FLUID MECHANICS
CEI 121

Flow in Pipelines

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- In considering the convenience and necessities in every day life, it is truly amazing to note the role played by conduits in transporting fluid.
- For example, the water in our homes is normally conveyed through pressure pipelines, from the distribution system, so that it will be available when and where we want it.
- Moreover, virtually all of this water leaves our homes as dilute wastes through sewers, another type of conduits. Oil is often transferred from their source by pressure pipelines to refineries while gas is conveyed by pipelines into a distribution network for supply.
- Thus, it can be seen that the fluid flow in conduits is of immense practical significance in civil engineering.

1. Differentiate between laminar and turbulent flows in pipelines.
2. Describe the velocity profile for laminar and turbulent flows.
3. Compute Reynolds number for flow in pipes.
4. Define the friction factor, and compute the friction losses in pipelines.
5. Recognize the source of minor losses, and compute minor losses in pipelines.
6. *Analyze simple pipelines, pipelines in series, parallel, and simple pipe networks*.

- This chapter introduces the fundamental theories of flow in pipelines as well as basic design procedures.
- In this chapter, the pipeline system is defined as a closed conduit with a circular cross-section with water flows (flowing full) inside it.
- It is a closed system, the water is not in contact with air (i.e. no free surface). Flow in a closed pipe results from a pressure difference between inlet and outlet. The pressure is affected by fluid properties and flow rate.
- Bernoulli equation can be written between two sections for Real flow as;

$$\frac{P_1}{\rho g} + z_1 + \frac{\alpha V_1^{\,2}}{2g} = \frac{P_2}{\rho g} + z_2 + \frac{\alpha V_2^{\,2}}{2g} + h_f$$

Types of Flow

- The physical nature of fluid flow can be categorized into three types, i.e. *laminar*, *transition* and *turbulent* flow. It has been mentioned earlier that **Reynolds Number (R_N)** can be used to characterize these flow.

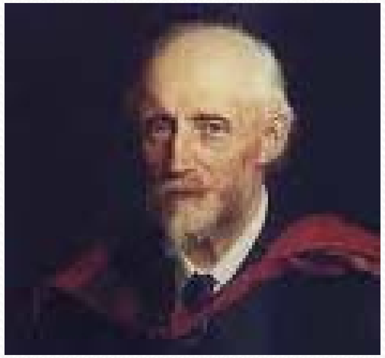
$$R_N = \frac{\rho VD}{\mu} = \frac{VD}{\nu} = \frac{\text{Interial Force}}{\text{Viscous Force}}$$

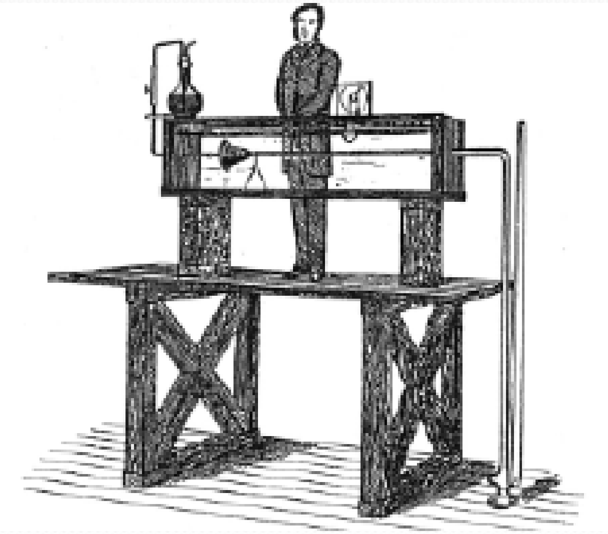
where ρ = density
μ = dynamic viscosity
ν = kinematic viscosity ($\nu = \mu/\rho$)
V = mean velocity
D = pipe diameter

- In general, flow in commercial pipes have been found to conform to the
- following condition:

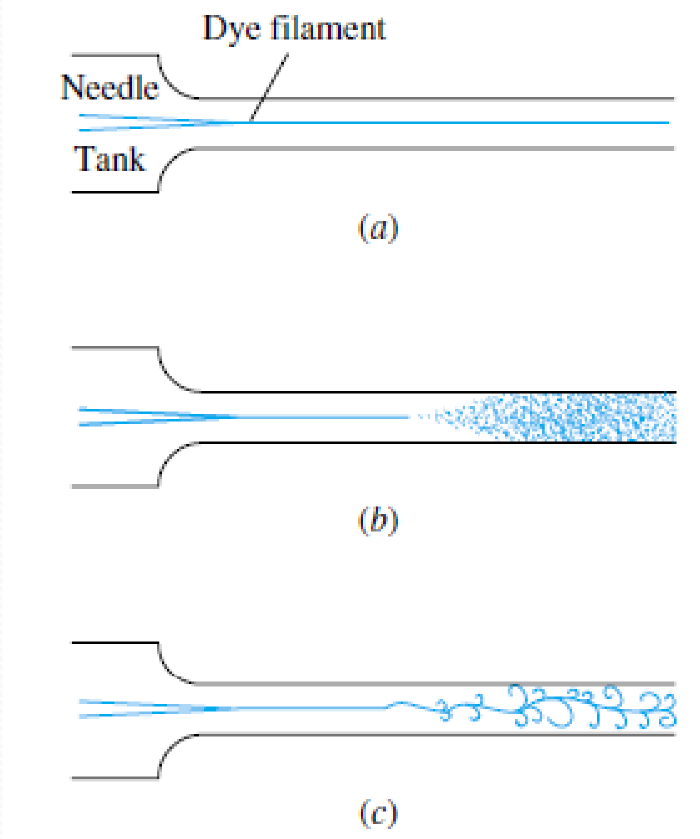
Laminar Flow:	$R_N < 2000$
Transitional Flow :	$2000 < R_N < 4000$
Turbulent Flow :	$R_N > 4000$

Osborne Reynolds 1883

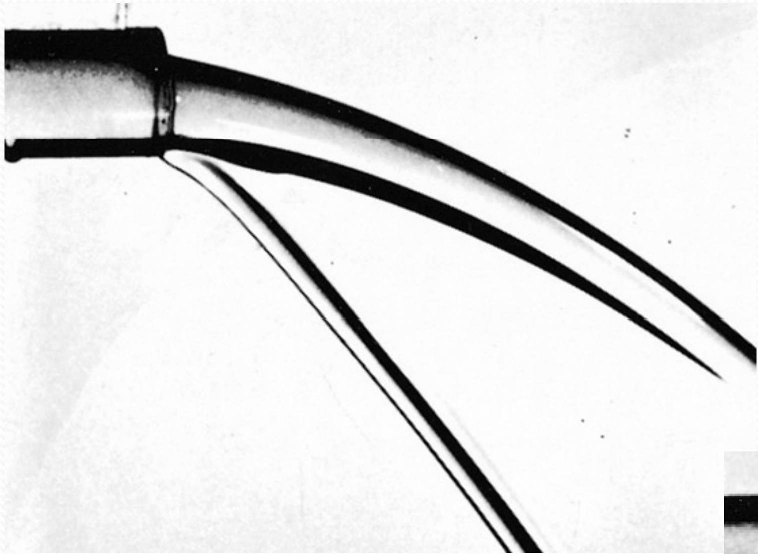




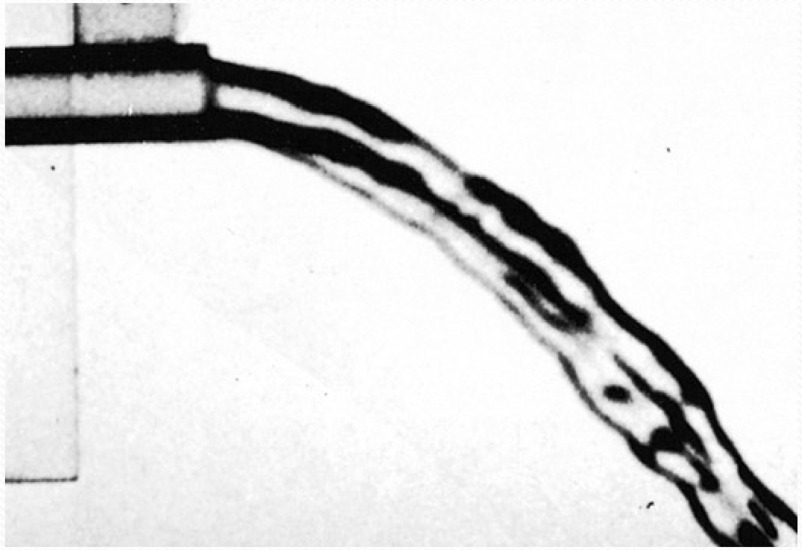
Osborne Reynolds Apparatus



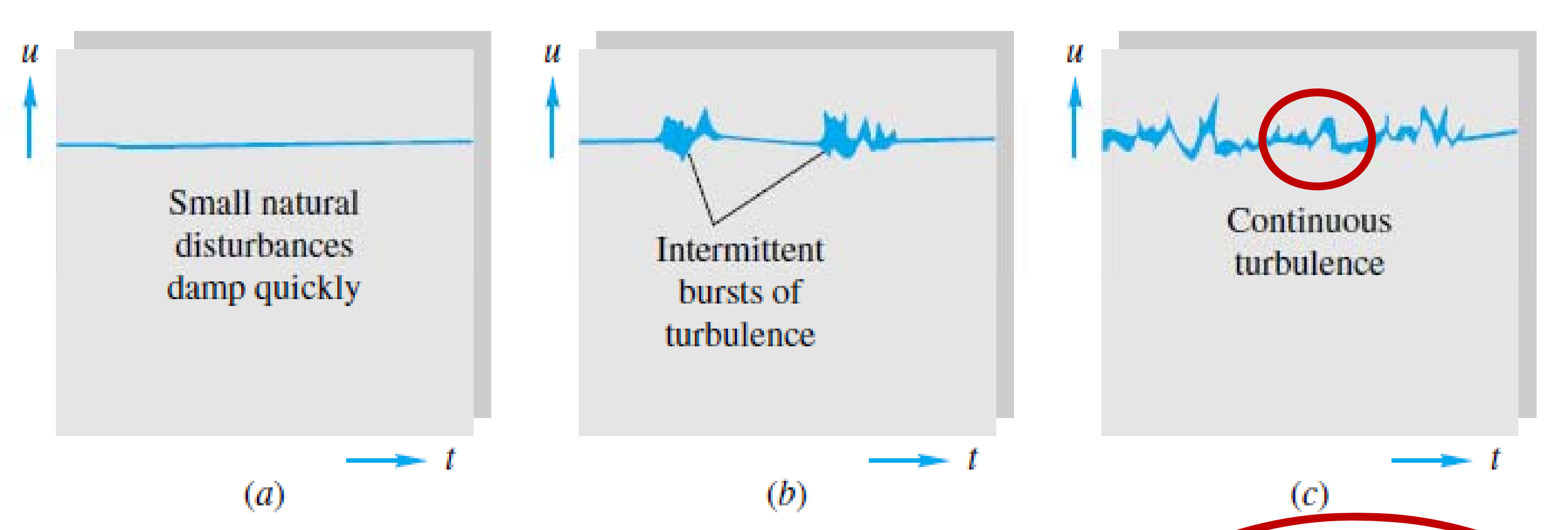
Reynolds' sketches of pipe-flow transition:
(a) low-speed, laminar flow;
(b) high-speed, turbulent flow;
(c) spark photograph of condition (*b*)



High viscosity, low Reynolds number, laminar flow



Low viscosity, high Reynolds number, turbulent flow

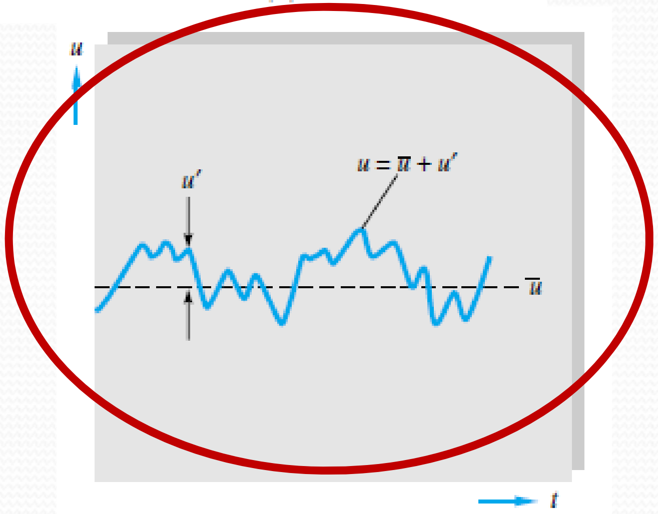


The three regimes of viscous flow:

a) Laminar flow at low R_N

b) Transition at intermediate R_N

c) Turbulent flow at high R_N



Example

An oil of S.G.=0.85, ν=1.8*10^{-5} m²/sec, D=10 cm, Q=0.5 l/sec

Determine the type of flow.

Solution

$$V = \frac{Q}{A} = \frac{0.5}{1000 * \frac{\pi * 0.1^2}{4}} = 0.063 \quad \text{m/sec}$$

$$R_n = \frac{\rho VD}{\mu} = \frac{VD}{\upsilon} = \frac{0.063 * 0.1}{1.8 * 10^{-5}} = 350 \langle 2000$$

The flow is laminar

Laminar Flow

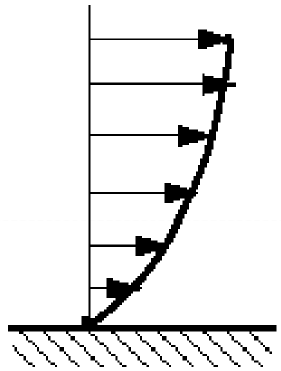
Laminar Flow

- Viscous shears dominate in this type of flow and the fluid appears to be moving in discreet layers. The shear stress is governed by Newton's law of viscosity:

$$\tau = \mu \frac{du}{dy}$$

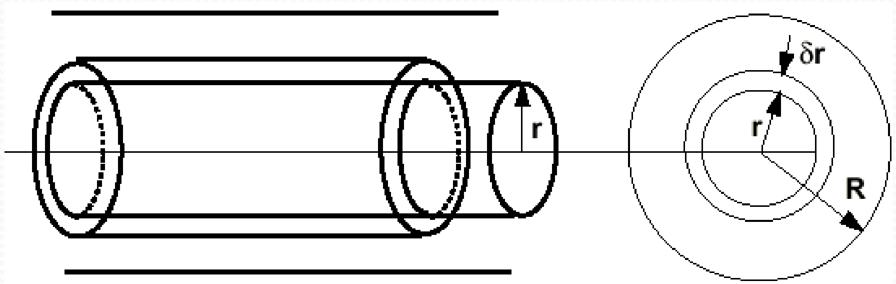
- In general the shear stress is almost impossible to measure. But for laminar flow it is possible to calculate the theoretical value for a given velocity, fluid and the appropriate geometrical shape.

- In reality, because fluids are viscous, energy is lost by flowing fluids due to friction which must be taken into account.
- The effect of friction shows itself as a pressure (or head) loss. In a pipe with a real fluid flowing, the shear stress at the wall retard the flow.
- The shear stress will vary with velocity of flow and hence with R_N. Many experiments have been done with various fluids measuring the pressure loss at various Reynolds numbers.
- Figure below shows a typical velocity distribution in a pipe flow. It can be seen the velocity increases from zero at the wall to a maximum in the mainstream of the flow.



A typical velocity distribution in a pipe flow

- In laminar flow the paths of individual particles of fluid do not cross, so the flow may be considered as a series of concentric cylinders sliding over each other – rather like the cylinders of a collapsible pocket telescope.
- Lets consider a cylinder of fluid with a length L, radius r, flowing ***steadily*** in the center of pipe.



Cylindrical of fluid flowing steadily in a pipe

- The fluid is in equilibrium, shearing forces equal the pressure forces.
- Shearing force = Pressure force

$$\tau\, 2\pi\, y\, L = \Delta P\, A = \Delta P\, \pi\, y^2$$

$$\tau = \frac{\Delta P}{L}\frac{r}{2}$$

- Taking the direction of measurement y (measured from the center of pipe);
-

$$\tau = -\mu \frac{du}{dy}$$

$$\frac{\Delta P}{L}\frac{r}{2} = -\mu \frac{du}{dr}$$

$$\frac{du}{dr} = -\frac{\Delta P}{L}\frac{r}{2\mu}$$

- In an integral form this gives an expression for velocity, with the values of y = 0 (at the pipe center) to r = D/2 (at the pipe wall)

$$u = -\frac{\Delta P}{L}\frac{1}{2\mu}\int_{y=0}^{y=D/2} y\,dy$$

$$u_r = -\frac{\left(D^2/4 - y^2\right)}{4\mu}\frac{\Delta P}{L}$$

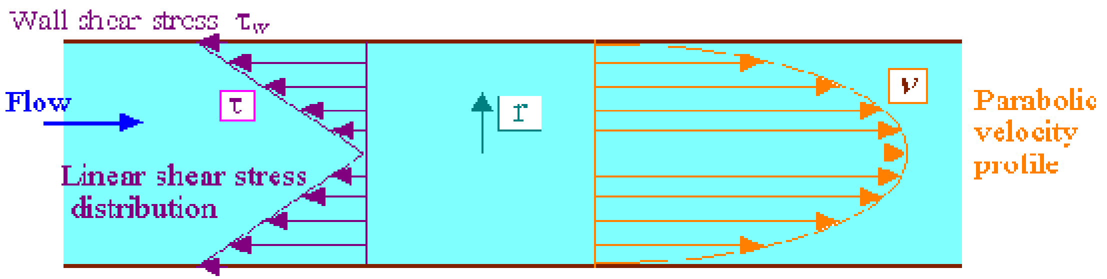
where ΔP = change in pressure

- L = length of pipe
- D = pipe Diameter
- y = distance measured from the center of pipe

- The maximum velocity is at the center of the pipe, i.e. when r = 0.

$$u_{\max} = -\frac{D^2}{16\mu}\frac{\Delta P}{L}$$

- It can be shown that the mean velocity is half the maximum velocity, i.e. $V_m = U_{max}/2$



Shear stress and velocity distribution in pipe for laminar flow

The discharge may be found using the **Hagen-Poiseuille** equation, which is given by the following;

$$Q = \frac{\Delta P}{L}\frac{\pi D^4}{128\mu}$$

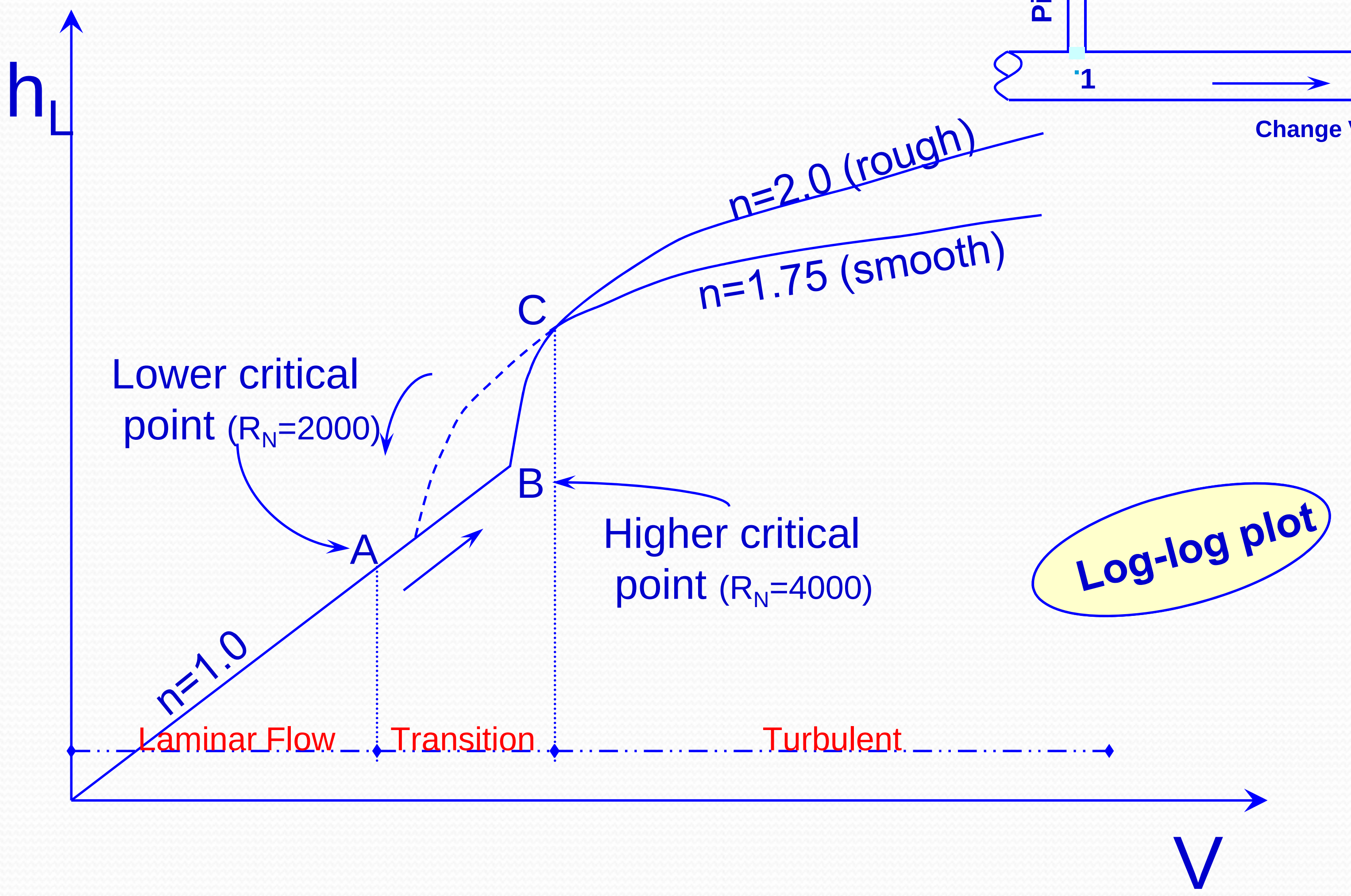
The ***Hagen-Poiseuille*** expresses the discharge Q in terms of the pressure gradient $\left(\frac{dP}{dx} = \frac{\Delta P}{L}\right)$, diameter of pipe, and viscosity of the fluid.

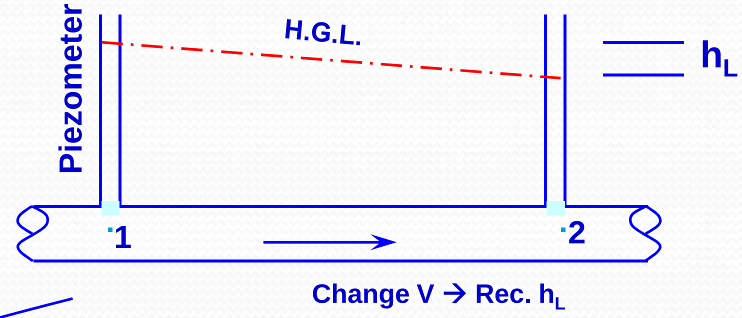
Pressure drop throughout the length of pipe can then be calculated by

$$\Delta P = \frac{128\mu L Q}{\pi D^4} \longrightarrow \quad h_l = \frac{32\mu\, L\, V}{\gamma\, D^2} \longrightarrow F = \frac{64}{R_N}$$

Pressure drop

Pressure drop against the velocity



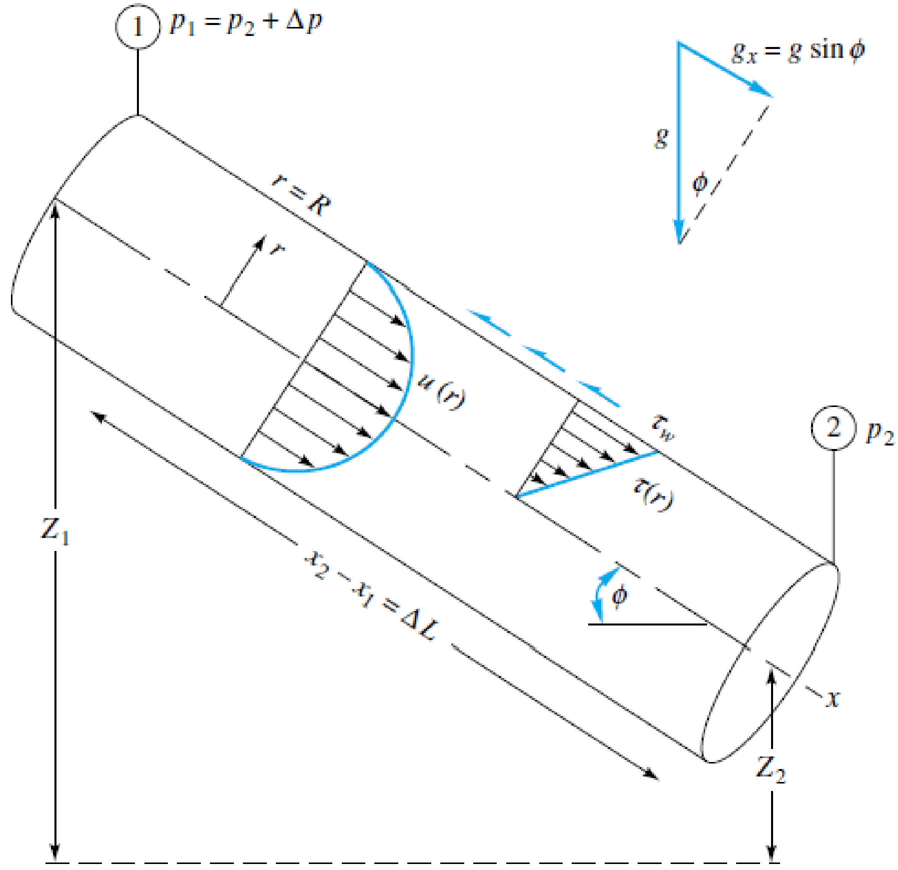


Pressure drop against the velocity

Osborn Reynolds carried out a wide range of experiments to characterise this transition in pipe flow. He has plotted the pressure drop against the velocity. This graph show's a clear change of gradient above certain velocity could be observed. When measurements were made gradually increasing the velocity, at low velocities the curve is linear with a gradient of 1. At point B the curve becomes irregular until point C. From point C onwards, the curve is again becomes linear with a gradient in the rage 1.75 to 2.0. This second section represents the turbulent flow regime. The pressure drop is greater than that for the laminar flow in the pipe. This is due to the higher energy dissipation. When the measurements were made starting from a higher flow velocity and decreasing it in small steps, the same curve is followed until point C. Then the data again become scattered and roughly follow a line that connects to the laminar flow section at A. This region where the data point become scattered is the shows the transition between laminar and turbulent flow regimes.

Friction Losses in Circular Pipe

Control volume of steady, fully developed flow between two sections in an inclined pipe.
Assumptions:-
Steady flow and pipe area is constant



The continuity

$$Q_1 = Q_2 = \text{const}$$

$$V_1 = \frac{Q_1}{A_1} \qquad V_2 = \frac{Q_2}{A_2}$$

The steady-flow energy equation

$$h_f = \left(z_1 + \frac{p_1}{\rho g}\right) - \left(z_2 + \frac{p_2}{\rho g}\right) = \Delta\left(z + \frac{p}{\rho g}\right) = \Delta z + \frac{\Delta p}{\rho g}$$

One-Dimensional Momentum Flux

$$\Delta p\ \pi R^2 + \rho g(\pi R^2)\ \Delta L \sin\phi - \tau_w(2\pi R)\ \Delta L = \dot{m}(V_2 - V_1) = 0$$

$$\Delta z = \Delta L \sin\phi$$

$$\Delta z + \frac{\Delta p}{\rho g} = h_f = \frac{2\tau_w}{\rho g}\frac{\Delta L}{R}$$

So far we have not assumed ***either laminar or turbulent*** flow. If we can correlate τ_w with flow conditions, we have solved the problem of head loss in pipe flow. Functionally, we can assume that

$$\tau_w = F(\rho, V, \mu, d, \epsilon)$$

where is the wall roughness height

The dimensionless parameter f is called the Darcy friction factor (1803–1858)

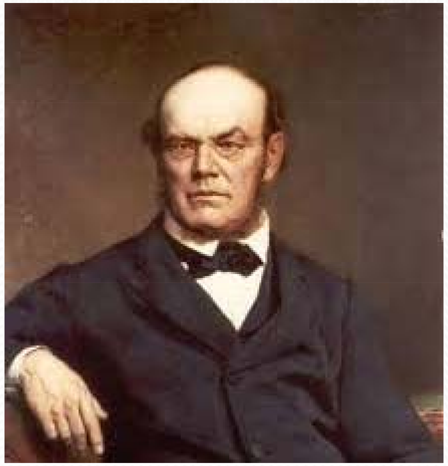
$$\frac{8\tau_w}{\rho V^2} = f = F\left(\mathrm{Re}_d, \frac{\epsilon}{d}\right)$$

$$\tau_w = \frac{\rho F\, V^2}{8}$$

Henry Darcy

Darcy-Weisbach Equation (1857)

$$h_l = \frac{F\, L\, V^2}{2\, g\, D} = \frac{8\, F\, L\, Q^2}{\pi^2\, g\, D^5}$$



Julius Weisbach

Turbulent

Turbulent flow

- This is the most commonly occurring flow in engineering practice in which fluid particles move erratically causing instantaneous fluctuations in the velocity components.
- These fluctuations cause additional shear stresses. In this type of flow both viscous and turbulent shear stresses exists.
- Thus, the shear stress in turbulent flow is a combination of laminar and turbulent shear stresses, and can be written as:

$$\tau = \tau_{laminar} + \tau_{turbulent} = (\mu + \varepsilon)\frac{dU}{dy}$$

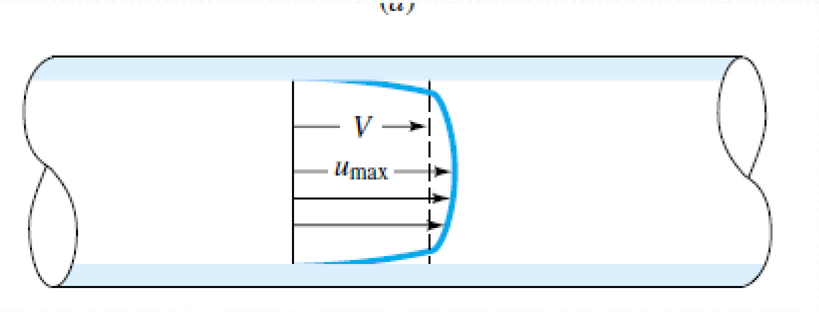
- where μ = dynamic viscosity
- ε = eddy viscosity which is not a fluid property but depends upon turbulence condition of flow.

- The velocity at any point in the cross-section will be proportional to the one-seventh power of the distance from the wall, which can be expressed as:

$$\frac{U_y}{U_{CL}} = \left(\frac{y}{R}\right)^{1/7}$$

- where U_y is the velocity at a distance *y* from the wall, U_{CL} is the velocity at the centerline of pipe, and R is the radius of pipe. This equation is known as the **Prandtl one-seventh law**.

- Figure below shows the velocity profile for turbulent flow in a pipe. The shape of the profile is said to be logarithmic.



Velocity profile for turbulent flow

Example

Glycerin (ρ = 1258 kg/m3, μ=9.60 x10^{-1} N.s/m^2) flows with a velocity of 3.6 m/s in a 150-mm diameter pipe. Determine whether the flow is laminar or turbulent.

Solution:

$$Re = \frac{\rho VD}{\mu}$$

$$Re = \frac{1258x3.6x0.15}{9.60x10^{-1}} = 708$$

Since Re=708, which is less than 2000, the flow is laminar.

Energy Losses due to friction

- When a liquid flows through a pipeline, shear stresses develop between the liquid and the pipe wall.
- This shear stress is a result of friction, and its magnitude is dependent upon the properties of the fluid, the speed at which it is moving, the internal roughness of the pipe, the length and diameter of pipe.
- **Friction loss**, also known as **major loss**, is a primary cause of energy loss in a pipeline system.

Friction Losses in Laminar flow

- In laminar flow, the fluid seems to flow as several layers, one on another. Because of the viscosity of the fluid, a shear stress is created between the layers of fluid.
- Energy is lost from the fluid to overcome the frictional forces produced by the shear stress.
- Energy loss is usually represented by the drop of pressure in the direction of flow.
- Therefore, the frictional head loss, h_f, can be written in terms of pressure drop along the pipeline, as follows:

$$h_f = \frac{\Delta P}{\rho g}$$

Substituting the Hagen-Poiseuille equation and applying the continuity equation, Q = VA, to the above resulted into the following expression:

$$h_f = \frac{32 \mu L V}{\gamma D^2}$$

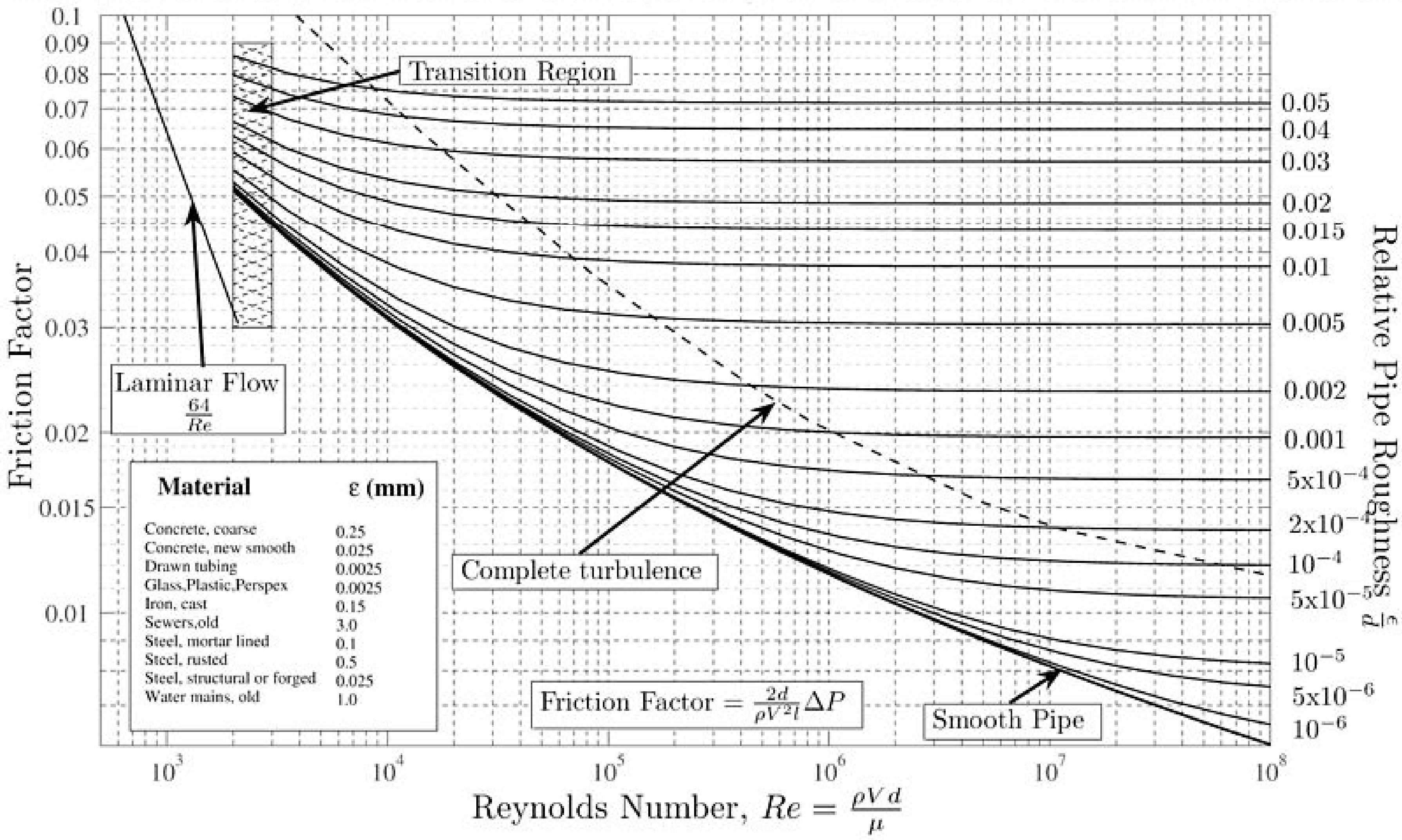
Friction Losses in Turbulent flow

- In turbulent flow, the friction head loss can be calculated by considering the pressure losses along the pipelines.
- In a horizontal pipe of diameter D carrying a steady flow there will be a pressure drop in a length L of the pipe.
- Equating the frictional resistance to the difference in pressure forces, and manipulating resulted into the following expression:

$$h_f = F \frac{L}{D} \frac{V^2}{2g}$$

- This equation is known as **Darcy-Weisbach (D-W)** equation, in which F is the friction factor. It should be noted that F is dimensionless, and the value is not constant

Moody Diagram



Minor Losses

Minor Losses

- In addition to head loss due to friction, there are always other head losses due to pipe expansions and contractions, bends, valves, and other pipe fittings. These losses are usually known as **minor losses (h_{Lm})**.

- In case of a long pipeline, the minor losses may be negligible compared to the friction losses, however, in the case of short pipelines, their contribution may be significant.

1- Losses due to pipe fittings

$$h_{Lm} = K\frac{V^2}{2g}$$

where h_{Lm}= minor loss

K = minor loss coefficient

V = mean flow velocity

Type	K
90° elbow	0.9
45° elbow	0.4
T-junction	1.8
Gate valve	0.25 - 25

Table 6.2: Typical K values

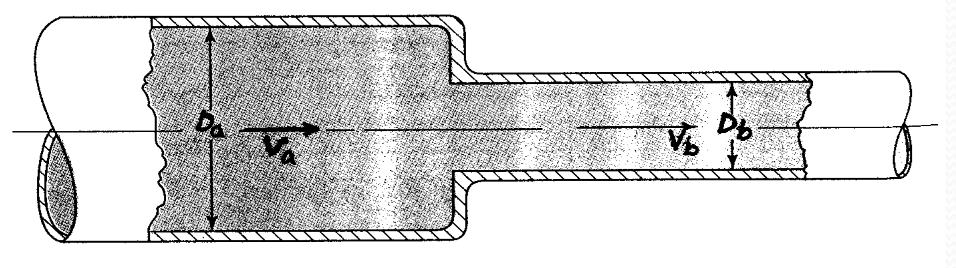
2- Sudden Contraction

The energy loss due to a sudden contraction can be calculated using the following;

$$h_{Lm} = K_C \frac{V_b^2}{2g}$$

The K_C is the coefficient of contraction and the values depends on the ratio of the pipe diameter (D_b/D_a) as shown below.

D_b/D_a	0.0	0.2	0.4	0.6	0.8	1.0
K	0.5	0.49	0.42	0.27	0.20	0.0



Flow at sudden contraction

3- Gradual Contraction

The energy loss due to a gradual contraction can be calculated using the following;

$$h_{Lm} = K_{Cg} \frac{V_b^{\ 2} - V_a^{\ 2}}{2g}$$

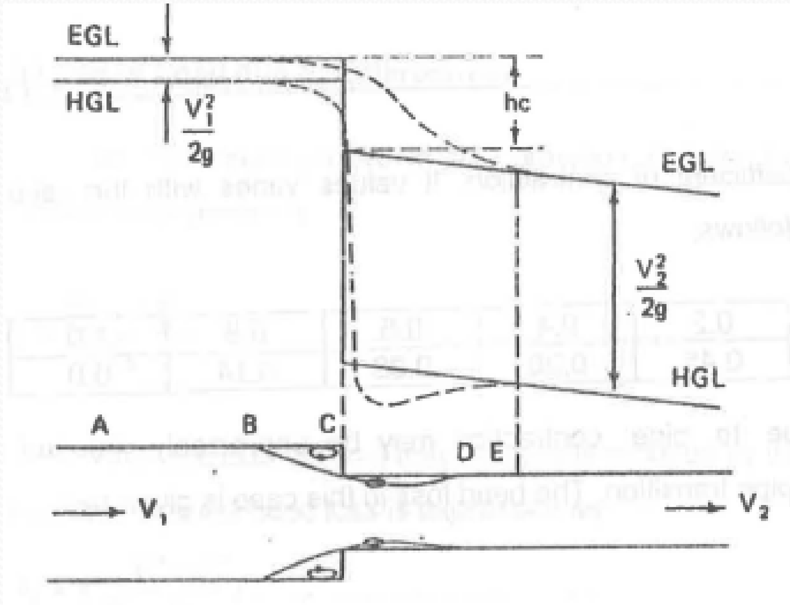
The K_C is the coefficient of gradual contraction and depend on the transition angle.

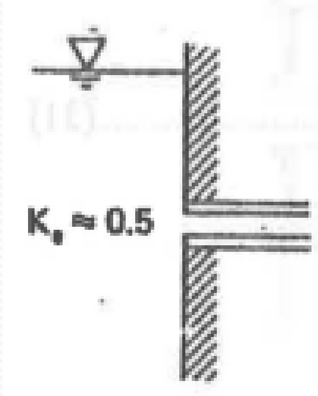
Angle	10	20	30	40
K	0.2	0.28	0.32	0.35

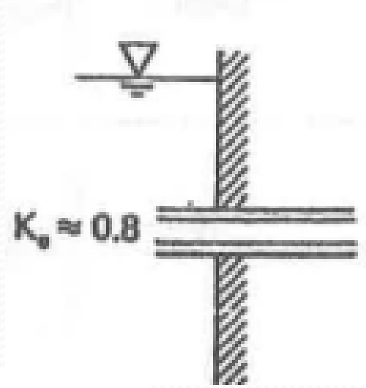
4- Entrance Losses

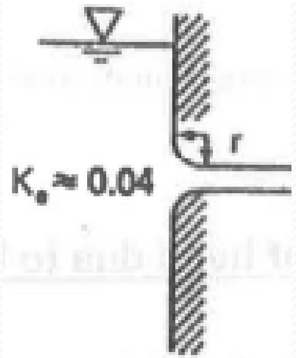
The loss of head at the entrance to a pipe from a large reservoir is a special case of loss of head due to contraction.

$$h_{Lm} = Ke\frac{V_2^{\ 2}}{2g}$$





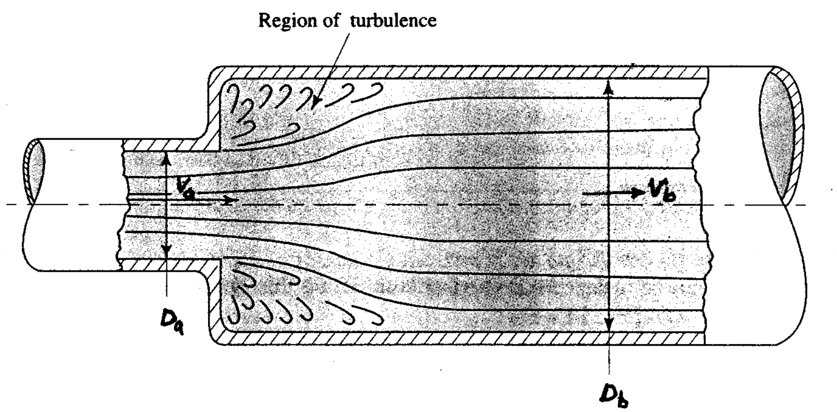




5- Sudden Enlargement

- As fluid flows from a smaller pipe into a larger pipe through sudden enlargement, its velocity abruptly decreases; causing turbulence that generates an energy loss.
- The amount of turbulence, and therefore the amount of energy, is dependent on the ratio of the sizes of the two pipes.
- The minor loss (h_{Lm})is calculated from;

$$h_{Lm} = \frac{(V_a - V_b)^2}{2g}$$



6- Gradual Enlargement

The energy loss due to a gradual enlargement can be calculated using the following;

$$h_{Lm} = K_{Cg} \frac{V_b^{\,2} - V_a^{\,2}}{2g}$$

The K_C is the coefficient of gradual contraction and depend on the transition angle.

Angle	10	20	30	40
K	0.39	0.80	1.0	1.06

7- Exit

A submerged pipe discharging into a large reservoir is a special case of loss of head due to enlargement. The flow velocity V in the pipe is discharged from the end of a pipe into a reservoir that is so large that the velocity within it is almost zero and the head loss in this case is;

$$h_{Lm} = \frac{{V_P}^2}{2g}$$

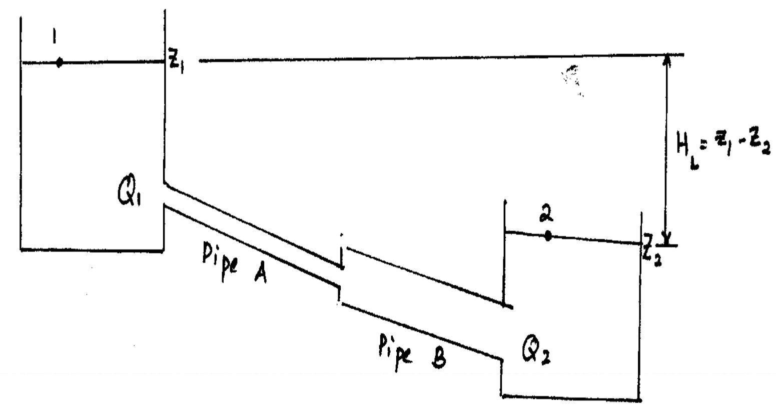
Pipe Flow Analysis

Pipe Flow Analysis

- Pipeline system used in water distribution, industrial application and in many engineering systems may range from simple arrangement to extremely complex one.
- Problems regarding pipelines are usually tackled by the use of continuity and energy equations.
- The head loss due to friction is usually calculated using the **D-W** equation while the minor losses are computed using equations depending on the appropriate conditions.

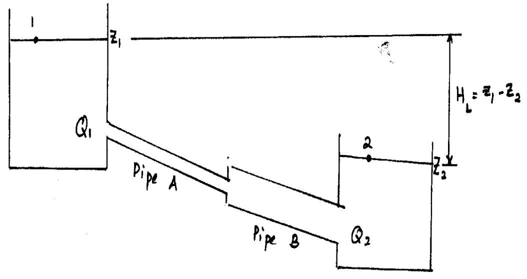
Pipes in Series

- When two or more pipes of different diameters or roughness are connected in such a way that the fluid follows a single flow path throughout the system, the system represents a series pipeline.
- In a series pipeline the total energy loss is the sum of the individual minor losses and all pipe friction losses.



Pipelines in series

▪ Referring to Figure, the Bernoulli equation can be written between points 1 and 2 as follows;



$$\frac{P_1}{\rho g} + z_1 + \frac{V_1^2}{2g} = \frac{P_2}{\rho g} + z_2 + \frac{V_2^2}{2g} + H_{L1-2}$$

where

$P/\rho g$ = pressure head
z = elevation head
$V^2/2g$ = velocity head
H_{L1-2} = total energy lost between point 1 and 2

Realizing that $P_1 = P_2 = P_{atm}$, and $V_1 = V_2 = 0.0$, then equation reduces to

$$z_1 - z_2 = H_{L1-2}$$

Or we can say that the different of reservoir water level is equivalent to the total head losses in the system.

The total head losses are a combination of the all the friction losses and the sum of the individual minor losses.

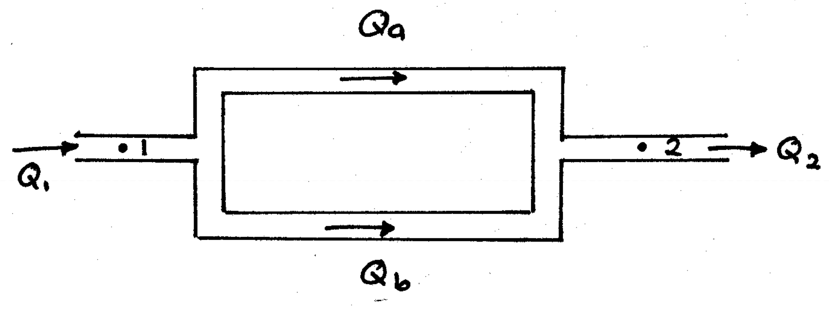
$$H_{L1-2} = h_{fa} + h_{fb} + h_{entrance} + h_{valve} + h_{expansion} + h_{exit}.$$

Since the same discharge passes through all the pipes, the continuity equation can be written as;

$$Q_1 = Q_2$$

Pipes in Parallel

- A combination of two or more pipes connected between two points so that the discharge divides at the first junction and rejoins at the next is known as pipes in parallel. Here the head loss between the two junctions is the same for all pipes.



Pipelines in parallel

- Applying the continuity equation to the system;

$$Q1 = Q_a + Q_b = Q_2$$

- The energy equation between point 1 and 2 can be written as;

$$\frac{P_1}{\rho g} + z_1 + \frac{V_1^2}{2g} = \frac{P_2}{\rho g} + z_2 + \frac{V_2^2}{2g} + H_L$$

- The head losses throughout the system are given by;

$$H_{L1-2} = h_{La} = h_{Lb}$$

- Above equations are the governing relationships for parallel pipe line systems. The system automatically adjusts the flow in each branch until the total system flow satisfies these equations.

- *Thank You*