

- Used for a series system in which relatively small minor losses exist along with a relatively large pipe friction loss, this method adds steps to the process of Method II-A.
- Minor losses are initially neglected and the same equation used in Method II-A is used to estimate the allowable velocity and volume flow rate.

11.3.3 Method II-C

- Used for a series system in which minor losses are significant in comparison with the pipe friction losses and for which a high level of precision in the analysis is desired, this method is the most time-consuming, requiring an algebraic analysis of the behavior of the entire system and the expression of the velocity of flow in terms of the friction factor in the pipe.
- Both of these quantities are unknown because the friction factor also depends on velocity (Reynolds number).
- An *iteration* process is used to complete the analysis.

11. Series Pipeline System

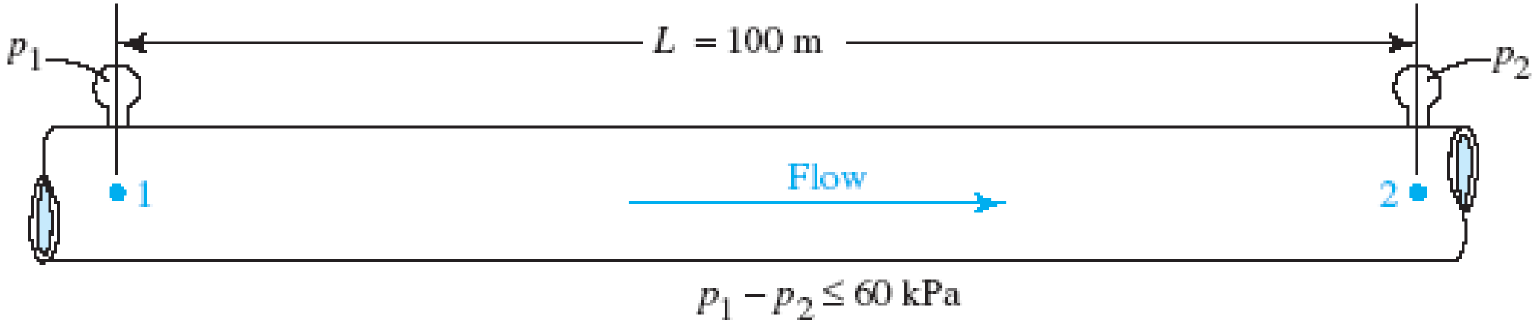
Example 11.2

A lubricating oil must be delivered through a horizontal 6-in Schedule 40 steel pipe with a maximum pressure drop of 60 kPa per 100 m of pipe. The oil has a specific gravity of 0.88 and a dynamic viscosity of 9.5×10^{-3} Pa. Determine the maximum allowable volume flow rate of oil.

Figure 11.4 shows the system. This is a Class II series pipeline problem because the volume flow rate is unknown and, therefore, the velocity of flow is unknown. Method II-A is used here because only pipe friction losses exist in the system.

11. Series Pipeline System

Example 11.2



Step 1 Write the energy equation for the system.

Step 2 Solve for the limiting energy loss .

Step 3 Determine the following values for the system:

Pipe flow diameter *D*

Relative roughness D/ε

Length of pipe *L*

Kinematic viscosity of the fluid ; may require using $\nu = \mu/\rho$

Example 11.2

Step 4 Use the following equation to compute the limiting volume flow rate, ensuring that all data are in the coherent units of the given system:

$$Q = -2.22\,D^2\sqrt{\frac{gDh_L}{L}}\log\left(\frac{1}{3.7D/\epsilon} + \frac{1.784\,\nu}{D\sqrt{gDh_L/L}}\right) \qquad (11\text{–}3)$$

We use points 1 and 2 shown in Fig. 11.3 to write the energy equation:

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} - h_L = \frac{p_2}{\gamma} + z_2 + \frac{v_2^2}{2g}$$

Example 11.2

Then we solve algebraically for h_L and evaluate the result:

$$h_L = \frac{p_1 - p_2}{\gamma} = \frac{60\ \text{kN}}{\text{m}^2} \times \frac{\text{m}^3}{(0.88)(9.81\ \text{kN})} = 6.95\ \text{m}$$

Other data needed are:

Pipe flow diameter, $D = 0.1541$ m [Appendix F]

Pipe wall roughness, $\epsilon = 4.6 \times 10^{-5}$m [Table 9.1]

Relative roughness, $D/\epsilon = (0.1541\ \text{m})/(4.6 \times 10^{-5}\ \text{m}) = 3350$

Length of pipe, $L = 100$ m

Kinematic viscosity of the fluid; use

$$\rho = (0.88)(1000\ \text{kg/m}^3) = 880\ \text{kg/m}^3$$

Example 11.2

Then

$$\nu = \mu/\rho = (9.5 \times 10^{-3}\ \text{Pa}\cdot\text{s})/(880\ \text{kg/m}^3) = 1.08 \times 10^{-5}\ \text{m}^2/\text{s}$$

We place these values into Eq. (11–3), ensuring that all data are in coherent SI units for this problem.

$$Q = -2.22(0.1541)^2\sqrt{\frac{(9.81)(0.1541)(6.95)}{100}}$$
$$\times \log\left[\frac{1}{(3.7)(3350)} + \frac{(1.784)(1.08 \times 10^{-5})}{(0.1541)\sqrt{(9.81)(0.1541)(6.95)/100}}\right]$$
$$Q = 0.057\ \text{m}^3/\text{s}$$

11.3.4 Spreadsheet solution for Method II-A Class II Series Pipeline Problems

- Fig 11.5 shows the spreadsheet for Method II-A Class II series pipeline problems.

APPLIED FLUID MECHANICS		**CLASS II SERIES SYSTEMS**	
Objective: Volume Flow Rate		**Method II-A: No minor losses**	
Example Problem 11.2 Figure 11.4		Uses Eq. (11–3) to find maximum allowable volume flow rate to maintain desired pressure at point 2 for a given pressure at point 1	
System Data:	SI Metric Units		
Pressure at point 1 =	*120* kPa	*Elevation at point 1* =	*0* m
Pressure at point 2 =	*60* kPa	*Elevation at point 2* =	*0* m
Energy loss: h_L =	*6.95* m		
Fluid Properties:		May need to compute $\nu = \eta/\rho$	
Specific weight =	*8.63* kN/m^3	*Kinematic viscosity* =	*1.08E-05* m^2/s
Pipe Data:			
Diameter: D =	*0.1541* m		
Wall roughness: ϵ =	*4.60E-05* m		
Length: L =	*100* m	***Results: Maximum values***	
Area: A =	*0.01865* m^2	Volume flow rate: Q =	0.0569 m^3/s
D/ϵ =	*3350*	Velocity: v =	3.05 m/s

11. Series Pipeline System

11.3.4 Spreadsheet solution for Method II-B Class II Series Pipeline Problems

- Fig 11.6 shows the spreadsheet for Method II-B Class II series pipeline problems.

APPLIED FLUID MECHANICS		CLASS II SERIES SYSTEMS	
Objective: Volume Flow Rate		Method II–A: No minor losses	
Example Problem 11.3		Uses Eq. (11–3) to estimate the allowable volume flow rate	
Figure. 11.7		to maintain desired pressure at point 2 for a given pressure at point 1	
System Data:	SI Metric Units		
Pressure at point 1 =	120 kPa	*Elevation at point 1 =*	0 m
Pressure at point 2 =	60 kPa	*Elevation at point 2 =*	0 m
Energy loss: h_L =	6.95 m		
Fluid Properties:		May need to compute $\nu = \eta/\rho$	
Specific weight =	8.63 kN/m^3	*Kinematic viscosity =*	1.08E-05 m^2/s
Pipe Data: 6–in Schedule 40 steel			
Diameter: D =	0.1541 m		
Wall roughness: ϵ =	4.60E-05 m		
Length: L =	100 m	***Results: Maximum values***	
Area: A =	0.01865 m^2	Volume flow rate: Q =	0.0569 m^3/s
D/ϵ =	3350	Velocity: v =	3.05 m/s

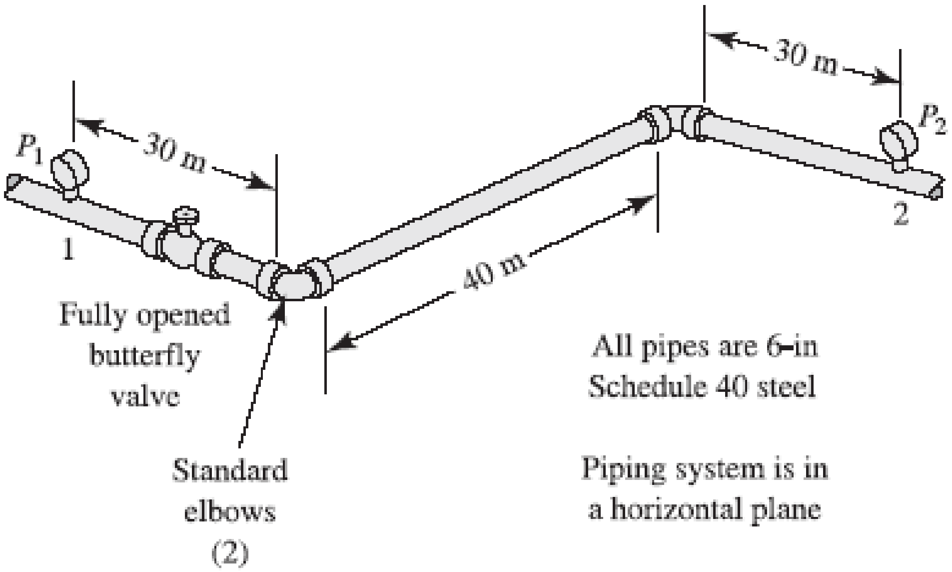
CLASS II SERIES SYSTEMS			*Volume flow rate: Q =*	0.0538 m^3/s	
Method II-B: *Use results of Method II-A; include minor losses; then pressure at point 2 is computed*			Given: Pressure p_1 =	120 kPa	
			Pressure p_2 =	**60.18 kPa**	
			NOTE: Should be >	**60 kPa**	
Additional Pipe Data:			***Adjust estimate for Q until p_2 is greater than desired pressure.***		
L/D =	649				
Flow velocity =	2.88 m/s		Velocity at point 1 =	2.88 m/s	→ If velocity is in pipe:
Velocity head =	0.424 m		Velocity at point 2 =	2.88 m/s	→ Enter "=B24"
Reynolds No. =	4.12E+04		Vel. head at point 1 =	0.424 m	
Friction factor: f =	0.0228		Vel. head at point 2 =	0.424 m	
Energy Losses in Pipe 1:		Qty.			
Pipe: K_1 = f(L/D) =	14.76	1	Energy loss h_{L1} =	6.26 m	Friction
2 std elbows: K_2 =	0.45	2	Energy loss h_{L2} =	0.38 m	
Butterfly valve: K_3 =	0.68	1	Energy loss h_{L3} =	0.29 m	
Element 4: K_4 =	0.00	1	Energy loss h_{L4} =	0.00 m	
Element 5: K_5 =	0.00	1	Energy loss h_{L5} =	0.00 m	
Element 6: K_6 =	0.00	1	Energy loss h_{L6} =	0.00 m	
Element 7: K_7 =	0.00	1	Energy loss h_{L7} =	0.00 m	
Element 8: K_8 =	0.00	1	Energy loss h_{L8} =	0.00 m	
			Total energy loss h_{Ltot} =	6.93 m	

Example 11.3

A lubricating oil must be delivered through the piping system shown in Fig. 11.7 with a maximum pressure drop of 60 kPa between points 1 and 2. The oil has a specific gravity of 0.88 and a dynamic viscosity of 9.5 x 10^{-3}Pa.s. Determine the maximum allowable volume flow rate of oil.

The system is similar to that in Example Problem 11.2. There are 100 m of 6-in Schedule 40 steel pipe in a horizontal plane. But the addition of the valve and the two elbows provide a moderate amount of energy loss.

Example 11.3



Initially, we ignore the minor losses and use Eq. (11–3) to compute a rough estimate of the allowable volume flow rate. This is accomplished in the upper part of the spreadsheet in Fig. 11.6 and it is identical to the solution shown in Fig. 11.5 for Example Problem 11.2. This is the starting point for Method II-B.

Example 11.3

1. A revised estimate of the allowable volume flow rate *Q* is entered at the upper right, just under the computation of the initial estimate. The revised estimate must be lower than the initial estimate.

2. The spreadsheet then computes the “Additional Pipe Data” using the known pipe data from the upper part of the spreadsheet and the new estimated value for *Q*.

Example 11.3

3. Note at the middle right of the spreadsheet that the velocities at reference points 1 and 2 must be entered. If they are in the pipe, as they are in this problem, then the cell reference “B24” can be entered because that is where the velocity in the pipe is computed. Other problems may have the reference points elsewhere, such as the surface of a reservoir where the velocity is zero. The appropriate value should then be entered in the shaded area.

Example 11.3

4. Now the data for minor losses must be added in the section called "Energy Losses in Pipe 1." The *K* factor for the pipe friction loss is automatically computed from known data. The values for the other two *K* factors must be determined and entered in the shaded area in
a manner similar to that used in the Class I spreadsheet. In this problem they are both dependent
on the value of f_T for the 6-in pipe. That value is 0.015 as found in Table 10.5

- Elbow (standard): $K = f_T(L_e/D) = (0.015)(30) = 0.45$
- Butterfly valve: $K = f_T(L_e/D) = (0.015)(45) = 0.675$

Example 11.3

5. The spreadsheet then computes the total energy loss and uses this value to compute the pressure at reference point 2. The equation is derived from the energy equation,

$$p_2 = p_1 + \gamma[z_1 - z_2 + v_1^2/2g - v_2^2/2g - h_L]$$

Example 11.3

6. The computed value for p_2 must be larger than the desired value as entered in the upper part of the spreadsheet. This value is placed close to the assumed volume flow rate to give you a visual cue as to the acceptability of your current estimate for the limiting volume flow rate. Adjustments in the value of *Q* can then be quickly made until the pressure assumes an acceptable value.

11. Series Pipeline System

11.3.5 Method II-C: Iteration Approach for Class II Series Pipeline Problem

- Below are the solution procedure for class ii systems with one pipe:

1. Write the energy equation for the system.
2. Evaluate known quantities such as pressure heads and elevation heads.
3. Express energy losses in terms of the unknown velocity v and friction factor *f*.
4. Solve for the velocity in terms of *f*.
5. Express the Reynolds number in terms of the velocity.

11. Series Pipeline System

11.3.5 Method II-C: Iteration Approach for Class II Series Pipeline Problem

6. Calculate the relative roughness D/ε.
7. Select a trial value of *f* based on the known D/ε and a Reynolds number in the turbulent range.
8. Calculate the velocity, using the equation from Step 4.
9. Calculate the Reynolds number from the equation in Step 5.
10. Evaluate the friction factor *f* for the Reynolds number from Step 9 and the known value of D/ε, using the Moody diagram, Fig. 8.6.
11. If the new value of *f* is different from the value used in Step 8, repeat Steps 8–11 using the new value of *f*.
12. If there is no significant change in *f* from the assumed value, then the velocityfound in Step 8 is correct.

Example 11.4

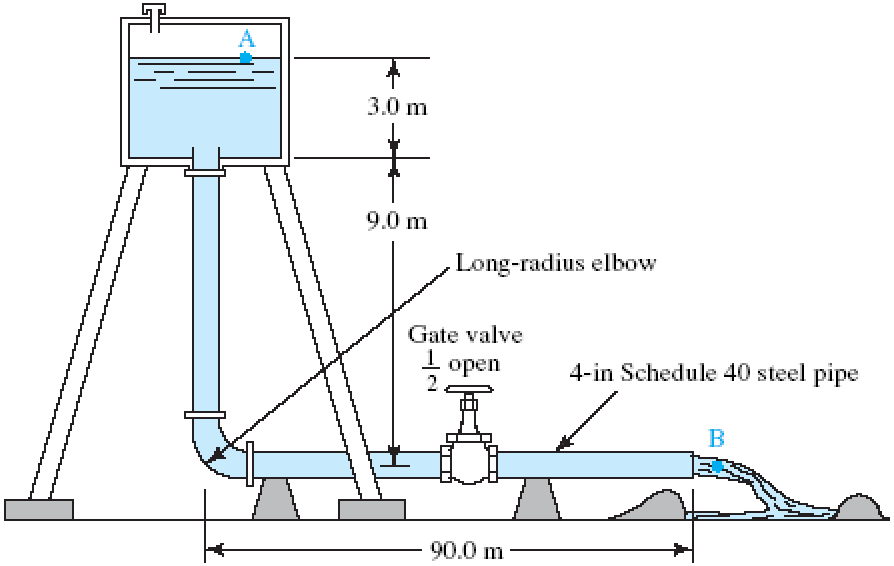
Water at 30°C is being supplied to an irrigation ditch from an elevated storage reservoir as shown in Fig. 11.8. Calculate the volume flow rate of water into the ditch. Begin with Step 1 of the solution procedure by writing the energy equation. Use A and B as the reference points and simplify the equation as much as possible.

Compare this with your solution:

$$\frac{p_A}{\gamma} + z_A + \frac{v_A^2}{2g} - h_L = \frac{p_B}{\gamma} + z_B + \frac{v_B^2}{2g}$$

11. Series Pipeline System

Example 11.4



Because $p_A=p_B=0$, and v_A is approximately zero, then

$$z_A - h_L = z_B + (v_B^2/2g)$$

$$z_A - z_B = (v_B^2/2g) + h_L \qquad (11\text{–}4)$$

11. Series Pipeline System

Example 11.4

There are four components of the total energy loss

$$h_L = h_1 + h_2 + h_3 + h_4$$

$$h_1 = 1.0(v_B^2/2g) \qquad \text{(entrance loss)}$$

$$h_2 = f(L/D)(v_B^2/2g) \qquad \text{(pipe friction loss)}$$

$$= f(99/0.1023)(v_B^2/2g)$$

$$= 967.7f(v_B^2/2g)$$

$$h_3 = f_T(L_e/D)(v_B^2/2g) \qquad \text{(long-radius elbow)}$$

$$= 20f_T(v_B^2/2g)$$

$$h_4 = f_T(L_e/D)(v_B^2/2g) \qquad \text{(half-open gate valve)}$$

$$= 160f_T(v_B^2/2g)$$

11. Series Pipeline System

Example 11.4

From Table 10.5, we find f_T = 0.017 for a 4-m steel pipe. Then we have

$$\begin{aligned} h_L &= (1.0 + 967.7f + 20f_T + 160f_T)(v_B^2/2g) \\ &= (4.06 + 967.7f)(v_B^2/2g) \qquad (11\text{–}5) \end{aligned}$$

You should have

$$v_B = \sqrt{235.44 / (5.06 + 967.7f)}$$

$$\begin{aligned} z_A - z_B &= (v_B^2/2g) + h_L \\ 12\text{ m} &= (v_B^2/2g) + (4.06 + 967.7f)(v_B^2/2g) \\ &= (5.06 + 967.7f)(v_B^2/2g) \end{aligned}$$

Example 11.4

Equation (11–6) represents the completion of Step 4 of the procedure. Now do Steps 5 and 6. We get

$$v_B = \sqrt{\frac{2g(12)}{5.06 + 967.7f}} = \sqrt{\frac{235.44}{5.06 + 967.7f}} \qquad (11\text{–}6)$$

$$N_R = \frac{v_B D}{\nu} = \frac{v_B(0.1023)}{8.03 \times 10^{-7}} = (1.274 \times 10^5)v_B \qquad (11\text{–}7)$$

$$D/\epsilon = (0.1023/4.57 \times 10^{-5}) = 2238$$

We find the values for velocity and the Reynolds number by using Eqs. (11–6) and (11–7):

$$v_B = \sqrt{\frac{235.44}{5.06 + (967.7)(0.02)}} = \sqrt{9.644} = 3.105 \text{ m/s}$$

$$N_R = (1.27 \times 10^5)(3.105) = 3.94 \times 10^5$$

Example 11.4

You should have f = 0.0175. Because this is different from the initial trial value of *f*, Steps 8–11 must be repeated now.

$$v_B = \sqrt{\frac{235.44}{5.06 + (967.7)(0.0175)}} = 3.27 \text{ m/s}$$

$$N_R = (1.27 \times 10^5)(3.27) = 4.15 \times 10^5$$

$$v_B = 3.27 \text{ m/s}$$

$$Q = A_B v_B = (8.213 \times 10^{-3} \text{ m}^2)(3.27 \text{ m/s}) = 0.027 \text{ m}^3/\text{s}$$

11. Series Pipeline System

11.4 Class III Systems

- A Class III series pipeline system is one for which you desire to know the size of pipe that will carry a given volume flow rate of a given fluid with a specified maximum pressure drop due to energy losses.
- Velocity is inversely proportional to the flow area found from

$$A = \pi D^2/4$$

- Therefore the energy loss is inversely proportional to the flow diameter *to the fourth power*.
- The size of the pipe is a major factor in how much energy loss occurs in a pipeline system.

11.4.1 Method III-A

- This simplified approach considers only energy loss due to friction in the pipe.
- We assume that the reference points for the energy equation are in the pipe to be designed and at a set distance apart.
- Because the flow diameter is the same at the two reference points, however, there is no difference in the velocities or the velocity heads.
- We can write the energy equation and then solve for the energy loss,

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} - h_L = \frac{p_2}{\gamma} + z_2 + \frac{v_2^2}{2g}$$

11.4.1 Method III-A

- But $v_1 = v_2$. Then we have

$$h_L = \frac{p_1 - p_2}{\gamma} + z_1 - z_2$$

- This value, along with other system data, can be entered into the following design equation (see References 12 and 13):

$$D = 0.66\left[\epsilon^{1.25}\left(\frac{LQ^2}{gh_L}\right)^{4.75} + \nu Q^{9.4}\left(\frac{L}{gh_L}\right)^{5.2}\right]^{0.04} \qquad (11\text{–}8)$$

11.4.1 Method III-A

- The result is the smallest flow diameter that can be used for a pipe to limit the pressure drop to the desired value.
- Normally, you will specify a standard pipe or tube that has an inside diameter just larger than this limiting value.

Example 11.5

Compute the required size of new clean Schedule 40 pipe that will carry 0.014 m^3/s of water at 15°C and limit the pressure drop to 13.79 kPa over a length of 30.5 m of horizontal pipe.

We first calculate the limiting energy loss. Note that the elevation difference is zero. Write

$$h_L = (p_1 - p_2)/\gamma + (z_1 - z_2) = (13.79\ \text{kPa}/9.81\ \text{kN/m}^3) + 0 = 1.402\ \text{m}$$

$$Q = 0.014\ \text{m}^3/\text{s} \qquad L = 30.5\ \text{m} \qquad g = 9.81\ \text{m/s}^2$$

$$h_L = 1.402\ \text{m} \qquad \epsilon = 4.572 \times 10^{-5}\ \text{m} \qquad \upsilon = 1.15 \times 10^{-6}\ \text{m}^2/\text{s}$$

Example 11.5

Now we can enter these data into Eq. (11–8):

$$D = 0.66\left[(4.572 \times 10^{-5})^{1.25}\left[\frac{(30.5)(0.014)^2}{(9.81)(1.402)}\right]^{4.75} + (1.15 \times 10^{-6})(0.014)^{9.4}\left[\frac{30.5}{(9.81)(1.402)}\right]^{5.2}\right]^{0.04}$$

$$D = 0.098 \text{ m}$$

The result shows that the pipe should be larger than D=0.098 m. The next larger standard pipe size is a 4-in Schedule 40 steel pipe having an inside diameter of D=0.1023 m.

11.4.2 Spreadsheet for Completing Method III-A for Class III Series Pipeline Problems

- Fig 11.9 shows the spreadsheet for Method III-A for Class III series pipeline problems.

APPLIED FLUID MECHANICS			III-A & III-B SI: CLASS III SERIES SYSTEMS		
Objective: Minimum pipe diameter			*Method III-A: Uses Equation 11-13 to compute the minimum size of pipe of a given length that will flow a given volume flow rate of fluid with a limited pressure drop. (No minor losses)*		
Problem 11.18					
System Data: SI Metric Units			**Fluid Properties:**		
Pressure at point 1 =	*673.2*	kPa	*Specific weight =*	*9.81*	kN/m^3
Pressure at point 2 =	*660*	kPa	*Kinematic Viscosity =*	*1.15E-06*	m^2/s
Elevation at point 1 =	*0*	m	**Intermediate Results in Eq. 11-13:**		
Elevation at point 2 =	*0*	m			
Allowable Energy Loss: h_L =	1.35	m	L/gh_L =	2.272727	
Volume flow rate: Q =	*0.06*	m^3/s	Argument in bracket:	2.75E-16	
Length of pipe: L =	*30*	m	**Final Minimum Diameter:**		
Pipe wall roughness: ε =	*1.50E-06*	m	Minimum diameter: *D* =	0.1574	m

11. Series Pipeline System

11.4.3 Method III-B

- Fig 11.10 shows the spreadsheet for Method III-B for Class III series pipeline problems.

APPLIED FLUID MECHANICS		
Objective: Minimum pipe diameter		
Problem 11.18		
System Data: SI Metric Units		
Pressure at point 1 =	*673.2*	kPa
Pressure at point 2 =	*660*	kPa
Elevation at point 1 =	*0*	m
Elevation at point 2 =	*0*	m
Allowable Energy Loss: h_L =	1.35	m
Volume flow rate: Q =	*0.06*	m^3/s
Length of pipe: L =	*30*	m
Pipe wall roughness: ε =	*1.50E-06*	m

III-A & III-B SI: CLASS III SERIES SYSTEMS		
Method III-A: *Uses Equation 11-13 to compute the minimum size of pipe of a given length that will flow a given volume flow rate of fluid with a limited pressure drop. (No minor losses)*		
Fluid Properties:		
Specific weight =	*9.81*	kN/m^3
Kinematic Viscosity =	*1.15E-06*	m^2/s
Intermediate Results in Eq. 11-13:		
L/gh_L =	2.272727	
Argument in bracket:	2.75E-16	
Final Minimum Diameter:		
Minimum diameter: D =	0.1574	m

CLASS III SERIES SYSTEMS		
Method III-B: *Use results of Method III-A; Specify actual diameter; Include minor losses; then pressure at Point 2 is computed.*		
Additional Pipe Data:		
Flow area: A =	0.007538	m^2
Relative roughness: D/ε =	65313	
L/D =	306	
Flow Velocity =	7.96	m/s
Velocity head =	3.229	m
Reynolds No. =	6.78E+05	
Friction factor: f =	0.0127	

Specified pipe diameter: D =	*0.09797*	m
4-inch Type K copper tube		
If velocity is in the pipe, enter "=B23" for value		
Velocity at point 1 =	*7.96*	m/s
Velocity at point 2 =	*7.96*	m/s
Vel. head at point 1 =	3.229	m
Vel. head at point 2 =	3.229	m
Results:		
Given pressure at point 1 =	673.2	kPa
Desired pressure at point 2 =	660	kPa
Actual pressure at point 2 =	***550.03***	***kPa***
(Actual p_2 should be > desired pressure)		

Energy losses in Pipe:	*K*	Qty.			
Pipe Friction: K_1 = f(L/D) =	3.89	1	Energy loss h_{L1} =	12.56	m
Element 2: K_2 =	*0.00*	*1*	Energy loss h_{L2} =	0.00	m
Element 3: K_3 =	*0.00*	*1*	Energy loss h_{L3} =	0.00	m
Element 4: K_4 =	*0.00*	*1*	Energy loss h_{L4} =	0.00	m
Element 5: K_5 =	*0.00*	*1*	Energy loss h_{L5} =	0.00	m
Element 6: K_6 =	*0.00*	*1*	Energy loss h_{L6} =	0.00	m
Element 7: K_7 =	*0.00*	*1*	Energy loss h_{L7} =	0.00	m
Element 8: K_8 =	*0.00*	*1*	Energy loss h_{L8} =	0.00	m
			Total energy loss h_{Ltot} =	12.56	m

Example 11.6

Extend the situation described in Example Problem 11.5 by adding a fully open butterfly valve and two long-radius elbows to the 30.5 m of straight pipe. Will the 4-inch Schedule 40 steel pipe size selected limit the pressure drop to 13.79 kPa with these minor losses added?

To simulate the desired pressure drop of 13.79 kPa, we have set the pressure at point 1 to be 703.26 kPa. Then we examine the resulting value of the pressure at point 2 to see that it is at or greater than 689.48 kPa.

Example 11.6

The spreadsheet in Fig. 11.10 shows the calculations. For each minor loss, a resistance factor *K* is computed as defined in Chapters 8 and 10. For the pipe friction loss,

$$K_1 = f(L/D)$$

and the friction factor *f* is computed by the spreadsheet using Eq. (8–7). For the elbows and the butterfly valve, the method of Chapter 10 is applied. Write

$$K = f_T(L_e/D)$$

Example 11.6

The result shows that the pressure at point 2 at the end of the system is 692.65 kPa. Thus the design is satisfactory. Note that the energy loss due to pipe friction is 0.863 m out of the total energy loss of 1.082 m. The elbows and the valve contribute truly minor losses.

11. Series Pipeline System

11.5 Pipeline Design for Structural Integrity

- Piping systems and supports must be designed for strength and structural integrity in addition to meeting flow, pressure drop, and pump power requirements.
- Consideration must be given to stresses created by the following:

1. Internal pressure
2. Static forces due to the weight of the piping and the fluid
3. Dynamic forces created by moving fluids inside the pipe (see Chapter 16)
4. External loads caused by seismic activity, temperature changes, installation procedures, or other application-specific conditions

11.5 Pipeline Design for Structural Integrity

- Structural integrity evaluation should consider pipe stress due to internal pressure, static loads due to the weight of the pipe and its contents, wind loads, installation processes, thermal expansion and contraction, hydraulic transients such as water hammer caused by rapid valve actuation, long-term degradation of piping due to corrosion or erosion.

11.5.1 Basic Wall Calculation

- Careful attention to unit consistency must be exercised.
- The basic wall thickness must be adjusted as follows:

$$t_{min} = t + A \qquad (11\text{–}10)$$

where *A* is a corrosion allowance based on the chemical properties of the pipe and the fluid and the design life of the piping.

11.5.1 Basic Wall Calculation

- The nominal minimum wall thickness is computed from

$$t_{nom} = t_{min}/(1 - 0.125) = t_{min}/0.875) = 1.143t_{min} \qquad (11–11)$$

$$t_{nom} = 1.143\left[\frac{pD}{2(SE + pY)} + A\right] \qquad (11–12)$$

11.5.2 Stress Due to Piping Installation and Operation

- External stresses on piping combine with the hoop and longitudinal stresses created by the internal fluid pressure.
- You should carefully design the supports for the piping system to minimize external stresses and to obtain a balance between constraining the pipe and allowing for expansion and contraction due to pressure and temperature changes.