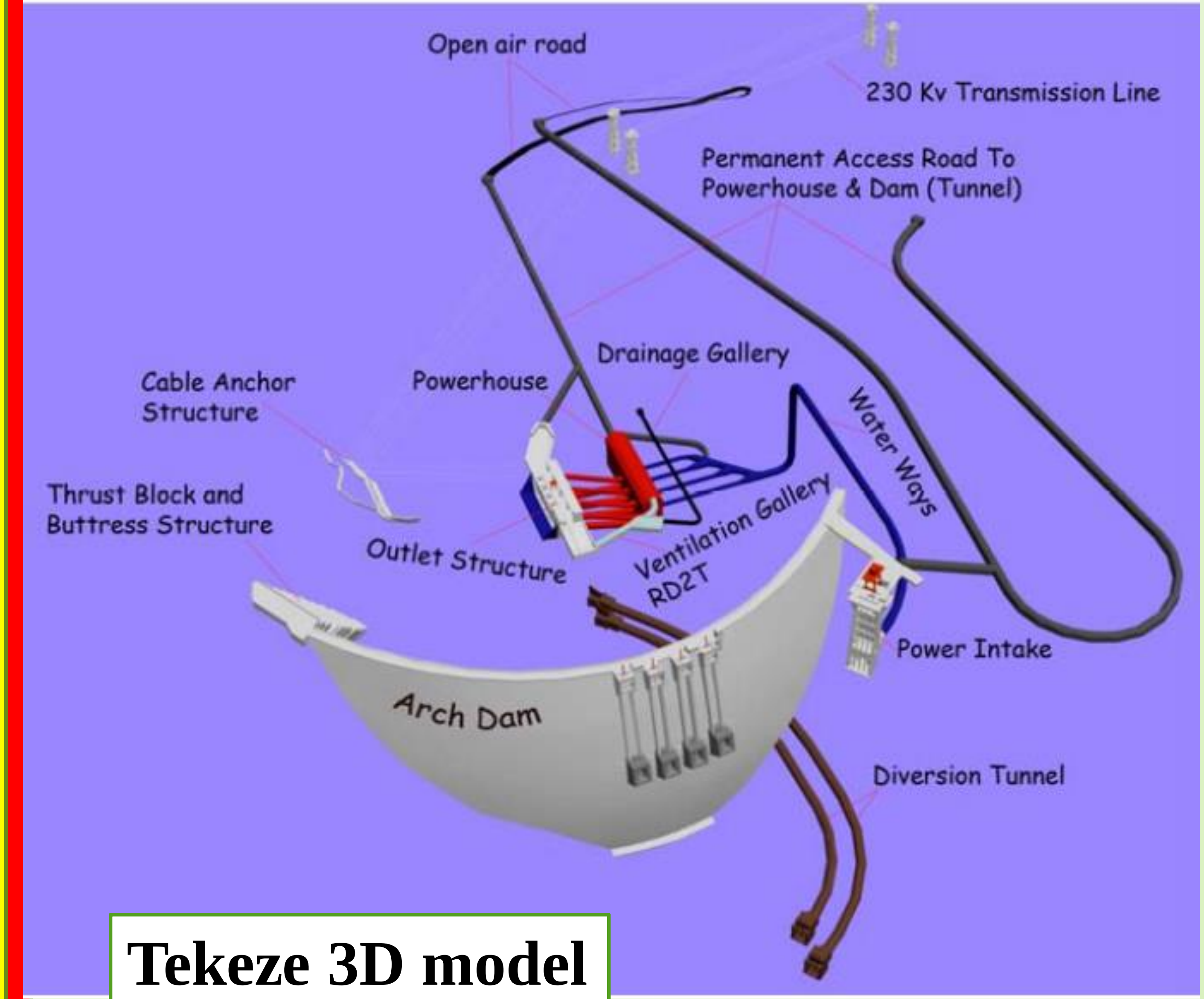
Chapter 7: Hydropower Machines and controls



Tekeze 3D model

Introduction

- The **powerhouse** of a hydroelectric development project is the place where the potential and kinetic energy of the water flowing through the water conducting system is transformed into mechanical energy of rotating turbines and which is then further converted to electrical energy by generators.

In order to achieve these functions, certain important equipment are necessary to:

- control the flow entering the turbines from the penstocks and direct the flow against the turbine blades for maximum efficient utilization of water power.
- couplings to link the turbine rotation to generator and transformers and
- switching equipment to convey the electric power generated to the power distribution system.
- Overhead cranes are required for lifting or lowering of turbines and generator during installation period or later for and maintenance.
- A control room is also essential in a powerhouse from where engineers can regulate the valves controlling water flow into the turbines or monitor the performance of each unit to the main power grid.

Introduction *contd.*

- Hydropower machine is the designation used for a machine that directly convert the hydraulic power in a water fall to mechanical power on the machine shaft.
- This power conversion involves losses that arise partly in the machine itself and partly in the water conduits to and from the machine.
- The hydropower machine may be operated with different flow rates Q from time to time according to a variable grid load, the alternating heads and flow discharges in the plant.
- Thus, the hydropower machines necessarily are equipped with facilities for regulation of the power input and output.
- In practice this is carried out by regulation of the flow discharge.
- Hydraulic turbines are machines which convert hydraulic energy in to mechanical energy .
- Use the potential energy and kinetic energy of water and rotate the **rotor** by dynamic action of water.

Introduction *contd.*

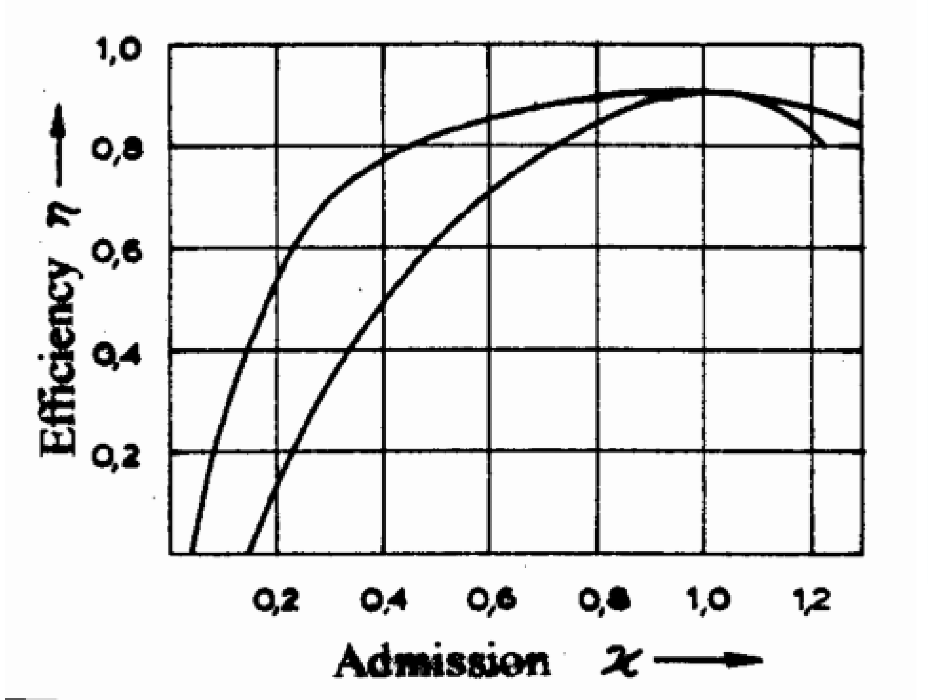
- The input power to the hydropower machine is not efficiently similarly utilized at all operating conditions.
- The machine performs the optimal efficiency for only one single combination of flow discharge, water head and rotational speed.
- The efficiency of the machine is generally expressed by

$$\eta = \frac{Mechanical\ output\ power}{net\ input\ power}$$

- According to the regulation means another quantity is defined as the admission κ and expressed as:

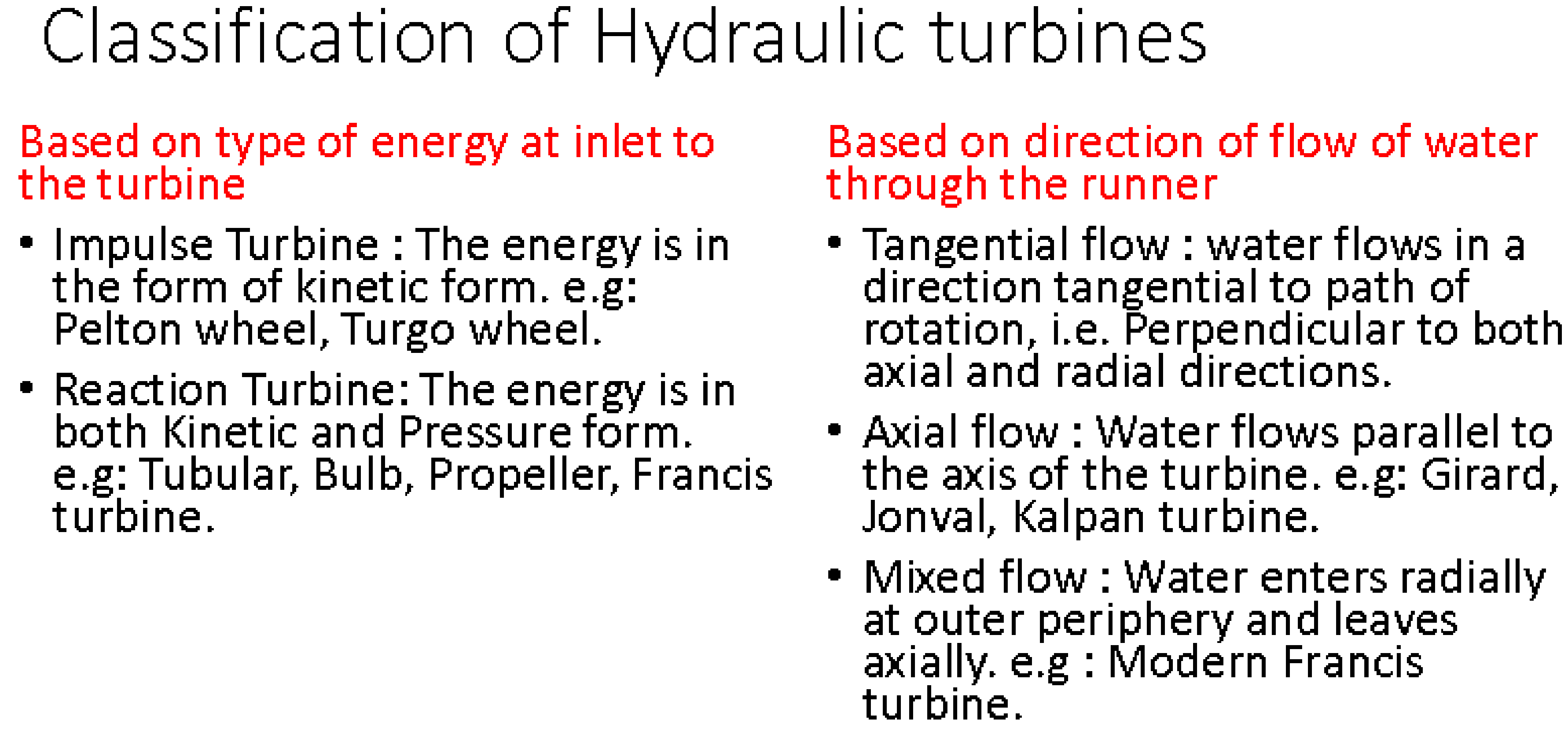
$$k = \frac{operating\ discharge}{discharge\ at\ maximum\ efficiency}$$

- The efficiency characteristics may be rather different from one turbine type to the othe



Hydraulic turbines

- Hydraulic turbines may be defined as prime movers that transform the kinetic energy of the falling water into mechanical energy of rotation and whose primary function is to drive a electric generator.



Classification of Hydraulic turbines

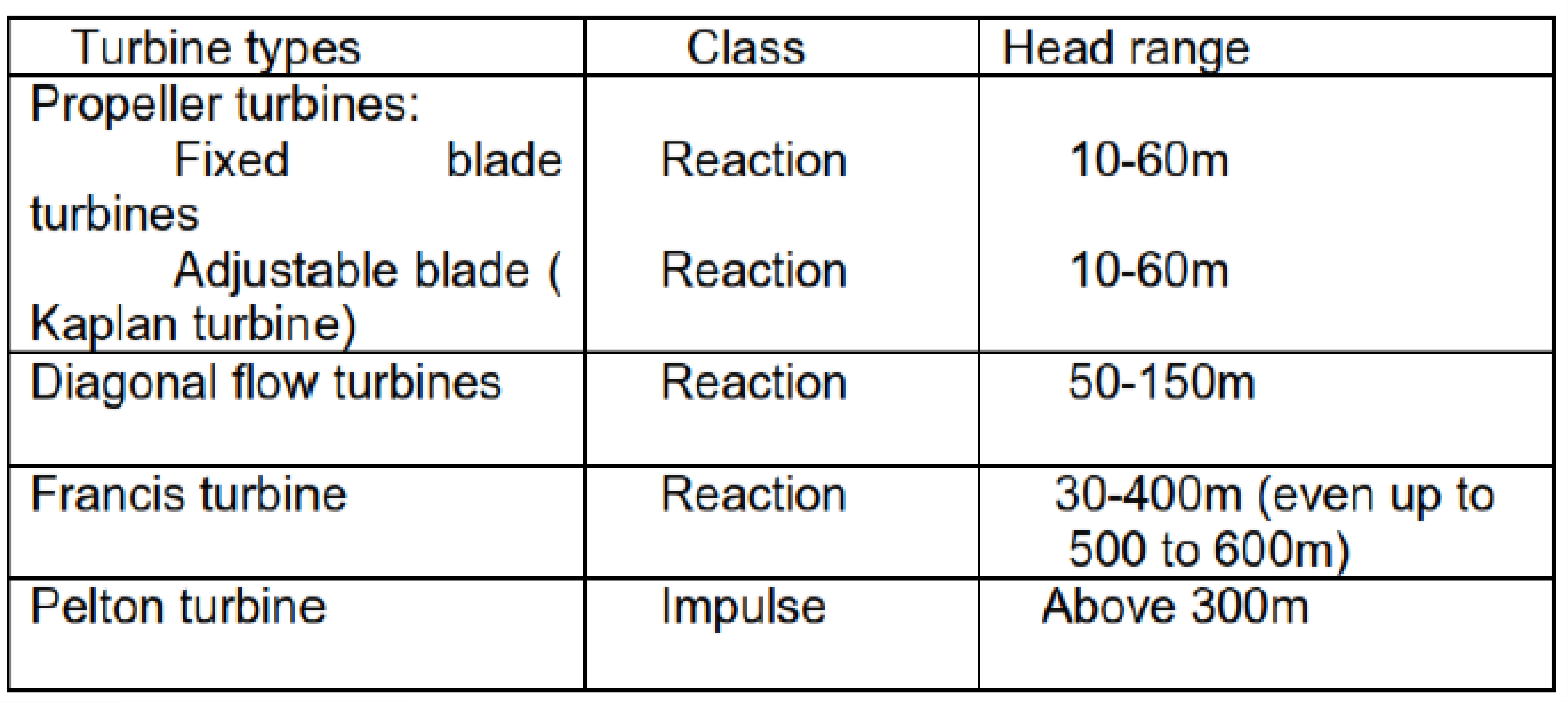
Based on type of energy at inlet to the turbine

- Impulse Turbine : The energy is in the form of kinetic form. e.g: Pelton wheel, Turgo wheel.
- Reaction Turbine: The energy is in both Kinetic and Pressure form. e.g: Tubular, Bulb, Propeller, Francis turbine.

Based on direction of flow of water through the runner

- Tangential flow : water flows in a direction tangential to path of rotation, i.e. Perpendicular to both axial and radial directions.
- Axial flow : Water flows parallel to the axis of the turbine. e.g: Girard, Jonval, Kalpan turbine.
- Mixed flow : Water enters radially at outer periphery and leaves axially. e.g : Modern Francis turbine.

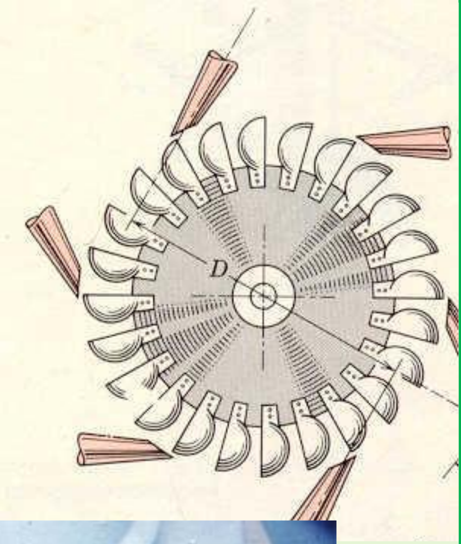
The basic types of impulse and reaction turbines are the following



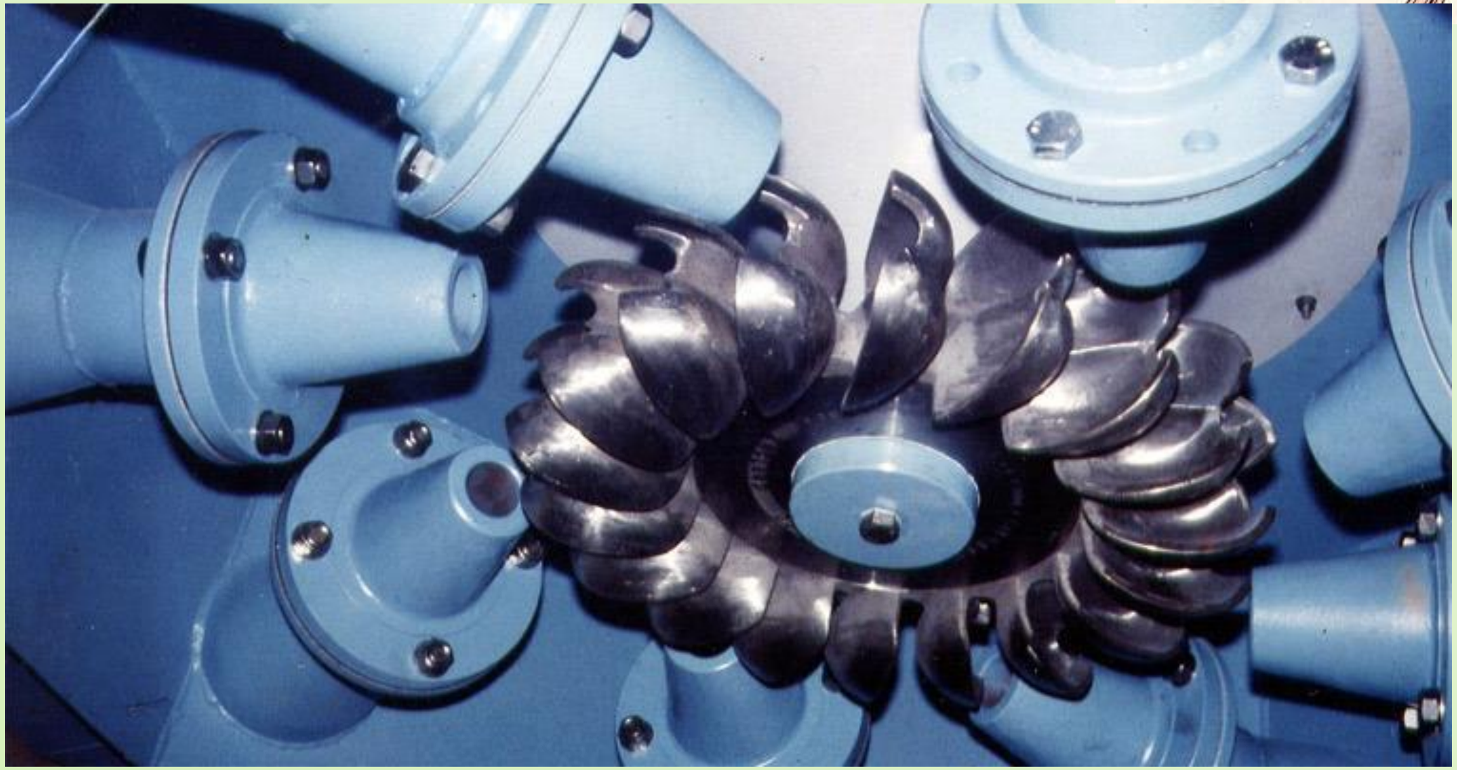
Turbine types	Class	Head range
Propeller turbines:		
Fixed blade turbines	Reaction	10-60m
Adjustable blade (Kaplan turbine)	Reaction	10-60m
Diagonal flow turbines	Reaction	50-150m
Francis turbine	Reaction	30-400m (even up to 500 to 600m)
Pelton turbine	Impulse	Above 300m

Impulse turbines

- the Pelton turbine is an impulse turbine that is used commonly in hydro power projects world wide for very high head installations.
- The runner of a Pelton turbine consists of a disk with buckets attached around its periphery.



- The buckets can be integrally cast with the disk or welded or bolted to the wheel centre.
- The buckets may vary in details of their construction but in general they are bowl-shaped and have a central dividing wall, or splitter, extending radially outward from the shaft.



Impulse turbines *contd.*

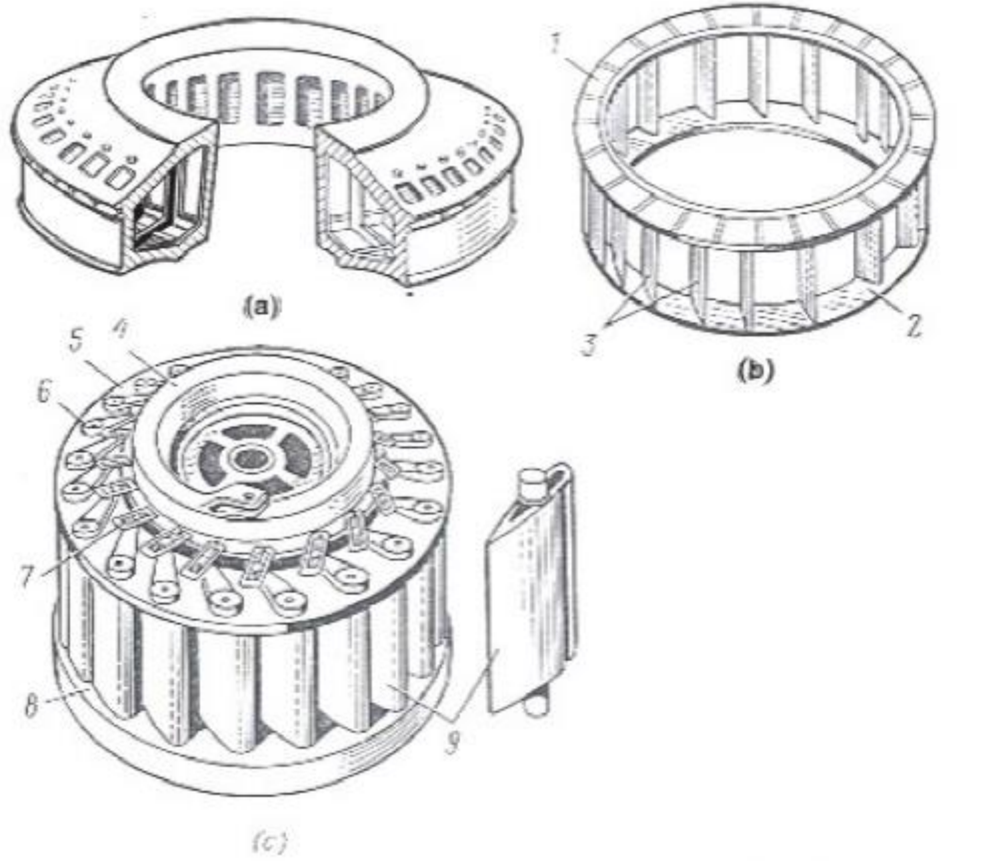
- The water is supplied through penstocks which end with one or several tapering nozzles.
- The water jet escaping from the nozzles hit the dividing wall which splits it into two streams, and the bowl-shaped portions of the buckets turn the water back, imparting the full effect of the jet to the runner.
- The quantity of water through the nozzle is controlled with the help of a spear-valve.

Reaction turbines

- A turbine has stationary as well as rotating members.
- The stationary components of a reactio turbine with vertical axis are shown in Figure

The purpose of each part is as follows:

- Stay ring, which forms the outer suppor of a turbine case. It resists heavy loads imposed by the equipment and the concrete of the power house structure. consists of an upper and lower circular plates joined by 10 to 16 stay vanes of streamline shape.

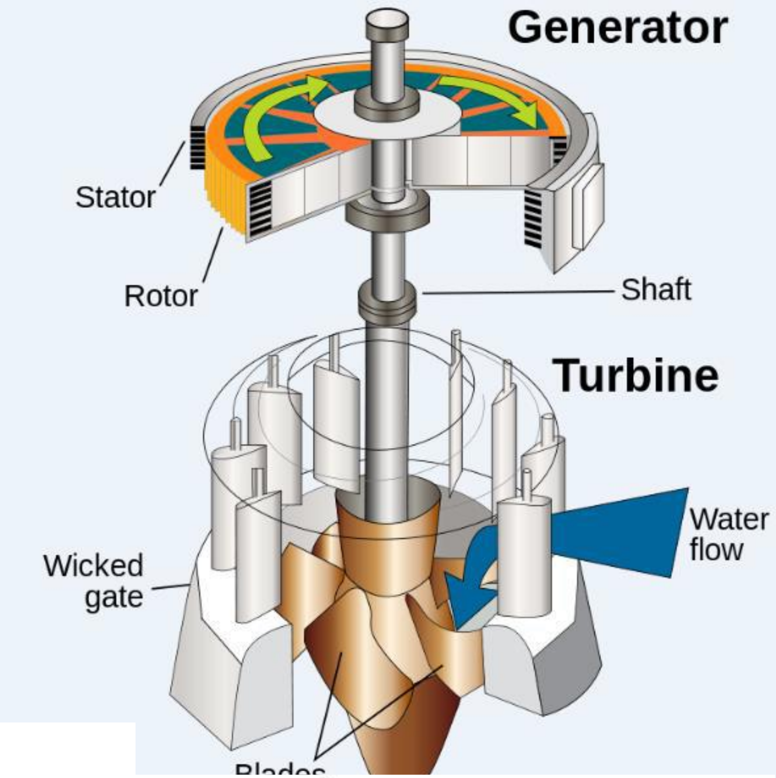


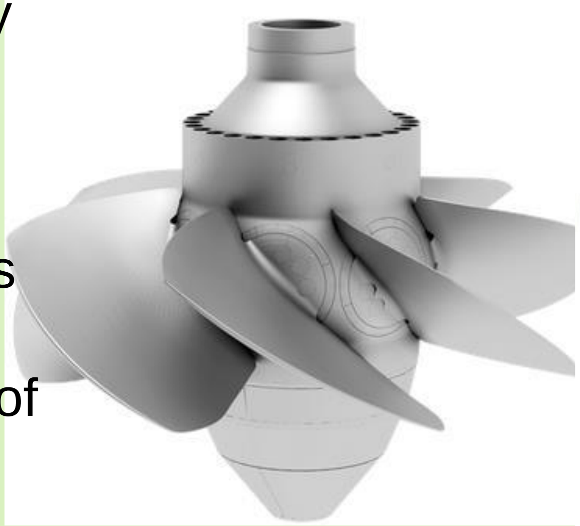
1=Upper circular plate of stay ring ; 2=Lower circular plate of stay ring; 3=Stay vanes; 4=Operating ring
5=Upper ring of wicket gates; 6=Levers; 7=Slotted guides ; 8= Lower ring of wicket gates; 9= Gates

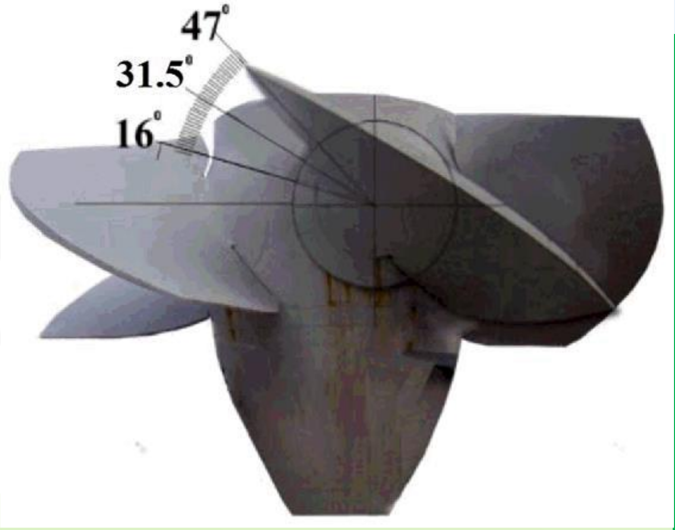
- Wicket gates, which are provided inside the stay rings regulate the discharge and direct the water flow towards the runner by their angle.
- Also, the wicket gates serve to start up and shutdown the turbine and to control its power output and rotational speed.

Axial flow reaction turbines

- The Kaplan type axial flow turbine, where the stream of water flows in the direction of the axis of the turbine.
- The runner of such a turbine has three to eight blades, cantilever mounted on a spherical or cylindrical hub equipped with a cone
- In a fixed blade propeller turbine, the blades are rigidly fastened to the hub at a permanent angle.
- In the adjustable blade propeller (or Kaplan) turbine, the blade angles can be adjusted by an hydraulic operated piston located within the hub.
- The advantage of having an adjustable blade is that the fixed blade wheels show peak efficiency at only a small range of load.
- If load is slightly higher or smaller than this range, its efficiency drastically decreases.
- On the other hand, the blade adjustable turbines can be operated in such a way that their efficiency remains high over a very large range of load.

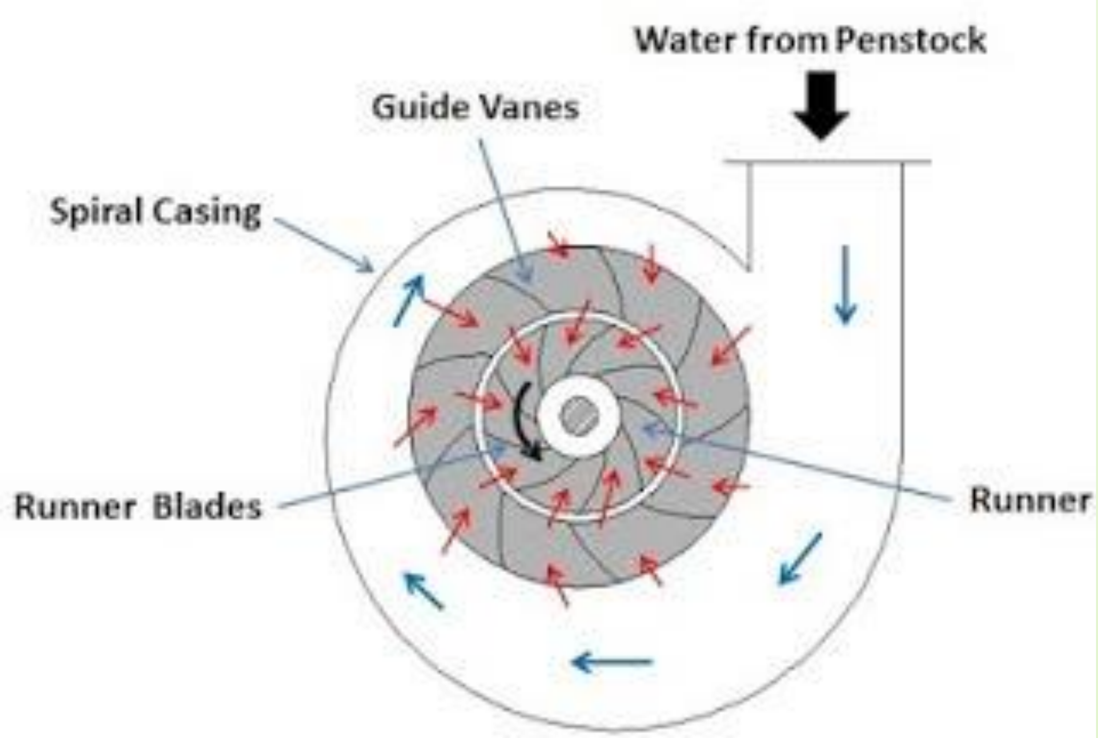






Radial flow reaction turbines

- The flow of water from the stationary part into the turbine runner is in a radial direction.
- Once inside the runners, the flow direction changes and gets directed downward.
- The runners of a Francis turbine are attached at their upper ends to a conical crown and the lower ends to a circular band.
- The shrouded buckets make an angle with the radial planes and bend at the bottom.
- The number of blades usually ranges from 14 to 19.
- As with the propeller turbine, the runner shape depends upon the head.



Turbine selection

After the range of head to be handled by a turbine has been evaluated by stream flow analysis the task of the designer is to choose:

- the total installation at the power station,
- an optimum turbine,
- the number of power generating units,
- the runner diameter,
- rotational speed, and
- runner axis elevation.

Turbine selection criteria

- The usual practice is to base selection on the annual energy output of the plant and the least cost of that energy for the particular scale of hydropower installation.
- In a theoretical sense, the energy output, E, can be expressed mathematically as plant output or annual energy in a functional relation as follows:

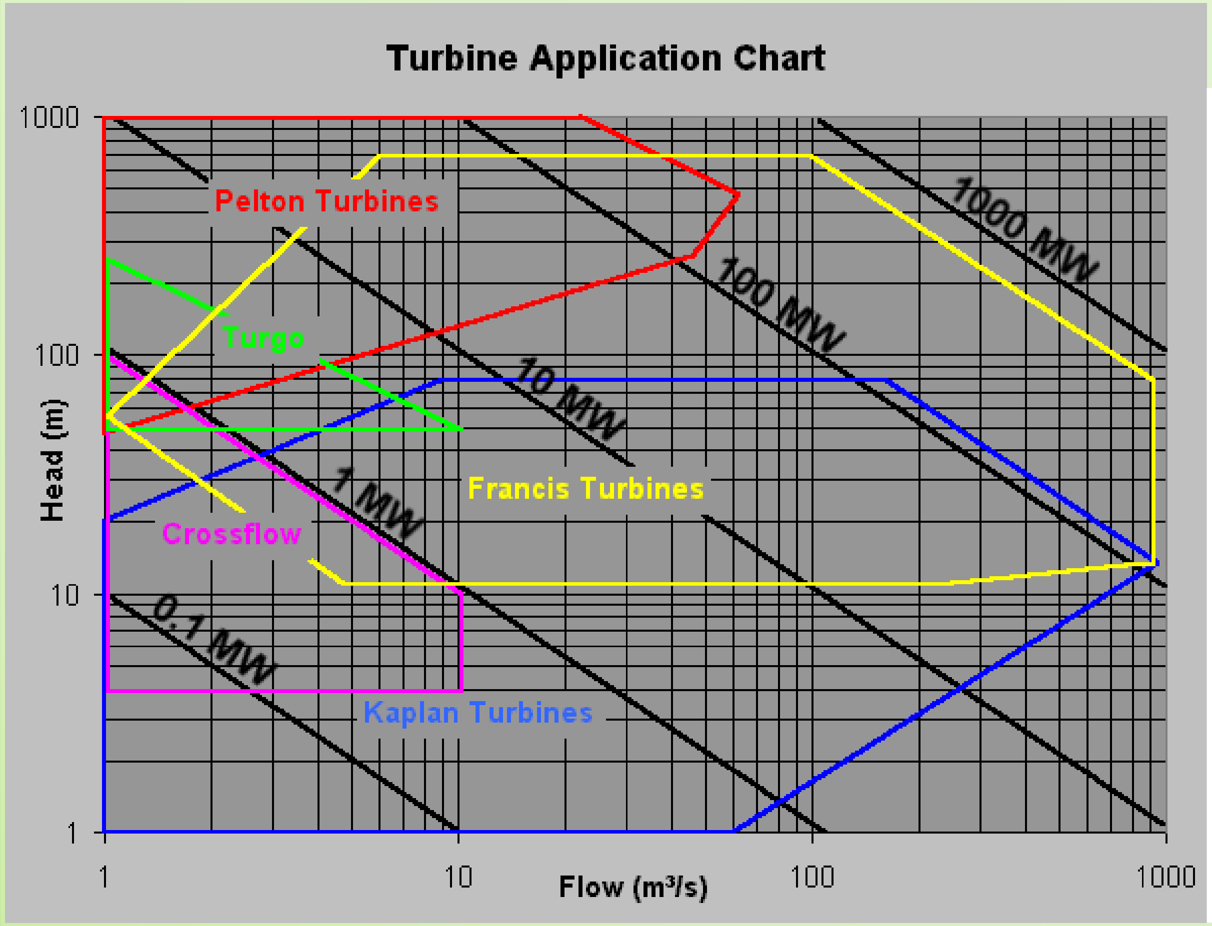
$E=f(h,q,TW,d,n,Hs,Pmax)$

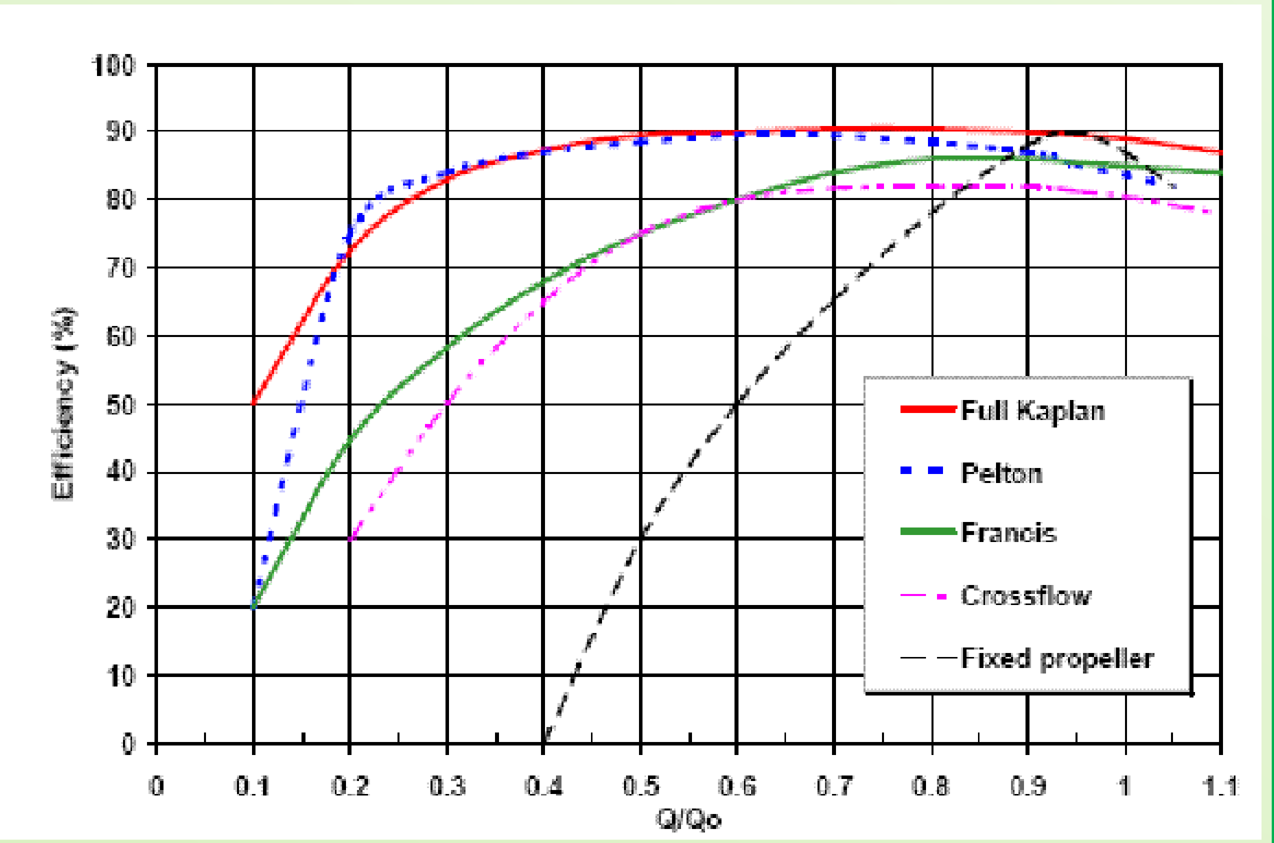
$h=net\ effective\ head$, $q=plant\ discharge\ capacity$,$TW=tail\ water\ elevation$

$d=diameterofrunner$, $n=generator\ speed$, $Hs=turbine\ setting\ elevation\ above\ tailwater$

$Pmax=maximum\ output\ expected\ ordesired\ at\ plant$.

Turbine selection





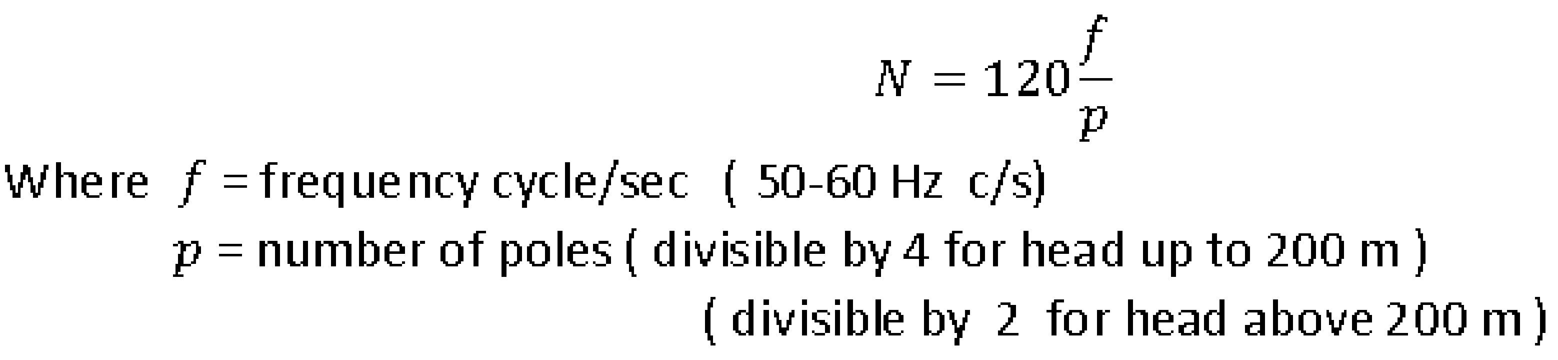
Characteristics of Turbines

The following factors as selection criteria are used:

- Turbine or synchronous speed
- Specific Speed
- Maximum Efficiency

In all modern hydraulic power plants, the turbines are directly coupled to the generator to reduce the transmission losses.

- This arrangement of coupling narrows down the range of the speed to be used for the prime mover.
- The generator generates the power at constant voltage and frequency and, therefore, the generator has to operate at its synchronous speed.
- The synchronous speed of a generator is given by



$$N = 120\frac{f}{p}$$

Where f = frequency cycle/sec (50-60 Hz c/s)

p = number of poles (divisible by 4 for head up to 200 m)

(divisible by 2 for head above 200 m)

Characteristics of Turbines *contd.*

- The speed of a turbine is an important parameter of design. The higher the speed, the smaller the diameter of the turbine runner & the cheaper the generator coupled to the turbine.
- High speed, however, makes a turbine more susceptible to cavitation.
- The ratio of the peripheral speed , v, of the bucket or vanes at the nominal diameter, D, to the theoretical velocity of water under the effective head, H, acting on the turbine is called the speed factor or peripheral coefficient ,ϕ.

$$\phi = \frac{v}{\sqrt{2gH}} = \frac{\omega r}{\sqrt{2gH}} = \frac{\pi DN}{60\sqrt{2gH}} = \frac{DN}{84.6\sqrt{H}}$$

D and H in m; N in rpm

Specific speed

- It is useful parameter for the selection of turbine for a given condition.
- It is defined as the speed at which a geometrically similar runner would rotate if it were so proportioned that it would develop 1 Kw when operating under a head of 1m.
- The turbine specific speed is a quantity derived from dimensional analysis.
- For a specific turbine type (Francis, Kaplan, Pelton), the turbine efficiency will be primarily a function of specific speed.

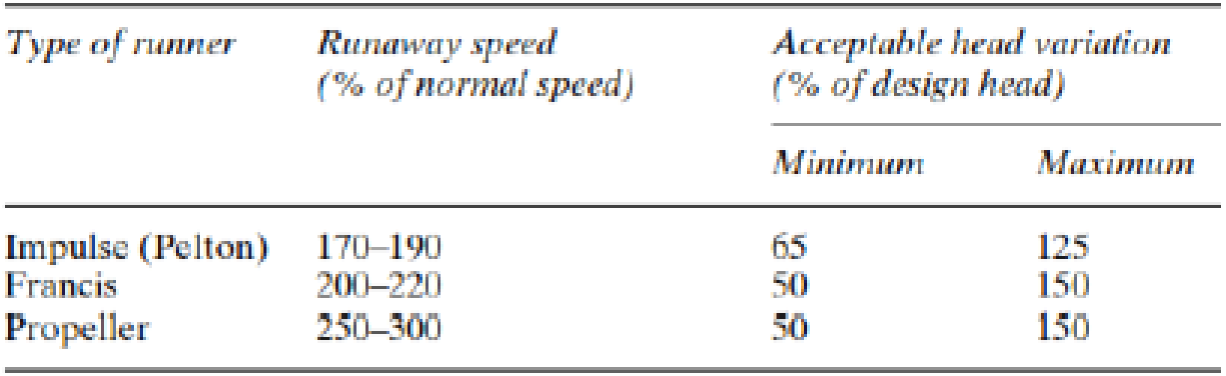
$$N_s = \frac{N\sqrt{P}}{H^{5/4}}$$

where N_s = *Specific speed*
N = *rotational speed. (rpm)*
P = *Power developed (kw)*
H = *effective head (m)*

Characteristics of Turbines *contd.*

Runaway speed

- If the external load on the machine suddenly drops to zero (sudden rejection) and the governing mechanism fails at the same time, the turbine will tend to race up to the maximum possible speed, known as runaway speed.
- This limiting speed under no-load conditions with maximum flow rate must be considered for the safe design of the various rotating components of the turbo generator unit.
- Runaway speeds and acceptable head variations



Type of runner	*Runaway speed (% of normal speed)*	*Acceptable head variation (% of design head)*	
		Minimum	*Maximum*
Impulse (Pelton)	170–190	65	125
Francis	200–220	50	150
Propeller	250–300	50	150

Characteristics of Turbines *contd.*

The following table suggests appropriate values of ϕ, which give the highest efficiencies for any turbine, the head & specific speed ranges & the efficiencies of the three main types of turbine.

Type of runner	ϕ	*Ns*	*H (m)*	Efficiency (%)
Impulse	0.43 – 0.48	8-17 17 17-30	>250	85-90 90 90-82
Francis	0.6 – 0.9	40 – 130 130-350 350-452	25-450	90-94 94 94-93
Popeller	1.4-2.0	380-600 600-902	<60	94 94-85

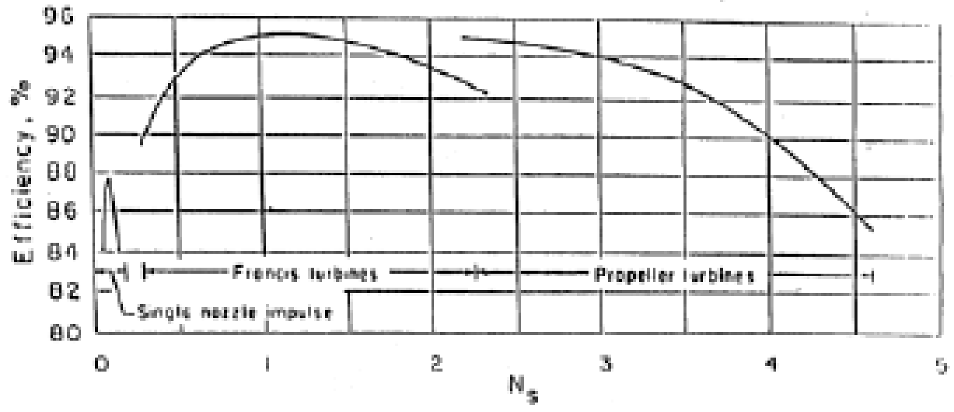


Figure 3. Dimensional Specific Speed

Source: Jack J. Fritz, ed., Small and Mini Hydropower Systems (New York: McGraw Hill, 1984), p. 5.88.

Characteristics of Turbines *contd.*

- For specific values of *Q* , *H,* and *N*, an optimum geometrical design would exist which would optimize the turbine efficiency.
- Determination of this optimum design would be performed using either experimental methods or (more recently) numerical CFD simulations.
- Alternatively, given a specific turbine design (i.e., Francis, Kaplan, Pelton), one would anticipate that there would be a specific set of operating conditions *Q* , *H,* and *N*, which would optimize the turbine efficiency.

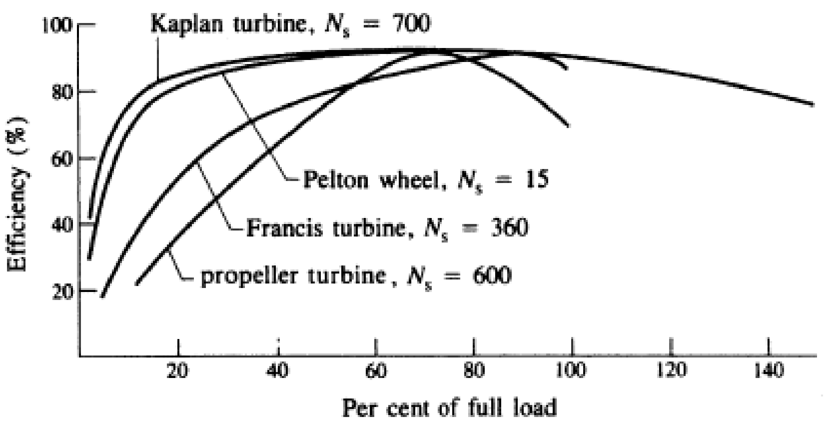
Meaning of specific speed

- Any turbine, with identical geometric proportions, even if the sizes are different, will have the same specific speed. If the model had been refined to get the optimum hydraulic efficiency, all turbines with the same specific speed will also have an optimum efficiency.
- In all modern power plants, it is common practice to select a high specific speed turbine because it is more economical as the size of the turbo-generator as well as that of power house will be smaller.

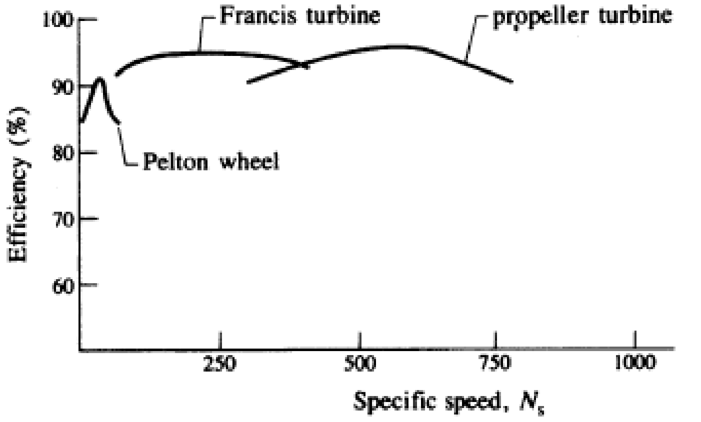
Maximum Efficiency

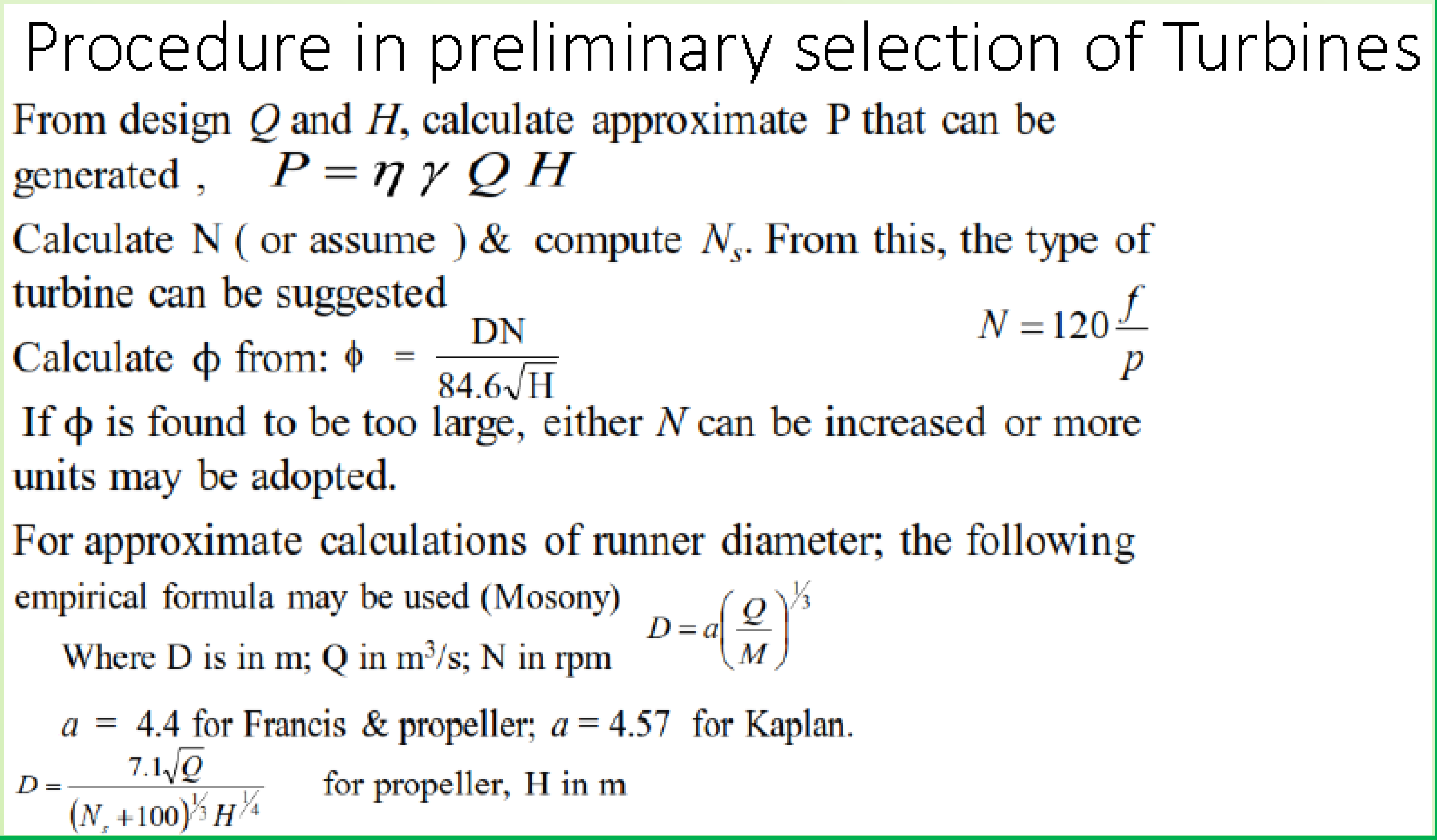
- The maximum efficiency depends upon the type of the runner used.
- In case of impulse turbine, low specific speed is not conducive to efficiency, since the diameter of the wheel becomes relatively large in proportion to the power developed so that the bearing tend to become too large.

(a) Efficiency versus per cent of full load



(b) Efficiency versus specific speed





Procedure in preliminary selection of Turbines

From design Q and H, calculate approximate P that can be generated , $P = \eta \gamma Q H$

Calculate N (or assume) & compute N_s. From this, the type of turbine can be suggested

$$N = 120\frac{f}{p}$$

Calculate φ from: $\phi = \frac{DN}{84.6\sqrt{H}}$

If φ is found to be too large, either N can be increased or more units may be adopted.

For approximate calculations of runner diameter; the following empirical formula may be used (Mosony)

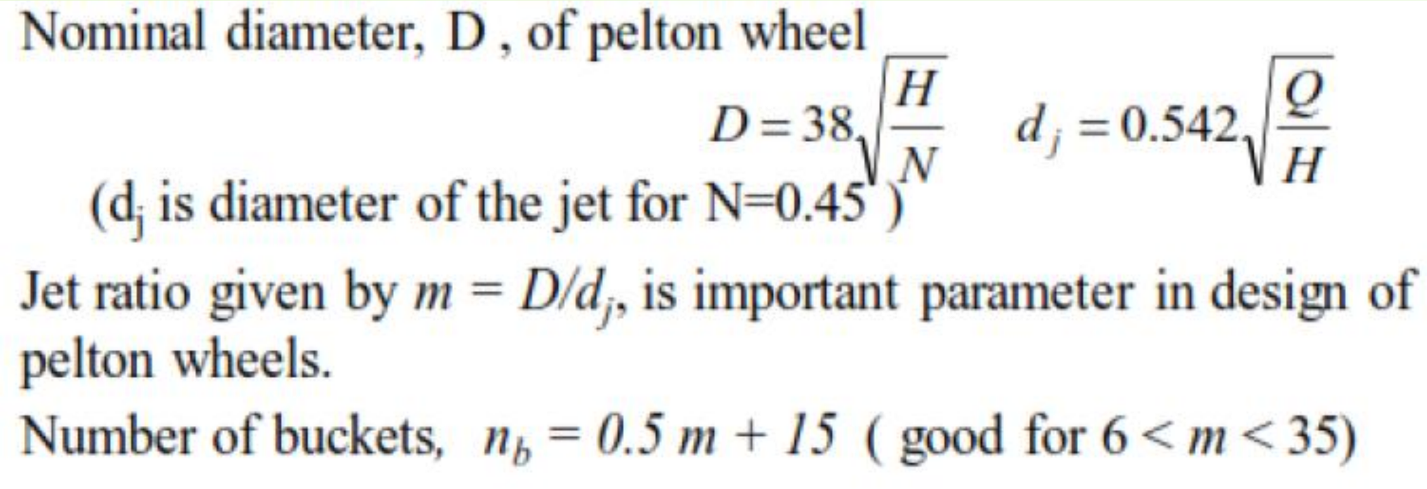
$$D = a\left(\frac{Q}{M}\right)^{1/3}$$

Where D is in m; Q in m^3/s; N in rpm

a = 4.4 for Francis & propeller; $a = 4.57$ for Kaplan.

$$D = \frac{7.1\sqrt{Q}}{(N_s + 100)^{1/3} H^{1/4}}$$ for propeller, H in m

Procedure in preliminary selection of Turbines *contd.*



Nominal diameter, D , of pelton wheel

$$D = 38\sqrt{\frac{H}{N}} \qquad d_j = 0.542\sqrt{\frac{Q}{H}}$$

(d_j is diameter of the jet for N=0.45)

Jet ratio given by $m = D/d_j$, is important parameter in design of pelton wheels.

Number of buckets, $n_b = 0.5\,m + 15$ (good for $6 < m < 35$)

Limits of use of turbine types

- Impulse turbines normally have most economical application at heads above 300m, but for small units and cases where surge protection is important, impulse turbines are used with lower heads.
- For Francis turbines the units can be operated over a range of flows from approximately 50 to 115% best-efficiency discharge. The approximate limits of head range from 60 to 125% of design head.
- Propeller turbines have been developed for heads from 5 to 60m but are normally used for heads less than 30m. For fixed blade propeller turbines the limits of flow operation should be between 75 and 100% of best-efficiency flow.
- Kaplan units may be operated between 25 and 125% of the best-efficiency discharge. The head range for satisfactory operation is from 20 to 140% of design head.

Determination of number of units

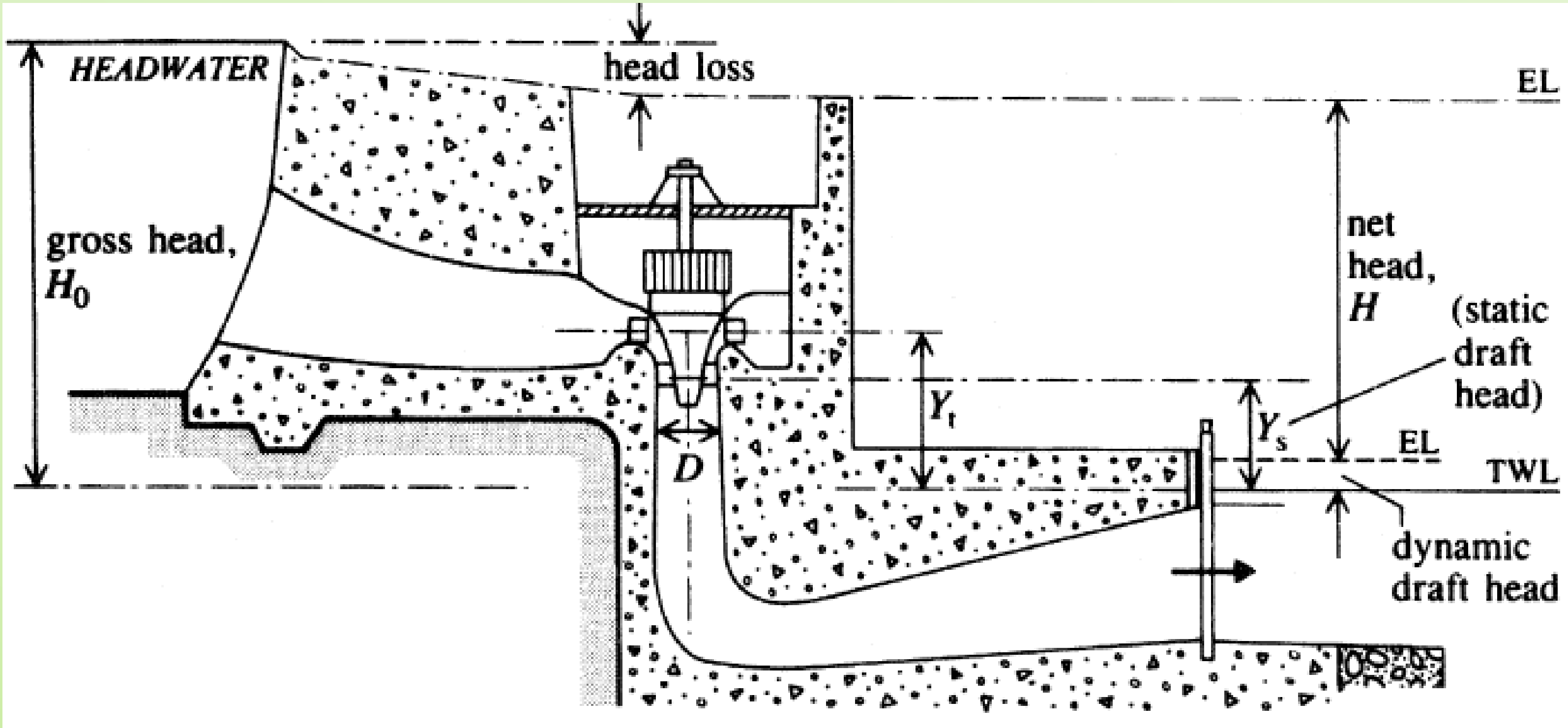
- Normally, it is most cost effective to have a minimum number of units at a given installation. However, multiple units may be necessary to make the most efficient use of water where flow variation is great.

Factors governing selection of number of units:

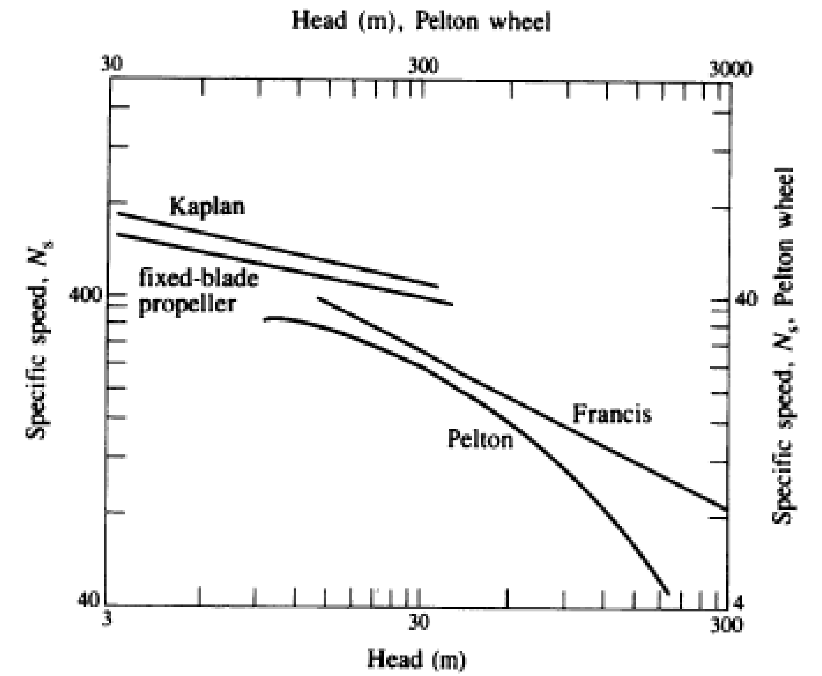
- Space limitations by geology or existing structure.
- Transportation facility
- Possibility of on site fabrication
- The current trend is to have small number of units having larger sizes, as studies have found out that larger sized units have a better efficiency.

Cavitation in turbines and turbine setting

- Cavitation results in pitting, vibration and reduction in efficiency and is certainly undesirable.
- Runners most seriously affected by cavitation are of the reaction type, in which the pressures at the discharge ends of the blades are negative and can approach the vapour pressure limits.
- Cavitation may be avoided by suitably designing, installing and operating the turbine in such a way that the pressures within the unit are above the vapour pressure of the water.
- Turbine setting or draft head, Ys, is the most critical factor in the installation of the reaction turbines.



Recommended limits of safe specific speeds



- The cavitation characteristic of a hydraulic machine is defined as the cavitation coefficient or plant sigma, σ, given by

$$\sigma = (H_a - H_v - Y_s)/H$$

Where $H_a - H_v = H_{b,}$ is the barometric pressure head (at sea level and 20°C , $H_b = 10.1m)$ and H is the effective head of the runner.

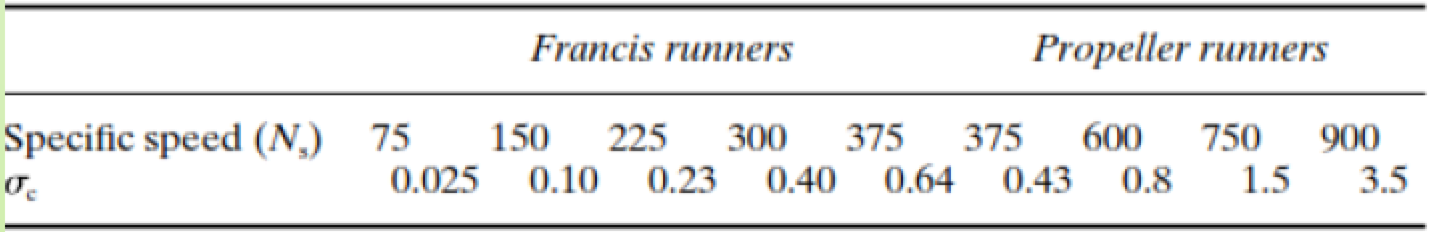
- The maximum permissible turbine setting Y_s (elevation above tailwater to the centreline of the propeller runners, or to the bottom of the Francis runners) can be written as:

$$Y_{s,max} = H_b - \sigma_c H$$

Where σ_c is the minimum (critical) value of σ at which cavitation occurs (usualy determined by experiment).

- If Y_s is negative the runner must be set below the tail water.

Typical values of σ_c for reaction turbines, versus their specific speeds



	Francis runners					Propeller runners			
Specific speed (N_s)	75	150	225	300	375	375	600	750	900
σ_c	0.025	0.10	0.23	0.40	0.64	0.43	0.8	1.5	3.5

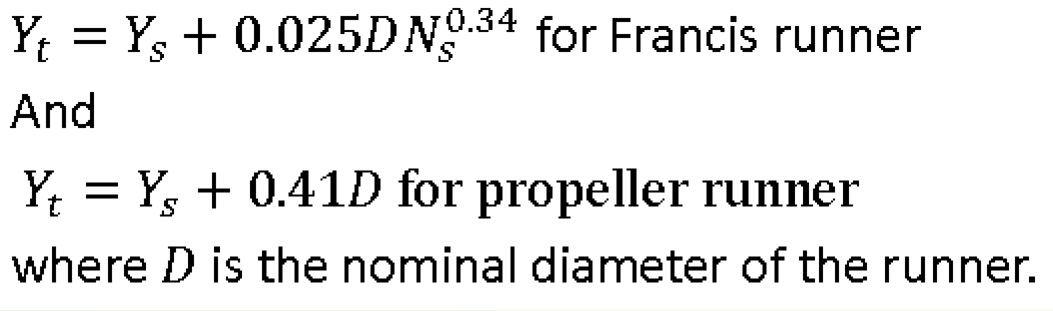
The above recommended limiting values of may also be approximated by $\sigma_c = 0.0432(\frac{N_s}{100})^2$ for Francis runners and

$\sigma_c = 0.28 + 0.0024(\frac{N_s}{100})^3$ for Propeller runners with an increase of σ_c by 10% for Kaplan turbines (Mosonyi, 1987).

Turbine Location

Position of centerline of runner (or centerline of distributor) for vertical axis turbines

- The preliminary calculations of the elevation of the distributor above the, Ytsuggest the following empirical relationships (based on knowledge of the existing plants (Doland, 1957)):



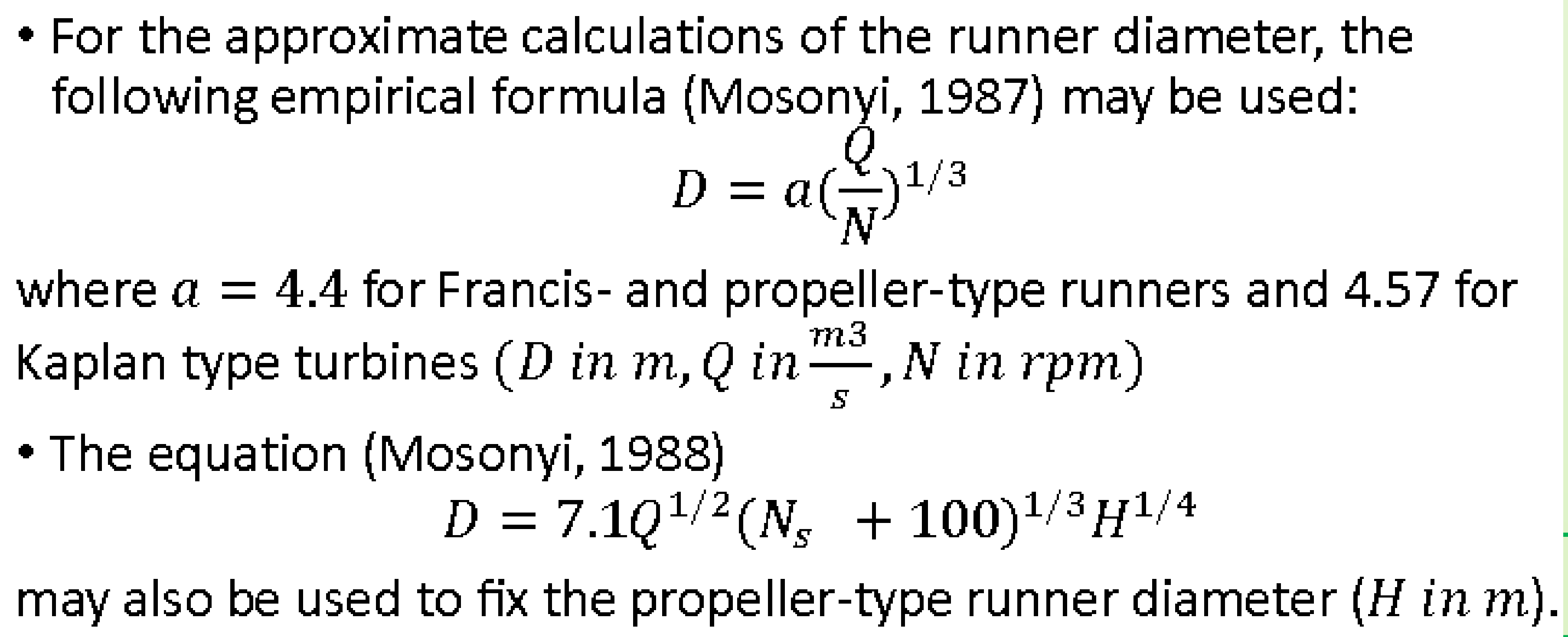
$Y_t = Y_s + 0.025 D N_s^{0.34}$ for Francis runner

And

$Y_t = Y_s + 0.41D$ **for propeller runner**

where D is the nominal diameter of the runner.

Runner diameter, *D*



- For the approximate calculations of the runner diameter, the following empirical formula (Mosonyi, 1987) may be used:

$$D = a(\frac{Q}{N})^{1/3}$$

where $a = 4.4$ for Francis- and propeller-type runners and 4.57 for Kaplan type turbines $(D\ in\ m, Q\ in \frac{m3}{s}, N\ in\ rpm)$

- The equation (Mosonyi, 1988)

$$D = 7.1Q^{1/2}(N_s \ + 100)^{1/3} H^{1/4}$$

may also be used to fix the propeller-type runner diameter $(H\ in\ m)$.

Runner diameter, D (contd.)

- The impulse wheels are fed by contracting nozzles and, in the case of the Pelton wheel turbine, the hydraulic efficiency is at its maximum when the speed factor Ø is around 0.45 and the smallest diameter of the jet,

$$d_j = 0.542(Q/H)^{1/2}$$

- The nominal diameter, D, of the Pelton wheel (also known as mean

or pitch diameter measured to the centreline of the jet) is thus given by

$$D = 38H^{1/2}/N$$

- The jet ratio m, defined as D/dj, is an important parameter in the design of Pelton wheels, and for maximum efficiency a jet ratio of about 12 is adopted in practice.
  - The number of buckets for a Pelton wheel is at an optimum if the jet is always intercepted by the buckets, and is usually more than 15. The following empirical formula gives the number of buckets n_b

approximately

$$n_b = 0.5m + 15$$

- This holds good for $6 < m < 35$.

Number of units installed

- For a given total plant capacity, total costs will generally increase with an increase in the number of units.
- Efficiencies of large units (turbine and generators) are higher than those of smaller ones of the same type.
- If the power demand is reasonably uniform it is practicable to install a small number of large units.
- As the efficiency of the hydraulic turbine decreases with the decrease of flow rate it is better to use a greater number of smaller machines for widely variable operating condition.

Turbine scroll case

- A scroll case is the conduit directing the water from the intake or penstock to the runner in reaction-type turbine installations
- In the case of impulse wheels a casing is usually provided only to prevent splashing of water and to lead water to the tail race.
- A spiral-shaped scroll case of the correct geometry ensures even distribution of water around the periphery of the runner with the minimum possible eddy formations.
- The shape and internal dimensions are closely related to the design of the turbine

Draft Tube

- In a reaction turbine, water leaves the runner with remaining kinetic energy. To recover as much of this energy as possible, the runner outlet is connected to a diffuser, called draft tube. The draft tube converts the dynamic pressure (kinetic energy) into static pressure.
- Draft tube permits a suction head to be established at the runner exit, thus making it possible for placing the wheel and connecting machinery at a level above that of water in the tail race under high water flow conditions of river, without loss of head.
- To operate properly, reaction turbines must have a submerged discharge.
- The water after passing through the runner enters the draft tube, which directs the water to the point of discharge.
- The aim of the draft tube is also to convert the main part of the kinetic energy at the runner outlet to pressure energy at the draft tube outlet.
- This is achieved by increasing the cross section area of the draft tube in the flow direction.
- In an intermediate part of the bend, however, the draft tube cross sections are decreased in the flow direction to prevent separation and loss of efficiency.

Energy Equation Applied to Draft Tube

Gross head= $\frac{P_B}{\gamma} + Z_B + \frac{V_B^2}{2g} + h_L$

- The velocity V_2 can be reduced by having a diverging passage
- To prevent cavitation, the vertical distance z_1 from the tail water to the draft tube inlet should be limited so that at no point within the draft tube or turbine will the absolute pressure drop to the vapour pressure of water.