



**CIVIL ENGINEERING
HYDRAULICS AND HYDRAULIC
MACHINERY**

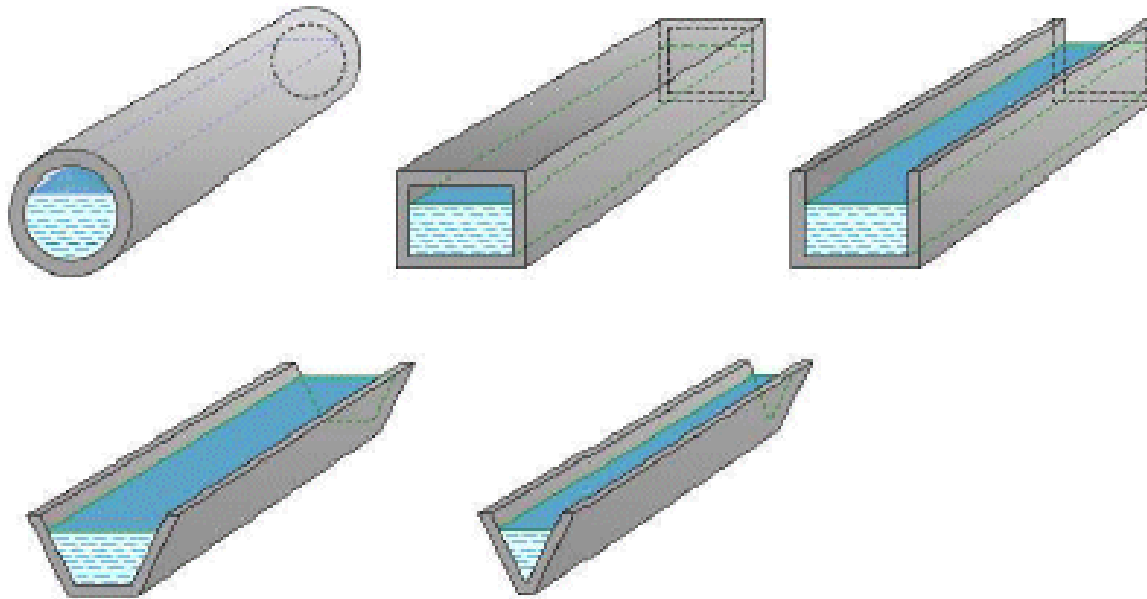


UNIT-I

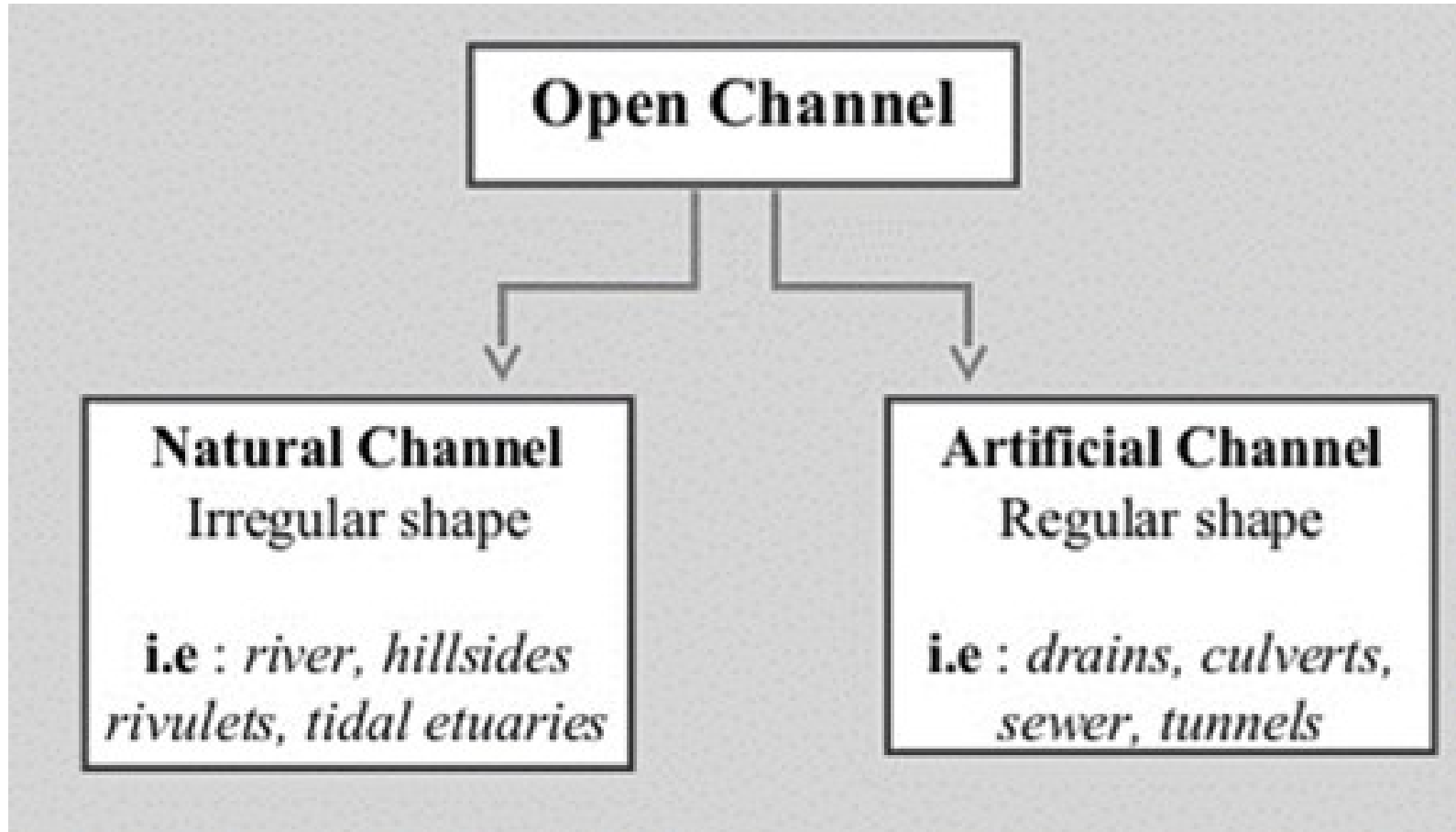
OPEN CHANNEL FLOW

INTRODUCTION

Open channel flow is a flow which has a free surface and flows due to gravity. Pipes not flowing full also fall into the category of open channel flow. In open channels, the flow is driven by the slope of the channel rather than the pressure.



TYPES OF CHANNELS

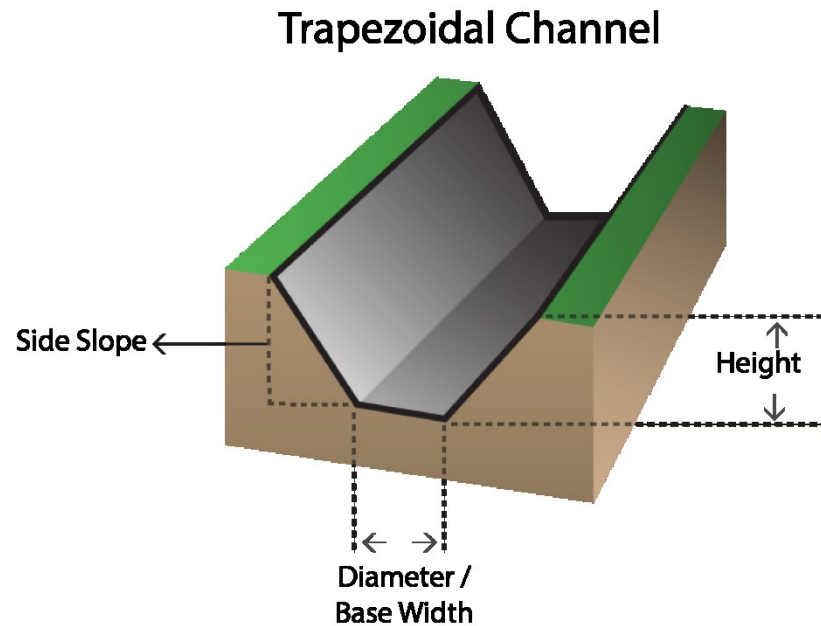


TYPES OF FLOW

- ⦿ Steady and Unsteady Flow
- ⦿ Uniform and Non-uniform Flow
- ⦿ Laminar and Turbulent Flow
- ⦿ Sub-critical, Critical and Super-critical Flow

STEADY AND UNSTEADY FLOW

- Steady flow happens if the conditions (flow rate, velocity, depth etc) do not change with time. The flow is unsteady if the depth is changes with time.



UNIFORM AND NON-UNIFORM FLOW

- ⦿ If for a given length of channel, the velocity of flow, depth of flow, slope of the channel and cross section remain constant, the flow is said to be Uniform
- ⦿ The flow is Non-uniform, if velocity, depth, slope and cross section is not constant.

NON-UNIFORM FLOW

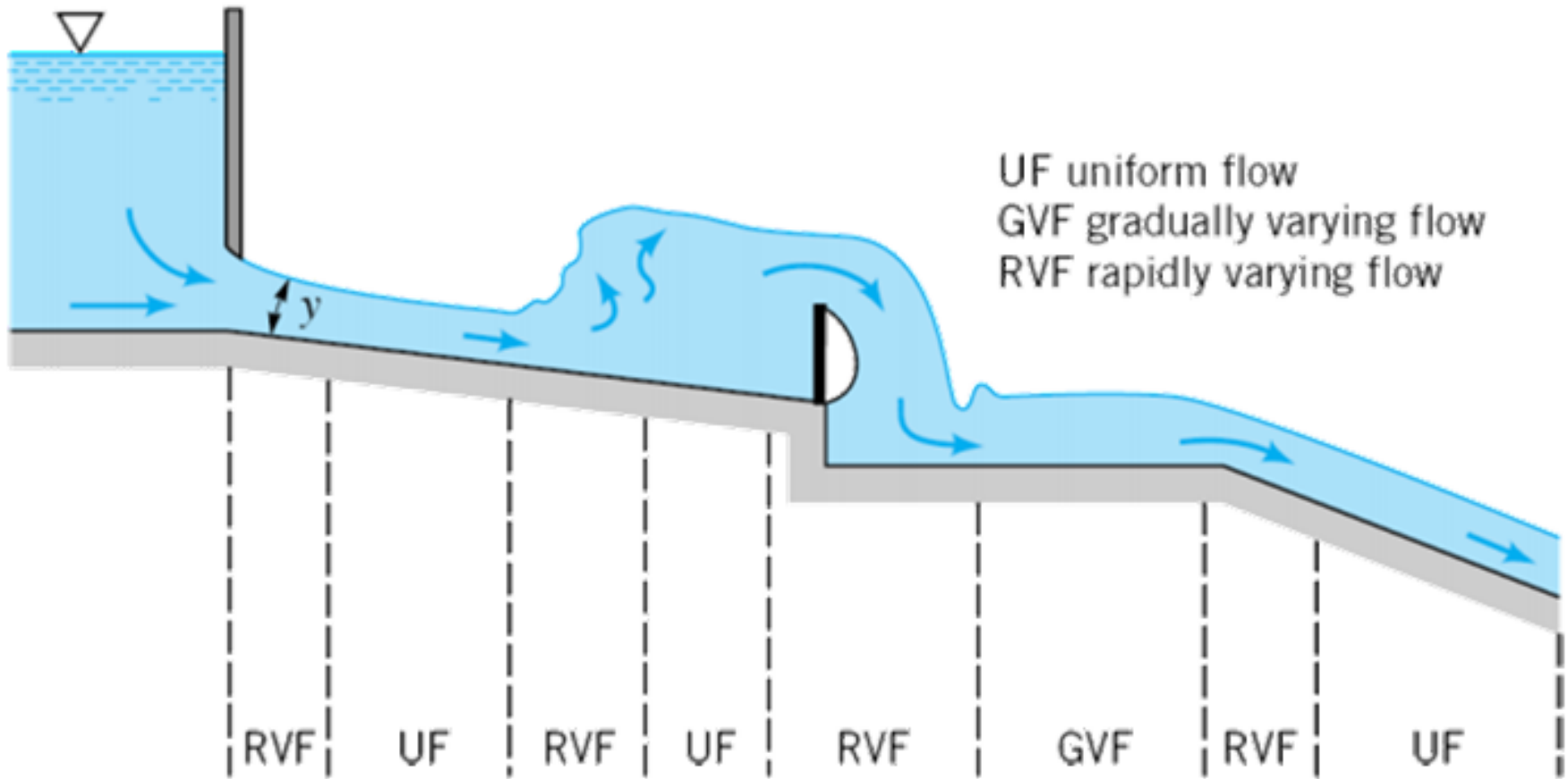
Gradually Varied Flow (GVF)

- ⦿ If the depth of the flow in a channel changes gradually over a length of the channel.

Rapidly Varied Flow (RVF)

- ⦿ If the depth of the flow in a channel changes abruptly over a small length of channel

PROFILE



LAMINAR, TURBULENT AND TRANSITION FLOW

- ⦿ Both laminar and turbulent flow can occur in open channels depending on the Reynolds number (Re)
- ⦿ **$Re = \rho VR / \mu$**
Where,
 - ⦿ ρ = density of water = 1000 kg/m³
 - ⦿ μ = dynamic viscosity
 - ⦿ R = Hydraulic Mean Depth
= Wetted Area / Wetted Perimeter

RANGE OF FLOWS

$$R_e = \rho V R / \mu$$

V is the average velocity of the fluid.

R is the hydraulic radius of the channel.

- ❖ Laminar flow: $Re < 500$
- ❖ Transitional flow: $Re > 500$ & $Re < 1000$
- ❖ Turbulent flow: $Re > 1000$

SUB-CRITICAL, CRITICAL AND SUPER-CRITICAL FLOW

The flow in open channel is said to be sub-critical if the Froude number (F_e) is less than 1.0.

The Froude number is defined as : $F_e = \frac{V}{\sqrt{gD}}$

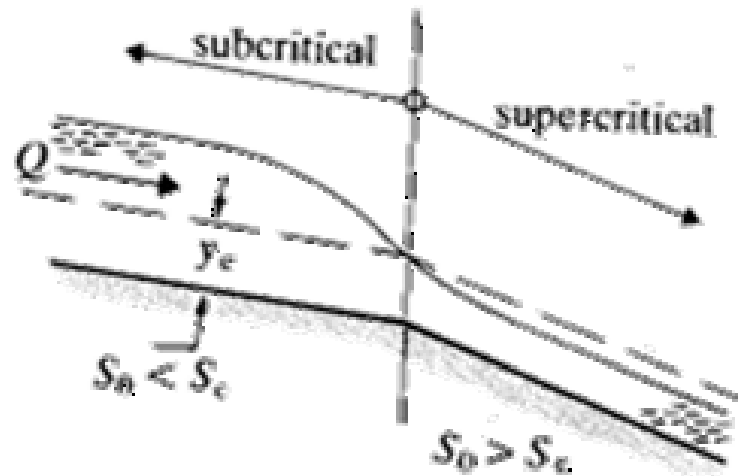
where V = Mean velocity of flow

D = Hydraulic depth of channel and is equal to the ratio of wetted area to the top width of channel

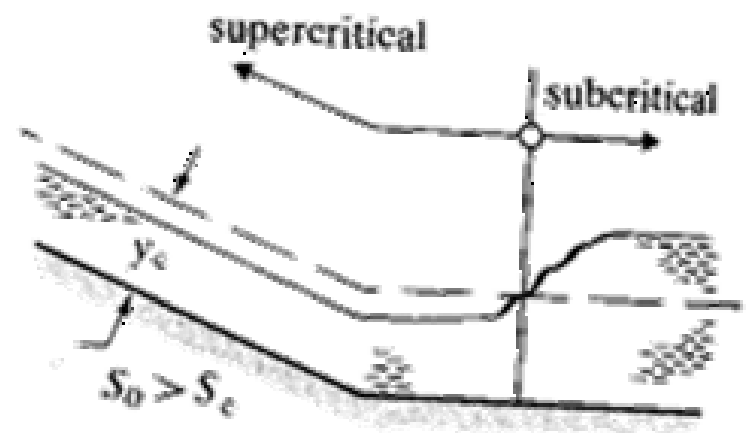
= $\frac{A}{T}$, where T = Top width of channel.

PROFILE

Sub-critical flow is also called tranquil or streaming flow. For sub-critical flow, $F_e < 1.0$. The flow is called critical if $F_e = 1.0$. And if $F_e > 1.0$, the flow is called super critical or shooting or rapid or torrential.



(a) Subcritical to supercritical

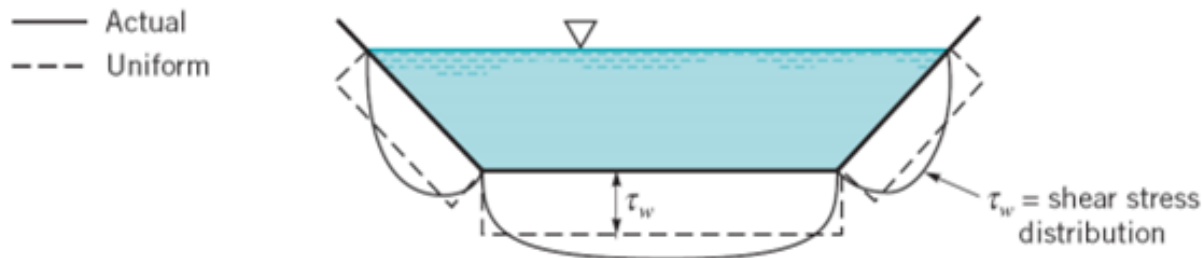
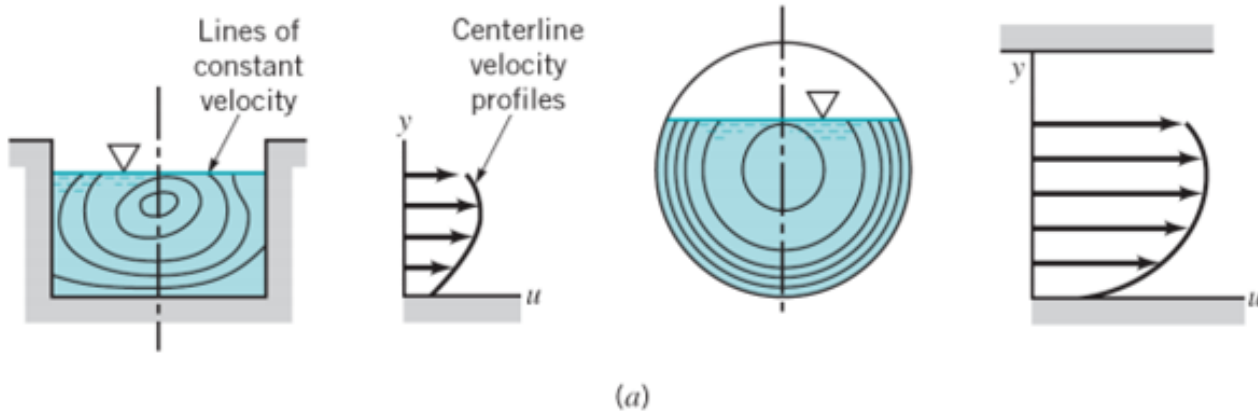


(b) Supercritical to subcritical

Figure of transition from sup to super-critical flow

VELOCITY DISTRIBUTION

- Velocity is always vary across channel because of friction along the boundary.
- The maximum velocity usually found just below the surface.



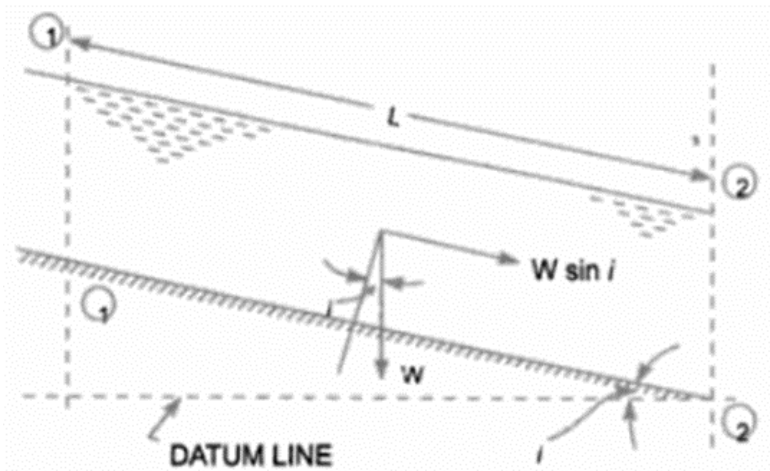
DISCHARGE THROUGH OPEN CHANNELS

- ① Discharge is the quantity of water flowing through the given cross section per unit time. Basically, used to determine the rate of flow for the given cross section.
- ① Various formulas can be used to estimate the discharge through the given open channel.
- ① Following are the formulas / methods to determine the discharge
 - ① Chezy's formula
 - ① Manning's formula
 - ① Bazin's formula
 - ① Kutter's formula

CHEZY'S FORMULA

Forces acting on the water between sections 1-1 & 2-2

1. Component of weight of Water = $W \sin i \rightarrow$
2. Friction Resistance = $f P L V^2 \leftarrow$



where

$$W = \text{density} \times \text{volume} \\ = w (AL) = wAL$$

Equate both Forces:

$$f P L V^2 = wAL \sin i$$

CHEZY'S FORMULA

$$V = \sqrt{\frac{w}{f}} \sqrt{\frac{A}{P} \sin i} \rightarrow 1$$

$$\frac{A}{P} = m = \text{Hydraulic Radius} \rightarrow 2$$

$$\sqrt{\frac{w}{f}} = C = \text{Chezy's Constant} \rightarrow 3$$

CHEZY'S FORMULA

substitute Eqn. 2 & 3 in Eqn. 1,

$$V = C\sqrt{m. \sin i}$$

for small values of i , $\sin i = \tan i = i$

$$\therefore V = C\sqrt{m. i}$$

BAZIN'S FORMULA

- ⦿ Chezy's formula can also be used with Bazins' Formula

$$C = \frac{157.6}{1.81 + \frac{k}{\sqrt{m}}}$$

where

- ⦿ k = Bazin's constant
- ⦿ m = Hydraulic Radius

BAZIN'S FORMULA

Values of K in Bazin's Formula

<i>No.</i>	<i>Surface of channel</i>	<i>Bazin's constant (K)</i>
1.	Smooth cement plaster or planed wood	0.11
2.	Concrete, brick, or unplanned wood	0.21
3.	Smooth rubble masonry or poor brickwork	0.83
4.	Earth channels in very good condition	1.54
5.	Earth channels in rough condition	3.17
6.	Dredged earth channels, average condition	2.36

KUTTER'S FORMULA

- Chezy's formula can also be used with Bazins' Formula in MKS system as follows:

$$C = \frac{23 + \frac{0.00155}{i} + \frac{1}{N}}{1 + \left(23 + \frac{0.00155}{i}\right) \frac{N}{\sqrt{m}}}$$

where

- N = Roughness co-efficient
- i = Slope of the bed
- m = Hydraulic mean depth

MANNING'S FORMULA

- ⦿ The value of C according to Manning's formula as follows:

$$C = \frac{1}{N} m^{1/6}$$

where

- ⦿ N = Manning's constant
- ⦿ i = Slope of the bed
- ⦿ m = Hydraulic mean depth

PROBLEMS

- ① Find the velocity of flow and rate of flow of water through a rectangular channel of 6 m wide and 3 m deep, when it is running full. The channel is having bed slope as 1 in 2000. Take Chezy's constant $C = 55$
- ① Find slope of the bed of a rectangular channel of width 5m when depth of water is 2 m and rate of flow is given as 20 m³/s. Take Chezy's constant, $C = 50$.
- ① Find the discharge through a trapezoidal channel of 8 m wide and side slopes of 1 horizontal to 3 vertical. The depth of flow is 2.4 m and Chezy's constant $C = 55$. The slope of bed of the channel is 1 in 4000

MOST ECONOMICAL SECTIONS

1. Cost of construction should be minimum
2. Discharge should be maximum

Types of channels based on shape:

1. Rectangular
2. Trapezoidal
3. Circular

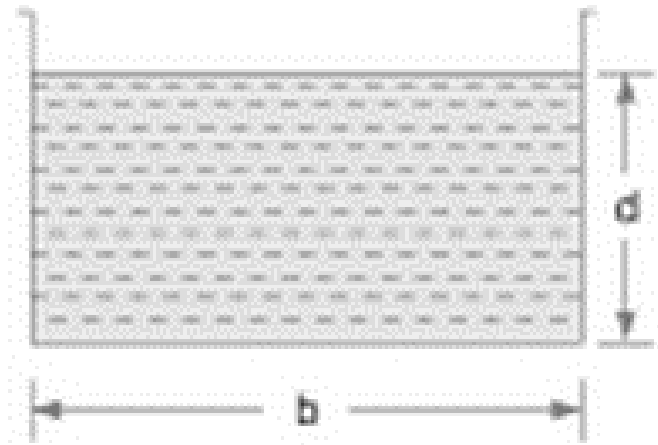
$$Q = A V = A C \sqrt{m i}$$

$$Q = K \frac{1}{\sqrt{P}} \quad \text{where } K = A C \sqrt{A i}$$

If P is minimum, Q will be maximum

RECTANGULAR SECTION

for most economical section,
P should be minimum



$$\frac{dP}{d(d)} = 0$$

$$A = bd \Rightarrow b = \frac{A}{d} \rightarrow 1$$

$$P = b + 2d = \frac{A}{d} + 2d \rightarrow 2$$

RECTANGULAR SECTION

for most economical section, P should be minimum

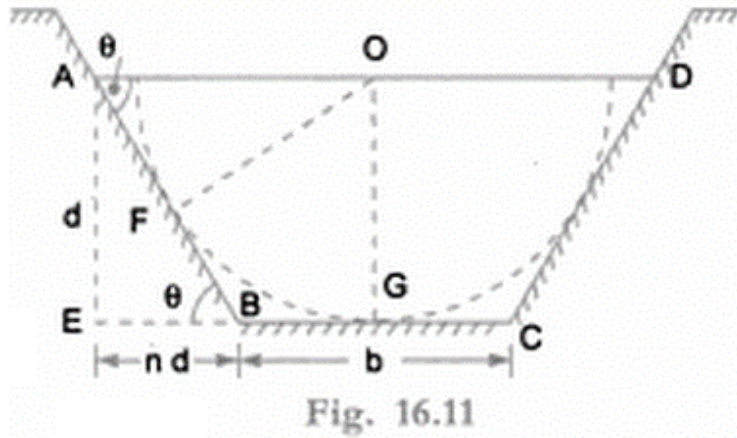
$$\frac{dP}{d(d)} = 0 \Rightarrow \frac{d \left[\frac{A}{d} + 2d \right]}{d(d)} = 0 \Rightarrow \frac{-A}{d^2} + 2 = 0$$

$$\Rightarrow A = 2d^2 \Rightarrow bd = 2d^2$$

$$b = 2d \text{ or } d = b/2$$

$$m = \frac{A}{P} = \frac{bd}{b+2d} = \frac{2d^2}{2d+2d} = \frac{d}{2}$$

TRAPEZOIDAL SECTION



for most economical section,

P should be minimum

$$\frac{dP}{d(d)} = 0$$

$$A = (b + nd)d \Rightarrow b = \frac{A}{d} - nd \rightarrow 1$$

$$P = b + 2d\sqrt{n^2 + 1} = \frac{A}{d} - nd + 2d\sqrt{n^2 + 1} \rightarrow 2$$

TRAPEZOIDAL SECTION

for most economical section, P should be minimum

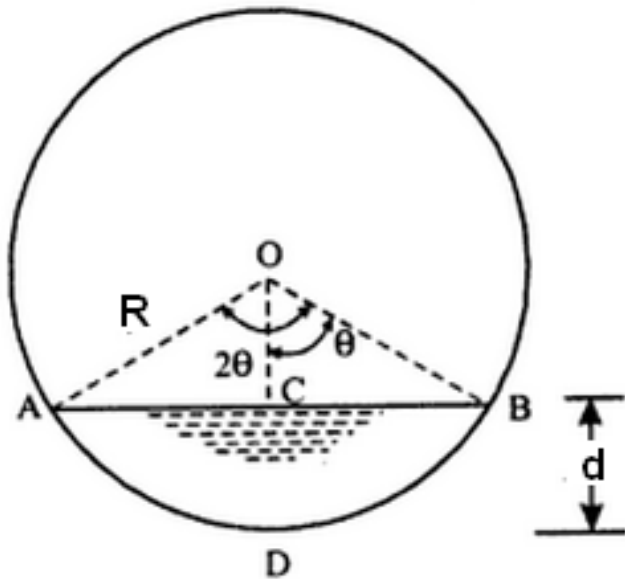
$$\frac{dP}{d(d)} = 0 \Rightarrow \frac{d \left[\frac{A}{d} - nd + 2d\sqrt{n^2 + 1} \right]}{d(d)} = 0$$

$$\Rightarrow \frac{b + 2nd}{2} = d\sqrt{n^2 + 1}$$

$$m = \frac{d}{2} \text{ and}$$

$$\theta = 60^\circ$$

CIRCULAR SECTION



Circular channel.

for Max. Velocity,

$$\frac{d \left[\frac{A}{P} \right]}{d\theta} = 0$$

for Max. Discharge,

$$\frac{d \left[\sqrt{\frac{A^3}{P}} \right]}{d\theta} = 0$$

PROBLEMS

1. A trapezoidal channel has side slopes of 1 horizontal and 2 vertical and the slope of the bed is 1 in 1500. The area of cross section is 40m^2 . Find dimensions of the most economical section. Determine discharge if $C=50$.
2. A rectangular channel of width 4 m is having a bed slope of 1 in 1500. Find the maximum discharge through the channel. Take $C=50$.
3. The rate of flow of water through a circular channel of diameter 0.6m is 150 litres/s. Find the slope of the bed of the channel for maximum velocity. Take $C=50$.

NON – UNIFORM FLOW

- ⦿ In Non-uniform flow, velocity varies at each section of the channel and the Energy Line is not parallel to the bed of the channel.

This can be caused by

- ⦿ Differences in depth of channel and
- ⦿ Differences in width of channel.
- ⦿ Differences in the nature of bed
- ⦿ Differences in slope of channel and
- ⦿ Obstruction in the direction of flow

SPECIFIC ENERGY

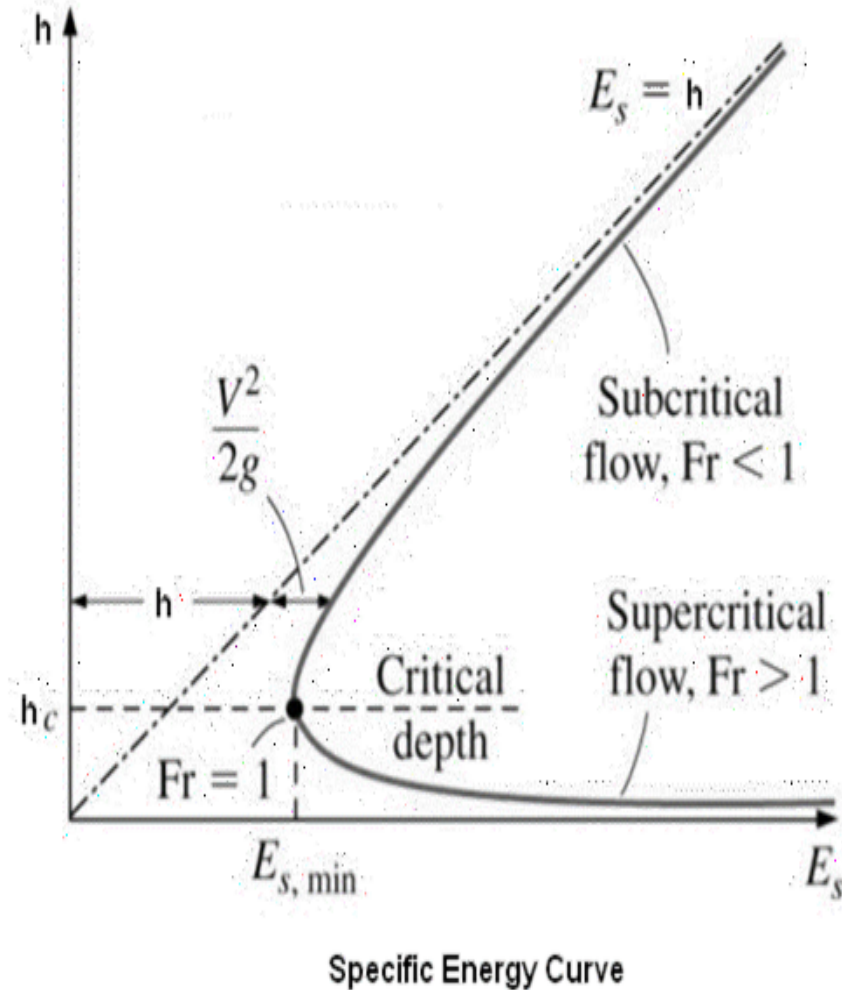
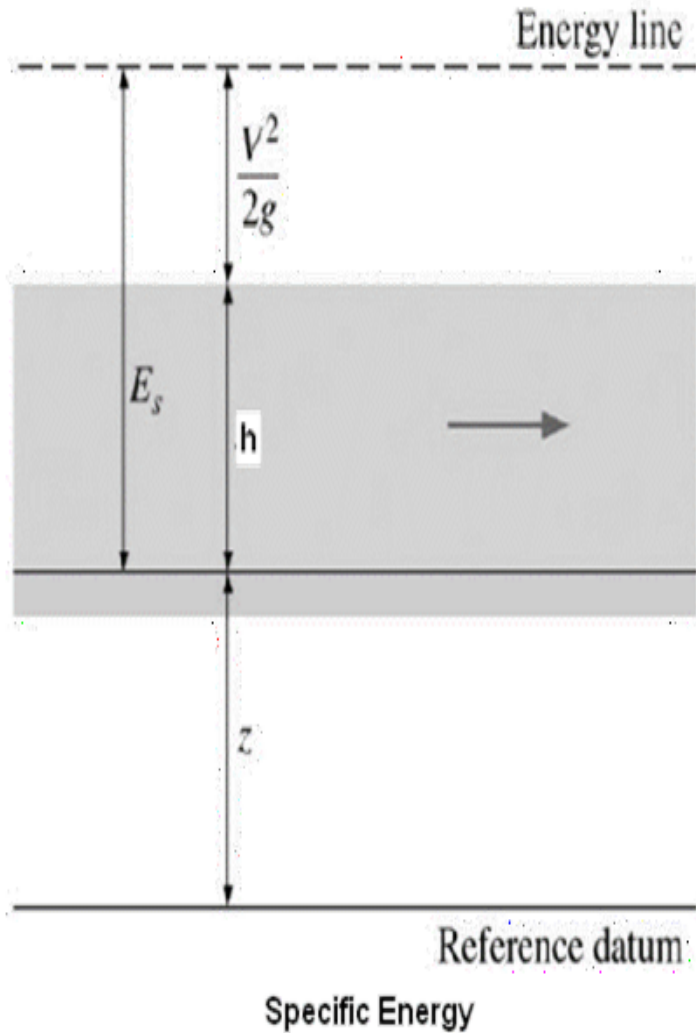
Total Energy of flowing fluid, $E = z + h + \frac{v^2}{2g}$

where z = Height of bottom of channel above datum,

If the channel bottom is taken as datum,

$E_s = h + \frac{v^2}{2g}$ which is called as Specific Energy

Specific energy curve



Modified equation of specific energy curve

$$Q = A V \Rightarrow V = \frac{Q}{A} = \frac{Q}{bh}$$

If discharge per unit width, $q = \frac{Q}{b} = \text{constant}$

$$V = \frac{Q}{bh} = \frac{q}{h}$$

$$\therefore E_s = h + \frac{V^2}{2g} = h + \frac{q^2}{2gh^2}$$

Critical velocity

for Critical Depth, $\frac{dE}{dh} = 0$

where, $E = h + \frac{q^2}{2gh^2}$

$$h_c = \left[\frac{q^2}{g} \right]^{\frac{1}{3}} \Rightarrow h_c^3 = \frac{q^2}{g} \Rightarrow h_c^3 \cdot g = q^2 \rightarrow 1$$

substitute value $q = \frac{Q}{b} = \frac{bh \cdot v}{b} = h_c V_c$ in Eqn. 1

$$\Rightarrow V_c = \sqrt{gh_c}$$

Relation between specific energy and depth of flow

Minimum Specific Energy in terms of Critical Depth; $E = h + \frac{q^2}{2gh^2}$

when specific energy is minimum, Depth of flow is critical

$$E = h_c + \frac{q^2}{2gh_c^2} \text{ substitute } h_c = \left[\frac{q^2}{g} \right]^{\frac{1}{3}} \text{ or } h_c^3 = \frac{q^2}{g}$$

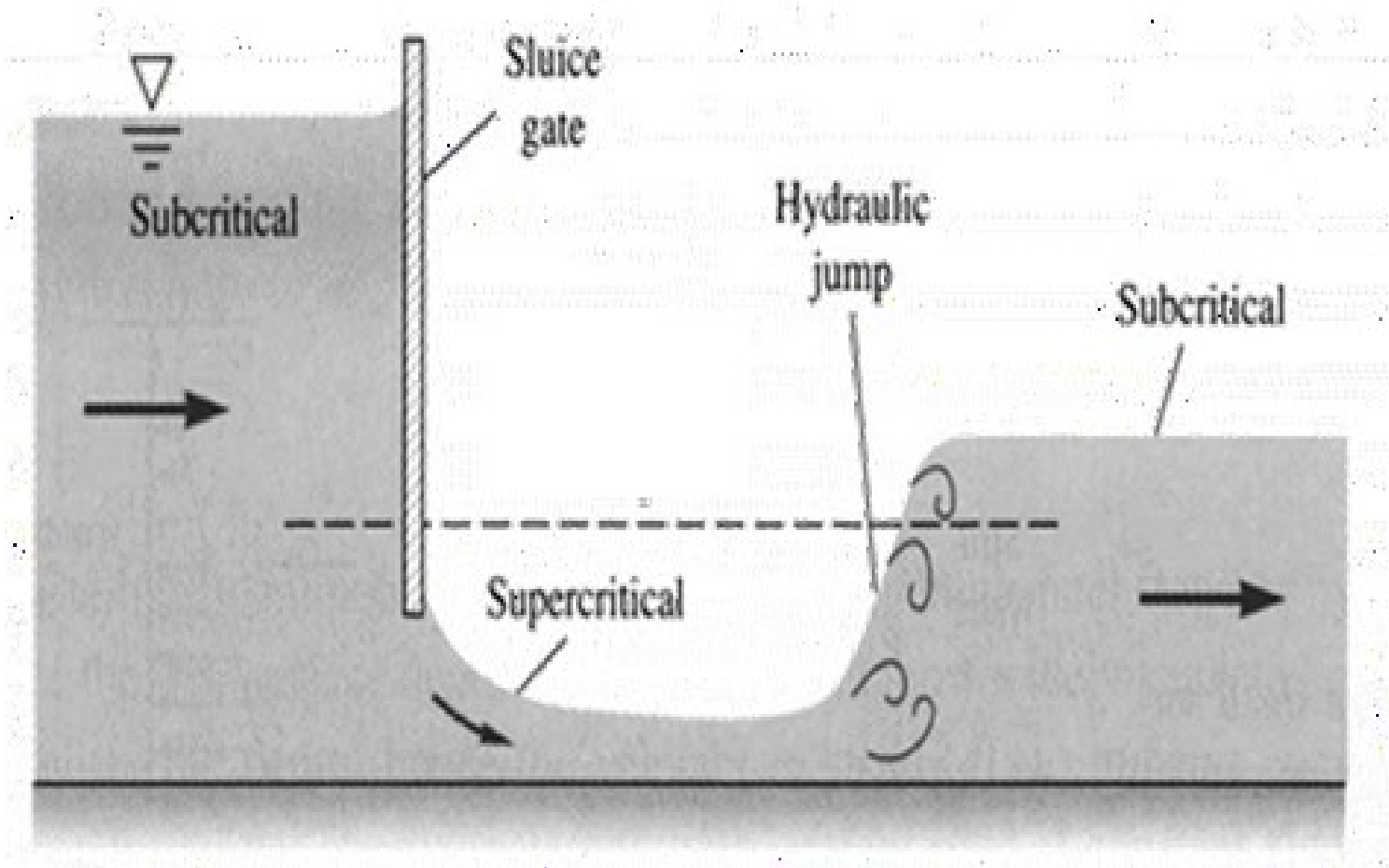
$$E_{\min} = h_c + \frac{h_c^3}{2gh_c^2} = h_c + \frac{h_c}{2} = \frac{3h_c}{2}$$

$$\text{or } h_c = \frac{2E_{\min}}{3}$$

Problems

1. The specific energy for a 3 m wide channel is to be 3 kg-m/kg. What would be the max. possible discharge.
2. The discharge of water through a rectangular channel of width 6 m, is 18 m³/s when depth of flow of water is 2 m. Calculate:
 - i) Specific Energy
 - ii) Critical Depth
 - iii) Critical Velocity
 - iv) Minimum Energy
3. The specific energy for a 5 m wide rectangular channel is to be 4 Nm/N. If the rate of flow of water through the channel is 20 m³/s, determine the alternate depths of flow.

Hydraulic Jump



Hydraulic Jump

The hydraulic jump is defined as the rise of water level, which takes place due to transformation of the unstable shooting flow (super-critical) to the stable streaming flow (sub-critical).

When hydraulic jump occurs, a loss of energy due to eddy formation and turbulence flow occurs.

The most typical cases for the location of hydraulic jump are:

1. Below control structures like weir, sluice are used in the channel
2. when any obstruction is found in the channel,
3. when a sharp change in the channel slope takes place.
4. At the toe of a spillway dam

Hydraulic Jump

$$d_2 = -\frac{d_1}{2} + \sqrt{\frac{d_1^2}{4} + \frac{2q^2}{gd_1}} \rightarrow \text{interms of } q$$

$$d_2 = -\frac{d_1}{2} + \sqrt{\frac{d_1^2}{4} + \frac{2v_1^2 d_1}{g_1}} \rightarrow \text{interms of } v_1$$

$$d_2 = \frac{d_1}{2} \left(\sqrt{1 + 8F_e^2} - 1 \right) \rightarrow \text{interms of } F_e$$

Hydraulic Jump

Loss of Energy:

$$h_L = E_1 - E_2 = \left[\frac{[d_2 - d_1]^3}{4d_1d_2} \right]$$

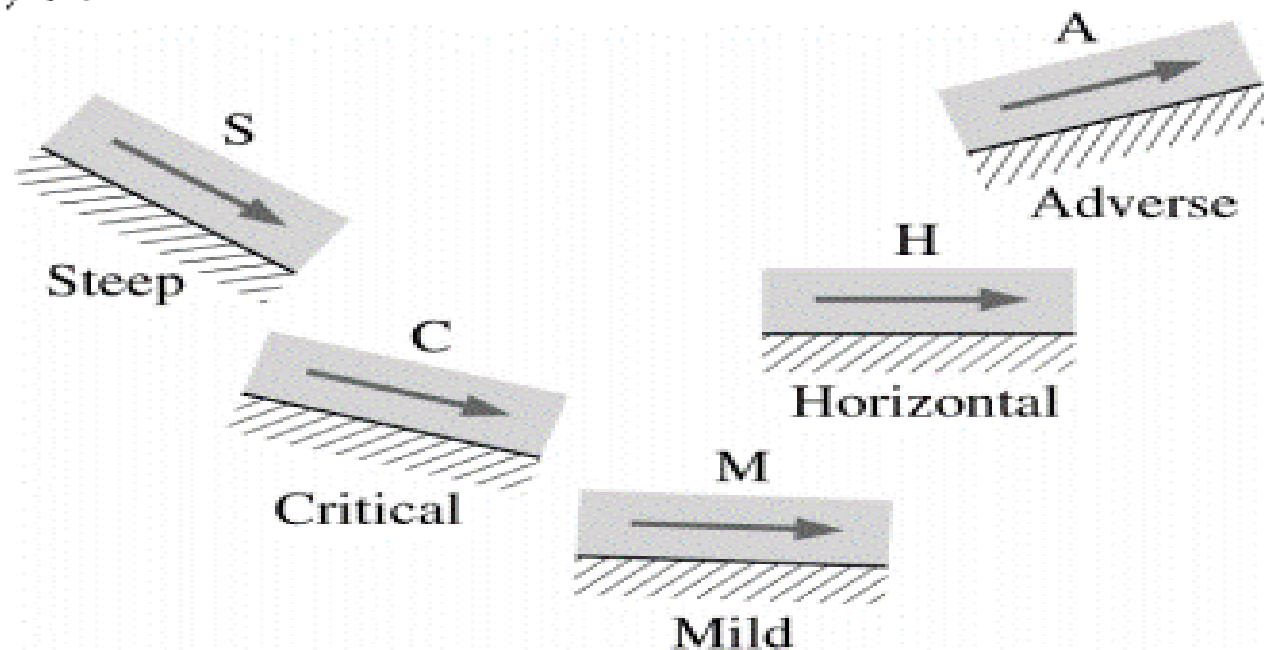
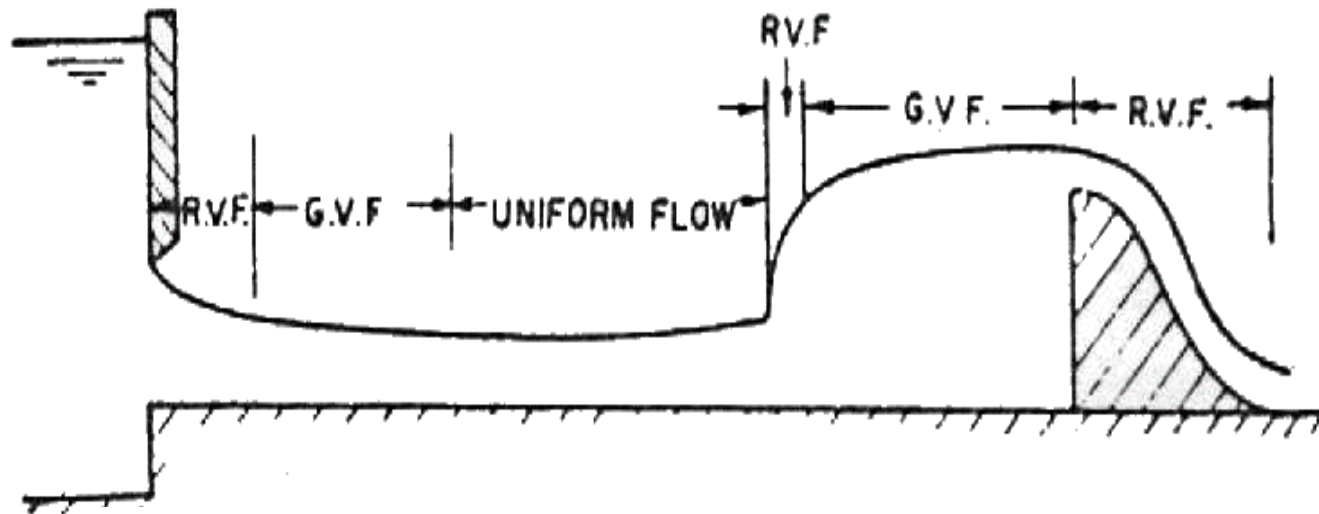
Length of jump = 5 to 7 times of $(d_2 - d_1)$

Hydraulic Jump = $d_2 - d_1$

Problems

1. The depth of flow of water, at a certain section of a rectangular channel of 2 m wide is 0.3 m. The discharge through the channel is $1.5 \text{ m}^3/\text{s}$. Determine whether a hydraulic jump will occur, and if so, find its height and loss of energy per kg of water.
2. A sluice gate discharges water into a horizontal rectangular channel with a velocity of 10 m/s and depth of flow of 1 m. Determine the depth of flow after jump and consequent loss in total head.

Gradually Varied Flow (GVF)



Gradually Varied Flow (GVF)

In GVF, depth and velocity vary slowly, and the free surface is stable. The GVF is classified based on the channel slope, and the magnitude of flow depth.

- ⦿ Steep Slope (S): $S_o > S_c$ or $h < h_c$
- ⦿ Critical Slope (C): $S_o = S_c$ or $h = h_c$
- ⦿ Mild Slope (M): $S_o < S_c$ or $h > h_c$
- ⦿ Horizontal Slope (H): $S_o = 0$
- ⦿ Adverse Slope(A): $S_o = \text{Negative}$

where

S_o : the slope of the channel bed,

S_c : the critical slope that sustains a given discharge as uniform flow at the critical depth (h_c).

Flow Profiles

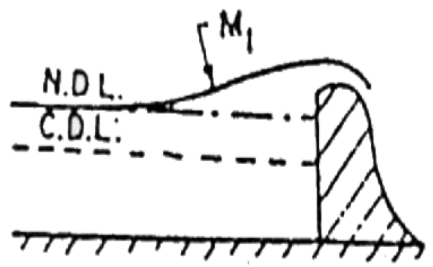
The surface curves of water are called flow profiles (or water surface profiles). Depending upon the zone and the slope of the bed, the water profiles are classified into 12 types as follows:

- | | |
|---------------------------|------------|
| ⦿ Mild slope curves | M1, M2, M3 |
| ⦿ Steep slope curves | S1, S2, S3 |
| ⦿ Critical slope curves | C1, C2, C3 |
| ⦿ Horizontal slope curves | H2, H3 |
| ⦿ Averse slope curves | A2, A3 |

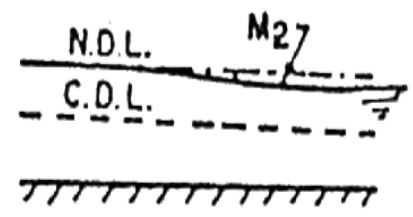
In all these curves, the letter indicates the slope type and the subscript indicates the zone.

For example S2 curve occurs in the zone 2 of the steep slope

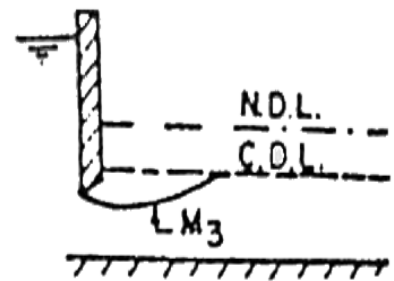
Flow Profiles



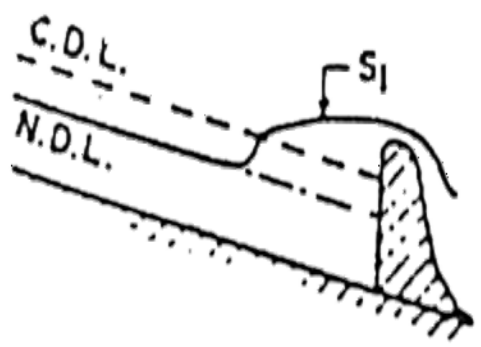
(a)



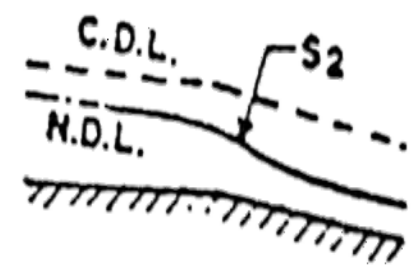
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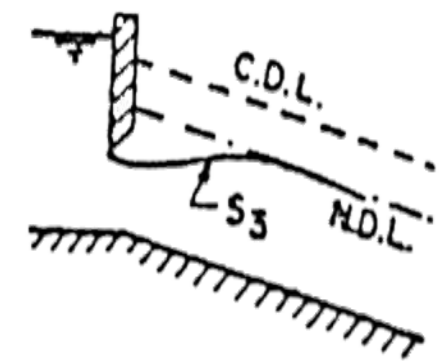
(c)



(a)

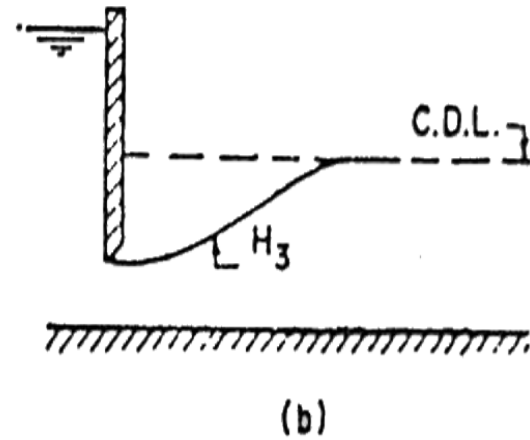
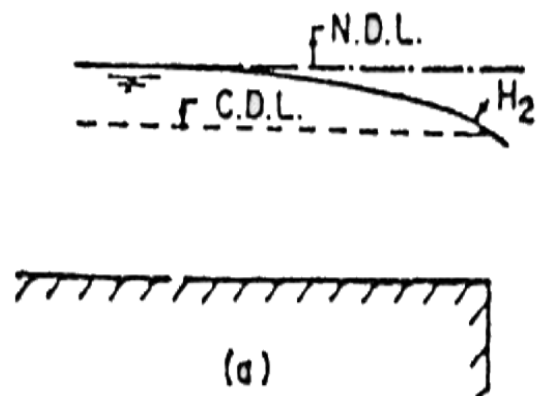
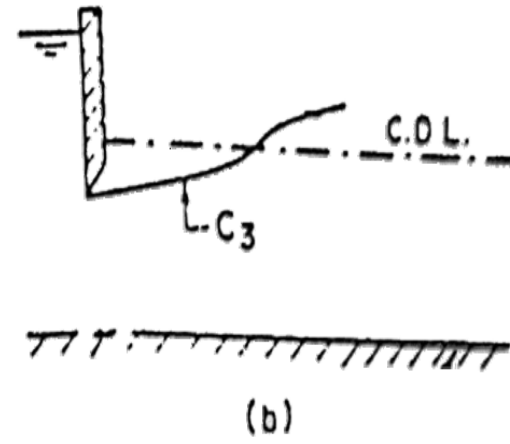
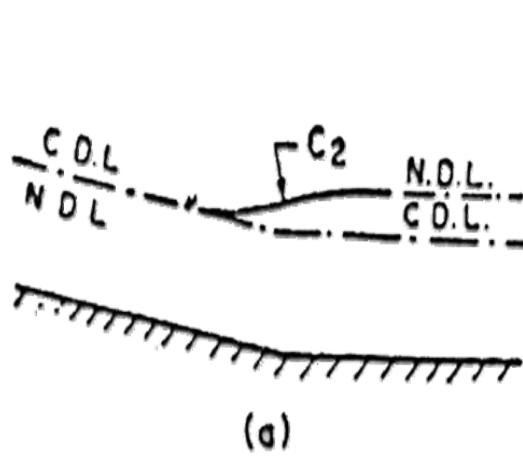


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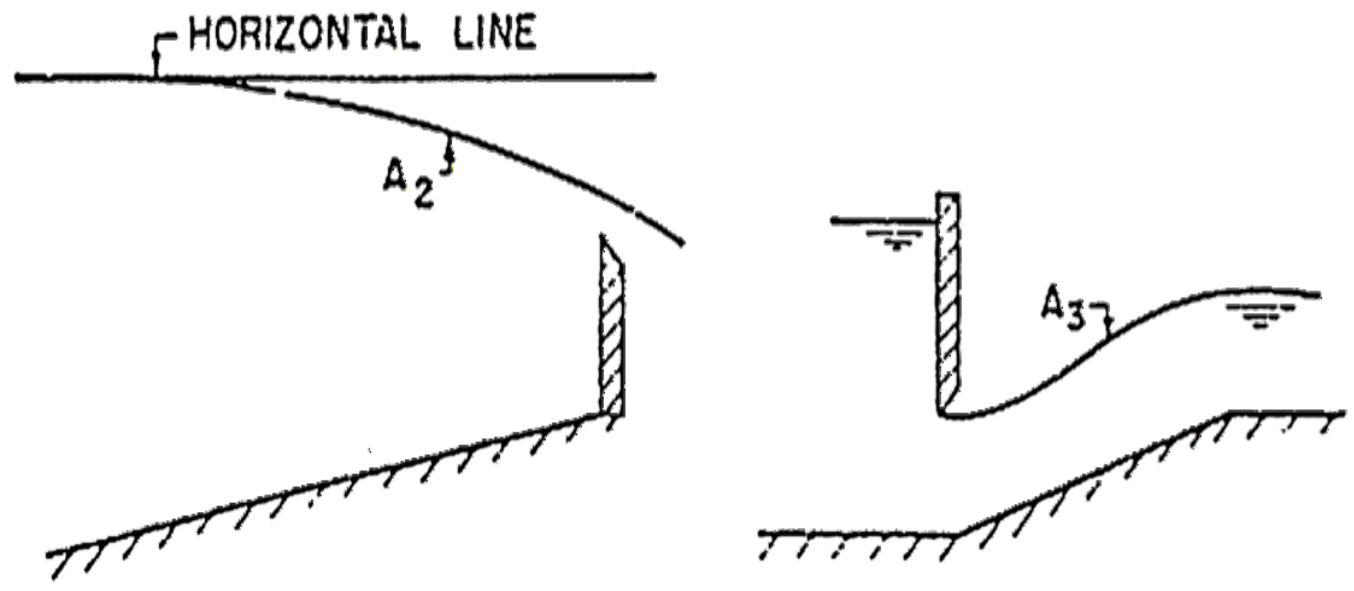


(c)

Flow Profiles



Flow Profiles



Gradually Varied Flow (GVF)

- ⦿ If $dh/dx = 0$, Free Surface of water is parallel to the bed of channel
- ⦿ If $dh/dx > 0$, Depth increases in the direction of water flow (Back Water Curve)
- ⦿ If $dh/dx < 0$, Depth of water decreases in the direction of flow (Dropdown Curve)

Problems

1. Find the rate of change of depth of water in a rectangular channel of 10 m wide and 1.5 m deep, when water is flowing with a velocity of 1 m/s. The flow of water through the channel of bed slope in 1 in 4000, is regulated in such a way that energy line is having a slope of 0.00004.
2. Find the slope of the free water surface in a rectangular channel of width 20 m, having depth of flow 5 m. The discharge through the channel is $50 \text{ m}^3/\text{s}$. The bed of channel is having a slope of 1 in 4000. Take $C=60$.



UNIT-II

DIMENSIONAL ANALYSIS

Introduction

- Many practical real flow problems in fluid mechanics can be solved by using equations and analytical procedures. However, solutions of some real flow problems depend heavily on experimental data.
- Sometimes, the experimental work in the laboratory is not only time-consuming, but also expensive. So, the main goal is to extract maximum information from fewest experiments.
- In dimensional analysis we are only concerned with the nature of the dimension i.e. its quality not its quantity.
- Dimensions are properties which can be measured.
- Ex.: Mass, Length, Time etc.,

Secondary or Derived Dimensions

Secondary dimensions are those quantities which possess more than one fundamental dimension.

- ⊙ Geometric properties

a) Area	m^2	L^2
b) Volume	m^3	L^3

- ⊙ Kinematic properties

a) Velocity	m/s	L/T	$L.T^{-1}$
b) Acceleration	m/s^2	L/T^2	$L.T^{-2}$

- ⊙ Dynamic properties

a) Force	N	ML/T	$M.L.T^{-1}$
b) Density	kg/m^3	M/L^3	$M.L^{-3}$

Find Dimensions for the following:

1. Stress / Pressure
2. Surface Tension
3. Angular Velocity
4. Momentum
5. Torque
6. Work
7. Power
8. Kinetic Energy
9. Dynamic Viscosity
10. Kinematic Viscosity

Use of Dimensional Analysis

- ⦿ Conversion from one dimensional unit to another

- ⦿ Checking units of equations (Dimensional Homogeneity)

- ⦿ Defining dimensionless relationship using
 - Rayleigh's Method
 - Buckingham's π -Theorem

- ⦿ Model Analysis

Dimensional Homogeneity

Dimensional Homogeneity means the dimensions in each equation on both sides equal.

Let us consider the equation, $V = \sqrt{2gH}$

Dimension of L.H.S. $= V = \frac{L}{T} = LT^{-1}$

Dimension of R.H.S. $= \sqrt{2gH} = \sqrt{\frac{L}{T^2} \times L} = \sqrt{\frac{L^2}{T^2}} = \frac{L}{T} = LT^{-1}$

Dimension of L.H.S. $=$ Dimension of R.H.S. $= LT^{-1}$

\therefore Equation $V = \sqrt{2gH}$ is dimensionally homogeneous. So it can be used in any system of units.

Rayleigh's Method

To define relationship among variables:

This method is used for determining the expression for a variable which depends upon maximum three or four variables only.

Methodology:

- ⦿ Let X is a function of X_1, X_2, X_3 and mathematically it can be written as $X = f(X_1, X_2, X_3)$
- ⦿ This can be also written as: $X = K (X_1^a, X_2^b, X_3^c)$ where K is constant and a, b and c are arbitrarily powers
- ⦿ The values of a, b and c are obtained by comparing the powers of the fundamental dimension on both sides.

Buckingham's π -Theorem

This method of analysis is used when number of variables are more.

Theorem:

If there are n variables in a physical phenomenon and those n variables contain m dimensions, then variables can be arranged into $(n-m)$ dimensionless groups called Φ terms.

Explanation:

- ⦿ If $f(X_1, X_2, X_3, \dots, X_n) = 0$ and variables can be expressed using m dimensions then
- ⦿ $f(\pi_1, \pi_2, \pi_3, \dots, \pi_{n-m}) = 0$ where, $\pi_1, \pi_2, \pi_3, \dots$ are dimensionless groups.
- ⦿ Each π term contains $(m + 1)$ variables out of which m are of repeating type and one is of non-repeating type.
- ⦿ Each π term being dimensionless, the dimensional homogeneity can be used to get each π term.

Selecting Repeating Variables:

- Avoid taking the quantity required as the repeating variable.
- Repeating variables put together should not form dimensionless group.
- No two repeating variables should have same dimensions.
- Repeating variables can be selected from each of the following properties.
 - ⦿ Geometric property → Length, height, width, area
 - ⦿ Flow property → Velocity, Acceleration, Discharge
 - ⦿ Fluid property → Mass density, Viscosity, Surface tension

Example

Problem 12.11 The pressure difference Δp in a pipe of diameter D and length l due to viscous flow depends on the velocity V , viscosity μ and density ρ . Using Buckingham's π -theorem, obtain an expression for Δp .

Solution.

Δp is a function of D, l, V, μ, ρ or $\Delta p = f(D, l, V, \mu, \rho)$

or $f_1(\Delta p, D, l, V, \mu, \rho) = 0$... (i)

Total number of variables, $n = 6$

Number of fundamental dimension, $m = 3$

Number of π -terms $= n - 3 = 6 - 3 = 3$

Hence equation (i) is written as $f_1(\pi_1, \pi_2, \pi_3) = 0$... (ii)

Each π -term contains $m + 1$ variables, i.e., $3 + 1 = 4$ variable. Out of four variables, three are repeating variables.

Choosing D, V, μ as repeating variables, we have π -terms as

$$\pi_1 = D^{a_1} \cdot V^{b_1} \cdot \mu^{c_1} \cdot \Delta p$$

$$\pi_2 = D^{a_2} \cdot V^{b_2} \cdot \mu^{c_2} \cdot l$$

$$\pi_3 = D^{a_3} \cdot V^{b_3} \cdot \mu^{c_3} \cdot \rho$$

Example

First π -term $\pi_1 = D^a \cdot V^b \cdot \mu^c \cdot \Delta p$

Substituting the dimensions on both sides,

$$M^0 L^0 T^0 = L^{a_1} \cdot (LT^{-1})^{b_1} \cdot (ML^{-1}T^{-1})^{c_1} \cdot ML^{-1}T^{-2}$$

Equating the powers of M, L, T on both sides,

Power of M , $0 = c_1 + 1, \quad \therefore c_1 = -1$

Power of L , $0 = a_1 + b_1 - c_1 - 1, \quad \therefore a_1 = -b_1 + c_1 + 1 = 1 - 1 + 1 = 1$

Power of T , $0 = -b_1 - c_1 - 2, \quad \therefore b_1 = -c_1 - 2 = 1 - 2 = -1$

Substituting the values of a_1, b_1 and c_1 in π_1 ,

$$\pi_1 = D^1 \cdot V^{-1} \cdot \mu^{-1} \cdot \Delta p = \frac{D\Delta p}{\mu V}$$

Second π -term $\pi_2 = D^{a_2} \cdot V^{b_2} \cdot \mu^{c_2} \cdot l$

Substituting the dimensions on both sides,

$$M^0 L^0 T^0 = L^{a_2} \cdot (LT^{-1})^{b_2} \cdot (ML^{-1}T^{-1})^{c_2} \cdot L$$

Equating the powers of M, L, T on both sides

Power of M , $0 = c_2, \quad \therefore c_2 = 0$

Power of L , $0 = a_2 + b_2 - c_2 + 1, \quad \therefore a_2 = -b_2 + c_2 - 1 = -1$

Power of T , $0 = -b_2 - c_2, \quad \therefore b_2 = -c_2 = 0$

Substituting the values of a_2, b_2 and c_2 in π_2 ,

$$\pi_2 = D^{-1} \cdot V^0 \cdot \mu^0 \cdot l = \frac{l}{D}$$

Example

Third π -term $\pi_3 = D^{a_3} \cdot V^{b_3} \cdot \mu^{c_3} \cdot \rho$

Substituting the dimension on both sides,

$$M^0 L^0 T^0 = L^{a_3} \cdot (LT^{-1})^{b_3} \cdot (ML^{-1}T^{-1})^{c_3} \cdot ML^{-3}$$

Equating the powers of M, L, T on both sides

Power of M , $0 = c_3 + 1, \quad \therefore c_3 = -1$

Power of L , $0 = a_3 + b_3 - c_3 - 3, \quad \therefore a_3 = -b_3 + c_3 + 3 = -1 - 1 + 3 = 1$

Power of T , $0 = -b_3 - c_3, \quad \therefore b_3 = -c_3 = -(-1) = 1$

Substituting the values of a_3, b_3 and c_3 in π_3 ,

$$\pi_3 = D^1 \cdot V^1 \cdot \mu^{-1} \cdot \rho = \frac{\rho DV}{\mu}$$

Substituting the values of π_1, π_2 and π_3 in equation (ii),

$$f_1 \left(\frac{D\Delta p}{\mu V}, \frac{l}{D}, \frac{\rho DV}{\mu} \right) = 0 \quad \text{or} \quad \frac{D\Delta p}{\mu V} = \phi \left[\frac{l}{D}, \frac{\rho DV}{\mu} \right] \quad \text{or} \quad \Delta p = \frac{\mu V}{D} \phi \left[\frac{l}{D}, \frac{\rho DV}{\mu} \right]$$

Experiments show that the pressure difference Δp is a linear function $\frac{l}{D}$. Hence $\frac{l}{D}$ can be taken out of the functional as

$$\Delta p = \frac{\mu V}{D} \times \frac{l}{D} \phi \left[\frac{\rho DV}{\mu} \right]. \text{ Ans.}$$

Expression for difference of pressure head for viscous flow

$$h_f = \frac{\Delta p}{\rho g} = \frac{\mu V}{D} \times \frac{l}{D} \times \frac{1}{\rho g} \phi [R_e] \quad \left\{ \because \frac{\rho DV}{\mu} = R_e \right\}$$

$$= \frac{\mu V l}{\rho g D^2} \phi [R_e]. \text{ Ans.}$$

- For predicting the performance of the hydraulic structures (such as dams, spillways etc.) or hydraulic machines (such as turbines, pumps etc.) before actually constructing or manufacturing, models of the structures or machines are made and tests are conducted on them to obtain the desired information.
- Model is a small replica of the actual structure or machine The actual structure or machine is called as Prototype
Models can be smaller or larger than the Prototype.
- Model Analysis is actually an experimental method of finding solutions of complex flow problems

Similitude or Similarities

- ◉ Similitude is defined as the similarity between the model and prototype in every aspect, which means that the model and prototype have similar properties.

Types of Similarities:

- Geometric Similarity → Length, Breadth, Depth, Diameter, Area, Volume etc.,
- Kinematic Similarity → Velocity, Acceleration etc.,
- Dynamic Similarity → Time, Discharge, Force, Pressure Intensity, Torque, Power

Geometric and kinematic Similarity

- ⦿ The geometric similarity is said to exist between the model and prototype if the ratio of all corresponding linear dimensions in the model and prototype are equal.

$$\frac{L_p}{L_m} = \frac{B_p}{B_m} = \frac{D_p}{D_m} = L_r \quad \frac{A_p}{A_m} = L_r^2 \quad \frac{V_p}{V_m} = V_r^3$$

- ⦿ The kinematic similarity is said exist between model and prototype if the ratios of velocity and acceleration at corresponding points in the model and at the corresponding points in the prototype are the same.

$$\frac{V_p}{V_m} = V_r \quad \frac{a_p}{a_m} = a_r$$

Dynamic Similarity

- ⦿ The dynamic similarity is said exist between model and prototype if the ratios of corresponding forces acting at the corresponding points are equal

$$\frac{F_p}{F_m} = F_r$$

- ⦿ It means for dynamic similarity between the model and prototype, the dimensionless numbers should be same for model and prototype. Also the directions of the velocities in the model and prototype should be same

Types of Forces Acting on Moving Fluid

⦿ Inertia Force, F_i

- It is the product of mass and acceleration of the flowing fluid and acts in the direction opposite to the direction of acceleration.
- It always exists in the fluid flow problems.

⦿ Viscous Force, F_v

- It is equal to the product of shear stress due to viscosity and surface area of the flow.
- It is important in fluid flow problems where viscosity is having an important role to play

Types of Forces Acting on Moving Fluid

⦿ Gravity Force, F_g

- It is equal to the product of mass and acceleration due to gravity of the flowing fluid.
- It is present in case of open surface flow.

⦿ Pressure Force, F_p

- It is equal to the product of pressure intensity and cross sectional area of flowing fluid
- It is present in case of pipe-flow

Types of Forces Acting on Moving Fluid

- ◎ Surface Tension Force, F_s
 - It is equal to the product of surface tension and length of surface of the flowing fluid

- ◎ Elastic Force, F_e
 - It is equal to the product of elastic stress and area of the flowing fluid

Model Laws

- The laws on which the models are designed for dynamic similarity are called model laws or laws of similarity.
- If the viscous forces are predominant, the models are designed for dynamic similarity based on Reynold's number.
- Reynold's Model law:
 - Models based on Reynolds's Number includes:
 - Pipe Flow
 - Resistance experienced by Sub-marines, airplanes, fully immersed bodies etc.

Model Laws

◎ Froude Model Law:

The laws on which the models are designed for dynamic similarity are called model laws or laws of similarity.

Froude Model Law is applied in the following fluid flow problems:

- Free Surface Flows such as Flow over spillways, Weirs, Sluices, Channels etc.
- Flow of jet from an orifice or nozzle
- Where waves are likely to formed on surface
- Where fluids of different densities flow over one another

⦿ Euler Model Law:

Euler Model Law is applied in the following cases:

- Closed pipe in which case turbulence is fully developed so that viscous forces are negligible and gravity force and surface tension is absent
- Where phenomenon of cavitations takes place.

Model Laws

◎ Weber Model Law:

Weber Model Law is applied in the following cases:

- Capillary rise in narrow passages
- Capillary movement of water in soil
- Capillary waves in channels
- Flow over weirs for small heads

Model Laws

⦿ Mach Model Law:

Mach Model Law is applied in the following cases:

- Flow of aero plane and projectile through air at supersonic speed i.e., velocity more than velocity of sound
- Aero dynamic testing,
- Underwater testing of torpedoes, and
- Water-hammer problems

Problems

1. Water flowing through a pipe of diameter 30 cm at a velocity of 4 m/s. Find the velocity of oil flowing in another pipe of diameter 10cm, if the conditions of dynamic similarity is satisfied between two pipes. The viscosity of water and oil is given as 0.01 poise and 0.025 poise. The specific gravity of oil is 0.8.
2. In 1 in 40 model of a spillway, the velocity and discharge are 2 m/s and 2.5 m³/s. Find corresponding velocity and discharge in the prototype
3. In a 1 in 20 model of stilling basin, the height of the jump in the model is observed to be 0.20m. What is height of hydraulic jump in the prototype? If energy dissipated in the model is 0.1kW, what is the corresponding value in prototype?

Problems

4. A 7.2 m height and 15 m long spillway discharges $94 \text{ m}^3/\text{s}$ discharge under a head of 2m. If a 1:9 scale model of this spillway is to be constructed, determine the model dimensions, head over spillway model and the model discharge. If model is experiences a force of 7500 N, determine force on the prototype.
5. A Dam of 15 m long is to discharge water at the rate of 120 cumecs under a head of 3 m. Design a model, if supply available in the laboratory is 50 lps
6. A 1:50 spillway model has a discharge of 1.5 cumecs. What is the corresponding discharge in prototype?. If a flood phenomenon takes 6 hour to occur in the prototype, how long it should take in the model



UNIT-III

IMPACT OF JET ON VANES

Introduction

◎ Impact of Jets

The jet is a stream of liquid comes out from nozzle with a high velocity under constant pressure. When the jet impinges on plates or vanes, its momentum is changed and a hydrodynamic force is exerted. Vane is a flat or curved plate fixed to the rim of the wheel.

a) Force exerted by the jet on a stationary plate

- Plate is vertical to the jet
- Plate is inclined to the jet
- Plate is curved

b. Force exerted by the jet on a moving plate

- Plate is vertical to the jet
- Plate is inclined to the jet
- Plate is curved

Impulse-Momentum Principle

From Newton's II Law:

$$F = m a = m (V_1 - V_2) / t$$

Impulse of a force is given by the change in momentum caused by the force on the body.

$$Ft = mV_1 - mV_2 = \text{Initial Momentum} - \text{Final Momentum}$$

Force exerted by jet on the plate in the direction of jet,

$$\begin{aligned} F &= m (V_1 - V_2) / t \\ &= (\text{Mass} / \text{Time}) (\text{Initial Velocity} - \text{Final Velocity}) \\ &= (\rho Q) (V_1 - V_2) = \mathbf{(\rho a V) (V_1 - V_2)} \end{aligned}$$

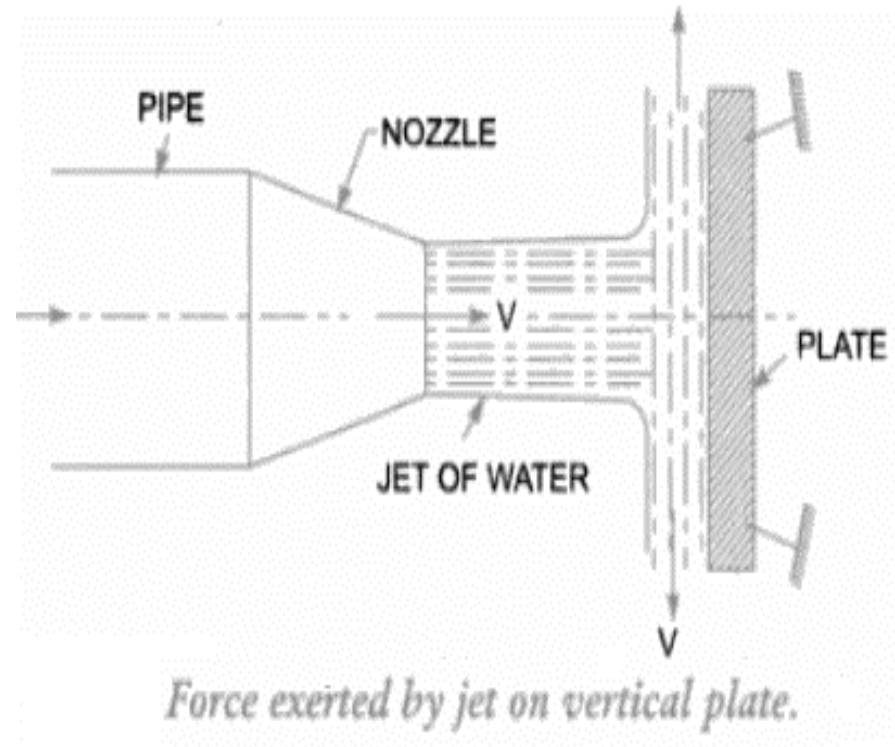
Force exerted by the jet on a stationary plate

Plate is vertical to the jet

$$F = \rho a V^2$$

If Plate is moving at a velocity of 'U' m/s,

$$F = \rho a (V-U)^2$$



Problems

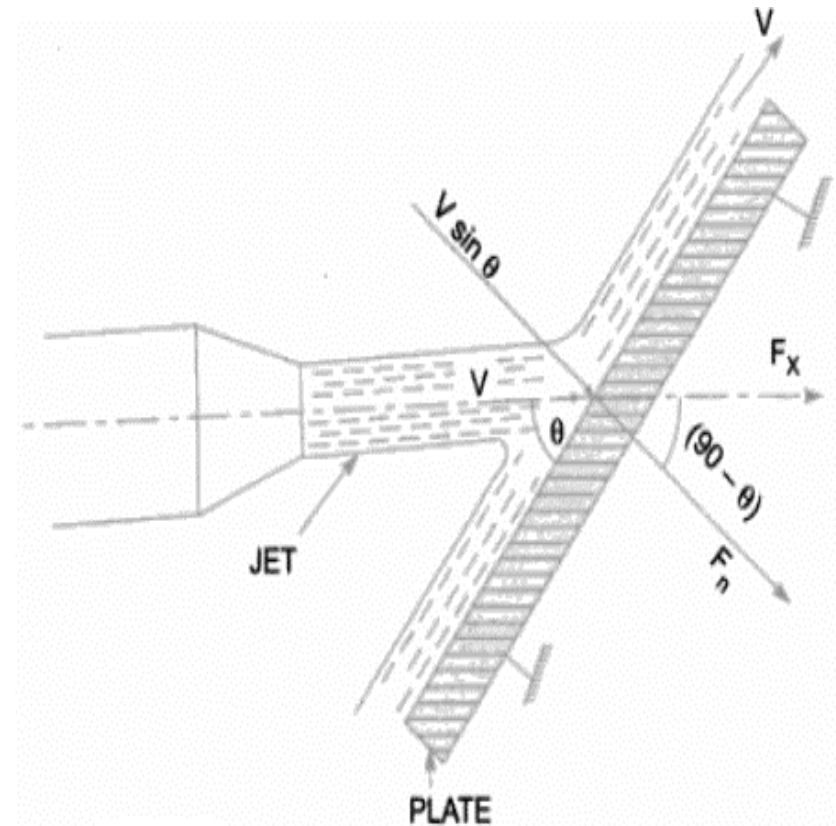
1. A jet of water 50 mm diameter strikes a flat plate held normal to the direction of jet. Estimate the force exerted and work done by the jet if
 - The plate is stationary
 - The plate is moving with a velocity of 1 m/s away from the jet along the line of jet. The discharge through the nozzle is 76 lps.
2. A jet of water 50 mm diameter exerts a force of 3 kN on a flat vane held perpendicular to the direction of jet. Find the mass flow rate.

Force exerted by the jet on a stationary plate

$$F_N = \rho a V^2 \sin \theta$$

$$F_x = F_N \sin \theta$$

$$F_x = F_N \cos \theta$$



Jet striking stationary inclined plate.

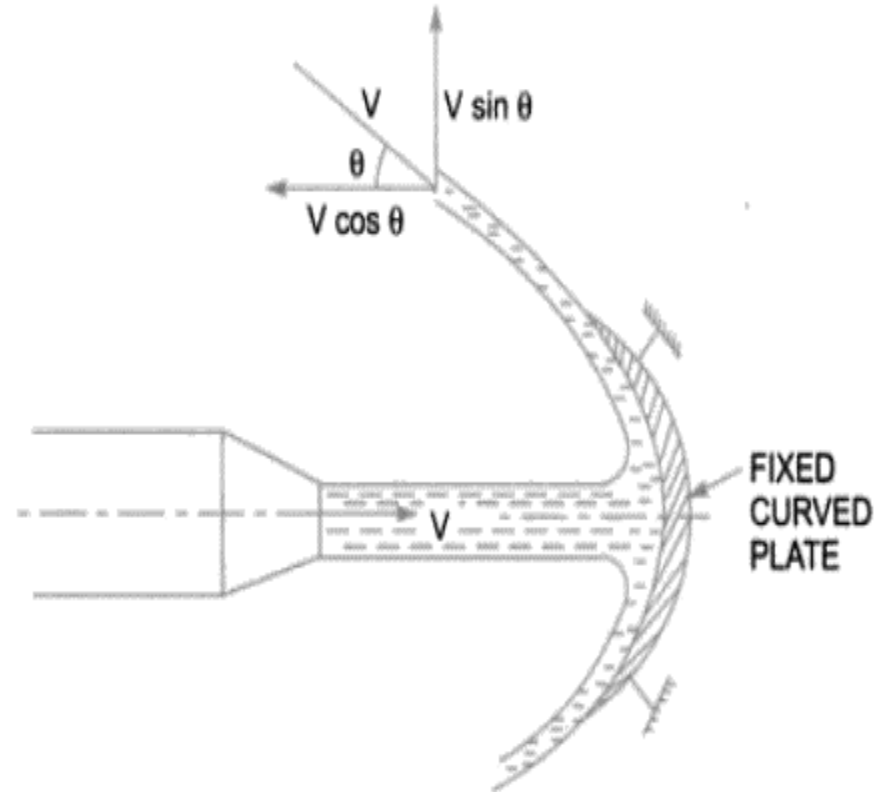
Problems

1. A jet of data 75 mm diameter has a velocity of 30 m/s. It strikes a flat plate inclined at 45° to the axis of jet. Find the force on the plate when.
 - The plate is stationary
 - The plate is moving with a velocity of 15 m/s along and away from the jet.
 - Also find power and efficiency in case (b)

Force exerted by the jet on a stationary curved plate

Plate is Curved and Jet strikes at Centre

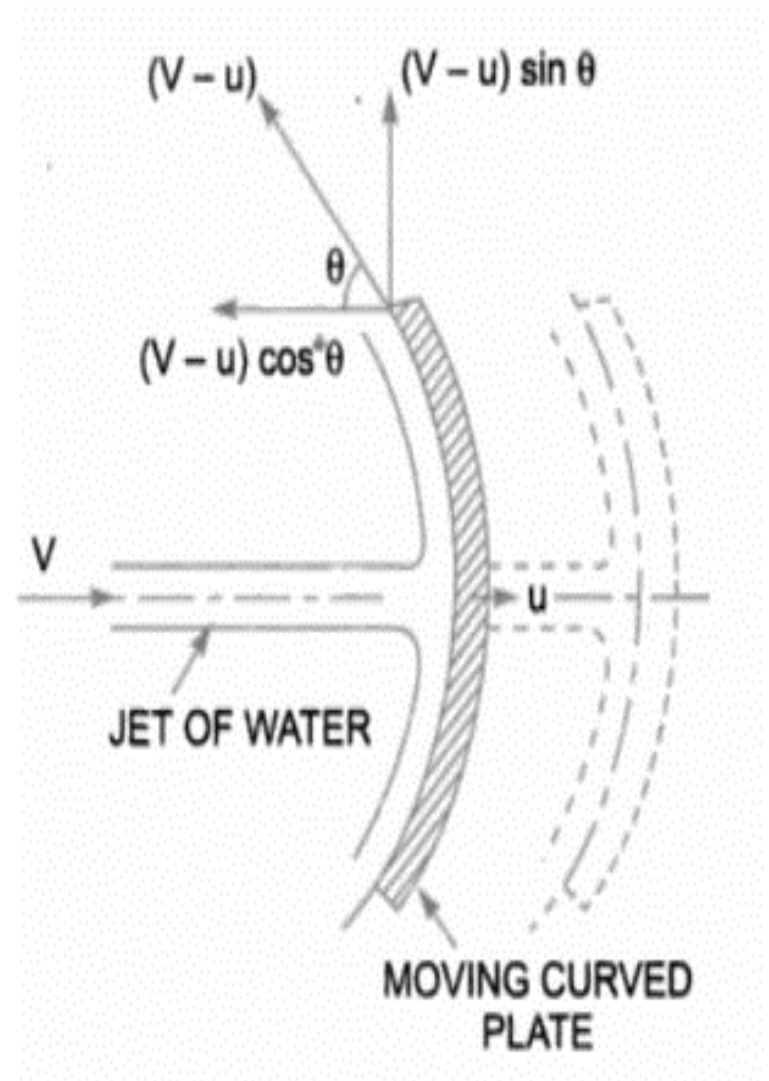
$$F = \rho a V^2 (1 + \cos \theta)$$



Force exerted by the jet on a moving curved plate

Plate is Curved and Jet strikes at Centre

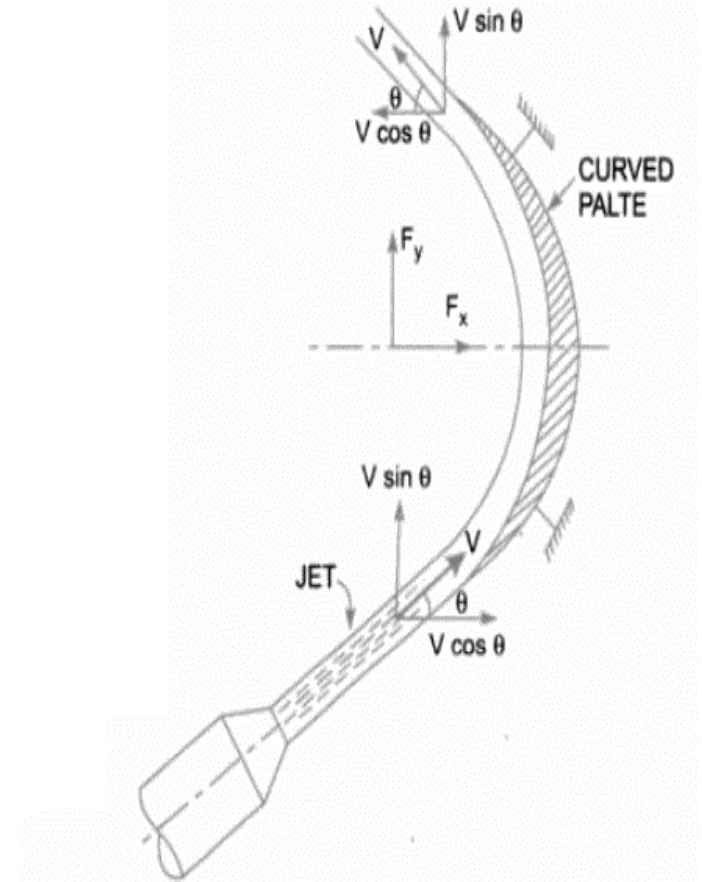
$$F = \rho a(V-U)^2 (1 + \cos \theta)$$



Force exerted by the jet on a stationary plate (Symmetrical Plate)

Plate is Curved and Jet strikes at tip

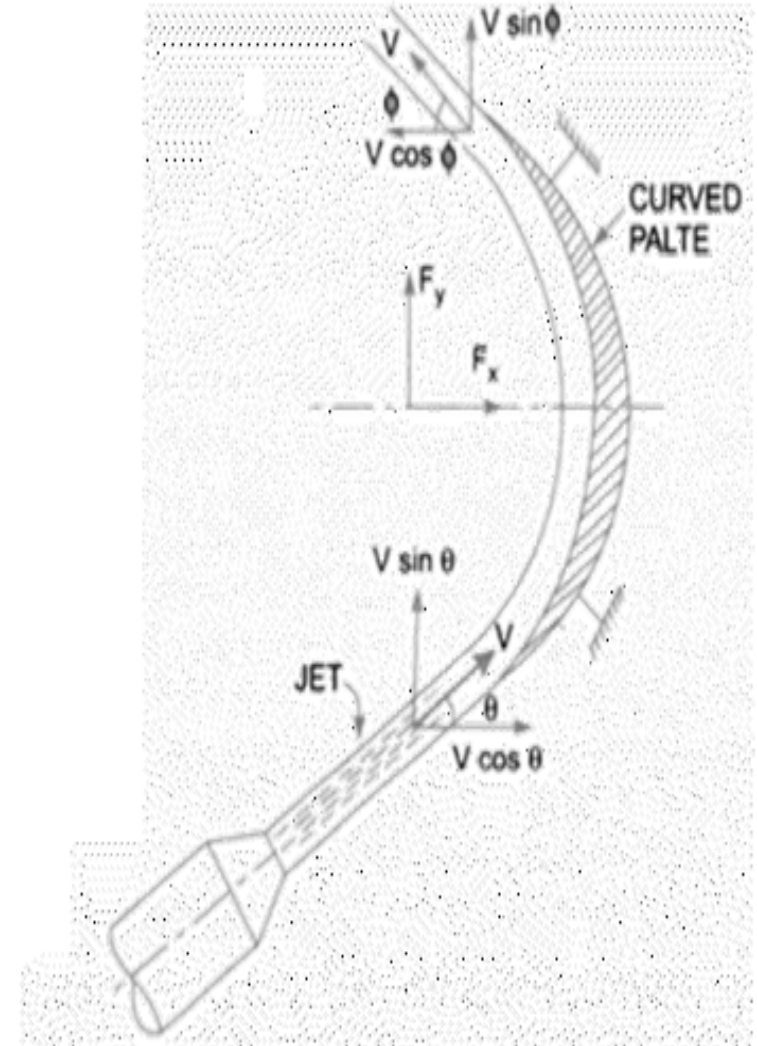
$$F_x = 2\rho aV^2 \cos \theta$$



Force exerted by the jet on a stationary plate

Plate is Curved and Jet strikes at tip

$$F_x = \rho a V^2 (\cos \theta + \cos \phi)$$



Force exerted by the jet on a moving plate

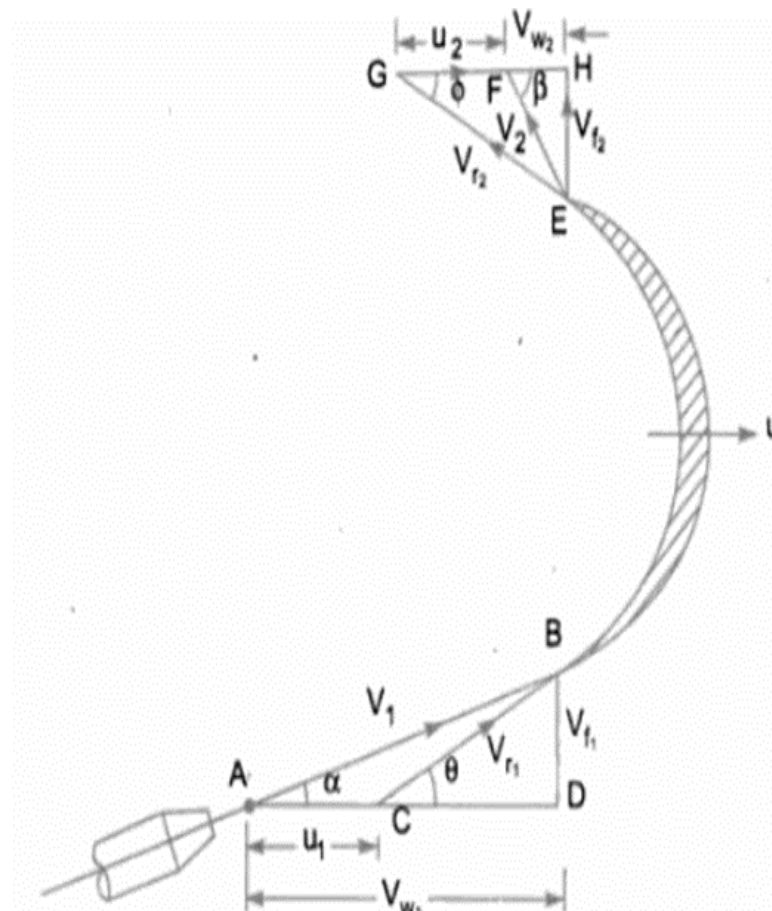
Considering Relative Velocity,

If $\beta < 90^\circ$

$$F_x = \rho a V_{r1} (V_{r1} \cos \theta + V_{r2} \cos \phi)$$

OR

$$F_x = \rho a V_{r1} (V_{w1} + V_{w2})$$



Jet striking a moving curved vane at one of the tips.

Force exerted by the jet on a moving plate

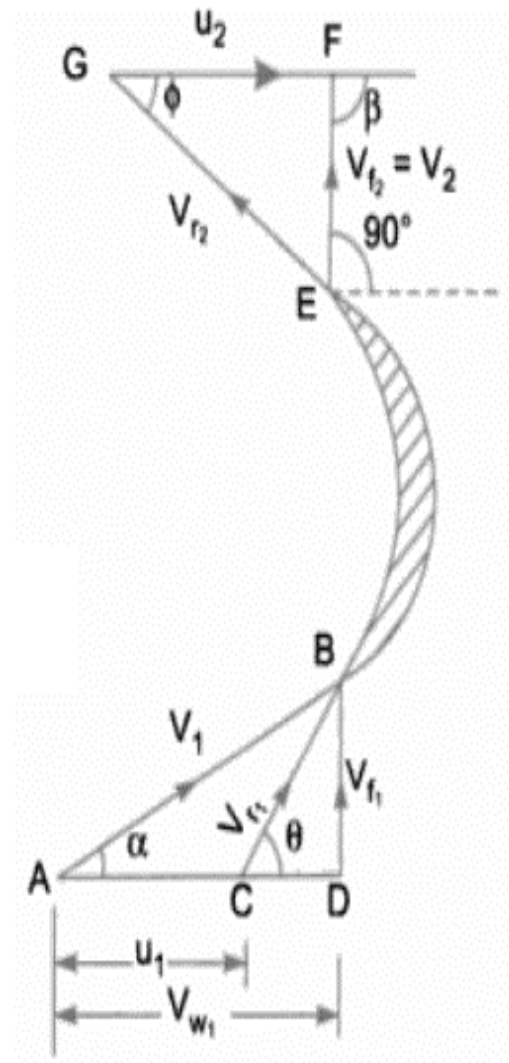
Considering Relative Velocity,

If $\beta = 90^\circ$

$$F_x = \rho a V_{r1} (V_{r1} \cos \theta - V_{r2} \cos \phi)$$

OR

$$F_x = \rho a V_{r1} (V_{w1})$$



Force exerted by the jet on a moving plate

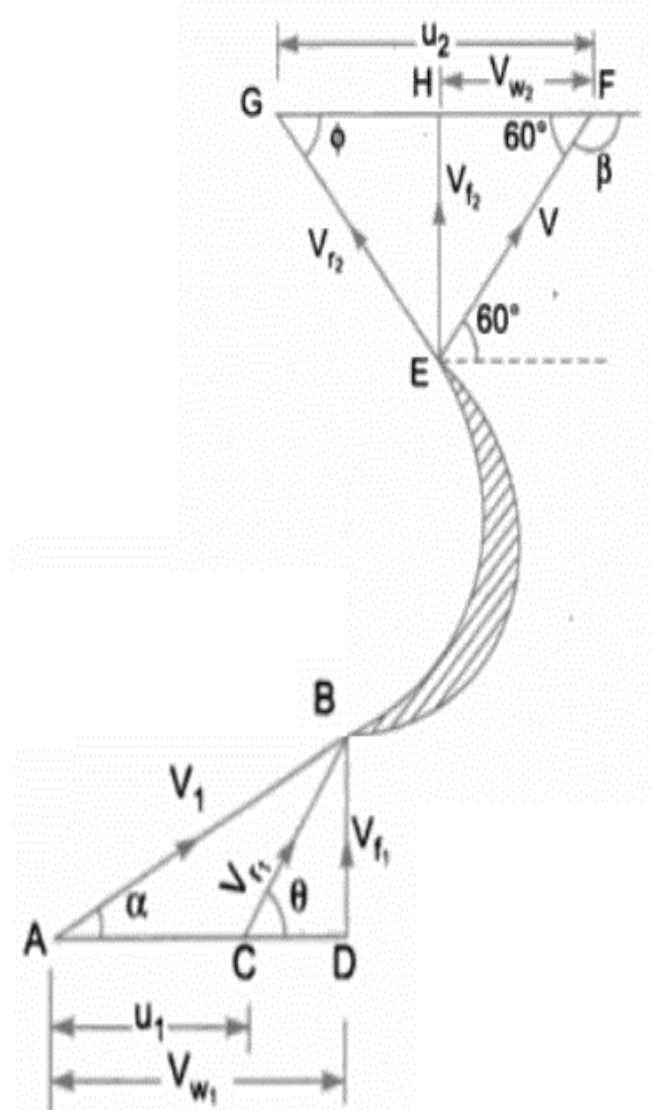
Considering Relative Velocity,

If $\beta = 90^\circ$

$$F_x = \rho a V_{r1} (V_{r1} \cos \theta - V_{r2} \cos \phi)$$

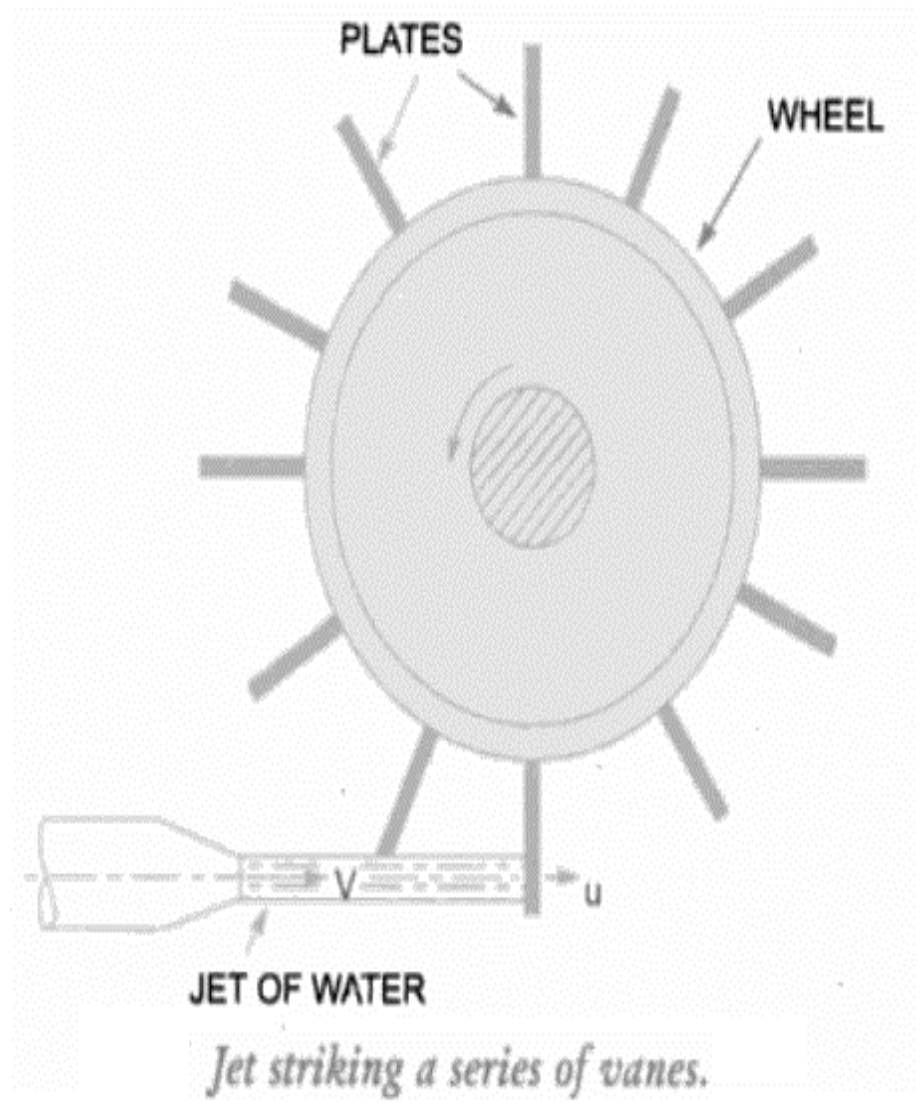
OR

$$F_x = \rho a V_{r1} (V_{w1} - V_{w2})$$



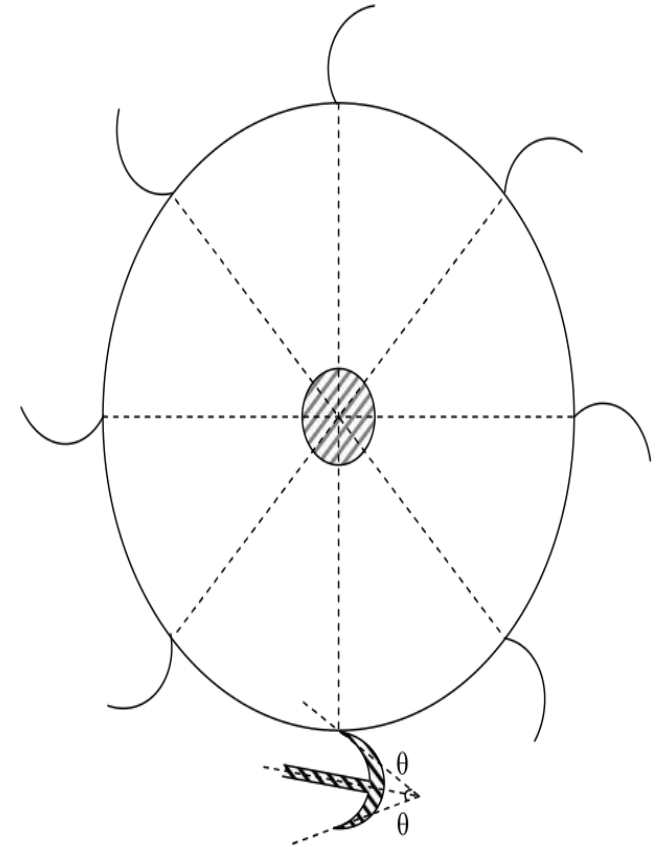
Impact of jet on a series of flat vanes mounted radially on the periphery of a circular wheel

$$F = \rho a V (V-U)$$



Impact of jet on a series of flat vanes mounted radially on the periphery of a circular wheel

$$F = \rho a V (V - U) (1 + \cos \theta)$$



Force exerted by the jet on a moving plate (PELTON WHEEL)

Considering Relative Velocity,

$$F_x = \rho a V_{r1} (V_{r1} - V_{r2} \cos \phi)$$

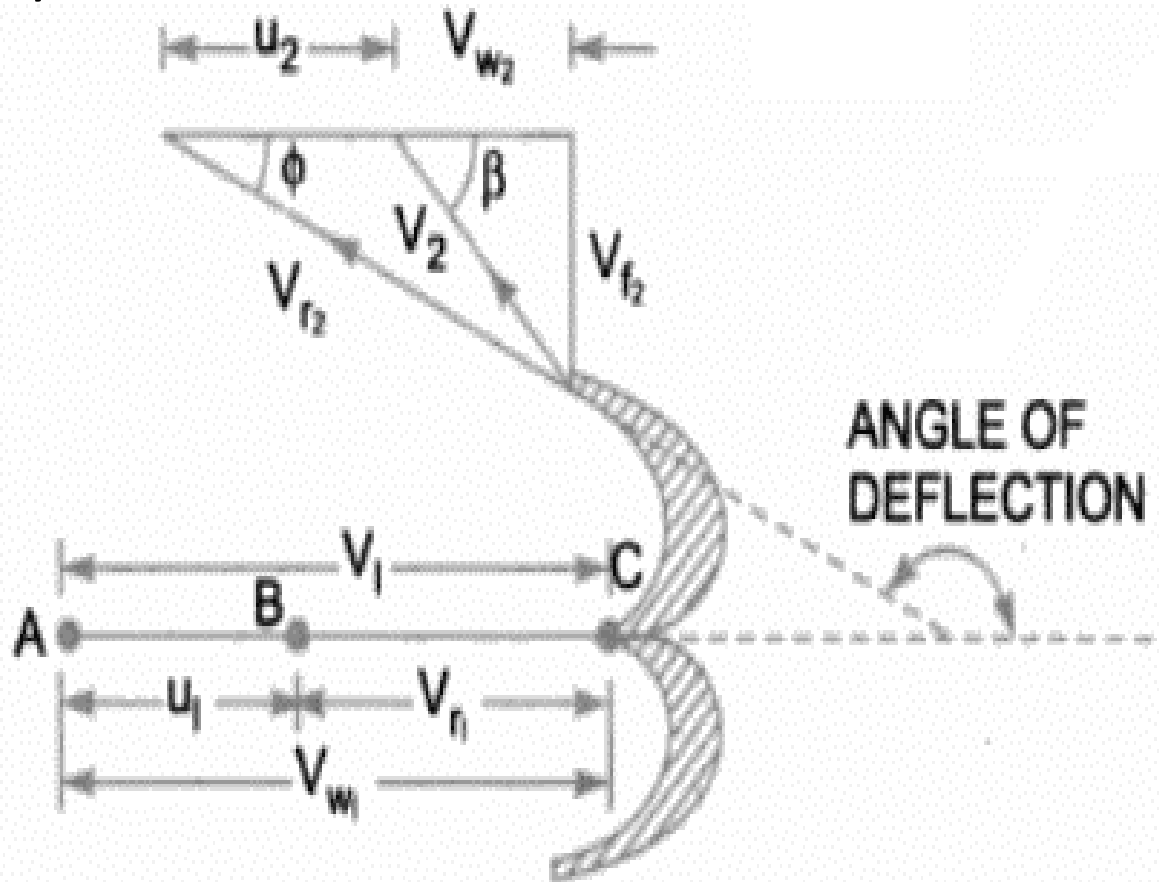
OR

$$F_x = \rho a V_{r1} (V_{w1} - V_{w2})$$

Work done / sec = F.U

Power = F. U

$$\text{Efficiency} = \frac{F.U}{\frac{1}{2} mV^2}$$



Layout of Hydropower Installation

H_g = Gross Head

h_f = Head Loss due to Friction

$$= \frac{4 \times f \times L \times V^2}{D \times 2g}$$

Where

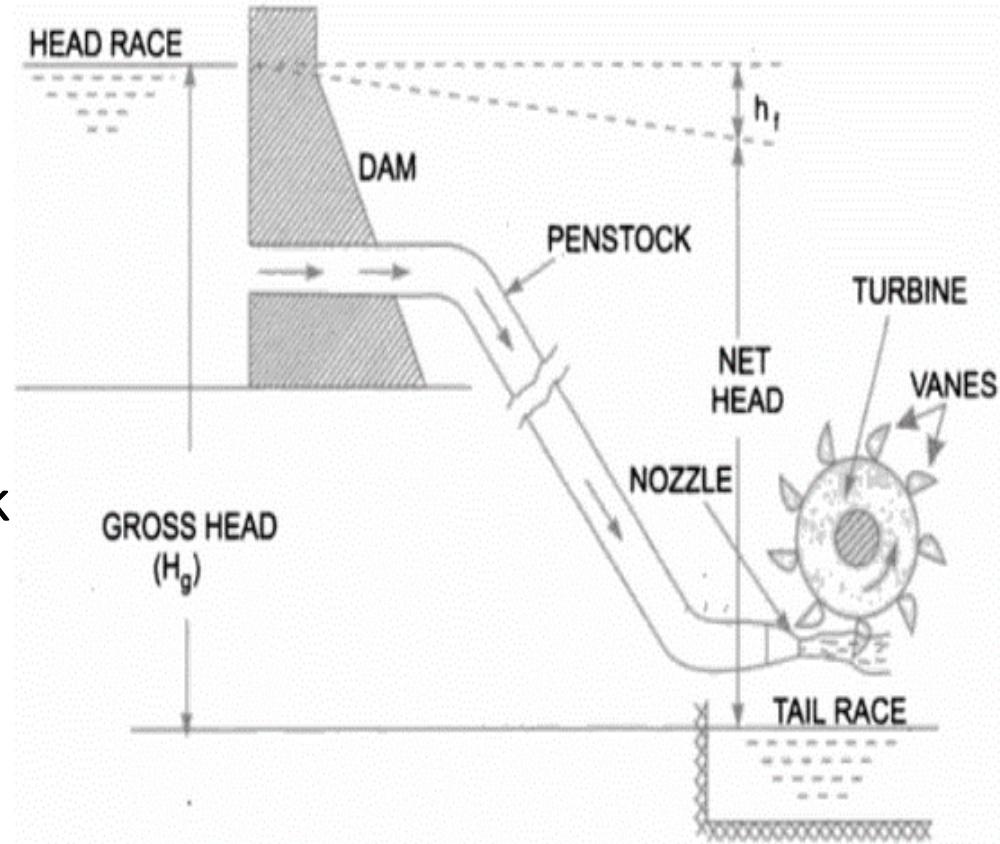
V = Velocity of Flow in Penstock

L = Length of Penstock

D = Dia. of Penstock

H = Net Head

$$= H_g - h_f$$



Layout of a hydro-electric power plant.

Efficiencies of Turbine

1. Hydraulic Efficiency

$$\eta_h = \frac{\text{Power delivered to runner}}{\text{Power supplied at inlet}} = \frac{\text{R.P.}}{\text{W.P.}}$$

2. Mechanical Efficiency

$$\eta_m = \frac{\text{Power at the shaft of the turbine}}{\text{Power delivered by water to the runner}} = \frac{\text{S.P.}}{\text{R.P.}}$$

3. Volumetric Efficiency

$$\eta_v = \frac{\text{Volume of water actually striking the runner}}{\text{Volume of water supplied to the turbine}}$$

4. Overall Efficiency

$$\eta_o = \frac{\text{Volume available at the shaft of the turbine}}{\text{Power supplied at the inlet of the turbine}} = \frac{\text{Shaft power}}{\text{Water power}}$$

$$= \frac{\text{S.P.}}{\text{W.P.}} = \frac{\text{S.P.}}{\text{W.P.}} \times \frac{\text{R.P.}}{\text{R.P.}} = \frac{\text{S.P.}}{\text{R.P.}} \times \frac{\text{R.P.}}{\text{W.P.}} \left(\begin{array}{l} \because \frac{\text{S.P.}}{\text{R.P.}} = \eta_m \\ \text{and } \frac{\text{R.P.}}{\text{W.P.}} = \eta_h \end{array} \right)$$

$$= \eta_m \times \eta_h$$

1. A jet of water having a velocity of 35 m/s strikes a series of radial curved vanes mounted on a wheel. The wheel has 200 rpm. The jet makes 20° with the tangent to wheel at inlet and leaves the wheel with a velocity of 5 m/s at 130° to tangent to the wheel at outlet. The diameters of wheel are 1 m and 0.5 m. Find
 - Vane angles at inlet and outlet for radially outward flow turbine.
 - Work done
 - Efficiency of the system



UNIT-IV

HYDRAULIC TURBINES

Classification of Turbines

1. According to type of energy at Inlet
 - a) Impulse Turbine - Pelton Wheel
Requires High Head and Low Rate of Flow
 - a) Reaction Turbine - Francis, Kaplan
Requires Low Head and High Rate of Flow
2. According to direction of flow through runner
 - a) Tangential Flow Turbine - Pelton Wheel
 - b) Radial Flow Turbine - Francis Turbine
 - c) Axial Flow Turbine - Kaplan Turbine
 - d) Mixed Flow Turbine - Modern Francis Turbine
3. According to Head at Inlet of turbine
 - a) High Head Turbine - Pelton Wheel
 - b) Medium Head Turbine - Francis Turbine
 - c) Low Head Turbine - Kaplan Turbine

Classification of Turbines

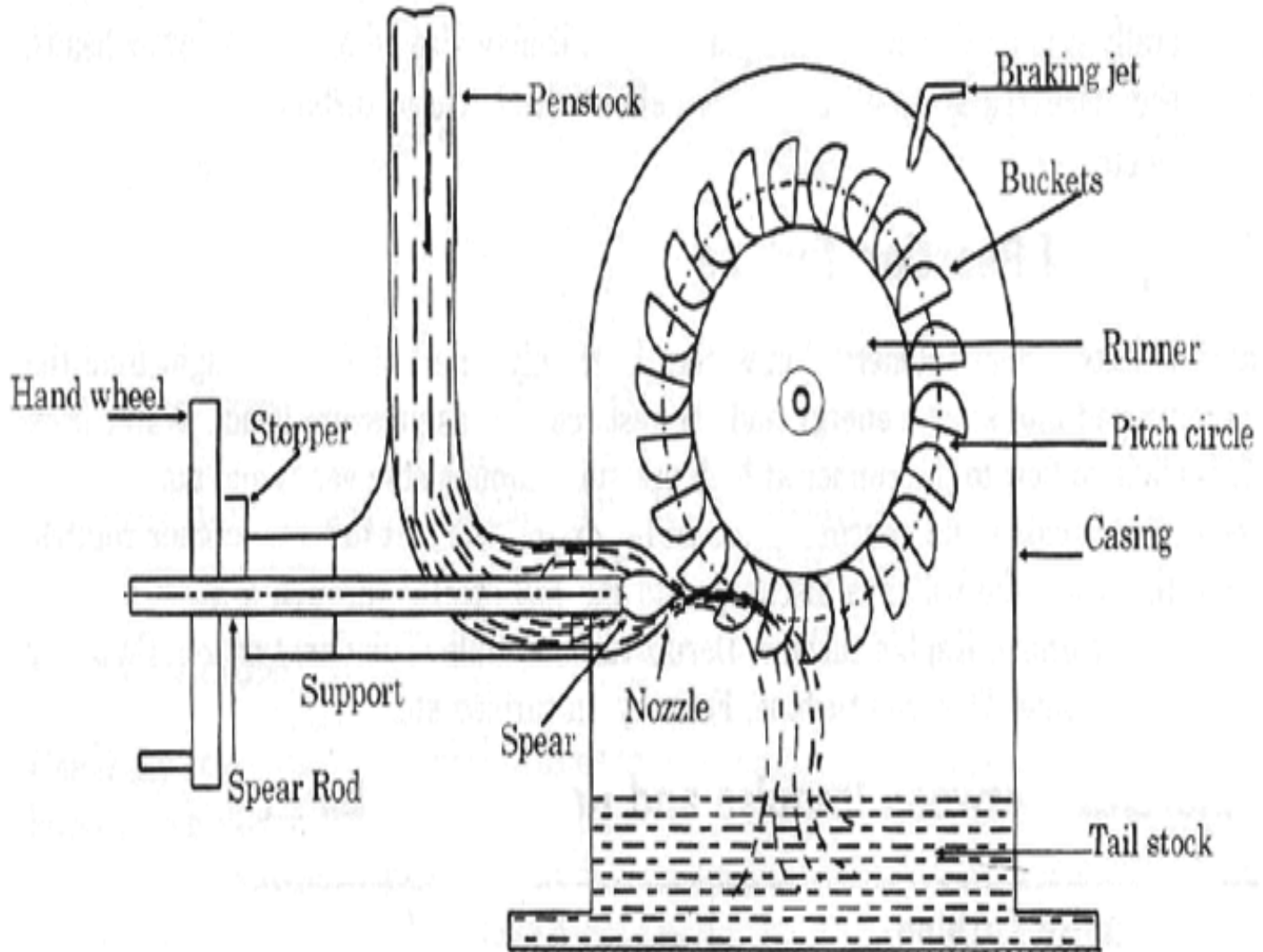
4. According to Specific Speed of Turbine

- a) Low Specific Speed Turbine - Pelton Wheel
- b) Medium Specific Speed Turbine - Francis Turbine
- c) High Specific Speed Turbine - Kaplan Turbine

5. According to Disposition of Turbine Shaft

- a) Horizontal Shaft - Pelton Wheel
- b) Vertical Shaft - Francis & Kaplan Turbines

Pelton Wheel Turbine



Design of Pelton Wheel Turbine

Guidelines:

1. Jet Ratio = Pitch Diameter of wheel / Dia. of Jet = D/d

2. Speed Ratio = Velocity of Wheel / Velocity of Jet = u/V

3. Velocity of Wheel $u = u_1 = u_2 = \frac{\pi DN}{60}$

4. Overall Efficiency $\eta_0 = \eta_m \times \eta_h$

5. Water Power, W.P. = $\frac{1}{2}mV^2 = \rho a V_1 [V_{w_1} + V_{w_2}] \times u = \rho Q [V_{w_1} + V_{w_2}] \times u$

6. Shaft Power, S.P. = $\eta_o = \frac{\text{S.P.}}{\text{W.P.}}$

7. No. of Buckets = $(0.5 \times \text{Jet Ratio}) + 15$

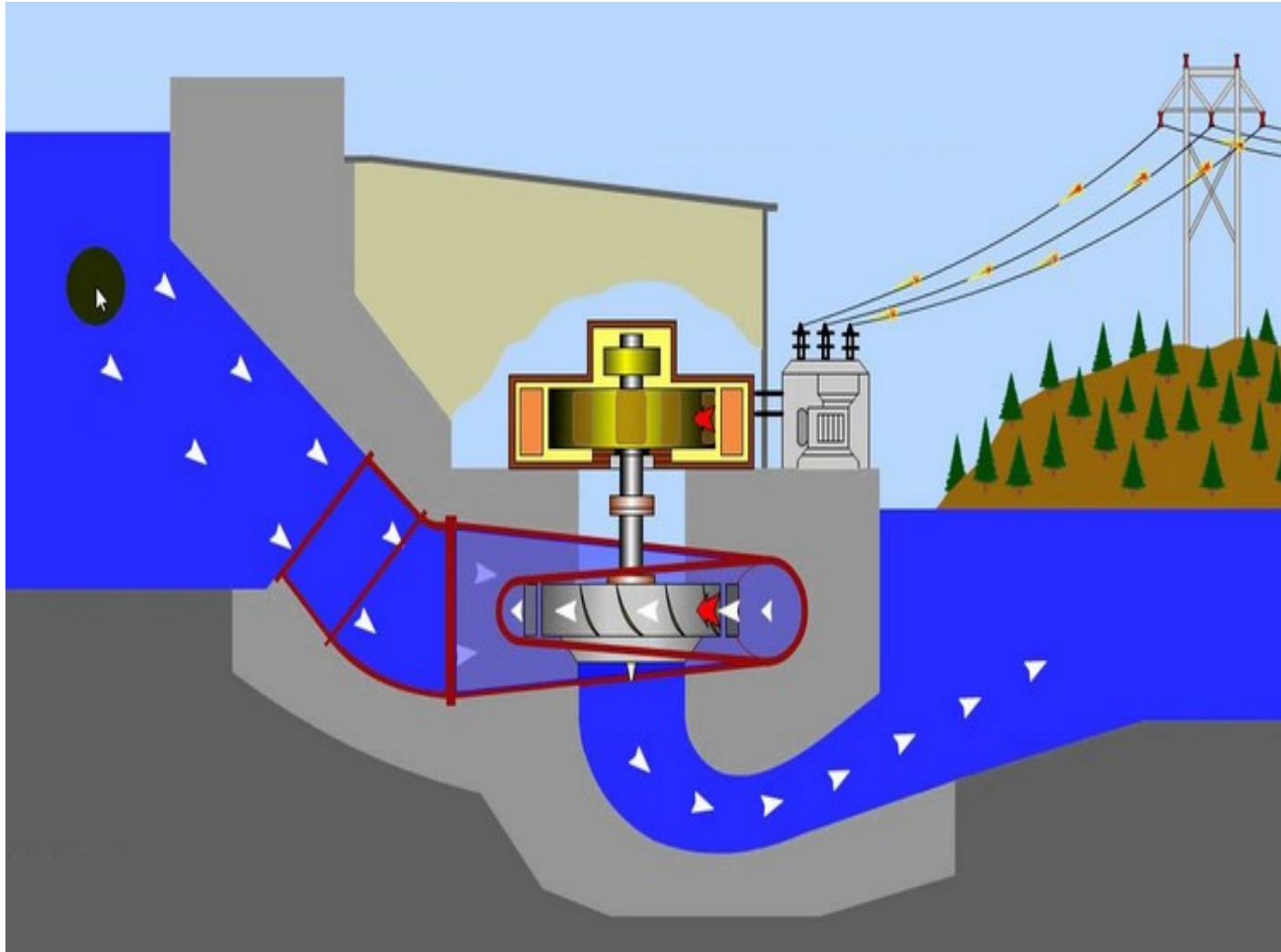
Problems

1. A Pelton wheel has a mean bucket speed of 10 m/s with a jet of water flowing at the rate of 700 lps under a head of 30 m. The buckets deflect the jet through an angle of 160° . Calculate the power given by water to the runner and the hydraulic efficiency of the turbine. Assume the coefficient of nozzle as 0.98.
2. A Pelton wheel has to develop 13230 kW under a net head of 800 m while running at a speed of 600 rpm. If the coefficient of Jet $C_y = 0.97$, speed ratio is 0.46 and the ratio of the Jet diameter is $1/16$ of wheel diameter. Calculate
 - i) Pitch circle diameter
 - ii) the diameter of jet
 - iii) the quantity of water supplied to the wheel

Problems

3. Design a Pelton wheel for a head of 80m. and speed of 300 RPM. The Pelton wheel develops 110 kW. Take co-efficient of velocity= 0.98, speed ratio= 0.48 and overall efficiency = 80%.
4. A double jet Pelton wheel develops 895 MKW with an overall efficiency of 82% under a head of 60m. The speed ratio = 0.46, jet ratio = 12 and the nozzle coefficient = 0.97. Find the jet diameter, wheel diameter and wheel speed in RPM.

Francis Turbines



Design of Francis Turbine

Guidelines:

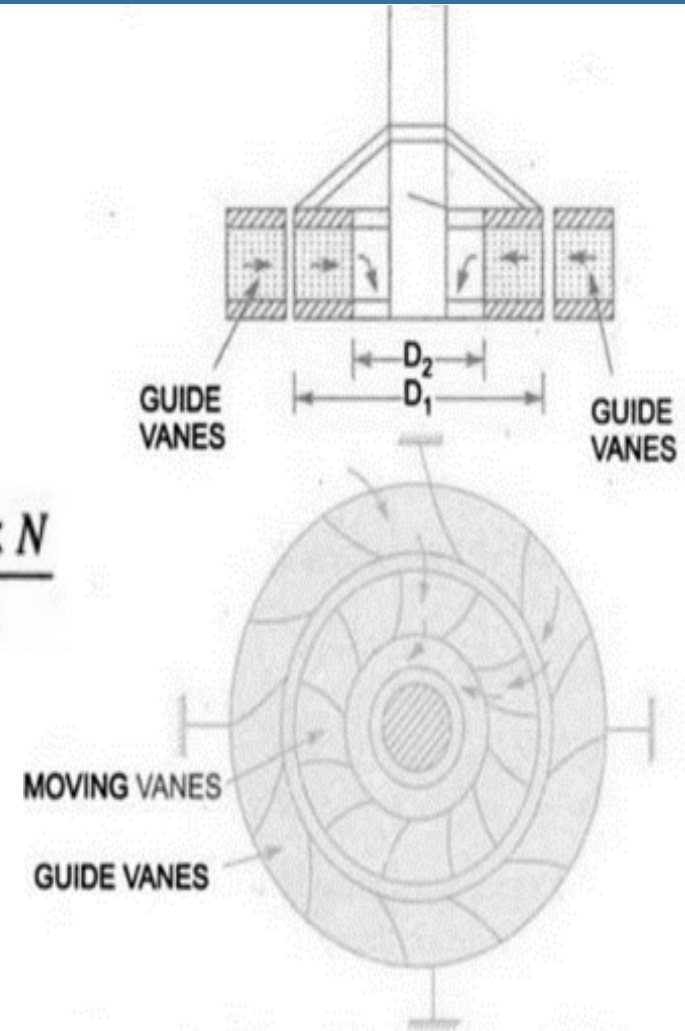
1. Velocity of Wheel, $u = u_1 = u_2 = \frac{\pi DN}{60}$

2. Work done per second or Power,

$$= \rho a V_1 [V_{w_1} u_1 \pm V_{w_2} u_2] = \rho Q [V_{w_1} u_1 \pm V_{w_2} u_2]$$

3. Velocity of Wheel, $u_1 = \frac{\pi D_1 \times N}{60}$, $u_2 = \frac{\pi D_2 \times N}{60}$

4. Discharge, $Q = \pi D_1 B_1 V_{f_1} = \pi D_2 B_2 V_{f_2}$



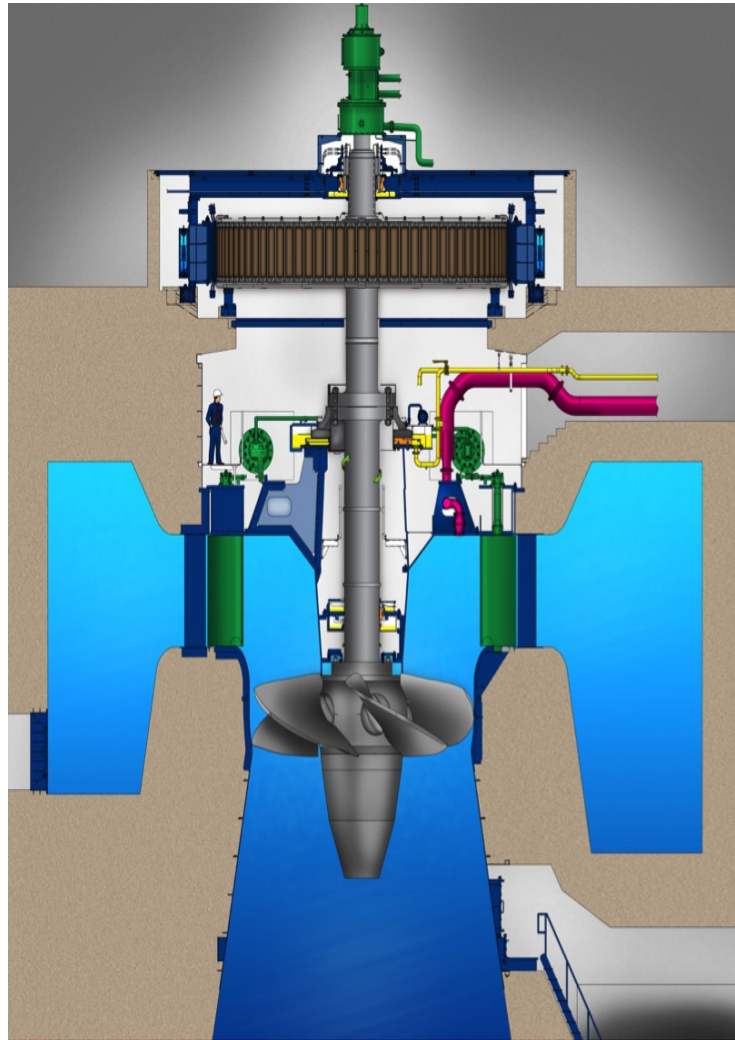
Problems

1. A reaction turbine works at 450 rpm under a head of 120 m. Its diameter at inlet is 1.2 m and the flow area is 0.4 m^2 . The angle made by the absolute and relative velocities at inlet are 20° and 60° respectively with the tangential velocity. Determine
 - (i) the discharge through the turbine
 - (ii) power developed
 - (iii) efficiency.

Assume radial discharge at outlet.

2. A Francis turbine has inlet wheel diameter of 2 m and outlet diameter of 1.2 m. The runner runs at 250 rpm and water flows at 8 cumecs. The blades have a constant width of 200 mm. If the vanes are radial at inlet and the discharge is radially outwards at exit, make calculations for the angle of guide vane at inlet and blade angle at outlet

Kaplan Turbines



Design of Kaplan Turbine

Guidelines:

1. Velocity of Wheel, $u_1 = u_2 = \frac{\pi D_m \times N}{60}$ where Mean diameter, $D_m = \frac{D_o + D_b}{2}$
2. Work done per second = $\rho a V_1 [V_{w_1} + V_{w_2}] \times u = \rho Q [V_{w_1} + V_{w_2}] \times u$
3. Velocity of Flow at Inlet and Outlet are equal $V_{f_1} = V_{f_2}$
4. Discharge, $Q = \frac{\pi}{4} (D_o^2 - D_b^2) \times V_{f_1}$
5. Flow Ratio = $\frac{V_{f_1}}{\sqrt{2gH}}$

Problems

1. A Kaplan turbine develops 9000 kW under a net head of 7.5 m. Overall efficiency of the wheel is 86% The speed ratio based on outer diameter is 2.2 and the flow ratio is 0.66. Diameter of the boss is 0.35 times the external diameter of the wheel. Determine the diameter of the runner and the specific speed of the runner.

2. A Kaplan turbine working under a head of 25 m develops 16,000 kW shaft power. The outer diameter of the runner is 4 m and hub diameter is 2 m. The guide blade angle is 35° . The hydraulic and overall efficiency are 90% and 85% respectively. If the velocity of whirl is zero at outlet, determine runner vane angles at inlet and outlet and speed of turbine.

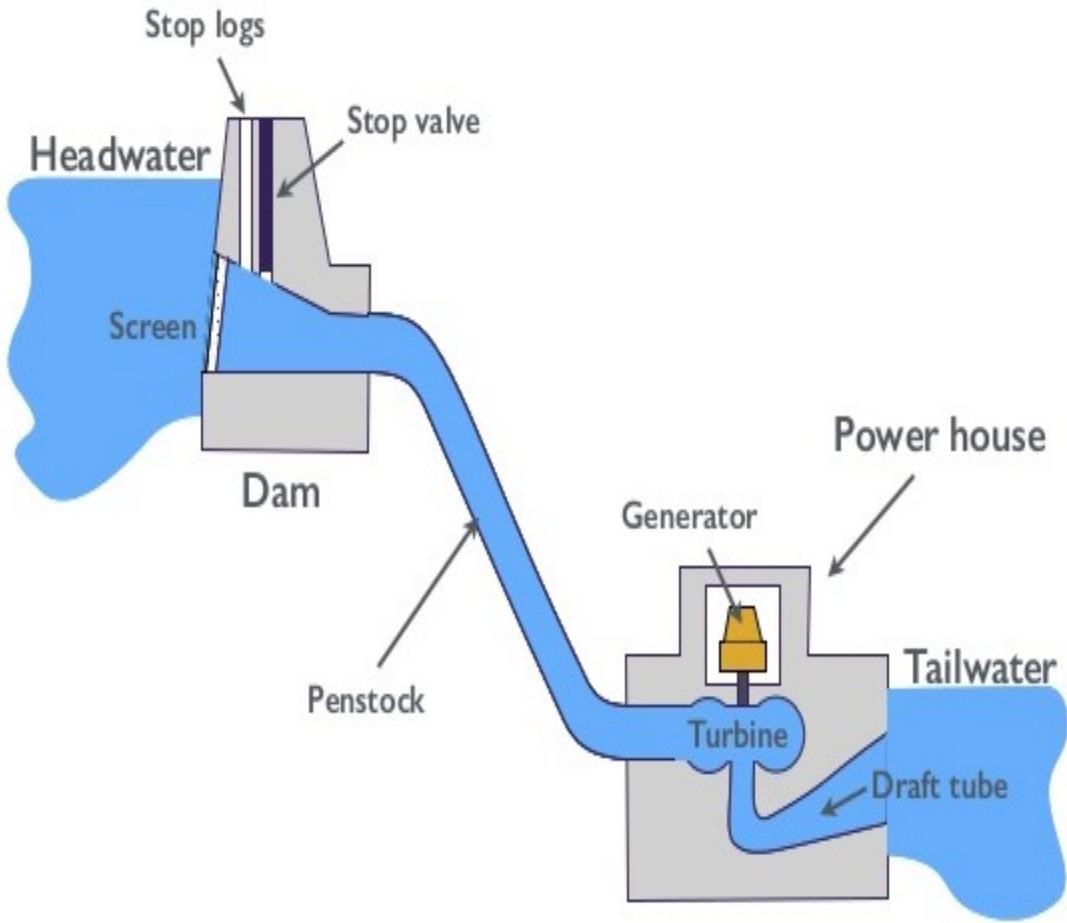
Draft Tube

The water after working on the turbine, imparts its energy to the vanes and runner, there by reducing its pressure less than that of atmospheric Pressure. As the water flows from higher pressure to lower Pressure, It can not come out of the turbine and hence a divergent tube is Connected to the end of the turbine.

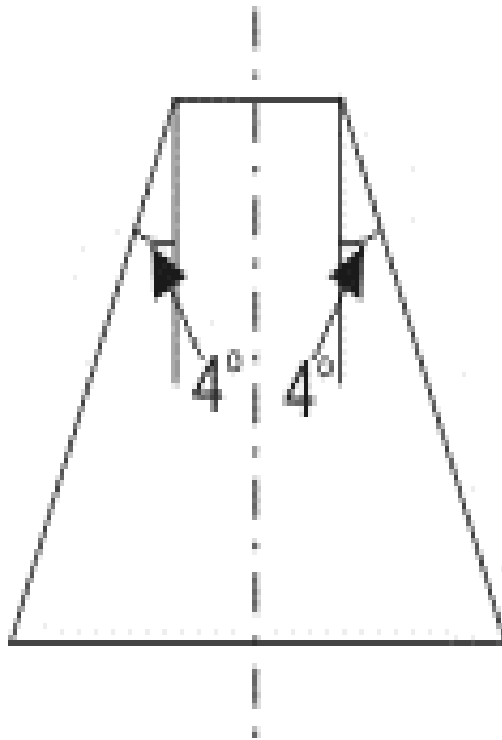
Draft tube is a divergent tube one end of which is connected to the outlet Of the turbine and other end is immersed well below the tailrace (Water level).

The major function of the draft tube is to increase the pressure from the inlet to outlet of the draft tube as it flows through it and hence increase it more than atmospheric pressure. The other function is to safely Discharge the water that has worked on the turbine to tailrace.

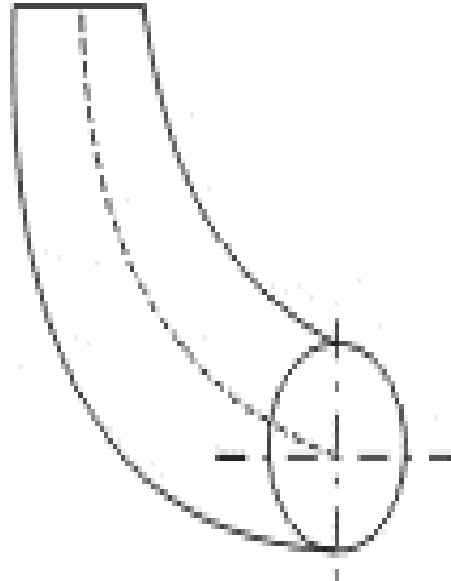
Draft Tube



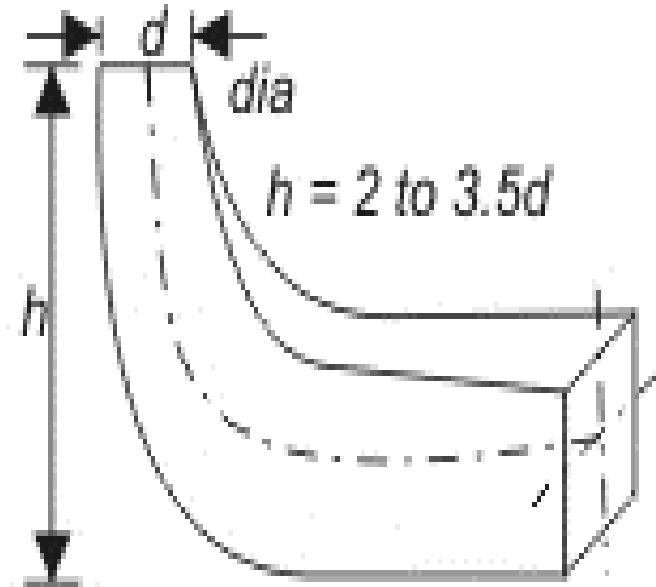
Types of Draft Tube



(a) Straight type



(b) Simple elbow type



(c) Elbow type with varying cross-section

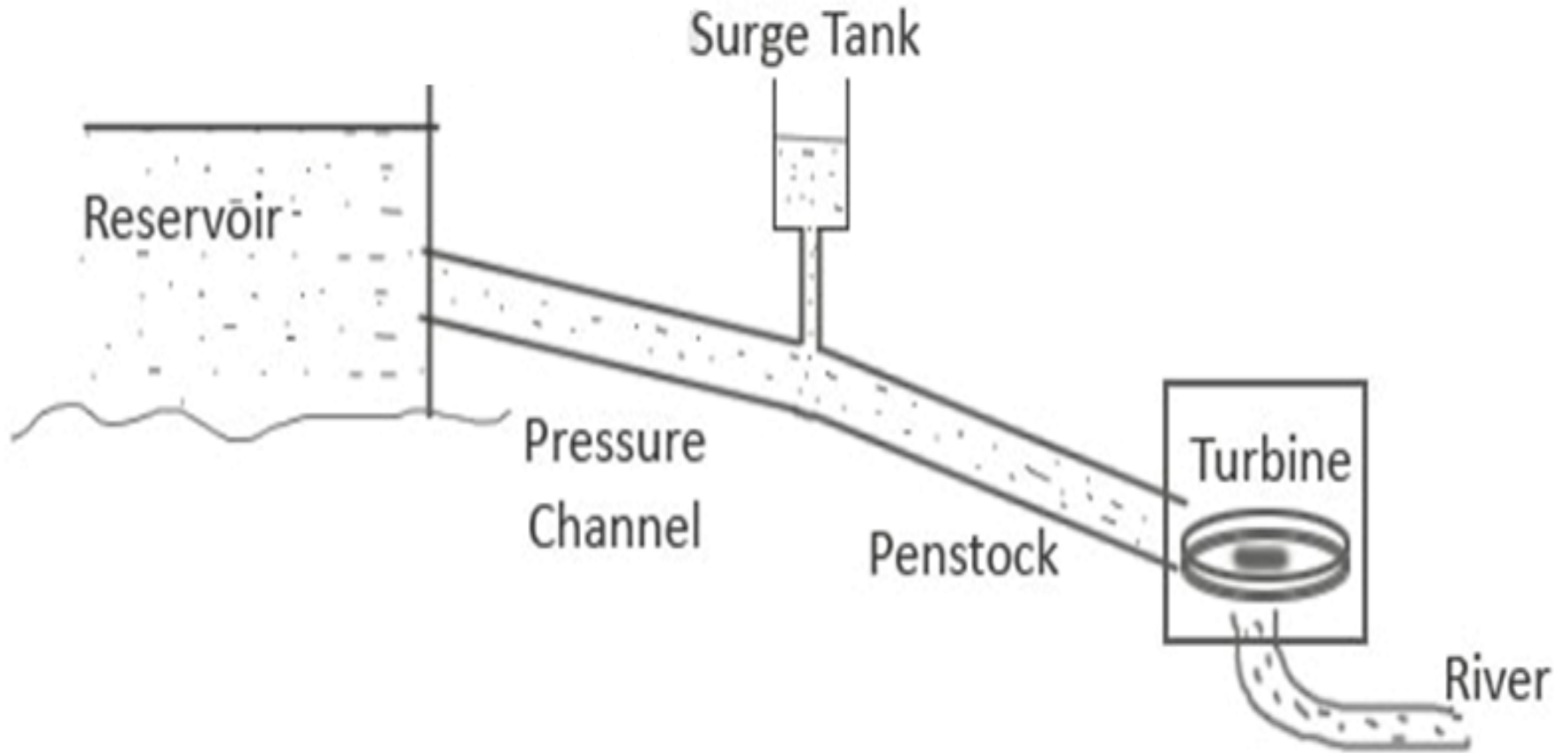
Surge Tanks

Surge tank (or surge chamber) is a device introduced within a hydropower water conveyance system having a rather long pressure conduit to absorb the excess pressure rise in case of a sudden valve closure. The surge tank is located between the almost horizontal or slightly inclined conduit and steeply sloping penstock and is designed as a chamber excavated in the mountain.

It also acts as a small storage from which water may be supplied in case of a sudden valve opening of the turbine.

In case of a sudden opening of turbine valve, there are chances of penstock collapse due to a negative pressure generation, if there is no surge tank.

Surge Tanks



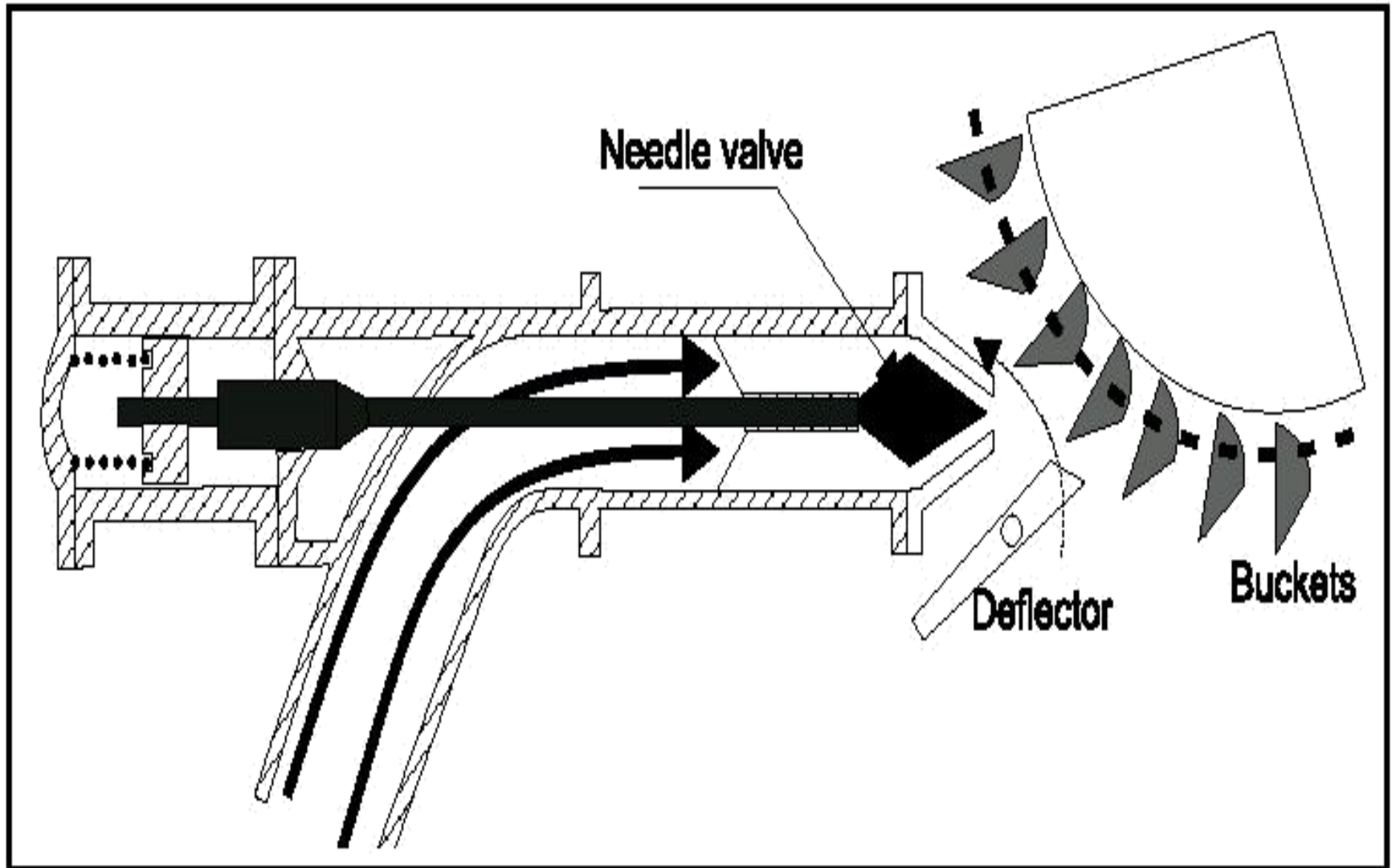
Governing means Speed Regulation.

Governing system or governor is the main controller of the hydraulic turbine. The governor varies the water flow through the turbine to control its speed or power output.

1. Impulse Turbine

- a) Spear Regulation
- b) Deflector Regulation
- c) Combined

Governing of Turbines



Performance of Turbines under unit quantities

The unit quantities give the speed, discharge and power for a particular turbine under a head of 1m assuming the same efficiency. Unit quantities are used to predict the performance of turbine.

1. Unit speed (N_u) - Speed of the turbine, working under unit head $N_u = \frac{N}{\sqrt{H}}$

2. Unit power (P_u) - Power developed by a turbine, working under a unit head $P_u = \frac{P}{\sqrt{H}}$

3. Unit discharge (Q_u) - The discharge of the turbine working under a unit head $Q_u = \frac{Q}{H^{3/2}}$

Unit quantities

Unit Speed, Unit discharge and Unit Power is definite characteristics of a turbine.

If for a given turbine under heads H_1, H_2, H_3, \dots the corresponding speeds are N_1, N_2, N_3, \dots , the corresponding discharges are Q_1, Q_2, Q_3, \dots and the powers developed are P_1, P_2, P_3, \dots . Then

$$\text{Unit speed} = N_u = \frac{N_1}{\sqrt{H_1}} = \frac{N_2}{\sqrt{H_2}} = \frac{N_3}{\sqrt{H_3}}$$

$$\text{Unit Discharge} = Q_u = \frac{Q_1}{\sqrt{H_1}} = \frac{Q_2}{\sqrt{H_2}} = \frac{Q_3}{\sqrt{H_3}}$$

$$\text{Unit Power} = P_u = \frac{P_1}{H\sqrt{H_1}} = \frac{P_2}{H\sqrt{H_2}} = \frac{P_3}{H\sqrt{H_3}} \text{ or } P_u = \frac{P_1}{H_1^{3/2}} = \frac{P_2}{H_2^{3/2}} = \frac{P_3}{H_3^{3/2}}$$

Thus if speed, discharge and power developed by a turbine under a certain head are known, the corresponding quantities for any other head can be determined.

Specific Speed of a Turbine (N_s)

The specific speed of a turbine is the speed at which the turbine will run when developing unit power under a unit head. This is the type characteristics of a turbine. For a set of geometrically similar turbines the specific speed will have the same value.

$$N_s = \frac{N\sqrt{P}}{H^{5/4}}$$

Problems

1. Suggest a suitable type of turbine to develop 7000 kW power under a head of 20m while operating at 220 rpm. What are the considerations for your suggestion.
2. A turbine is to operate under a head of 25m at 200 rpm. The discharge is $9 \text{ m}^3/\text{s}$. If the efficiency is 90%, determine:
 - i) Power generated
 - ii) Speed and Power at a head of 20m

Characteristics Curves of Turbine

These are curves which are characteristic of a particular turbine which helps in studying the performance of the turbine under various conditions. These curves pertaining to any turbine are supplied by its manufacturers based on actual tests.

The characteristic curves obtained are the following:

- a) Constant head curves or main characteristic curves
- b) Constant speed curves or operating characteristic curves
- c) Constant efficiency curves or Muschel curves

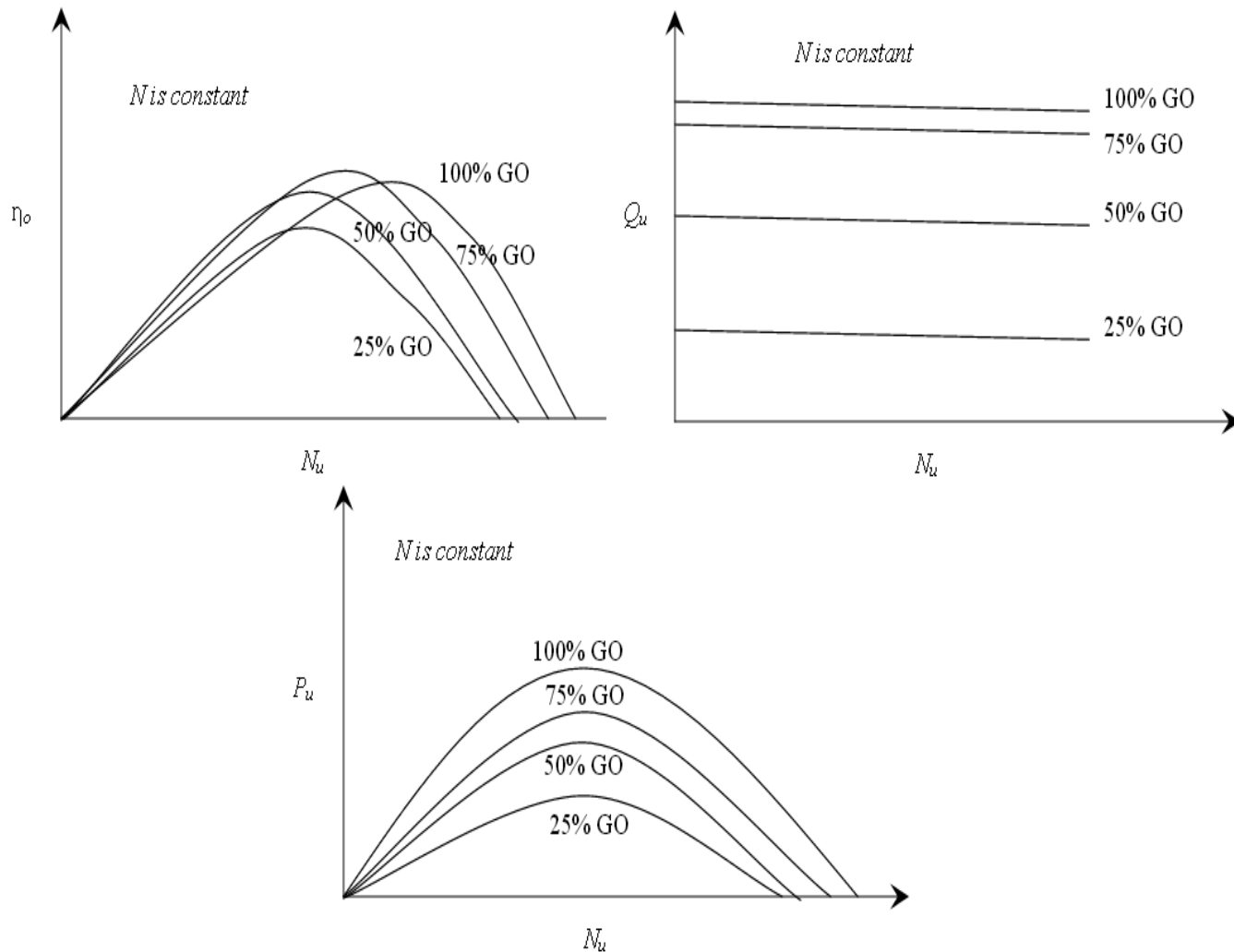
Constant head curves:

Maintaining a constant head, the speed of the turbine is varied by admitting different rates of flow by adjusting the percentage of gate opening. The power P developed is measured mechanically. From each test the unit power P_u , the unit speed N_u , the unit discharge Q_u and the overall efficiency are determined.

The characteristic curves drawn are

- a) Unit discharge vs unit speed
- b) Unit power vs unit speed
- c) Overall efficiency vs unit speed

Constant head curves or main characteristic curves



Main Characteristic curves of a Pelton turbine

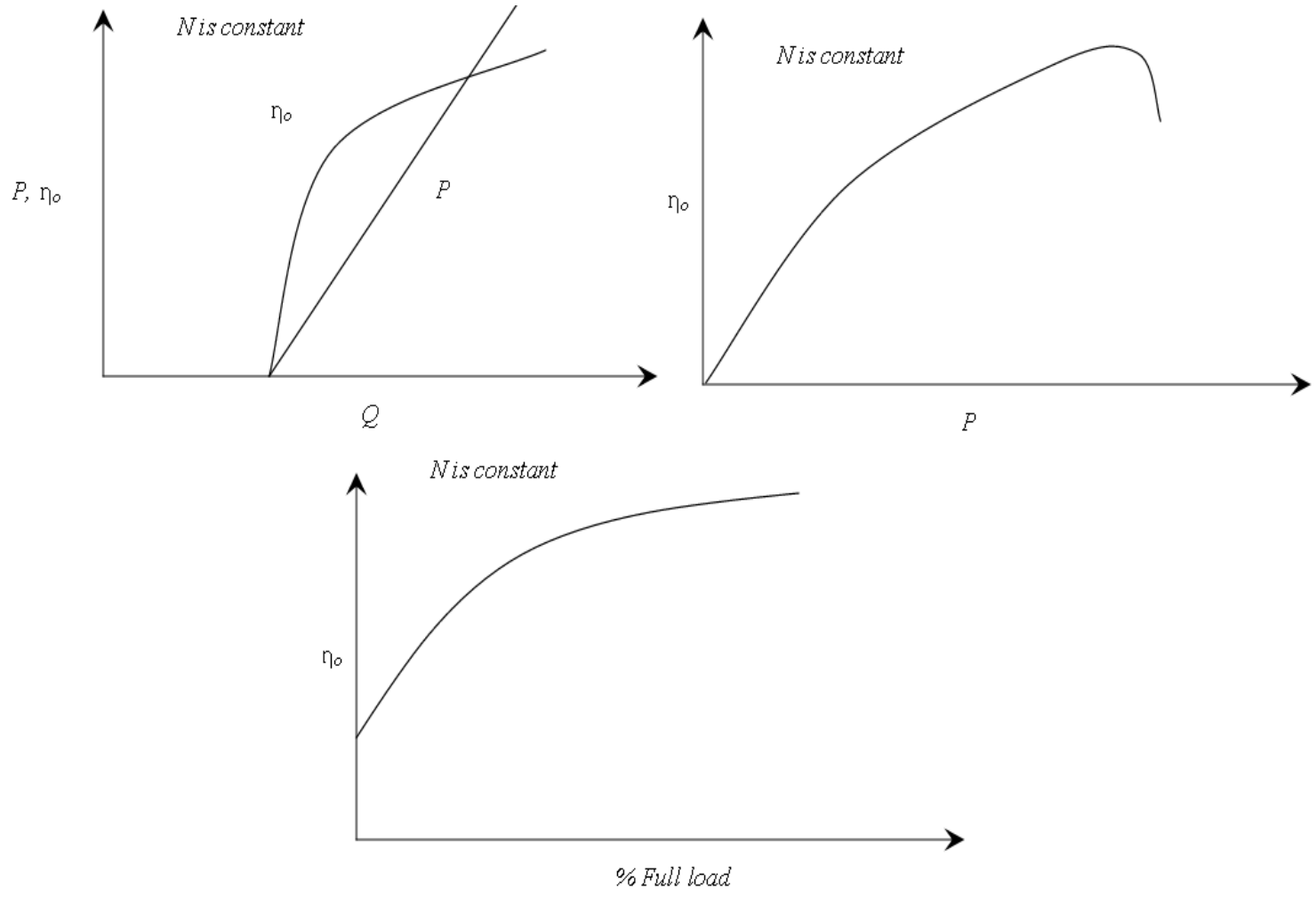
Constant speed curves or operating characteristic curves

Constant speed curves:

In this case tests are conducted at a constant speed varying the head H and suitably adjusting the discharge Q . The power developed P is measured mechanically. The overall efficiency is aimed at its maximum value. The curves drawn are

- P vs Q
- η_o vs Q
- η_o vs P_u
- $\eta_{o\ max}$ vs % Full load

Constant speed curves or operating characteristic curves



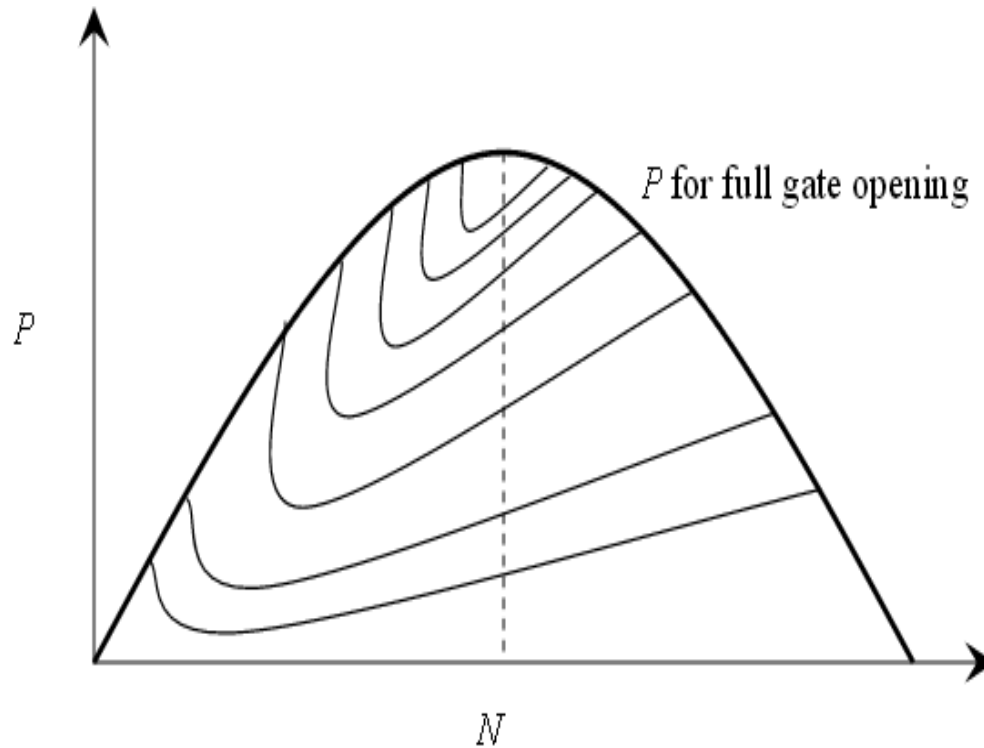
Operating Characteristic curves of a turbine

Constant efficiency curves:

These curves are plotted from data which can be obtained from the constant head and constant speed curves. The object of obtaining this curve is to determine the zone of constant efficiency so that we can always run the turbine with maximum efficiency.

This curve also gives a good idea about the performance of the turbine at various efficiencies.

Constant efficiency curves or Muschel curves



Constant Efficiency curves for Reaction turbine

Similitude of Turbines

Dimensionless Numbers:

$$\frac{Q}{ND^3}, \frac{gH}{N^2 D^2}, \frac{P}{\rho N^3 D^5}$$

Where

Q = Discharge

N = Speed of Wheel

D = Dia. of Wheel

H = Head

P = Shaft Power

Problems

1. A hydraulic turbine develops 120 KW under a head of 10 m at a speed of 1200 rpm and gives an efficiency of 92%. Find the water consumption and the specific speed. If a model of scale 1: 30 is constructed to operate under a head of 8m what must be its speed, power and water consumption to run under the conditions similar to prototype.
2. A model turbine 1m in diameter acting under a head of 2m runs at 150 rpm. Estimate the scale ratio if the prototype develops 20 KW under a head of 225 m with a specific speed of 100.

If the pressure of a liquid in course of its flow becomes equal to its vapour pressure at the existing temperature, then the liquid starts boiling and the pockets of vapour are formed which create vapour locks to the flow and the flow is stopped. The phenomenon is known as **cavitation**.

To avoid cavitation, the minimum pressure in the passage of a liquid flow, should always be more than the vapour pressure of the liquid at the working temperature. In a reaction turbine, the point of minimum pressure is usually at the outlet end of the runner blades, i.e., at the inlet to the draft tube.

Methods to avoid Cavitations

- (i) Runner/turbine may be kept under water.
- (ii) Cavitation free runner may be designed.
- (iii) By selecting materials that can resist better the cavitation effect.
- (iv) By polishing the surfaces.
- (v) By selecting a runner of proper specific speed for given load.



UNIT-V

CENTRIFUGAL PUMPS

1. Introduction
2. Classification of Pumps
3. Pump Installation Details
4. Work done by Pump – Velocity Triangles at Inlet & Outlet
5. Heads and Efficiencies
6. Minimum Starting Speed
7. Specific Speed of Pump
8. Model Analysis of Pumps
9. Cavitations in Pumps

A pump is a hydraulic machine which converts mechanical energy into hydraulic energy or pressure energy.

A centrifugal pump works on the principle of centrifugal force.

In this type of pump the liquid is subjected to whirling motion by the rotating impeller which is made of a number of backward curved vanes. The liquid enters this impeller at its center or the eye and gets discharged into the casing enclosing the outer edge of the impeller.

Generally centrifugal pumps are made of the **radial flow** type only ($\alpha = 90^\circ$)

Classification of Pumps

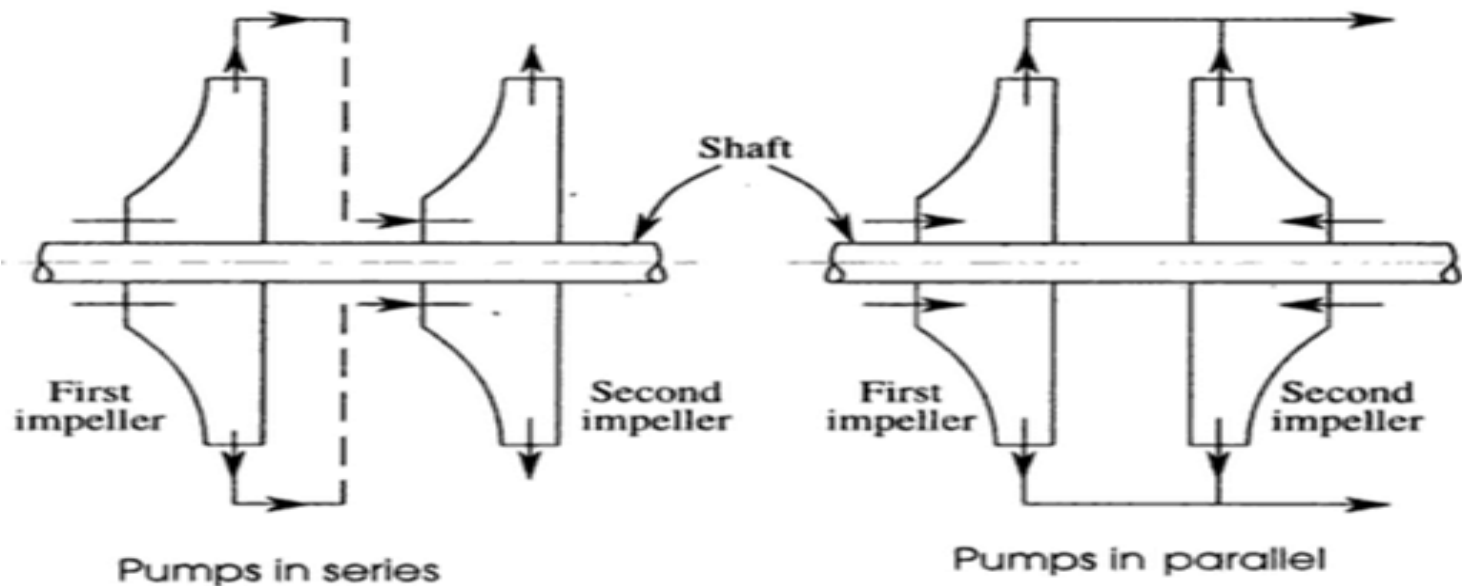
1. According to No. of Impellers
 - a) Single Stage Pump
 - b) Multistage Pump
2. According to Disposition of Shaft
 - a) Vertical Shaft Pump
 - b) Horizontal Pump
3. According to Head

a) Low Head Pump	-	$H < 15\text{m}$
b) Medium Head Pump	-	$15\text{m} < H < 40\text{m}$
c) High Specific Speed Turbine	-	$H > 40\text{m}$

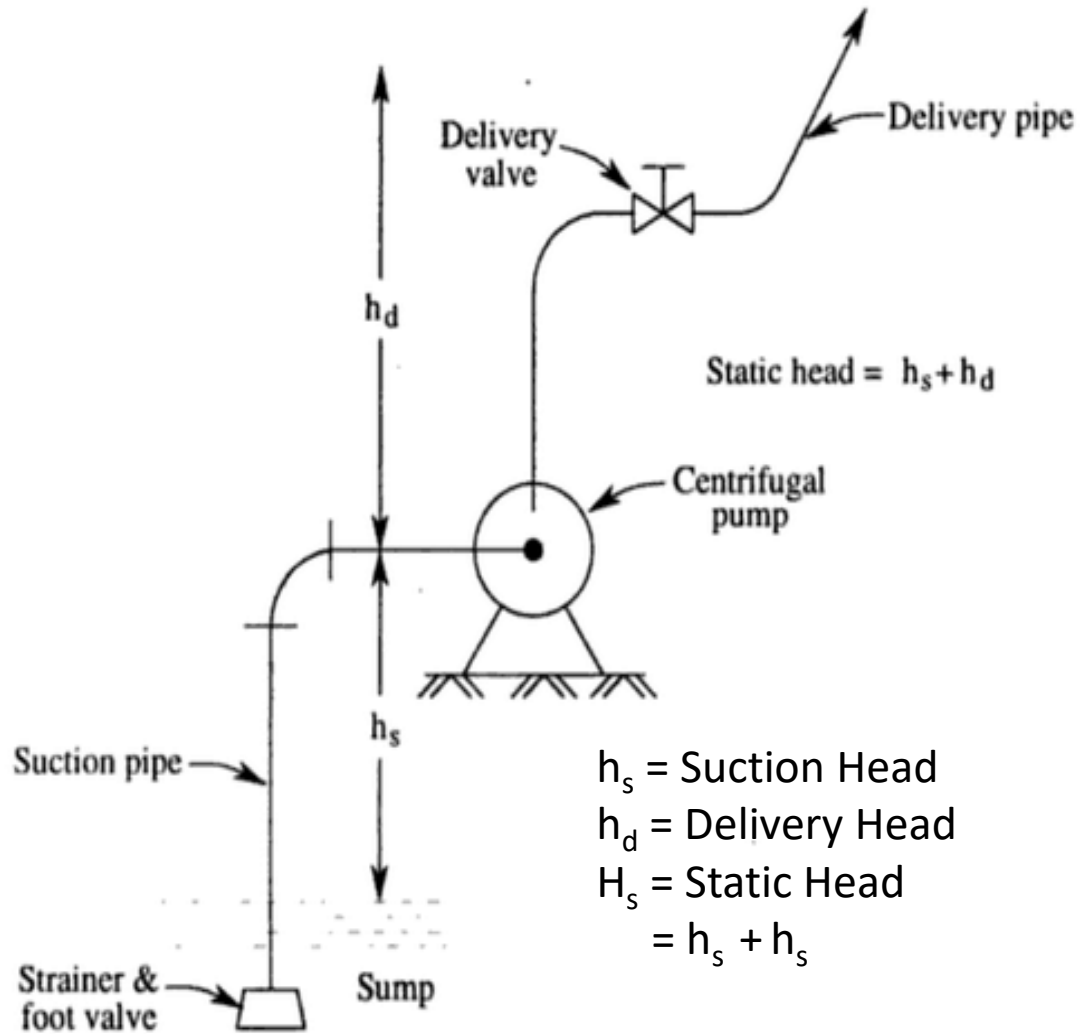
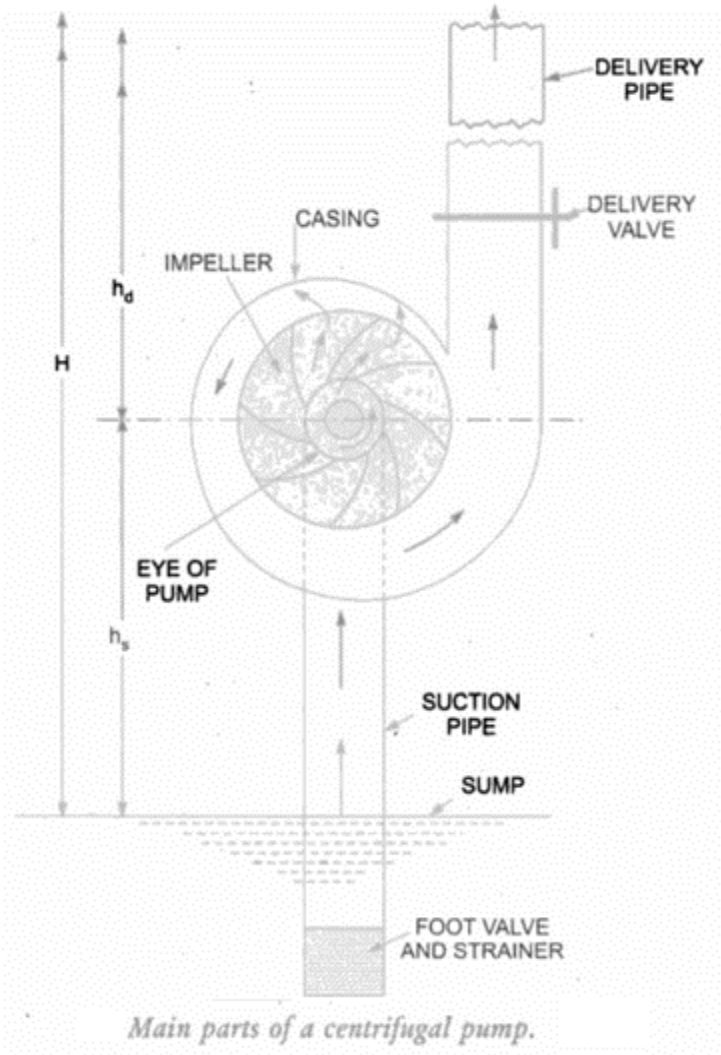
Multi stage centrifugal pumps

A centrifugal pump containing two or more impellers is called a multistage centrifugal pump.

- For higher pressures at the outlet, impellers can be connected in series.
- For higher flow output, impellers can be connected parallel.



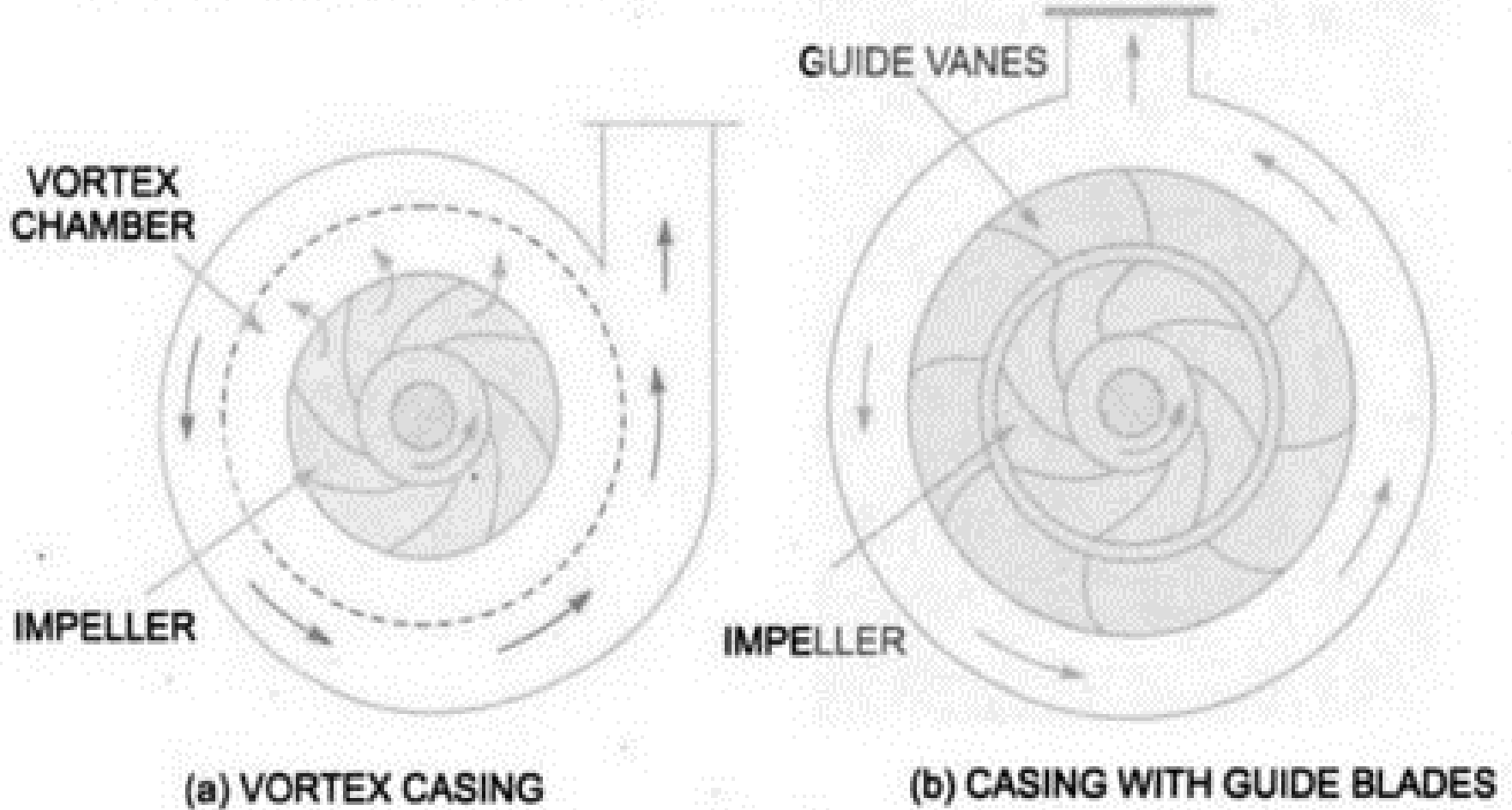
Components of Centrifugal Pump



Components of Pump

1. Strainer and Foot Valve
2. Suction Pipe and its fittings
3. Pump
4. Delivery Valve
5. Delivery Pipe and its fittings

Components of Pump



Different types of casing.

Manometric Head

Manometric head (H_m):

It is the total head developed by the pump.

This head is slightly less than the head generated by the impeller due to some losses in the pump.

H_m = Suction Head + Delivery Head + Head Loss + Velocity Head in Delivery Pipe

$$= h_s + h_d + h_f + V_d^2/2g$$

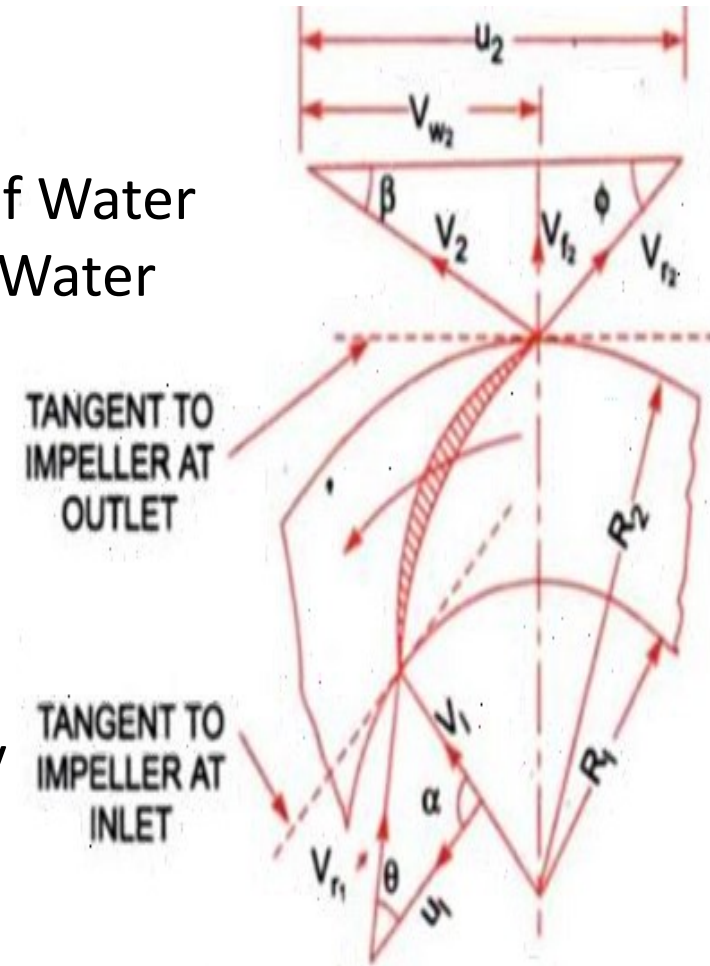
Velocity Triangles at Inlet and Outlet

Head Imparted by Impeller to Water = Work done per Second
 $= \rho Q (V_{w2} U_2)$

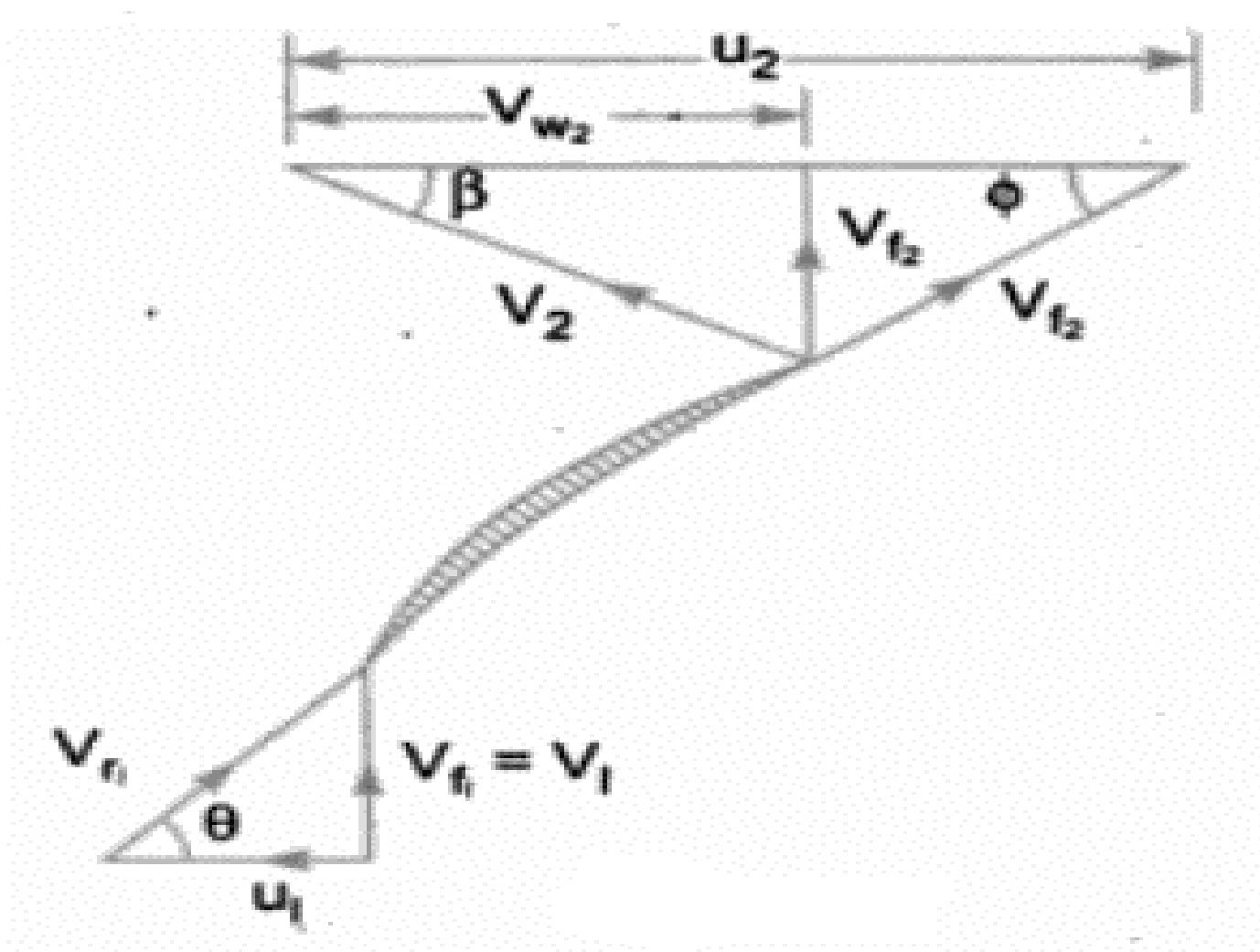
Head Imparted by Impeller to Unit Weight of Water
 = Work done per Second per Unit Weight of Water
 $= \rho Q (V_{w2} U_2) / mg$
 $= \rho Q (V_{w2} U_2) / (\rho Q) g$
 $= V_{w2} U_2 / g$

Manometric Efficiency:

$\eta_{man} = \text{Manometric Head} / \text{Head Imparted by Impeller to Water}$
 $= H_m / [(V_{w2} U_2) / g]$
 $= g H_m / V_{w2} U_2$



Velocity Triangles at Inlet and Outlet



Problems

A centrifugal pump will start delivering liquid only if the head developed by the impeller is more than the manometric head (H_m). If the head developed is less than H_m no discharge takes place although the impeller is rotating. When the impeller is rotating, the liquid in contact with the impeller is also rotating. This is a forced vortex, in which the increase in head in the impeller is given by

$$\text{Head rise in impeller} = \frac{u_2^2}{2g} - \frac{u_1^2}{2g}$$

Discharge takes place only when

$$\frac{u_2^2}{2g} - \frac{u_1^2}{2g} \geq H_m$$

substituting for u_1 , u_2 and H_m in Equation (10.13), we obtain

$$N = \frac{120\eta_m V_{w_2} D_2}{\pi(D_2^2 - D_1^2)}$$

which is the minimum speed for the pump to discharge liquid.

Specific Speed of Pump

The specific speed of a centrifugal pump is defined as the speed of a geometrically similar pump which would deliver *one cubic metre* of liquid per second against a head of *one metre*. It is denoted by ' N_s '.

$$N_s = \frac{N\sqrt{Q}}{H_m^{3/4}}$$

Model Analysis of Pump

Before manufacturing the large sized pumps, their models which are in complete similarity with the actual pumps (also called prototypes) are made. Tests are conducted on the models and performance of the prototypes are predicted. The complete similarity between the model and actual pump (prototype) will exist if the following conditions are satisfied :

1. Specific speed of model = Specific speed of prototype

$$(N_s)_m = (N_s)_p \quad \text{or} \quad \left(\frac{N\sqrt{Q}}{H_m^{3/4}} \right)_m = \left(\frac{N\sqrt{Q}}{H_m^{3/4}} \right)_p$$

Cavitations in Pump

Cavitation is the formation of bubbles or cavities in liquid, developed in areas of relatively low pressure around an impeller. The imploding or collapsing of these bubbles trigger intense shockwaves inside the pump, causing significant damage to the impeller and/or the pump housing.

If left untreated, pump cavitations can cause:

- a) Failure of pump housing
- b) Destruction of impeller
- c) Excessive vibration leading to premature seal and bearing failure
- a) Higher than necessary power consumption

Precaution: $NPSHA > NPSHR$

Where $NPSHA$ = Net Positive Suction Head Available

$NPSHR$ = Net Positive Suction Head Required