CHAPTER 1

Hydropower Machinery

Introduction

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 utilization of the power in the waterfall is evaluated by the so-called power *plant efficency* η_a, which is the ratio between the mechanical power output from the machine shaft and the gross hydraulic power of the power plant. The plant efficiency η_a is a variabel quantity that depends on the design of the water conduits to and from the hydropower machine and the operating conditions.

The conduits are normally made with flow cross sections according to optimal design criteria. In practise that means conduit cross section areas are as small as possible to get low investment costs. However, the smaller the cross sections are, the higher the losses become. Similar consequenzies are resulting from increasing lengths of the conduits. Both these effects means a correspondingly lower plant efficiency η_a.

The hydropower machine may be operated with different flow rates Q from time to time according to the variable grid load, the alternating heads and flow discharges in the plant. These circumstances means that the hydropower machines necessarily are equipped with facilities for regulation of the power input and output. In practise this is carried out by regulation of the flow discharge.

The input power to the hydropower machine is however, not efficiently similar utilized at all operating conditions. The fact is that the machine performs the optimal efficiency for only one single combination of flow discharge, water head and rotational speed. This means a characteristic, which is denoted as the efficiency of the machine and generally expressed by

$$\eta = \frac{\text{mechanical output power}}{\text{net input power}} \tag{1.1}$$

where *net input power* means the gross hydraulic power of the power plant minus power losses in the conduits to and from the hydropower machine.

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

$$\kappa = \frac{\text{operating discharge}}{\text{discharge at max. efficiency}} \tag{1.2}$$

An example of the efficiency characteristic of a hydropower turbine as a function of the admission, is shown on Fig. 1.1. As being discribed in the following chapters, the efficiency charateristic may be rather different from one turbine type to the other as shown in the example Fig. 1.2.

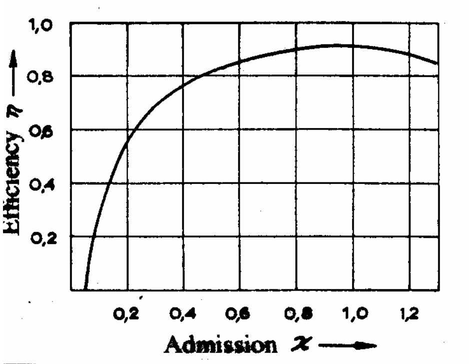


Fig. 1.1 Efficiency of a hydroturbine

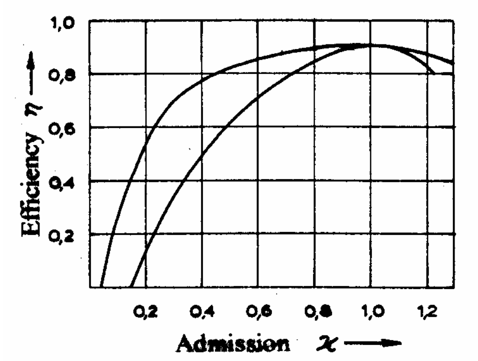


Fig.1.2 Efficiency of two different tubine types

A similar difference may also be found for the same turbine type dependent on the design of the turbine.

By preliminary and approximate evaluations of the output power of hydromachines, the plant efficiency η_a is chosen fairly low, for example η_a = 0.765 at full load. With discharge Q [m^3/s], water head H [m], water density of ρ = 1000 kg/m^3 and the indicated value of η_a the mechanical power output from the machine becomes

$$P = 7.5\ QH \quad [kW] \tag{1.3}$$

1.1 Brief review of hydropower machines

1.1.1 The eldest hydropower machines

The eldest and most primitive type of machines for utilizing water power are the *water wheels*. They were in use in China and Egypt several tousand years ago. The eldest type of these were the *undershot wheels,* Fig. 1.3, which were arranged in the river channel with horizontal shaft. The river water was flowing into the buckets on the underside of the wheel, which in this way was revolved by the velocity energy in the river flow. With this type of water wheels rather low powers were obtained because of low efficiency and the effective flow discharges were small.

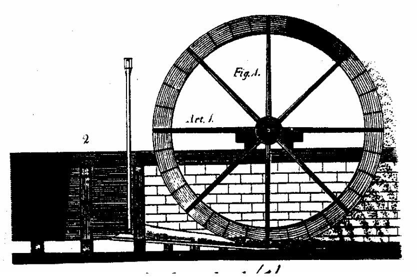
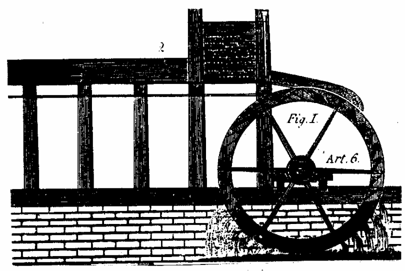


Fig. 1.3 Undershot wheel /1/



F ig.1.4 Overshot wheel /1!

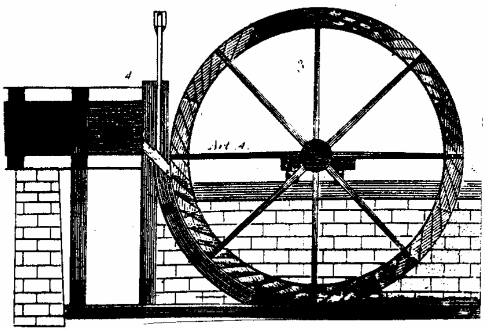


Fig. 1.5 Breast wheel /1/

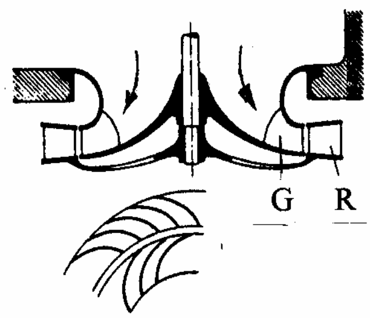
Later on the water wheels were installed in artificial falls that were erected by building a canal to guide the water into the wheel. Depending on the available water head two other wheel types in addition came up to be used. These were the so-called *overshot wheels*, Fig. 1.4, and *breast wheels,* Fig.1.5, which also were arranged with horizontal shaft. On the overshot wheel the water was guided into the buckets on the top side of the wheel, whereas on the breast wheel the water was guided into the buckets somewhere about the height of the wheel shaft. These wheels were revolved by the weight of the water filling in the buckets, and for the best designs of the wheels an efficiency up to 85 % was obtained at water heads higher than three meter.

The water wheels were employed mostly in Middle Europe throughout the Middle Ages. In Norway on the other hand, the so-called *Kvernkallen* (the Old mill-man) was the most widespred hydro machine. This had a vertical shaft to which the runner was fixed. The runner was equipped with radial tilted blades to which the water was flowing along a steep open canal. In this way the Kvernkallen utilized only the velocity energy of the flowing water. And this power transfer went on with relatively great losses especially for the plane blades, and the efficiency might be lower than 50 %..

1.1.2 Turbines

The industrial development throughout the 18. and 19. century the need for more energy was increasing so much that the water wheels no longer got hold of sufficient energy supply. New energy sources like wapour power was adopted, but further development toke place also on utilization of water power. In 1750 the physicist J. A. Segner invented a reaction runner, which has got its name after him. This runner utilized the impulse force from a water jet and was the forerunner of the turbines. Just after this the mathematician Leonard Euler developed the turbine theory, which is valid today too.

Turbine is a designation that was introdused in 1824 in a dissertation of the French engineer Burdin. Next step was made by engineer Fourneyron when he designed and put to operation the first real turbine in 1827. At that time this machine was a kind of a revolution with the unusual great power output of 20 – 30 kW and a runner diameter of 500 mm.



Figur 1.6 Radial turbine of Fournevron /4/

A principle sketch axially through the guide vane cascade G and the runner R of Fourneyron's turbine is shown on Fig. 1.6. Because the water flow has a radial direction through the turbine runner, it may be designated as *radial turbine.*

However, two other turbine designers Henschel and

Jonval,developed about 1840, independent of each other, a turbine each with axial water flow through it. In addition they were the first ones to apply draft tube and in that way to utilize the water head between runner outlet and tail water level.

In the time interval until 1850 several designers improved the machines, but most serious was the work by the English engineer Francis. He developed and made a turbin in 1849, which has got its name after him. This turbine looked fairly similar to that one Euler had foreseen. An axial section through the guide vane cascade and the runner of this turbine is shown on Fig. 1.7. The water flows radially through the guide vane cascade G towards the runner R and further out in the axial direction.

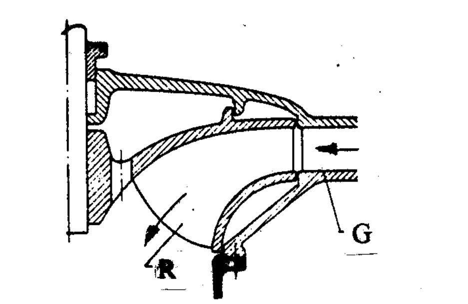
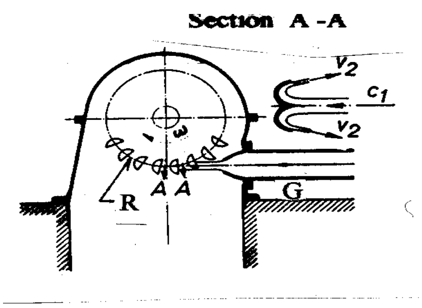


Fig. 1.7 Axial section of Francis turbine /4/

In the year 1870 professor Fink introdused an important improvement by making the guide vanes turning on a pivot in order to regulate the flow discharge.

The turbines mentioned above, were operating at relatively low heads compared with turbines nowadays. Addionally the water was flowing into the turbine runner with a certain pressure above the atmospheric through a guide vane cascade comprising the whole periphery of the runner. A turbine design principally different from these, was developed by the American engineer Pelton. He made his first runner in 1890, and Fig. 1.8 shows that the water in this case flows as a jet from a nozzle through atmospheric air into the runner buckets. The buckets are designed to split the jet in two halves, which are deflected almost 180^o before they leave the buket. In this way the impulse force from the deflection is transferred to the runner. By the invention of the Pelton turbine a machine type was developed for utilization of the highest water heads in the nature.



Figur. 1.8 Principle of Pelton turbine /2/

In the region of low pressure turbines a great step forward was made when professor Kaplan designed his propeller turbine, which was patented in 1913. This turbine had fixed runner blades, and was developed for utilizing the lowest water heads. Fig. 1.9 shows an axial section through a Kaplan turbine. Not very long after making the propeller turbine, Kaplan further developed his turbine by making the runner blades revolving. This was an important improvement for an economic and efficient governing of the turbine output.

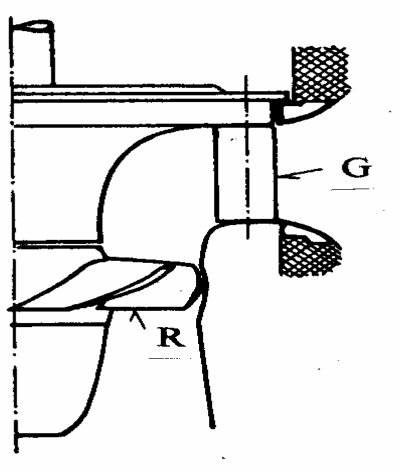


Fig. 1.9 Kaplan turbine /2/

After the brief review above of the hydropower machines, one can summerize that the only machine types that have been developed to be dominant in modern times are Pelton, Francis and Kaplan turbines. The reason is that these three types supplement each other in an excellent way. As a basic rule one can say that Pelton turbines are used for relatively high heads and small water discharges, Kaplan turbines for the lowest heads and the largest water discharges and Francis turbines for the region between the other two turbine types.

1.2 Arrangement of hydropower plants

The discharge operating a water turbine, is conveyed from a river or a water course through an intake and a conduit to the turbine. From the turbine the discharge is conducted through a so-called tail rase canal to a downstream river course.

A brief review of the main details in a hydropower plant is given in the following sections. Fig. 1.10 shows schematically an example of a plant arrangement with indication of the localisation of the details to be mentioned.

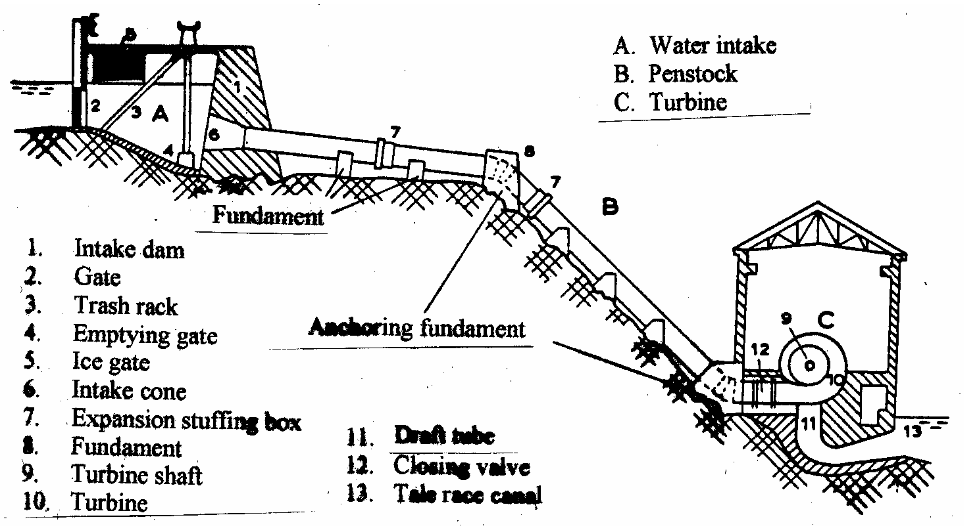


Fig. 1.10 Arrangement of a hydropower plant /2/

Fig.1.11 shows in principle /3/ the water conduits of a traditional Norwegian power plant with a high head Francis turbine. Downstream from the upstream reservoir the coarse trash rack, intake gate, head race tunnel, surge shaft, sand trap, fine trash rack, penstock isolating valve with air valve, pressure shaft, spherical valve, turbine, draft tube, draft tube gate, outlet surge shaft and tale race tunnel.

Water intake

The water intake is normally constructed in connection with an accumulation dam (1) Fig.1.10, in the river course.

The shallow water intake is equipped with a *coarse trash rack* (3) which prevents trees, branches, debris and stones from entering the conduit system to the turbine. An *intake gate* (2) is arranged to

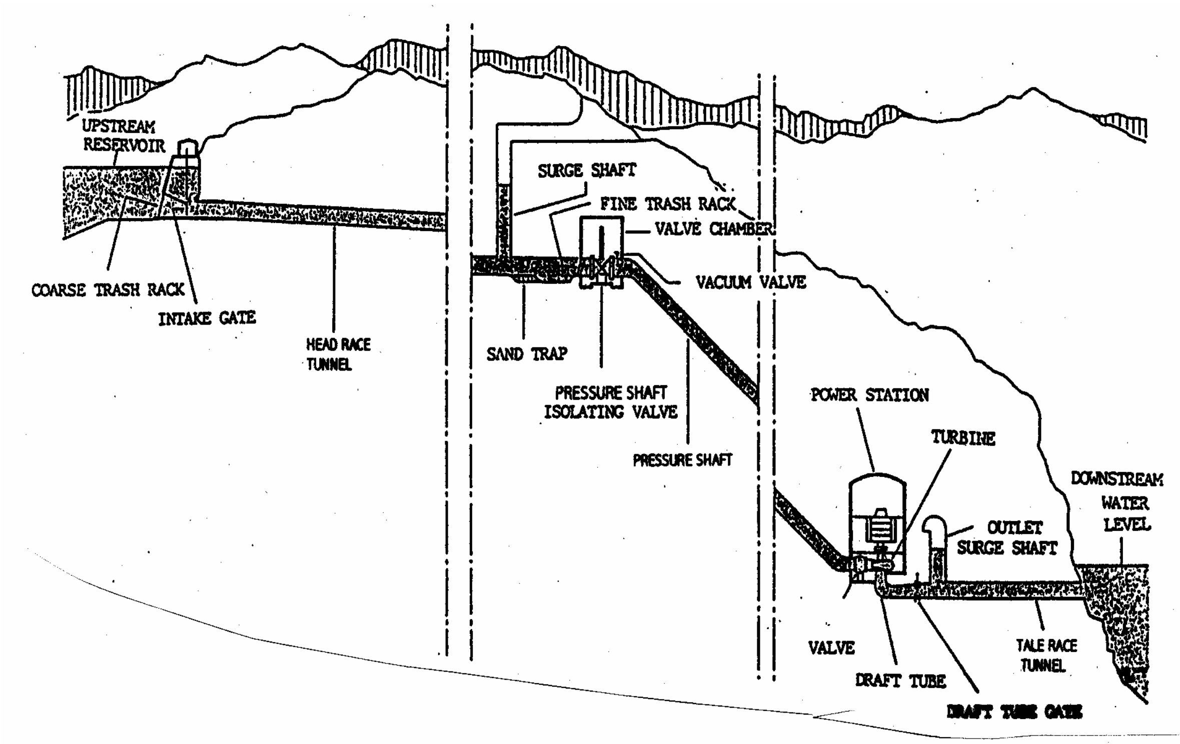


Fig. 1.11 Sketch showing in principle the water conduits of a traditional Norwegian high head power plant /3/

shut off the water delivery when the conduit system has to be emptied. In addition a small gate (4) may be arranged for drainage of the leakage through the main gate.

A deep water intake takes the water directly from the reservoir. It has no trash rack. There is a sump below the intake. Its main function is to collect blasting stones from the piercing of the the head race tunnel into the reservoir. It also traps stones sliding into the reservoir close to the intake. Deep water intakes allows for very strong regulation of the reservoirs. An intake gate is installed with the same function as described for the shallow water intake.

Conduit system

From the water intake to the turbine it is a conduit system constructed as open canal, tunnel, penstock or pressure shaft or a combination of these.

Open canals are usually digged in the ground, blasted in rock or built up as a chute of wood or concrete.

In high head power plants it is normally a so-called *head race tunnel* between the water intake and the pressure shaft. It may either be drilled and blasted or bored with a tunnel boring machine (TBM). The latter method leaves a much smoother wall surface than the first one, and consequently the head loss is significantly smaller for the same cross section. At the end of the head race tunnel there is a *sand trap*. Beside the sump in the tunnel floor the cross section of the tunnel is gradually increased to reduce the water velocity and allow for a better sedimentation of suspended particles.

At the downstream end of the head race tunnel there is also a *surge chamber system*. The function of the surge chamber is briefly to reduce water hammer pressure variations and keep the mass oscillations, caused by load changes, within acceptable limits and decrease the oscillations to stable operation as soon as possible. At the end of long head race tunnels it is also normally istalled a gate. This makes it possible to empty the pressure shaft and penstock upstream of the turbine, for inspection and maintenance without emptying the head race tunnel. Before the water enters the pressure shaft it passes a *fine trash rack*. It is the last protection of the valve and the turbine against floating debris or smaller stones if the sand trap is full or omitted.

The pressure shaft may either be lined or unlined. Where the rock is of sufficiently high quality the shafts are normally unlined. The excavation of the rock masses may be done either by drilling and blasting or by boring with TBM-machines. Shafts in lower quality rock is being lined either by concrete or by steel plate lining embedded in concrete. Lining of the shafts reduces the losses but increases the costs.

A steel penstock connects the shaft with the valve in the machine hall. Inside the rock the penstock is embedded in a concrete plug. Penstocks are normally welded pipe constructions of steel plates. A flange connects the penstock with the valve.

Penstocks above ground are mounted on foundation concrete blocks where the penstock may slide according to thermal expansion. In certain positions the penstocks are fixed in reinforced concrete anchoring blocks (8) on Fig. 1.10. Between these anchoring blocks the penstocks are equipped with expansion stuffing boxes (7) in Fig. 1.10.

At the upstream end of a penstock an automatic isolating valve is normally installed. This valve closes automatically if a pipe rupture should occur.

Turbine

The main parts of the turbine, with reference to Fig. 1.10, are:

- the guide vane cascade, usually adjustable, gives the water flow the velocity and the direction required for the inlet to
- the runner where the hydraulic power is transferred to mechanical power on
- the turbine shaft (9) to which the runner is fixed. The turbine shaft is guided in a
- radial bearing and an
- axial bearing that is loaded with the axial force from the runner, caused by the water pressure and impulses from the flow, and the weight of the rotating parts.
- The scroll case (10) conducts the water flow to the guide vane cascade.
- The draft tube (11) conducts the water flow from the turbine outlet into the tale race canal.

Closing valve

Upstream of the turbine a closing device (12) on Fig. 1.10, is installed. Depending on water head and capasity it may be a gate, butterfly valve, gate valve or a spherical valve. By submerged turbines a closing device, normally a gate, is installed also at the outlet from the draft tube.

References

1. Hunter, Louis C.: A History of Industrial Power in the United States, 1780 – 1930. The University Press of Virginia, 1979. ISBN 0-8139-0782-9 (v.1).

2. Kjølle, A.: Water Power Machines (in Norwegian), Universitetsforlaget, Oslo, 1980. ISBN 82-00-27780-1.
3. Kværner Brug: COURSE III Lecture compendium, Oslo 1986.
4. Sundby, G.: Abstract of Lectures on Water Power Machines (in Norwegian) at NTH 1937- 38. Trondheim