Lecture No 15

Title:
Design and Operation of Hydropower Plants

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Outline

- Introduction
- Types of turbines
  - reaction turbines
  - impulse turbines
- Turbine efficiency
  - Optimal design of the impulse turbines
- Future perspectives

Introduction (1)

- Moving water has much higher power density than moving air
  - This is because of about 800-times higher mass density
- Ocean currents, surface waves and hydropower, driven mainly by winds and latent heat flux, are essentially third-order solar energy
- Tidal water flow is driven by gravity forces
  - it is essentially the only energy form on Earth that does not originate from nuclear energy transformation, either in the Sun or on Earth
- Only hydropower provides today significant amount of energy: 4170 TWh of electricity (2.5% of total) in 2016

Introduction (2)

- Hydro energy is utilised in hydro power stations that capture water flowing from a height, either in rivers, water falls or artificial dams
- The power that can be captured (hydraulic power) is:

$$N_h = \rho g Q H$$

  - where: ρ – water density (kg/m^3), g = 9.81 m/s^2, Q – volumetric flow rate of water (m^3/s) and H is the drop height (m)

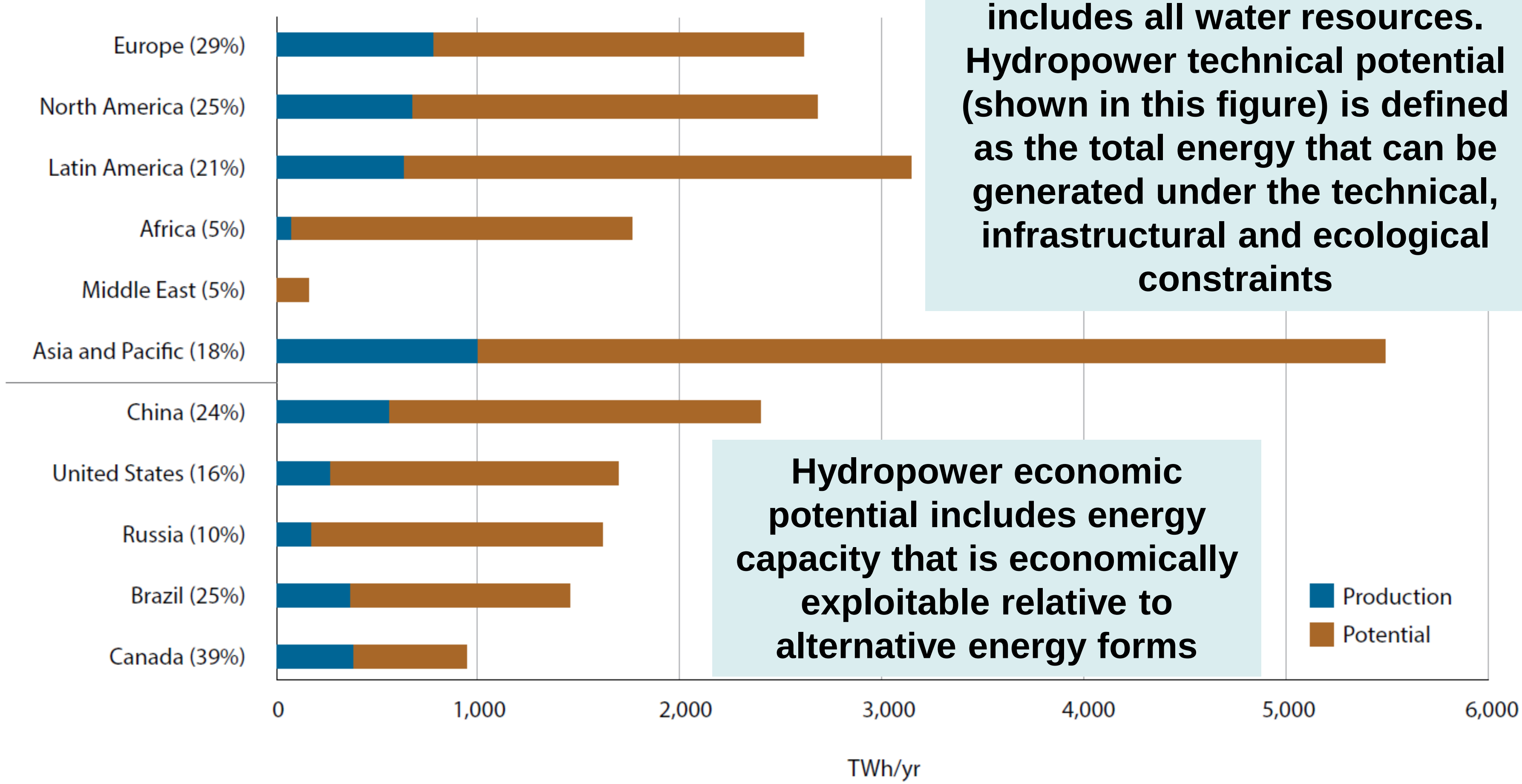
- Natural ranges of Q and H are wide:
  - Niagara Falls: Q = 1420 m^3/s, H = 52 m
  - Val Strem: Q = 0.71 m^3/s, H = 216 m

Introduction (3)

- Hydro power is the most mature of the renewable technologies to generate electricity
  - 70% of all renewable electricity in 2015 originated from hydro power
- Net installed capacity has increased to over 1267 GW in 2017 and the electricity production to 4170 TWh in 2016
- Even though the growth rates are modest in comparison with wind and solar, it will be the dominant renewable technology for the nearest future

Hydropower Production and Potential

Hydropower theoretical potential includes all water resources. Hydropower technical potential (shown in this figure) is defined as the total energy that can be generated under the technical, infrastructural and ecological constraints



Hydropower economic potential includes energy capacity that is economically exploitable relative to alternative energy forms

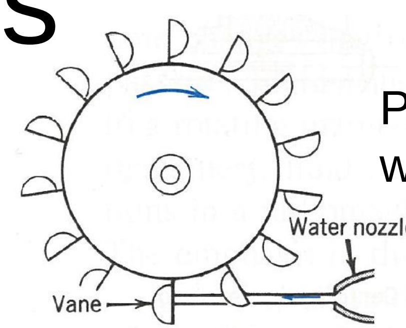
Technical potential and percent of it as production are shown

Hydropower Advantages

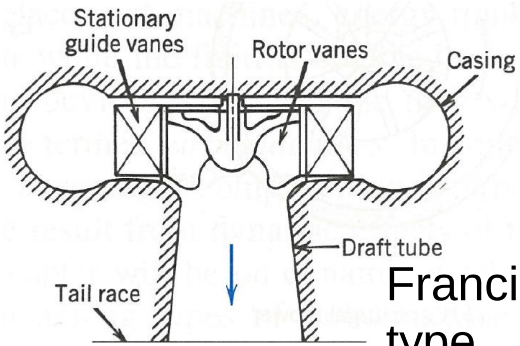
- Apart from attractive economics, there are some other advantages of hydro power
  - water supply fluctuations are far less random than in wind power
  - water can be held in or pumped up into high reservoirs
- thanks to these features hydropower is a popular choice for peak supply and is used to level out fluctuations in electricity demand

Types of Water Turbines

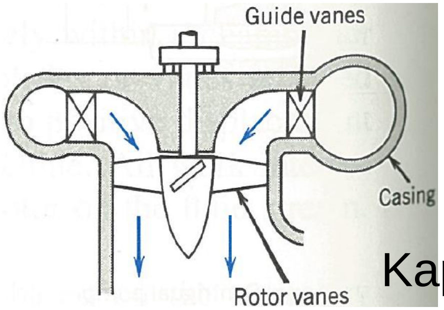
- Hydropower is power derived from the mechanical energy of fluid
- Machines that extract energy from a fluid stream are called **turbines**
- The assembly of vanes, blades, or buckets attached to the turbine shaft are called the **rotor**, **wheel** or **runner**
- In hydraulic turbines the working fluid is water, so the flow is incompressible



Pelton wheel



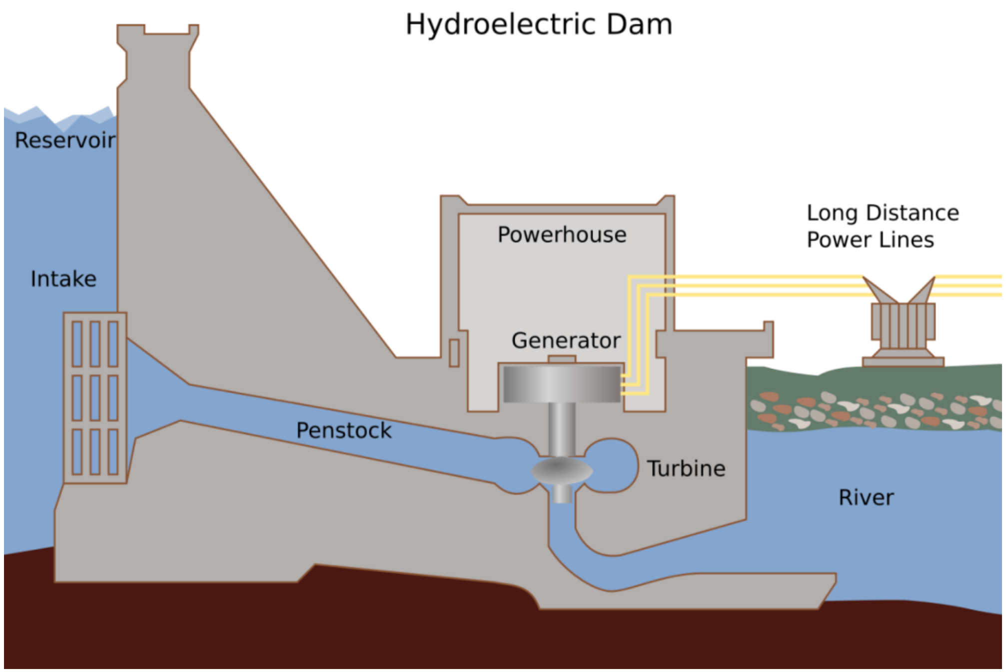
Francis type



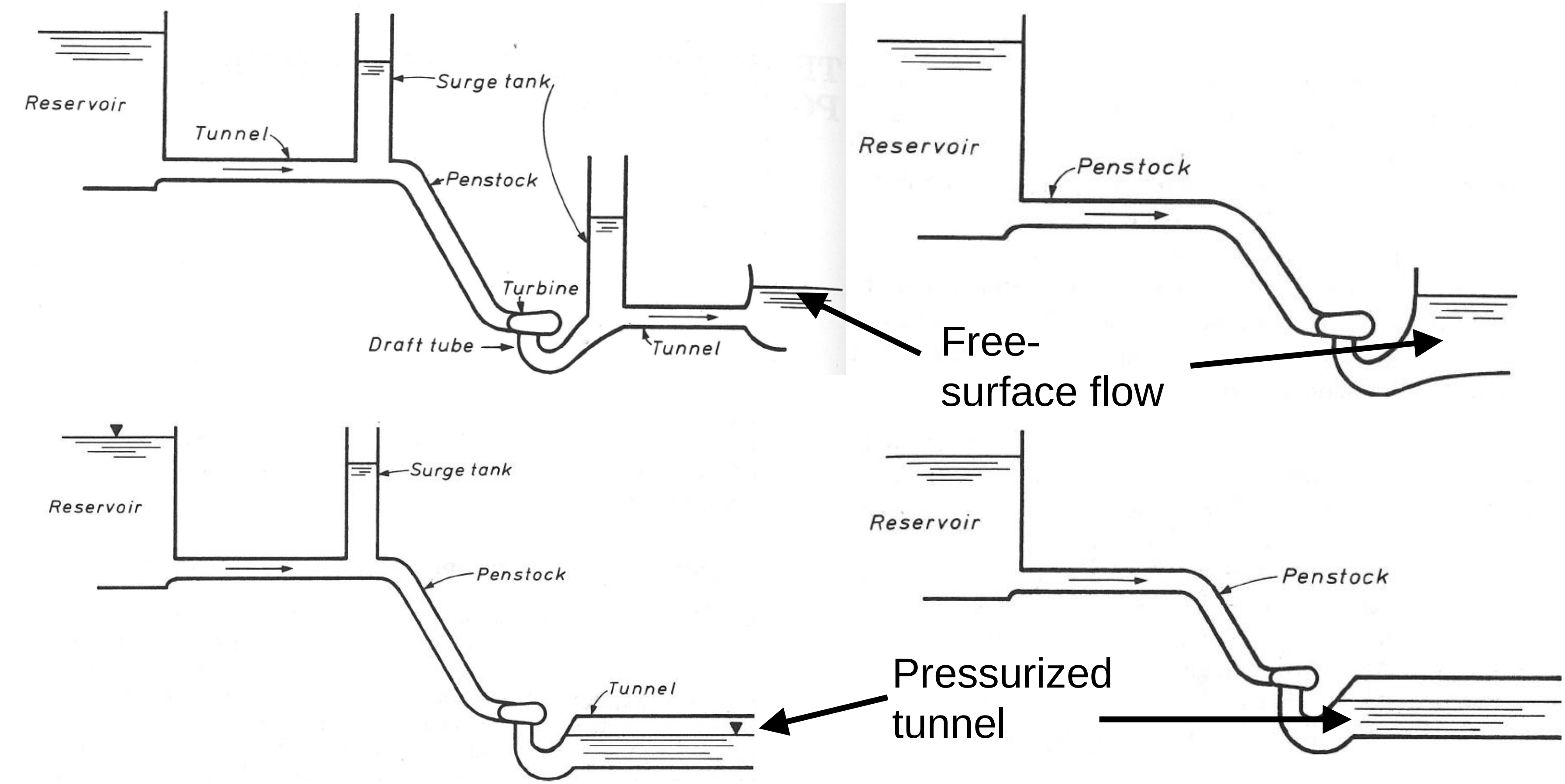
Kaplan type

Schematic of a Hydroelectric Power Plant

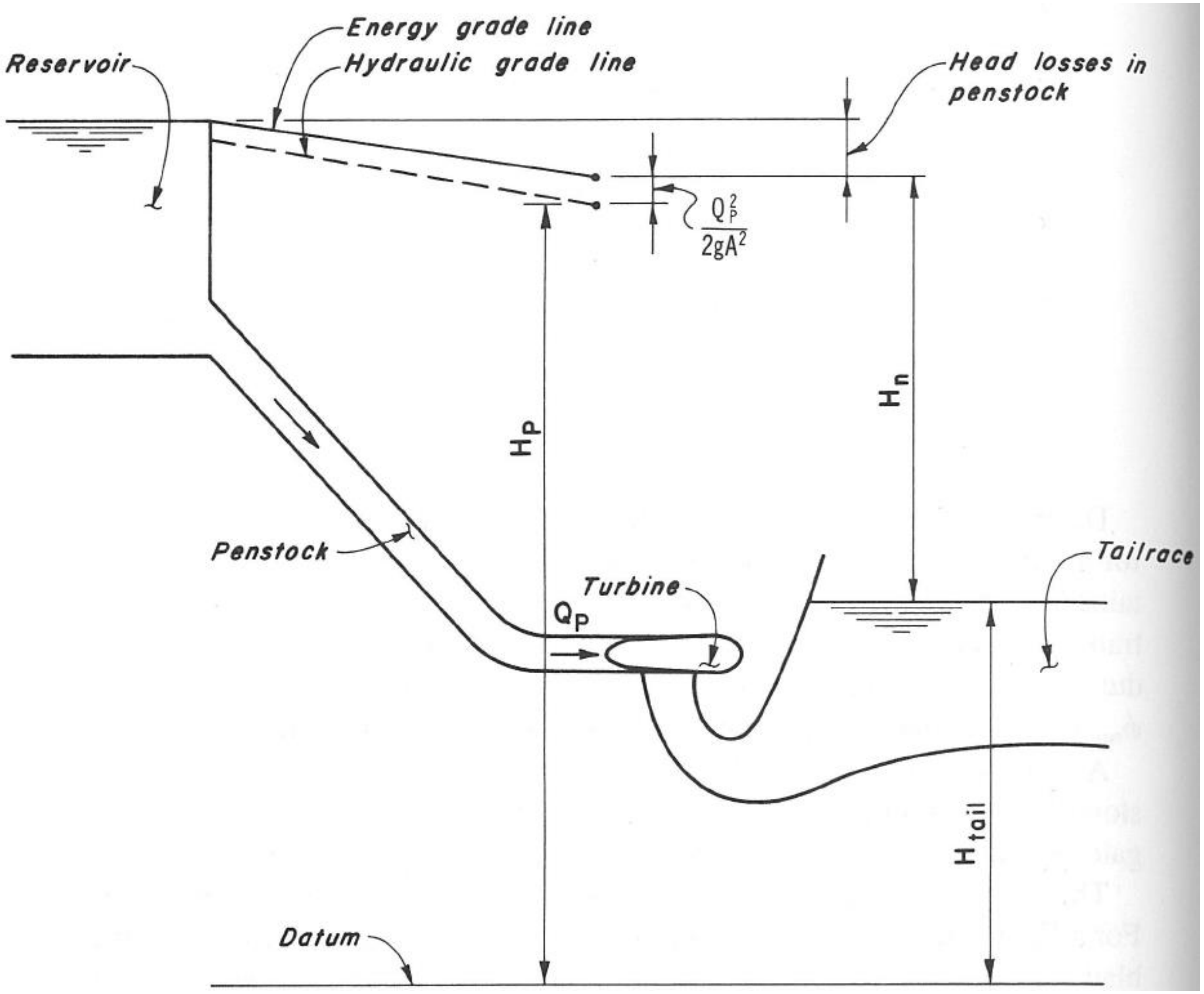
- An upstream conduit (penstock) conveys water from the upstream reservoir to the turbine
- Outflow from the turbine is carried downstream through the conduit system
- An electrical generator is coupled to the turbine



Typical Hydroelectric PP Layouts



Turbine Boundary Conditions



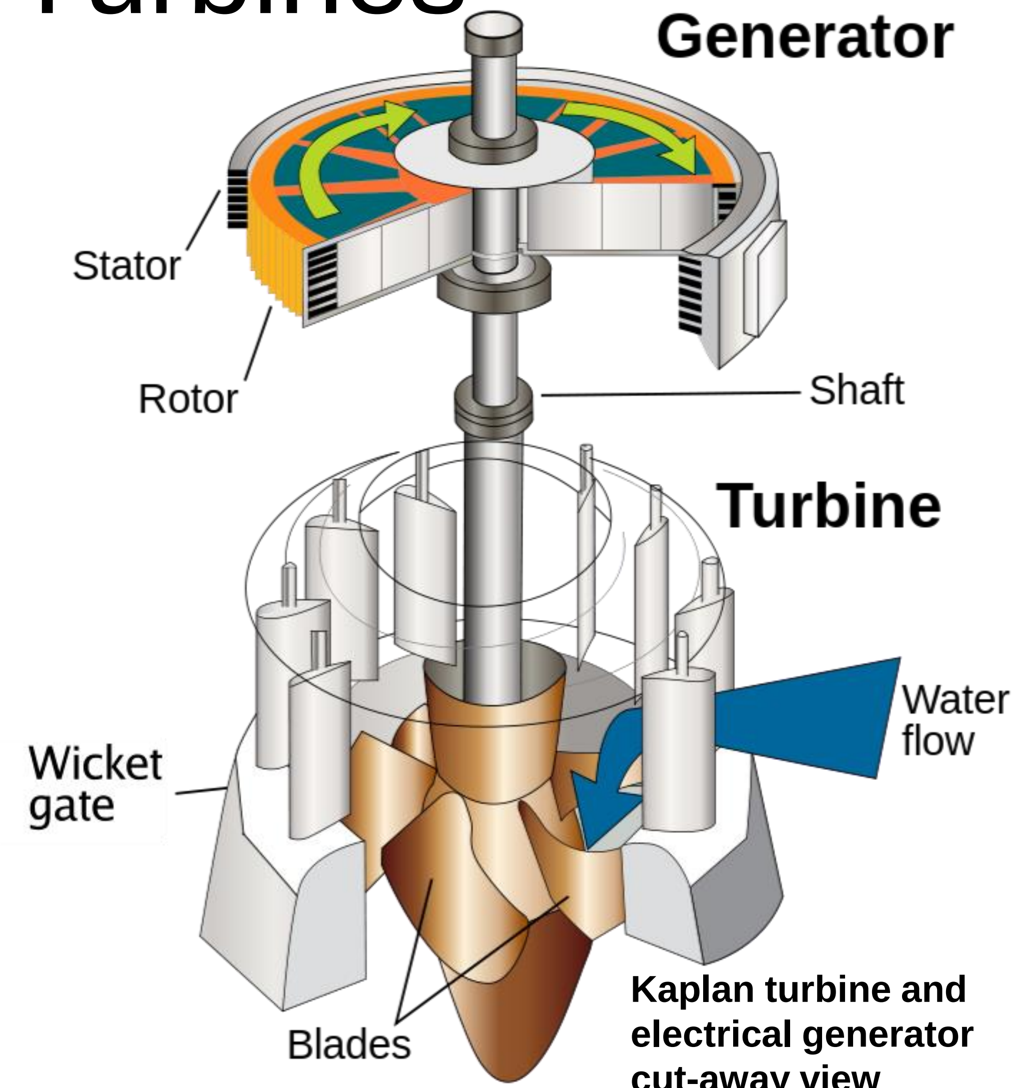
Q_P – volumetric flow to turbine (m^3/s)
H_P – piezometric head at turbine inlet (m)
H_n – net head (m)
H_{tail} – tailwater level above datum (m)
A – cross-section area of the pressure conduit at the turbine inlet (m^2)

$$H_P = H_n + H_{tail} - \frac{Q_P^2}{2gA^2}$$

Water Turbines

Two main types of water turbines:
Impulse turbines – run by a water jet in plane with turbine runner, e.g. Pelton turbine
Reaction turbines – pressure changes within moving blades, e.g. Kaplan and Francis turbines

Type of water turbine is chosen based on the water head:
Kaplan turbine (shown here) applies when water head is low
Francis turbine is used for intermediate water head
Pelton turbine is used for very large water heads and low flows

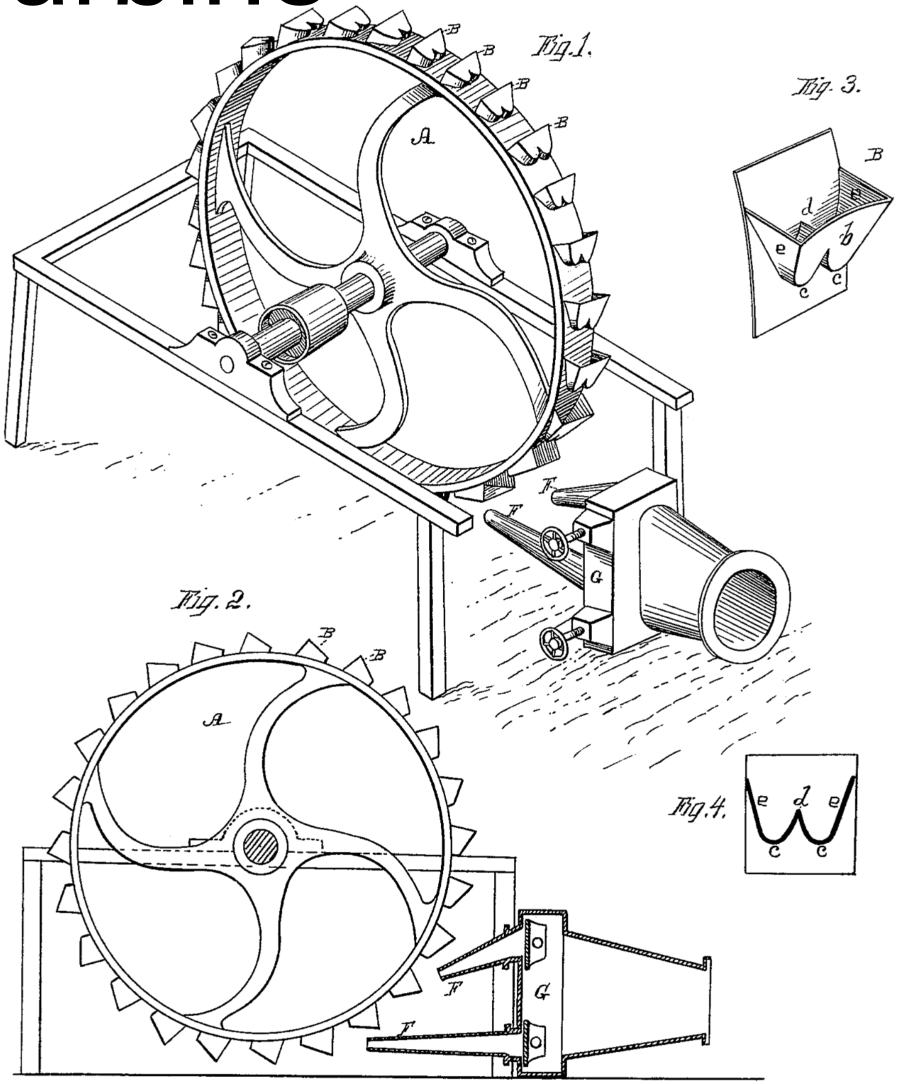


Kaplan turbine and electrical generator cut-away view

Pelton Turbine

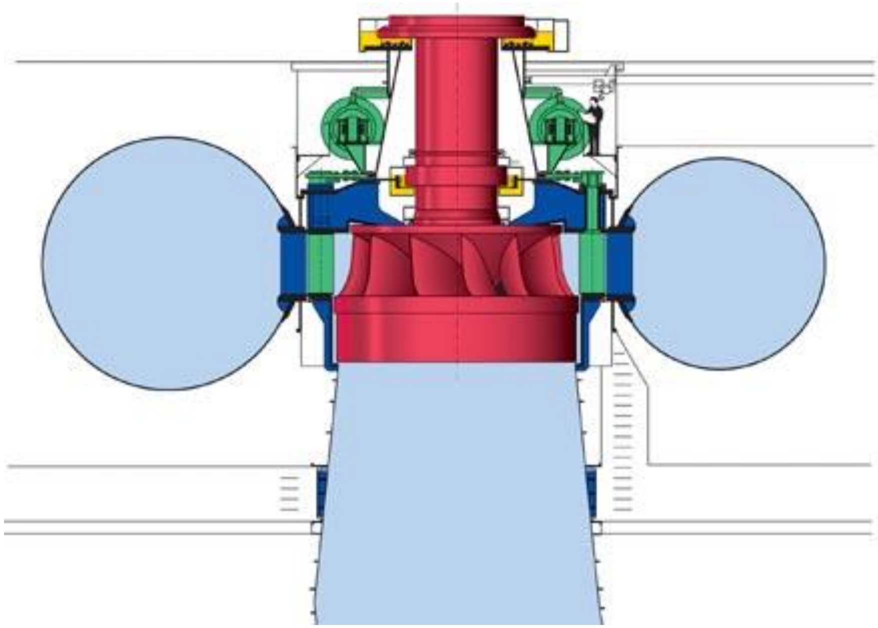
Figure from Pelton's original patent.

Nozzles direct forceful, high-speed streams of water against a series of spoon-shaped buckets, also known as impulse blades, which are mounted around the outer rim of a drive wheel—also called a runner.
The impulse energy of the water jet exerts torque on the bucket-and-wheel system, spinning the wheel



Francis Turbine

Side-view cutaway of a vertical Francis turbine. Here water enters horizontally in a spiral shaped pipe (spiral case) wrapped around the outside of the turbine's rotating *runner* and exits vertically down through the center of the turbine.



Small Francis turbine.
Large Francis turbines are individually designed for each site to operate with the given water supply and water head at the highest possible efficiency, typically over 90%.

Francis Turbine

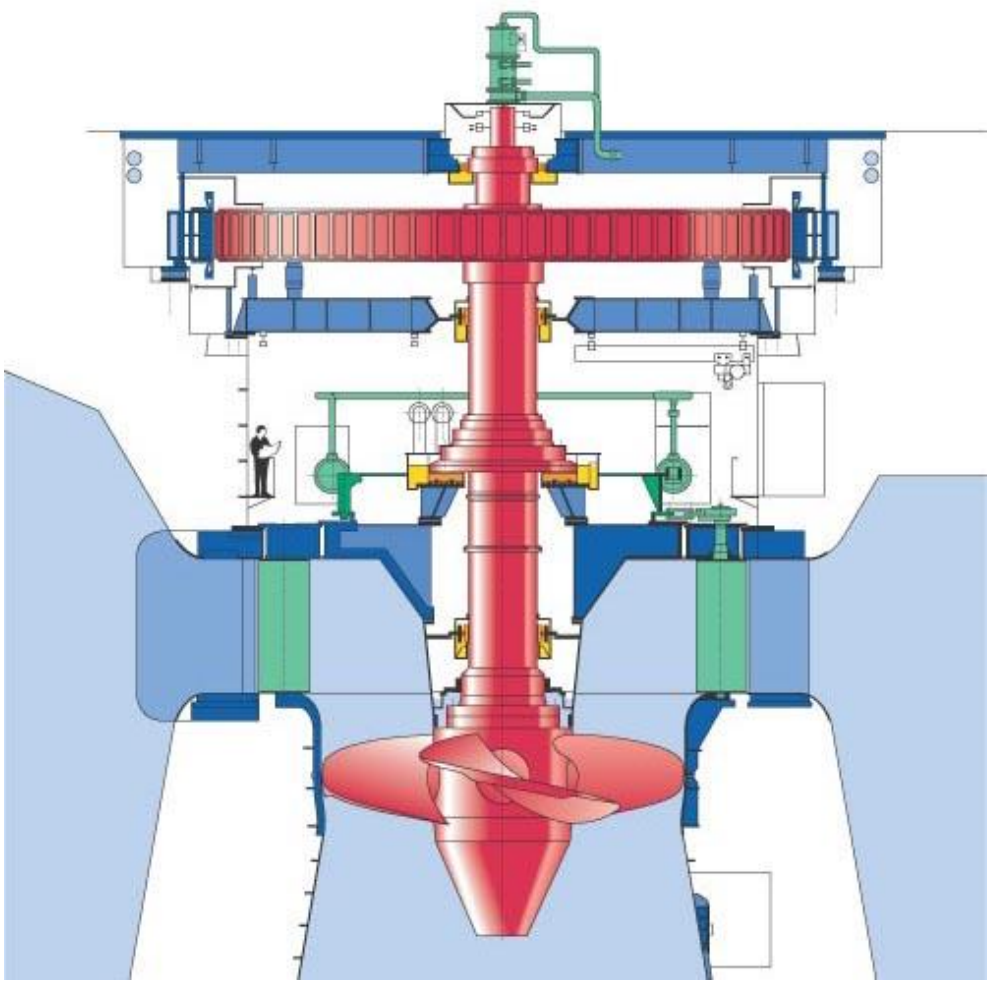
The Francis turbine is a type of reaction turbine, a category of turbine in which the working fluid comes to the turbine under immense pressure and the energy is extracted by the turbine blades from the working fluid. A part of the energy is given up by the fluid because of pressure changes occurring in the blades of the turbine, quantified by the expression of degree of reaction, while the remaining part of the energy is extracted by the volute casing of the turbine.

Three Gorges Dam Francis turbine runner

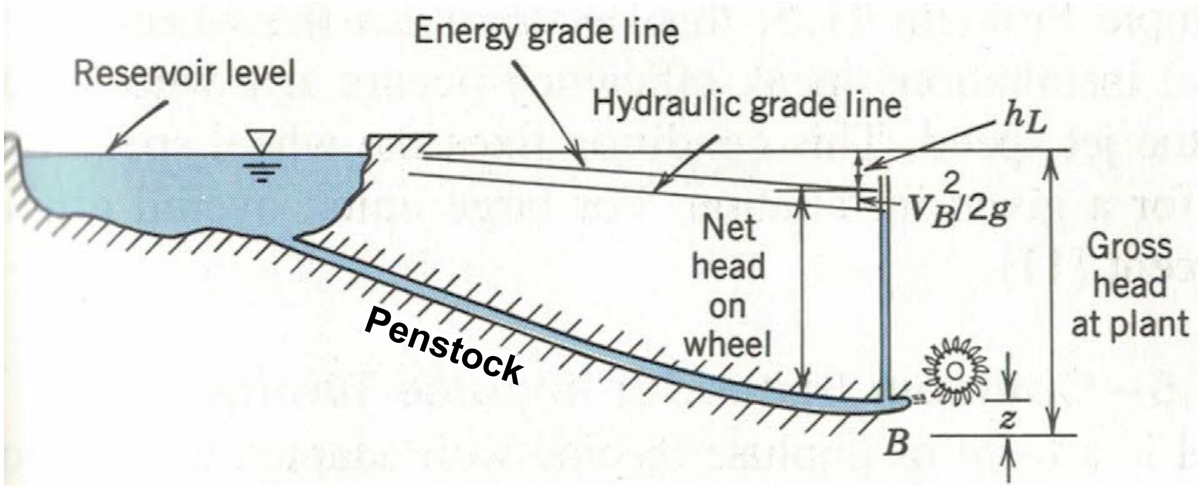
At the exit, water acts on the spinning cup-shaped runner features, leaving at low velocity and low swirl with very little kinetic or potential energy left. The turbine's exit tube is shaped to help decelerate the water flow and recover the pressure.

Kaplan Turbine

The **Kaplan turbine** is a propeller-type water turbine which has adjustable blades.
The Kaplan turbine was an evolution of the Francis turbine. Its invention allowed efficient power production in low-head applications which was not possible with Francis turbines.
The head ranges from 10–70 metres and the output ranges from 5 to 200 MW. Runner diameters are between 2 and 11 metres.
Ecological damage concerns:
- improving survival rate of fish
- preventing oil leakages



Typical Impulse Turbine Installation



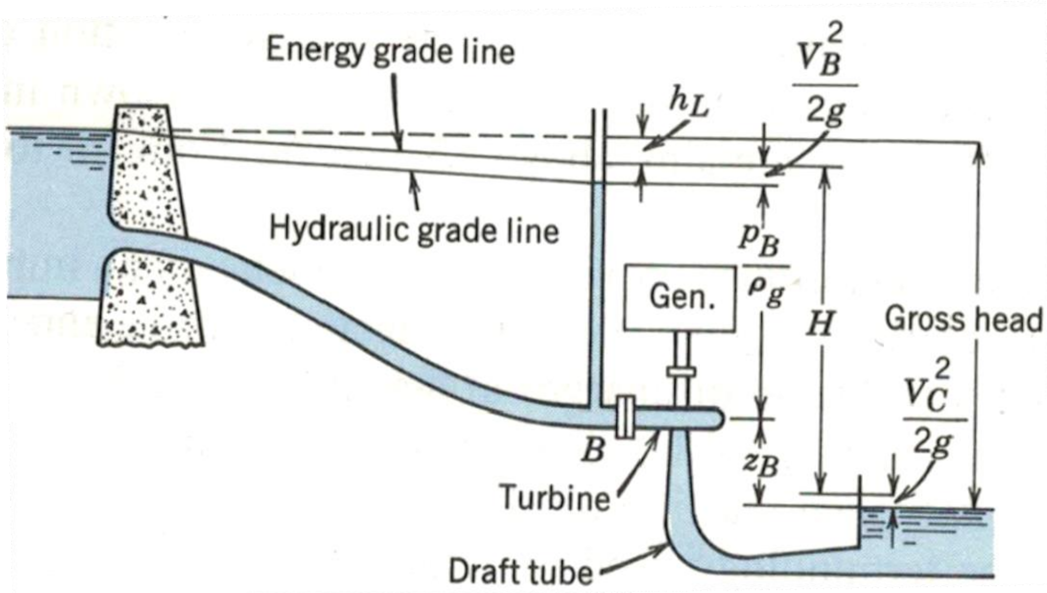
For large units, **overall efficiency** may be up to 88%

Gross head available is the difference between the levels in the supply reservoir (headwater) and the tailrace

The **net (or effective) head** is taken as the difference of the total head at the nozzle entrance and the elevation of the nozzle centreline ***z***

In practice **the penstock is sized** so that at rated power the net head is 85-95% of the gross head.

Typical Reaction Turbine Installation



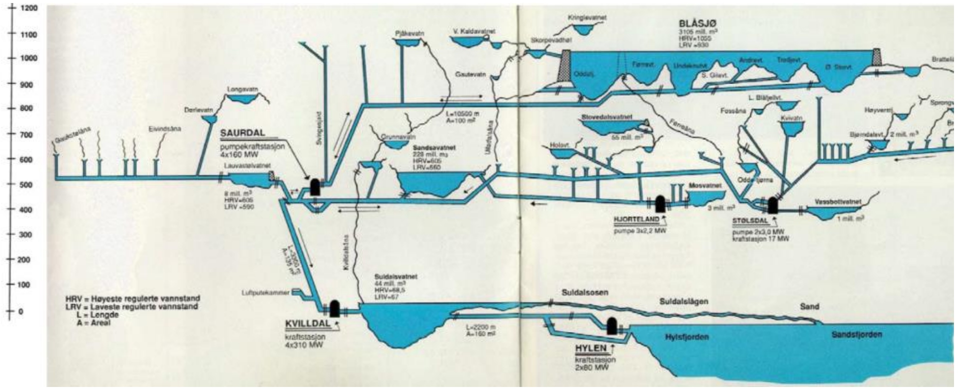
Gross head is the difference between the headwater and the tailwater levels

Net head, *H*, (used to calculate efficiency), is the difference between the elevation of the energy grade line just upstream of the turbine and that of the tailrace

Note the **net head (or effective head)** definition: net head accounts for velocity heads in the headwater and tailwater

Hydropower Plant Design

- Each hydropower is custom-designed to achieve optimal flow conditions
- The design respond to:
  - surrounding topography
  - existing hydrological regime
  - prevailing enviro-nmental and social constraints
  - existing infrastructure



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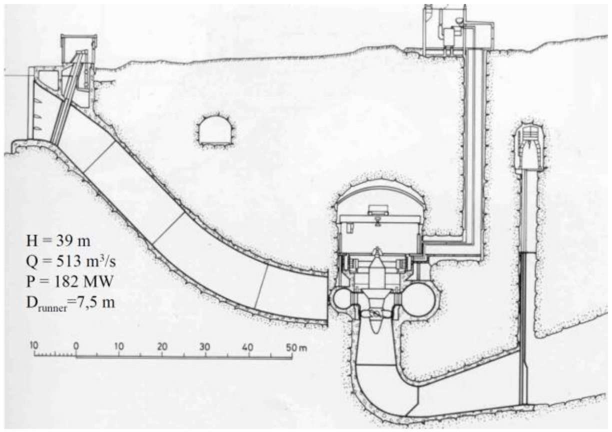


LIGGA power Plant

Classification and Types of HPP

- Even though each hydropower plant is site-specific, they can be classified according to the following parameters
  - Size or installed capacity (micro, small, medium and large)
  - Head availability (high, medium and low)
  - Operation regime (run-of-river, storage, pump storage)
  - purpose of plant structures (energy generation, flood protection, drought mitigation, irrigation, water supply, improved conditions)

Storage (Hoover dam)

Run-of-river HPP (on Rhine)

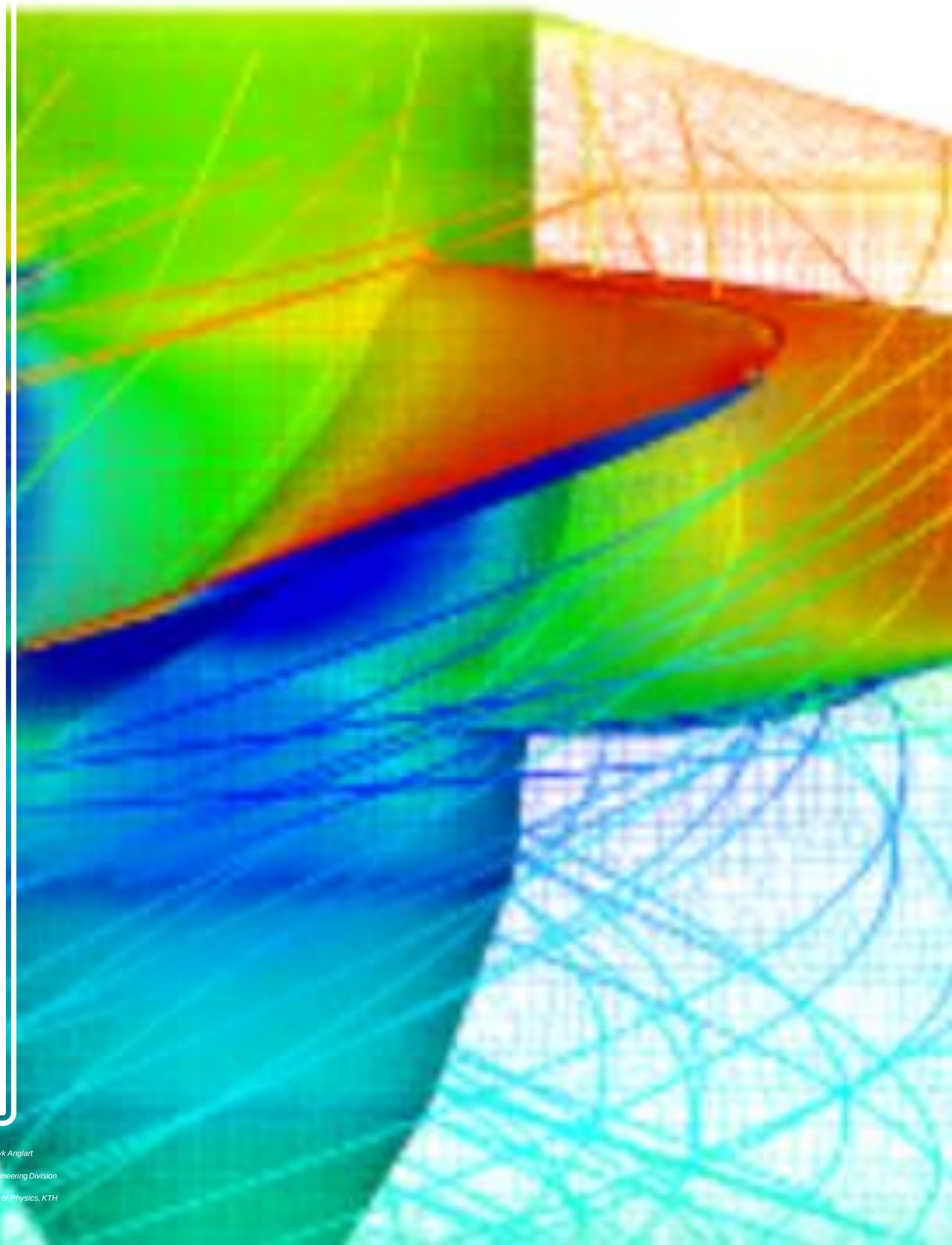
Small Hydro-power Plants

- Small hydro-power plants have emerged recently as a renewable, easily developed, inexpensive energy resource
- Depending on output, they are loosely categorized as:
  - small hydro power systems (2 – 25 MW)
  - mini hydro power systems (100 kW – 2 MW)
  - micro hydro power system (5 – 100 kW)
  - pico hydro power systems (up to 5 kW)

- Such small systems are mainly providing energy to the local community and are not connected to the grid

Turbomachinery Analysis

- Depending on the information needed, various analyses are performed
  - Three-dimensional CFD calculations can provide details of velocity and pressure distributions inside the turbine
    - This can be helpful to optimize the turbine design
  - If overall information on the flow rate, pressure change, torque and power is desired, then a finite control volume analysis is sufficient
- In this course we concentrate on overall analysis using a control volume approach and the angular momentum principle



Angular Momentum Principle

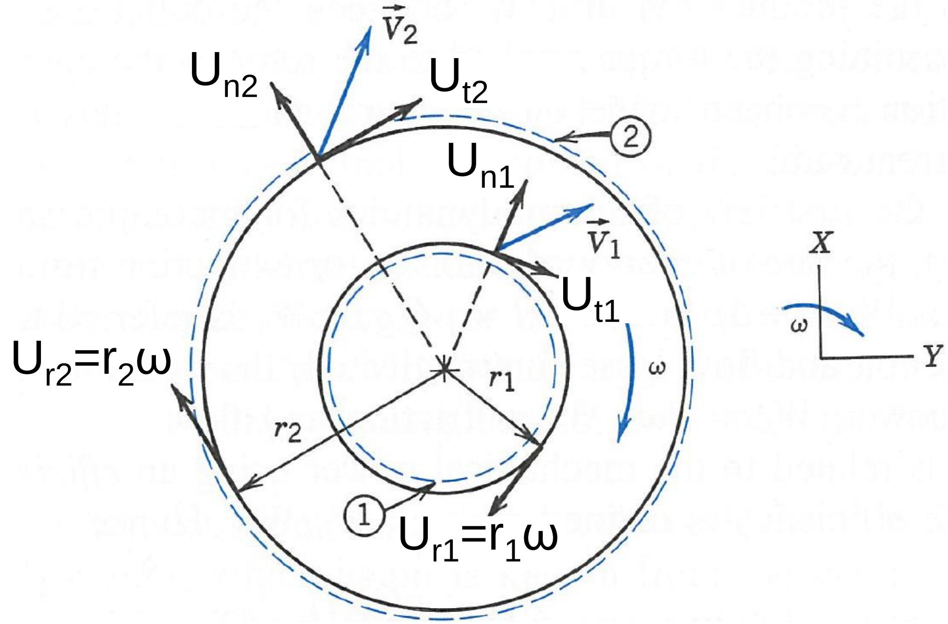
- The angular momentum equation is the fundamental equation used in the design of water turbines
- For turbomachinery (water turbines, pumps, etc) it is convenient to chose a fixed control volume enclosing the rotor and to evaluate the shaft torque
- As first approximation, torque due to surface forces is ignored and body force contribution is neglected by symmetry. What remains is a balance between torque acting on the shaft and the angular momentum of fluid

Euler Turbomachine Equation

The angular momentum equation can be simplified (neglecting friction and gravity) and applied to a control volume enclosing the rotor to evaluate the shaft torque.
As a result, we obtain so-called Euler turbomachine equation

$$T_s = \left(r_2 U_{t2} - r_1 U_{t1} \right) W$$

T_s – shaft torque,
r_1 – fluid entrance radius,
r_2 – fluid exit radius,
U_{1t} – fluid tangential velocity at inlet,
U_{t2} – fluid tangential velocity at outlet
W - mass flow rate through turbine



Control volume of rotor and absolute velocity components for Euler turbomachine equation
ω – angular velocity (rad/s)
$U_{r1,2}$ – rotor blade speed at $r_{1,2}$

Turbine Mechanical Power

The rate of work (power) done on turbomachine rotor is given by a product of rotor angular velocity (ω) and applied torque (T_s):

$$N_m = \omega T_s = \omega\left(r_2 U_{t2} - r_1 U_{t1}\right) W$$

Other useful forms of the equation:

Since $U_r = r\,\omega$, (here U_r is the tangential speed of the rotor at radius r) then:

$$N_m = \left(U_{r2} U_{t2} - U_{r1} U_{t1}\right) W$$

Dividing the equation with Wg we obtain a quantity with dimension of length often termed as **head** (equivalent to energy per unit weight of flowing fluid):

$$H = \frac{N_m}{Wg} = \frac{1}{g}\left(U_{r2} U_{t2} - U_{r1} U_{t1}\right)$$

Turbine Efficiency (1)

For hydraulic turbines the efficiency is defined as:

$$\eta_t \equiv \frac{N_m}{N_h} = \frac{\omega T_s}{\rho Q g H}$$

Here $\mathbf{N_h}$ is the so-called **hydraulic power** determined from the first law of thermodynamics, and ρ is the fluid density.
Correspondingly, $\mathbf{N_m}$ is called a mechanical power, that is the actual power measured on the turbine shaft. $\mathbf{N_m}$ is less than $\mathbf{N_h}$ due to friction and flow losses within turbine. Thus $\eta_t < 1$.
H in the efficiency equation is always the net head of the system

Large turbines can achieve efficiencies of 96% or greater

Turbine Efficiency (2)

- For example, Three Gorges Dam on Yangtze (Chang Jiang) River in Hubei, China, has an average turbine efficiency of η_t=95%

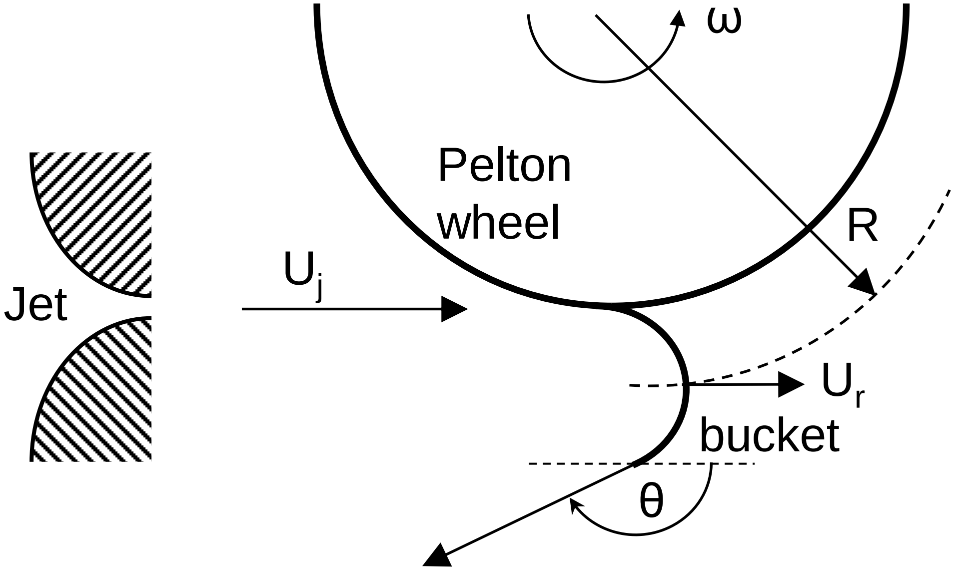
- With a dam height 101 m, a hydraulic head of H=80.6 m, a flow rate of up to 900 m^3/s for each generator, each turbine has a maximum power of $\rho Q g H \eta_t \sim= 676$ MW

- With 32 turbines, the facility has a capacity of about 21.6 GW

Optimum Speed for Impulse Turbine (1)

Assumptions:

Neglect torque due to surface forces
Neglect torque due to body forces
Neglect mass of water on wheel
Steady flow
All jet water acts on the bucket
Bucket height is small compared to wheel, hence $r_1 \sim r_2 \sim R$
No change in jet speed relative to bucket



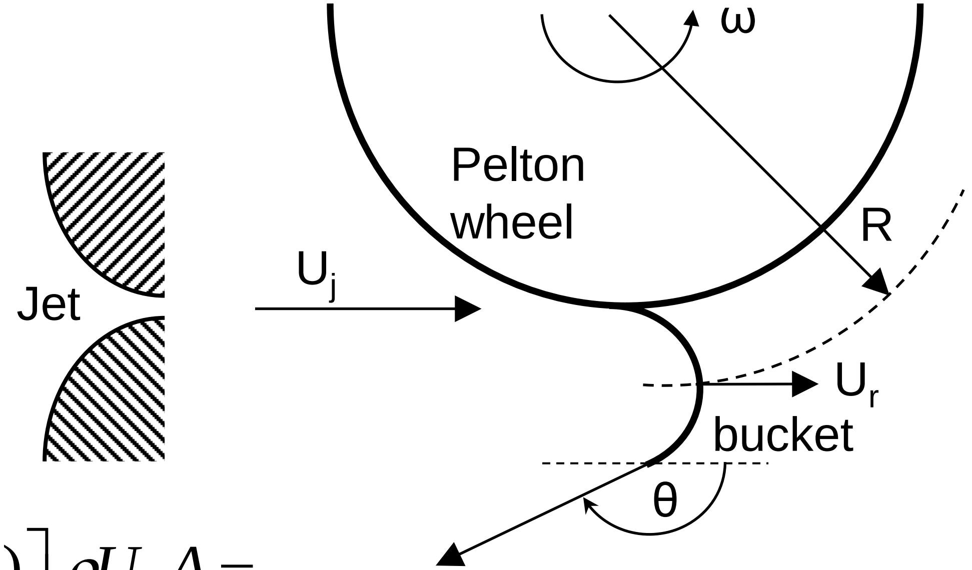
The angular momentum principle gives:

$$T_s = \left(r_2 U_{t2} - r_1 U_{t1}\right) W = \left[R(U_j - U_r)\cos\theta - R(U_j - U_r) \right] \rho U_j A =$$
$$R(U_j - U_r)\rho U_j A(\cos\theta - 1) = \rho Q R(U_j - U_r)(\cos\theta - 1)$$

Optimum Speed for Impulse Turbine (2)

Thus, the angular momentum principle gives: Since:

$$T_s = \left(r_2 U_{t2} - r_1 U_{t1}\right) W$$



we have:

$$T_s = \left[R(U_j - U_r)\cos\theta - R(U_j - U_r) \right] \rho U_j A =$$

$$R(U_j - U_r)\rho U_j A(\cos\theta - 1) = \rho Q R (U_j - U_r)(\cos\theta - 1)$$

This equation gives us a relationship for the torque T_s in terms of main parameters, such as volumetric flow rate Q, wheel radius R, jet velocity U_j, etc

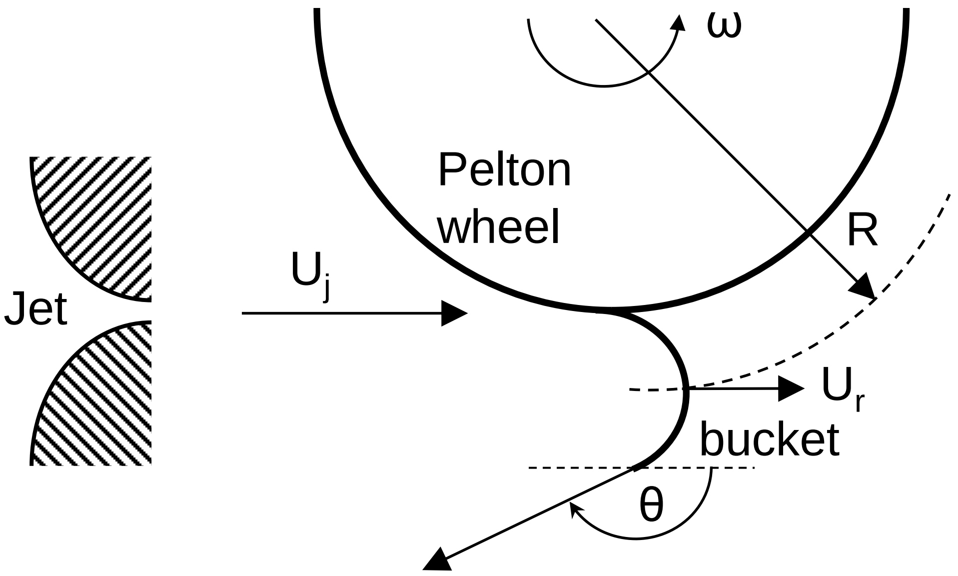
Optimum Speed for Impulse Turbine (3)

Thus, the torque exerted by the shaft on water is:

$$T_s = \rho Q R (U_j - U_r)(\cos\theta - 1)$$

The output torque exerted by water on the wheel is just equal and opposite:

$$T_{out} = -T_s = \rho Q R (U_j - U_r)(1 - \cos\theta)$$



The corresponding hydraulic power output is:

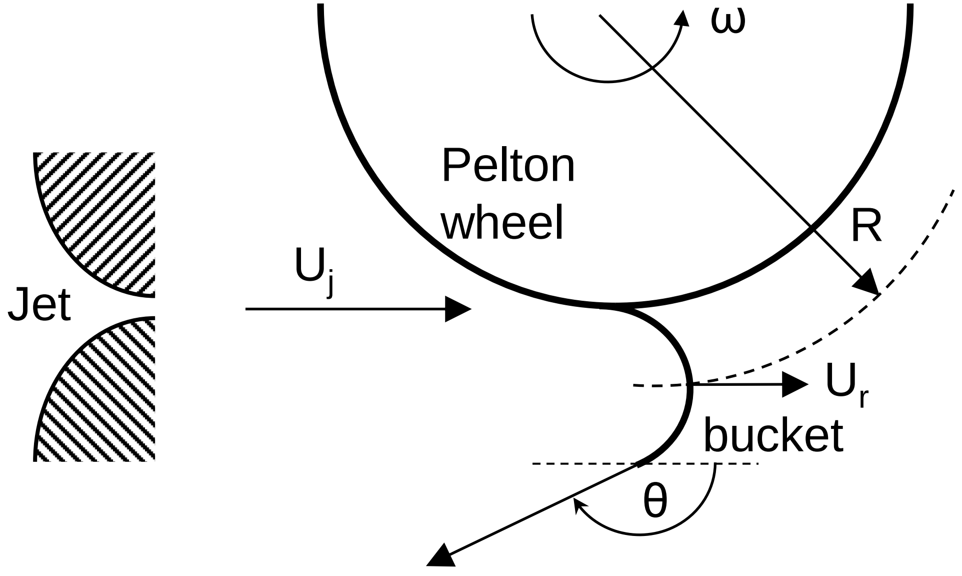
$$N_{out} = \omega T_{out} = \rho Q R \omega (U_j - U_r)(1 - \cos\theta) = \rho Q U_r (U_j - U_r)(1 - \cos\theta)$$

Optimum Speed for Impulse Turbine (4)

The maximum power can be found from: $\frac{dN_{out}}{dU_r} = 0$

Which gives $U_r = U_j/2$, and the corresponding maximum power is

$$N_{out,\max} = \rho Q U_j^2 (1 - \cos\theta)/4$$



Note that the power decreases with decreasing angle θ. The absolute maximum is when θ = 180° and then $N_{out,max} = \rho^* Q U^2/2$.
In practice, 180° angle is not achievable and it can be up to 165°. Then [1-cos(165°)] = 1.97, which gives about 1.5% below the absolute maximum power.

Optimization of Impulse Turbine (1)

It has been shown that the maximum output power of the impulse turbine is obtained when $U_r = U_j/2$ and that it is equal to

$$N_{out,\max} = \rho Q U_j^2 (1 - \cos\theta)/4$$

Since $Q = A_j U_j$, where A_j is the jet cross-section area, then,

$$N_{out,\max} = \rho A_j U_j^3 (1 - \cos\theta)/4$$

Optimization of Impulse Turbine (2)

We apply energy equation for steady incompressible pipe flow through the penstock. Using index 1 for the free surface of the reservoir and index j for the jet at the orifice, we have

$$\frac{p_1}{\rho}+\alpha_1\frac{U_1^2}{2}+gz_1-\left(\frac{p_j}{\rho}+\alpha_j\frac{U_j^2}{2}+gz_j\right)=\left(\xi_{ep}+C_{fp}\frac{4L_p}{D_p}\right)\frac{U_p^2}{2}+\xi_{nozzle}\frac{U_j^2}{2}=h_{loss}$$

Here $p_1 = p_j = p_a$ – pressure at locations (1) and (j) equal to the atmospheric pressure, ξ_{ep} – local loss coefficient at entrance to penstock, L_p – penstock length, D_p – penstock equivalent diameter, C_{fp} – Fanning friction factor in penstock, h_{loss} – total head loss

Optimization of Impulse Turbine (3)

Taking: $U_1 = 0$,
$\alpha_1 = \alpha_j = 1$,
$\xi_{ep} << C_{fp} \times 4L_p/D_p$,
$\xi_{nozzle} = 0$,

$$g\left(z_1 - z_j\right) = gH = C_{fp}\frac{4L_p}{D_p}\frac{U_p^2}{2} + \frac{U_j^2}{2}$$

or

$$U_j^2 = 2gH - C_{fp}\frac{4L_p}{D_p}U_p^2$$

Optimization of Impulse Turbine (4)

The turbine power is now obtained as:

$$N = \rho A_j U_j^3 (1-\cos\theta)\big/4 = U_j \rho A_j U_j^2 (1-\cos\theta)\big/4 =$$

$$U_j \left(2gH - C_{fp} \frac{4L_p}{D_p} U_p^2 \right) \frac{\rho A_j (1-\cos\theta)}{4}$$

From continuity: $U_p = U_j(D_j/D_p)^2$, thus,

$$U_j^2 = 2gH - C_{fp} \frac{4L_p}{D_p} U_p^2 =$$

$$2gH - C_{fp} \frac{4L_p}{D_p} \left(\frac{D_j}{D_p} \right)^4 U_j^2$$

$$\Rightarrow \quad U_j^2 = \frac{2gH}{1 + C_{fp} \frac{4L_p}{D_p} \left(\frac{D_j}{D_p} \right)^4}$$

Optimization of Impulse Turbine (5)

Now the turbine power N can be expressed in terms of the gross head H and ratio D_j/D_p as follows:

$$N = \rho A_j U_j^3 \frac{(1-\cos\theta)}{4} = \rho A_j \frac{(1-\cos\theta)}{4} \left[\frac{2gH}{1 + C_{fp} \frac{4L_p}{D_p} \left(\frac{D_j}{D_p} \right)^4} \right]^{\frac{3}{2}}$$

Optimization of Impulse Turbine (6)

Let us denote $D_j/D_p = x$ and seek the power maximum as a function of *x*:

The power is now:

$$N(x) = \rho \frac{\pi D_p^2}{4} \frac{(1-\cos\theta)}{4} x^2 \left[\frac{2gH}{1 + C_{fp} \frac{4L_p}{D_p} x^4} \right]^{\frac{3}{2}}$$

and its derivative against *x* is:

$$\frac{\mathrm{d}N(x)}{\mathrm{d}x} = \frac{\rho}{gH} \frac{\pi D_p^2}{4} \frac{(1-\cos\theta)}{4} x \left(1 - 2C_{fp} \frac{4L_p}{D_p} x^4 \right) \left[\frac{2gH}{1 + C_{fp} \frac{4L_p}{D_p} x^4} \right]^{\frac{5}{2}}$$

Optimization of Impulse Turbine (7)

We find the turbine power maximum at:

$$x = \left(C_{fp} \frac{8L_p}{D_p} \right)^{-0.25}$$

Thus:

$$D_{j,opt} = \left(\frac{D_p^5}{8C_{fp} L_p} \right)^{0.25}$$

This gives us $U_{j,opt}$:

$$U_{j,opt}^2 = \frac{2gH}{1 + C_{fp} \frac{4L_p}{D_p} \left(\frac{D_{j,opt}}{D_p} \right)^4} = \frac{4}{3} gH$$

Optimization of Impulse Turbine (8)

Finally, the optimum (or maximum) turbine power:

$$N_{opt} = \rho A_j U_{j,opt}^3 \frac{(1-\cos\theta)}{4} = \frac{\rho\pi}{16}\left(\frac{4}{3}gH\right)^{\frac{3}{2}} \frac{(1-\cos\theta)}{4}\left[\frac{D_p^5}{8C_{fp}L_p}\right]^{\frac{1}{2}}$$

The total head loss is:

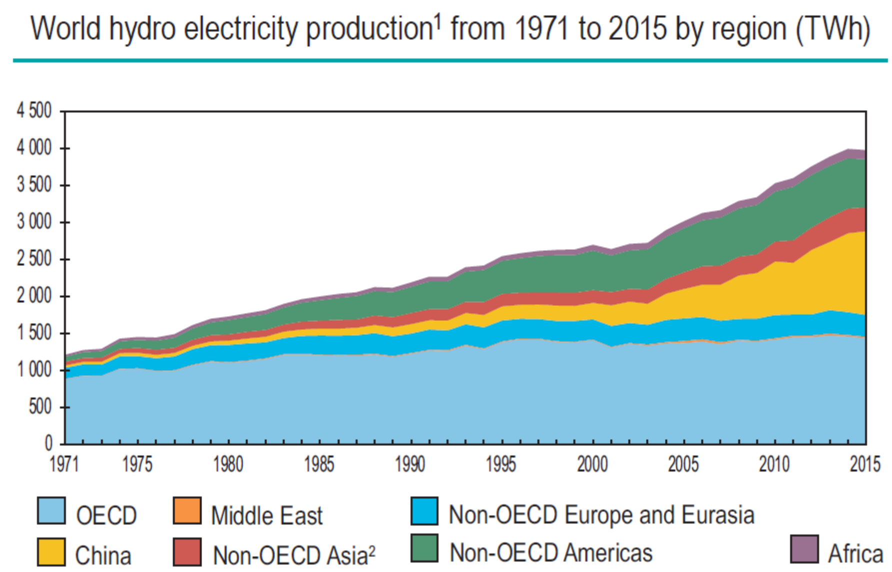
$$h_{loss} = C_{fp}\frac{4L_p}{D_p}\frac{U_p^2}{2} = \frac{1}{3}gH$$

The solution suggests that, at the optimum power, the total head loss is 1/3 of the gross head available at the site. The net head is then 2/3 of the gross head.

Actual practice is to use larger penstocks than suggested here to reduce h_{loss}

Future Perspectives (1)

- Since year ~2003 growth of hydropower has become highest in the history
- However, the total potential for hydropower is limited
- The World Energy Council estimates that about 10000 TWh/y remains that could be exploited, increasing world hydropower by factor 3.7
- The greatest potential is in Asia, Africa and Latin America



Future Perspectives (2)

- In addition to the hydropower, the following moving water power is considered for electricity production:
  - wave power
  - tidal power
  - marine current power

- This power is not harvested in large quantities yet: it produced just over 1 TWh of electric energy from 0.5 GW of installed capacity in 2014
- Nevertheless, all this ocean-based power represents resources similar to the hydropower and it is likely to be harnessed by humans more extensively in the future

Future Perspectives (3)

Wave Energy

- Wave energy is produced when winds blow across the surface of the open ocean
- Average wave power density along the shore can range from a few kW/m to over 60 kW/m
- Wave energy conversion devices (Pelamis, Wave Dragon, oscillating water column with Wells turbines) can capture a substantial fraction of this energy
- Total wave power worldwide is about 2-3 TW
- Only a small fraction of this total power could be ever practically used

Future Perspectives (4)

Marine Currents

- Underwater turbines can be used, in principle, to capture some of the oceanic current energy
- Main challenges are:
  - The most energetic currents (such as Antarctic Circumpolar Current) are in deep oceans, making any construction work practically impossible
  - Using too much of marine current energy (such as for example Gulf Stream) could change their flow pattern with tremendous consequences for the climate

Future Perspectives (5)

Tidal Power

- Tidal power comes from dissipation of Earth's angular momentum through motion of ocean water pulled by the Moon
- Roughly 3.75 TW is dissipated, with a small fraction to increase the Moon's orbital energy
- Most of this power is lost in deep ocean
- It can be effectively harvested only in places with large tidal estuaries fed by narrow channels
- The global potential for tidal power is estimated ~3% (500-1000 TWh/y)
- But only fraction of this would be developed due to environmental, economic and other constraints