EWCE 331
Water Supply Engineering

Lecture 4

Instructor

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Lecture outline

Surface water collection and transmission

Topics	References
• **Water Supply Network Analysis** ✓ **Dead-end Method** ✓ **Equivalent Pipe Method**	**1. A Text Book of Water Supply Engineering** Authors: M. A. Aziz 1st ed., Hafiz Book Center **3. Water Supply and Sanitation** Authors: M. Feroz Ahmed, Md. Mujibur Rahman 1st ed., ITN-BUET **3. Water and Environmental Engineering** Authors: M. Habibur Rahman, Abdullah Al-Muyeed 1st ed., ITN-BUET

Significance/ Purpose of Pipe Network Analysis

- A pipe network is analyzed for the determination of the nodal pressure heads, head loss and the link discharges.

- As the discharges withdrawn from the network vary with time, it results in a continuous change in the nodal pressure heads and the link discharges.

- The network is analyzed for the worst combination of discharge withdrawals that may result in low-pressure heads in some areas.

Significance/ Purpose of Pipe Network Analysis

- It is also required to identify pipe links that would be closed in an emergency to meet firefighting demand in some localities due to limited capacity of the network.
- The effect of closure of pipelines on account of repair work is also studied by analyzing a network.
- Thus, network analysis is critical for proper operation and maintenance of a water supply system.

Hydraulic Analysis of Water Distribution System

Distribution Main:

- A pipeline in which there are multiple withdrawals is called a distribution main.

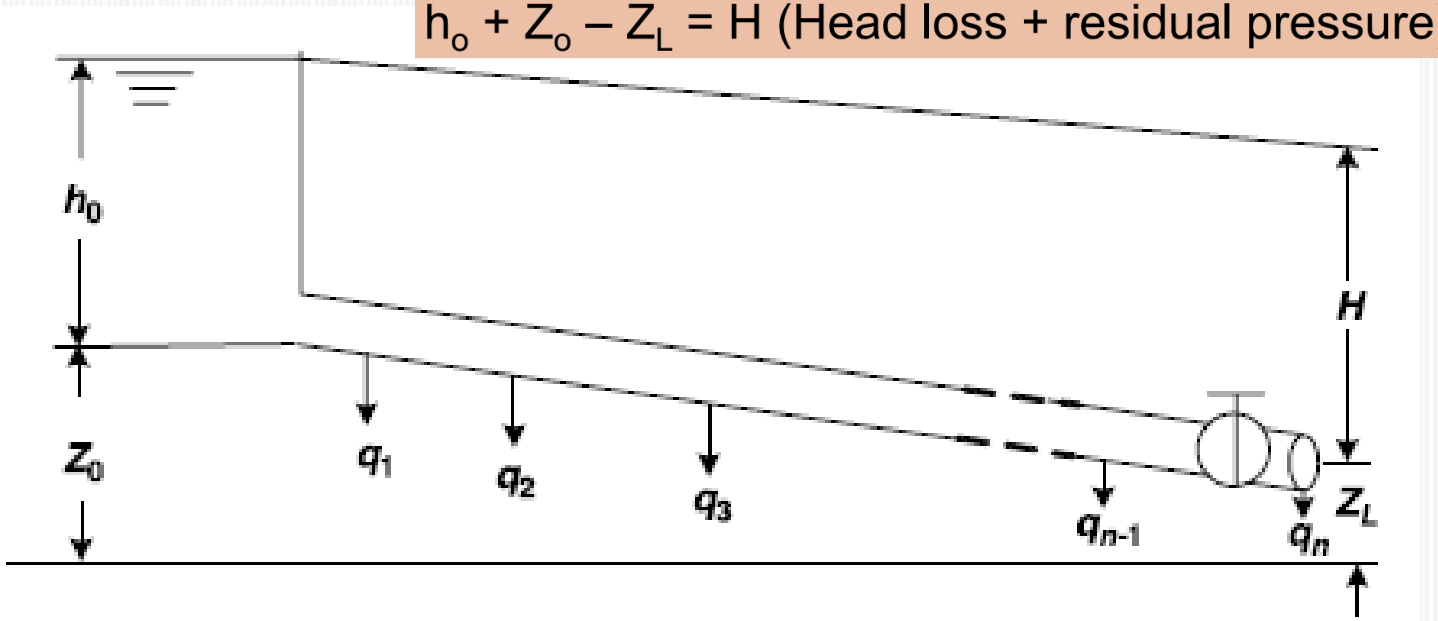
- In a distribution main, water may flow on account of gravity (Fig. 1) or by pumping (Fig. 2) with withdrawals q_1, q_2, q_3, . . . , q_n at the nodal points 1, 2, 3, . . . , n.

Hydraulic Analysis of Water Distribution System

Distribution Main:

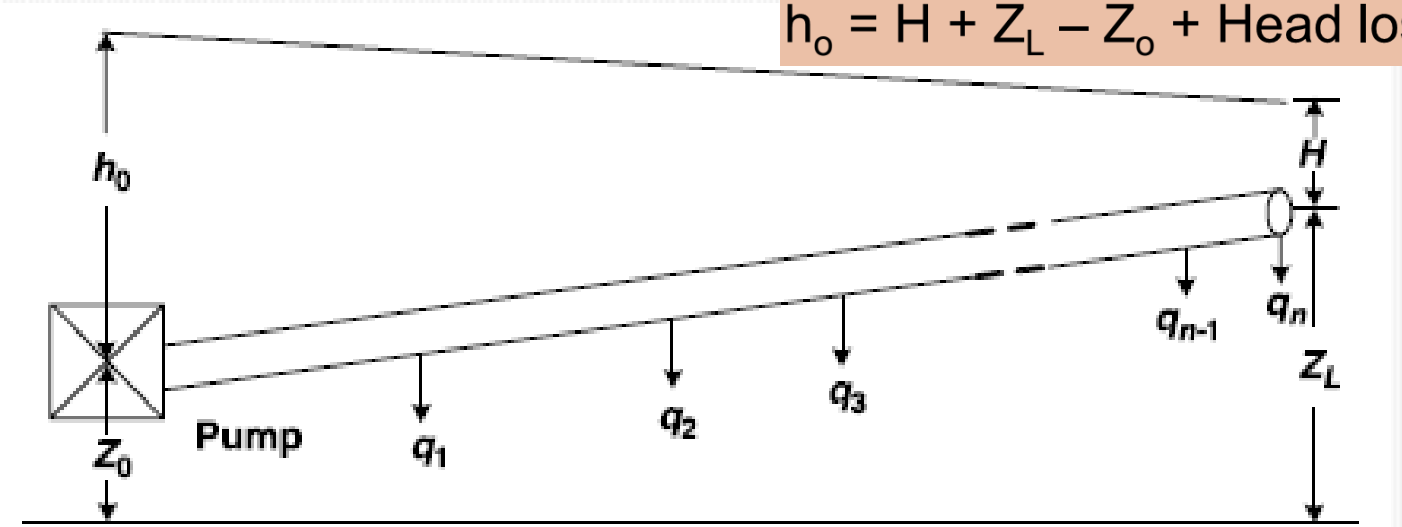
$h_o + Z_o - Z_L = H$ (Head loss + residual pressure)

Fig 1: A gravity sustained distribution mair



$h_o = H + Z_L - Z_o$ + Head loss

Fig 2: A pumpin distribution mair



Hydraulic Analysis of Water Distribution System

Distribution Main:

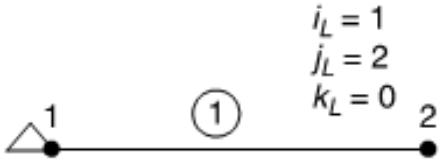
- In the analysis of a distribution main, one is required to find the nodal heads h_1, h_2, h_3, . . . , H.

- The discharge flowing in the j th pipe link Q_j is given by –

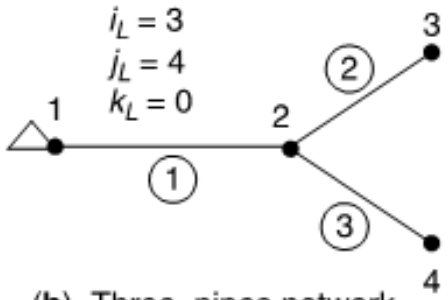
$$Q_j = \sum_{p=0}^{j} Q_{n-p}$$

Hydraulic Analysis of Water Distribution System

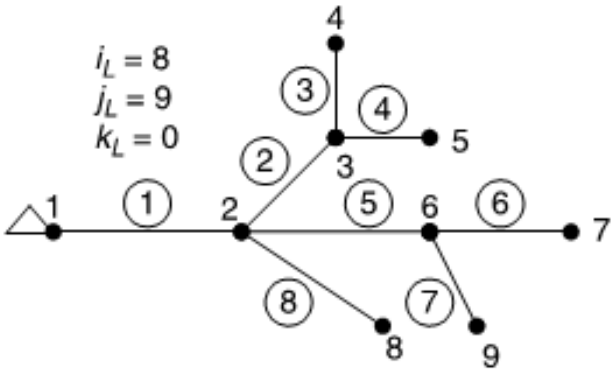
Pipe Node Connectivity



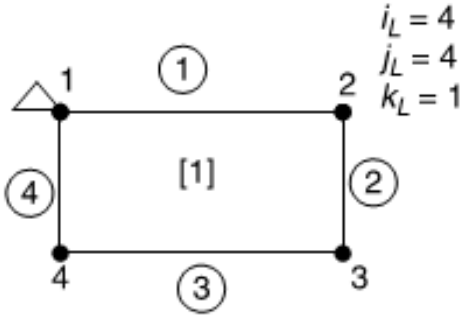
(a) Single pipe network



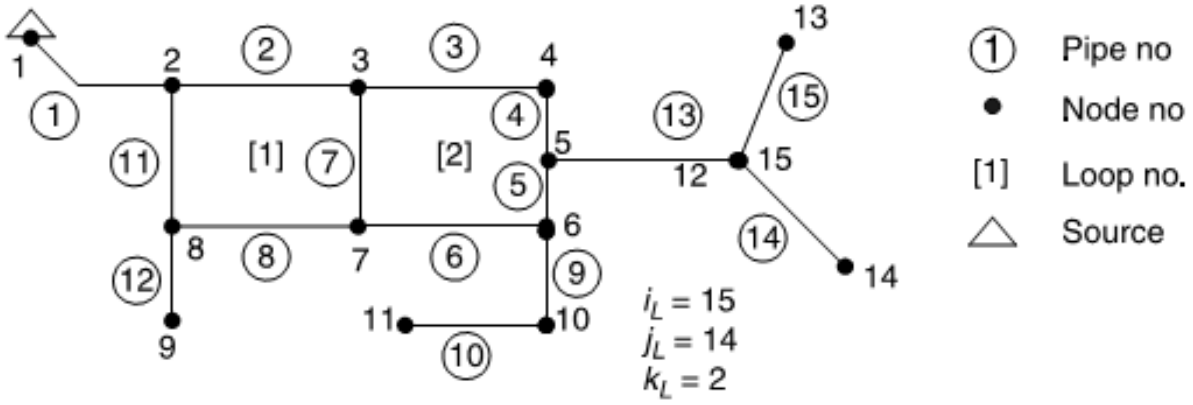
(b) Three pipes network



(c) Branched pipe network



(d) Single looped network



(e) Branched & looped network

$$i_L = j_L + k_L - 1$$

i_L = no. of pipes
j_L = no. of nodes
k_L = no. of loops

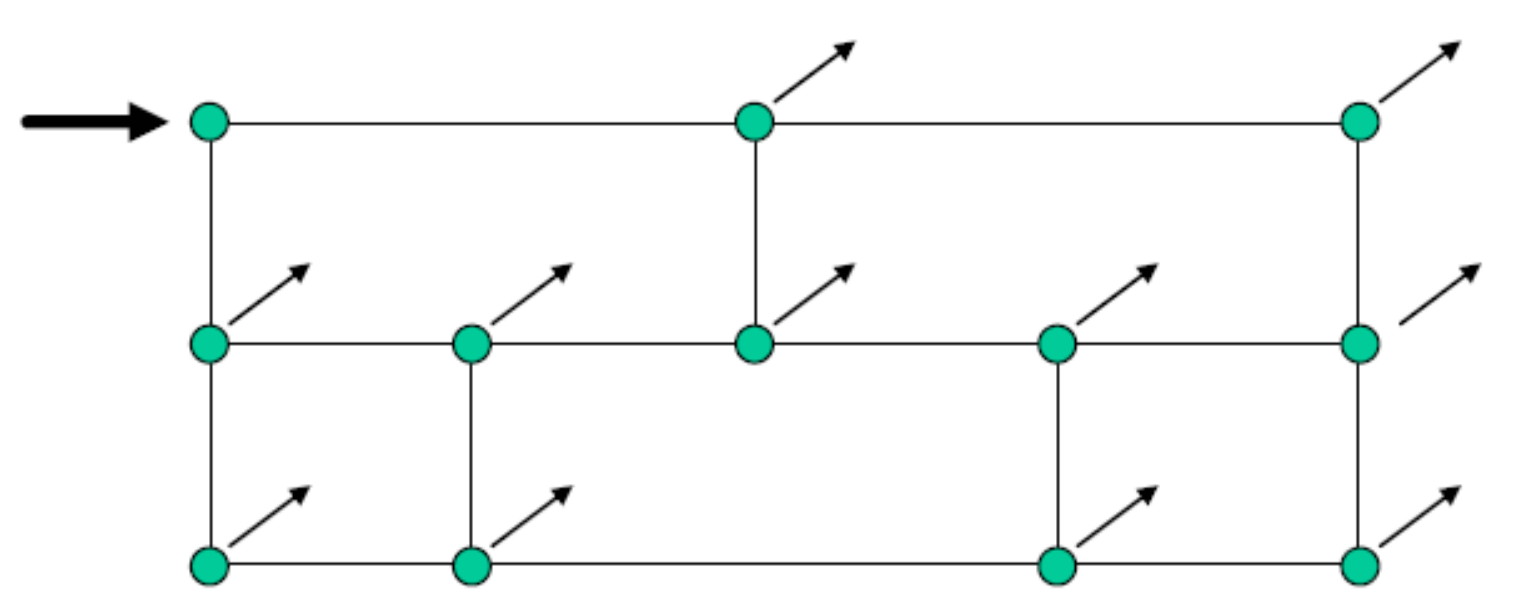
Hydraulic Analysis of Water Distribution System

Most commonly used methods are:

(a) Dead-end method

(b) Equivalent pipe method

(c) Hardy-Cross method

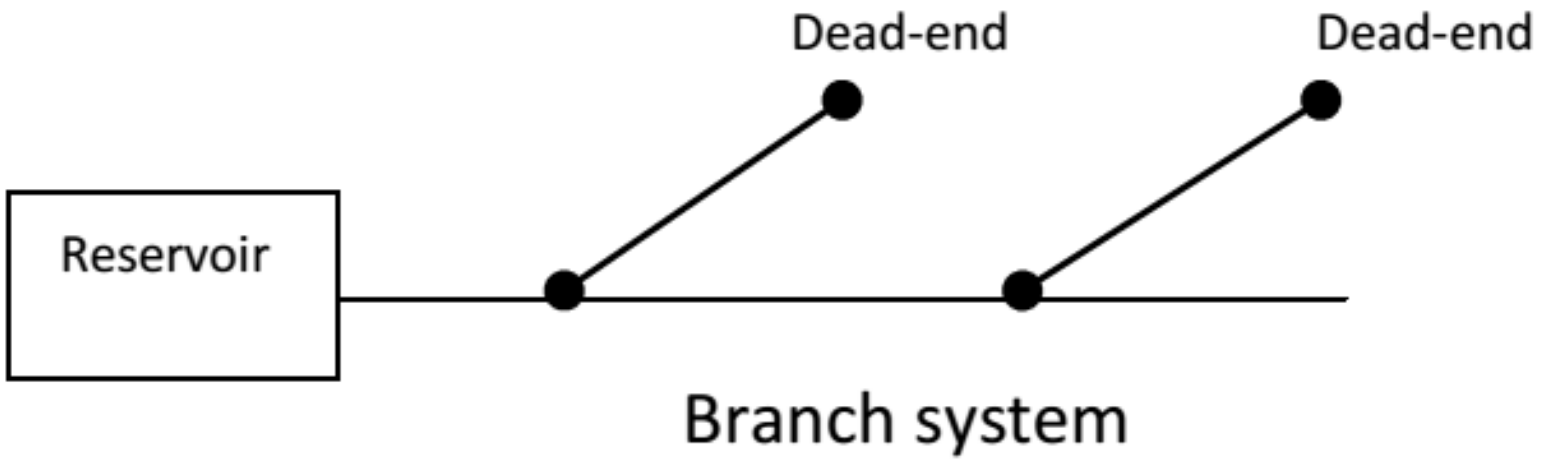


Hydraulic Analysis of Water Distribution System

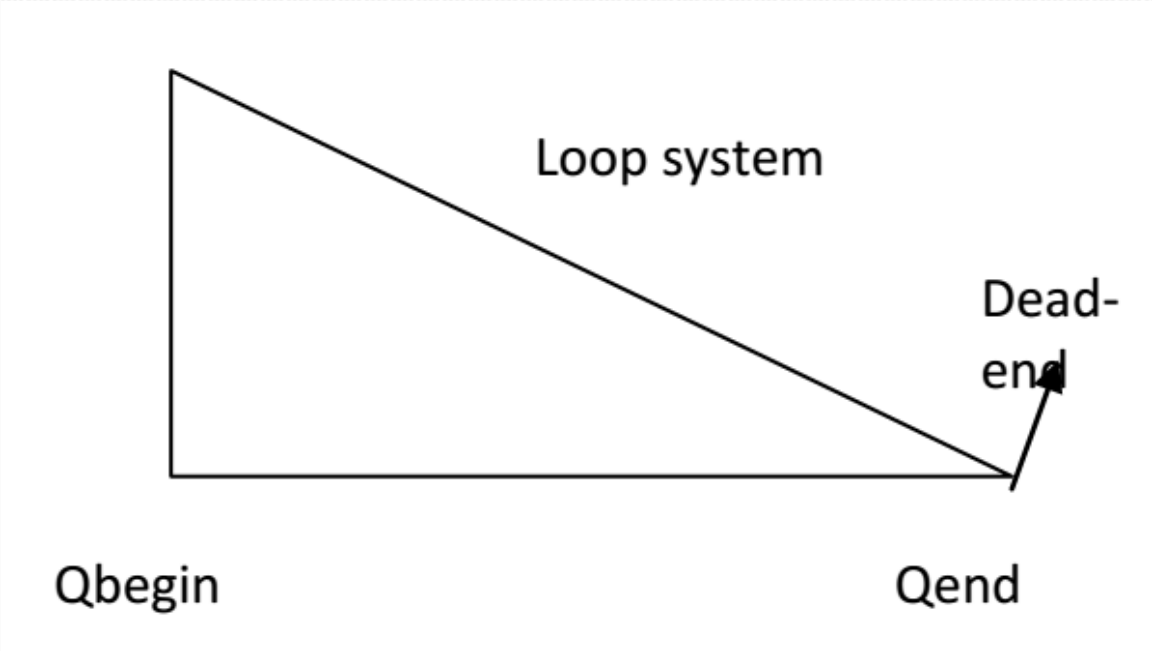
a) Dead-end method:

- Determine the locations of "dead-ends" providing that water will be distributed in the shortest way.

- At the dead-end points, there will be no flow distribution.

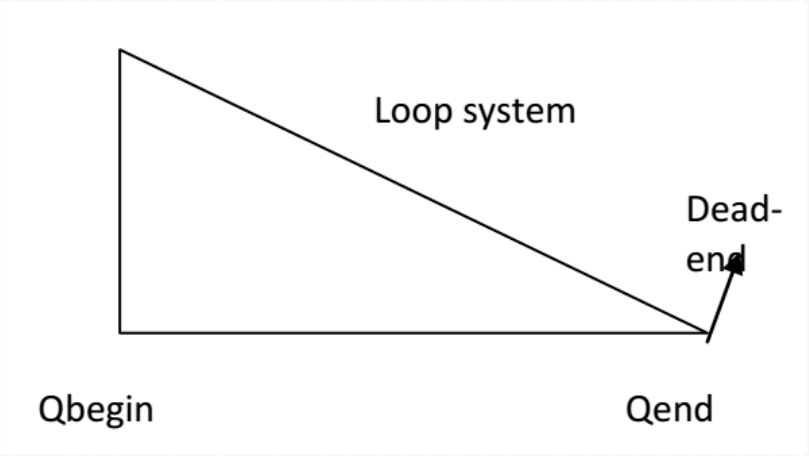


Hydraulic Analysis of Water Distribution – Dead-end Method



- To apply dead-end method for loop systems, convert it to branch system.
- To do this, a dead-end point is identified for each loop.

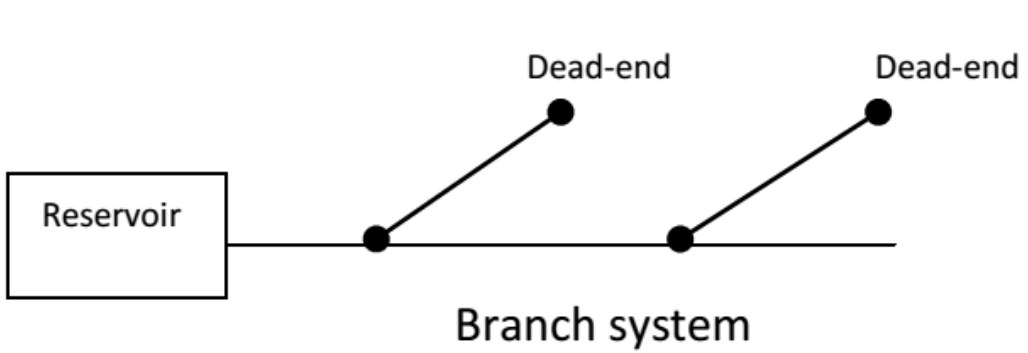
Hydraulic Analysis of Water Distribution – Dead-end Method

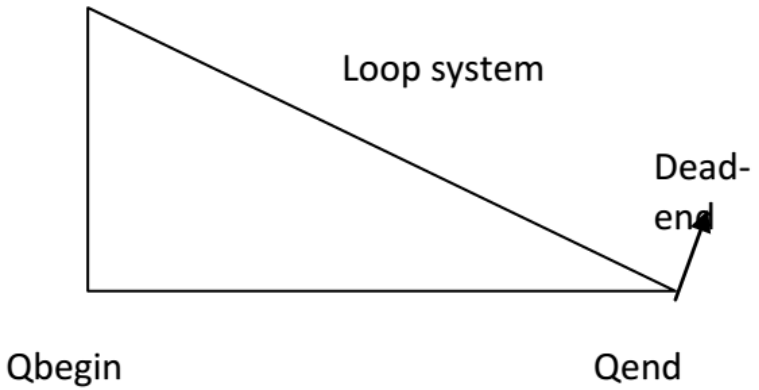


- The location of dead end point is chosen such that distance travelled to reach dead-end point from 2 different directions will almost equal to each other. Because, in a closed loop,

$$\sum HL_{from\ one\ direction} \cong \sum HL_{from\ other\ direction}$$

Hydraulic Analysis of Water Distribution – Dead-end Method





- Start calculations from dead-ends to service reservoir.
- Calculate the total flow rate to be distributed (Q_{max_h} + Q_{fire})
- To estimate design flow rate of each pipe, calculate -
  - ✓ Q distributed
  - ✓ Q begin
  - ✓ Q end

Hydraulic Analysis of Water Distribution – Dead-end Method

To calculate Q distributed:

- Population density coefficients (k) are calculated from the areas to where water to be distributed.

- Population density in each area is determined according to number of building stories:

Number of story	1	2	3	4	5
One-sided buildings	0.5	1	1.5	1.75	2
Two-sided buildings	1	2	3	3.5	4

- Unit of k = population/m length of pipe

Hydraulic Analysis of Water Distribution – Dead-end Method

To calculate Q distributed:

- Equivalent pipe lengths for each pipe:

$$(L_{eq})_i = k.\ L_i$$

- Distributed flow in unit pipe length:

$$q = \frac{Qtotal}{\sum L_{eq}}$$

- Distributed flow (Q_{dist}) in each pipe:

$$(Q_{dist})_i = q.\ (L_{eq})_i$$

Hydraulic Analysis of Water Distribution – Dead-end Method

To determine design flow:

A) For the pipes having dead-end:

$$Q_{design} = 0.577Q_{dist} + Q_{end} + Q_{fire}$$

B) For the pipes having no dead-end:

$$Q_{design} = 0.55Q_{dist} + Q_{end} + Q_{fire}$$

Hydraulic Analysis of Water Distribution – Dead-end Method

- Diameter of each pipe is selected providing that velocity should be within the allowable range.

- Head losses through each pipe is calculated by using Darcy-Weisbach or Hazen-Williams equation.

Hydraulic Analysis of Water Distribution – Dead-end Method

H_L calculation according to Darcy-Weisbach:

- The continuity equation for steady flow in a circular pipe of diameter D is –

$$Q = \frac{\pi}{4} D^2 V \qquad \ldots\ldots\ldots (1)$$

where, V = average velocity of flow, and

Q = volumetric rate of flow, called discharge.

Hydraulic Analysis of Water Distribution – Dead-end Method

H_L calculation according to Darcy-Weisbach:

- The head loss on account of surface resistance is given by the Darcy–Weisbach equation

$$H_L = \frac{fLV^2}{2gD} \qquad \text{…….. (2)}$$

where, L = the pipe length, and

f = coefficient of surface resistance (friction factor)

Hydraulic Analysis of Water Distribution – Dead-end Method

H_L calculation according to Darcy-Weisbach:

- Eliminating V between equations (1) and (2), the following equation is obtained:

$$H_L = \frac{8 f L Q^2}{\pi^2 g D^5} \quad \text{..... (3)}$$

- The coefficient of surface resistance (f) for turbulent flow depends on the average height of roughness projection (ε) of the pipe wall.

Hydraulic Analysis of Water Distribution – Dead-end Method

H_L calculation according to Darcy-Weisbach:

- The average height of roughness projection (ε) of pipe wall for commercial pipes is listed in Table 1.

Pipe Material	Roughness Height (mm)
1. Wrought iron	0.04
2. Asbestos cement	0.05
3. Poly(vinyl chloride)	0.05
4. Steel	0.05
5. Asphalted cast iron	0.13
6. Galvanized iron	0.15
7. Cast/ductile iron	0.25
8. Concrete	0.3 to 3.0
9. Riveted steel	0.9 to 9.0

Roughness height varies with manufacturing processes for the same material.

Hydraulic Analysis of Water Distribution – Dead-end Method

H_L calculation according to Darcy-Weisbach:

- The coefficient of surface resistance also depends on the Reynolds number **R** of the flow, defined as –

$$\mathbf{R} = \frac{VD}{\nu} \quad \ldots\ldots\ldots (4)$$

where, ν = kinematic viscosity of fluid

$$\nu = 1.792 \times 10^{-6} \left[1 + \left(\frac{T}{25}\right)^{1.165}\right]^{-1} \quad \ldots\ldots\ldots (5)$$

where, T = temperature (°C)

Hydraulic Analysis of Water Distribution – Dead-end Method

H_L calculation according to Darcy-Weisbach:

- Eliminating V between Eqs. (1) and (4), the following equation is obtained:

$$\mathbf{R} = \frac{4Q}{\pi \nu D} \quad \text{..... (6)}$$

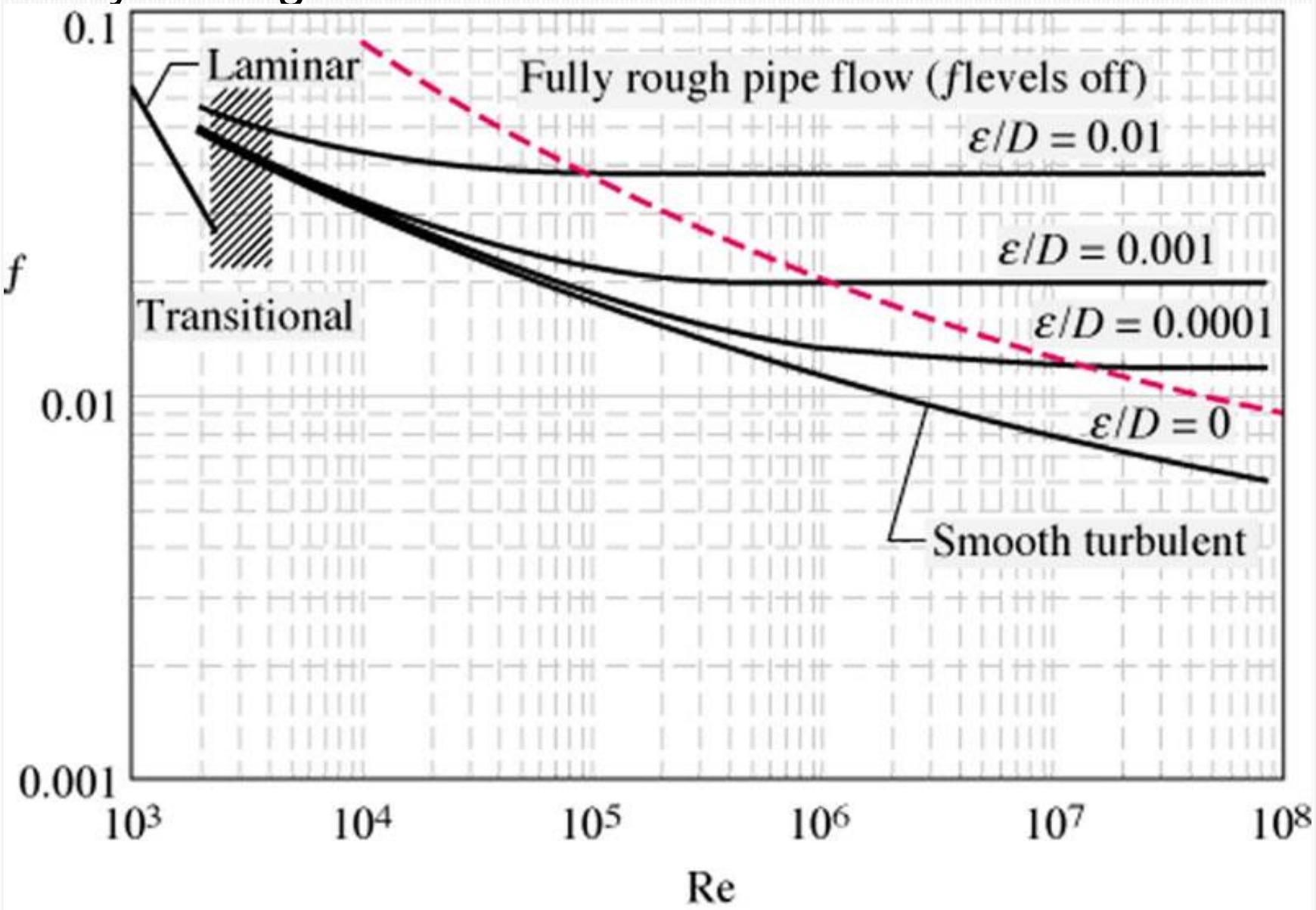
- For turbulent flow (R ≥4000), Colebrook (1938) found the following implicit equation for f:

$$f = 1.325\left[\ln\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathbf{R}\sqrt{f}}\right)\right]^{-2} \quad \text{..... (7)}$$

Using Eq. (7), Moody (1944) constructed a family of curves between f and R for various values of relative roughness ε /D.

Hydraulic Analysis of Water Distribution – Dead-end Method

Moody' s Diagram

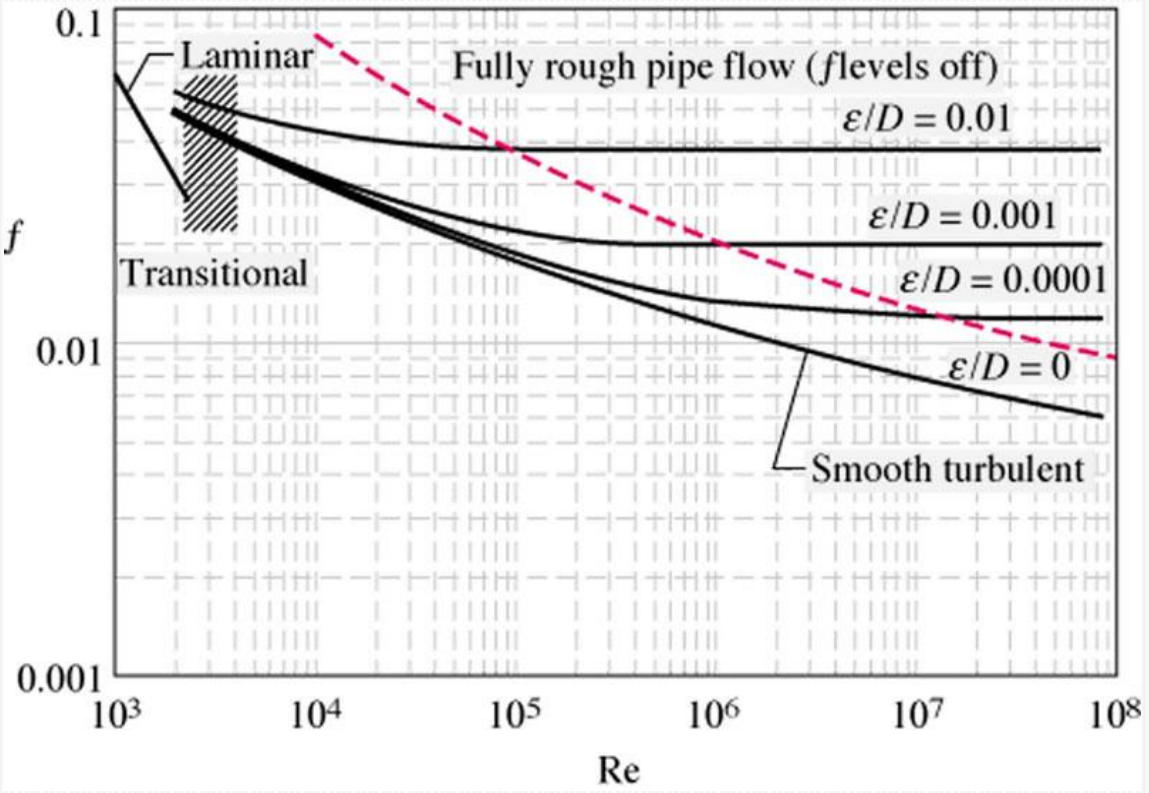


Hydraulic Analysis of Water Distribution – Dead-end Method

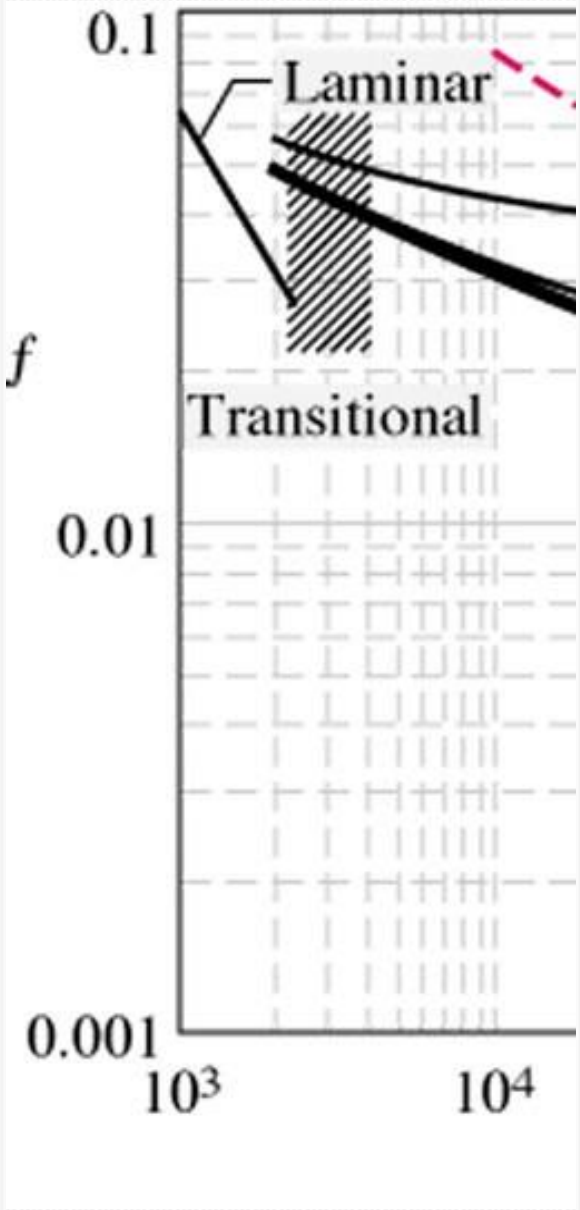
Moody’ s Diagram

For a given Reynolds number of flow, as the relative roughness is increased, the friction factor *f* decreases.

For a given relative roughness , the friction factor *f* decreases with increasing Reynolds number until the zone of complete turbulence is reached.



Hydraulic Analysis of Water Distribution – Dead-end Method



Moody' s Diagram

The **transition region** is shown in the shaded area **(2300<Re<4000)**

The friction factors alternate between laminar and turbulent flow.

Hydraulic Analysis of Water Distribution – Dead-end Method

Moody’ s Diagram

Application:

The Moody diagram is used to help determine the value of **the friction factor, *f*** for turbulent flow.

- First determine the value of the Reynolds number (calculations)
- Then determine the relative roughness (dividing Diameter of the pipe to the pipe roughness).

Hydraulic Analysis of Water Distribution – Dead-end Method

Moody’ s Diagram

Application:

Basic data required for applying Moody’s Diagram are:

1. The pipe inside diameter (for D)

2. The pipe material (for ε)

3. The flow velocity, and the kind of fluid and its temperature (for R), from which the viscosity can be found.

Hydraulic Analysis of Water Distribution – Dead-end Method

H_L calculation according to Darcy-Weisbach:

- For laminar flow (R ≤ 2000),f depends on R only and is given by the Hagen – Poiseuille equation as follows –

$$f = \frac{64}{\mathbf{R}} \quad \text{..... (8)}$$

- For R lying in the range between 2000 and 4000 (called transition range),

$$f = \left\{ \left(\frac{64}{\mathbf{R}}\right)^{8} + 9.5\left[\ln\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{\mathbf{R}^{0.9}}\right) - \left(\frac{2500}{\mathbf{R}}\right)^{6}\right]^{-16} \right\}^{0.125} \quad \text{..... (9)}$$

Hydraulic Analysis of Water Distribution – Dead-end Method

H_L calculation according to Hazen-Williams:

$$H_L = k.Q^{1.85}.L \qquad \text{…….. (10)}$$

where $$k = \left(\frac{1}{0.278CD^{2.63}}\right)^{\frac{1}{0.54}}$$

- Piezometric elevations and pressures are calculated.
- To do this, water level in the reservoir and diameter and length of the main line have to be known.

Hydraulic Analysis of Water Distribution System

Simple Pipe Network Design Procedure:

(i) Assign the required demand at each node

(ii) Estimate the discharge flowing through the pipes

(iii) Assume possible pipe diameters

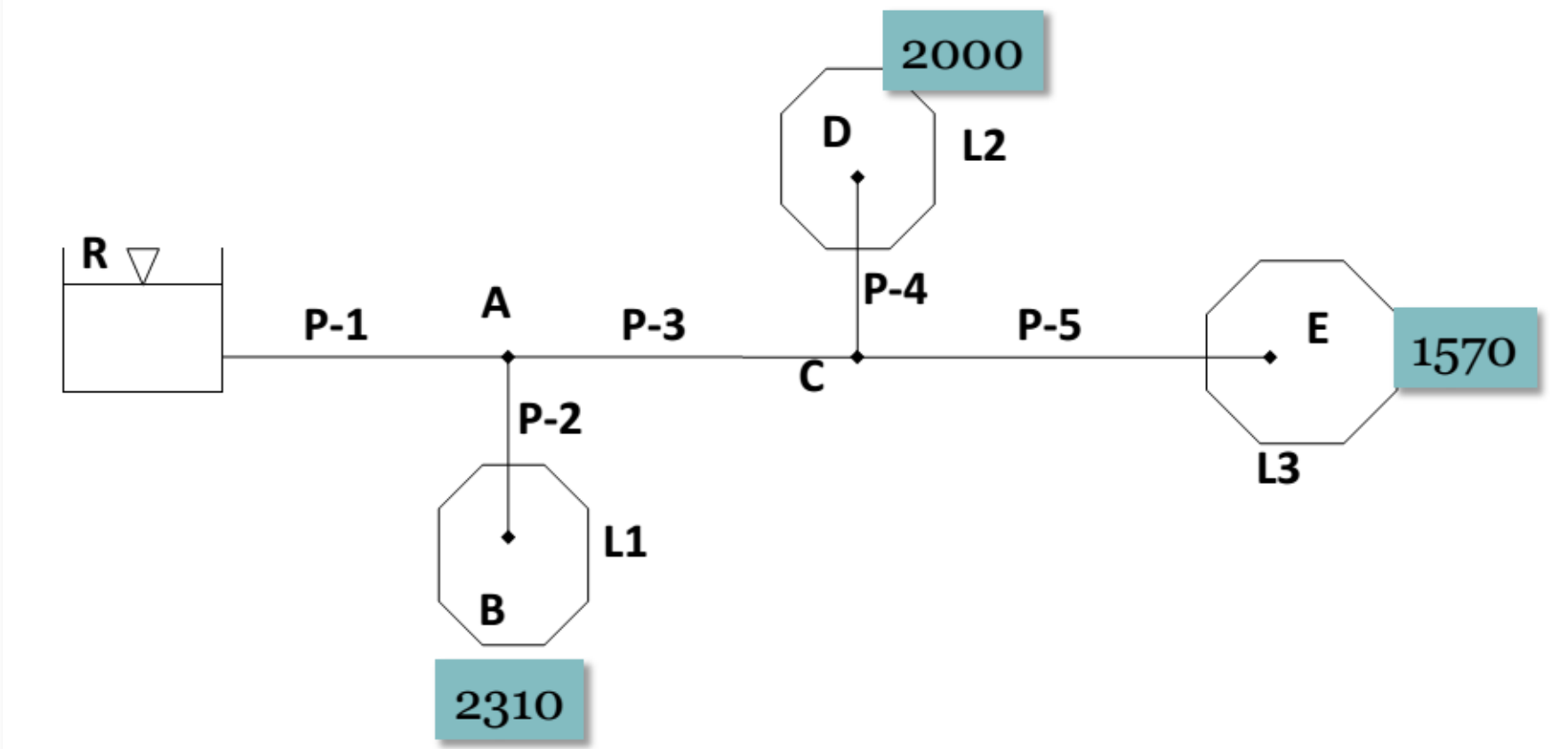
(iv) Calculate the head loss through the pipes

(vi) Compare this terminal pressure with the desired minimum and maximum pressures.

Hydraulic Analysis of Water Distribution System

Simple Pipe Network Design Procedure:

(vii) If the required condition is not satisfied, then repeat steps (ii) through (vi) until the required conditions are met.

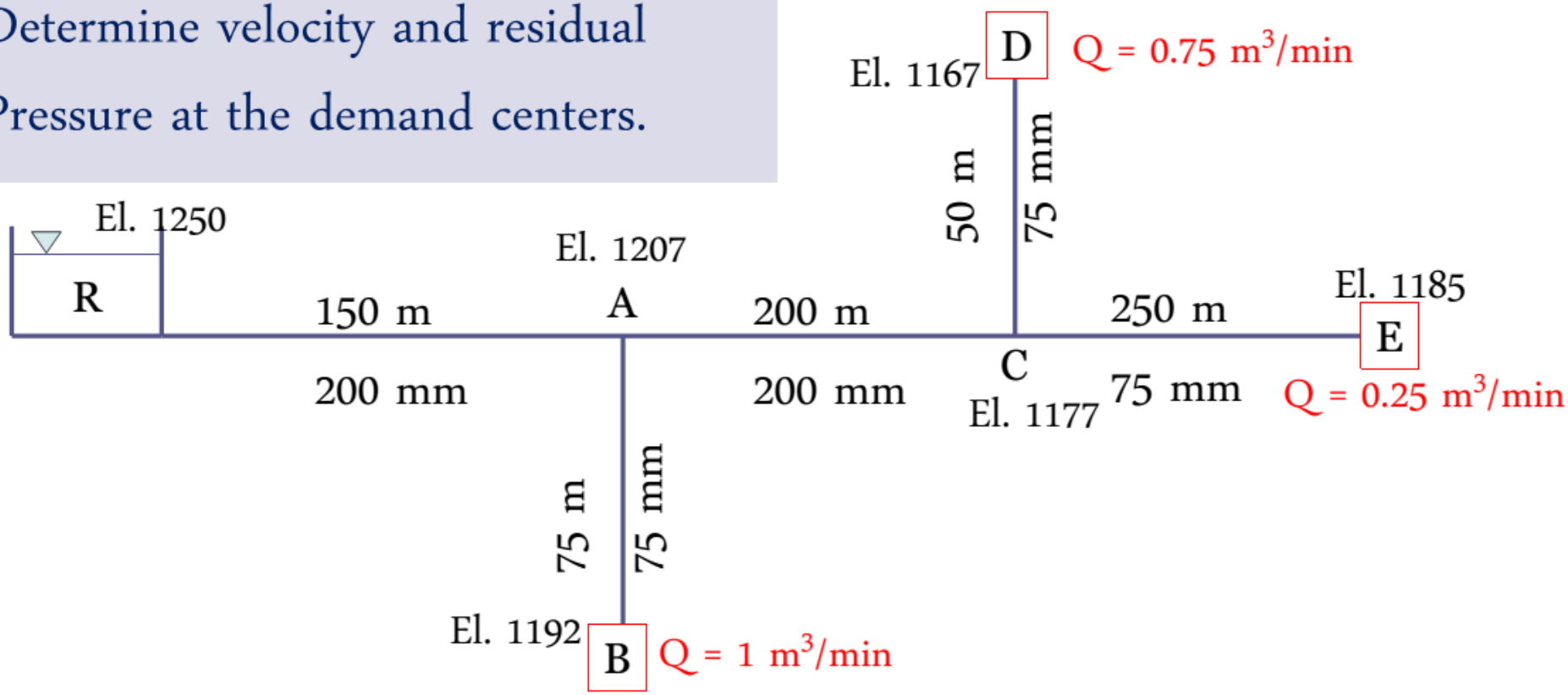


Hydraulic Analysis of Water Distribution

Example: Simple Pipe Network Design

Determine velocity and residual

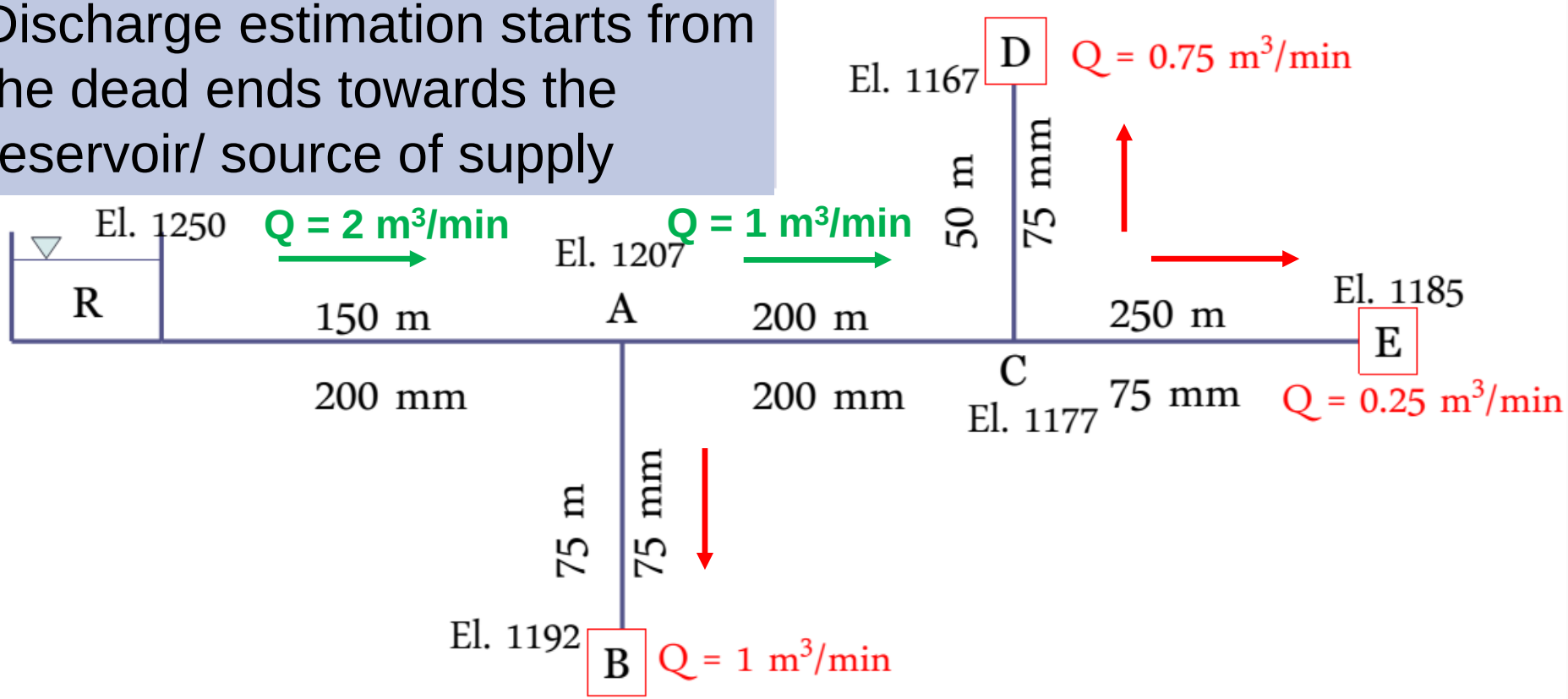
Pressure at the demand centers.



Hydraulic Analysis of Water Distribution System

Solution: Estimation of Discharge

Discharge estimation starts from the dead ends towards the reservoir/ source of supply

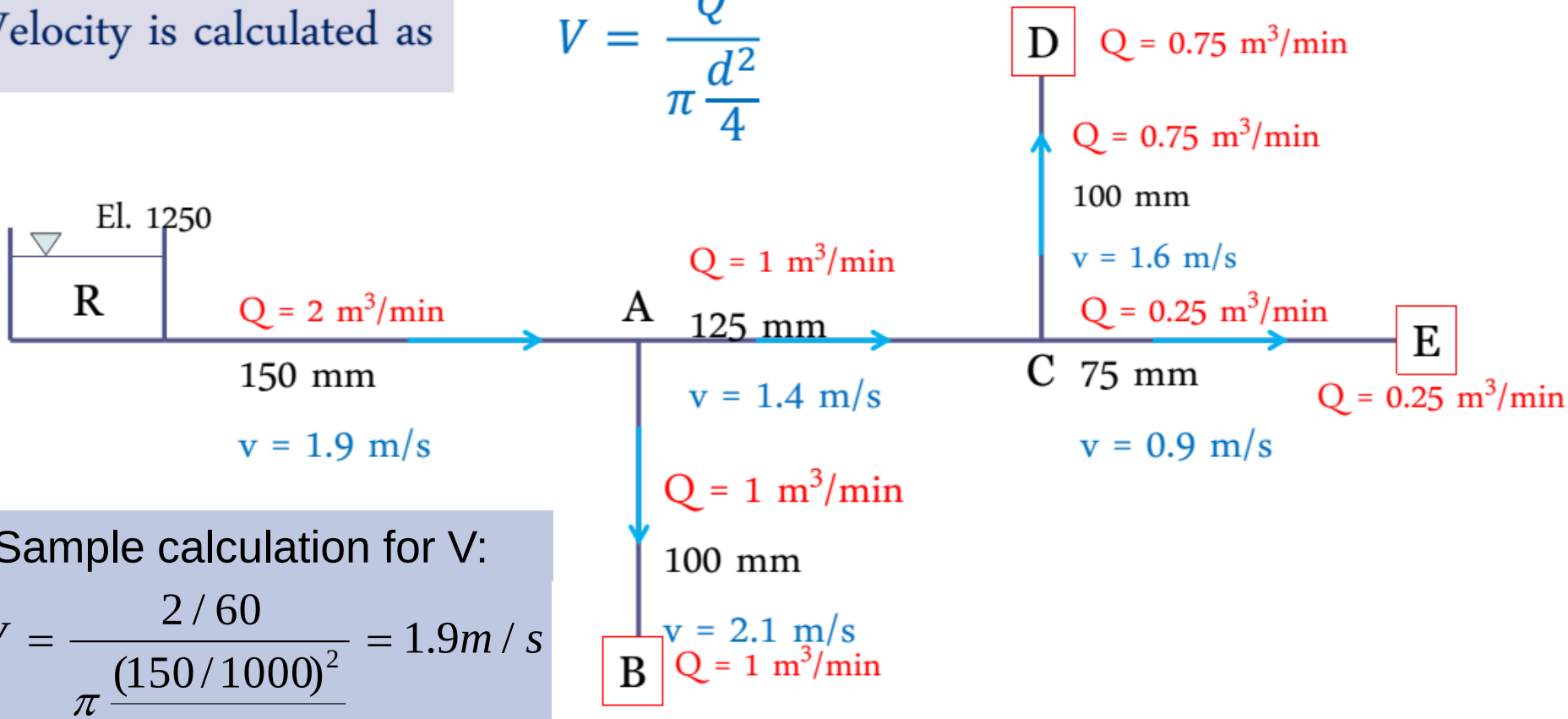


Hydraulic Analysis of Water Distribution System

Solution: Velocity Calculation

Velocity is calculated as

$$V = \frac{Q}{\pi \frac{d^2}{4}}$$



Sample calculation for V:

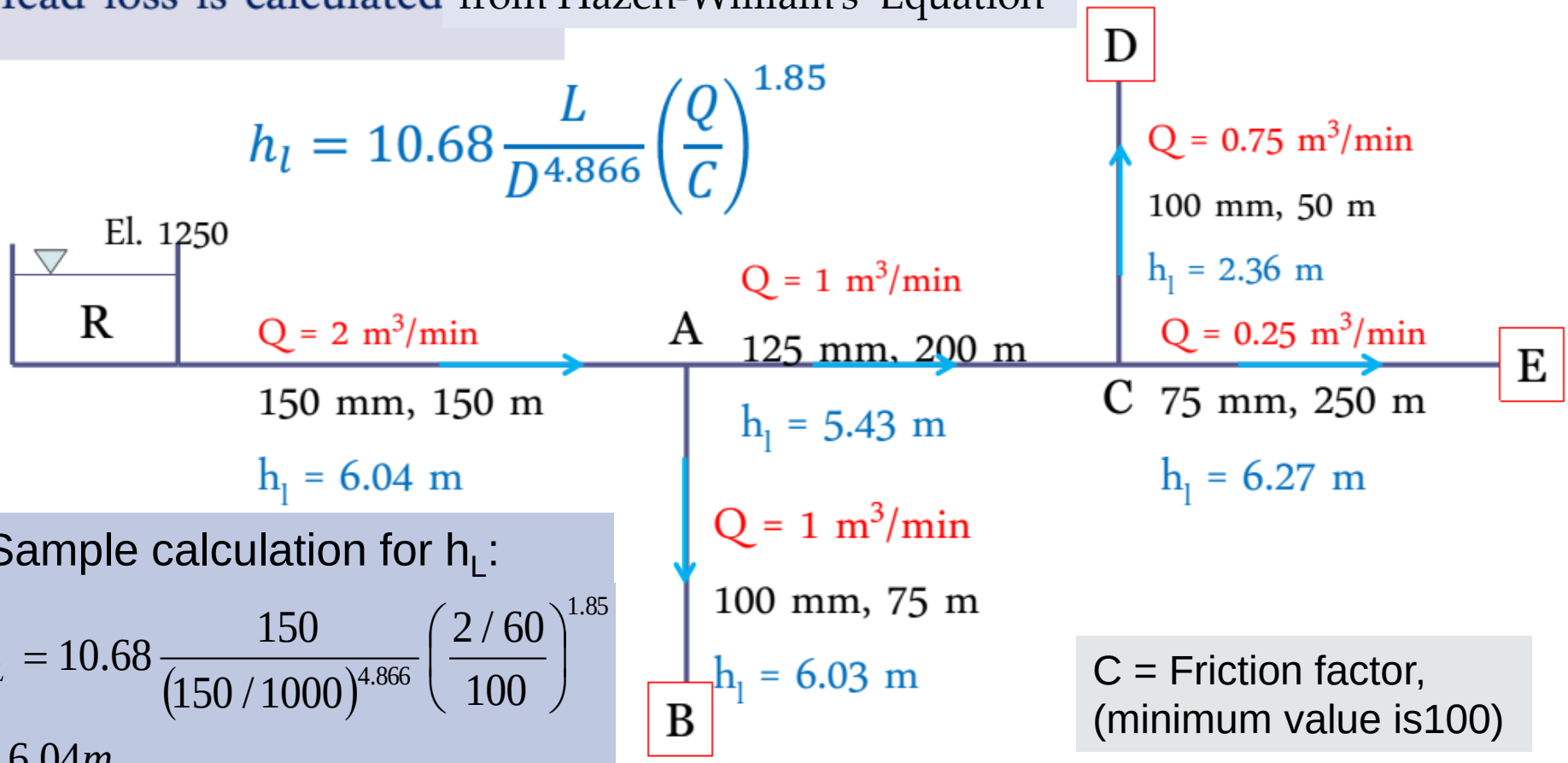
$$V = \frac{2/60}{\pi \frac{(150/1000)^2}{4}} = 1.9 m/s$$

Hydraulic Analysis of Water Distribution System

Solution: Head Loss Calculation

Head loss is calculated from Hazen-William's Equation

$$h_l = 10.68 \frac{L}{D^{4.866}} \left(\frac{Q}{C}\right)^{1.85}$$



Sample calculation for h_L:

$$h_L = 10.68 \frac{150}{(150/1000)^{4.866}} \left(\frac{2/60}{100}\right)^{1.85}$$

$$= 6.04m$$

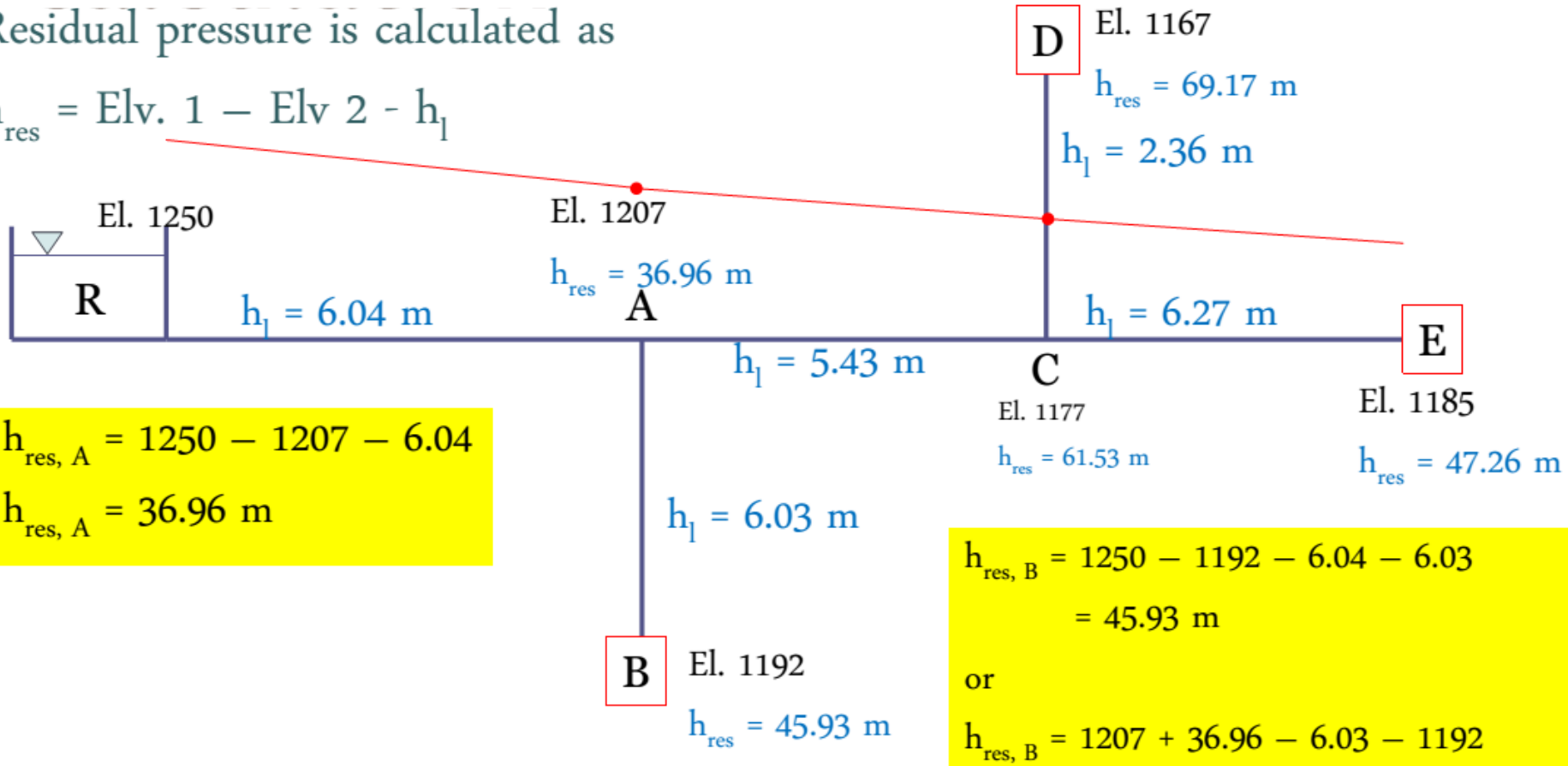
C = Friction factor, (minimum value is100)

Hydraulic Analysis of Water Distribution System

Solution: Residual Pressure Calculation

Residual pressure is calculated as

h_{res} = Elv. 1 – Elv 2 - h_l



$h_{res, A}$ = 1250 – 1207 – 6.04

$h_{res, A}$ = 36.96 m

$h_{res, B}$ = 1250 – 1192 – 6.04 – 6.03

= 45.93 m

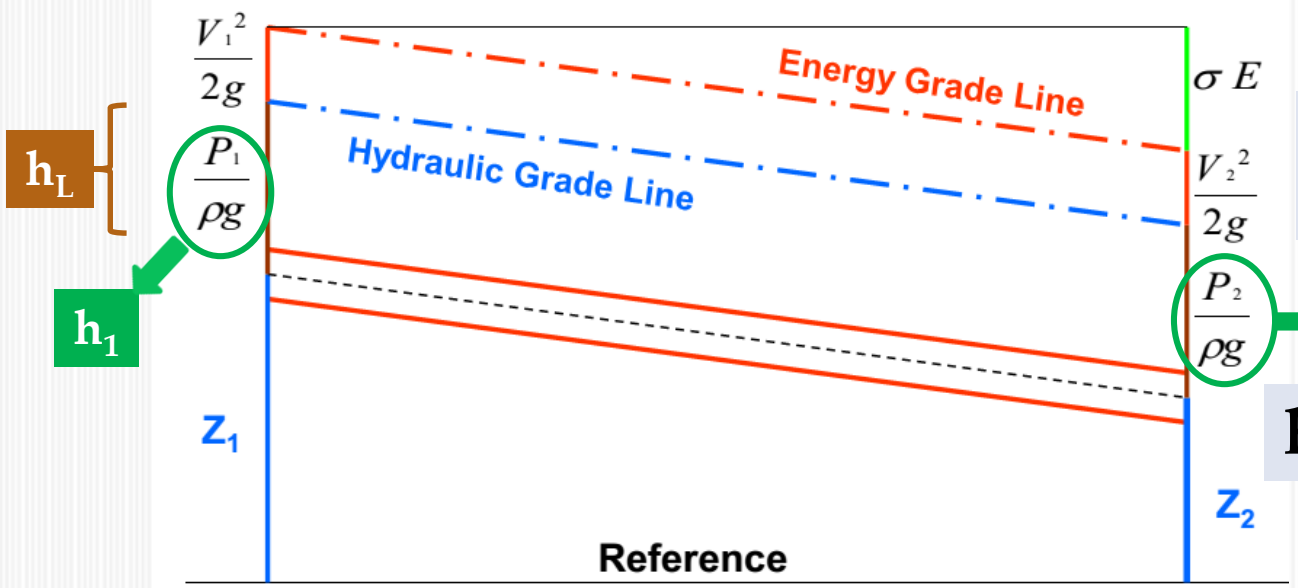
or

$h_{res, B}$ = 1207 + 36.96 – 6.03 – 1192

= 45.93 m

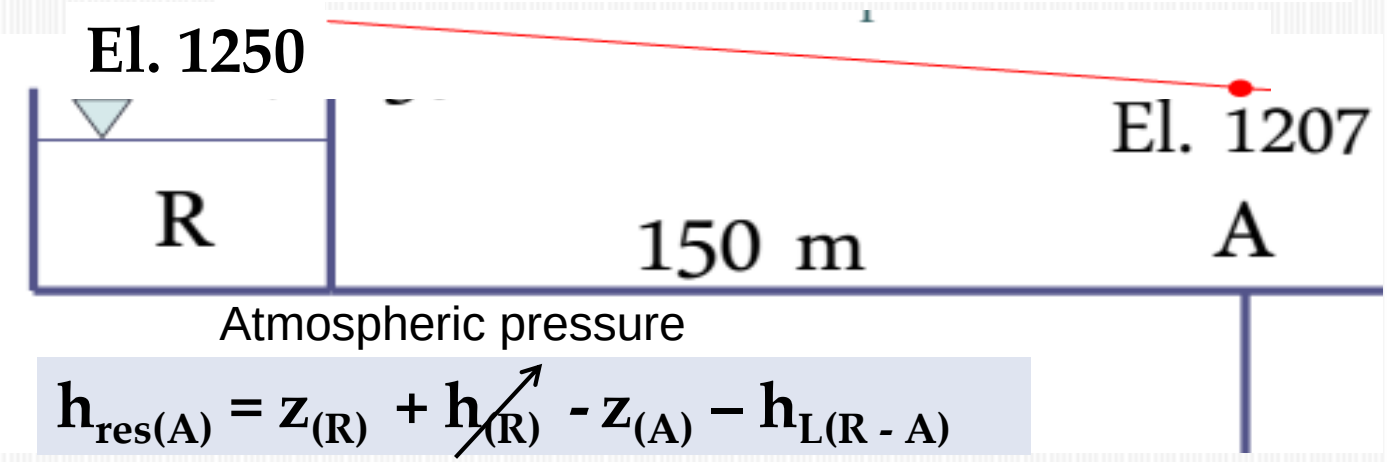
Hydraulic Analysis of Water Distribution System

Principle of Residual Pressure Calculation



h_1, h_2 = pressure head
h_L = head loss

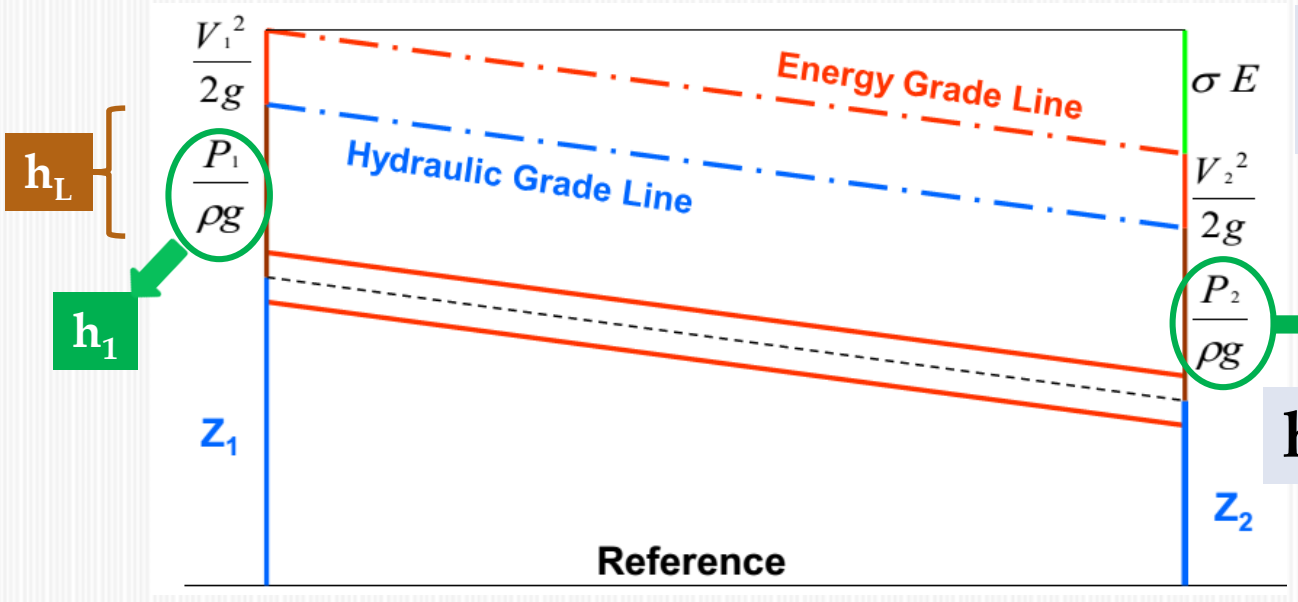
$$h_2 = z_1 + h_1 - z_2 - h_L$$



$$h_{res(A)} = z_{(R)} + \cancel{h_{(R)}} - z_{(A)} - h_{L(R-A)}$$

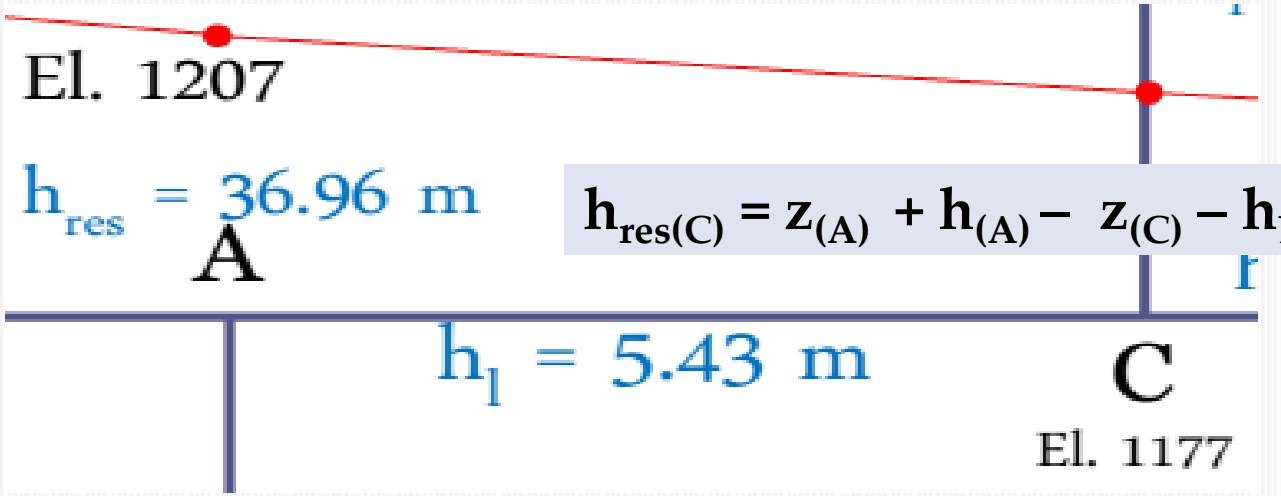
Hydraulic Analysis of Water Distribution System

Principle of Residual Pressure Calculation



h_1, h_2 = pressure head
h_L = head loss

$$h_2 = z_1 + h_1 - z_2 - h_L$$



$$h_{res(C)} = z_{(A)} + h_{(A)} - z_{(C)} - h_{L(A-C)}$$

Hydraulic Analysis of Water Distribution System

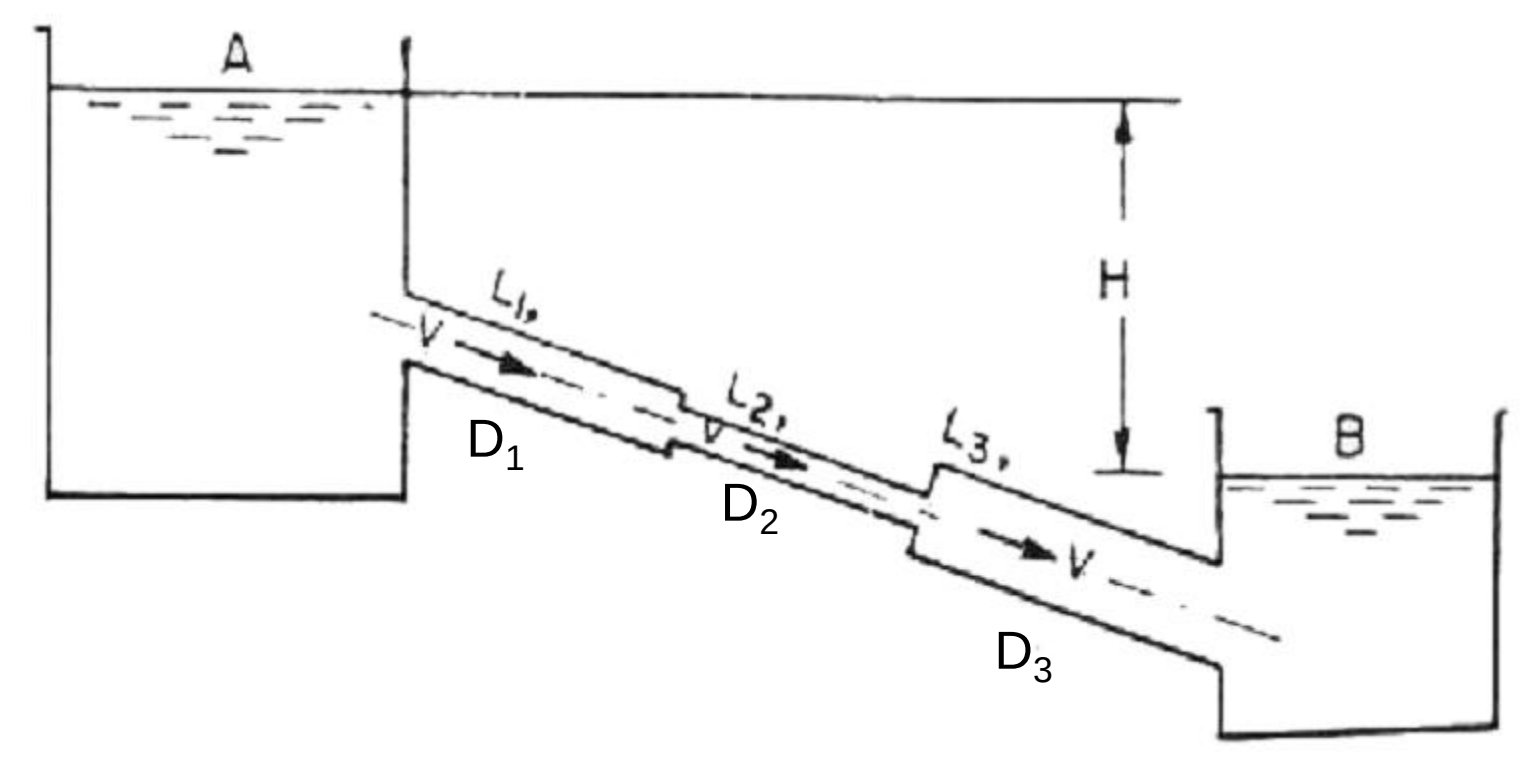
Compound Pipe Flow

- When two or more pipes with different diameters are –
  - ✓ connected together head to tail (in series) or
  - ✓ connected to two common nodes (in parallel).

Hydraulic Analysis of Water Distribution System

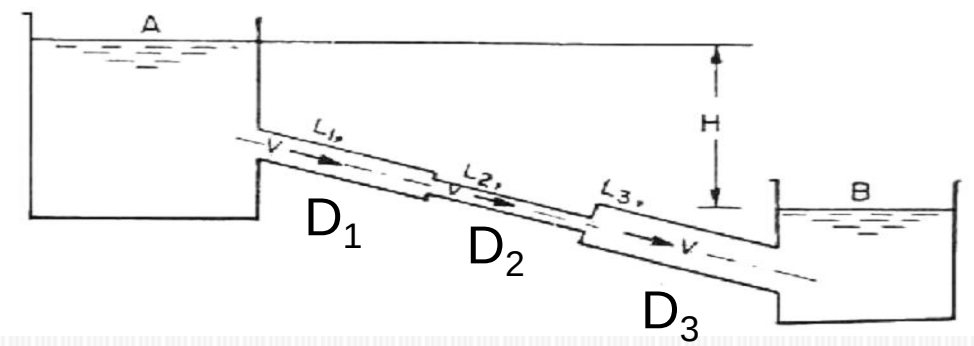
(A) Flow Through Pipes in Series

- Pipes of different lengths and different diameters connected end to end (in series) to form a pipeline



Hydraulic Analysis of Water Distribution System

(A) Flow Through Pipes in Series



- **Discharge**: The discharge through each pipe is the same

$$Q = A_1V_1 = A_2V_2 = A_3V_3$$

- **Head loss**: The difference in liquid surface levels is equal to the sum of the total head loss in the pipes

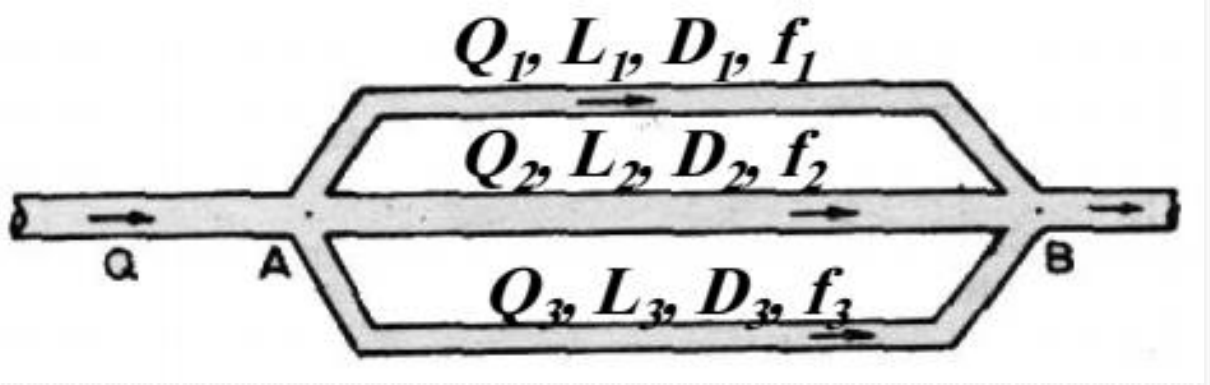
$$H_L \text{ total} = H_{L1} + H_{L2} + H_{L3}$$

Hydraulic Analysis of Water Distribution System

(B) Flow Through Parallel pipes

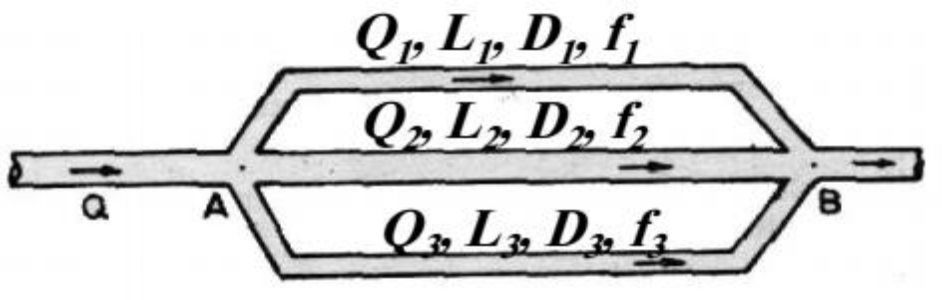
- If a main pipe divides into two or more branches and again join together downstream to form a single pipe, then the branched pipes are said to be connected in parallel (compound pipes).

- Points A and B are called nodes.



Hydraulic Analysis of Water Distribution System

(B) Flow Through Parallel Pipes



- **Discharge**:

$$Q = Q_1 + Q_2 + Q_3 = \sum_{i=1}^{3} Q_i$$

- **Head loss**: the head loss for each branch is the same

$$h_L = h_{f1} = h_{f2} = h_{f3}$$

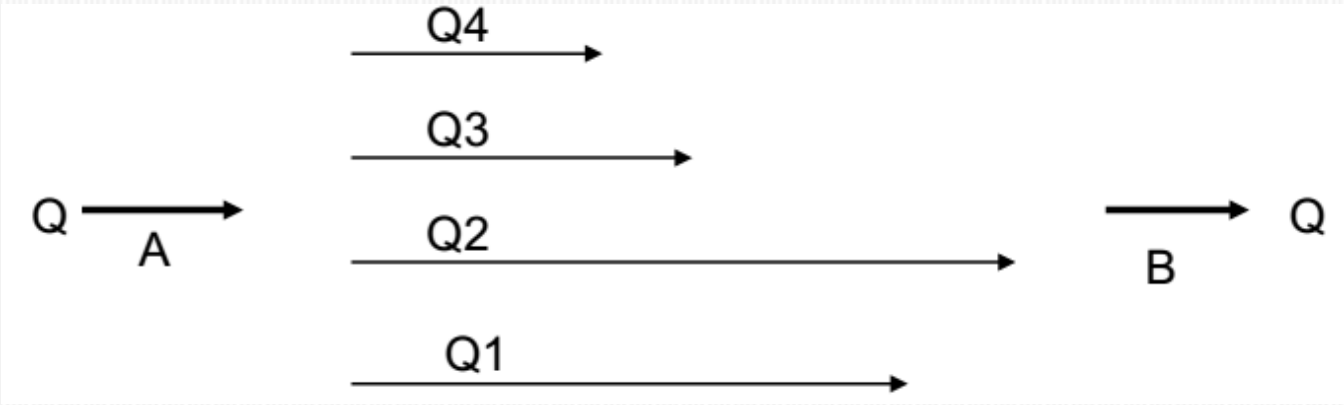
Darcy-Weisbach Formula

$$f_1 \frac{L_1}{D_1} \frac{V_1^2}{2g} = f_2 \frac{L_2}{D_2} \frac{V_2^2}{2g} = f_3 \frac{L_3}{D_3} \frac{V_3^2}{2g}$$

Hydraulic Analysis of Water Distribution System

Example of Parallel Pipes

Four pipes connected in parallel as shown. The following details are given

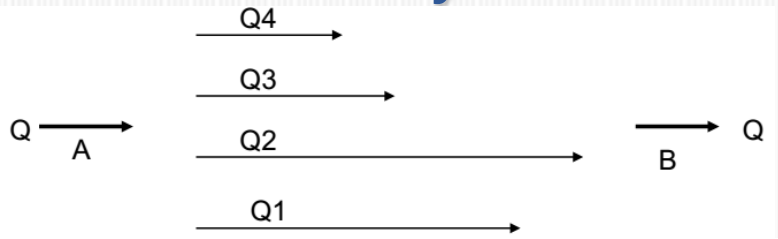


Pipe	L (m)	D (mm)	f
1	200	200	0.020
2	300	250	0.018
3	150	300	0.015
4	100	200	0.020

If $Z_A = 150$ m , $Z_B = 144$m, determine the discharge in each pipe (assume $P_A = P_B = P_{atm}$)

Hydraulic Analysis of Water Distribution System

Solution for Parallel Pipes



Pipe	*L* (m)	*D* (mm)	*f*
1	200	200	0.020
2	300	250	0.018
3	150	300	0.015
4	100	200	0.020

$Z_A = 150\ \text{m}$, $Z_B = 144\text{m}$,

$Z_A - Z_B = h_f = h_{f1} = h_{f2} = h_{f3} = h_{f4}$ (neglect minor losses)

$150 - 144 = 6 = h_{fi} = f_i \frac{L_i}{D_i} \frac{V_i^2}{2g}$

Darcy-Weisbach Formula

$$H_L = \frac{fLV^2}{2gD}$$

But Vi = $\frac{Q_i}{A_i} = \frac{Q_i}{\frac{\pi}{4} \times D_i^2}$

$$6 = \frac{8 f_i L_i Q^2}{\pi^2 g D_i^2}$$ Substitute for Pipe 1, 2, 3 and 4

$Q = 0.0762 + 0.1146 + 0.28 + 0.1078 = 0.579\ \text{m}^3/\text{s}$

Hydraulic Analysis of Water Distribution System

(b) Equivalent Pipe method:

- Equivalent pipe is a method of reducing a combination of pipes into a simple pipe system for easier analysis of a pipe network, such as a water distribution system.

- An equivalent pipe is an imaginary pipe in which the head loss and discharge are equivalent to those for the real pipe system.

- There are three main properties of a pipe: diameter, length, and roughness.

Hydraulic Analysis – Equivalent Pipe Method

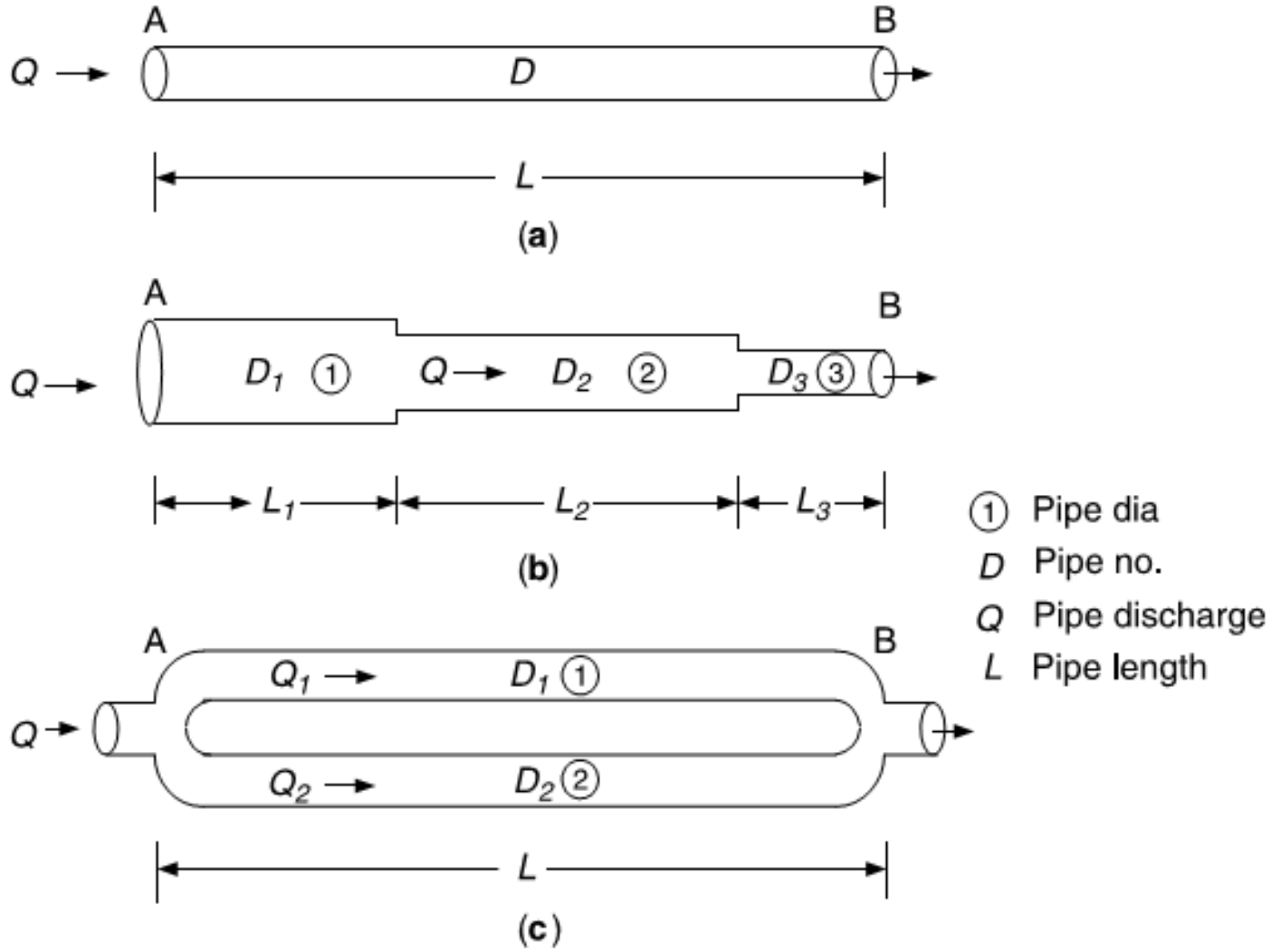


Figure 2.17. Pipe arrangements.

Hydraulic Analysis – Equivalent Pipe Method

- Therefore, for a system of pipes with different diameters, lengths, and roughness factors, one could assume a specific roughness factor (most commonly C = 100) and diameter (most commonly D = 8").

- The most common formula for computing equivalent pipe is the Hazen-Williams formula.

$$h_L = 10.5 \frac{Q^{1.85} L}{C^{1.85} D^{4.87}} \quad \text{..... (11)}$$

Hydraulic Analysis – Equivalent Pipe Method

Example:

For the pipe system shown in Figure 1, determine the length of a single equivalent pipe that has a diameter of 8 inches.

Use the Hazen - Williams equation and assume that C_{HW}= 120 for all pipes.

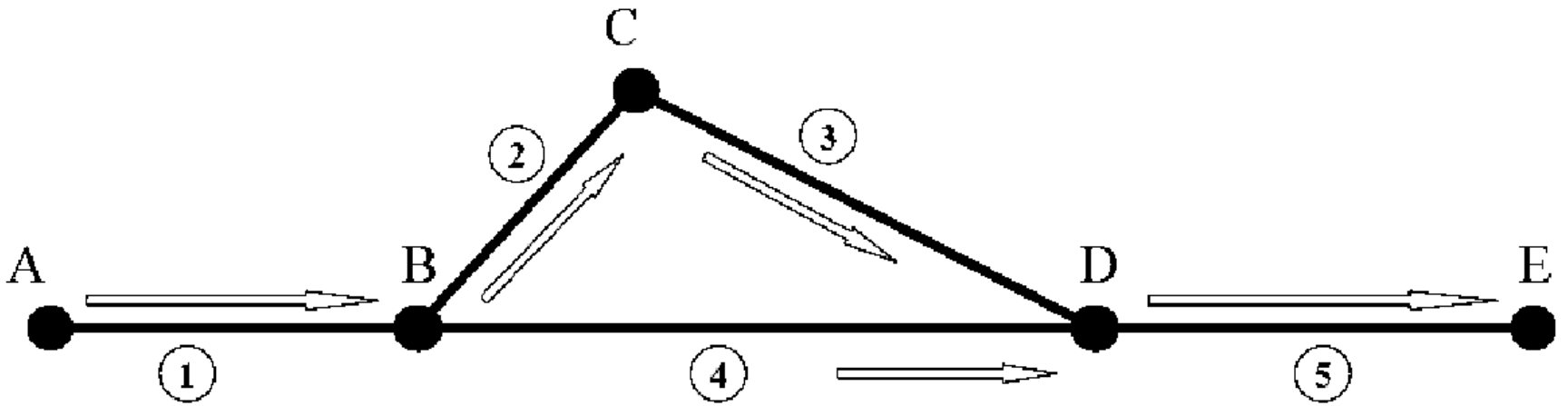


Figure 1. Pipe System for equivalent pipe problem

Hydraulic Analysis – Equivalent Pipe Method

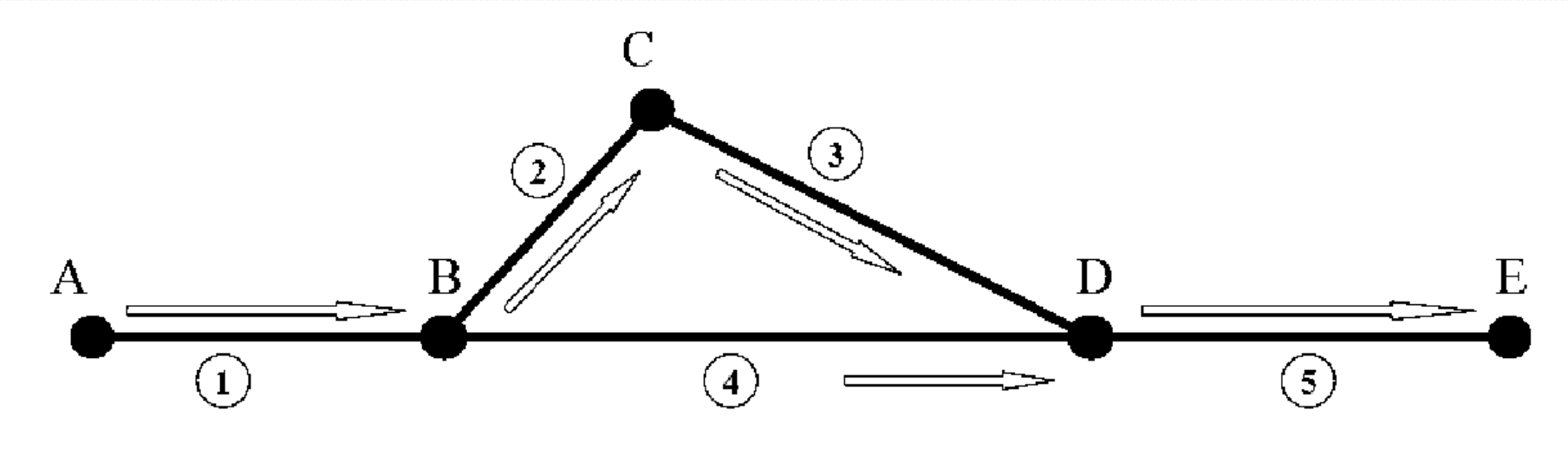


Figure 1. Pipe System for equivalent pipe problem

Table 1. Pipe Data for Figure 1 Pipe System

	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5	
Length	500	500	800	1000	700	ft
Diameter	12	6	8	10	12	in

Hydraulic Analysis – Equivalent Pipe Method

Solution:

a) **Firstly**, determine an equivalent pipe (with D=8 in) for pipes #2 and #3 in series.

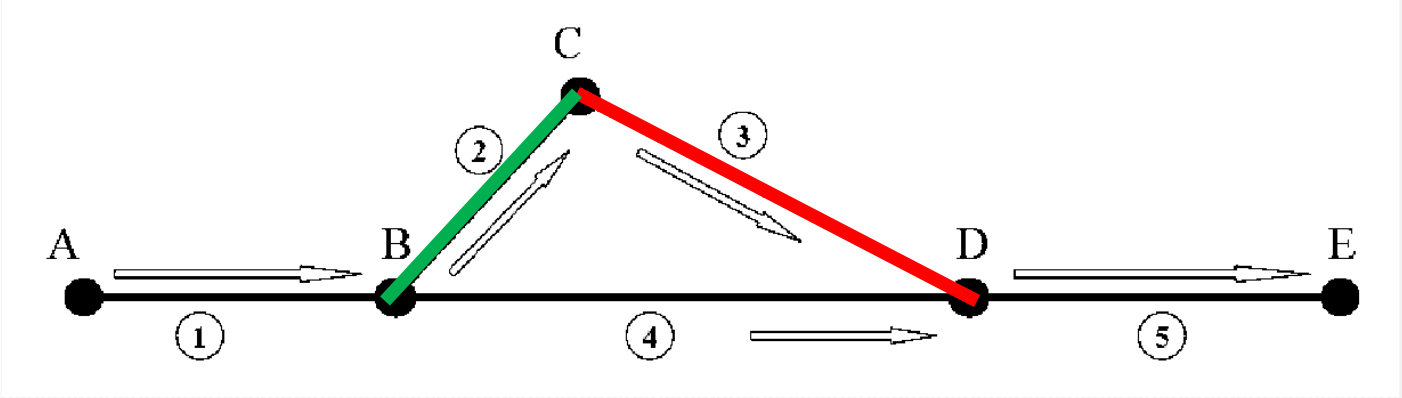
- Use a flow of 800 gpm through pipes #2 and #3.
- Use the Hazen Williams equation, with **Q in gpm and diameter (D) in inches**.

$$h_L = 10.5 \frac{Q^{1.85} L}{C^{1.85} D^{4.87}}$$

- Calculate the head loss in pipe 2 and pipe 3 (recognizing that the flow in pipe 3 must also be 800 gpm)

Hydraulic Analysis – Equivalent Pipe Method

Solution:



	Pipe 2	Pipe 3	
C	120	120	
L	500	800	ft
D	6	8	in
Q	800	800	gpm
h_L	28.49666	11.23213	ft

$$h_L = 10.5 \frac{Q^{1.85} L}{C^{1.85} D^{4.87}}$$

- The total head loss is the sum of these two

  H_L total = 39.73 ft

Hydraulic Analysis – Equivalent Pipe Method

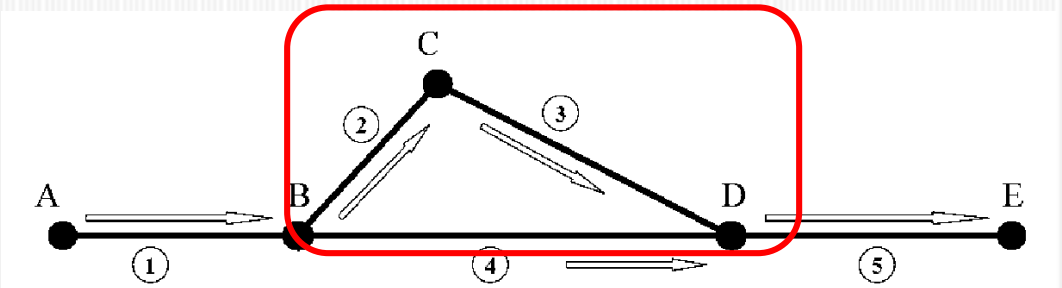
Solution:

- Now, the equivalent length for a 8 in pipe is calculated by rearranging the H-W formula and solving for L as follows:

D = 8 inch
Q = 800 gpm
C = 120

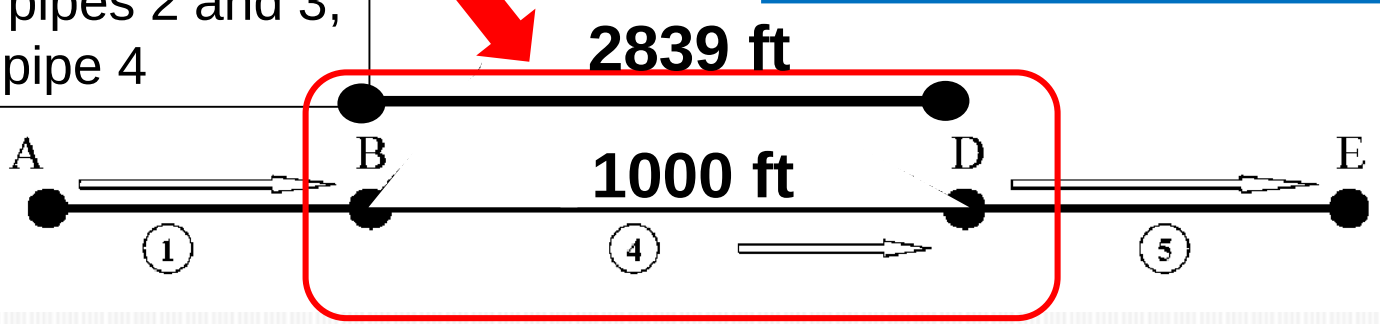
$$L = \frac{h_L C^{1.85} D^{4.87}}{10.5 Q^{1.85}}$$

$$= 2839\ ft$$



h_L from B to D = 39.73 ft

Equivalent pipe for pipes 2 and 3, which is parallel to pipe 4



Hydraulic Analysis – Equivalent Pipe Method

Solution:

b) **Secondly**, determine an equivalent pipe for pipe #4 and the parallel equivalent pipe from part (a).

- Use the head loss resulting from the flow for part (a) as the basis for determining the equivalent pipe length (use D=8 in).

- Determine the flow split between these two parallel pipes (i.e., for 800 gpm through the part (a) pipe, calculate the flow in the parallel pipe 4, and the total flow)

Hydraulic Analysis – Equivalent Pipe Method

Solution:

Now that we know the head loss from node B to node D is 39.73 feet, we can determine the flow in pipe #4 by the H-W formula, rearranged as follows:

Q for pipe 4

$$Q = \frac{h_L^{0.54} C D^{2.63}}{3.56 L^{0.54}}$$

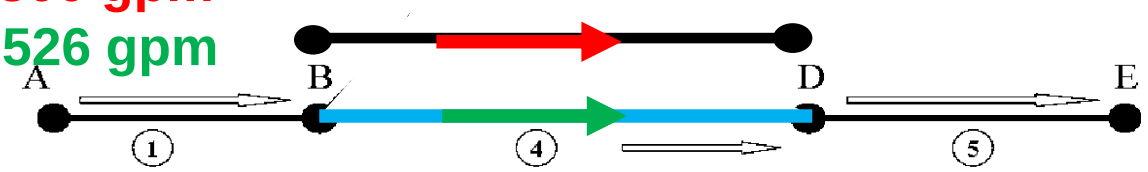
= 2526 gpm

For pipe 4
L = 1000 ft
D = 10 inch
C = 120

Now the total flow between nodes B and D is then the sum: **$Q_{B\text{-}D}$ = 2526 + 800 = 3326 gpm**

h_L from B to D = 39.73 ft

$Q_{2,3}$ = 800 gpm
Q_4 = 2526 gpm



Hydraulic Analysis – Equivalent Pipe Method

Solution:

Finally using the H-W equation, we can calculate an equivalent length of an 8 inch pipe that gives the existing head loss with this flow:

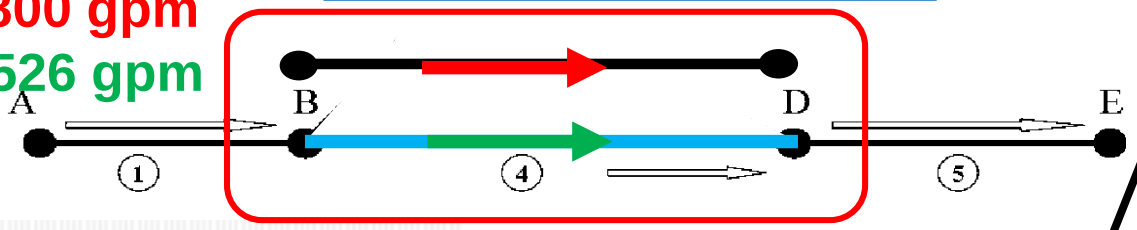
D = 8 inch
$Q_{B\text{-}D}$= 3326 gpm
C = 120
h_L = 39.73 ft

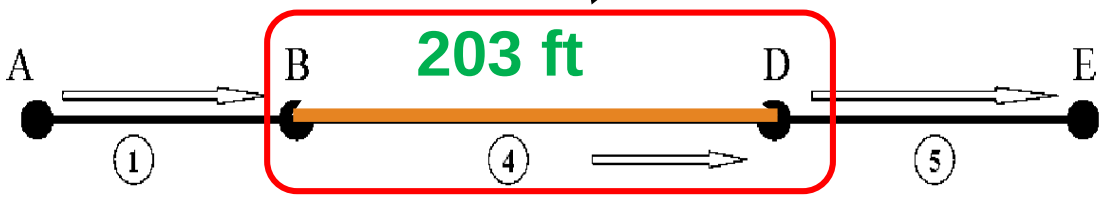
$$L = \frac{h_L C^{1.85} D^{4.87}}{10.5 Q^{1.85}}$$

= 203 ft

h_L from B to D = 39.73 ft

$Q_{2,3}$ = 800 gpm
Q_4 = 2526 gpm





Hydraulic Analysis – Equivalent Pipe Method

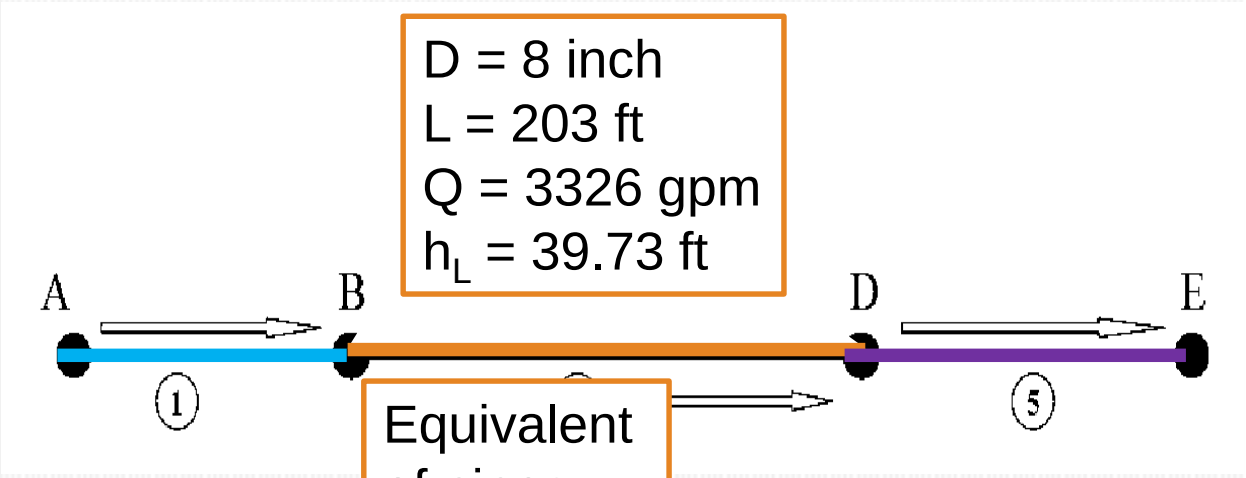
Solution:

c) Finally, determine a single equivalent pipe (D = 8 in) for the three pipes in series, pipe #1, the pipe from part (b), and pipe #5.

- Next we can use the H-W formula to calculate the head loss in pipes #1 and #5, recognizing that the flow in each must be the same as the flow determined for node B to node D (e.g., 3326 gpm)

Hydraulic Analysis – Equivalent Pipe Method

Solution:



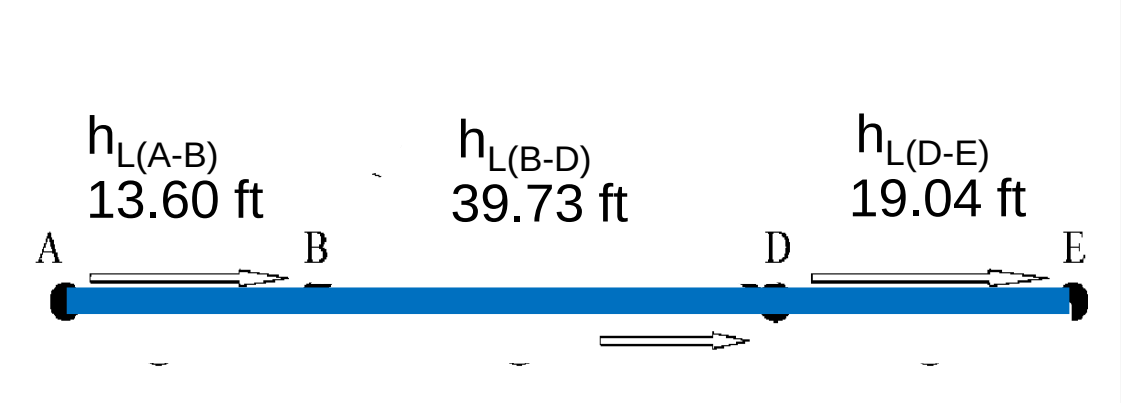
	Pipe 1	Pipe 5	
C	120	120	
L	500	700	ft
D	12	12	in
Q	3326	3326	gpm
h_L	13.60007	19.0401	ft

$$h_L = 10.5 \frac{Q^{1.85} L}{C^{1.85} D^{4.87}}$$

Hydraulic Analysis – Equivalent Pipe Method

Solution: The total head loss is then the sum:

$h_L = 39.73 + 13.60 + 19.04 = \mathbf{72.37\ ft}$



Now, we can calculate an equivalent length based on this head loss and to flow.

$$L = \frac{h_L C^{1.85} D^{4.87}}{10.5 Q^{1.85}}$$

= 369 ft

Q= 3326 gpm
h_L = 72.37 ft
D = 8 inch
C = 120

Hydraulic Analysis – Equivalent Pipe Method

Solution:

d) Show that your pipe is hydraulically equivalent by calculating the head loss for this single pipe and comparing it to the sum of the head losses for pipes in the original system.

- Recalculate the head loss in each of the original pipes.

- Sum the head loss from each node to the next one, recognizing that there are two ways of getting from node B to node D (use either one, but not both).

Hydraulic Analysis – Equivalent Pipe Method

Solution:

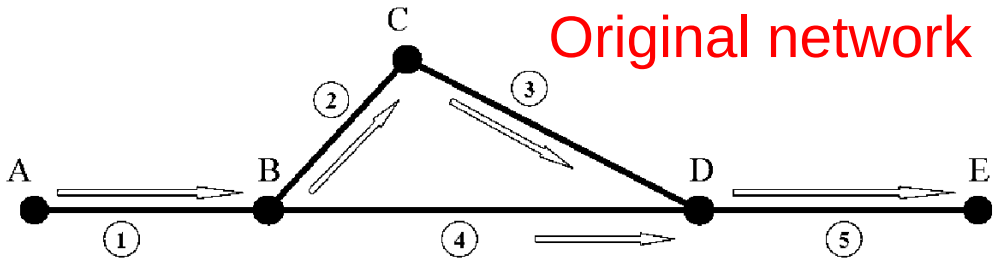
$$h_L = 10.5 \frac{Q^{1.85} L}{C^{1.85} D^{4.87}}$$

	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5	
C	120	120	120	120	120	
L	500	500	800	1000	700	ft
D	12	6	8	10	12	in
Q	3325.68	800	800	2525.684	3325.68	gpm
h_L	13.60007	28.49666	11.23213	39.72879	19.0401	ft

Total h_L = **72.36896 ft**

For h_L from B to D,
either h_L for pipe 4
or sum of h_L for pipes 2 and 3

Original network



Equivalent network



Total h_L = **72.37 ft**