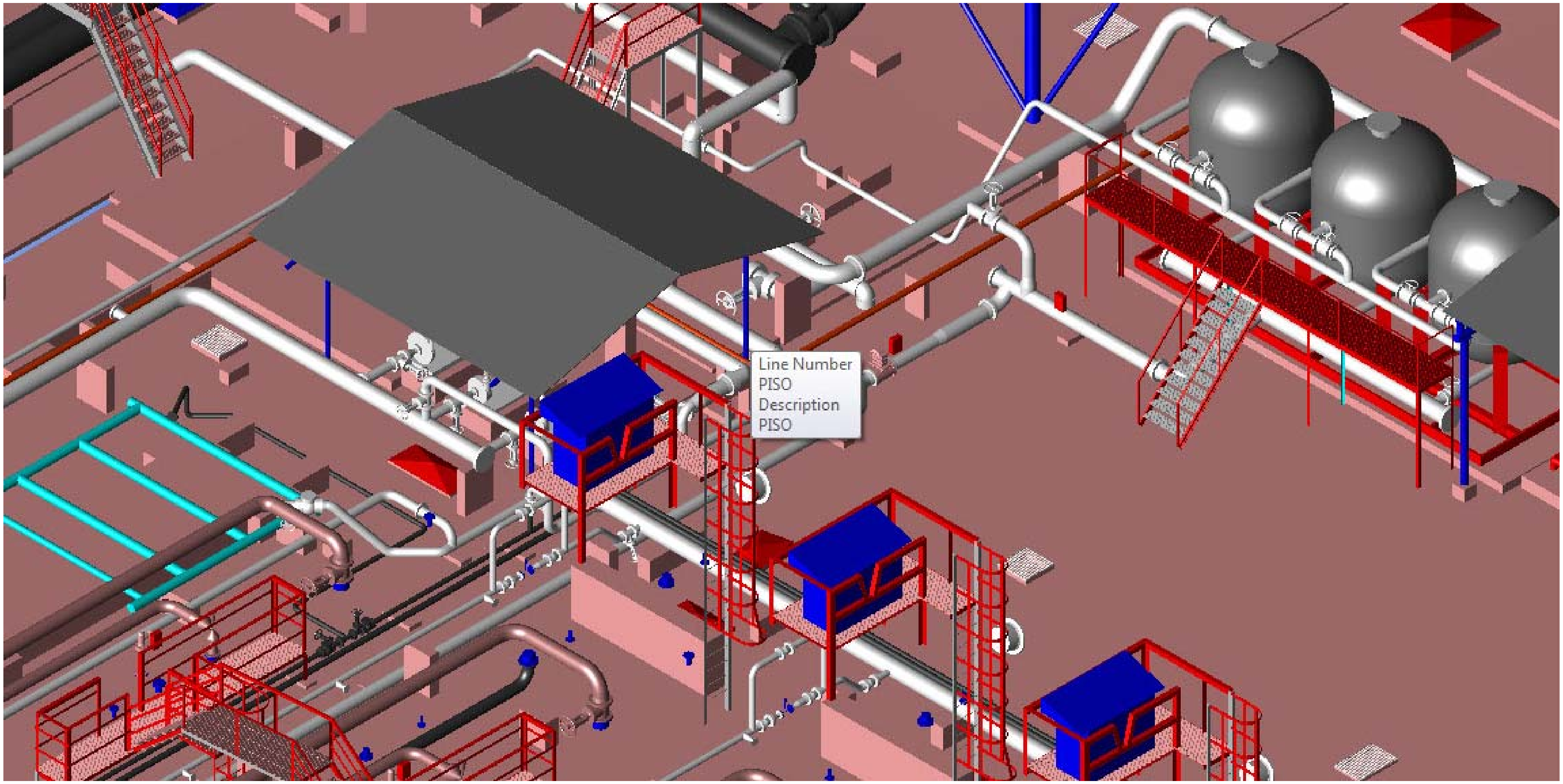
Steady Flow in Pipe Networks



Prof. Arturo S. Leon, Ph.D., P.E., D.WRE
Florida International University

Video of pipe flows

3D Petrochemical Refinery

https://www.youtube.com/watch?v=tkmozP-97M4

Typical components of a pipe system

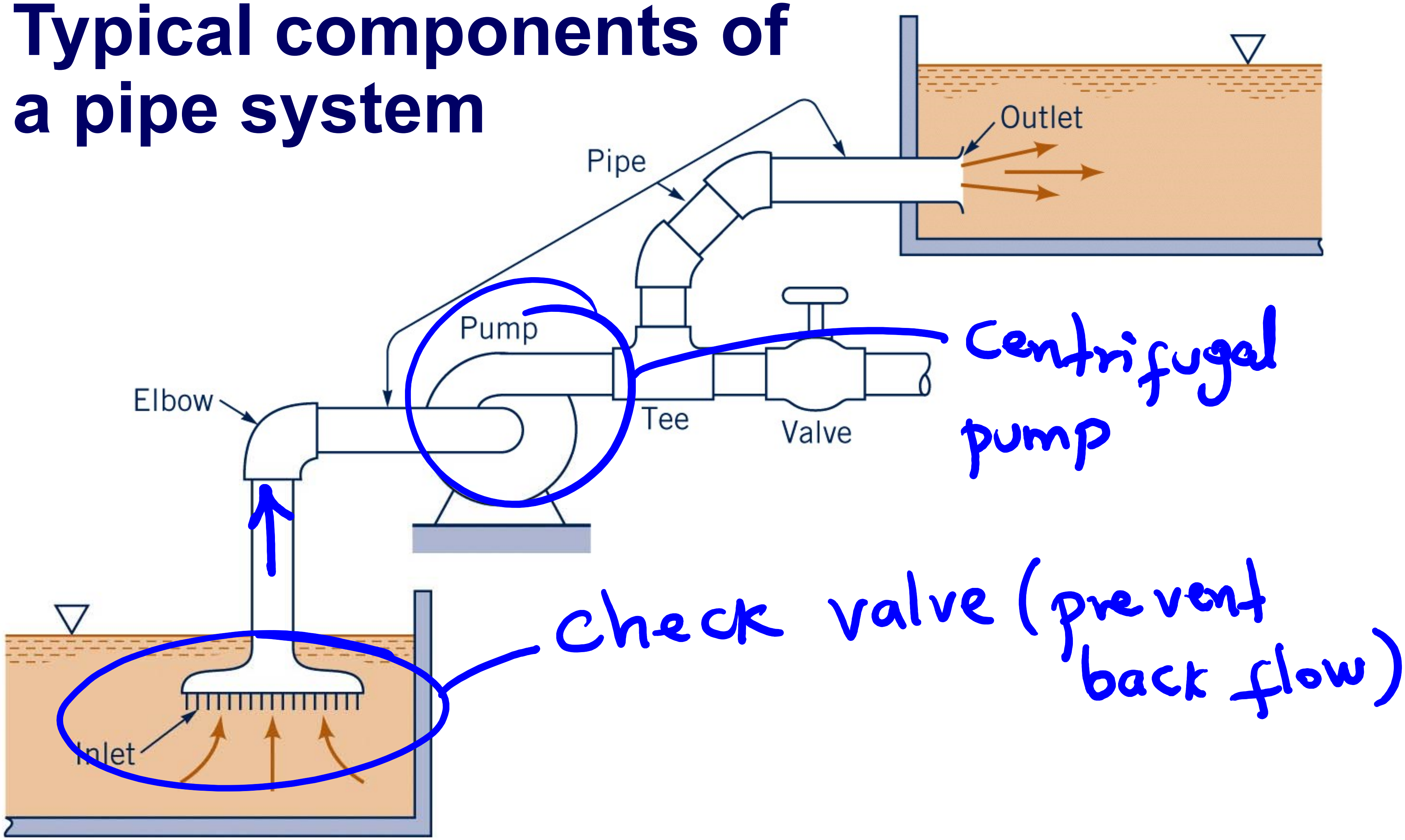
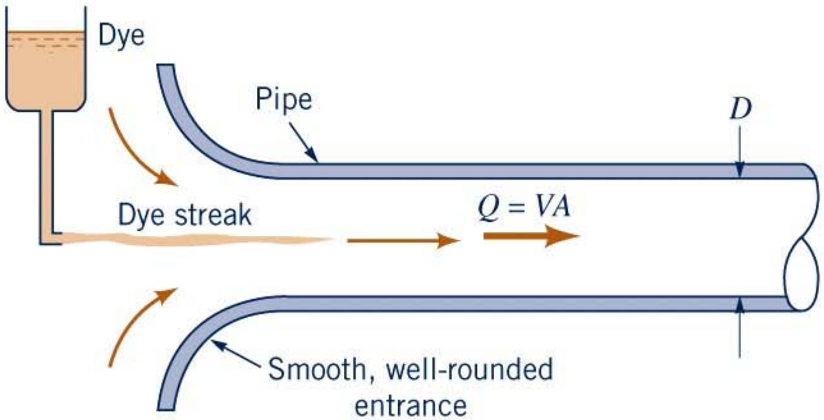


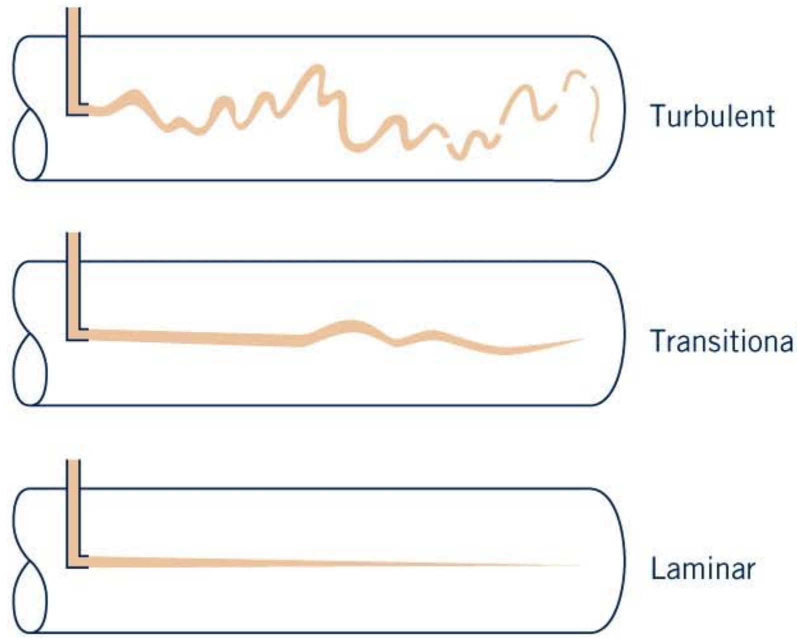
Figure 8.1

Laminar or Turbulent Flow?



$$Re = \frac{V \cdot D}{\nu}$$

(a)



(b)

Figure 8.3

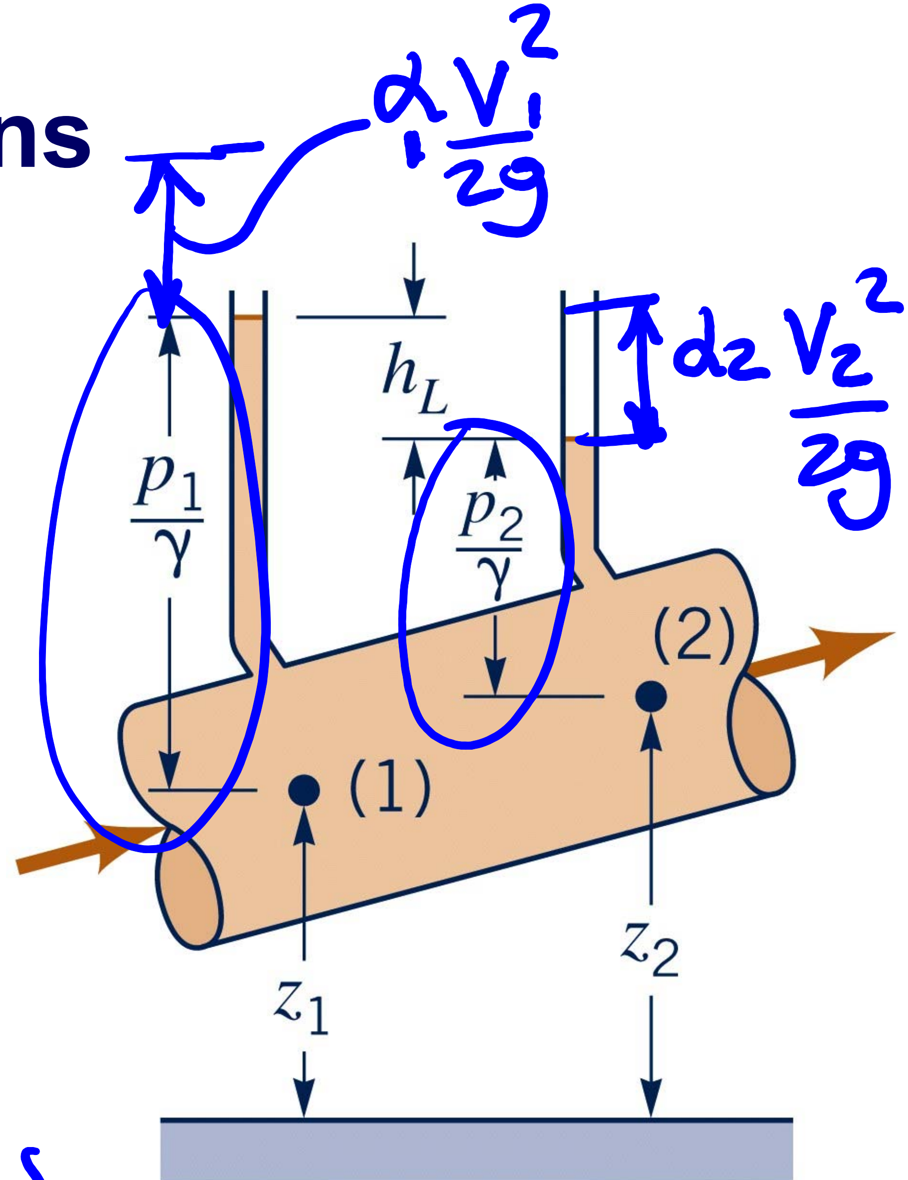
Typical dye streaks

V: velocity
D: Diameter
ν: kinematic viscosity

$Re \leq 2000$ (Laminar)
$2000 < Re < 4000$ (transitional)
$Re \geq 4000$ (turbulent)

Energy considerations

$$\frac{p_1}{\gamma} + \alpha_1 \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \alpha_2 \frac{V_2^2}{2g} + z_2 + h_L$$



$\frac{P}{\gamma}$: Pressure head (Static pressure)

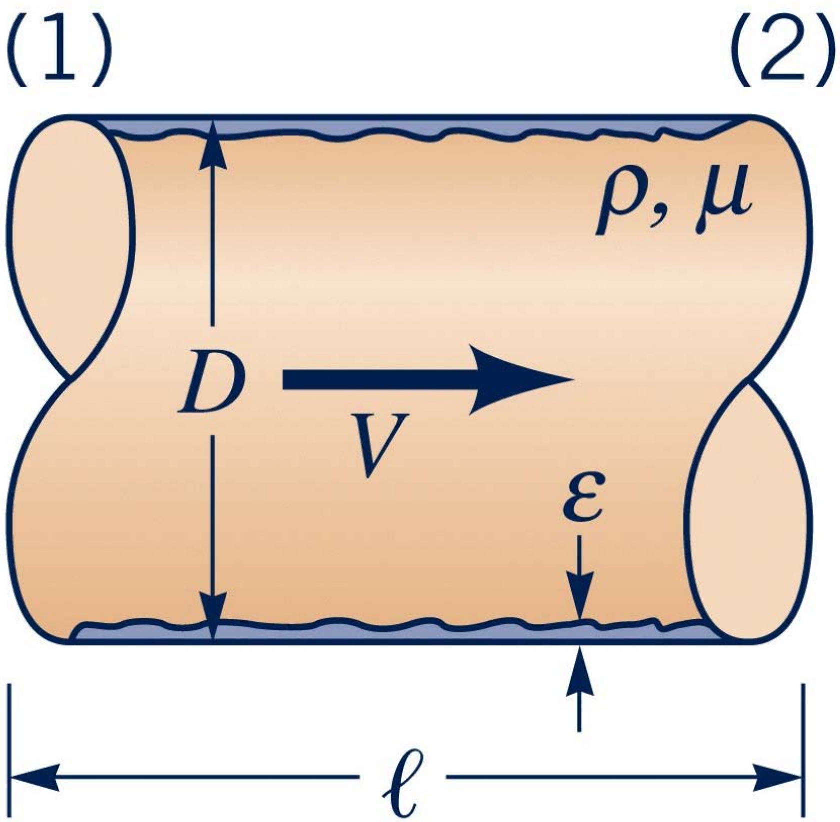
$\frac{V^2}{2g}$: velocity head

$\alpha_1, \alpha_2 \approx 1.0$ for most applications

z : elevation head

Total head losses: Major + Minor

Major losses (pipe friction)



$$h_{L\,\text{major}} = f\,\frac{\ell}{D}\,\frac{V^2}{2g}$$

The Moody chart

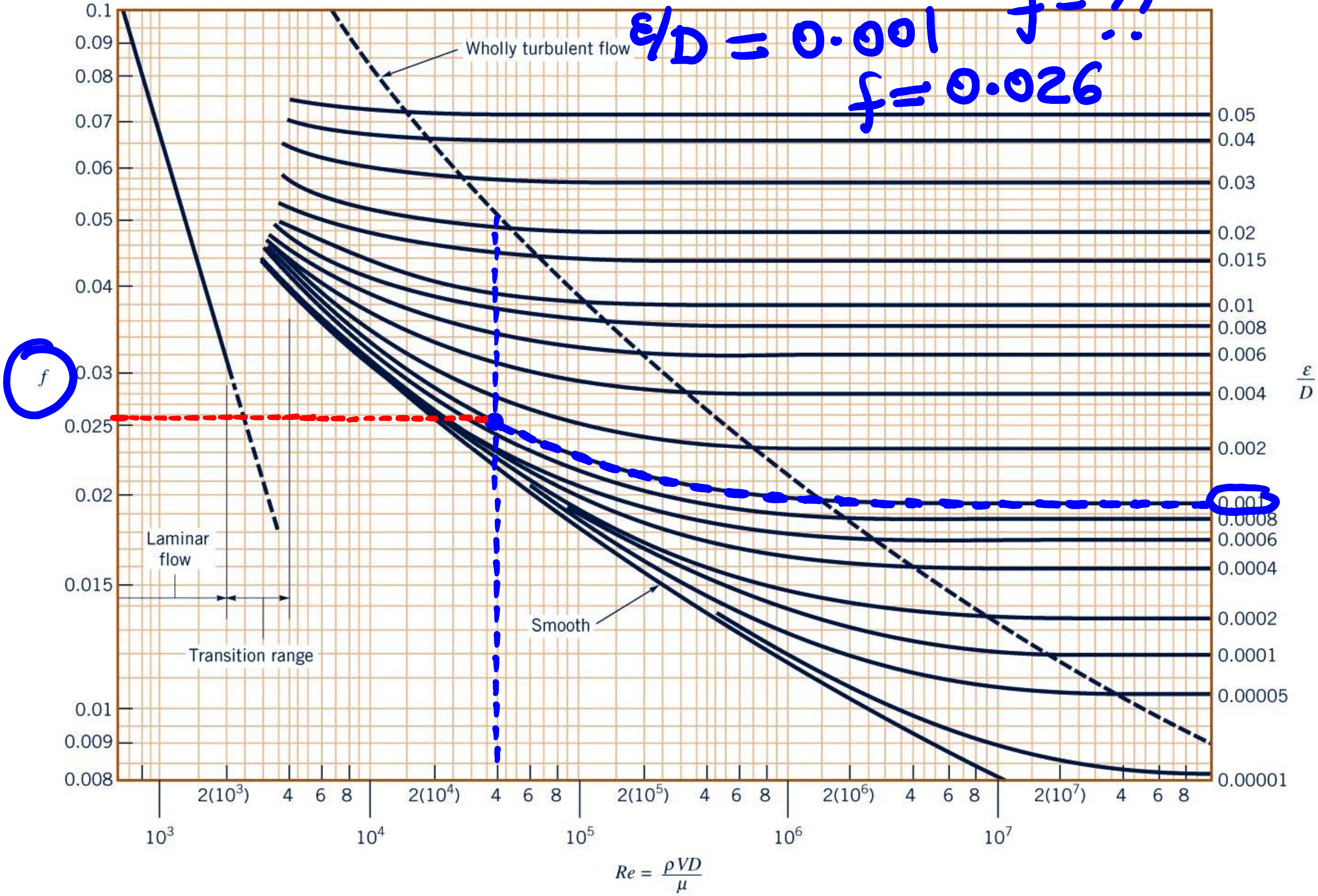
f: friction factor

$Re = 4 \times 10^4$

$\varepsilon/D = 0.001$

$f = ??$

$f = 0.026$



Friction factor for the entire nonlaminar range

Iteration is required

Colebrook formula (Implicit)

$$\frac{1}{\sqrt{f}} = -2.0 \log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}}\right)$$

No iteration is required

Haaland formula (Explicit)

$$\frac{1}{\sqrt{f}} = -1.8 \log_{10}\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{\text{Re}}\right]$$

Table 8.1

Equivalent Roughness for New Pipes [Adapted from Moody (Ref. 7) and Colebrook (Ref. 8)]

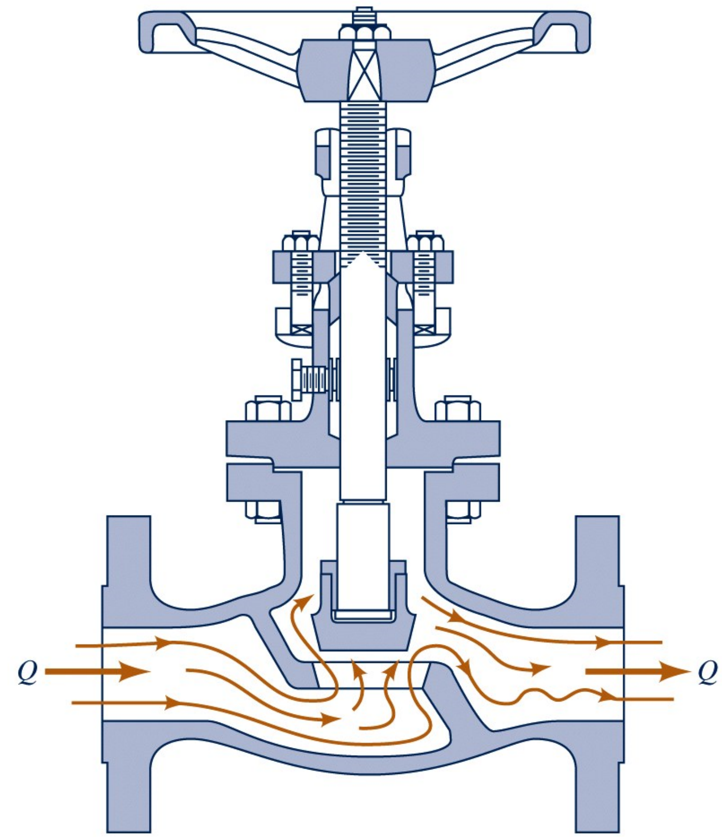
	Equivalent Roughness, ε	
Pipe	**Feet**	**Millimeters**
Riveted steel	0.003–0.03	0.9–9.0
Concrete	0.001–0.01	0.3–3.0
Wood stave	0.0006–0.003	0.18–0.9
Cast iron	0.00085	0.26
Galvanized iron	0.0005	0.15
Commercial steel or wrought iron	0.00015	0.045
Drawn tubing	0.000005	0.0015
Plastic, glass	0.0 (smooth)	0.0 (smooth)

Table 8.1

low high
(depends on surface finishing)

Minor losses (Local losses)

(a)



(b)

$$h_{L\,\mathrm{minor}} = K_L \frac{V^2}{2g}$$

K_L : Local loss coefficient

Entrance flow conditions and loss coefficient

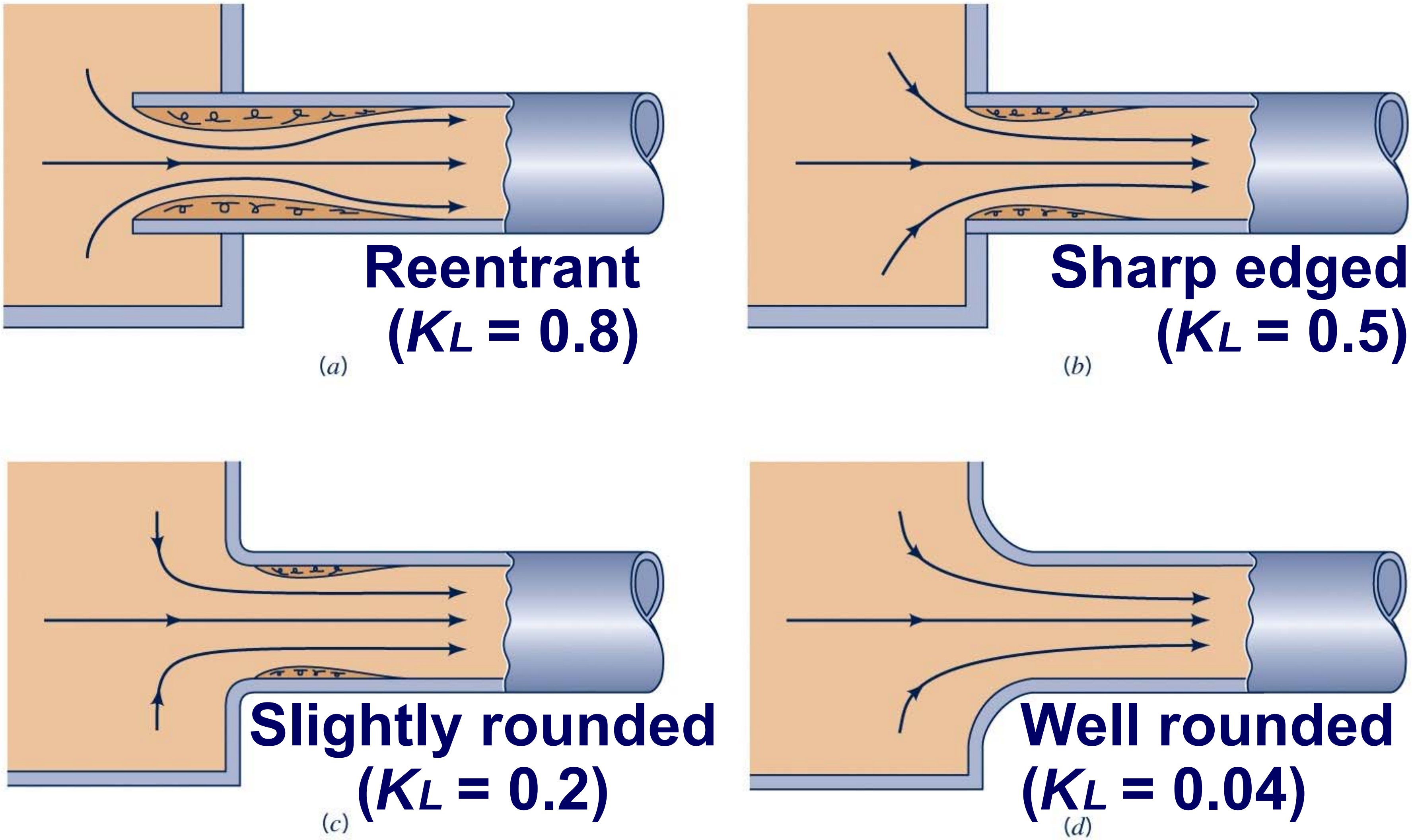


Figure 8.22

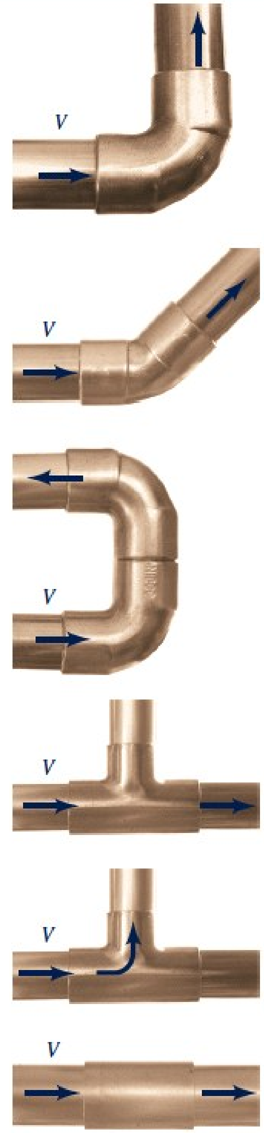
Head Loss coefficients

Threaded elbow

Flanged elbow

Loss Coefficients for Pipe Components $\left(h_L = K_L \frac{V^2}{2g}\right)$ (Data from Refs. 5, 10, 27)

Component	K_L
a. Elbows	
Regular 90°, flanged	0.3
Regular 90°, threaded	1.5
Long radius 90°, flanged	0.2
Long radius 90°, threaded	0.7
Long radius 45°, flanged	0.2
Regular 45°, threaded	0.4
b. 180° return bends	
180° return bend, flanged	0.2
180° return bend, threaded	1.5
c. Tees	
Line flow, flanged	0.2
Line flow, threaded	0.9
Branch flow, flanged	1.0
Branch flow, threaded	2.0
d. Union, threaded	0.08
***e. Valves**	
Globe, fully open	10
Angle, fully open	2
Gate, fully open	0.15
Gate, $\frac{1}{4}$ closed	0.26
Gate, $\frac{1}{2}$ closed	2.1
Gate, $\frac{3}{4}$ closed	17
Swing check, forward flow	2
Swing check, backward flow	∞
Ball valve, fully open	0.05
Ball valve, $\frac{1}{3}$ closed	5.5
Ball valve, $\frac{2}{3}$ closed	210



90° elbow

45° elbow

180° return bend

Tee

Tee

Union

Example:

A 40-m long, 12-mm diameter pipe with a friction factor of 0.020 is used to siphon 30°C water from a tank as shown in Fig. 8.50. Determine the maximum value of *h* allowed if there is to be no cavitation within the hose. Neglect minor losses.

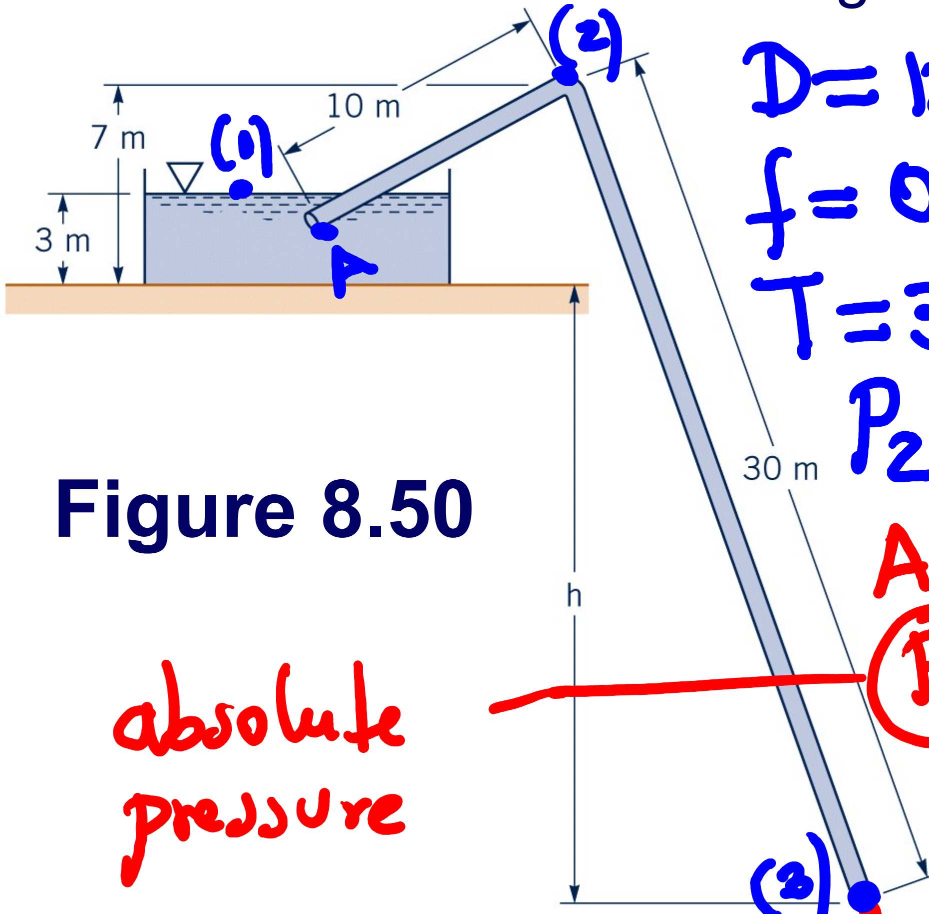


Figure 8.50

$D = 12\ mm\ (0.012\ m)$

$f = 0.020$

$T = 30°C$

$P_2 = P_v$ (Vapour pressure)

Any Fluid Mechanics book

$P_v (T = 30°C) = 4.24 \times 10^3\ \frac{N}{m^2}$

absolute pressure

$P = P_{atm}$

$\rho_{(T=30°C)} = 995.7\ kg/m^3$

$$\gamma_{30^\circ C} = \rho \cdot g = 9.768\ \frac{kN}{m^3}$$

$* \quad E_1 = E_2$

$$\frac{P_1}{\gamma} + \cancel{\frac{V_1^2}{2g}} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_{L_{1-2}}$$

≈ 0

$$\boxed{P_1 = P_{atm}}$$

$$\frac{101.3\ \cancel{kN}/m^2}{9.768\ \cancel{kN}/m^3} + 0 = \frac{4.24\ \cancel{kN}/m^2}{9.768\ \cancel{kN}/m^3} + \frac{V_2^2}{2g} + 4 + \frac{0.020 \times 10}{0.012}\left(\frac{V_2^2}{2g}\right)$$

$$\boxed{V_2 = 2.56\ m/s}$$

$* \quad Q = A \cdot V$

$$V_2 = V_3 = 2.56\ m/s$$

$* \quad E_1 = E_3 \approx 0$

$$\cancel{\frac{P_1}{\gamma}} + \cancel{\frac{V_1^2}{2g}} + z_1 = \cancel{\frac{P_3}{\gamma}} + \frac{V_3^2}{2g} + z_3 + h_{L_{1-3}}$$

$$h_{L} = \frac{f L}{D}\frac{V^2}{2g}$$

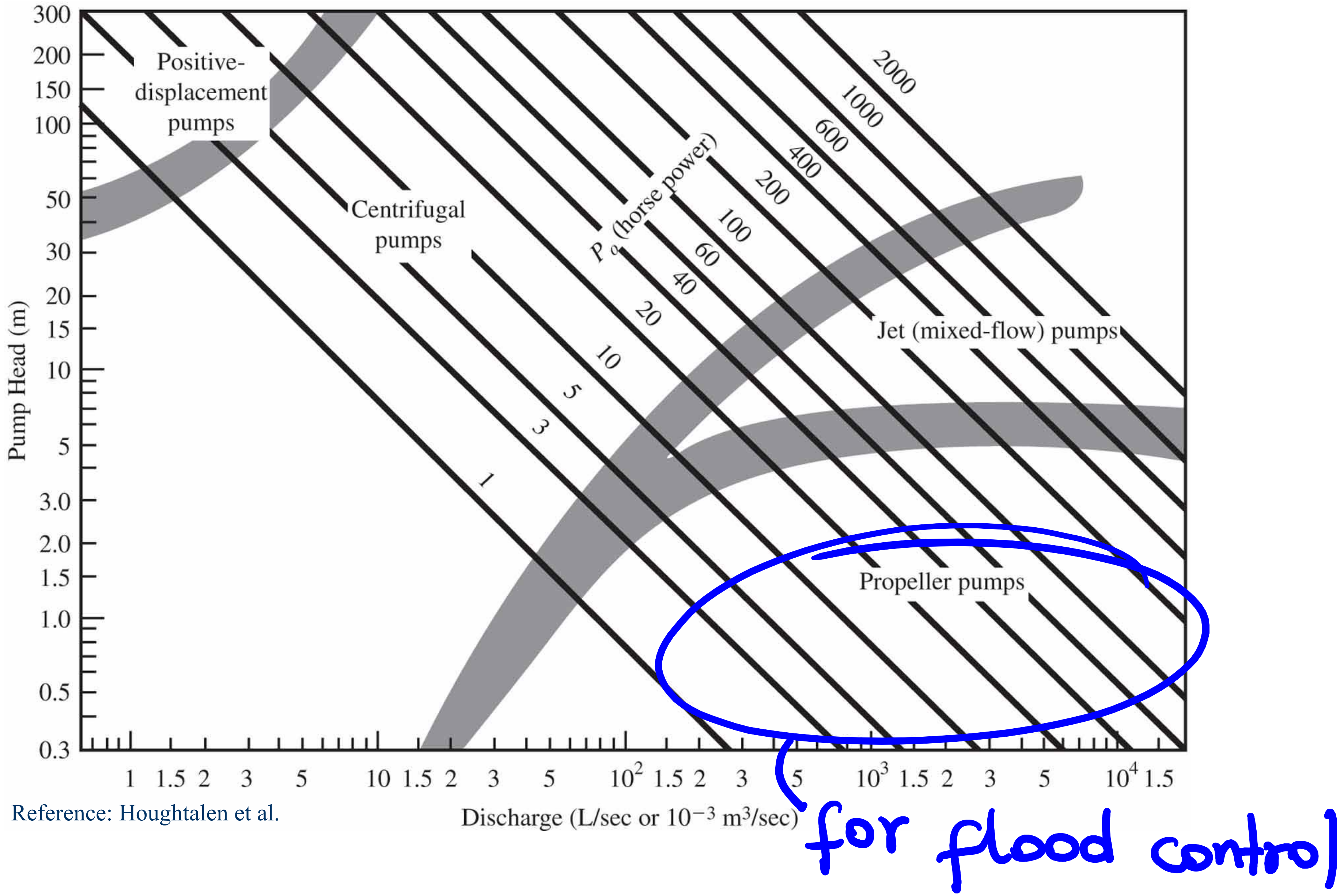
$$h + 3 = \frac{2.56^2}{2 \times 9.81}\left[1 + \frac{0.020 \times 40}{0.012}\right]$$

$$\boxed{h = 19.6\ \text{m}}$$

Hydraulic Pumps

Arturo S. Leon, Ph.D., P.E., D.WRE

Typical discharge, head, and power requirements for different types of pumps

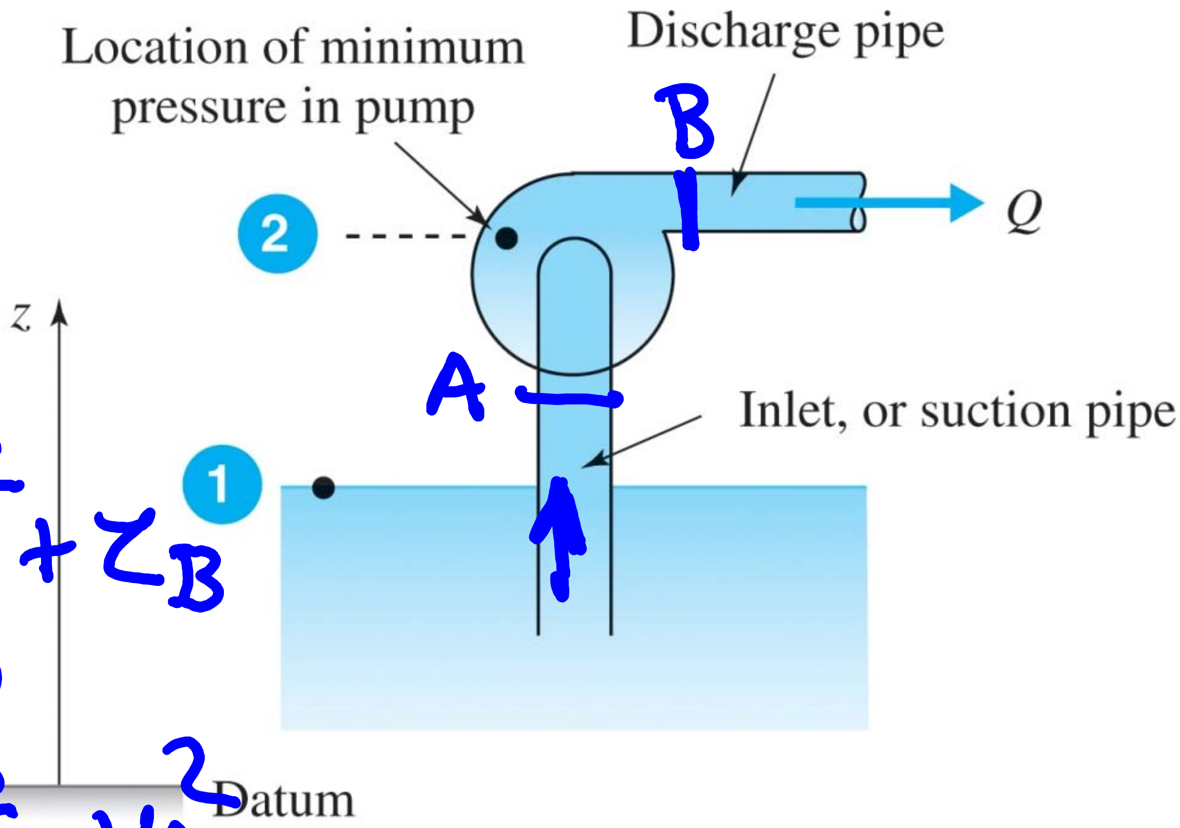


Reference: Houghtalen et al.

Pump Performance Characteristics

$$E_A + H_p = E_B$$

$$\frac{P_A}{\gamma} + \frac{V_A^2}{2g} + z_A + H_p = \frac{P_B}{\gamma} + \frac{V_B^2}{2g} + z_B$$



$$H_p = \frac{P_B - P_A}{\gamma} + \frac{V_B^2 - V_A^2}{2g} + z_B - z_A$$

H_p = actual head gained by the fluid from the pump

For large pressure heads

$$H_p \approx \frac{P_B - P_A}{\gamma}$$

theoretical power

Pump Performance Characteristics (Cont.)

$$P = \frac{\gamma Q H_p}{550}$$

P : Power in HP (horsepower)

$$\eta = \frac{\text{power gained by the fluid}}{\text{shaft power driving the pump (bhp)}}$$

$$\eta = \frac{\gamma Q H_p}{550(bhp)}$$

bhp: brake horse power

$$bhp = \frac{\gamma Q H_p}{550\,\eta}$$

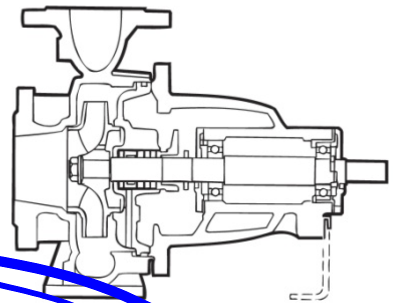
Where: γ in lb/ft^3, Q in ft^3/s and H_p in ft

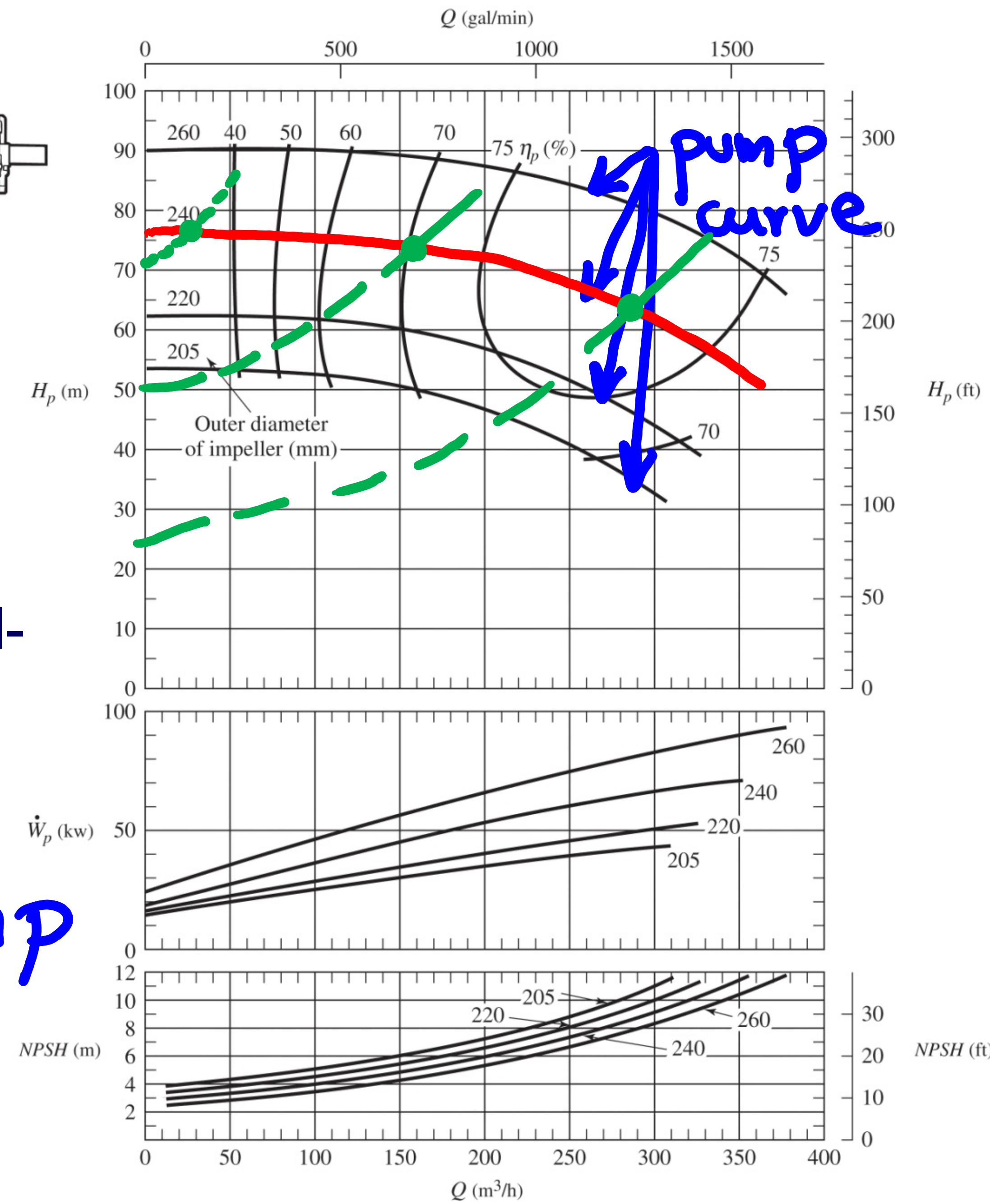
$\boldsymbol{\eta}$ = overall efficiency

Pump Performance Characteristics (Cont.)

Performance curves for four different impellers for a radial-flow pump (2900 RPM)

provided by pump manufacturer



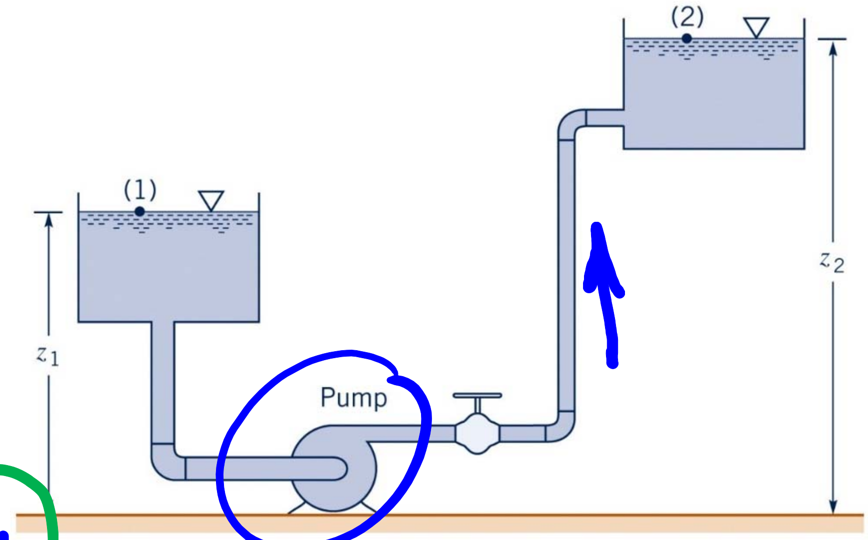


pump curve

Fig. 12.6 Radial-flow pump and performance curves for four different impellers with $N = 2900$ rpm ($\omega = 304$ rad/s). Water at 20°C is the pumped liquid. (Courtesy of Sulzer Pumps Ltd.)

System Characteristics and Pump Selection

The energy equation between points (1) and (2) gives



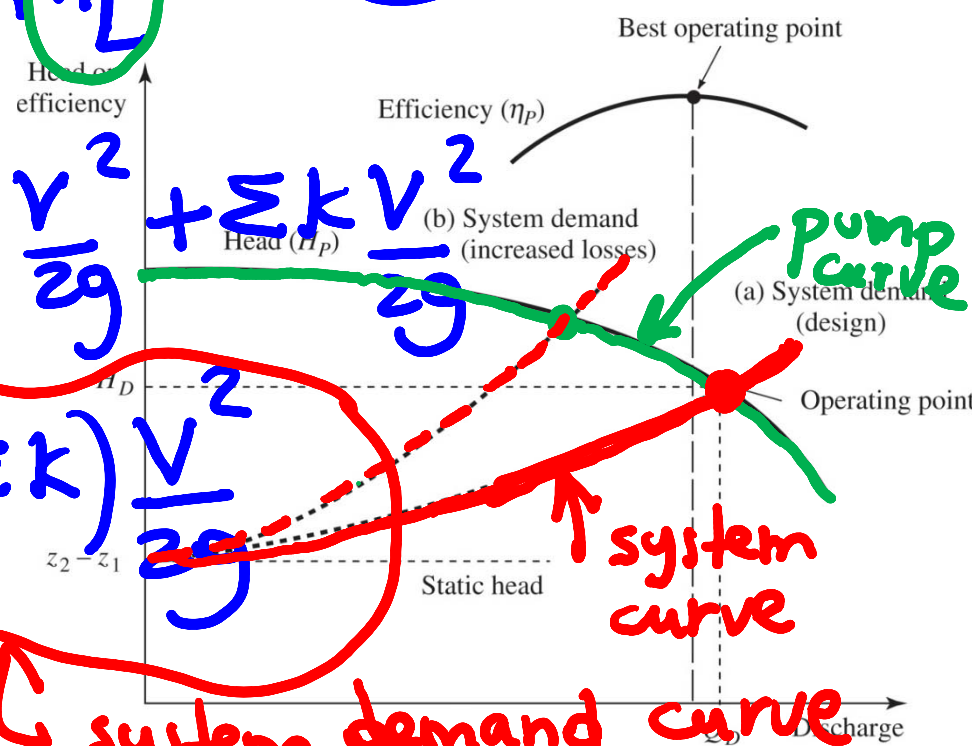
$$E_1 + H_p = E_2$$

$$\cancel{\frac{P_1}{\gamma}} + \underbrace{\frac{V_1^2}{2g}}_{\approx 0} + z_1 + H_p = \cancel{\frac{P_2}{\gamma}} + \underbrace{\frac{V_2^2}{2g}}_{\approx 0} + z_2 + h_L$$

$$H_p = z_2 - z_1 + \frac{fL}{D}\frac{V^2}{2g} + \Sigma k \frac{V^2}{2g}$$

$$\boxed{H_p = z_2 - z_1 + \left(\frac{fL}{D} + \Sigma k\right)\frac{V^2}{2g}}$$

system demand curve



H_p = actual head gained by the fluid from the pump

System Characteristics and Pump Selection

- To select a pump, it is necessary to utilize both the **system curve** **(determined by the system equation)**, and the **pump performance curve**.
- The intersection of both curves represents the **operating point for the system**.
- The operating point should be near the best efficiency point.

Pumps in Parallel

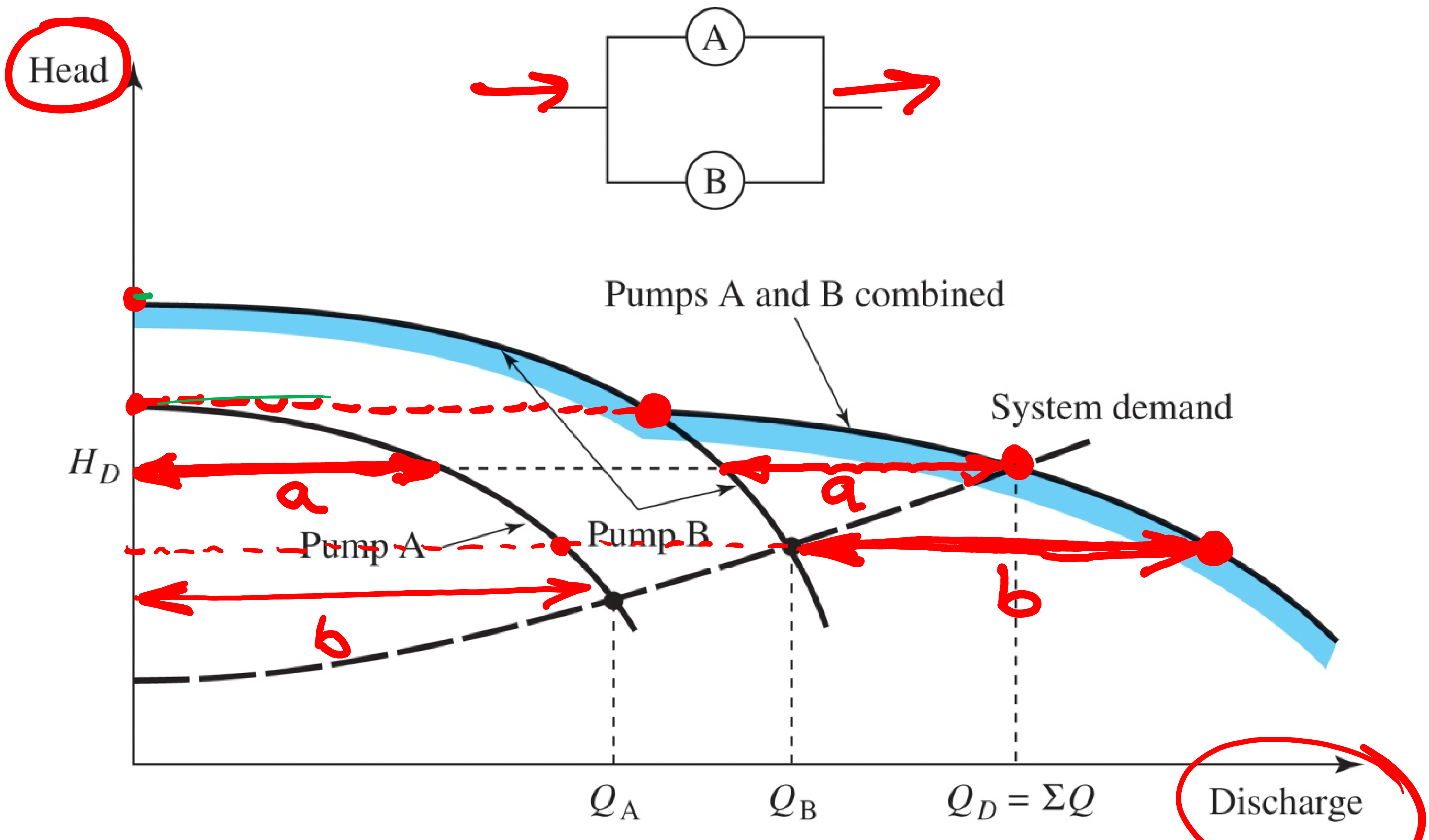


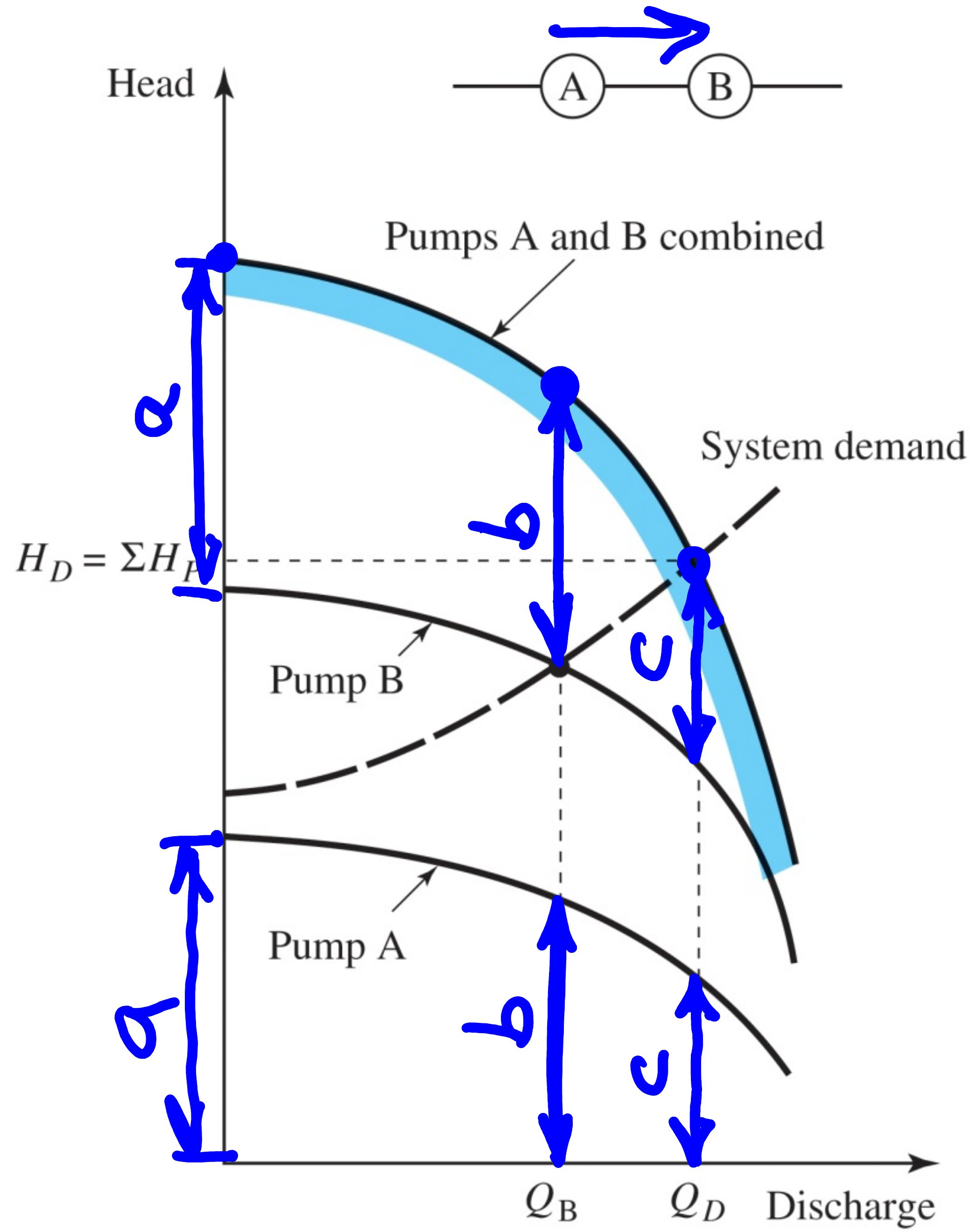
Fig. 12.17 Characteristic curves for pumps operating in parallel.

Pumps in Series

Q with only pump A
= 0

Q with only pump B
= Q_B

Q with both pumps
= Q_D



Effect of ope

Fig. 12.18 Characteristic curves for pumps operating in series.

Example 12.7. Water is pumped between two reservoirs in a pipeline with the following characteristics:
D = 300 mm, L = 70 m, f = 0.025, ΣK = 2.5. The radial-flow pump characteristic curve is approximated by the formula

$$\boxed{H_P = 22.9 + 10.7Q - 111Q^2} \quad \ldots \; 1$$

pump curve

where H_P is in meters and Q is in m^3/s. Determine the discharge Q_D and pump head H_D for the following situations:
(a) $z_2 - z_1$ = 15 m, one pump placed in operation; (b) $z_2 - z_1$ = 15 m, with two identical pumps operating in parallel; and (c) the pump layout, discharge, and head for $z_2 - z_1$ = 25 m.

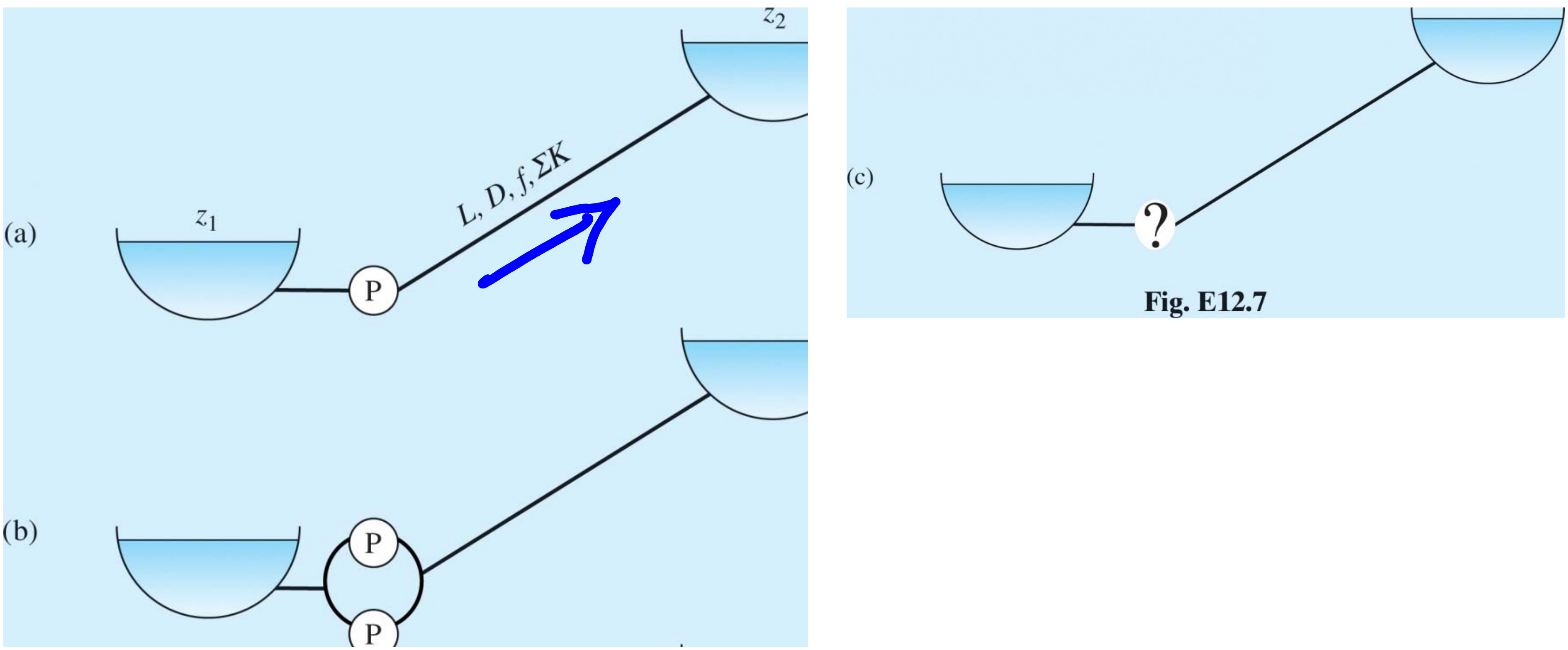


Fig. E12.7

a) $Z_2 - Z_1 = 15\,m$ [one pump].

System curve: $H_p = Z_2 - Z_1 + \left(\frac{fL}{D} + \Sigma k\right) \frac{Q^2}{2gA^2}$

$$H_p = 15 + \left(\frac{0.025 \times 70}{0.3} + 2.5\right) \frac{Q^2}{2 \times 9.81 \times \left[\frac{\pi \times 0.3^2}{4}\right]^2}$$

$$\boxed{H_p = 15 + 85.09\,Q^2} \quad \ldots (2)$$

(1) = (2) $\quad 15 + 85.09\,Q^2 = 22.9 + 10.7\,Q - 111\,Q^2$

$$Q = 0.23\ m^3/s$$

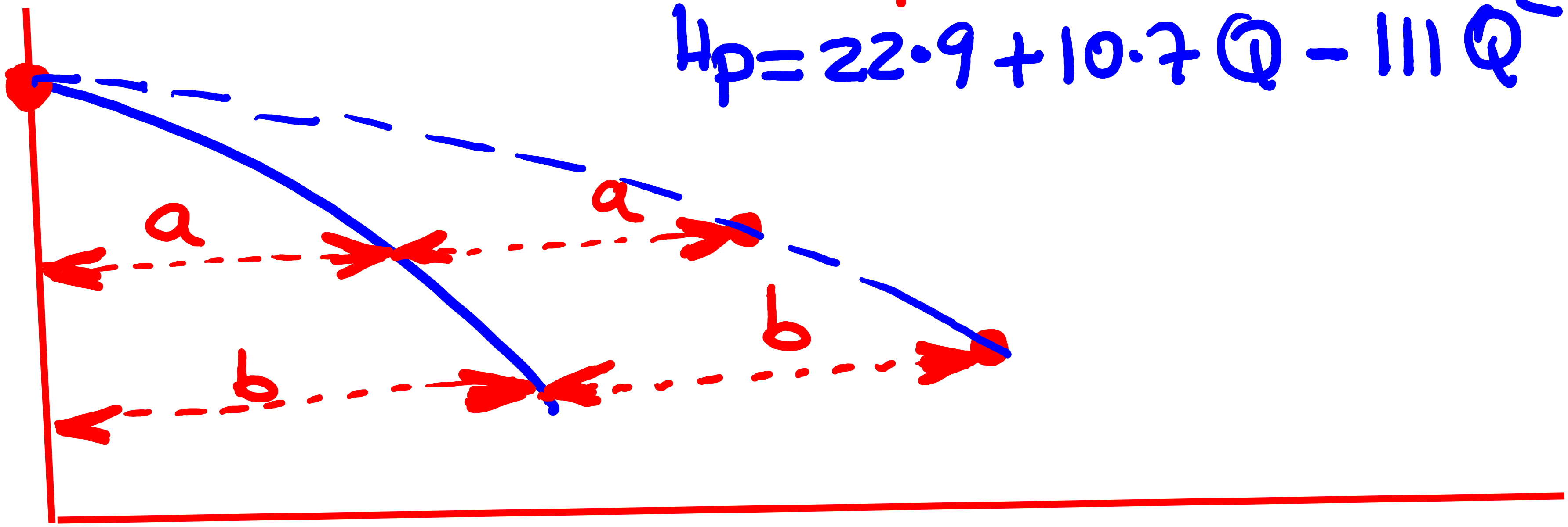
In (1) or (2)

$$H_p = 19.5\ m$$

ⓑ $Z_2 - Z_1 = 15\,m$, two pumps in parallel.

For one pump:

$$H_p = 22.9 + 10.7\,Q - 111\,Q^2$$



For two pumps: $$H_p = 22.9 + 10.7\left(\frac{Q}{2}\right) - 111\left(\frac{Q}{2}\right)^2$$

For "N" pumps: $$H_p = 22.9 + 10.7\left(\frac{Q}{N}\right) - 111\left(\frac{Q}{N}\right)^2$$

For two pumps in parallel

$$15 + 85.09\,Q^2 = 22.9 + 10.7\left(\frac{Q}{2}\right) - 111\left(\frac{Q}{2}\right)^2$$

$$Q = 0.29\ m^3/s$$

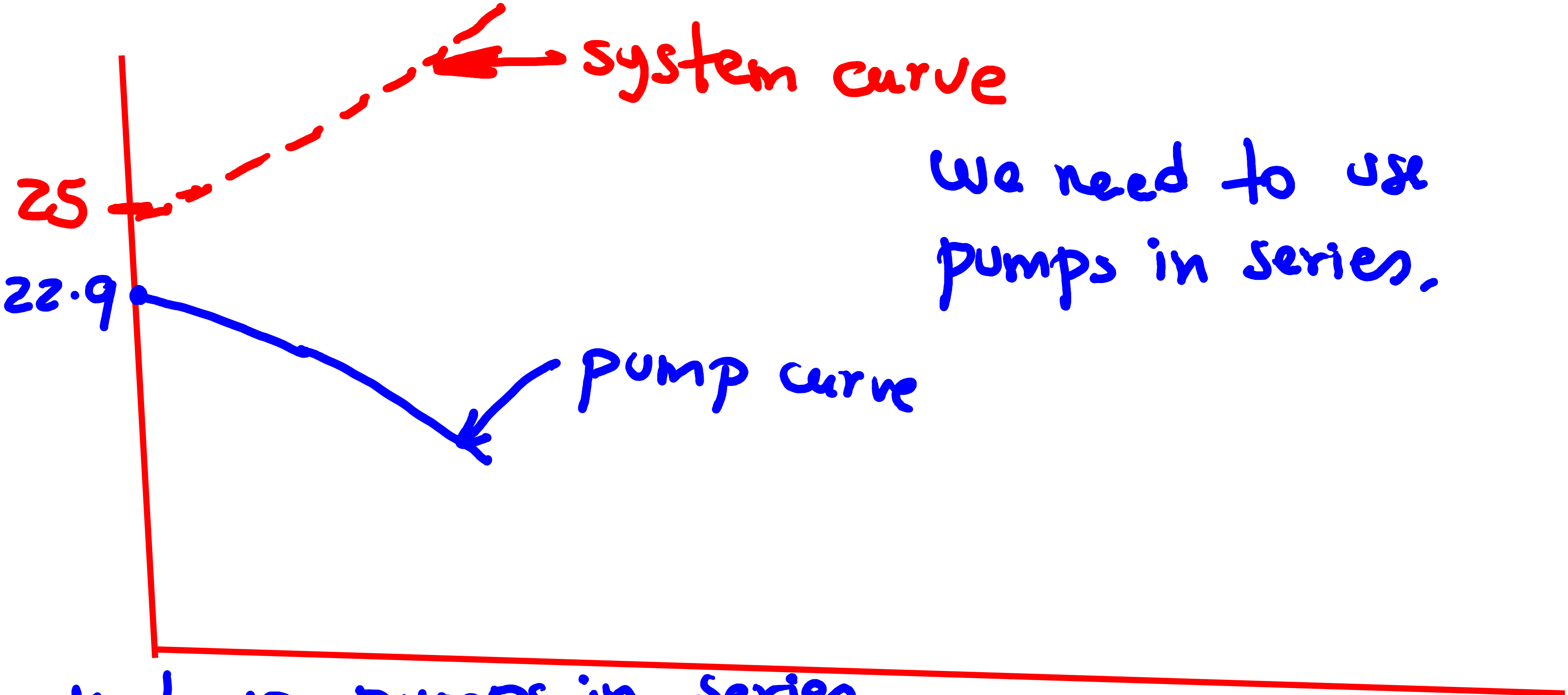
$$H_p = 22.2\ m$$

ⓒ $z_2 - z_1 = 25\ m$

Q, H_p [How many pumps, series or parallel]

System curve

$$H_p = 25 + 85.09\,Q^2$$



We need to use pumps in series.

* two pumps in series.

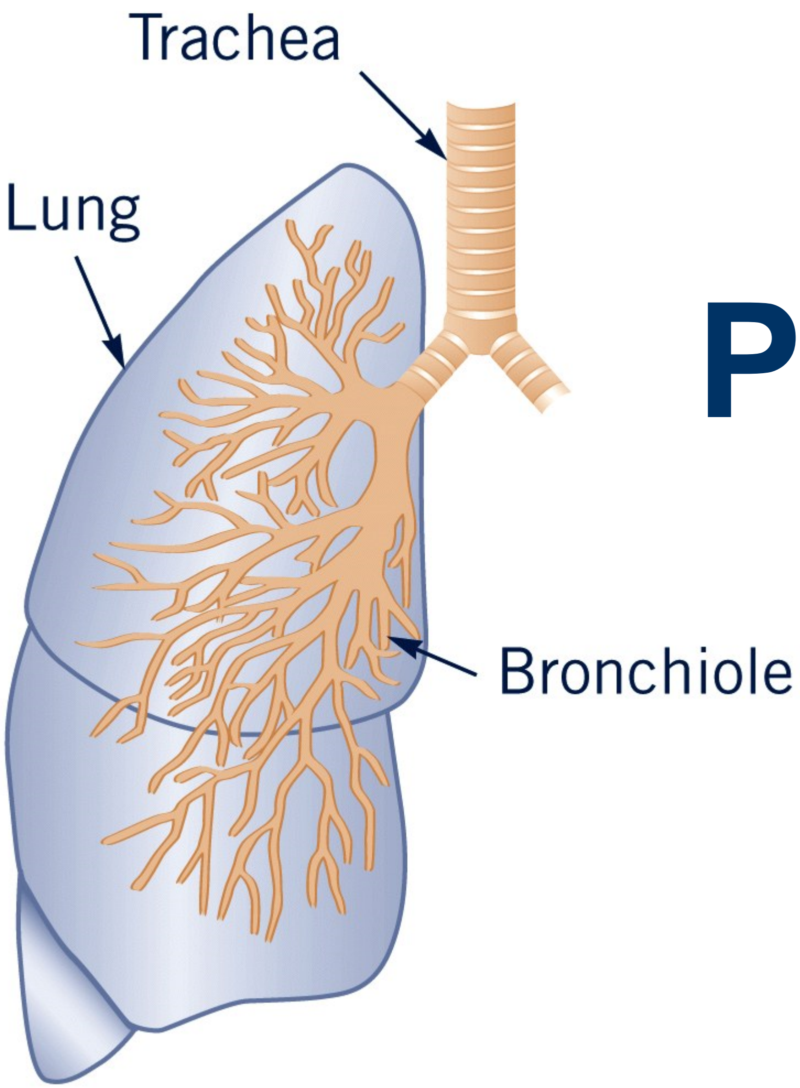
$$H_p = 2\left(22.9 + 10.7Q - 111Q^2\right)$$

* For "N" pumps in series

$$H_p = N\left(22.9 + 10.7Q - 111Q^2\right).$$

$$2\left(22.9 + 10.7Q - 111Q^2\right) = 25 + 85.09\,Q^2$$

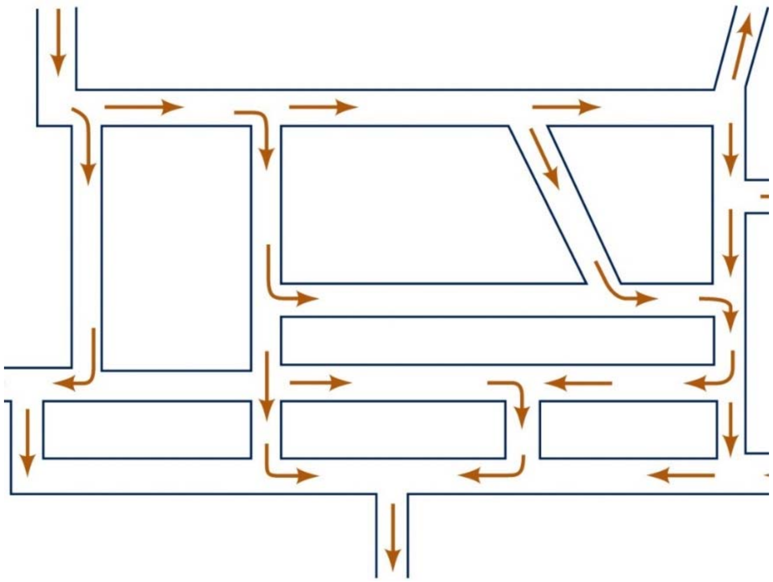
$Q = 0.30\ m^3/s$, $H_p = 32.7\ m$



Pipe Networks

Arturo S. Leon, Ph.D., P.E., D.WRE

Pipe networks



(b)

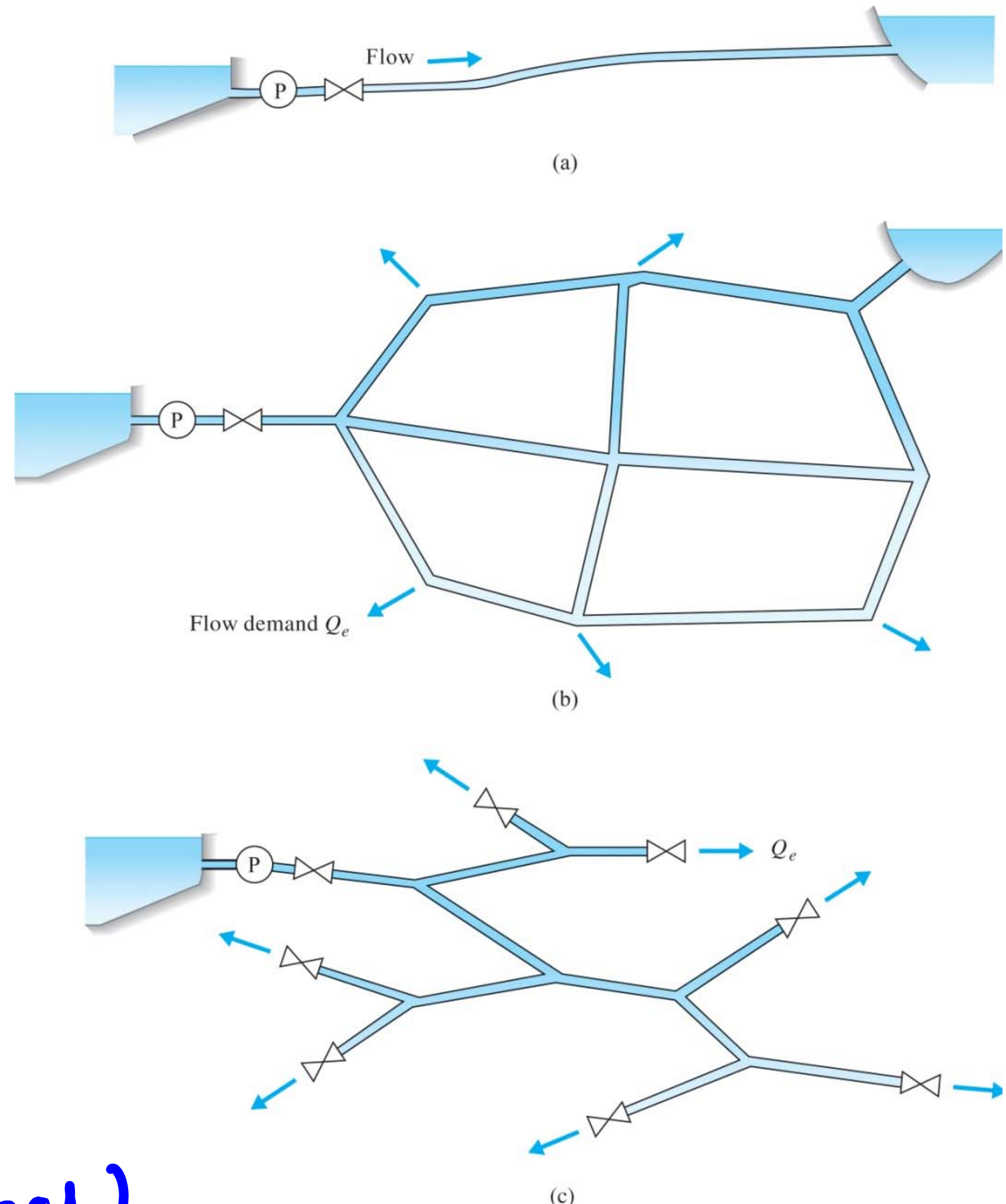


Fig. 11.1 Pipe systems: (a) single pipe; (b) distribution network; (c) tree network.

Assumptions:

* Steady flow
* flow is 1D (bi_directional)

Frictional Losses in Pipe Elements

Frictional losses in piping are commonly evaluated using the **Darcy–Weisbach** or **Hazen–Williams** equation. The Darcy–Weisbach formulation provides a more accurate estimation.

$$h_L = R Q^{\beta}$$

Where:
h_L = head loss over length L of pipe
***R* = Resistance coefficient** **(This is not hydraulic radius)**
Q = discharge in the pipe
β = exponent

<u>Darcy-Weisbach relation</u> (β = 2)

$$h_f = f \frac{L}{D} \frac{V^2}{2g} \qquad \left\{ R = \frac{fL}{2gDA^2} \right.$$

$$f = 1.325 \left\{ \ln_e \left[0.27 \left(\frac{\varepsilon}{D} \right) + 5.74 \left(\frac{1}{Re} \right)^{0.9} \right] \right\}^{-2}$$

Swamee-Jain

$$f = \left\{ -1.8 \log_{10} \left[\left(\frac{\varepsilon}{3.7D} \right)^{1.11} + \frac{6.9}{Re} \right] \right\}^{-2}$$

Haaland

Hazen–Williams equation (For Water)

$$R = \frac{K_1 L}{C^{\beta} D^{m}}$$

$$K_1 = \begin{cases} 10.59 \ (SI) \\ 4.72 \ (English) \end{cases}$$

Where:

C = Hazen–Williams roughness coefficient, $m = 4.87$, $\beta = 1.85$

Table 11.1 Nominal Values of the Hazen–Williams Coefficient C

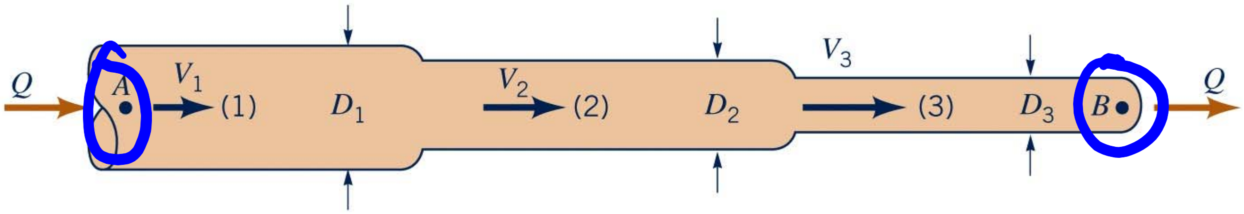
Type of pipe	C
Extremely smooth; asbestos-cement	140
New or smooth cast iron; concrete	130
Wood stave; newly welded steel	120
Average cast iron; newly riveted steel; vitrified clay	110
Cast iron or riveted steel after some years of use	95–100
Deteriorated old pipes	60–80

Simple Pipe Systems

$Q_1 = Q_2 = Q_3$

Series Piping System

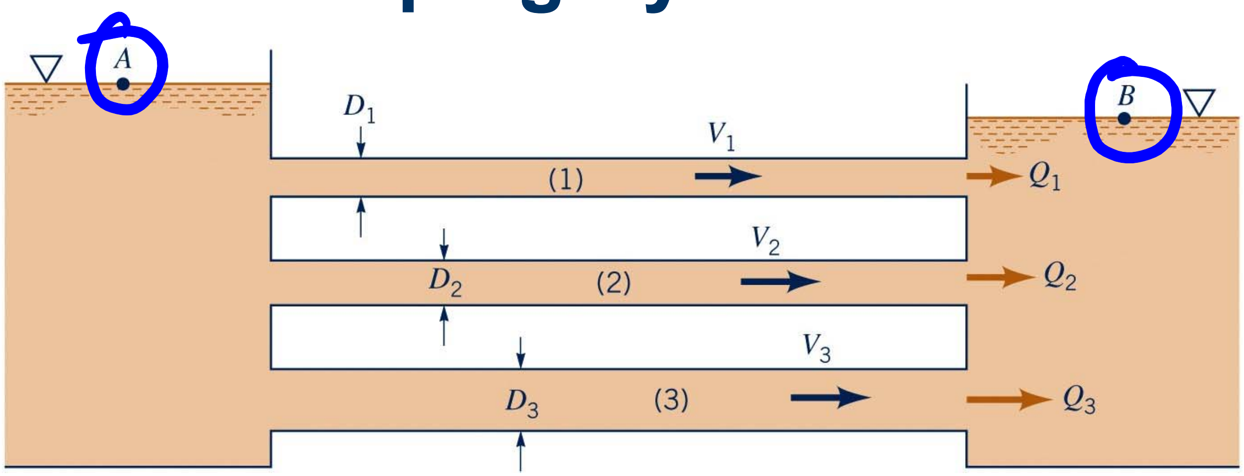
$h_{L_{A-B}} = h_{L_1} + h_{L_2} + h_{L_3}$



Parallel Piping System

$Q_{AB} = Q_1 + Q_2 + Q_3$

$h_{L_{AB}} = h_{L_1} = h_{L_2} = h_{L_3}$



Branch Piping

$$\sum Q_{node} = 0$$

$$\sum Q_{in} = \sum Q_{out}$$

$$Q_1 = Q_2 + Q_3$$

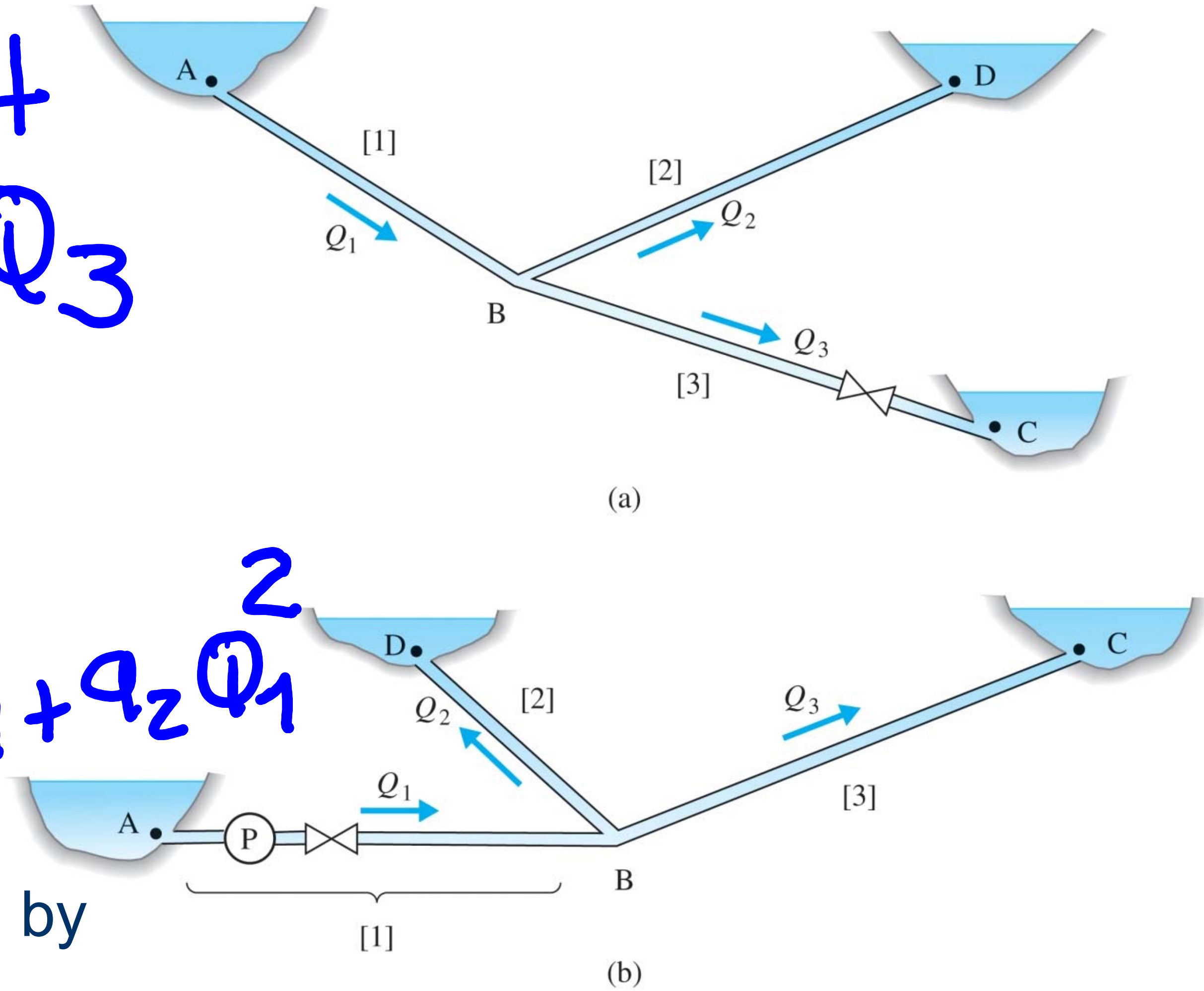


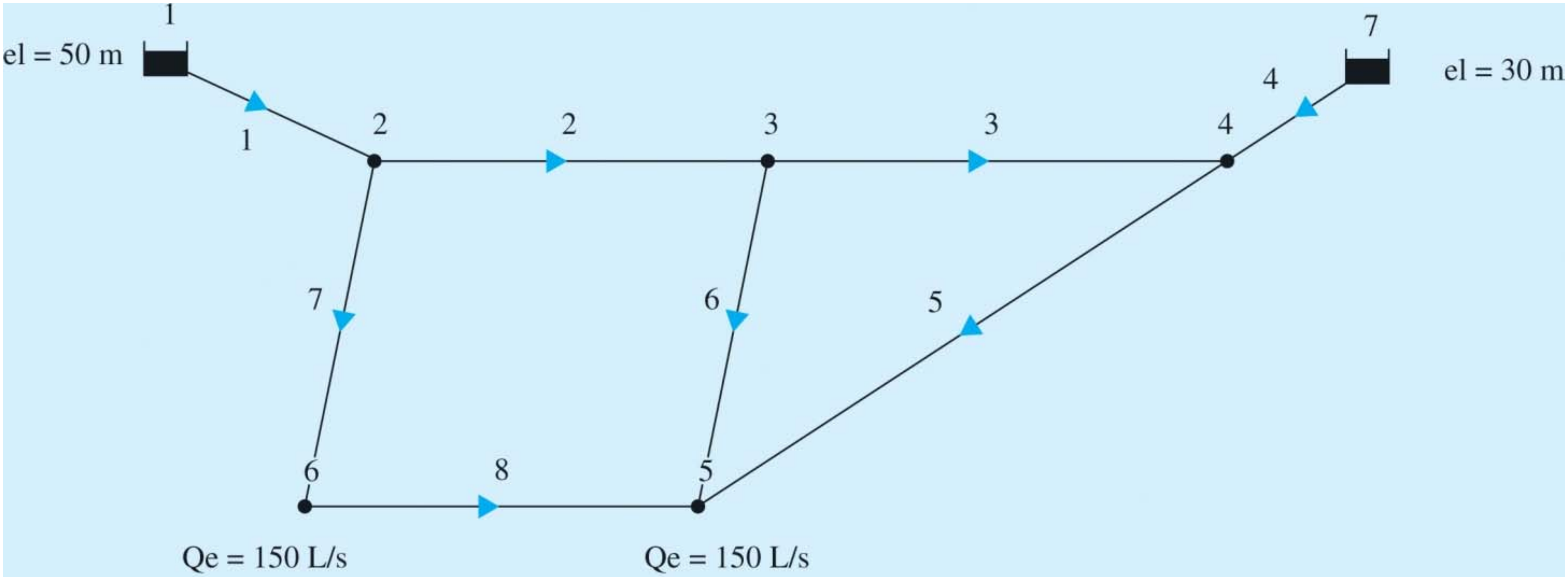
Fig. 11.5 Branch piping systems: (a) gravity flow; (b) pump-driven flow.

Approximation of pump curves:

$$H_p(Q_1) = a_0 + a_1 Q_1 + a_2 Q_1^2$$

H_p = actual head gained by the fluid from the pump

Example 11.7. For the piping system (**commercial steel**) shown below, determine the flow distribution and piezometric heads at the junctions. Use the **EPANET Model** (https://www.epa.gov/water-research/epanet).



Show demo on how to use the EPANET Model

Link – Node Table:

Link ID	Start Node	End Node	Length m	Diameter mm
1	1	2	66	250
2	2	3	330	250
3	3	4	130	250
4	4	7	66	250
5	4	5	260	250
6	3	5	200	250
7	2	6	200	250
8	6	5	260	250

Important Considerations in EPANET

EPANET defaults to gallons per minute and other Customary US units. To change to SI units do the following:
Project > Analysis Options... > Flow Units > LPS (or LPM or other SI units for flow) (This also changes units for pipe lengths and head to meters and pipe diameters to mm.)

- **Length:** The actual length of the pipe in feet (meters)
- **Diameter:** The pipe diameter in inches (mm)
- **Roughness:** The roughness coefficient of the pipe. It is unitless for Hazen-Williams or Chezy-Manning roughness and has units of millifeet (mm) for Darcy-Weisbach roughness.
- **Loss Coefficient:** Unitless minor loss coefficient associated with bends, fittings, etc. Assumed 0 if left blank.
- **Initial Status:** Determines whether the pipe is initially open, closed, or contains a check valve. **If a check valve is specified then the flow direction in the pipe will always be from the Start node to the End node**

Results:

Network Table - Links at 24:00 Hrs

Link ID	Length m	Diameter mm	Roughness mm	Flow LPS	Velocity m/s	Friction Factor	Status
Pipe C1	66	250	0.045	341.34	6.95	0.014	Open
Pipe C2	330	250	0.045	143.08	2.91	0.015	Open
Pipe C3	330	250	0.045	66.54	1.36	0.016	Open
Pipe C8	260	250	0.045	48.26	0.98	0.017	Open
Pipe C7	200	250	0.045	198.26	4.04	0.015	Open
Pipe C6	260	250	0.045	76.54	1.56	0.016	Open
Pipe C5	55	250	0.045	25.19	0.51	0.018	Open
Pipe C4	130	250	0.045	-41.34	0.84	0.017	Open

Network Table - Nodes at 0:00 Hrs

Node ID	Elevation m	Base Demand LPS	Demand LPS	Head m	Pressure m
Junc N2	0	0	0.00	40.79	40.79
Junc N3	0	0	0.00	32.29	32.29
Junc N4	0	0	0.00	30.32	30.32
Junc N6	0	150	150.00	31.11	31.11
Junc N5	0	150	150.00	30.26	30.26
Resvr N1	50	#N/A	-341.34	50.00	0.00
Resvr N7	30	#N/A	41.34	30.00	0.00

Results (Cont.):