Bule Hora University

Mechanical Engineering Department

Turbomachinery (MEng 3201)

By. Desta Kalbessa (MSc.)

CHAPTER 1

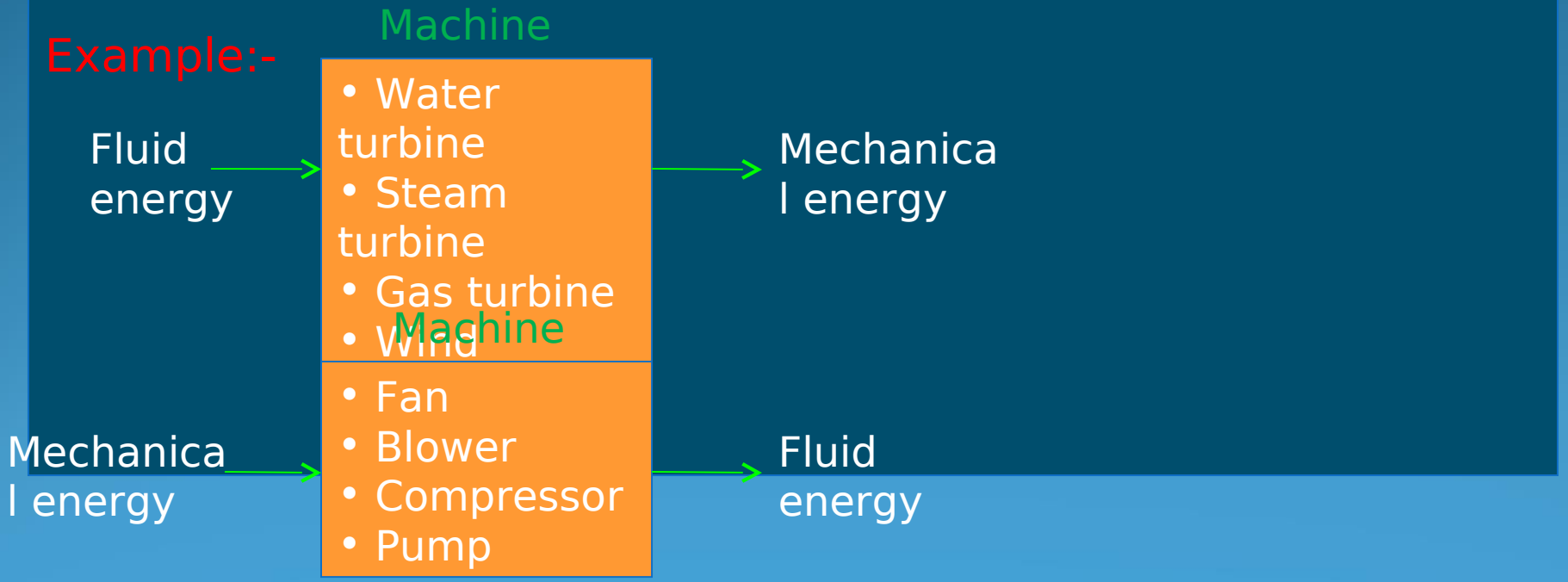
Introduction

What is a Turbomachine ?

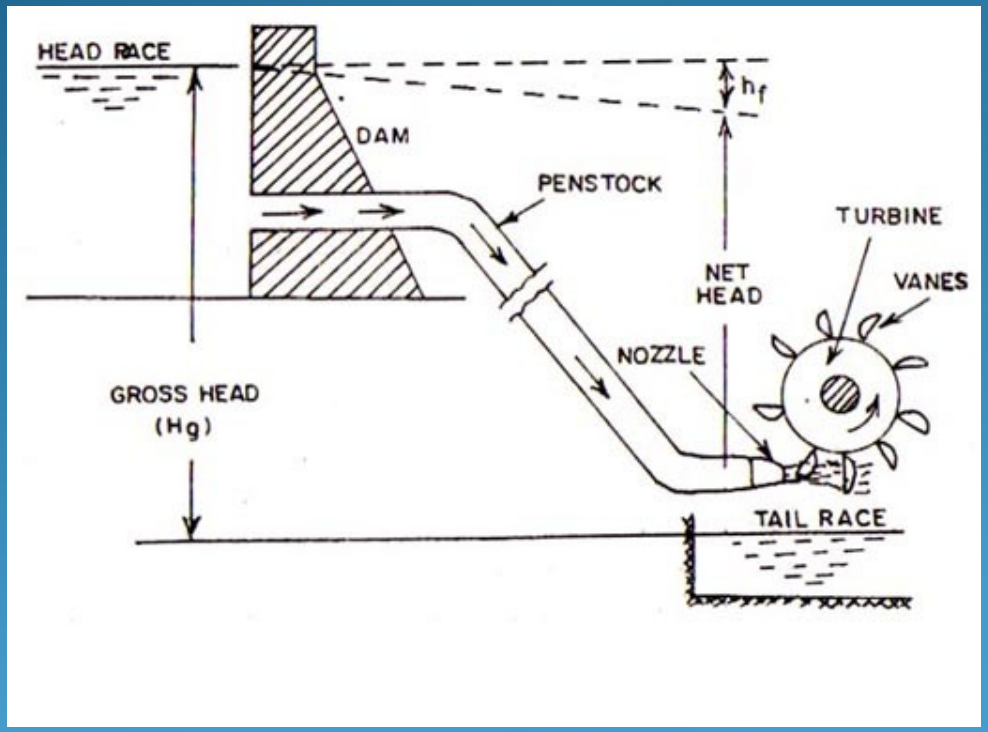
The term Turbomachine consists of two words, namely Turbo and Machine.

- Turbo is a latin word meaning ‘spin’ or ‘swirl’.
- Machine in this context may be defined as an energy converter which converts one form of energy into another.

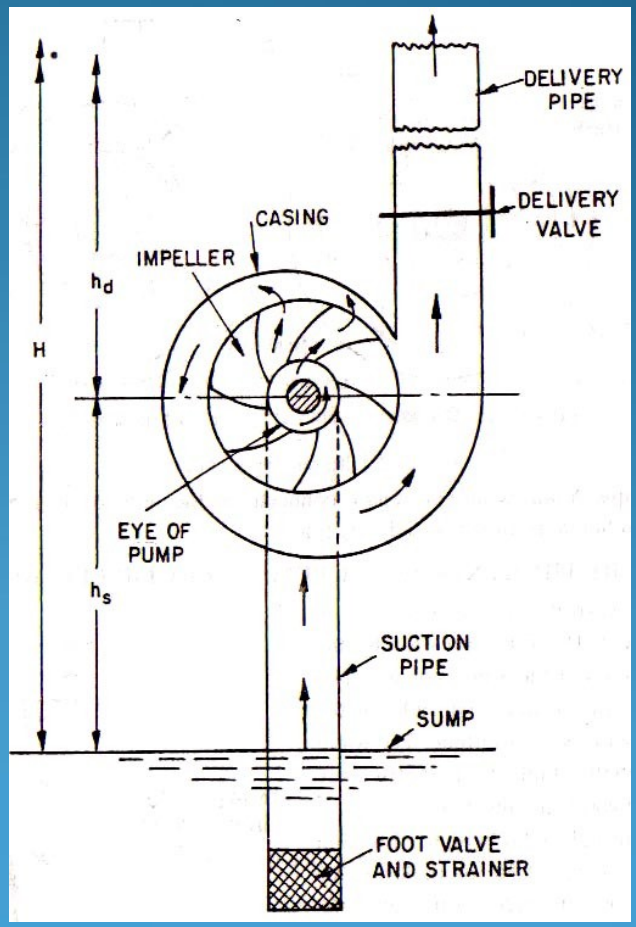
Example:-



•The term Turbomachinery, therefore, defined as a device that extracts energy from a fluid (eg:- a turbine) or imparts energy to a fluid (eg:- a pump) by a dynamic action of rotating parts (rotors, impellers, vanes,...).



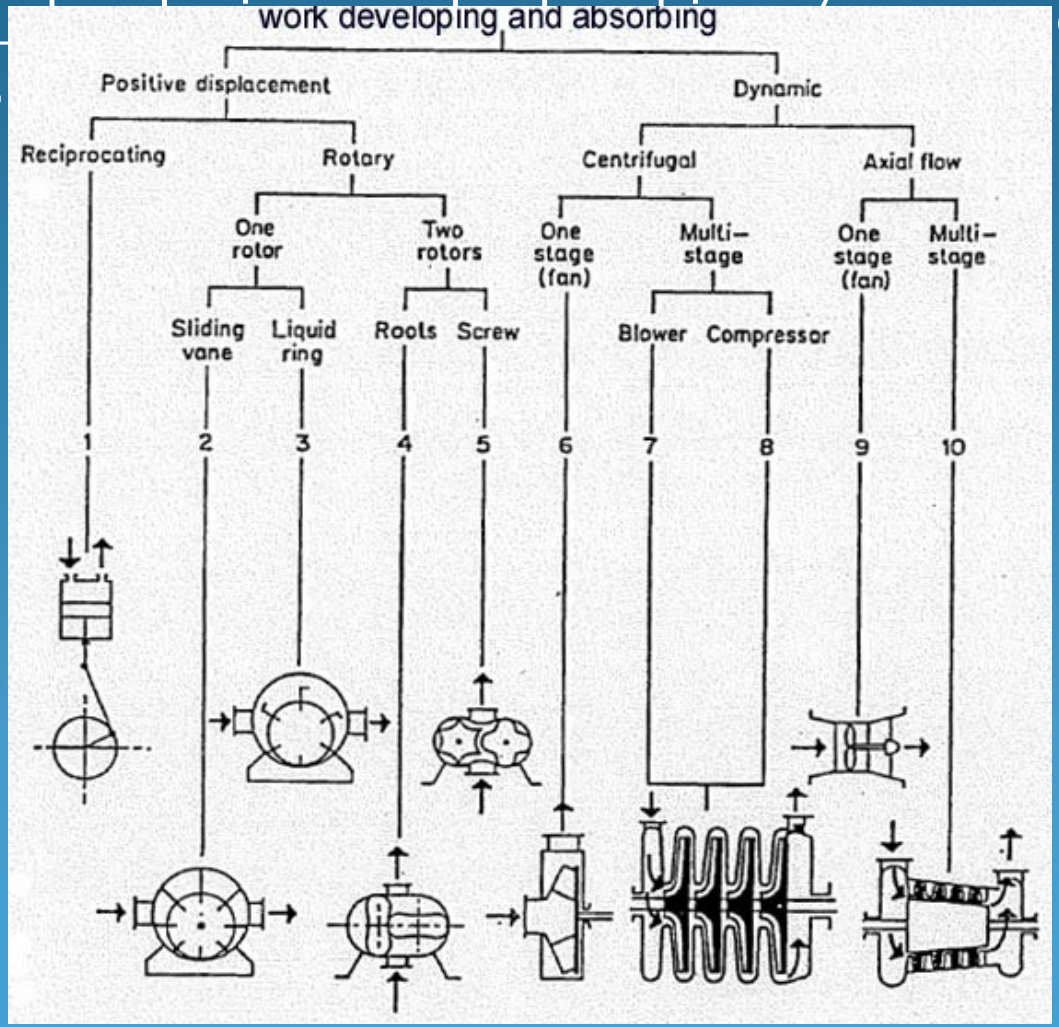
Turbine



Pump

In the discussion of thermodynamics, machines were classified as:

- work developing (eg:- turbines, engines,...),
- work absorbing (eg:- pumps, compressors, blowers, fans,...),
- non-work [illegible] ozzles, heat exchangers,..



Classification of Turbomachines

a) Power classifications (power is added or extracted from the fluid)

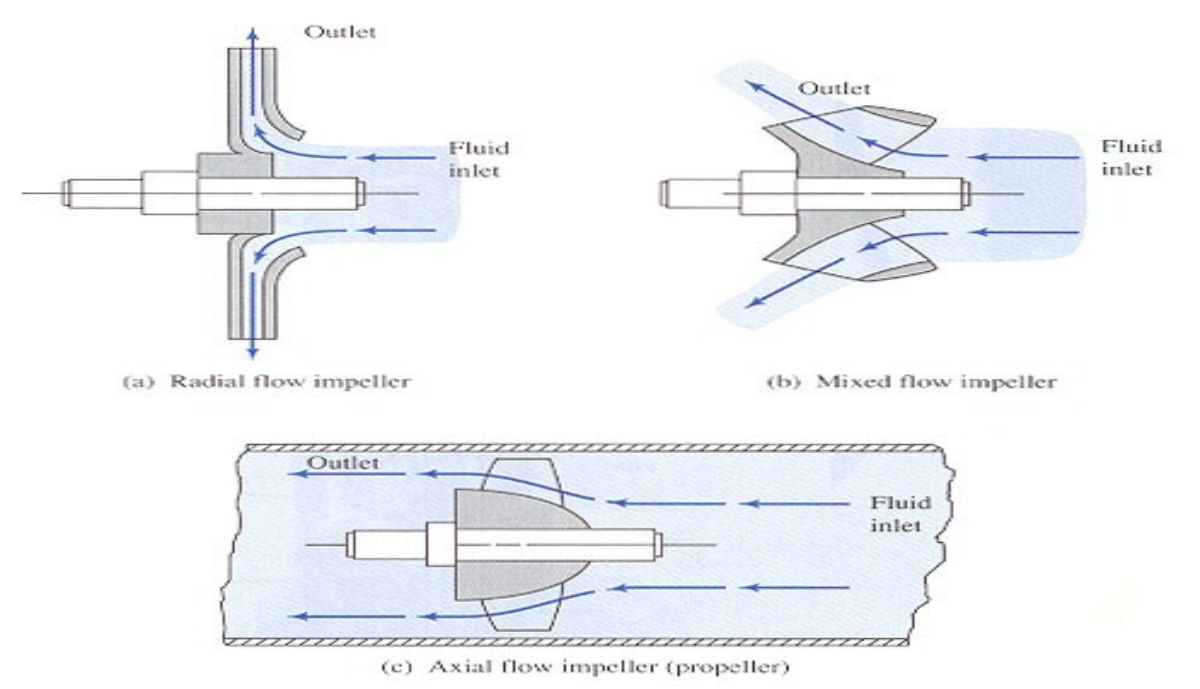
- **Power absorbing machines**:- extracts or absorbs mechanical power and increase the energy of a fluid. These include pumps, fans, blowers and compressors Fluids to be used can be liquids (water), air, steam.
- **Power developing machines**:- extracts or absorbs energy from a fluid and develop or produce mechanical power. These include water (hydraulic) turbines, steam turbines, gas turbines, wind turbines. Fluids to be used can be liquids(water), steam, gas, air.

b) The manner in which the fluid moves through and around a machine

- **Open flow or enshrouded**:- in which there is no casing or enclosure for the rotating member. *E.g* wind turbines, propellers,
- **Enclosed flow or shrouded**:- in which the rotating member is enclosed in a casing so that the working fluid can not be diverted to flow around the edge of

c) Flow path

- Radial flow machines:- in which the fluid moves on streamlines perpendicular to the axis of the shaft.
- Axial flow machines:- in which the fluid moves on streamlines parallel to the axis of the shaft.
- Mixed flow machines:- in which the fluid moves on streamlines partly axial and partly radial.



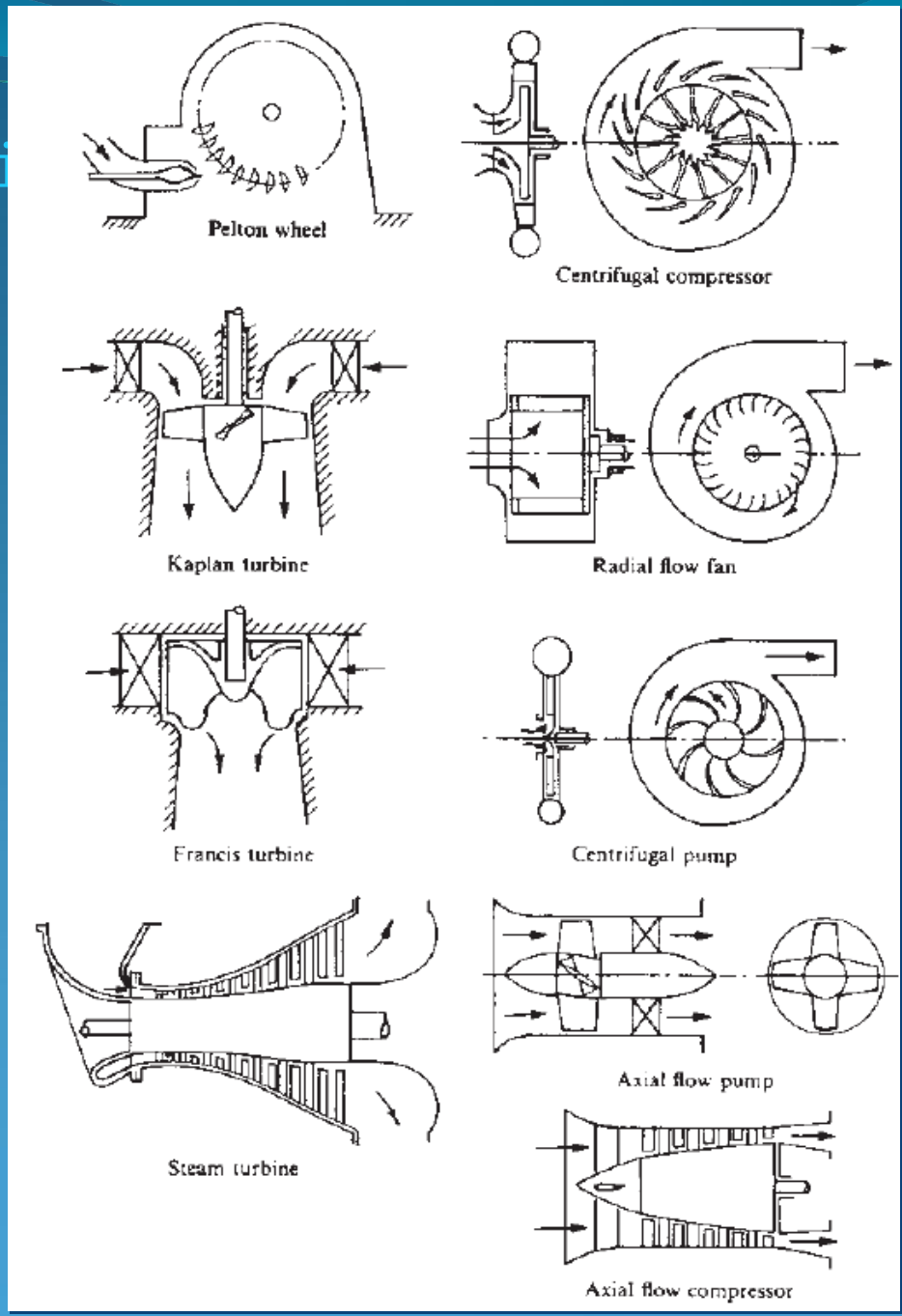
d) Compressibility of the fluid

- Incompressible:- in which the density of a fluid is constant throughout the entire flow process. eg:- water
- Compressible:- in which the density of a fluid is not constant. eg: air

e) Impulse or reaction machines

- Impulse machines:- in which at the inlet of the turbine the energy available is only kinetic energy. In an impulse machine, all the pressure change take place in nozzles. eg:- Pelton turbine
- Reaction machines:- in which at the inlet of the turbine the energy available is both kinetic and pressure energy. eg:- Francis turbines

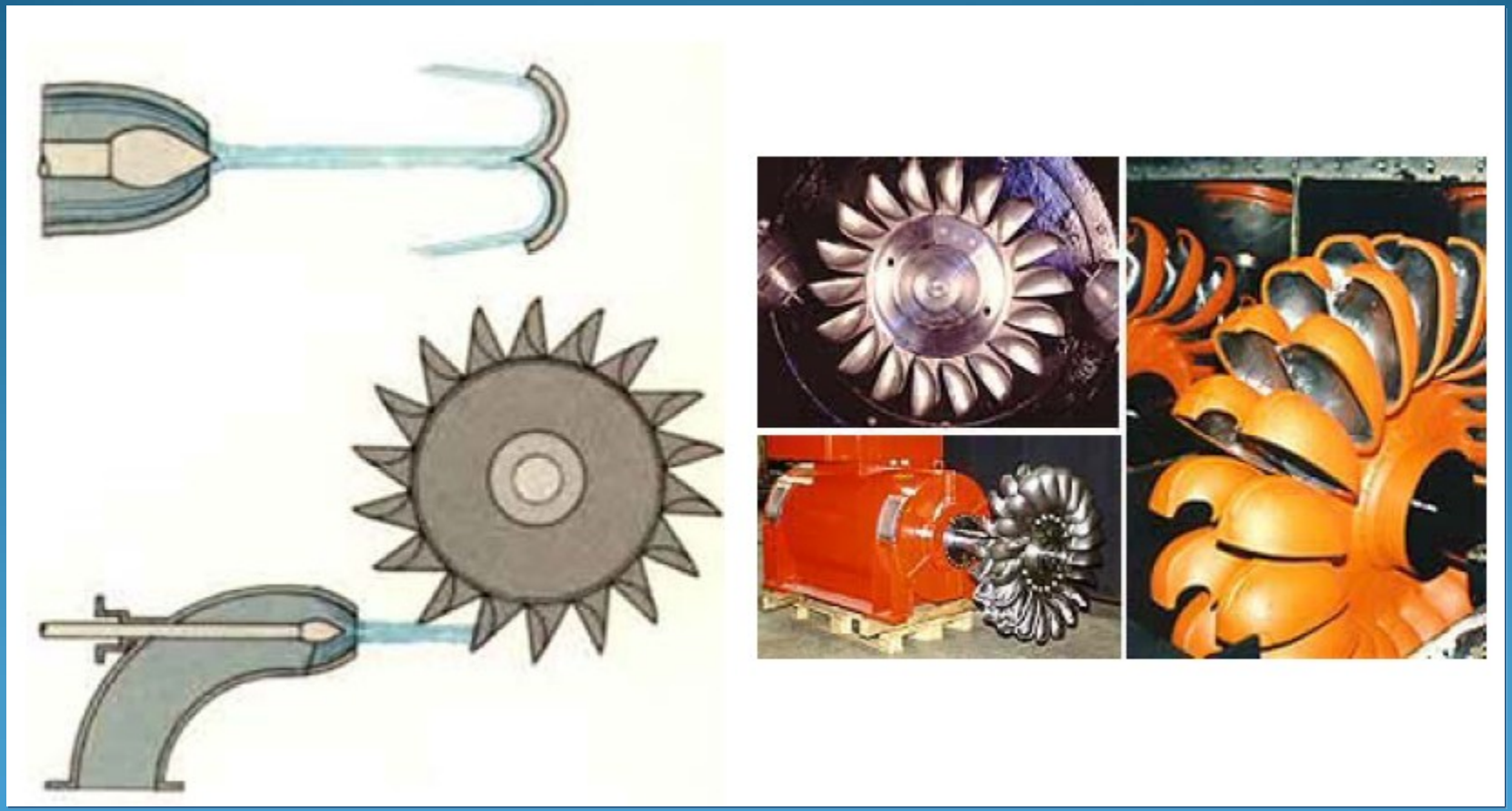
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1. Introduction…

Types and shapes of Turbomachines…

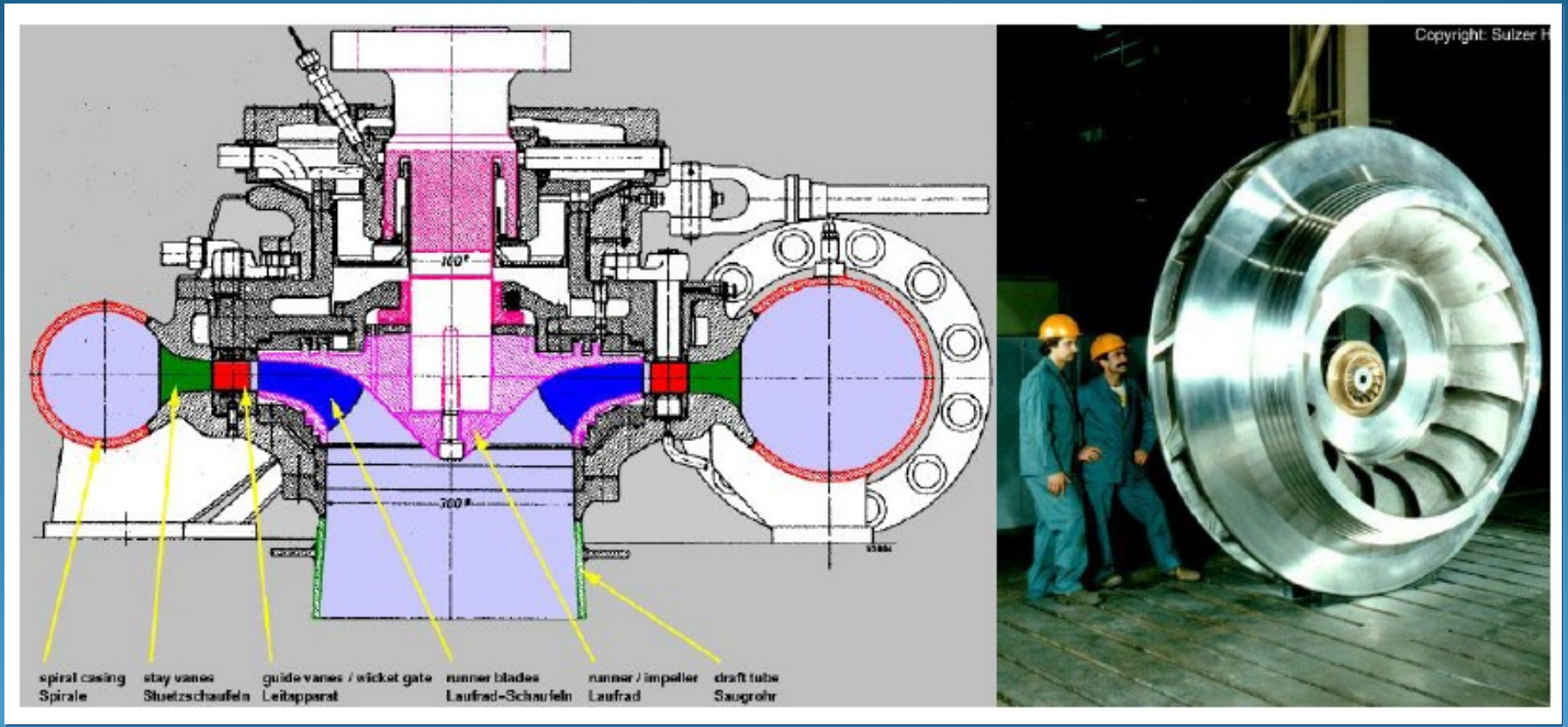
Pelton water turbine



1. Introduction…

Types and shapes of Turbomachines…

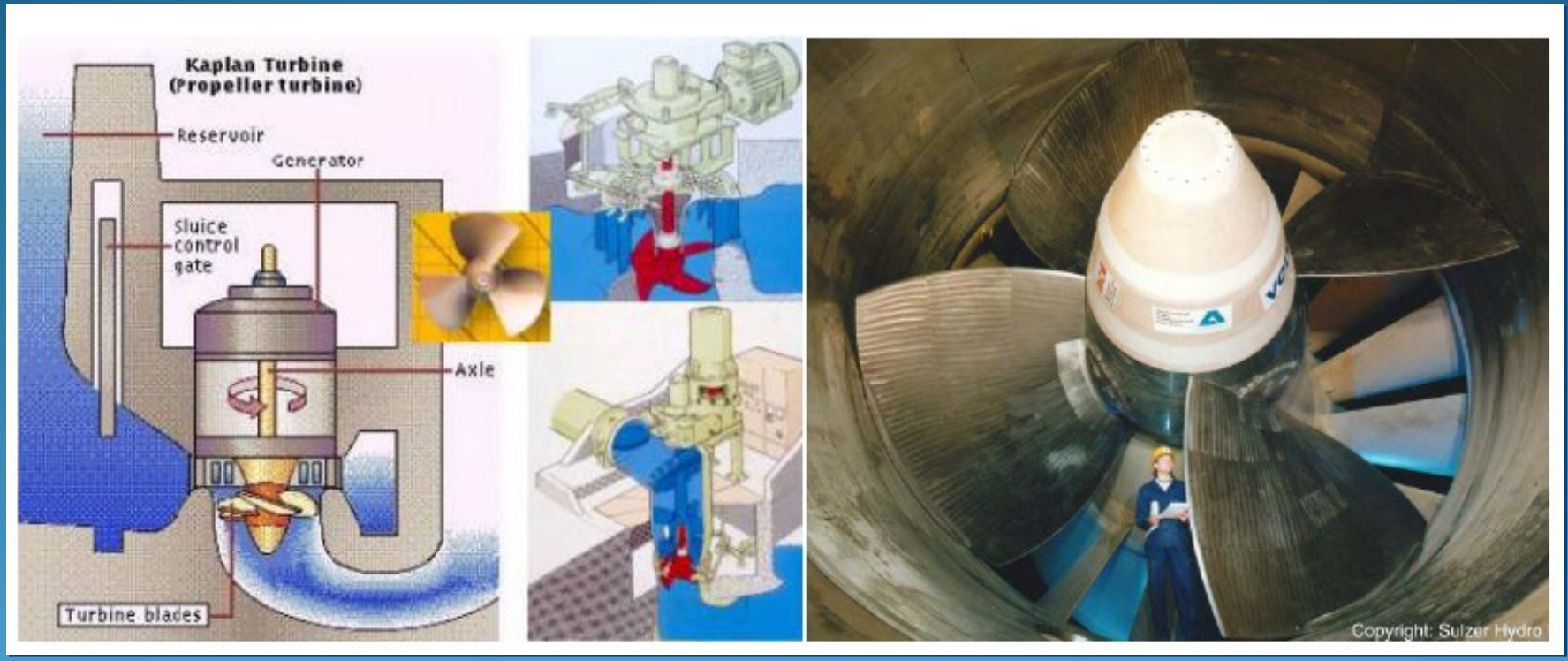
Francis water turbine



1. Introduction…

Types and shapes of Turbomachines…

Kaplan water turbine



1. Introduction…

Types and shapes of Turbomachines…

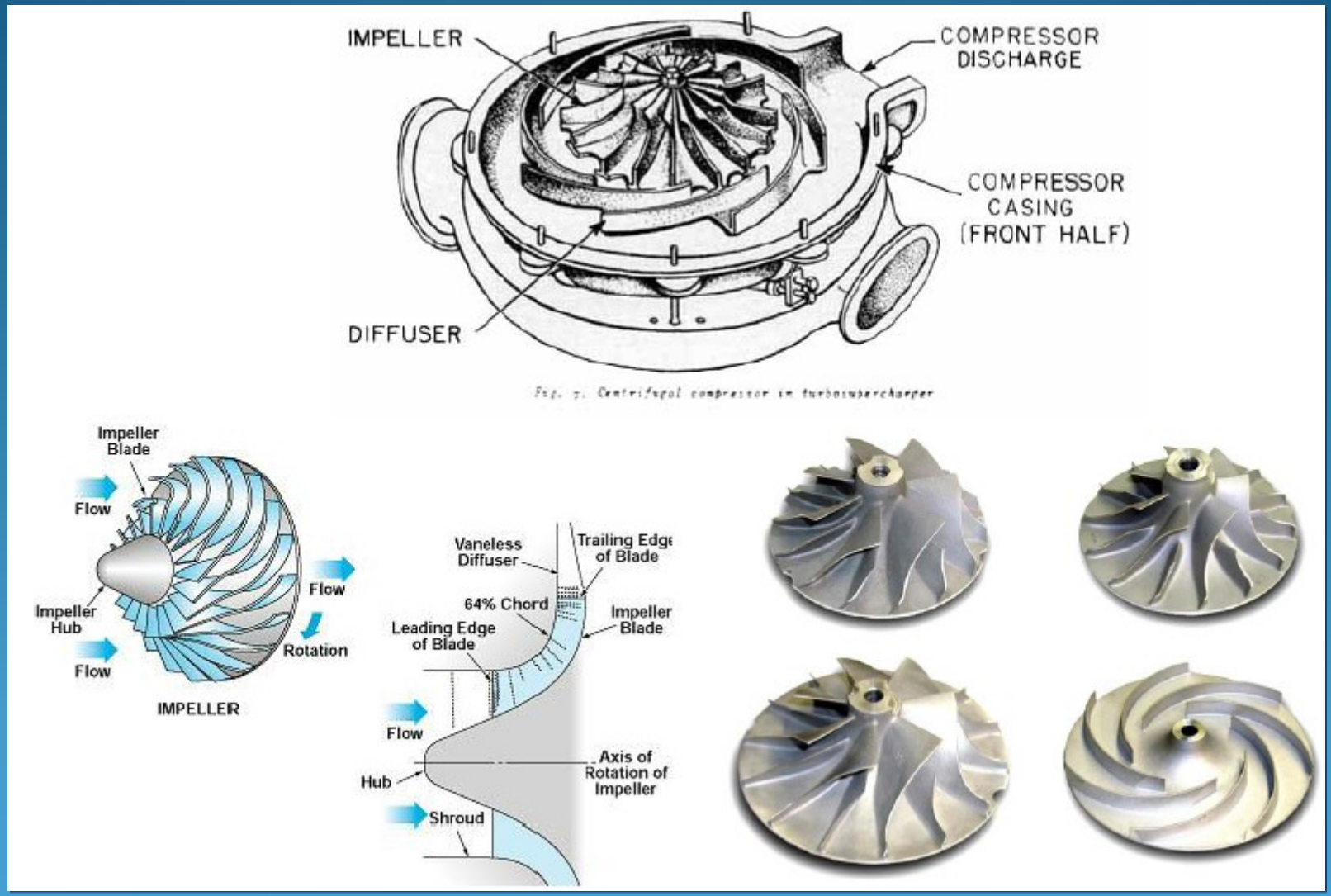
Wind turbine



1. Introduction…

Types and shapes of Turbomachines…

Centrifugal compressors



1. Introduction…

Types and shapes of Turbomachines…

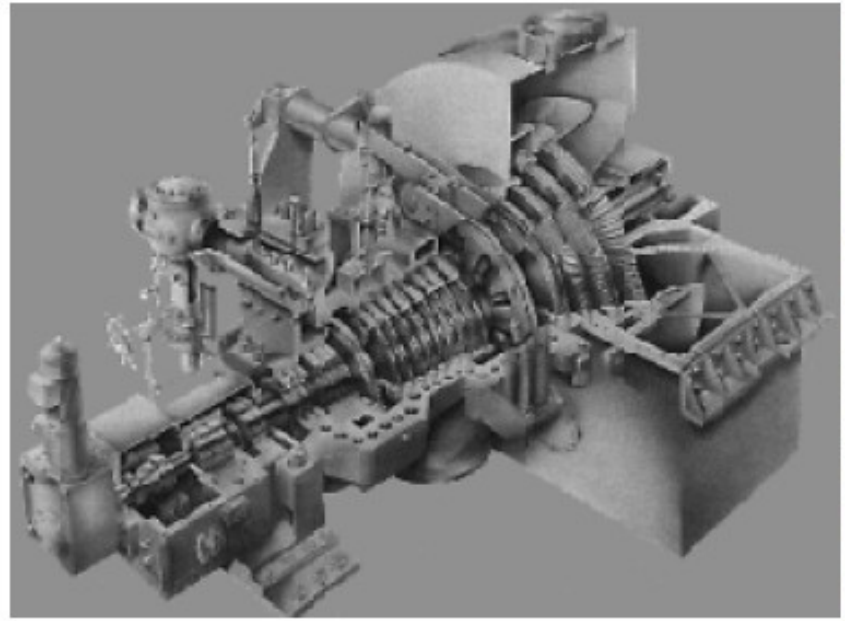
Turbocharger



1. Introduction…

Types and shapes of Turbomachines…

Steam turbine

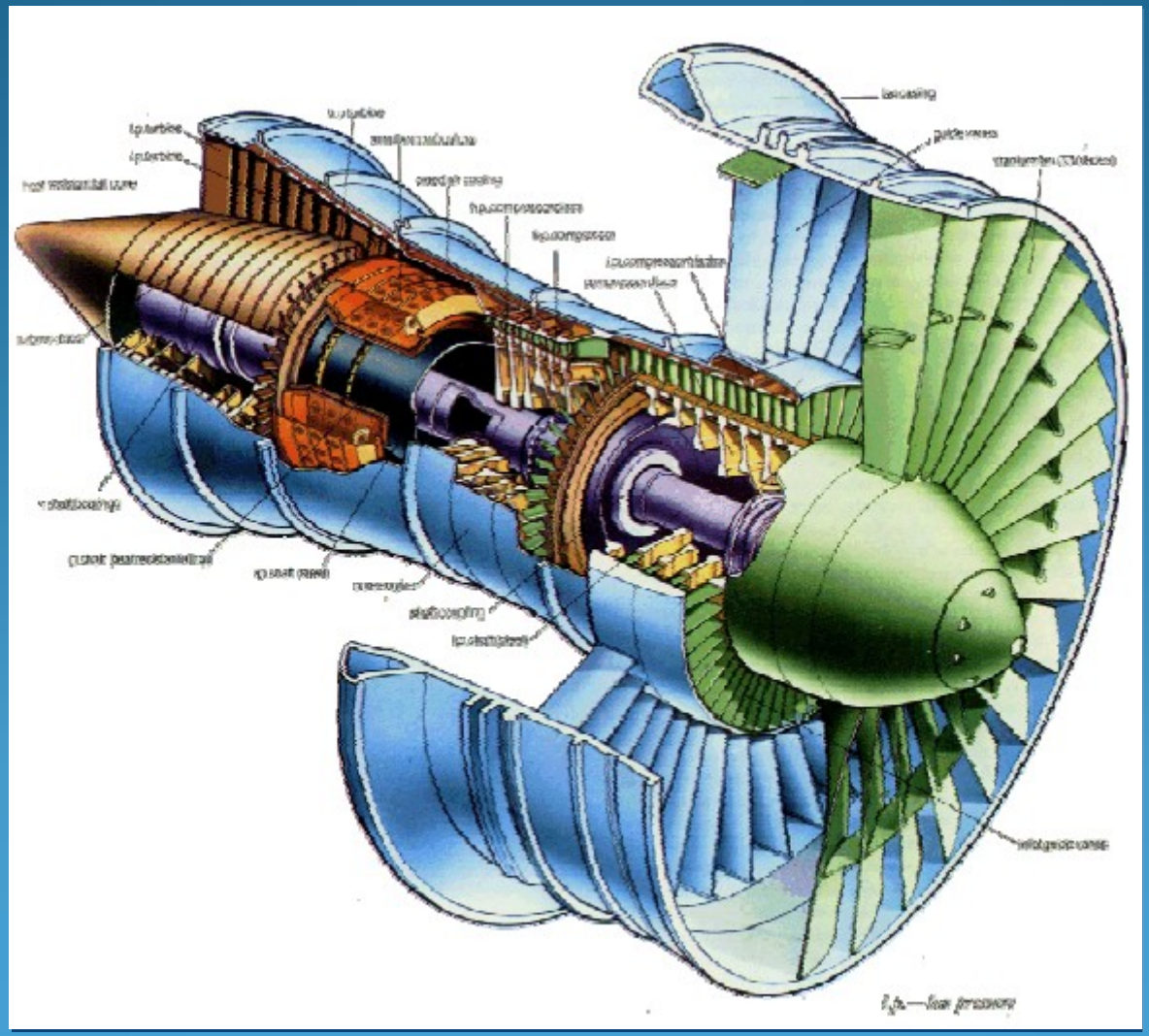




1. Introduction…

Types and shapes of Turbomachines…

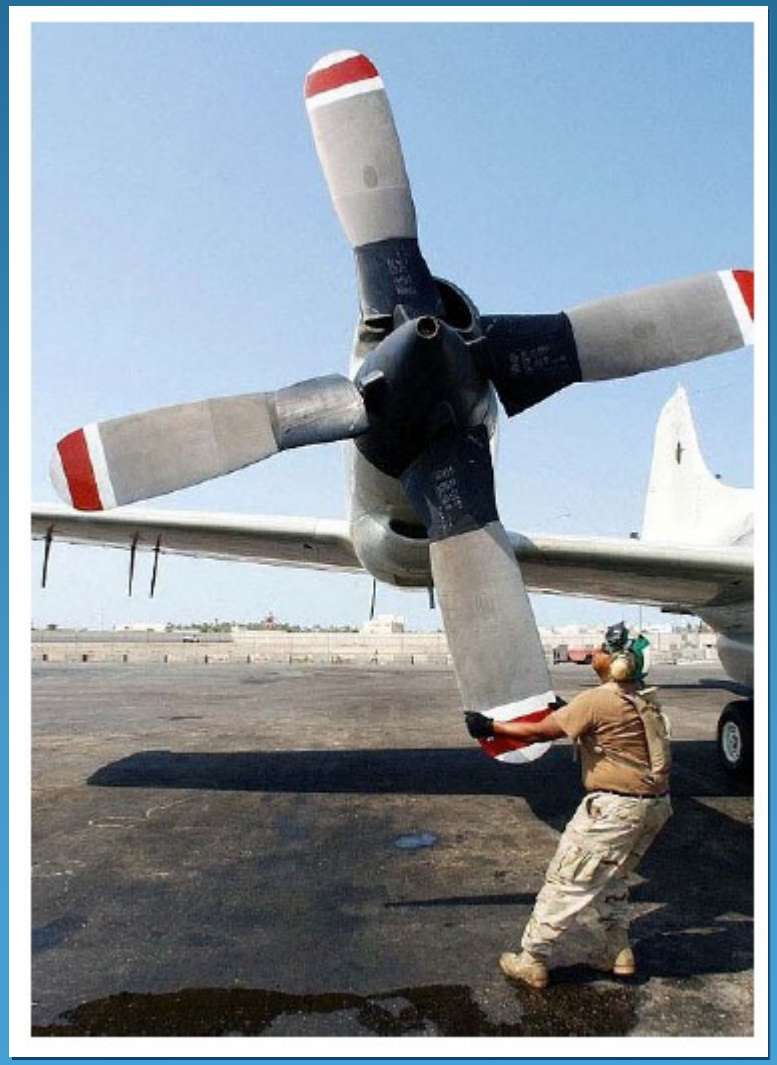
Aircraft jet-engine



1. Introduction…

Types and shapes of Turbomachines…

Aircraft propeller-engines



Applications of Turbomachinery:

- The area of application of turbomachinery ranges from small sized computer fans to gigantic steam turbines providing more than one million shaft horsepower used for power production.
- Turbomachinery is essential to the operation of the world.
- Turbines are used in all significant electricity production throughout the world in *steam power plants*, *gas turbine power plants*, *hydro-electricity power plants* and *wind farms*.
- More than 90% of the world electricity is produced by turbomachinery.
- Pumps are used to transport water around municipal water systems, in industry and in homes.
- Pumps and turbines are also essential in the transportation of fuel-oil and gas around pipe networks.
- Gas turbines are also used to power all large passenger aircraft either in the form of turboprop or turbofan engines and also through a gearbox to power helicopter engines

- Air compressors and Fans are another very popular turbomachine.
- Turbochargers and Superchargers are also a turbomachines which are used for engine power enhancement.

Concepts and definitions

The basic concept in turbomachinery is that, there should be energy transfer between one or more rotating blade rows (rotor) and a continuously flowing fluid

Some definitions/terminologies:

- **Blade*:*** The name given to the part of the turbine, compressor or fan that guides the flow. It can be stationary or rotating.
- **Blade passage*:*** The space between two adjust rotor or stator blades. Usually, this is the empty space that the fluid passes through.
- **Blade span*:*** The length of the blade in radial direction.
- **Bucket*:*** Another name for blade.
- **Runner*:*** Name of the rotating element of a turbmachine, often used in hydraulic turbines.

- **Guide vane:** Another name for stator blades, often used with hydraulic turbines.
- **Hub:** The lower radius at which the blades are attached.
- **Impeller:** Rotating element of a pump.
- **Rotor:** Rotating row of blades found after stator in a turbine, and before a stator for a compressor.
- **Stator:** Stationary row of blades found before rotor in a turbine, and after rotor for a compressor.
- **Stage:** A stator and a rotor combined. It can be found either in a compressor or in a turbine.
- **Scroll Casing:** A casing that resembles a sea shell for radial turbomachinery which aims to ensure an equal distribution of flow around the periphery by reducing the area of the device.
- **Volute:** Another name for scroll casing.

Continuity Equation

States that for a steady flow through a turbomachine, mass *m* remains constant. If A_i and A_e are the flow areas at inlet and exit along the passage respectively, then

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

For a steady flow,

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e$$

$$\rho_i A_i V_i = \rho_e A_e V_e = \text{constant}$$

where, ρ_i *is the density at inlet,*
ρ_e *is the density at exit,*
V_i *is the velocity at inlet,*
V_e *is the velocity at exit.*

First Law of Thermodynamics

According to the First Law of Thermodynamics, if a system completes a cycle and during it heat is supplied and work is done, then

$$\oint (\delta Q - \delta W) = 0$$

If a system undergoes a change of state or a process, then the general first law equation is given by,

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

For a steady-state

$$\dot{Q}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) = \dot{W}_{cv} + \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

(energy rate in) (energy rate out)

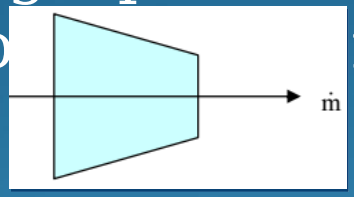
Newton's Second Law of Motion

States that the sum of all the forces on a control volume in a particular direction is equal to the rate of change of momentum of the fluid across the control volume.

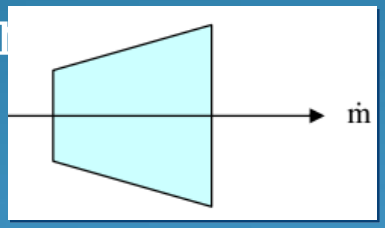
$$\sum F = \dot{m}(V_2 - V_1)$$

Adiabatic Flow in Nozzles and Diffusers

- Nozzle is a device to increase the velocity of a fluid while decreasing pressure at the same time. Examples: fire ho mixing jets



- Diffuser is a device to increase the pressure of a fluid while decreasing velocity at the same time. Example: air i engine



- General 1st LAW expression for both nozzles and diffusers in simple compressible open system:

$$Q - W = h_2 - h_1 + \frac{{V_2}^2 - {V_1}^2}{2}$$

- Nozzles and Diffusers have significant changes in kinetic energy of fluid moving through CV. However, change in potential energy is usually negligible.

- Nozzles and diffusers generally do not have work interactions with surroundings (w = 0).
- Furthermore, often nozzles and diffusers are adiabatic.
- **The most simplified 1st law expression:**
  - **if w = 0 and q = 0** and 1st Law is stated:

$$0 = h_2 - h_1 + \frac{{V_2}^2 - {V_1}^2}{2}$$

Compressible flow turbomachines

- Compressible flow turbomachines are similar to the incompressible flow pumps and turbines.
- The main difference is that the density of the fluid changes significantly from the inlet to the outlet of the compressible flow machines.
- Compressor and pumps that add energy to the fluid, causing a significant pressure rise and a corresponding significant increase in density
- Compressible flow turbomachines remove energy from the fluid, causing a lower pressure and a smaller density at the outlet than at the inlet.
- Compressible flow: If the density of fluid changes during flow (e.g., high-speed gas flow)
- When analyzing rockets, spacecraft, and other systems that involve high-speed gas flows, the flow speed is often expressed by Mach number

$$\text{Ma} = \frac{V}{c} = \frac{\text{Speed of flow}}{\text{Speed of sound}}$$

Ma = 1 Sonic flow
Ma < 1 Subsonic flow
Ma > 1 Supersonic flow
Ma >> 1
Hypersonic flow

Dimensionless parameters

Considering the power P(W) developed by a hydraulic machine depends on the head H(m), flow rate Q(m^3/s), density ρ(kg/m^3), speed N(rps) for turbines and N(rpm) for pumps, runner diameter D(m), and acceleration due to gravity g(m/s^2), then the dimensionless parameters can be derived using dimensional analysis (Buckingham PI theorem) as,

1. Head coefficient $= \frac{gh}{N^2 D^2}$

2. Flow coefficient $= \frac{Q}{ND^3}$

3. Power coefficient $= \frac{P}{\rho N^3 D^5}$

4. Specific speed based on Q, for pumps, N_{sp} $= \frac{N\sqrt{Q}}{(gh)^{3/4}}$

5. Specific speed based on power, for Turbines $= N_{st} = \frac{N\sqrt{P}}{\rho^{1/2}(gh)^{5/4}}$

These dimensionless parameters are useful in model analysis.

Model analysis is the study of models of actual machines. In order to predict the performance of turbo machines such as turbines, pumps, compressors, model analysis is employed. That means, before manufacturing the real or actual machines, models of machines are made and tests are conducted to get the required information.

The model is, therefore, a small replica of the actual machine or the prototype.
The model analysis is actually an experimental analysis of finding out solutions of complex problems using models of the actual system.

Advantages of model analysis

- the performance of the actual turbo machine can easily be predicted in advance from its model. The reliability depends on the degree of similarity that exists between the model and the prototype.
- a relationship between the variables influencing the problem in terms of the dimensionless parameters can be obtained.
- the most economical, efficient and safe design may be selected.

The similarity between the model and its prototype is called Similitude. There are three types of similarities that must exist between the model and the prototype.

1. Geometric similarity:- a model and a prototype are geometrically similar if and only if all dimensions in all three coordinates have the same linear-scale ratio.

Let, L_m = Length of model and L_p = Length of prototype

B_m = Breadth of model and B_p = Breadth of prototype

D_m = Diameter of model and D_p = Diameter of prototype

V_m = Volume of model and V_p = Volume of prototype

Dimensionless parameters…

For geometric similarity between the model and the prototype, the following relations must exist.

- for length ratio,

$$\frac{L_p}{L_m} = \frac{B_p}{B_m} = \frac{D_p}{D_m} = G_r$$

where, G_r is called the *scale ratio*

- for area ratio,

$$\frac{A_p}{A_m} = \frac{L_p \times B_p}{L_m \times B_m} = G_r \times G_r = G_r^2$$

- for volume ratio,

$$\frac{V_p}{V_m} = \left(\frac{L_p}{L_m}\right)^3 = \left(\frac{B_p}{B_m}\right)^3 = \left(\frac{D_p}{D_m}\right)^3 = G_r^3$$

In addition, i) all angles are preserved in geometric similarity,

ii) all flow directions are preserved,

iii) the orientation of the model and prototype with respect to the surrounding must be identical,

iv) the homologous points (the points which have the same relative location) must be related by the same linear-scale ratio.

Dimensionless parameters…

Fig.1, shows a prototype and a one-tenth model of a blade. The scale ratio is also applicable to the fasteners used. The angle of attack w.r.t the free stream is the same 10^0 not 1^0. All physical details on the model must be scaled. That is, the nose radius, the surface roughness, etc. Any departure will lead to the violation of geometric similarity.

Note:- Models which appear similar in shape but violate geometric similarity should not be compared !

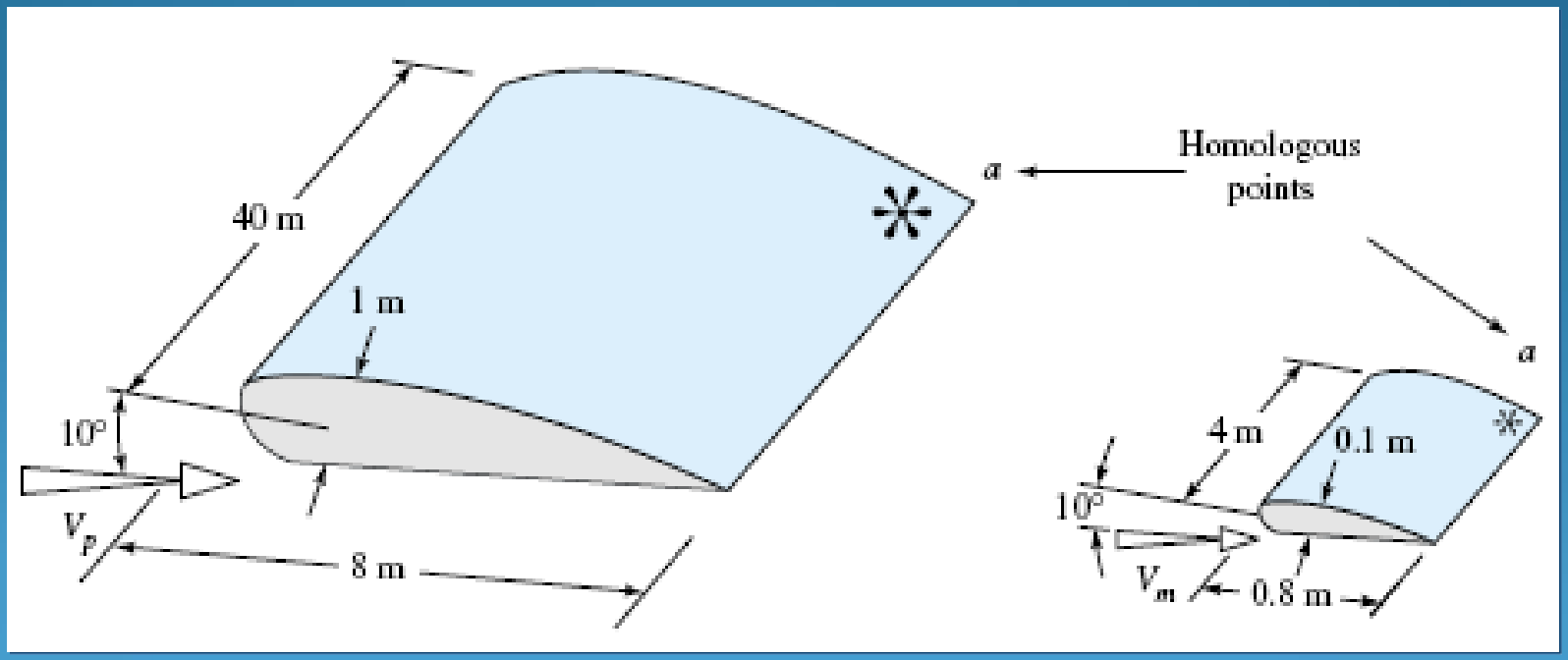


Fig.1 Prototype and model with geometric similarity

Dimensionless parameters…

2. Kinematic similarity:- a model and prototype are kinematically similar if and only if they have the same velocity or acceleration scale ratio. That is, the homologous particles lie at homologous points and homologous time as shown in Fig. 2.

Let, V_{m1} = velocity of fluid at point 1 in the model,

V_{m2} = velocity of fluid at point 2 in the model,

V_{p1} = velocity of fluid at point 1 in the prototype,

V_{p2} = velocity of fluid

- for v $\frac{V_{p1}}{V_{m1}} = \frac{V_{p2}}{V_{m2}} = V_r$

- for $\frac{a_{p1}}{a_{m1}} = \frac{a_{p2}}{a_{m2}} = a_r$

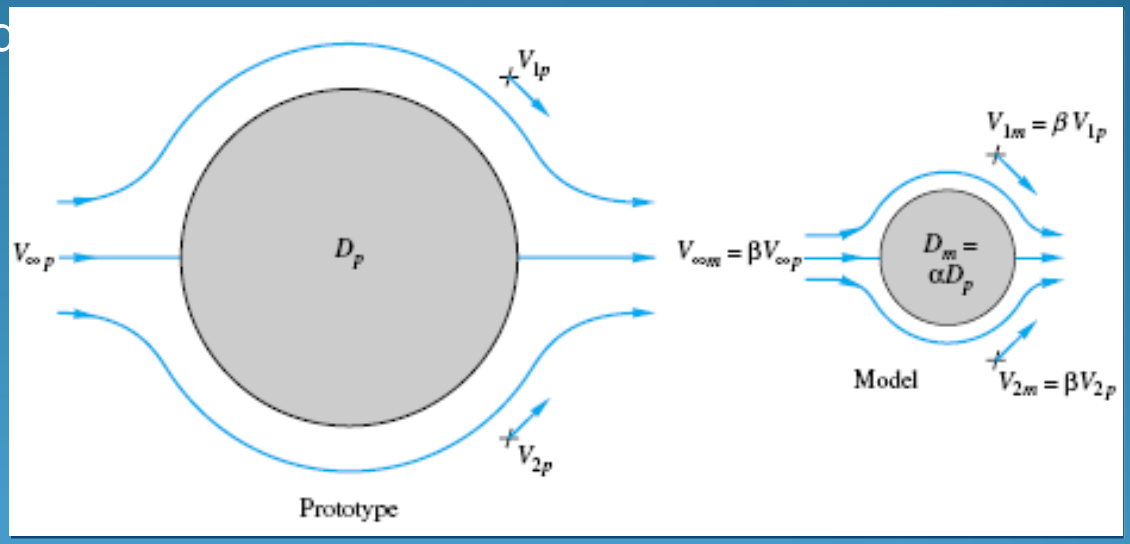


Fig. 2 Prototype and model of a disc

Where, V_r is the velocity ratio,

a_r is the acceleration ratio.

Note:- the directions of the velocity in the model and the prototype should be the same

Dimensionless parameters…

3. Dynamic similarity:- a model and prototype are dynamically similar if and only if they have the same force-scale ratio and the ratios of corresponding forces acting at the corresponding points are equal and also the directions are the same.

Let, F_{im} = inertia force at a point in the model,

F_{gm} = gravity force at a point in the model,

F_{ip} = inertia force at a point in the prototype,

F_{gp} = gravity force at the point in the prototype,

$$\frac{F_{ip}}{F_{im}} = \frac{F_{gp}}{F_{gm}} = F_r$$

and,

$$F_i = F_p + F_g + F_f$$

Where, F_r is the force ratio,

F_p is the pressure force,

F_f is the friction force.

Dimensionless parameters…

From the derived dimensionless parameters, specific speed has a particular importance in turbomachinery as it can be used to indicate the type of machine (axial, mixed, radial etc.). Based on their specific speed value, turbomachines may be classified as,

- low specific speed,
- medium specific speed, and
- high specific speed.

The dimensionless specific speed gives the same numerical value irrespective of the system of units adopted. However, in practice dimensional specific speed is used. The dimensional specific speed is given by,

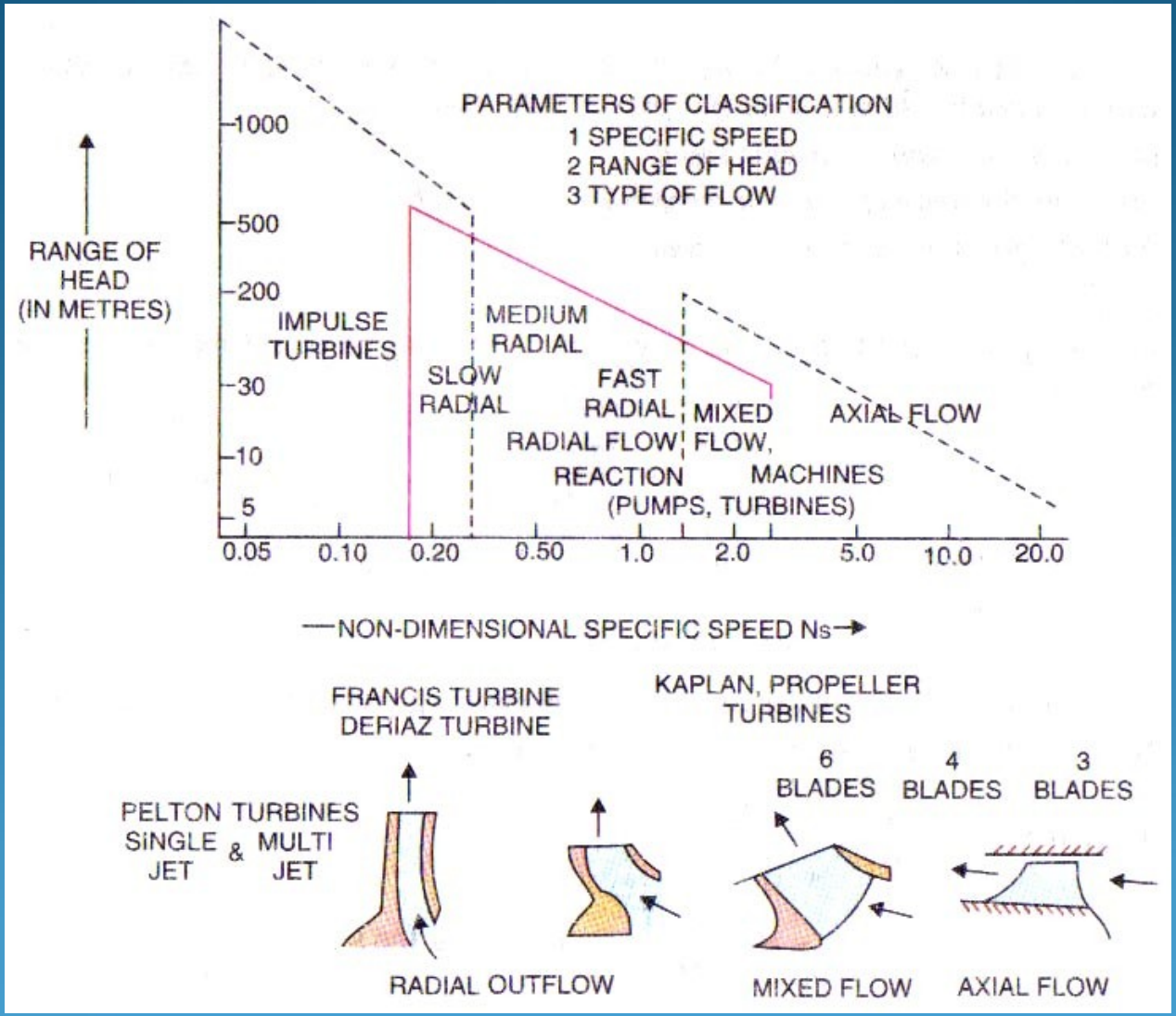
$$N_s = \frac{N\sqrt{Q}}{H^{3/4}}$$ for pumps

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

Where the units to be used in SI are:- Q in m^3/s, N in rps for turbine and in rpm for pumps, H in m, P in W.

Note:- Specific speed ranges for different turbomachines is available in Table 1 and 2.

Dimensionless parameters...



Range of Turbomachines classified on the basis of specific speed(N_s) and head(H).

Dimensionless parameters…

For supplementary notes, refer

- Refernce-1 (Turbomachinery design and theory)
  Page 52 -60 and 81 – 88
- Refernce-2 (Fluid mechanics and machinery)
  Page 285 - 287

Class work

1. One-fifth scale of a pump was tested in a laboratory at 1000 rpm. The head developed and the power input at the best efficiency point were found to be 8 m and 30 kW respectively. If the prototype pump has to work against a head of 25 m, determine its working speed, the power required to drive and the ratio of the flow rates handled by the two pumps.
2. *An axial-flow pump is to be operated at a speed of 2500 rpm against a head of 400 m. What flow rate will be delivered by the most efficient pump ?*