The primary application of hydraulic turbines is to drive electric generators in central power stations. Since the turbine shaft is usually rigidly coupled to the generator shaft with one set of bearings supporting both, for lubrication purposes the two units can be considered to be one machine. There is a wide range of sizes and operational characteristics for hydraulic turbines depending on the volume of water available and the pressure head of that water. Hydraulic turbines in commercial applications range in capacity from less than 1 MW to more than 750 MW. These units operate from as low as 40 rpm to as high as 2200 rpm, but the typical operating range is 100–200 rpm.

Many of the locations suitable for large hydroelectric installations are in remote, often mountainous areas, with difficult access. Under these conditions, capital costs for plant construction and transmission lines are high. Therefore, for the power generated to be competitive in cost, plants must be designed for minimum maintenance and long service life. Generally, this has been accomplished, and the majority of hydroelectric units installed during the last 90 years are still in service.

Although many of the large hydroelectric installations are in remote locations, many are comparatively accessible. In recent years, the development of some of these more accessible locations has been aided by the introduction of the pumped storage concept and the use of bulb turbines.

Thermal and nuclear power plants, as well as open-flume hydroelectric turbines, operate most efficiently at relatively constant loads. Thus, during off-peak periods, if the plant can be operated at or near full load, the power in excess of the load requirement is comparatively low in cost. If a suitable location is available, this power can be used during low demand periods to pump water up to a storage reservoir. During periods of peak demand, the water can be used then to drive hydroelectric generators to supplement the power available from the base load stations. In effect, pumped storage is a method of storing low cost, off-peak power for use during peak demand periods.

Some pumped storage plants are equipped with both turbines and pumps. The generator is built as a combination motor/generator. During pumping operations, the turbine may
be disconnected from the main shaft, or the turbine casing may be blown dry with compressed air so that the turbine operates without load. Similar arrangements are used with the pump. Quite a few new installations are equipped with reversible pump/turbines, and reversible motor/generators. There may be some sacrifice in efficiency with the combination pump/turbine. For example:

1. As a pump it may be less efficient than a unit designed as a pump alone.
2. As a turbine it may be less efficient than a unit designed as a turbine alone.

However, the lower cost of the combination machine generally offsets this loss of efficiency.

Bulb turbines (also called tubular turbines) are low head machines for what are referred to as “flow-of-stream” river applications. They can be used for relatively small, low cost installations that can be readily blended into the surrounding countryside. These machines have permitted the development of hydroelectric power in locations where installation of the older types of turbine would not be practical or economic.

I. TURBINE TYPES

Several types of hydraulic turbine are used. They can be considered to be impulse (Pelton) or reaction (pressure) types. Reaction turbines include the inward flow (Francis), diagonal flow (Deriaz), and propeller types. Bulb turbines are reaction turbines using a propeller-type runner. The choice of which type of unit to use in a particular application is a function of the pressure head and the quantity of flow available.

A. Impulse Turbines

In an impulse turbine, usually called a Pelton turbine, jets of water are directed by nozzles against shaped buckets on the rim of a wheel. The impulse force of the jets pushes the buckets on the rim of a wheel and causes the wheel to revolve. The buckets move in the same direction as the jets of water. For a turbine of this type to operate efficiently, the velocity of the jets must be high; thus, a high pressure head of water is required. Pelton turbines are usually designed for pressure heads in the range of about 500–3900 ft (150–1200 m). Single units with outputs up to 200 MW have been built.

Pelton turbines are built with the shaft either horizontal or vertical. Horizontal shaft machines are built with either one or two nozzles per runner. Usually, they are used for small to moderate-sized installations. A single runner may be connected directly to a generator, or two runners may be used, both on the same side of the generator or one on each side.

Vertical shaft Pelton turbines with four to six nozzles are now being used for larger installations. A cutaway of an installation with four nozzles is shown in Figure 13.1. In this machine, the nozzle tips are actuated by hydraulic pistons located inside the nozzle bodies. The deflectors are actuated by a ring and lever arrangement, which in turn is actuated by hydraulic servopistons. In many older machines, servopistons that operate the nozzle tips are located outside the nozzles, and a mechanical linkage is used to operated the nozzle tips.

Pelton turbines are used in a number of pumped storage applications. Both horizontal and vertical shaft machines are used for this purpose. If a horizontal shaft machine is used, the turbine is often mounted at one side of the generator/motor with the pump at the other side. Other arrangements can be used. In vertical shaft machines, the turbine
normally is mounted above the pump so that the pump will operate with a positive pressure at the suction. The pump usually is coupled to the shaft through a clutch, which allows it to be disconnected and stopped during turbine operation. In some installations, the water is blown out of the pump, and it is left coupled to the turbine during turbine operation. The water is blown out of the turbine for pump operation. In some cases, the turbine is used to start the pump and motor and bring them up to speed. The water flow to the turbine is then shut off and the water is blown out of the casing.

B. Reaction Turbines

In reaction turbines, the flow of water impinges on a set of curved blades which, in effect, are the nozzles. The reaction of the water on the nozzles (blades) causes them to move in the opposite direction.
In a Francis turbine (Figure 13.2), the water flows radially inward from a volute casing and is turned through 90 degrees in the blades before flowing to the tail race outlet. In a Deriaz turbine (Figure 13.3 and 13.7) the direction of water flow is partially turned in the volute casing so that the flow is diagonally through the blades. The shaped boss then turns the water through the remaining angle to direct it into the tail race outlet. In propeller turbines, the direction of flow is controlled by a volute casing or a flume so that the water flows axially through the turbine.

Francis and Deriaz turbines are intermediate to high head machines. The various propeller turbines (fixed blade, Kaplan, and bulb) are low head machines.

1. Francis Turbines

Francis turbines are probably the most widely applied hydraulic turbine. They are now also widely used as reversible pump/turbines. Originally used for intermediate head installations, the range of use of the Francis turbine has been extended well up into the head range that was formerly the exclusive province of impulse turbines. Francis turbines are being used at heads ranging from about 65 to 1650 ft (20–500 m), and even higher head units are under development. Outputs in the 200–400 MW per unit range are common, and units rated at up to 750 MW are in service.

Small Francis turbines are sometimes built with horizontal shafts, but larger Francis turbines are nearly always vertical shaft machines. Water is brought in from the penstock through a spiral (volute) casing (Figure 13.4) from which it is directed into the turbine guide vanes by fixed vanes in the stay ring or speed ring (Figure 13.5). The movable guide vanes control the flow of water into the turbine to maintain the turbine speed constant as the load varies. They can be operated by a single regulating ring actuated by one or
Figure 13.3  Deriaz Turbine; also see cross-sectional view (Figure 13.7).

Figure 13.4  Spiral casing for Francis turbine.
two hydraulic servomotors (Figure 13.5), or by individual servomotors (Figure 13.6). With a regulating ring, the individual vanes are connected to the ring through shear pins so that if one vane is jammed by a foreign object during closing, the remainder of the vanes can still be closed to shut off the turbine.

2. Diagonal Flow Turbines

The efficiency of Francis turbines drops off quite rapidly if the flow is less than the design value, or if the pressure head varies significantly. Where either of these conditions exists, a diagonal flow or Deriaz turbine can sometimes be used.

In the Deriaz turbine, both the guide vanes and the runner blades are adjustable (Figure 13.7). The runner blades are adjusted by a hydraulic servomotor located either in the turbine shaft or in the runner boss. The guide vanes are usually controlled by a regulating ring, similar to those used with Francis turbines. Movement of the guide vanes and runner blades are synchronized by the control system to maintain runner speed with changes in load, and keep the efficiency high as changes in the pressure head occur.

Deriaz turbines are presently built for pressure heads in the range of about 60–425 ft (18–130 m). Designs suitable for heads up to about 650 ft (200 m) are available. The
Figure 13.6  Guide vane adjustment with individual servomotors. This operating mechanism for a Kaplan turbine is equally applicable to Francis turbines.

Figure 13.7  Cross section of Deriaz turbine.
usual construction is with a vertical shaft. Single units with ratings up to about 150 MW are in service. The larger units are reversible pump/turbines.

3. Fixed Blade Propeller Turbines

Fixed blade propeller turbines are vertical shaft machines. The blades of the runner (Figure 13.8) are cast integrally, with the hub or welded to it. Because of the low heads at which propeller turbines operate, comparatively small changes in the head water or tail water level can make significant changes in the total head acting on the turbine. With a fixed blade turbine this may cause marked changes in the efficiency of the turbine. For that reason, fixed blade propeller turbines (usually referred to simply as propeller turbines) are used only in locations where the head is fairly constant. Relatively few installations of this type of turbine exist. Outputs range up to about 40 MW per unit.

4. Kaplan Turbines

The Kaplan turbine (Figure 13.9) is the largest class of low head hydraulic turbine. The runner blades are adjustable, operated by either a hydraulic servo-motor inside the runner hub or by a servomotor in the shaft with a mechanical linkage to the blade adjustment mechanism in the hub. The former arrangement is used for most new machines. As with Deriaz turbines, the controls for the guide vane adjustment and runner blade adjustment are synchronized to provide an optimum setting for each load and head condition. A typical Kaplan turbine installation is shown in cross section in Figure 13.10.

Kaplan turbines are built for heads from about 13–250 ft (4–75 m). Single units with power outputs from as little as 1 MW to units with outputs in the 175 MW range are in service.

(a) Bulb Turbines. The bulb turbine is actually a special application of the Kaplan turbine. As shown in Figure 13.11, the conventional Kaplan turbine is mounted vertically with a spiral casing carrying the water into the stay ring. From the turbine, a draft tube carries the water out to the tail race, creating a suction head on the turbine. In contrast, the bulb turbine has the turbine mounted in a bulb-shaped section of the flume with the
water flowing essentially straight through the turbine. The arrangement is much more compact and is less costly to construct.

The shaft of bulb turbines is either horizontal or angled slightly downward toward the turbine. With a horizontal shaft, the generator is usually mounted in a bulb-shaped casing inside the flume and is driven directly from the turbine (Figure 13.12). A mechanical drive to a generator mounted on the surface may also be used. With an angled shaft, the shaft may be extended out of the flume to drive a surface mounted generator directly, or the generator may be mounted inside the flume.

Bulb turbines for heads up to 75 ft (23 m) are in service. Unit outputs are usually less than about 10 MW, but units up to 50 MW are in service.

(b) S-Turbines. S-turbines (tubular turbines) are similar to bulb turbines except that the generator is not located in the bulb. The runner blade controls (where regulated) are contained in the bulb but a drive shaft extends out of the Kaplan runner and through a portion of the S-shaped draft casing into a generator room, where it is connected to a generator. The S-turbine operates with heads of approximately 49 ft (15 m) and power outputs up to 15 MW.
Figure 13.10 Cross section of Kaplan turbine.
Figure 13.11  Comparison of bulb (top) and Kaplan (bottom) turbines.
II. LUBRICATED PARTS

The main parts of hydraulic turbines requiring lubrication are the turbine and generator bearings, the guide vane bearings, the control valve, governor, and control system, and the compressors.

A. Turbine and Generator Bearings

Horizontal shaft machines require journal bearings to support the rotating parts, including the generator armature. With the exception of Pelton turbines, thrust bearings are also
required to absorb the thrust of the water acting on the runner. Vertical shaft machines require guide bearings to keep the shaft centered and aligned, and thrust bearings to carry the weight of the rotating parts and absorb the thrust of the water acting on the runner.

Vertical shaft machines have a guide bearing above the turbine, and one or two guide bearings at the upper, or generator, end of the shaft. In some cases with long shafts, an additional guide bearing is installed about midway between the turbine guide bearing and the generator guide bearing. For reasons of accessibility, normally the thrust bearing is installed at the upper end of the shaft, either above the armature or just below it. A combination guide and thrust bearing located above the armature and a guide bearing below is sometimes referred to as a two-bearing arrangement. In the so-called umbrella type, a combination thrust and guide bearing (Figure 13.13) is located below the armature, and in the semi umbrella type separate guide and thrust bearings are located below the armature. Most current medium and large machines are of either the umbrella or semiumbrella type.

1. Journal and Guide Bearings

The bearings of horizontal shaft machines are of the fluid film type, with babbitt-lined, split shells. Oil lifts to assist starting may be used in the journal bearings when the rotating parts are extremely heavy. At stabilized operating conditions, oil-lubricated journal and guide bearings will operate in the range of $140^\circ F$ ($60^\circ C$).

Two general types of turbine guide bearing are used in vertical shaft machines. Many older turbines are equipped with water-lubricated rubber or composition bearings. This construction minimizes sealing requirements at the top of the turbine casing but is not too satisfactory when the water carries silt and other solids. As a result, most machines are built with a stuffing box at the top of the turbine, and a babbitt-lined guide bearing (Figure 13.10). Various types of seal are used in the stuffing boxes, including carbon ring packing and gland packing.
The upper guide bearings are either babbitt-lined, split cylindrical shell-type bearings (Figure 13.14) or segment bearings (Figure 13.15). The segment-type bearings are becoming increasingly popular because they permit easy adjustment of shaft alignment and bearing clearance. The segments may be crowned, that is, machined to a radius slightly larger than that of the journal plus the thickness of the oil film to permit easier formation of oil films. The construction shown in Figures 13.14 and 13.15, with the journal formed by an overhanging collar on the shaft and an oil dam extending up under the collar, is now common. It eliminates the need for an oil seal below the bearing. Bearings running directly on a machined journal on the shaft, with either an oil seal below the bearing or an oil reservoir fastened to the shaft and rotating with it, are also used.

2. Thrust Bearings

Thrust bearings of horizontal shaft machines are of the tilting pad or fixed pad type. For a reversible pump/turbine, tilting pad bearings designed for operation in either direction must be used. Thrust bearings for vertical shaft hydroelectric units are among the most highly developed forms of these bearings now in use. As pointed out earlier, the thrust bearing must support the weight of the rotating parts plus the hydraulic thrust of the water acting on the turbine runner. Single bearings capable of supporting loads in excess of 2000 tons are in service. Because of the high thrust loads thrust bearings operate at the highest temperatures. Operating temperatures generally are in the range of 212°F (100°C).

Tilting pad thrust bearings are used on all larger machines. Some older machines are equipped with tapered land bearings. Bearings of the Kingsbury and Michell type, in which the pads tilt on a pivot or on a rocking edge on the bottom of the pad, were used on many older machines. Most newer designs use flexible supports under the pads to permit the slight amount of tilt needed to form wedge oil films. Bearings with flexible pad supports, which can be run in either direction, are particularly suited to reversible pump/turbine units. Springs (Figure 13.16), elastomeric pads, interconnected oil pressure cylinders, and flexible metallic supports are all used. Spherical supports are also used. The bearing segments may be flat, or crowned slightly to aid in the formation of oil films.
In many of the larger machines, provision is made to pump up the bearings with high pressure oil to assist starting (Figure 13.16).

B. Methods of Lubricant Application

The bearings of hydroelectric sets are either self-lubricated or supplied with lubricant by a central circulation system. Circulation systems may be either unit systems (a separate system is used for each unit in a station) or station systems (all the units in a station are supplied from one system). In many cases, one or more of the bearings may be of the self-lubricating type, with a unit system supplying the other bearings.

In self-lubricated bearings, the oil is contained in a tank surrounding the shaft (Figures 13.13–13.15). Oil is lifted by grooves in the bearings, or by a ring pump on the shaft. Cooling coils can be located in the tank, or with a cylindrical shell bearing a cooling jacket may be located around the bearing shell. External cooling coils may also be used, but these are generally suitable only for relatively high speed machines, which generate sufficient pumping force to circulate the oil through the external circuit.

C. Governor and Control Systems

Older hydroelectric units were equipped with mechanical hydraulic control systems with a mechanical speed-sensitive device and a hydraulic system to actuate the guide vanes, and the runner blades if a Deriaz or Kaplan turbine were used. Newer machines are often equipped with electrical speed-sensitive devices and electronic systems.

Older hydraulic turbine hydraulic systems generally operated at 150 psi and used the same oil as the bearing oil system. Current units operate with pressures in the 1000 psi range but can go as high as 2000 psi. The hydraulic systems are now usually separate systems and require antiwear hydraulic fluids for the higher pressure systems. There is also a trend toward use of environmentally acceptable fluids for these applications. Hydraulic pumps are driven by electric motors. Air-charged accumulators (air over oil) are
used to maintain system pressure and supply the large fluid flow necessary to adjust rapidly to meet sudden changes in load. They also provide a source of fluid under pressure to shut the turbine down in the event of a failure in the system. Emergency shutdown may also be assisted by the use of closing weights on the guide vane operating mechanism, or by designing the vanes that will be closed by water pressure if the hydraulic system fails.

D. Guide Vanes

The guide vanes, or wicket gates, are manufactured with an integral stem at each end that serves as the bearing journal. One bearing is used at the bottom and one or two bearings at the top. A thrust bearing may also be required. These bearings, as well as the bearings of the operating mechanism, are grease lubricated. Centralized application systems are now usually used to supply these bearings.

E. Control Valves

In some turbines, the guide vanes are arranged to close tightly and act as the shutoff valve for the turbine. In most installations, however, separate closing devices on the water inlet are used. In the case of pump turbines, closing devices on both the inlet and outlet are used.

Closing devices include sluice valves, rotary valves (Figure 13.17), butterfly valves, and spherical valves. All are designed for hydraulic operation. Closing weights may be used for emergency shutdown. Bearings are grease lubricated.

F. Compressors

In most hydroelectric plants, compressed air is required to maintain the pressure in the hydraulic accumulators. Compressed air is also used to blow out the draft tube and turbine casing when maintenance is to be performed. Compressed air also blows out the pump or turbine when the changeover from pump to turbine operation, or vice versa, is made in pump/turbine installations. Compressed air is also used in some impulse turbine installations to keep the tail water out of the turbine when the tail water level is high. Compressors operated in hydroelectric plants are critical pieces of equipment. Air compressors can be four-stage units and can operate with discharge pressures up to 1000 psi.

III. LUBRICANT RECOMMENDATIONS

The need for extreme reliability and long service life of hydroelectric plants generally dictates that premium, long life lubricants be used. Rust- and oxidation-inhibited premium oils are usually used for oil applications. Viscosities usually are of ISO viscosity grade 32, 46, 68, or 100, depending on bearing design, speeds, and operating temperatures. Oils with excellent water-separating characteristics are desirable. While start-up temperatures are rarely below freezing, the oils used must have adequate fluidity for proper circulation at those temperatures. Where oil lifts are not used for starting, oils with enhanced film strength may be desirable to provide additional protection during starting and stopping.

Hydraulic system requirements for older units were generally be met with oils of the same types used for bearing lubrication. More modern high pressure systems have been separated from the bearing oil systems and may require antiwear-type hydraulic fluids. Good air separation properties are desirable to ensure that air picked up in the accumulators separates readily in the reservoir.
Greases used in grease-lubricated bearings require good water resistance and rust protection. They should be suitable for use in centralized lubrication systems and should have good pumpability at the lowest water temperatures. Both lithium and calcium soap grease are used. NLGI no. 2 consistency greases are usually used, but in some extremely cold locations, NLGI no. 1 consistency greases are selected.

Compressors used in hydroelectric plants can be lubricated as outlined in Chapter 17.