Water (hydro) turbines

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Water turbine development 1

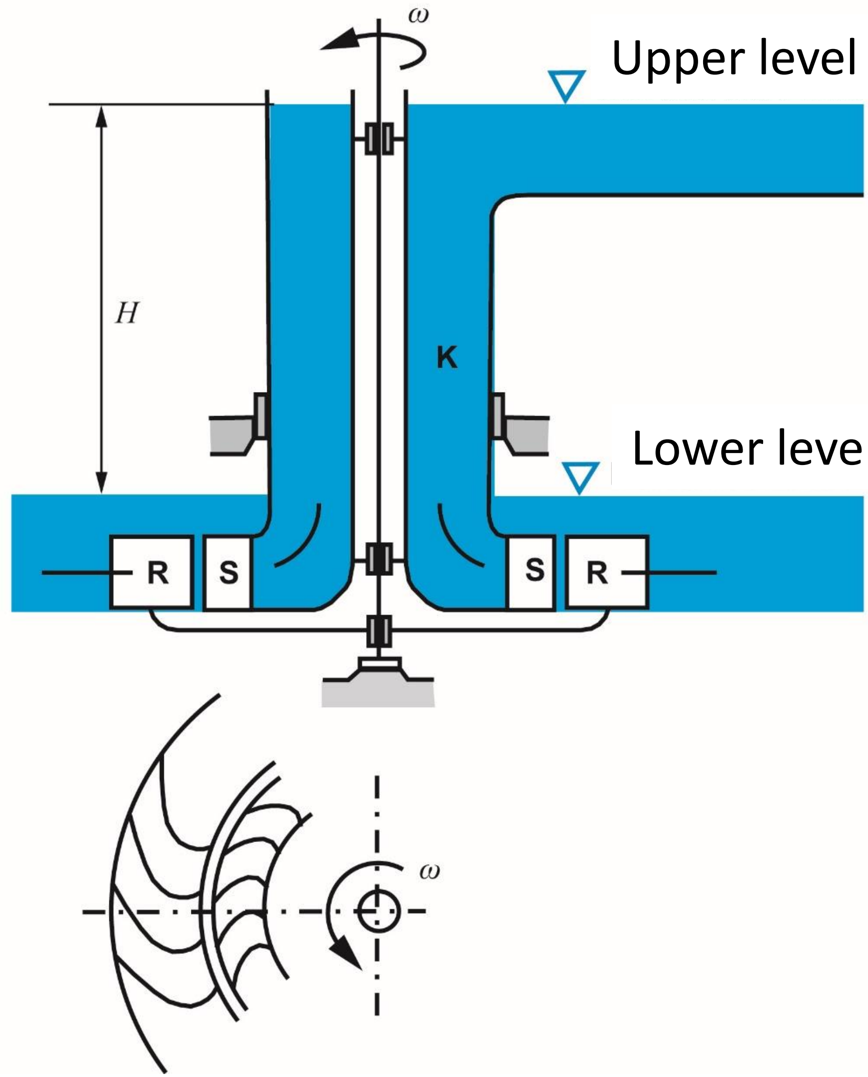
- The oldest device for converting water energy into mechanical energy is the **water mill**. The driving force of the water mill arises either because of the water weight or because of overpressures of water congestion but not as a result of changes in water momentum, so water mills are not considered as turbines.
- Around **1500, Leonardo da Vinci** described a reaction force for diverting water flow.

Water turbine development 2

- In **1750**, the Hungarian scientist **Johann Segner** practically elaborated the application of the reaction force to drive a water wheel (the **Segner wheel**).
- By mathematically interpreting the work of the Segner wheel, the Swiss scientist **Euler** laid the foundations of a turbine theory, which is still valid today (slightly updated) (**the Euler equations** or the main equations of turbo-machines).

Water turbine development 3

- In 1827, the first water turbine - **Fourneyron turbine** was patented in France
- In the Fourneyron turbine, water flows through the stator blades from the shaft to the rim and strikes the rotor blades, which transform the water energy into mechanical energy.



Water turbine development 4

- The German **Henschel (1837)** and the French hydro-engineer **Jonval (1841)** independently patent a turbine later called the **Henschel-Jonval turbine.**
- In this turbine, the water flow is parallel with the shaft, and for the first time a **diffuser** is installed into the turbine, i.e. a suction pipe that allows the exploitation of the entire available head, although the turbine rotor is substantially raised above the downstream water level.

Water turbine development 4

- **1863** Frenchman **Girard** patented a turbine in which water also flows axially, but freely flows out of the rotor, i.e. it does not completely fill the space between the blades.
- The construction of these turbines has been abandoned for the reason that better usability is achieved in modern turbines.
- Large modern water turbines operate at hydraulics efficiencies greater than 90%.

Water turbine development 5

- **In 1849** American engineer **J.B. Francis** revolutionizes the construction of water turbines with the design of an inward-flow reaction turbine.
- **In 1877** American engineer **L.A. Pelton** patented the first free jet turbine.
- **In 1913** Czech professor **V. Kaplan** patented a propeller turbine, followed by propeller turbines with adjustable blades.

Water turbine development 6

- For the exploitation of hydropower potential with the low head and high flow as a subspecies of Kaplan turbine, the **tubular turbine** was developed.
- In **1952**, Swiss engineer **P. Deriaz** constructed a diagonal turbine, which was designed as a reversible machine (pump-turbine), but also began to be used as a water turbine.

Water turbine 1

A water turbine is a rotary engine that takes energy from moving water.

Flowing water is directed on to the blades of a turbine rotor (runner), creating a force on the blades. The force acts through a distance and produces work. In this way, energy is transferred from the water flow to the turbine rotor.

A water turbine is a propulsion machine in which the potential and kinetic energy of water is converted into mechanical rotational energy.

Usually, a turbine is connected by a shaft to a synchronous generator, in which mechanical rotational energy is converted into electricity.

Considering a way of energy conversion, i.e. according to the change of water pressure during the flow through the impeller, water turbines are divided into:

- pressure (reaction) turbines,
- free jet turbines (action, impulse turbines).

Reaction turbines 2

- At **reaction turbines**, the pressure at the inlet of the rotor is greater than the pressure at the outlet. Reaction turbines are acted on by water, which changes pressure as it moves through the turbine and gives up its energy. They must be encased to contain the water pressure (or suction), or they must be fully submerged in the water flow.

- In pressure turbines, some of the potential energy is transformed into kinetic energy in the stator (fixed blades) and part in the rotor (moving blades). Turbine rotation is caused by change of the water momentum and by reactive forces (pressure difference, Coriolis force, etc.).
- Most water turbines in use are reaction turbines. They are used in low and medium head applications. Types of reaction turbines are: Francis, Kaplan, Propeller, Bulb, Tyson, Water Wheel.

Action turbines 2

- At **impulse turbines**, the pressure at the inlet of the rotor is equal to the pressure at the outlet, i.e. all potential energy is transformed into the kinetic energy in the stator (nozzle) of the turbine. Rotational force is generated only by the change of water momentum due to the deflection of the water jet in rotor blades.
- Impulse turbines change the velocity of a water jet. The jet impinges on the turbine's curved blades which reverse the flow. The resulting change in momentum (impulse) causes a force on the turbine blades. No pressure change occurs at the turbine blades and the turbine doesn't require a housing for operation.
- Impulse turbines are most often used in very high head applications. Types of impulse turbines are: Pelton, Turgo, Michell-Banki (also known as the Crossflow or Ossberger turbine).

Basic types of water (hydraulic) turbines 1

PRESSURE (REACTION) TURBINES

- Francis turbine (Radial flow)
- Propeller or Kaplan turbine (Axial flow)
  - Kaplan turbine with vertical shaft (variable pitch blades)
  - Tubular turbine with horizontal shaft (fixed blades)
    - Bulb tubular
    - Shaft extension tubular
- Deriaz turbine

IMPULSE (ACTION) TURBINES

- Pelton turbine

REVERSIBLE PUMP-TURBINES

Basic types of water (hydraulic) turbines 2

- Depending on the water flow direction, the pressure turbines can be **radial (Francis), axial (propeller or Kaplan) or diagonal (Deriaz),** while impulse turbines are **tangential (Pelton).**

Pelton

Francis

Kaplan

Water turbine power

Power generated by a water turbine depends on:

- Flow rate [m^3/s]
- Head [m]
- Turbine rotor diameter [m]
- Turbine speed [rpm]
- Acceleration of gravity [m/s^2]
- Density of water [kg/m^3]
- Dynamic viscosity [Pa s]
- Absolute surface roughness [m]

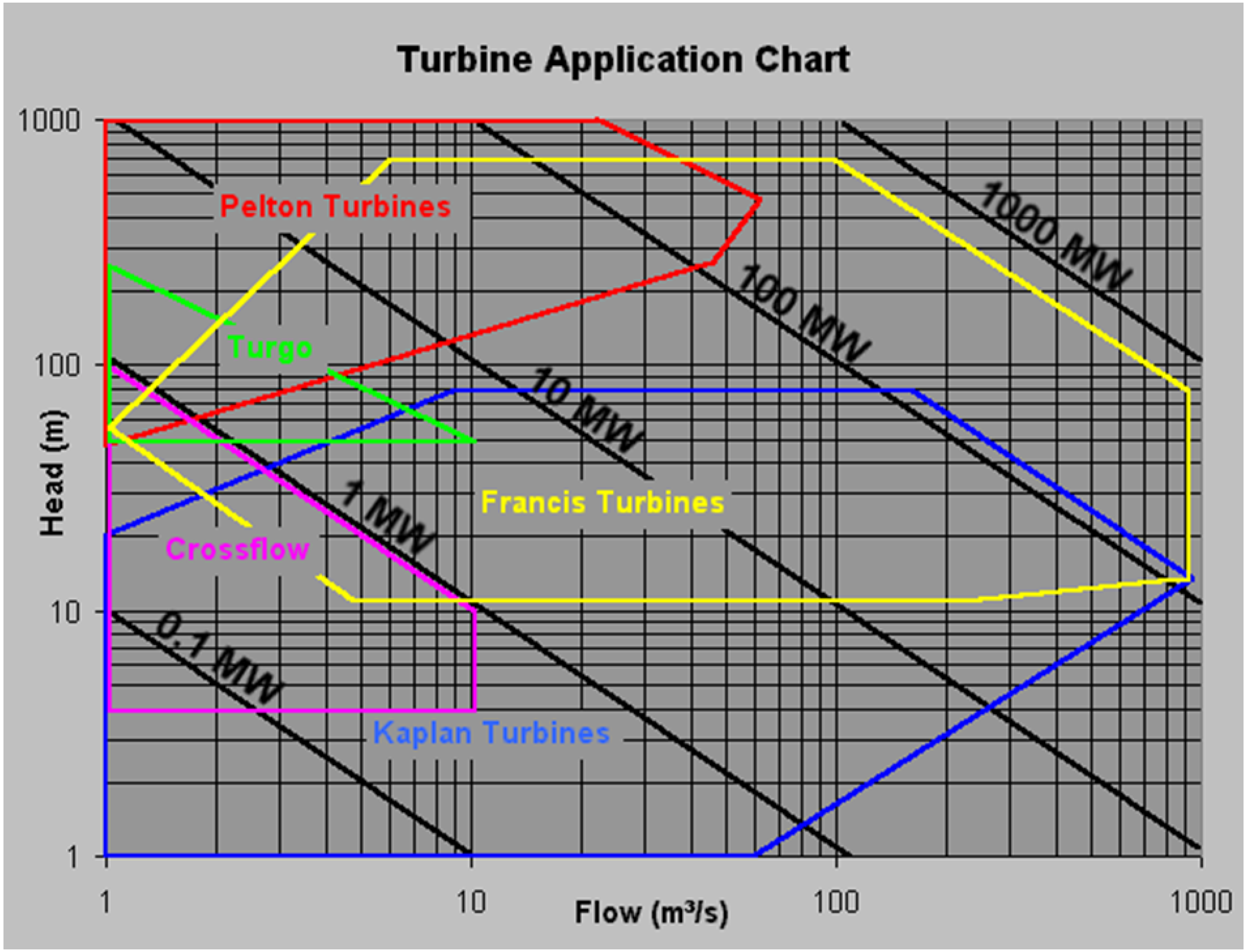
Application of particular types of turbines

- Turbine selection is based mostly on the available water head, and less so on the available flow rate.
- In general, impulse turbines are used for high head sites, and reaction turbines are used for low head sites.

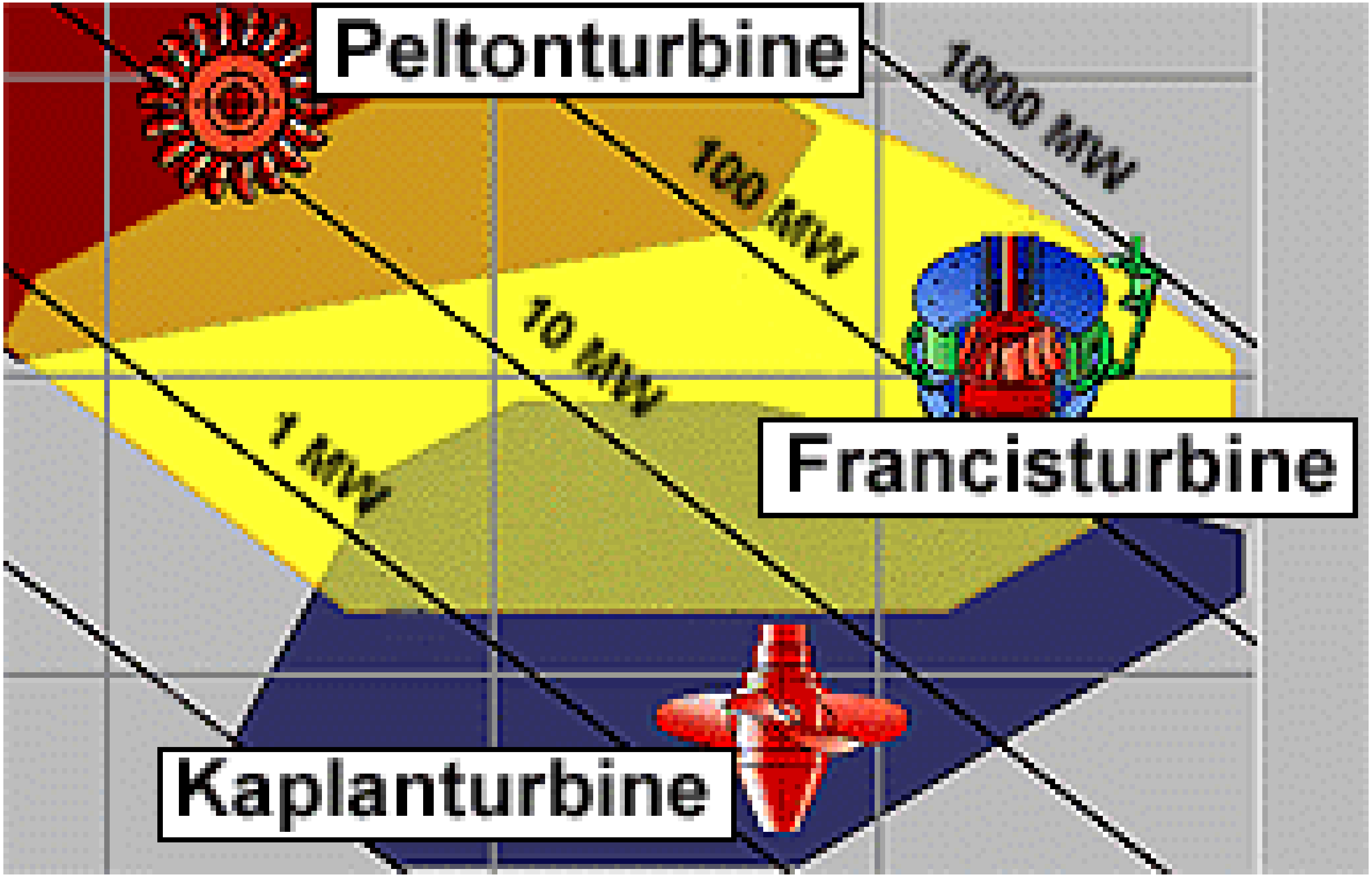
Type	n_s [rpm]	H [m]	flow (Q)
Pelton	2 - 70	400 - 2000	low
Francis	60 - 450	50 - 700	medium
Deriaz	170 - 430	40 - 200	medium
Kaplan	260 - 1000	20 - 70	high
tubular	> 800	1 - 20	high

- Michell-Banki 3 – 250 H [m]
- Turgo 50 – 250 H [m]

Turbine application chart 1



Turbine application chart 2



Specific Speed

- The specific speed, n_s , of a turbine characterizes the turbine's rotor shape in a way that is not related to its size. This allows a new turbine design to be scaled from an existing design of known performance. The specific speed is also the main criteria for matching a specific hydro site with the correct turbine type.
- The specific speed of a turbine can also be defined as the speed of an ideal, geometrically similar turbine, which yields one unit of discharge for one unit of head.
- The specific speed of a turbine is given by the manufacturer (along with other ratings) and will always refer to the point of maximum efficiency. These allow accurate calculations to be made of the turbine's performance for a range heads and flows.

$$n_s = n\sqrt{P} / H^{5/4}$$

(dimensioned parameter)

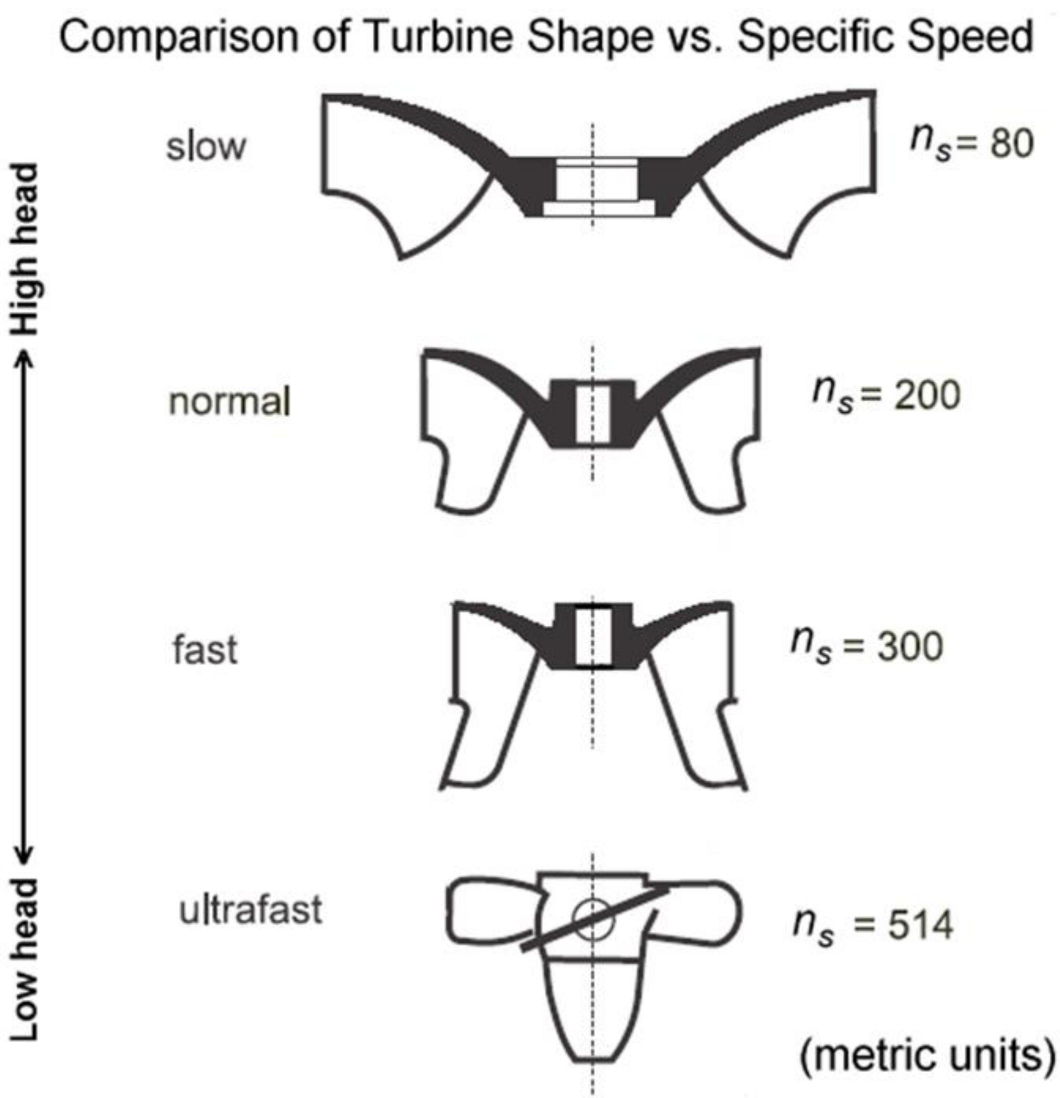
n = rpm

$$N_s = \frac{\Omega\sqrt{P/p}}{gH^{5/4}}$$

(dimensionless parameter)

Ω = angular velocity (radians/second)

Specific speed of turbine's rotor



Specific and runaway speed

- Example: Given a flow and head for a specific hydro site, and the rpm requirement of the generator, calculate the specific speed. The result is the main criteria for turbine selection.

- The specific speed is also the starting point for analytical design of a new turbine. Once the desired specific speed is known, basic dimensions of the turbine parts can be easily be calculated.

Runaway Speed

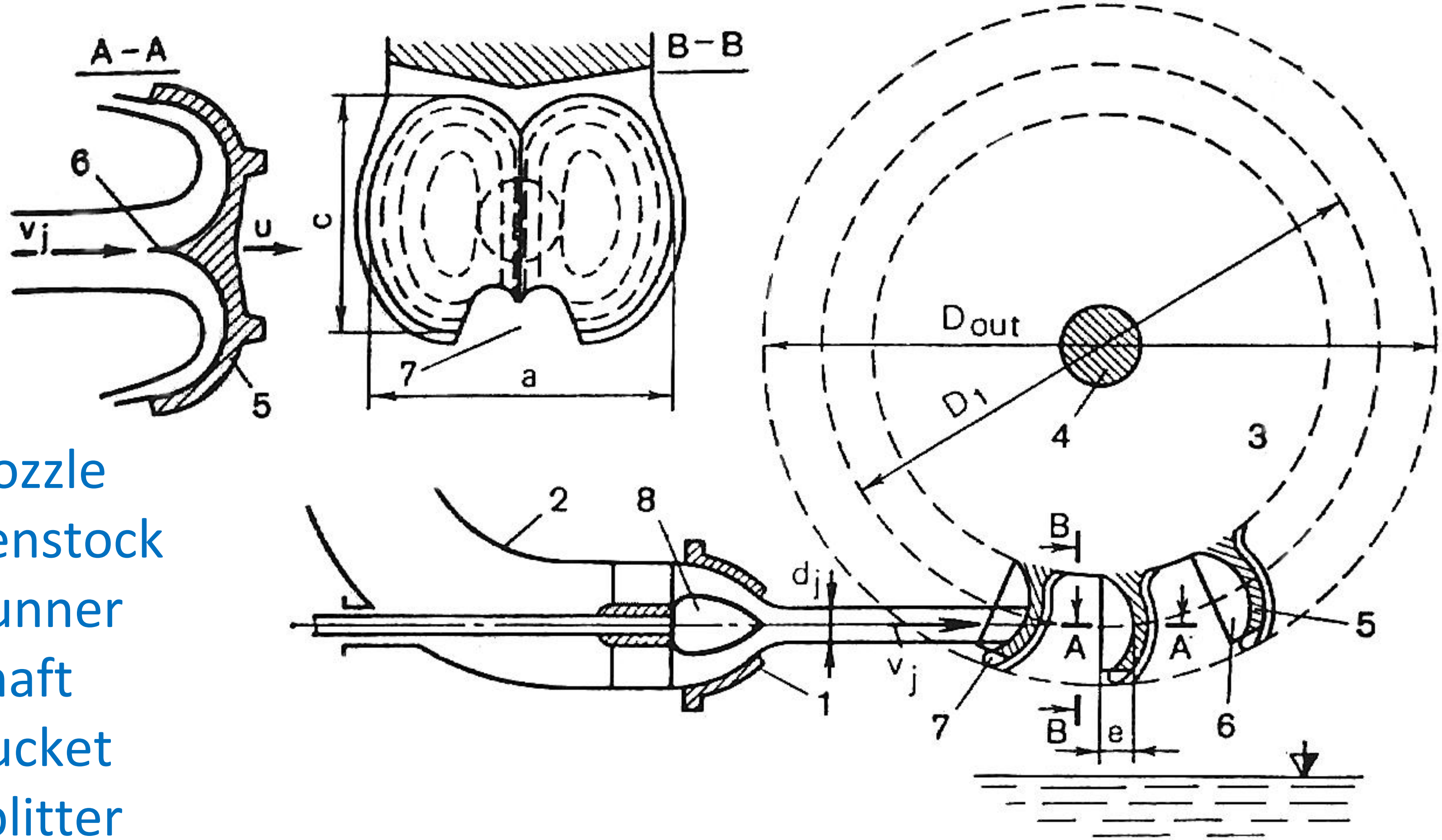
- The runaway speed of a water turbine is its speed at full flow, and no shaft load. The turbine will be designed to survive the mechanical forces of this speed. The manufacturer will supply the runaway speed rating.

Pelton turbine – impulse turbine

- The main representative of impulse (free jet, action) turbines is the Pelton Turbine.

- Built for high and low power purposes Used in conditions of large geodetic heads (more than 400-600 m) and relatively low flows.

Pelton turbine components

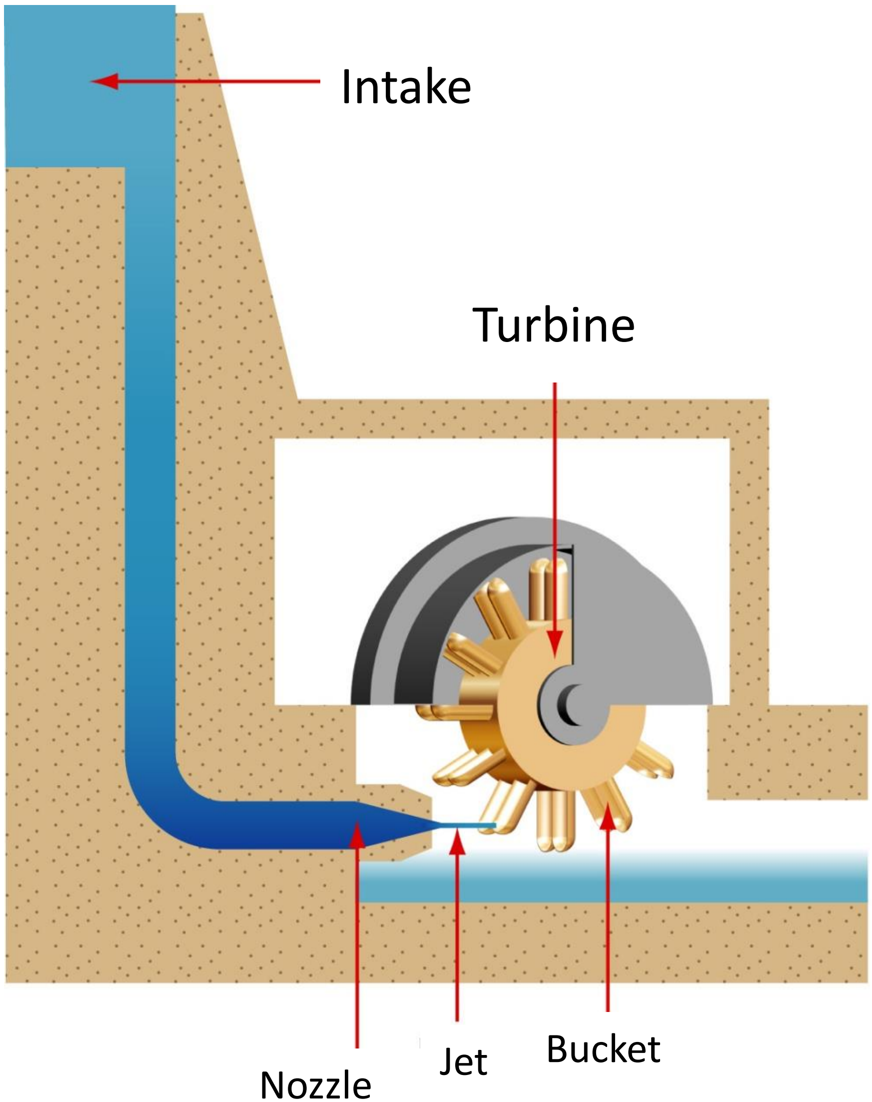


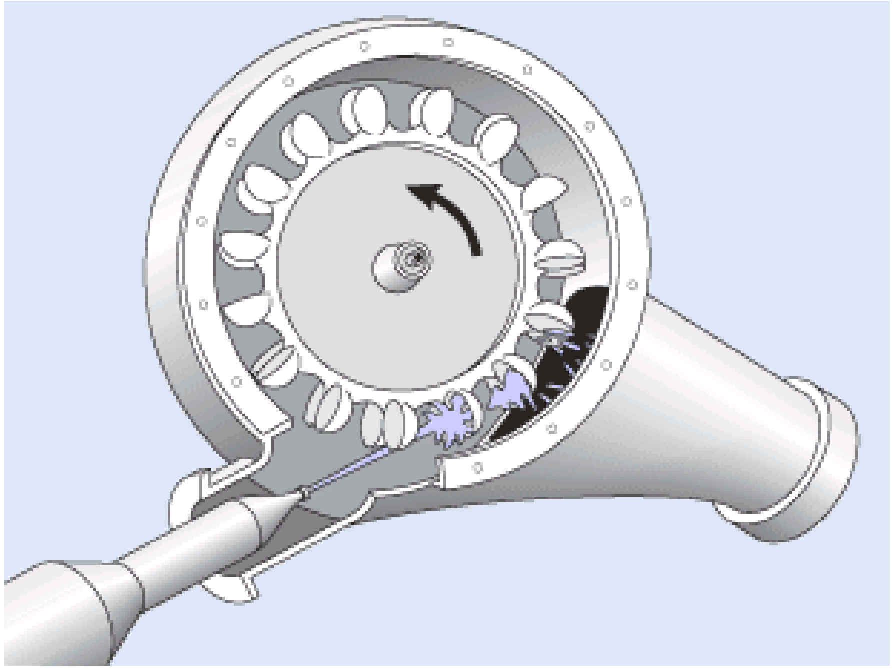
1 – Nozzle
2 – Penstock
3 – Runner
4 – Shaft
5 – Bucket
6 – Splitter
7 – Bucket edge
8 – Spear valve

Operation principle of Pelton turbine 1

- Water is fed through one or more nozzles located on the turbine housing tangentially to the runner (rotor) buckets (blades), positioned over the rim of runner.
- A jet of water flows out of the nozzle at a high speed, strikes the bucket and changes its direction due to its shape.
- Due to the deflection of the jet, i.e. the change of water momentum, the blade is actuated by an active force that causes the torque of the runner.
- As the nozzle and runner are above the water level, the runner rotates in the air.

Operation principle of Pelton turbine 2





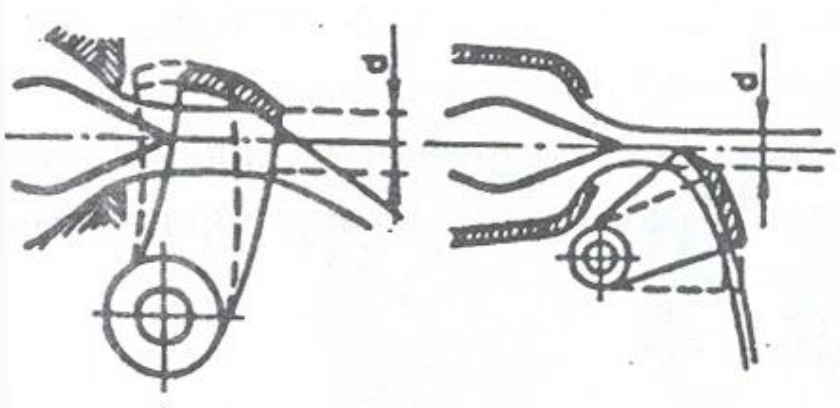
Operation principle of Pelton turbine 3

- According to the amount of water available, the Pelton turbine has one to six nozzles, with 12 to 40 buckets on the rotor.
- Buckets are divided into two equal oval sections by a sharp edge called the splitter.
- Pelton turbine power is controlled by varying the amount of water fed to the rotor by the spear (needle) valve.
- From the reservoir to the Pelton turbine, water is supplied by long pipelines.

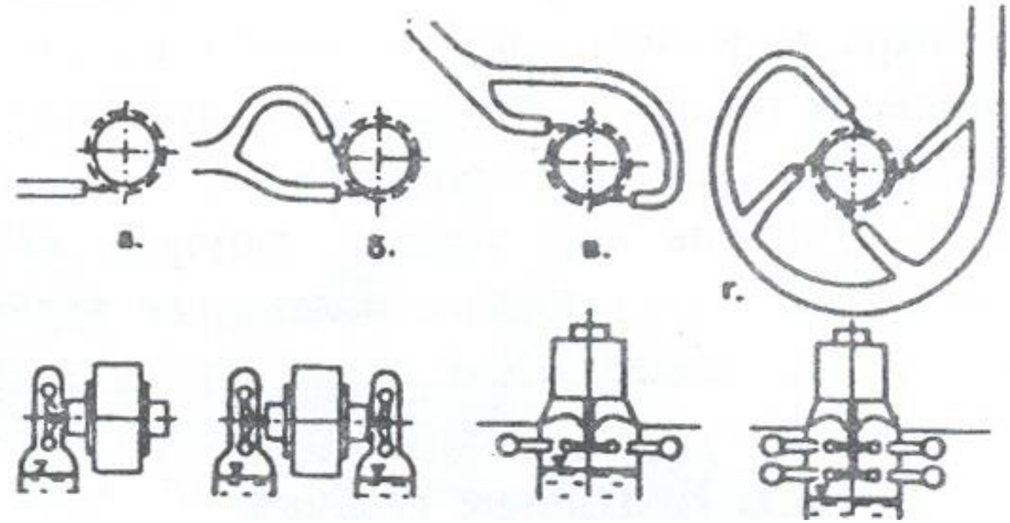
Operation principle of Pelton turbine 4

- In order to quickly reduce the turbine power to zero, jet deflectors are used, since the flow of water through the pipeline must not be abruptly interrupted due to dynamic pressures that would arise.

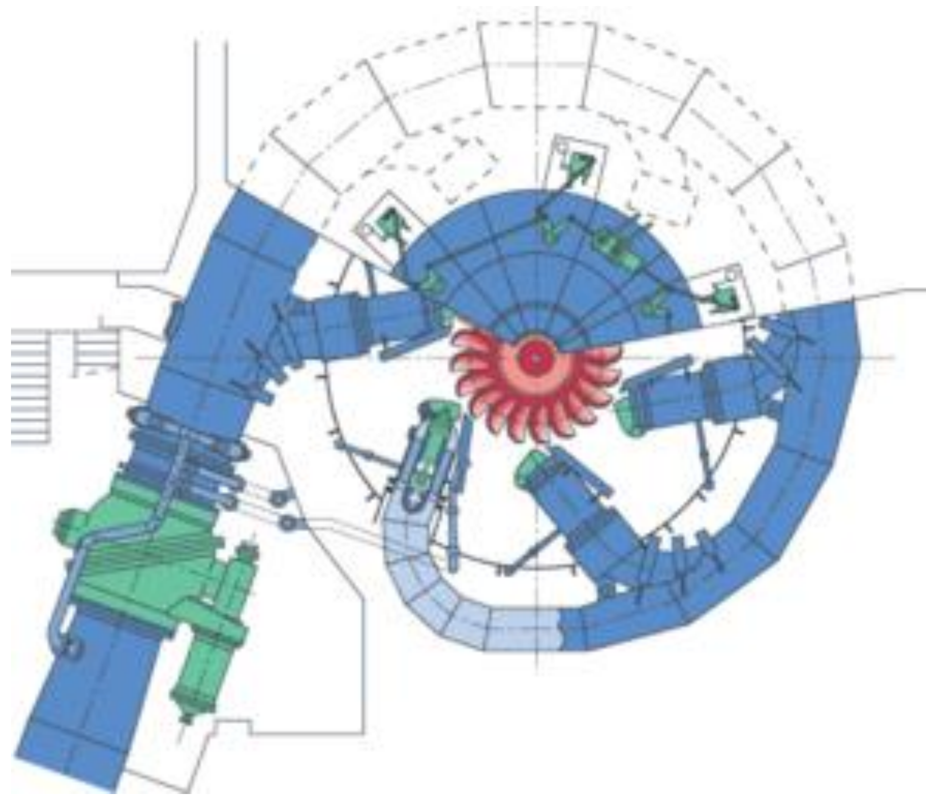
Deflector



Pelton turbine designs



Operation principle of Pelton turbine 5



Pressure (reaction) turbines 1

Pressure water turbines generally differ the most in the design of the impeller as the main part, while most of the other parts:

- Spiral casing (inlet),
- Stationary (stay) vanes ring,
- Draft tube (diffuser) and
- Bearings,

have similar construction and function.

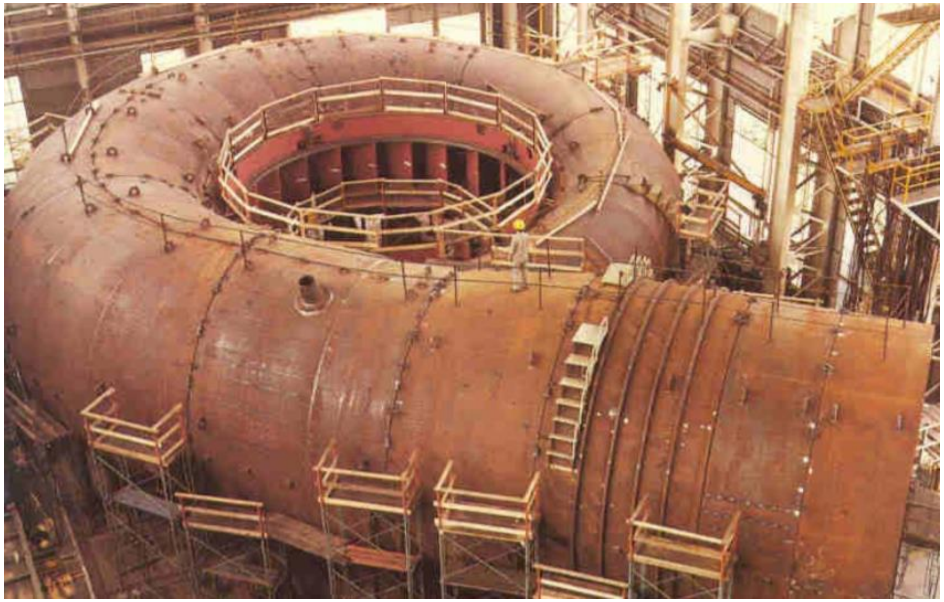
Spiral casing 1

Spiral casing is a part of a turbine that is used to uniformly distribute water around the turbine rim before entering the impeller.

- It ensures a uniform load around the impeller and prevents asymmetry that could cause forces and vibrations in the turbine.
- Spiral casing have Francis, Deriaz (diagonal) and most propeller turbines.
- Spiral casing can be open or closed, made of sheet metal, cast iron, concrete or combined iron-concrete.

Spiral casing 2

- The cross section of a spiral casing can be circular, elliptical, trapezoidal or rectangular.
- The type of casing is selected according to the available head and the power of the turbine.
- According to the distribution of water in the casing, a complete coil and a half-coil and a single and multiple coils are distinguished.
- Spiral casing mechanically fix the stationary vanes.



Stationary (stay) vanes ring

Stay vanes ring is the main load-bearing structure through which all static and dynamic loads are transferred to the concrete structure of the power house.

- It is made as a welded steel structure composed of two steel hoops interconnected by stationary vanes that direct water towards the guide vanes ring.

Guide vanes ring (Wicket gate) 1

Guide vanes ring regulates the flow of water through the turbine by rotating vanes and directs water to the runner blades at the optimal angle.

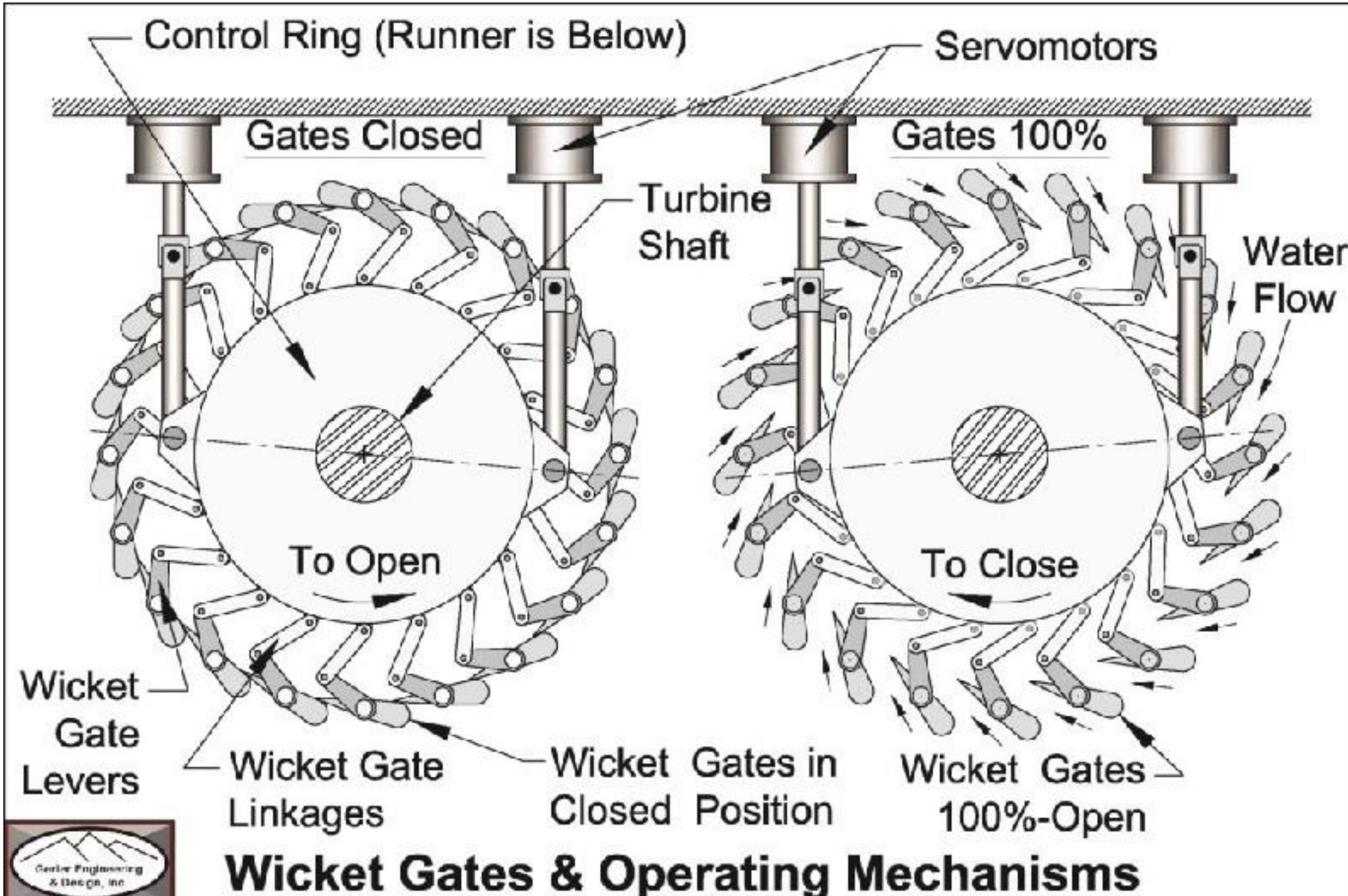
It consists of two hoops between which 20-32 hydraulically profiled vanes are radially placed.

- The rotation of the vanes, and thus the regulation of the flow of water through the turbine, is achieved by rotating the control ring with a servomotor, which is transferred by system of levers and linkages to each blade separately.

Guide vanes ring (Wicket gate) 2

- In incident situations such as a generator trip or a malfunction of a vital part of the turbine, guide vanes ring automatically closes the water supply to the turbine.
- The closure must not be too fast because of the risk of a water flow interruption in the impeller or diffuser, which could cause back stroke to the impeller.

Guide vanes ring (Wicket gate) 3



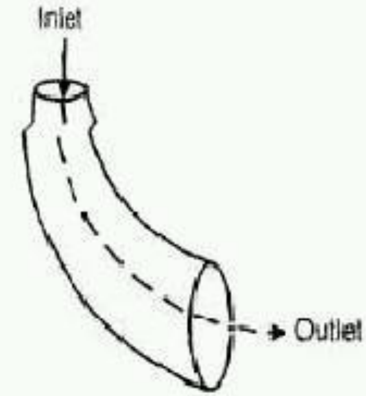
Diffuser (Draft tube) 1

After passing through the runner, water flows into the **diffuser**.

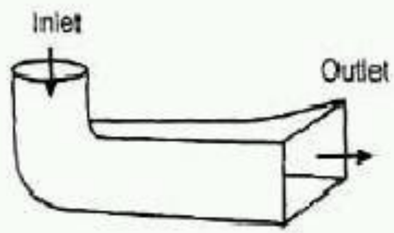
- The purpose of the diffuser (draft tube) is to reduce the output velocity, thereby reducing the energy losses and increasing the overall efficiency of the turbine.
- The diffuser enables turbine operation independently of changes in the downstream water level
- In vertical shaft turbines it changes the direction of water flow from vertical to horizontal, with the lowest hydrodynamic losses.

Diffuser (Draft tube) 2

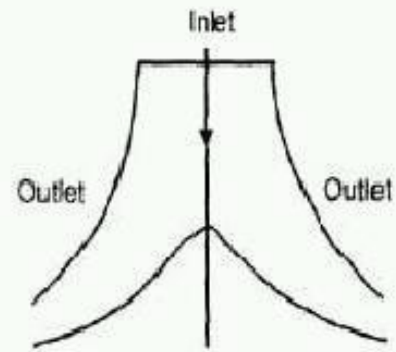
Conical or Divergent Draft Tube



Simple Elbow Draft Tube



Elbow Tube Having
Circular Cross-section
at inlet and rectangular at Outlet



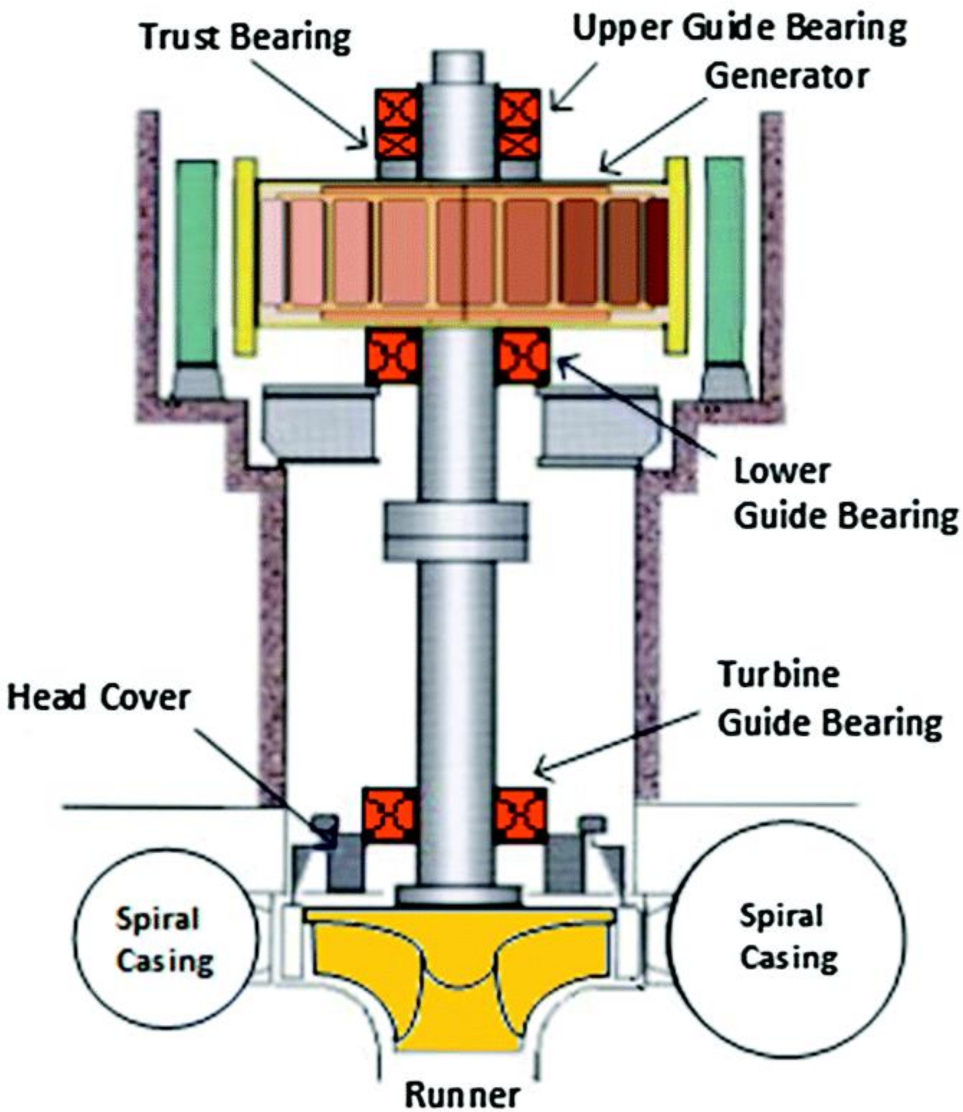
Hydracone or Moody
Spreading Draft Tube

Bearings 1

The forces applied to the turbine shaft are taken up by the axial bearing and one or more radial bearings.

- The axial bearing may be common to the turbine and generator, which are usually connected by a shaft.
- The main radial bearing, usually located next to the runner, is called the turbine guide bearing.

Bearings 2



Trust Bearing
Upper Guide Bearing
Generator
Lower
Guide Bearing
Head Cover
Turbine
Guide Bearing
Spiral
Casing
Spiral
Casing
Runner

Turbine head cover

The **turbine head cover** is used to direct the water and transfer the axial forces of the turbine guide bearing through the guide vanes ring and stay vanes ring to the foundations.

- On the head cover, besides the bearings, the turbine shaft seal, air valves and hydraulic locks are usually positioned.

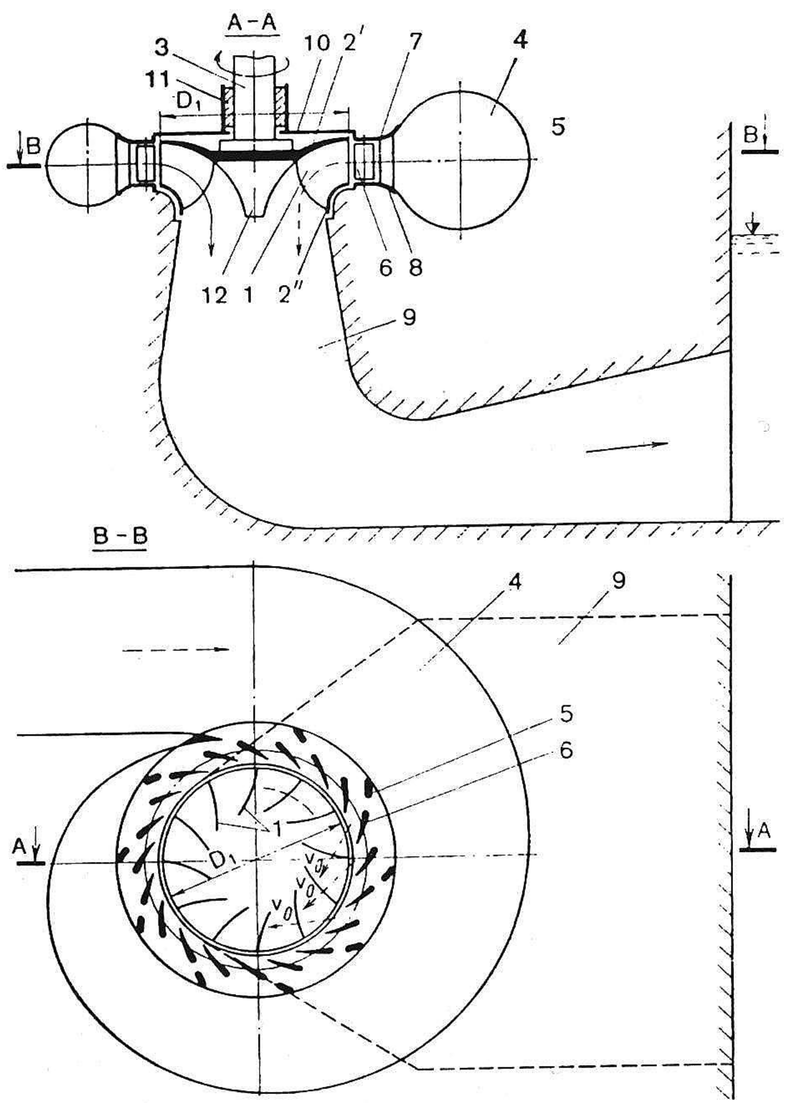
Francis turbine 1

- Pressure (radial) turbine.
- Applicable for medium heads (40-60 m to 500-700 m).
- The magnitude of torque on the runner depends on the water momentum change, the pressure difference, the Coriolis acceleration, the centrifugal acceleration, etc. The influence of each of these factors on the torque determines the degree of reaction of the turbine.
- The water is supplied by a penstock and uniformly distributed around the runner by a spiral casing.
- Rotation of the guide vanes ring changes the flow through the turbine (power control).

Francis turbine 2

- The rotation of the guide vanes results in a change of the flow angle to the runner blades, which causes considerable hydrodynamic losses, which is why the Francis turbine has relatively poor control properties.
- In the runner, which consists of 12-17 tightly fixed blades, water enters radially and exits axially through the diffuser into the turbine outlet channel. Using a diffuser reduces the turbine output losses associated with the kinetic energy of water.
- The Francis turbine typically has a vertical shaft as the horizontal shaft turbine is only suitable for low power application.

Francis turbine 3



1 – runner blades;

2 – upper i bottom runner ring;

3 – shaft;

4 – spiral chasing;

5 – stay vanes;

6 – guide vanes;

7 – upper hoop of stay vanes ring;

8 – bottom hoop of stay vanes ring;

9 – diffuser;

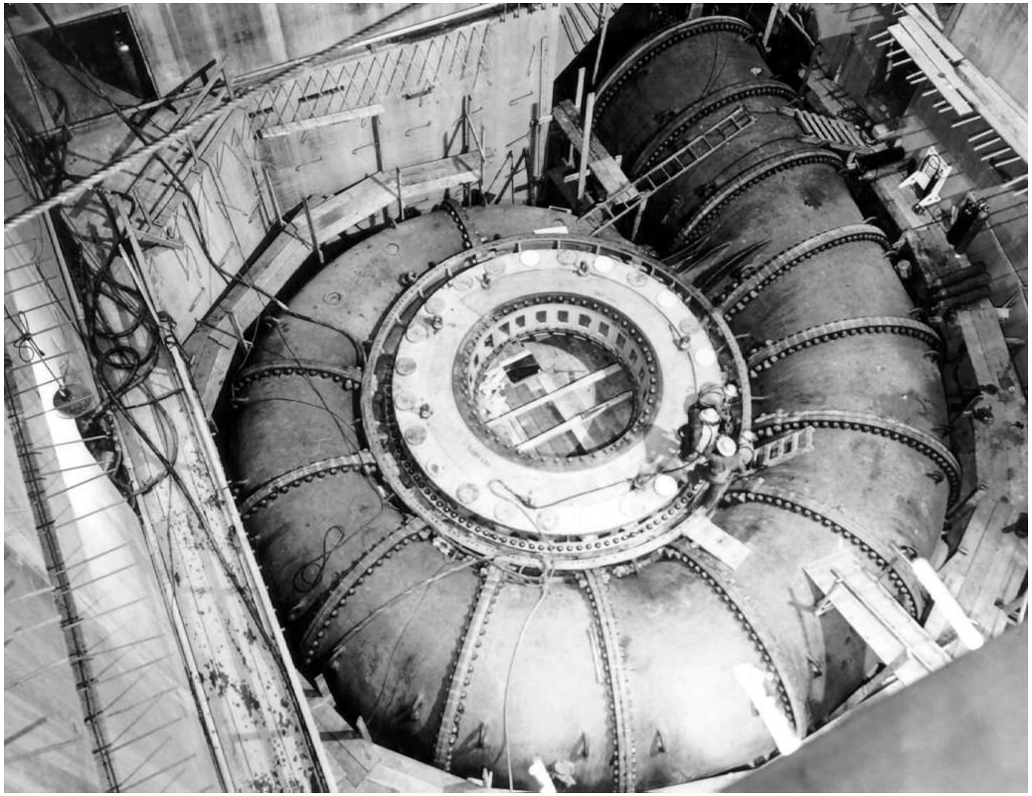
10 – head cover;

11 – turbine guide bearing;

12 – runner cone.

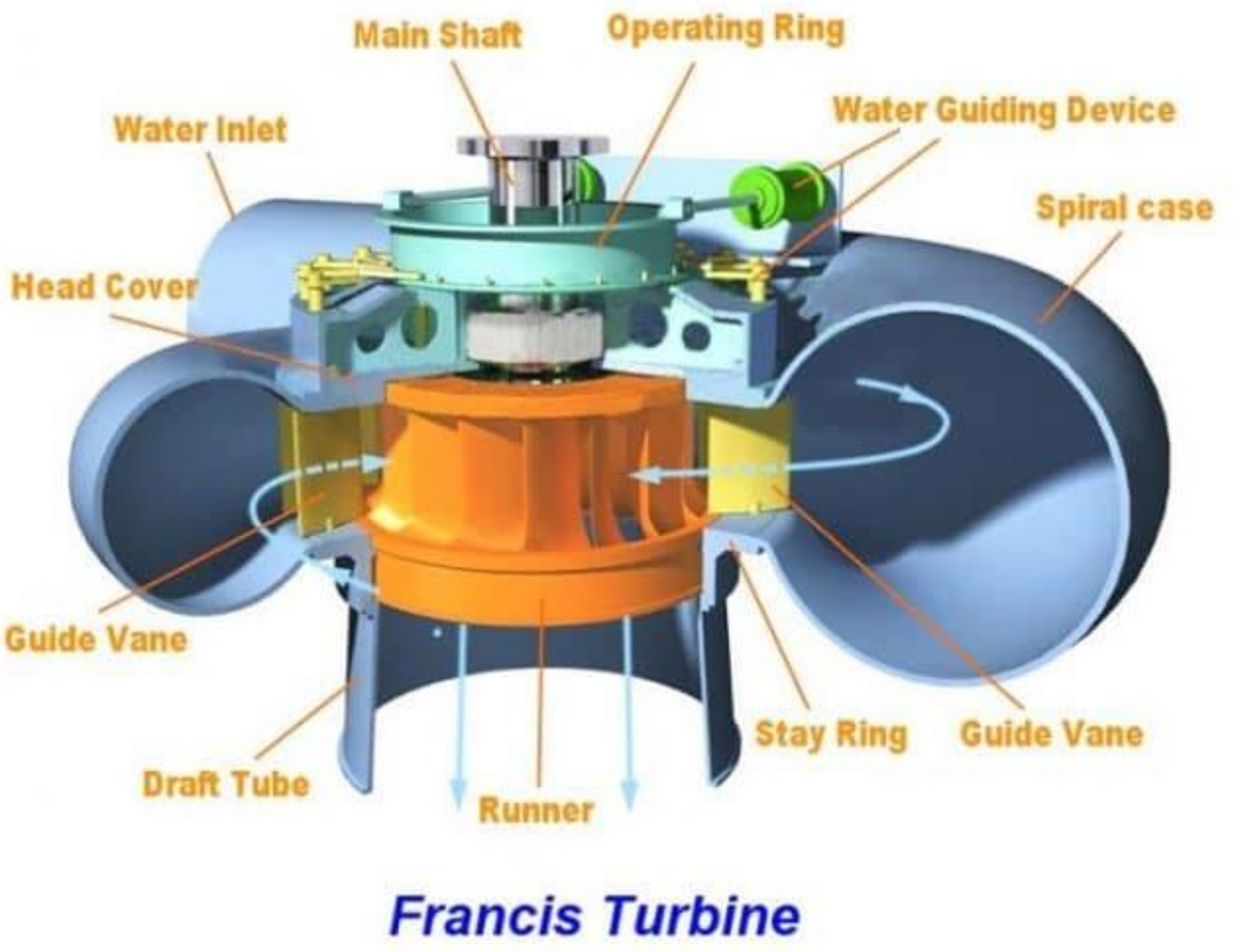
Francis turbine 4

Runner installation



Spiral casing

Francis turbine 5



Francis turbine water flow control

Low flow

High flow

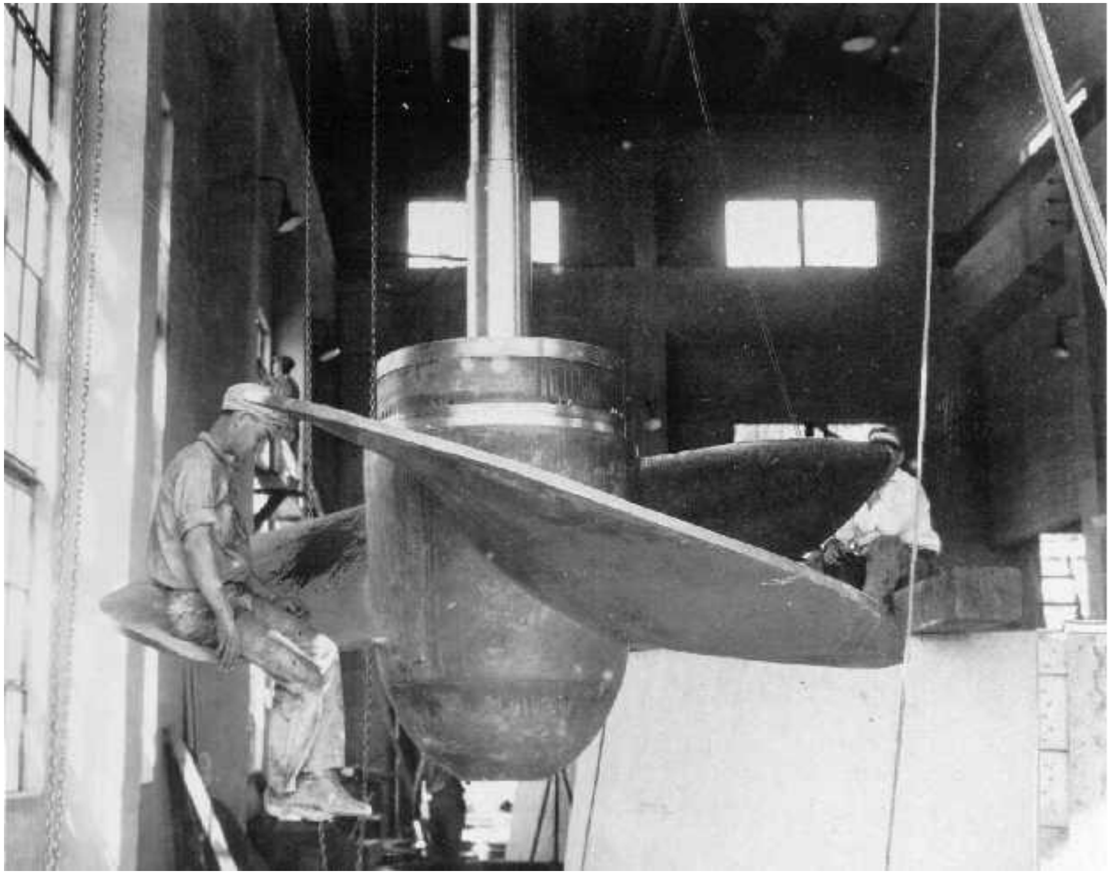
- The wicket gates (guide vanes) is the only control device of the Francis turbine. Movable blades regulate the flow of water through the turbine.

Propeller turbine 1

- Pressure (axial) turbine.
- Applicable for high flows and low heads (from 1-3 m to 60-70 m).
- The propeller turbine rotor consists of runner blades and runner cone.
- The runner has 3 to 8 blades (more blades for higher nominal head).
- Water is supplied to the runner axially (i.e., in the direction of the shaft) by a guide vanes (wicket gate), used for a flow and power control.

Propeller turbine 2

Propeller turbine with fixed runner blades.

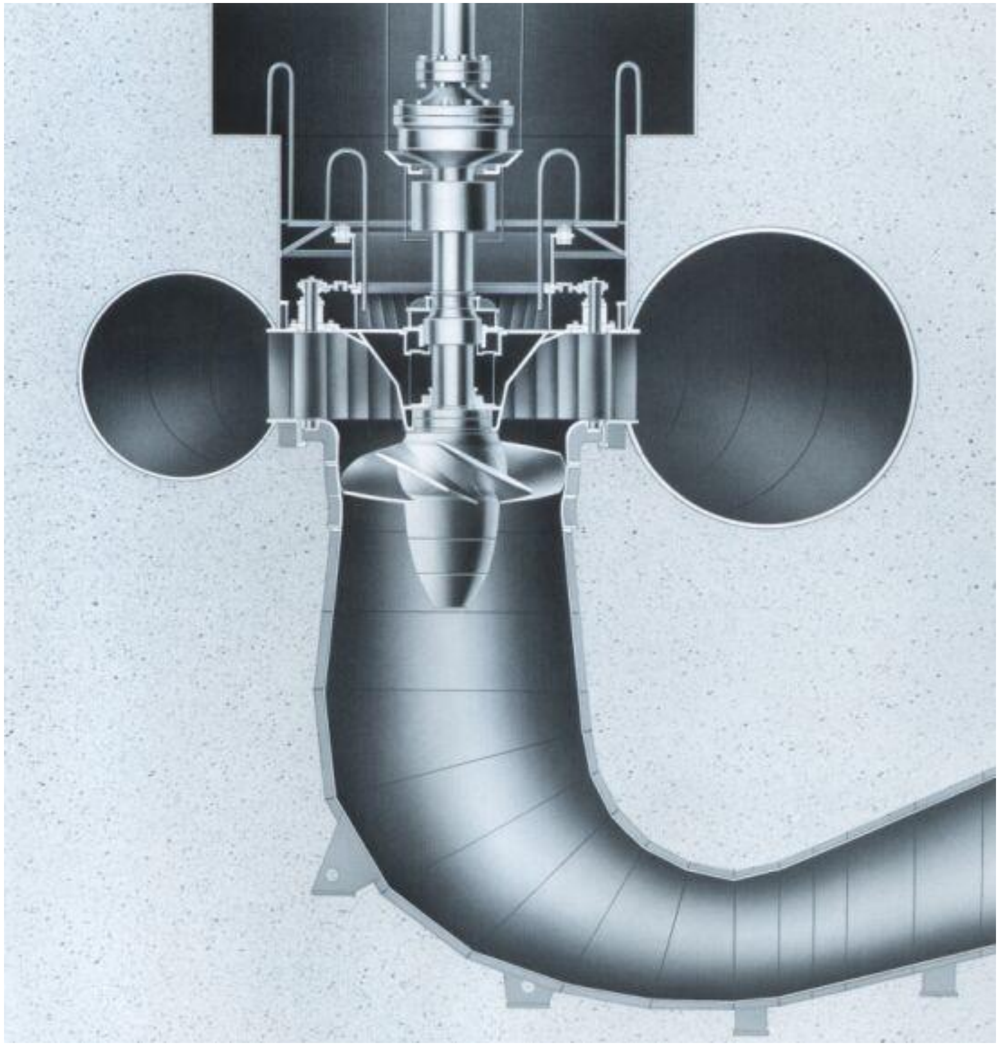


Fixed-blade propeller turbines are not flexible in operation – used only in small hydropower plants.

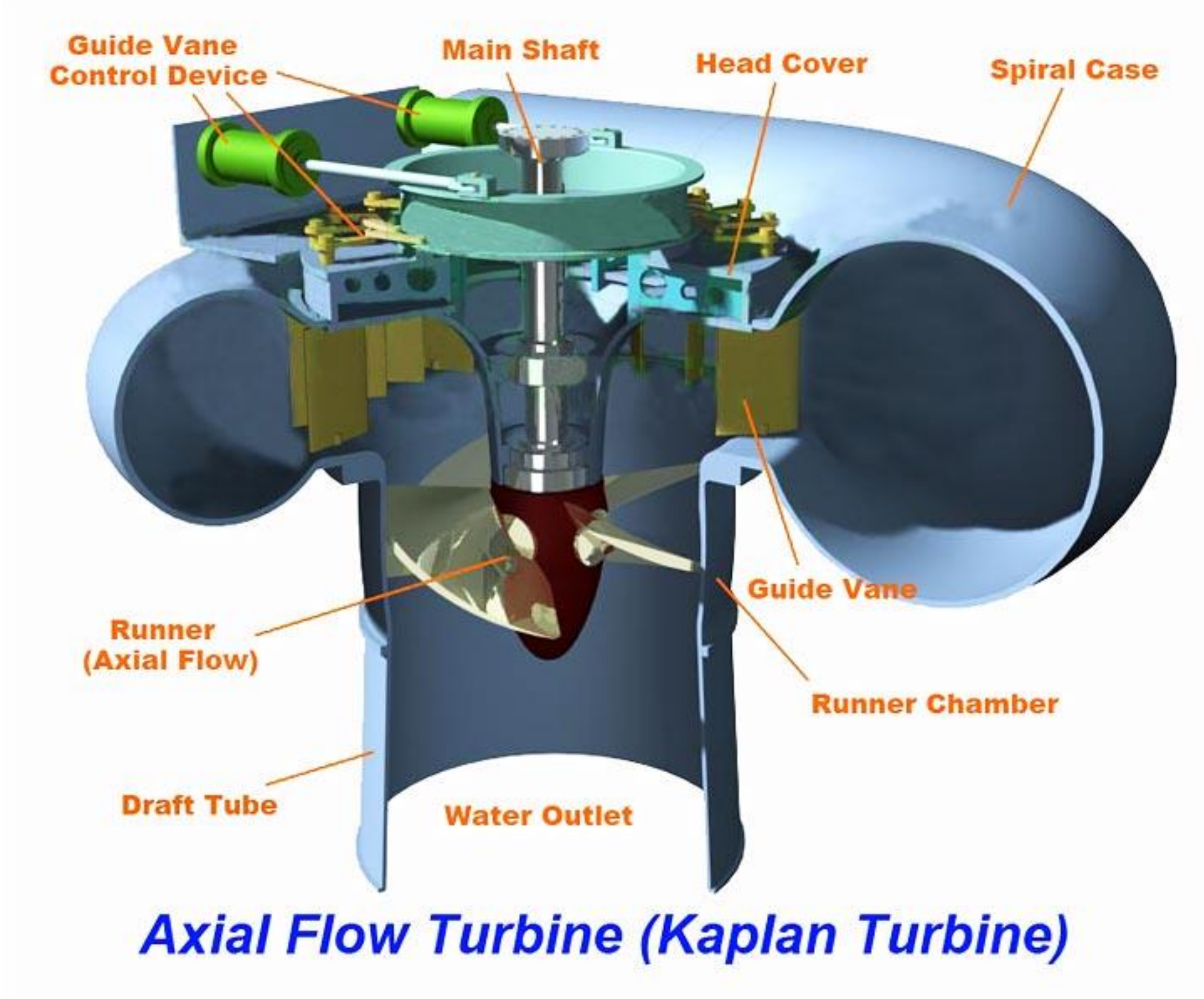
Kaplan turbine 1

- At most propeller turbines, runner blades can be rotated (adjusted) in operation to minimize collision losses and ensure water flow with the least hydraulic loss – **Kaplan turbine**
- The construction of turbines with rotating runner blades is more complex than the ordinary propeller turbines, but their energy efficiency characteristics is significantly better.

Kaplan turbine 2

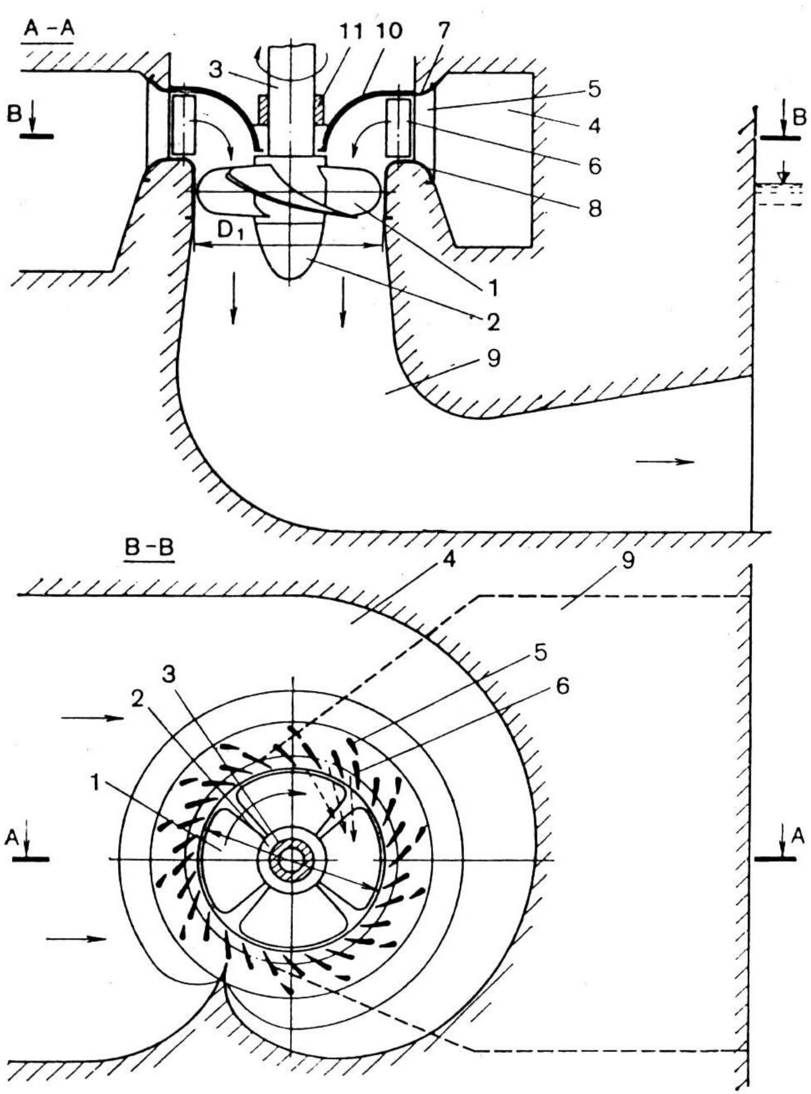


Kaplan turbine 3



Kaplan turbine

4



1 – runner

2 – runner cone

3 – shaft

4 – spiral casing

5 – stay vanes

6 – guide vanes

7 – upper hoop of stay vanes ring;

8 – bottom hoop of stay vanes ring;

9 – diffuser

10 – head cover

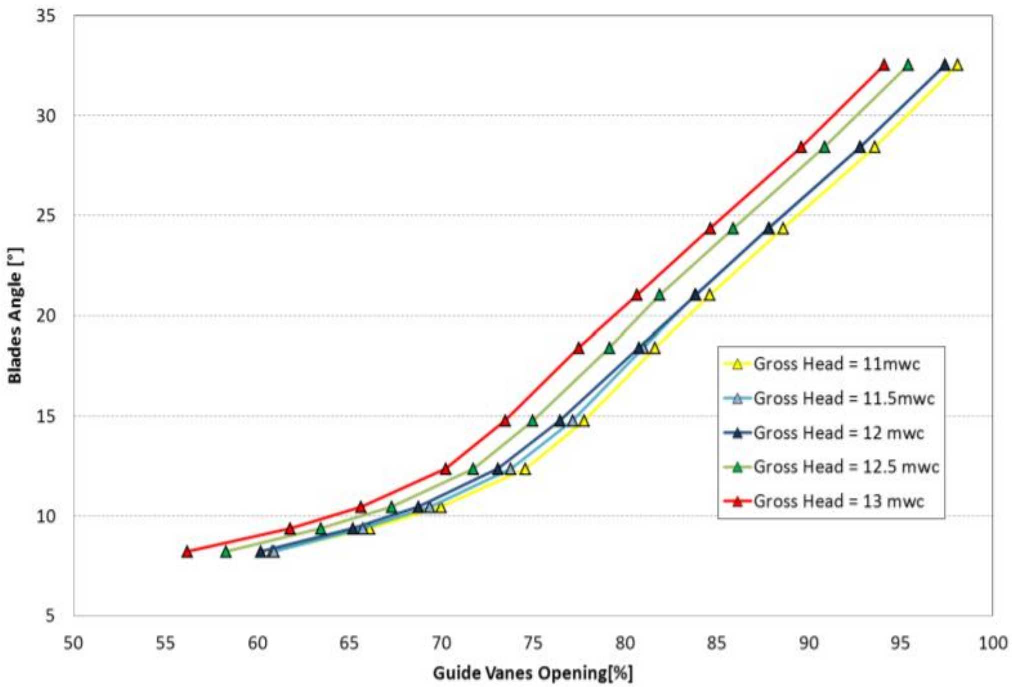
11 – turbine guide bearing

Kaplan turbine water flow control 1

- The main water flow through the Kaplan turbine is axial.
- The rotation angle of runner blades is determined by the opening of the wicket gate and available water head - $y_R(y_W,H_b)$, to achieve the highest efficiency in all operating conditions.

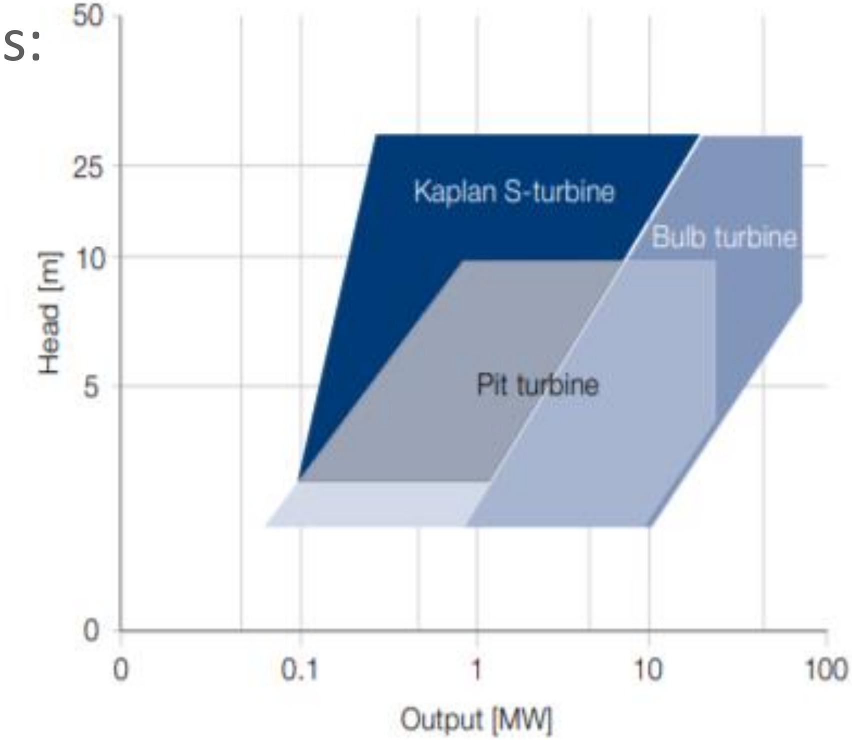
Kaplan turbine water flow control 2

- Dependence of runner blades angle and guide vanes opening in Kaplan turbines is shown by **Cam curves.**
- In addition to the guide vanes control, automatic control system in Kaplan turbines controls runner blades angle, so such turbines are called doubly regulated turbines.

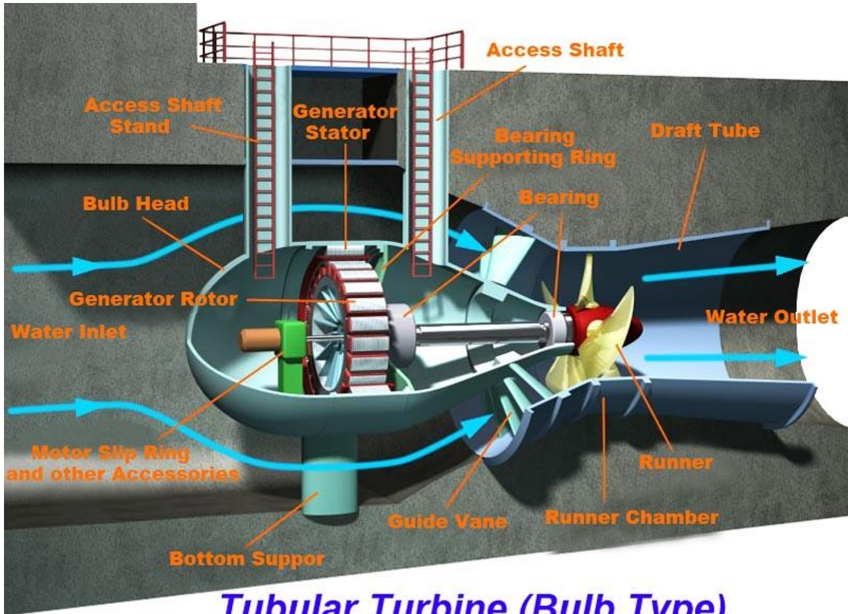


Tubular turbine 1

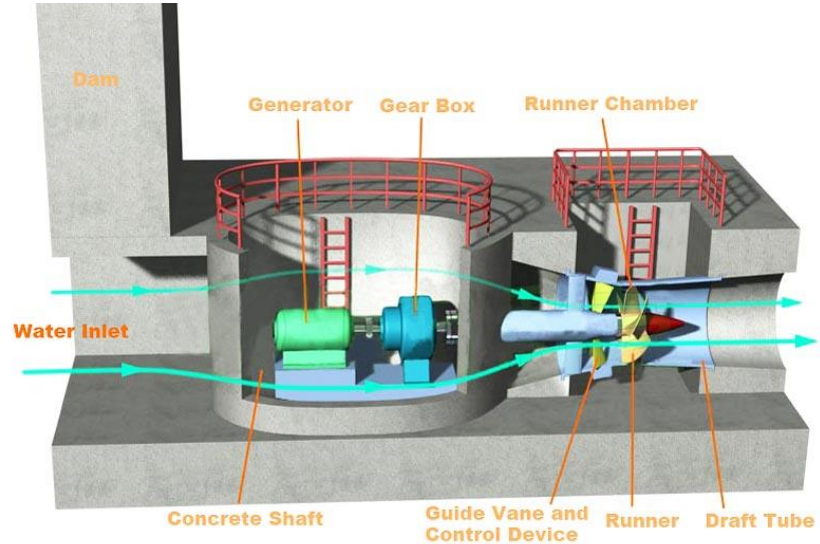
- A horizontal or (slightly tilted) propeller turbine placed in a tube is called a tubular turbine.
- Such turbines do not have a spiral chasing and due to the flat and coaxial diffuser have great efficiency.
- Three types of tubular turbines:
  - "S" type – low power
  - Pit type – low power
  - Bulb type – high power



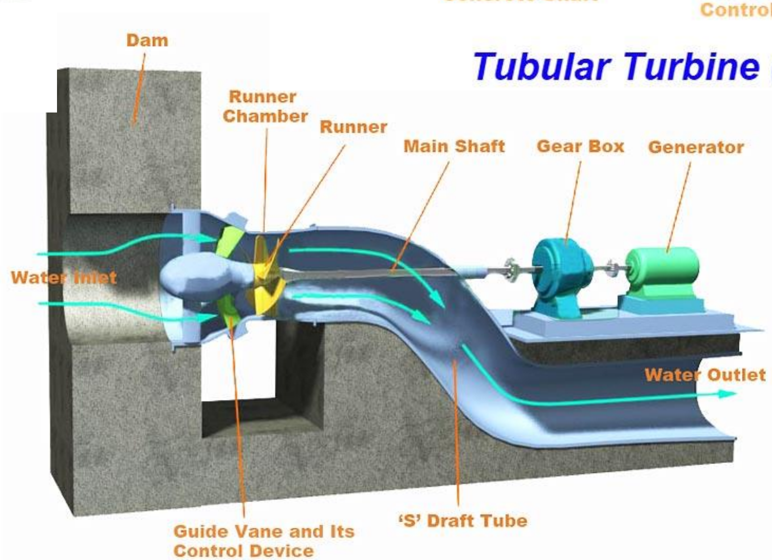
Tubular turbine 2



Tubular Turbine (Bulb Type)



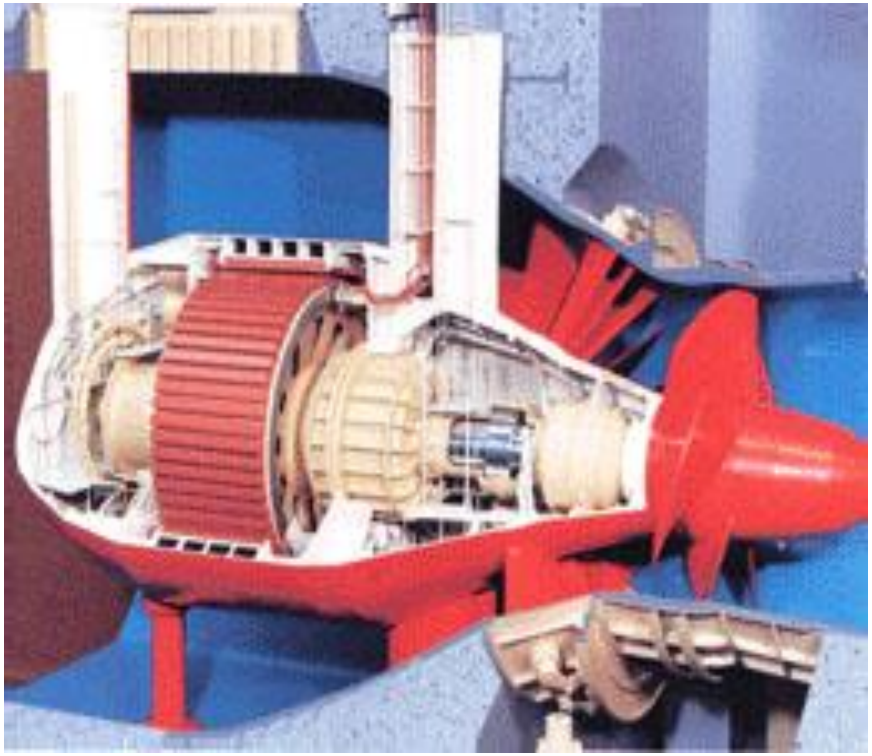
Tubular Turbine (Pit Type)

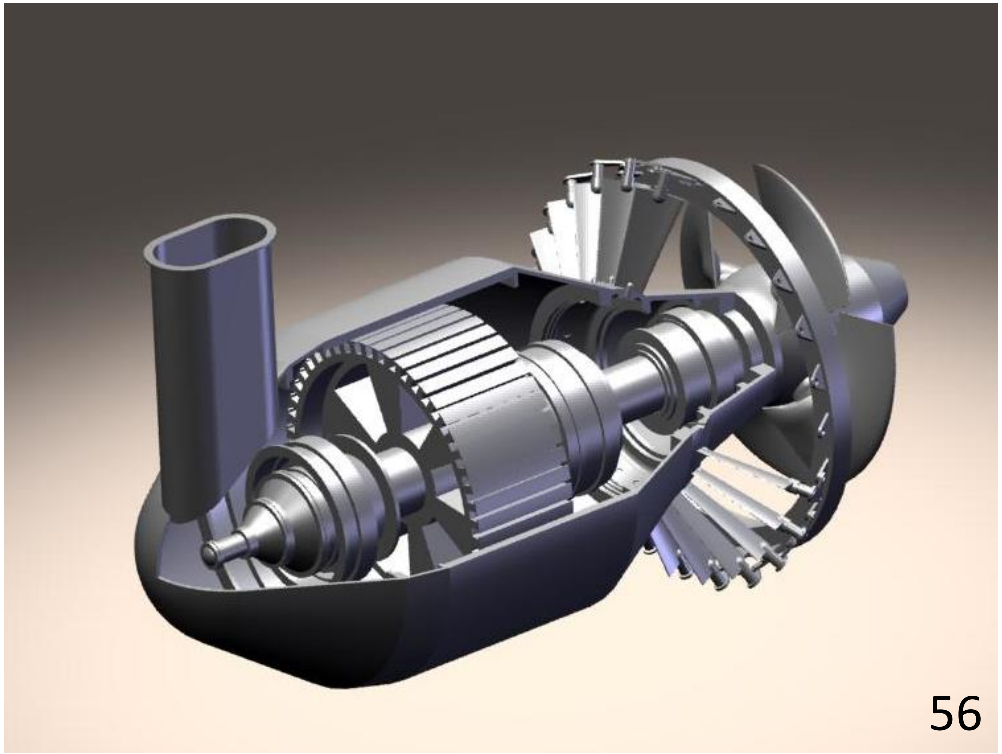


Tubular Turbine ('S' Type)

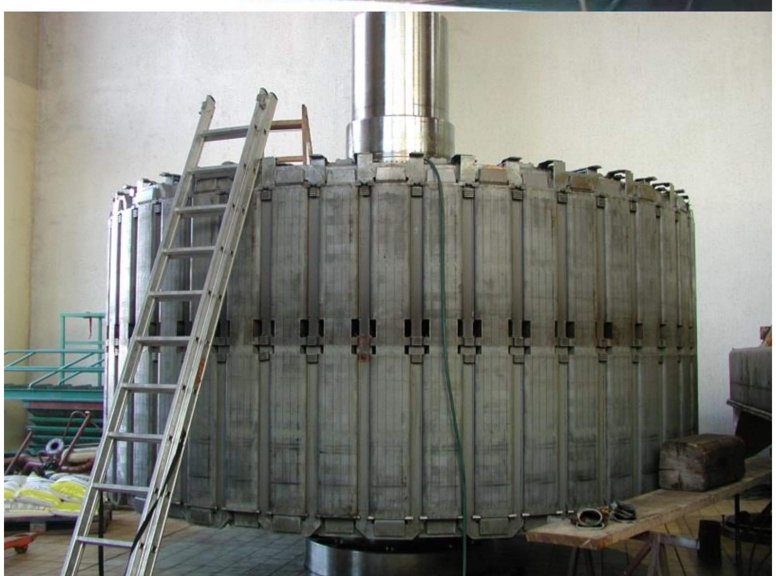
Tubular turbine 3

- Large tubular turbines are made with adjustable runner blades so they can be considered as Kaplan turbines.
- These turbines can develop high power even at very low heads.



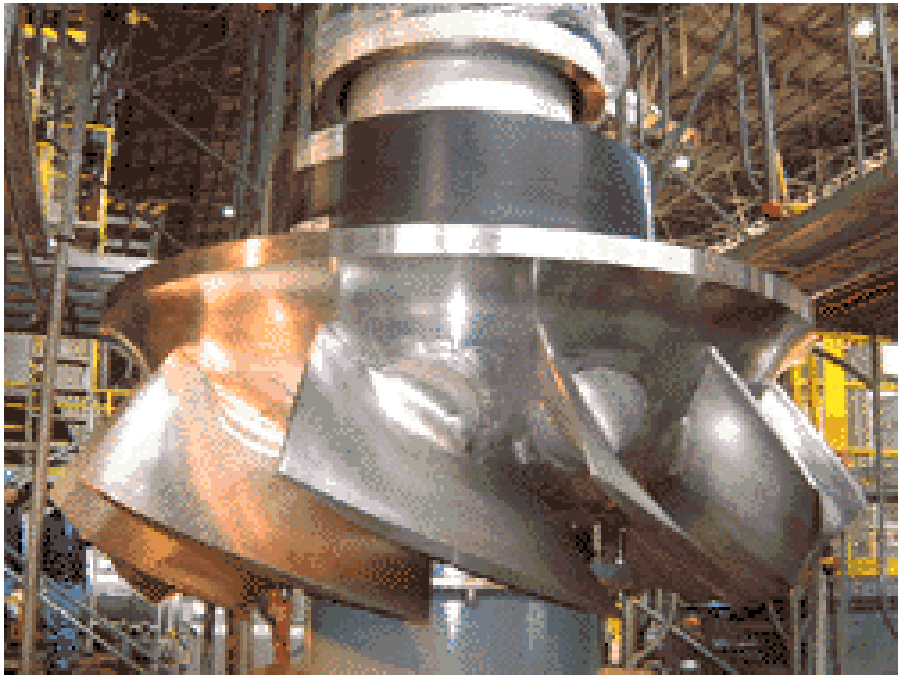


Generator – rotor and stator

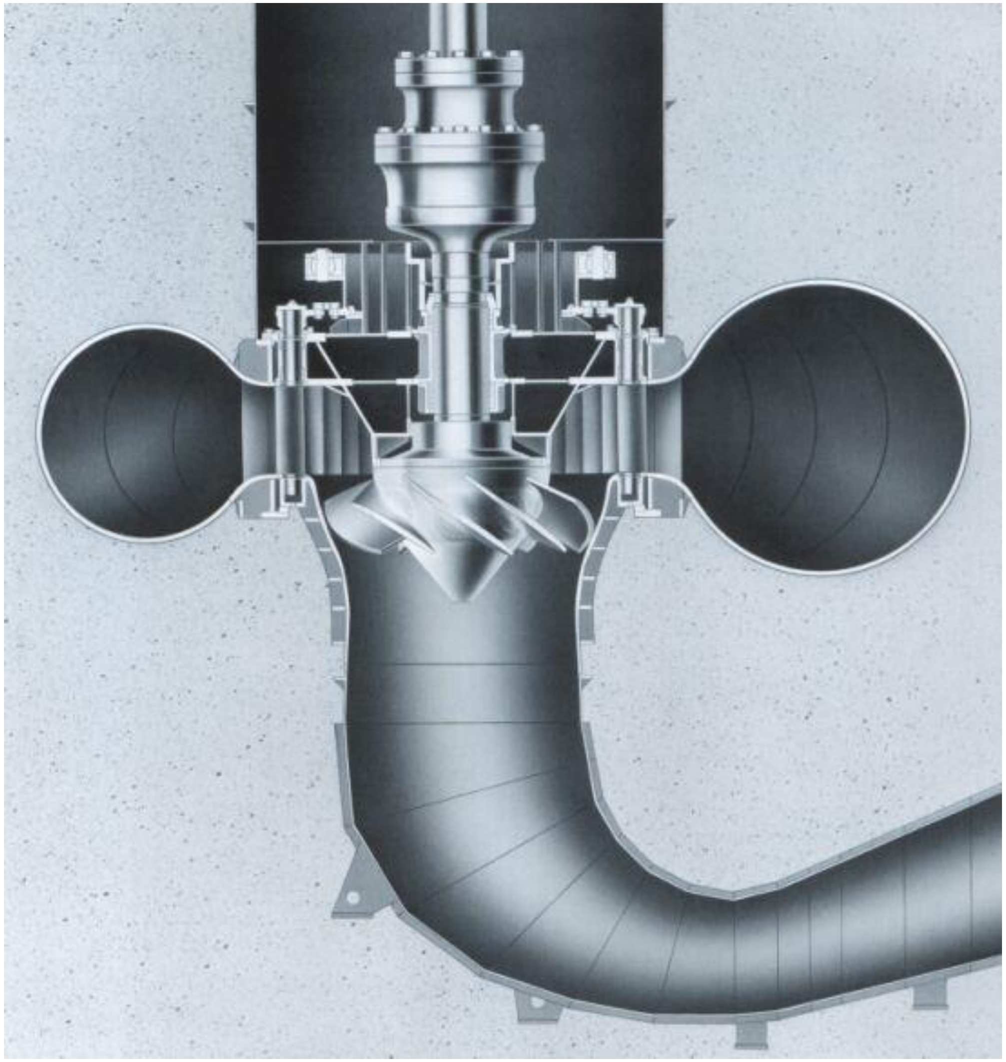


Deriaz (diagonal) turbine 1

- Water flows diagonally through the runner.
- Besides the guide vanes control, rotation of the runner blades is regulated, so double regulation is possible.



Deriaz (diagonal) turbine 2



Deriaz (diagonal) turbine 3

1 , 13 – spiral casing;
2 , 10 – stay vanes;
3 , 9 – guide vanes;
4 , 11 – guide vanes control mechanism;
5 - servo motor;
6 – draft tube;
7 - runner;
8 – head cover;
12 - shaft.