Mini-Hydro Power

1. Introduction:

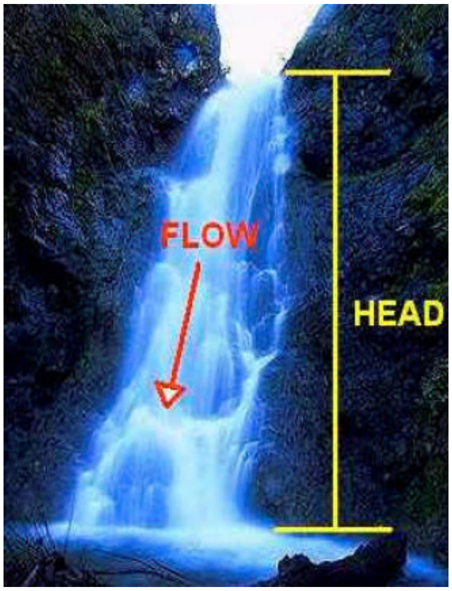
Hydropower is energy from water sources such as the ocean, rivers and waterfalls. “Mini-hydro” means which can apply to sites ranging from a tiny scheme to electrify a single home, to a few hundred kilowatts for selling into the National Grid. Small-scale hydropower is one of the most cost-effective and reliable energy technologies to be considered for providing clean electricity generation. The key advantages of small hydro are:

- High efficiency (70 - 90%), by far the best of all energy technologies.
- High capacity factor (typically >50%)
- High level of predictability, varying with annual rainfall patterns
- Slow rate of change; the output power varies only gradually from day to day (not from minute to minute).
- A good correlation with demand i.e. output is maximum in winter
- It is a long-lasting and robust technology; systems can readily be engineered to last for 50 years or more.

It is also environmentally benign. Small hydro is in most cases “run-of-river”; in other words any dam or barrage is quite small, usually just a weir, and little or no water is stored. Therefore run-of-river installations do not have the same kinds of adverse effect on the local environment as large-scale hydro.

2. Hydro Power Basics:

Head and Flow



Hydraulic power can be captured wherever a flow of water falls from a higher level to a lower level. The vertical fall of the water, known as the “head”, is essential for hydropower generation; fast-flowing water on its own does not contain sufficient energy for useful power production except on a very large scale, such as offshore marine currents. Hence two quantities are required: a Flow Rate of water **Q**, and a Head **H**. It is generally better to have more head than more flow, since this keeps the equipment smaller.

The Gross Head (H) is the maximum available vertical fall in the water, from the upstream level to the downstream level. The actual head seen by a turbine will be slightly less than the gross head due to losses incurred when transferring the water into and away from the machine. This reduced head is known as the Net Head.

Flow Rate (Q) in the river, is the volume of water passing per second, measured in m$_3$/sec. For small schemes, the flow rate may also be expressed in litres/second or 1 m$_3$/sec.

➢ Power and Energy

Power is the energy converted per second, i.e. the rate of work being done, measured in watts (where 1watt = 1 Joule/sec. and 1 kilowatt = 1000 watts).

In a hydro power plant, potential energy of the water is first converted to equivalent amount of kinetic energy. Thus, the height of the water is utilized to calculate its potential energy and this energy is converted to speed up the water at the intake of the turbine and is calculated by balancing these potential and kinetic energy of water.

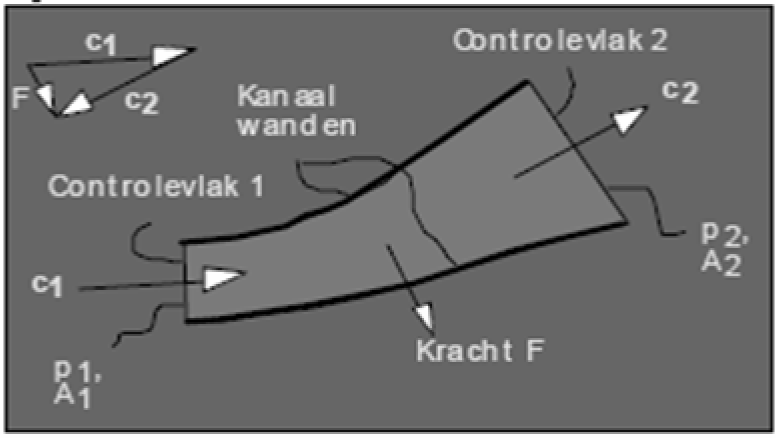
Potential energy of water $E_p = m*g*H$
Kinetic energy of water $E_k = ½ * m *c^2$

Where,

- m is mass of water (kg),
- **g** is the acceleration due to gravity (9.81 m/s^2),
- **H** is the effective pressure head of water across the turbine (m).
- **c** is the jet velocity of water at the intake of the turbine blade (m/s).

Thus, jet velocity $c = \sqrt{(2gH)}$

If a hydro turbine is considered as a system, force equation and Bernoulli's energy equation are applicable for the surface area of the turbine.



Force on control surface = Summation of Impulse and Pressure forces

$$\vec{F}=m\frac{d\vec{v}}{dt} \qquad F = \underbrace{\Phi_m \; \vec{c}_1 - \vec{c}_2}_{\text{impuls}} + \underbrace{p_1 A_1 - p_2 A_2}_{\text{druk}}$$

Also, Bernoulli’s energy equation –

$$p+\frac{1}{2}\rho c^2+\rho g Z=\text{konstant}$$

In the above equations, speed remains constant at inlet and outlet of turbine and so also pressure. Thus, mechanical energy delivered by the turbine is mainly due to the height difference of the hydro system. Hydro-turbines convert water force into mechanical shaft power, which can be used to drive an electricity generator, or other machinery. The power available is proportional to the product of *head* and *flow rate*. The general formula for any hydro system’s power output is:

$$\mathbf{P = \eta\ \rho\ g\ Q\ H}$$

Where:

- **P** is the mechanical power produced at the turbine shaft (Watts),
- **η** is the hydraulic efficiency of the turbine, **ρ** is the density of water (1000 kg/m$_3$),
- **g** is the acceleration due to gravity (9.81 m/s$_2$),
- **Q** is the volume flow rate passing through the turbine (m$_3$/s),
- **H** is the effective pressure head of water across the turbine (m).

The best turbines can have hydraulic efficiencies in the range 80 to over 90%, although this will reduce with size. Micro-hydro systems (<100kW) tend to be 60 to 80% efficient.

- **Capacity Factor**

‘Capacity factor’ is a ratio summarizing how hard a turbine is working, expressed as follows:

Capacity factor (%) =
Energy generated per year (kWh/year) / {Installed capacity (kW) x 8760 hours/year}

- **Energy Output**

Energy is the work done in a given time, measured in Joules. **Electricity** is a form of energy, but is generally expressed in its own units of kilowatt-hours (kWh) where 1 kWh = 3600 Joules and is the electricity supplied by 1 kW working for 1 hour. The annual energy output is then estimated using the Capacity Factor (CF) as follows:

Energy (kWh/year) = **P** (kW) × **CF** × 8760

3. Main Elements of a Hydro Power Scheme:

Main components of a small scale hydro power scheme can be summarized as follows:

- Water is taken from the river by diverting it through an intake at a weir.
- In medium or high-head installations water may first be carried horizontally to the forebay tank by a small canal or ‘leat’.

- Before descending to the turbine, the water passes through a settling tank or ‘forebay’ in which the water is slowed down sufficiently for suspended particles to settle out.
- Forebay is usually protected by a rack of metal bars (a trash rack) which filters out water-borne debris.
- A pressure pipe, or ‘penstock’, conveys the water from the forebay to the turbine, which is enclosed in the powerhouse together with the generator and control equipment.
- After leaving the turbine, the water discharges down a ‘tailrace’ canal back into the river.

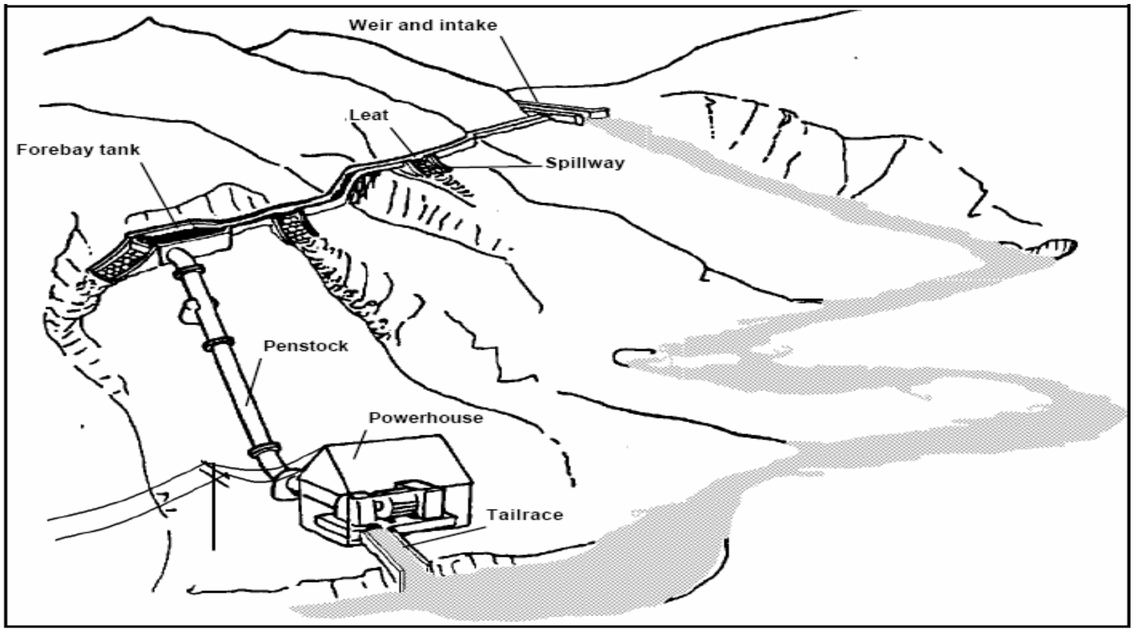


Figure 1: Main components of Hydro power Scheme

Measuring weirs

A flow measurement weir has a rectangular notch in it through which all the water in the stream flows. It is useful typically for flows in the region of 50-1000 l/s. The flow rate can be determined from a single reading of the difference in height between the upstream water level and the bottom of the notch. For reliable results, the crest of the weir must be kept 'sharp' and sediment must be prevented from accumulating behind the weir.

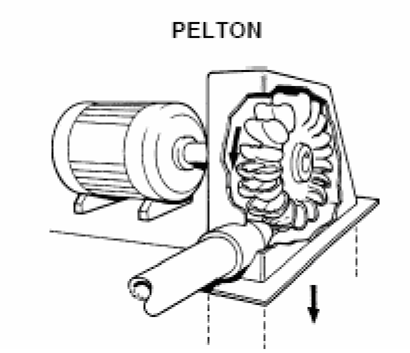
4. Types of turbine:

Turbines can be categorized mainly in two types: Impulse turbine and Reaction turbine.

Turbine Type	**Head Classification**		
	High (>50m)	*Medium (10-50m)*	*Low (<10m)*
Impulse	Pelton Turgo Multi-jet Pelton	Crossflow Turgo Multi-jet Pelton	Crossflow
Reaction		Francis (spiral case)	Francis (open-flume) Propeller Kaplan

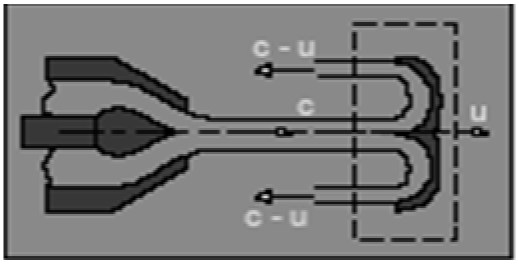
4.1 Impulse Turbines:

There are various types of impulse turbine.



- *Pelton Turbine* consists of a wheel with a series of split buckets set around its rim; a high velocity jet of water is directed tangentially at the wheel. The jet hits each bucket and is split in half, so that each half is turned and deflected back almost through 180º. Nearly all the energy of the water goes into propelling the bucket and the deflected water falls into a discharge channel.

The power output of a Pelton turbine is calculated as follows:



Force (F) acting on the bucket for flow rate (φ_m):

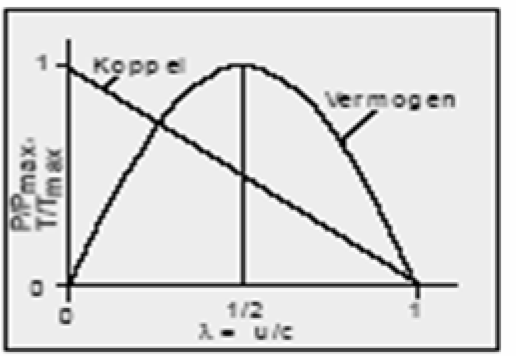
$$\vec{F}=\Phi_m\left(\vec{c}-\vec{u}\right)-(-)\left(\vec{c}-\vec{u}\right)=\Phi_m 2\left(\vec{c}-\vec{u}\right)$$

Torque (T) generated for turbine diameter (D):

$$\vec{T}=\vec{F}\frac{D}{2}=\Phi_m(c-u)D$$

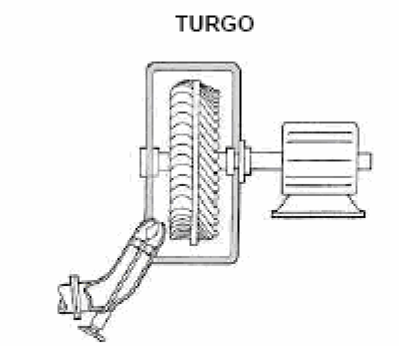
Power Output:

$$P=\omega T=2\Phi_m\left(c-u\right)u \qquad \frac{u}{D/2}=\omega$$



Maximum power output occurs when turbine speed is half of the jet speed as shown below:

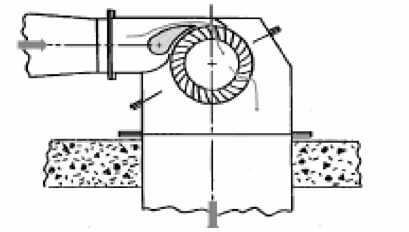
$$\frac{dP}{du}=0=\left(c-2u\right)\Rightarrow u=\frac{1}{2}c$$



- *Turgo turbine* is similar to the Pelton but the jet strikes the plane of the runner at an angle (typically 20°) so that the water enters the runner on one side and exits on the other. Therefore the flow rate is not limited by the discharged fluid interfering with the incoming jet (as is the case with Pelton turbines). As a consequence, a Turgo turbine can have a smaller diameter runner than a Pelton for an equivalent power.

- *Crossflow turbine* has a drum-like rotor with a solid disk at each end and gutter-shaped "slats" joining the two disks. A jet of water enters the top of the rotor through the curved blades, emerging on the far side of the rotor by passing through the blades a 2nd time. The shape of the blades is such that on each passage through the periphery of the rotor the water transfers some of its momentum, before falling away with little residual energy.

CROSSFLOW

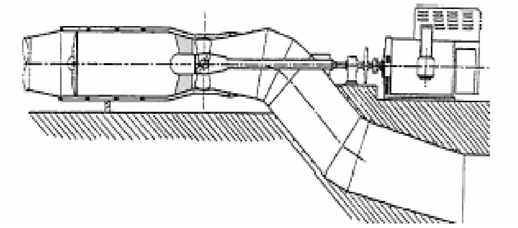


4.2 Reaction Turbines:

Reaction turbines exploit the oncoming flow of water to generate hydrodynamic lift forces to propel the runner blades. They are distinguished from the impulse type by having a runner that always functions within a completely water-filled casing. All reaction turbines have a diffuser known as a 'draft tube' below the runner through which the water discharges. The draft tube slows the discharged water and reduces the static pressure below the runner and thereby increases the effective head.

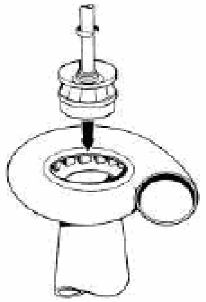
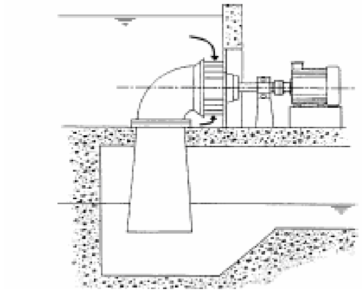
- *Propeller-type turbines* are similar in principle to the propeller of a ship, but operating in reversed mode. Various configurations of propeller turbine exist; a key feature is that for good efficiency the water needs to be given some swirl before entering the turbine runner. With good design, the swirl is absorbed by the runner and the water that emerges flows straight into the draft tube. Methods for adding inlet swirl include the use of a set of guide vanes mounted upstream of the runner with water spiralling into the runner through them.

PROPELLER



- Another method is to form "snail shell" housing for the runner in which the water enters tangentially and is forced to spiral in to the runner. When guide vanes are used, these are often adjustable so as to vary the flow admitted to the runner. In some cases the blades of the runner can also be adjusted, in which case the turbine is called *a Kaplan.* The mechanics for adjusting turbine blades and guide vanes can be costly and tend to be more affordable for large systems, but can greatly improve efficiency over wide range of flows.

- *Francis turbine* is essentially a modified form of propeller turbine in which water flows radially inwards into runner and is turned to emerge axially. For medium-head schemes, runner is most commonly mounted in a spiral casing with internal adjustable guide vanes.

SPIRAL-CASE FRANCIS 	OPEN-FLUME FRANCIS 

Since the cross-flow turbine is less costly (though less efficient) alternative to the spiral-case Francis, it is rare for these turbines to be used on sites of less than 100 kW output. Francis turbine was originally designed as a low-head machine, installed in an open chamber without a spiral casing. Although an efficient turbine, it was eventually superseded by the propeller turbine which is more compact and faster-running for the same head and flow conditions.

5. Design and Selection of Turbine:

For selection of a proper turbine for a specified head (Z) and flow rate (φ_v), turbine diameter (D) and rotational speed of the turbine (ω) play a significant role.

- ***Diameter in relation to head and flow rate:***

$$\Phi_v = \frac{\pi}{4} d^2 \sqrt{2 g Z}$$

or,

$$D = 7{,}7 \frac{\Phi_v^{\frac{1}{2}}}{(g Z)^{\frac{1}{4}}} \qquad 7{,}7 = \Delta, \textit{ specific diameter}$$

- ***Angular velocity in relation to head and flow rate:***

$$\omega = \frac{2u}{D} = \frac{2\,0{,}48\sqrt{2gZ}}{D}$$

or,

$$\omega = 0{,}178 \frac{(g Z)^{\frac{3}{4}}}{\Phi_v^{\frac{1}{2}}} \qquad 0{,}178 = \Omega, \textit{ specific angular velocity}$$

The figure below gives an idea for the selection of a turbine for various combinations of net head and discharge rate.

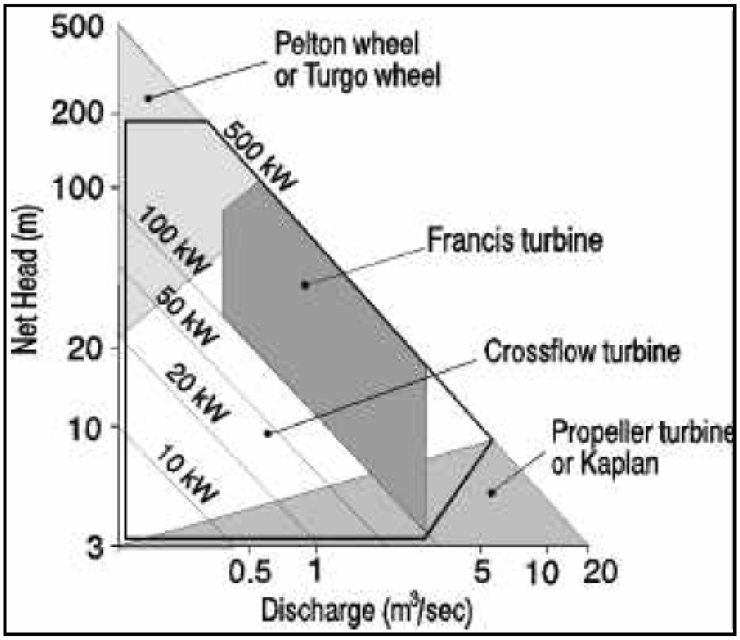
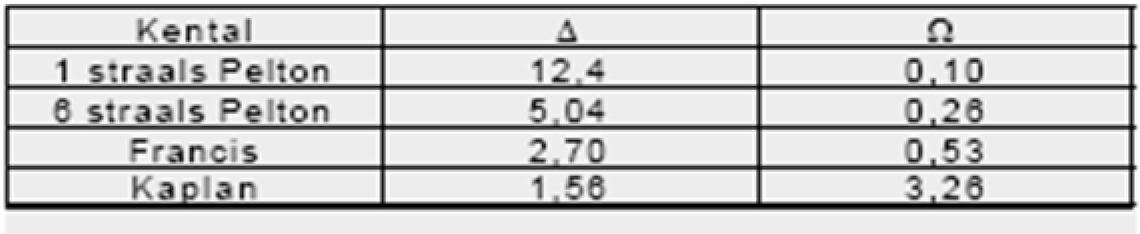


Figure 2: Turbine Selection based on Head and Discharge



Kental	Δ	Ω
1 straals Pelton	12,4	0,10
6 straals Pelton	5,04	0,26
Francis	2,70	0,53
Kaplan	1,56	3,26

At a given head and flow rate:

- Pelton turbine is big and strong, but low throughput and slow. Thus, it is convenient for “high head and low flow”.
- Kaplan turbine is small and fast, high throughput. Thus, it is convenient for “low head, high flow”.

- ***Turbine efficiency:***

A significant factor in the comparison of different turbine types is their relative efficiencies both at their design point and at reduced flows. Typical efficiency curves are shown in the figure below. An important point to note is that the Pelton and Kaplan turbines retain very high efficiencies when running below design flow; in contrast the efficiency of the Crossflow and Francis turbines falls away more sharply if run at below half their normal flow. Most fixed-pitch propeller turbines perform poorly except above 80% of full flow.

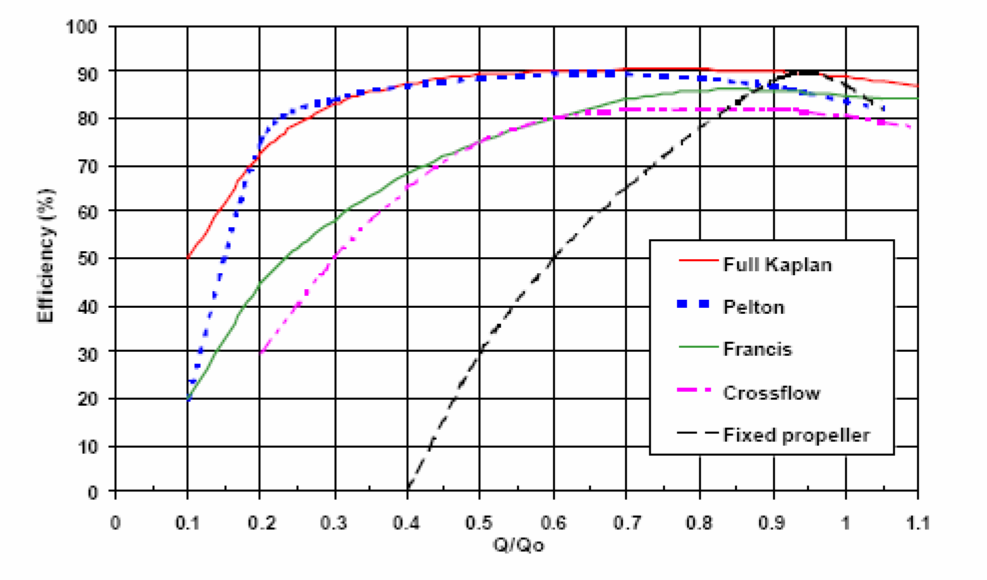


Figure 3: Efficiency of Various Turbines based on Discharge rate