STEAM TURBINE PRINCIPLES

INTRODUCTION

This section describes features, operational concerns and terminology common to most steam turbines. For information concerning a specific type of turbine or installation, consult the manufacturer's literature.

TURBINE CONSTRUCTION

Steam turbines convert heat energy from steam to mechanical energy. Conversion is accomplished by accelerating steam through nozzles, then transferring the energy of the flowing steam to moving blades. The moving blades are attached to a wheel or disk and produce shaft rotation.

Steam flows in the axial direction, or parallel to the shaft, in most turbines. In some small turbines, steam flows in the radial or tangential direction relative to the shaft.

The first set of nozzles is usually mounted in a nozzle block which is attached to the casing or is a part of it. Other nozzles and fixed blades may be mounted in disks called diaphragms. Diaphragms are mounted in the casing. Seals located where the shaft passes through the diaphragms prevent steam from bypassing the nozzles. The moving blades are known by various manufacturers as buckets, vanes or blades. They are mounted on or are an integral part of wheels or disks. The disks may be:

- Stacked on the shaft with keys.
- Shrunk onto the shaft.
- Integral with the shaft.

All types of disks are subject to cracking, however, keyed disks are most vulnerable to cracking in the keyway area. Keyed and shrink-fit disks are subject to fretting and other types of corrosion between the shaft and the disks. Both keyed and shrink-fit disks are also subject to loosening if the turbine overspeeds.

Turbines may be classified as impulse turbines or reaction turbines. In impulse turbines, all the nozzles are stationary, and there is no pressure differential across the wheels. Reaction turbines contain stationary nozzles, and the moving blades are also shaped to act as nozzles. Operation requires a differential pressure across the wheels. This has two consequences:

- Closer tolerances and seals are required between the blade tips and the casing.
- Compensation for the axial thrust, due to the pressure differential, is necessary.

Some turbines contain both impulse and reaction blading.

All turbines, except a few of unusual design, have alternating rows of fixed and moving blades. The fixed blades may be nozzles or guide vanes. Guide vanes redirect the steam to the correct direction to enter the next row of moving blades.

Blade design and materials vary with the application. Large turbines contain several different blade types. Blades near the turbine inlet must use high-strength alloys designed to withstand the high steam temperature. Steam temperatures and pressures drop as the steam passes through the turbine. Near the outlet, the steam pressure may fall below saturation for the temperature. Beyond this point, the steam contains water droplets. These droplets are highly erosive, therefore, the low stage blades are often provided with wear-resistant leading edges.

A turbine with one set of nozzles and one set of moving blades is called a single stage turbine. Any other arrangement is compounded and may be multistage. (The term "compounded" may also indicate a multi-casing arrangement.)

Drains are provided in turbine casings to remove condensate during warm-up. Multistage turbines also require condensate removal during operation, particularly from the lower stages.

Turbine rotors are supported by bearings. Radial bearings support the shaft and keep it in alignment. Thrust bearings limit the shaft axial movement to properly position the wheels and other rotating parts with respect to the nozzles, diaphragms and other stationary parts.

Steam turbines require seals or packing at locations such as:

- Diaphragm shaft openings.
- Reaction stage blade tips.
- Casing shaft openings or internal partitions.

Labyrinth seals are normally used where pressure differences are slight and leakage can be tolerated. These seals use a series of ridges (teeth in cross section) sized to closely fit the rotor. Each ridge produces a slight pressure drop; if enough ridges are placed in the seal, the total pressure drop will approximate the difference in pressure between the spaces separated by the seal. Minimum flow will result.

Where the pressure drop is too great for a reasonably-sized labyrinth, more than one stage of seals are used. The space(s) between stages is vented to a lower pressure steam or exhaust system.

Carbon packing consists of one or more spring-loaded segmented carbon rings that bear on the shaft. Carbon packing rings are often used as shaft-to-casing seals. The entire seal may consist of several carbon rings in series, or the carbon ring(s) may be the outer-most element in a sealing system consisting of labyrinth seals and carbon packing.

Condensing turbines operate with a vacuum at the exhaust end. They must be capable of containing a vacuum during warm-up, operation and cool-down. Air leakage through the casing opening along the shaft can cause loss of vacuum, damage to the seals and possible distortion of the shaft. Stages of seals are used on these machines. Low pressure "gland sealing steam" is supplied to the space between the innermost seal pair. Steam leaking into the casing prevents air from entering. A gland exhaust connection conducts excess gland sealing steam out of the machine.

Bearings require lubrication for proper function. Small machines will normally have simple lubrication systems consisting of a shaft-driven pump, an oil cooler and a filter or strainer. Coastdown time and bearing loading may not be sufficient to damage these machines if they continue to rotate after the shaft-driven pump becomes ineffective and the lubrication film breaks down. Larger turbines require more complex systems. High bearing loads and coastdown times greater than ten minutes may completely wreck a machine if it coasts down from operating speed without the lubrication system operating.

Turbine oil systems must:

- Reliably provide lubricant to the bearings.

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- Remove wear particles and heat of friction.
- Provide hydraulic force to the governor.
- Deal with water from condensing steam.

The lubricant must be carefully selected on the basis of physical characteristics that enhance a variety of properties. Demulsibility, or the ability to readily separate from water, is important for turbine oil. An internal or external purification system should be provided to remove accumulated water.

Large turbines are subject to distortion of the rotor. Distortion may be caused by the dead weight of the rotor or by uneven heating or cooling. Machines subject to distortion are provided with a jacking or turning gear to slowly rotate the rotor during unit warmup and cooldown, and rotate it periodically while the unit is at rest. The lubrication system normally must be in operation if the turning gear is to be used.

Figure 1 is a schematic drawing of a turbine. The unit shown is a composite sketch showing a wide variety of features that would probably not all be found on a small unit.
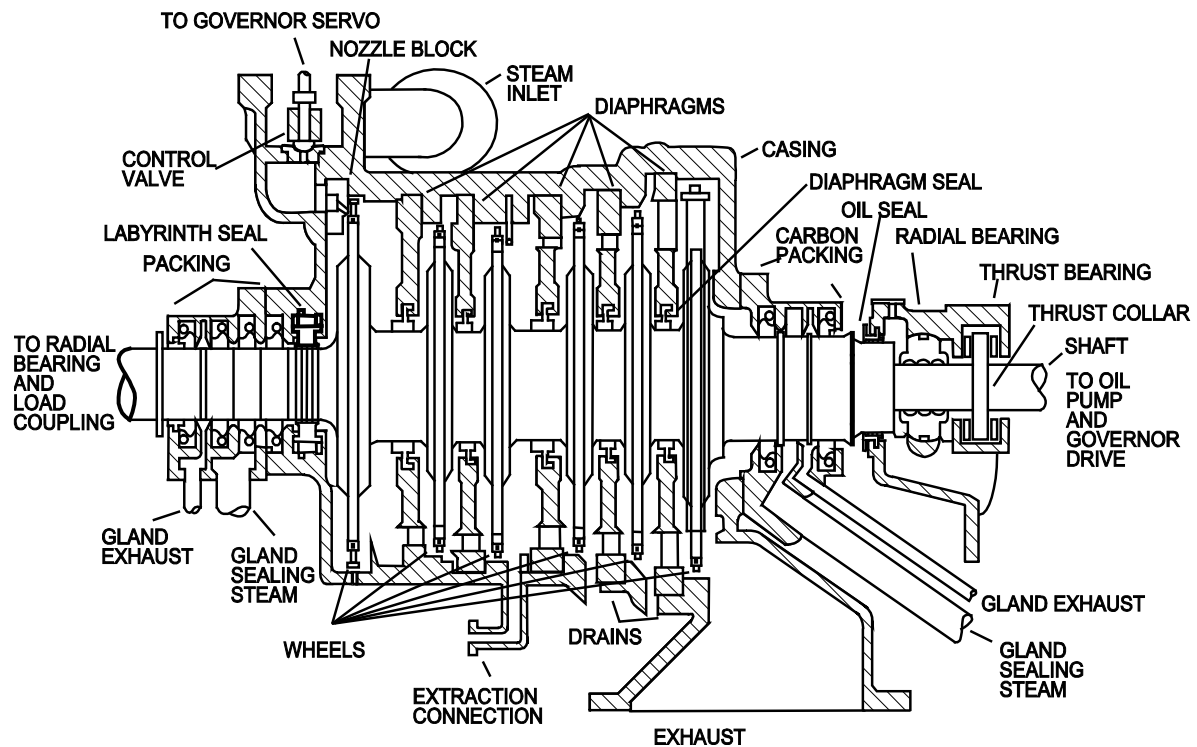

Figure 1. Steam Turbine Cross Section.

CASING ARRANGEMENTS

Most turbines have all their elements in a single casing. The largest turbines group numerous stages into several casings. Large utility turbine units often have three casings known as high pressure, intermediate pressure and low pressure.

Steam pressure drops when steam passes through nozzles or reaction blading. Steam expands as its pressure drops. To allow the expansion, the steam flow area of each stage must be larger than the steam flow area of the proceeding stage. To obtain more flow area, longer blades and larger wheel diameters are required. Also, steam flow may be divided into two parts, directed from the center of the casing to the ends. This flow division also provides equal axial thrust in both directions. The successively larger wheels and two-directional flow path give low pressure casings for large machines a distinctive wasp-waisted appearance.

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Multi-casing turbines are arranged in two ways. In cross-compounded units, steam flows from one turbine casing to another, and the individual turbine shafts drive different pieces of equipment or different pinions in the same gearset. In tandem-compounded units, steam also flows from one casing to the next, however, the casings are in a line, and the shafts are coupled together. Driven equipment may be coupled to the end(s) of the line of turbine elements.

TURBINE CONTROL

Steam is usually delivered to a turbine unit through a manual isolation valve, a strainer and a trip throttle valve. Trip throttle valves are designed to close quickly (trip) in case of turbine, driven machine or process upset. Most of these valves are held open by a piston in a cylinder pressurized with lubricating oil acting against a spring. Any signal which requires a turbine trip causes a relay valve to open. The relay valve dumps the oil pressure from the cylinder. Release of the oil pressure allows the spring to close the steam supply valve.

Trip throttle valves are sometimes called "Gimpel" valves, however, there are other manufacturers of such valves, so the name should not be used generically. Single boiler-turbine unit installations often omit the manual isolation valve, because there is no way to operate either the boiler or the turbine separately.

Steam flow is controlled by one or more parallel throttle valves positioned by the governor. The governor positions the controlling throttle valve(s) to control the speed of the machine in response to an external signal. On some machines, particularly small ones, a single valve is provided to control the machine and to trip shut if necessary.

Large turbine control valves consist of several small throttle valves arranged in parallel. Small valves opening fully in sequence are more efficient and are capable of more precise speed control than a single large valve. A series of valves with different length stems lifted in sequence by a single beam is the most common arrangement.

Partial arc or full arc steam admission may be used. Partial arc admission means steam is admitted to only a portion of the blading. Limiting admission is accomplished by installing an arc rather than a full circle of nozzles in the nozzle block or the diaphragm, or by partitioning a full circle of nozzles so that steam is admitted to only an arc. Large turbines with several throttle valves may use partial arc admission for low loads and, by sequential valve opening, change to full admission at higher loads.

As the steam passes through a multistage machine with partial arc admission, steam expansion and rotation effects increase the size of the arc. Partial arc admission subjects the first rows of blades to more stress than does full admission because the blades cool when they rotate away from the nozzles and reheat when they re-enter the steam flow. If the turbine is not specifically designed for part load service, extended operation in this mode may result in increased vibration levels and long-term damage from blade fatigue.

Turbine governors may be designed to control the turbine at variable or constant speed. Variable speed governors are used where the output of the driven device depends upon the speed. Examples include most fans, pumps and compressors. The governor may be designed to control the turbine speed in response to downstream pressure, system flow rate or some other parameter. Constant speed governors are used otherwise. The most common examples of machines with constant speed governors include ac generators and some compressors with movable vanes.

TURBINE OPERATION

Turbines may be designed to exhaust reduced pressure steam to another system. These turbines are called noncondensing or backpressure turbines. Other turbines are designed to exhaust steam to a condenser. These are called condensing turbines. Any turbine may be designed to exhaust steam, known as extraction or bleeder steam, at one or more intermediate pressures along its length.

In many industrial applications, the extraction steam can flow in either direction, e.g., it may be removed from the turbine for delivery to reduced pressure steam loads, or, if there is excess reduced

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pressure steam, it may flow into the turbine and produce power in the stages downstream of the extraction point. For this reason, controlling the extraction point is as crucial to safely operating the turbine as is controlling the main steam inlet.

Utility turbines are classified by duty cycle. Base load units operate full time at or near their nameplate rating. Peaking units operate under load only when electricity demand is greater than the base level. Reserve units are serviceable but not operating under load. Their status may be "cold," "hot" or "spinning" reserve depending upon how nearly ready they are to receive load.

There are different reserve classifications because steam turbines require a warm-up period before being placed on line. The rotor and casing must be warmed slowly to avoid thermal stresses. The rotor typically warms more slowly than the casing. Proper warm-up rates and procedures must be used to ensure equilibrium between the rotor and casing temperature. If equilibrium is not maintained, differential expansion may cause rubbing of parts. For a large turbine, the warm-up procedure involves the following activities:

- Starting and testing service systems, including main and reduced pressure steam, lubricating, control and seal oil, and cooling water.
- Engaging jacking or turning gear.
- Admitting a limited flow of steam for warm-up and draining the condensate formed.
- Raising condenser vacuum.
- Disengaging jacking gear and slowly rolling the turbine using steam.
- Accelerating in sequence to full speed and proper operating temperature.
- Preparing the generator to receive load.

The time interval required to raise a turbine from room temperature to the temperature required for loading is at least 15 to 30 minutes for small single stage machines and may be several days for large utility turbines.

Most turbines, even when warm enough to be rolled, must be loaded slowly and incrementally to heat evenly. The manufacturer's rate-of-temperature-rise curves should be obtained and applied by the operators.

Most utility turbines are designed to be base loaded. As they age, however, they are supplanted by newer and lower-cost producers, also designed to be base loaded. When unit status is changed from base load to peaking, careful analysis and attention to operating procedures are needed. Frequent changes from full load to part load operation or from on-line to reserve status may increase the risk of catastrophic failure because of the associated warming and cooling cycles. Long time periods at partial arc admission in machines designed for full arc admission may result in early blade failures because of thermal fatigue. Equipment modifications may be required.

TURBINE MECHANICAL HAZARDS

Overspeed is the most serious mechanical hazard of turbine operation. A slight overspeed can stress the rotating parts enough to distort them. A more serious overspeed can rub the blade ends against the casing. A severe overspeed may break the blades free of the wheel or rupture the wheel. Blade ejection or wheel rupture may also rupture the casing. Turbine overspeed protection is discussed in PRC.6.1.1.0.3.

Water induction can severely damage a turbine by destroying the thrust bearing, by thermal shock, or by distorting parts by uneven cooling. Water induction protection for small and most midsize turbines is adequately provided by properly warming and draining the steam lines and casing before startup, and by maintaining condensate drains in service during operation. Small turbines are defined as less than 1000 hp (750 kW) and midsize turbines are 1000 hp to 10,000 hp (750 kW to 7500 kW). Large turbines and turbines which use superheated steam require additional protection. These turbines also need to be protected against "cool vapor" (steam of the wrong temperature) induction.

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Excess vibration associated with critical speeds is another turbine hazard. Any mass has characteristic or resonant frequencies. The mass will vibrate at those frequencies when struck with a hammer. A speed corresponding to a resonant frequency is called a critical speed. Although a given rotor may have more than one critical speed, the speed corresponding to the main resonance, or "first critical," is normally the most dangerous. Integer multiples of that speed may also be troublesome. Manufacturers take great pains to keep operating speeds away from the critical speed, however, operational changes or turbine modifications may reduce the separation. If this occurs, unstable vibration, which is potentially destructive, may result.

Turbine casings are not normally designed to withstand the main steam supply pressure. Therefore, casings must be protected against overpressure. Noncondensing machines are normally protected by a casing relief valve. Condensing machines normally have a high-backpressure trip. Multi-casing machines require overpressure protection for only the lowest-pressure casing, unless the casings can be isolated from each other by valves. See PRC.6.1.1.0.3 for more information.

Steam turbines with forced lubrication systems require protection against loss of lubrication. Turbine operation without proper lubrication can result in severe bearing failure which, in extreme cases, can result in loss of clearance between rotating and stationary parts. Lubrication systems and their associated protective features are further discussed in PRC.6.1.1.0.5.

Bearing condition and various other measures of machine condition may be monitored by observing and analyzing machine vibration. Radial bearings typically fail over time. They produce higher vibration levels as their condition degrades. The thrust bearing, however, is the most heavily loaded and critical bearing in most turbines. Thrust bearing failures typically develop very quickly. They may result in catastrophic machine failure. Thrust bearing condition monitoring is usually part of vibration monitoring and analysis.