SECTION 3.1
STEAM-TURBINE FUNDAMENTALS

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INTRODUCTION

Steam turbines are used by utilities and industry to transform thermal energy to usable mechanical energy. The mechanical energy is typically used to turn a generator and thereby create electric power or turn a pump, fan, or other rotating equipment.

Electric energy is a vital component of modern industrial and energy-intensive economies. For over 100 years, the steam turbine has been a key element in providing reliable and economical electric power throughout the world. It is also of significant importance in a modern industrial plant where steam turbines are the most economical and reliable way to produce continuous mechanical work.

Steam turbines have been designed and built to accommodate a wide variety of mechanical power uses. Their outputs range from fractional horse power (less than 746 W) to over 1,500,000 kW.

This section covers how they work, fundamental turbine designs and elements, and turbine types. Section 3.2 covers more specific design information.

HISTORY OF STEAM TURBINES

Steam turbines have evolved significantly from the novelty reaction turbine developed by Hero of Alexandria in 120 B.C. to the modern utility or industrial power turbine. The first practical turbine designs were developed and patented by Sir Charles Parsons of England in 1884. His reaction turbine had steam entering the center of a double-flow cylinder and expanding axially toward each end through stages of fixed and rotating blades. The 3-in (7.6-cm) diameter rotor ran at 18,000 rpm and produced about 10 hp (7.5 kW). This design produced efficient power in a very compact size. At that time, a slow-speed steam engine with comparable output was hundreds of times larger.

In 1890, the first of four 75-kW Parsons designed turbines were installed in England, and they became the first use of a steam turbine in a public powerplant. In 1889, Sweden's Carl deLaval patented a 5-hp (3.7-kW) 30,000-rpm turbine that had only one stage. The velocity-compounded turbine stage was patented by England's Charles Curtis in 1896. The impulse stage design was developed by Rateau and Zoelly between 1894 and 1903.

The designs patented by these inventors were refined and licensed to other manufacturers that produced steam turbines. While other designs were produced in the 40 years following these first patents, the impulse, reaction, and velocity-compounded designs became dominant due to their lower manufacturing cost and higher efficiency.

To improve thermal efficiency, the concept of reheating the steam partway through the expansion phase was introduced in the 1930s and became common in the early 1950s. The need for economies of scale and improvements in thermal efficiency pushed designers to increase operating temperatures, pressures, and output.

By 1960, manufacturers were producing double-reheat turbines with supercritical steam inlet pressures. The highest inlet pressure of this era was 5000 psig (340 bar), and inlet temperatures were as high as 1200°F (650°C). Due to higher initial and maintenance costs, most utility turbines sold since then have lower inlet pressures and temperatures and reheat the steam only once.

The typical inlet conditions for units built since then are 2400 psig (163 bar) and 1000°F (538°C) for both main and reheat steam. While steam turbines have been built with outputs as high as 1500 MW, typical sizes range up to 800 MW for fossil-fuel-fired and 1200 MW for nuclear units.

Although electric utility turbines and powerplants are designed to produce electric power, at one speed, as efficiently as possible, industrial users have a wide variety of needs. These needs include variable speed, mechanical and electric power, and steam extraction for processes. Utility and industrial market forces are presently tending to emphasize lower operating costs, greater operating flexibility, and lower environmental emissions. These forces have led to the development of combined-cycle plants for both utility and industrial users. Steam and gas turbines are combined to increase the overall thermal efficiency.

In a combined-cycle plant, large gas turbines (up to 250 MW) are used to generate electric power. The waste heat from the gas-turbine exhaust is used to produce steam through a fired or unfired boiler—the heat recovery steam generator (HRSG). The steam is then used to power a steam turbine and/or is extracted for process demands.

Combined-cycle plants can be constructed in less time than a comparable coal or nuclear plant and produce lower levels of emissions than those using fossil fuels (coal and oil) by burning natural or synthetic gas. The present overall thermal efficiency of operating combined-cycle plants is up to 58 percent (lower heating value) with designs expected soon that can reach 60 percent.

Existing utility and industrial steam turbines and plant sites can be "repowered" by adding a new gas turbine and HRSG to replace the original boiler. Repowering is an option to produce power and steam more efficiently and with potentially lower levels of emissions.

Designs have also been developed in which the steam and gas turbines are configured on a single shaft and together can produce over 250 MW of electric power and varying amounts of extraction steam. The single-shaft configuration reduces the site installation cost.

Research into new steam-turbine designs has focused on ways to improve efficiency and reliability. The emphasis has been on more efficient steam path blading profiles and ways to reduce internal leakage. Some of these improvements are being retrofitted into existing turbines to improve output capability and efficiency.

Gas-turbine design concepts are now being incorporated into new steam-turbine designs. Steam turbines have been tested in service up to 1500°F (815°C) to search for ways to improve thermal efficiency.

STEAM-TURBINE FUNDAMENTALS

All steam turbines work by using the same basic process. This process draws heavily from the study of thermodynamics. (See Figs. 3.1.1 and 3.1.2.)

1. Thermal energy is transferred to pressurized water, and steam is created. The steam then contains a high amount of potential energy (*b* to *c*).
2. The potential energy of the steam is converted to mechanical work as the steam expands through a nozzle and impacts or reacts with a blade (*c* to *d*).
3. The mechanical work of many sets of moving blades attached to a shaft produces rotational power (turbine).

The above process is repeated after the exhaust steam is cooled and condensed back to a liquid (*d* to *a*). The complete process is known as the *Rankine cycle.*

The Rankine cycle is usually configured to extract as much usable work as possible for the amount of energy input to the steam. Typically, the amount of steam superheat (*c*) is maximized, the steam is reheated at least once after it has partially expanded, and steam is extracted from the turbine to preheat boiler feedwater (feedwater heating). The

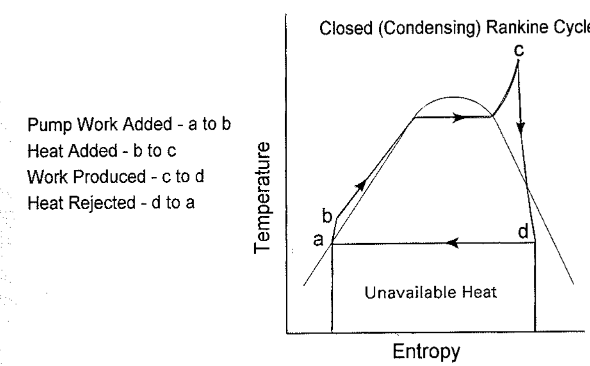

FIGURE 3.1.1 Condensing Rankine cycle.

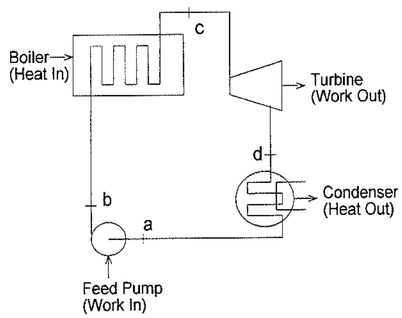

FIGURE 3.1.2 Basic steam plant configuration.

Rankine cycle efficiency is also maximized by keeping the turbine exhaust temperature and pressure as low as possible.

BASIC STEAM ENERGY TO WORK PROCESSES

In a reciprocating steam engine, steam presses equally on the cylinder walls and piston (see Fig. 3.1.3). Since the piston moves, the steam does work, using some of its internal energy to do so. The steam cools as its pressure drops. Similarly, steam in a nozzle box presses equally on all walls, but it escapes through the nozzle to form a high-speed jet (see Fig. 3.1.4). Reaction pressure P_R on the wall area opposite the nozzle is not balanced by the escaping steam. If the box is fixed, steam leaves at the top absolute speed and exerts pressure P_1 on anything in its path. If the box moves, P_R does work on it by speeding it in a direction opposite to the jet motion. In that case, the absolute jet speed is correspondingly slower.

When the steam discharge pressure is 53 percent or more of the box pressure, the nozzle needs only a converging cross section. When the discharge pressure is much less than 53 percent, the converging section should be followed by a diverging section (see Fig. 3.1.5). The area of exit cross section depends on the pressure ratio.

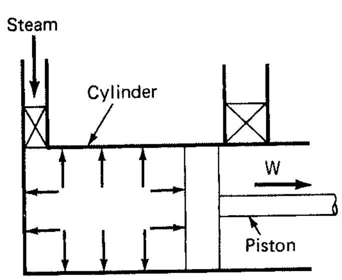

FIGURE 3.1.3 Expanding steam in reciprocating steam engine moves the piston and converts energy to work.

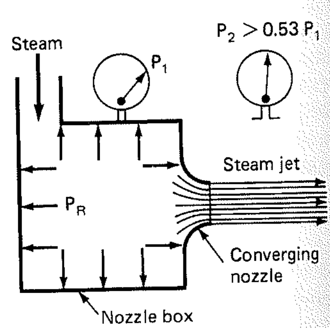

FIGURE 3.1.4 Diverging nozzle is required if the discharge pressure is under 53 percent.

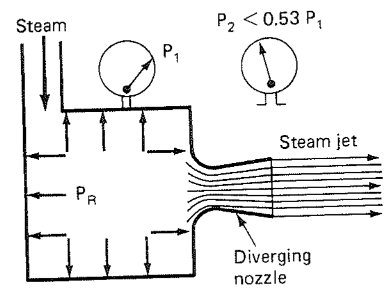

FIGURE 3.1.5 Converging-diverging nozzle.

Impulse-turbine nozzles organize the steam so that it flows in well-formed high-speed jets. Moving buckets absorb the jet's kinetic energy and convert it to mechanical work in a rotating shaft (Fig. 3.1.6). When the bucket is locked, the jet enters and leaves with equal speed and develops maximum force *F*, but no mechanical work is done. As the bucket is allowed to speed up, the jet moves more slowly and force *F* shrinks. Figure 3.1.7 shows how both the force and the work done vary with the blade speed. The steam jet does maximum work when the bucket speed is just one-half of the steam speed. In this condition, the moving bucket leaves behind it a trail of inert steam, since all kinetic energy is converted to work. The starting force or torque of this ideal turbine is double the torque at its most efficient speed.

For practical reasons, most impulse turbines mount their buckets on the rims of disks, and nozzles feed steam from one side (Fig. 3.1.8). Pressurized steam from the nozzle box flows through parallel converging nozzles formed by vanes or foils. In converting the thermal energy of steam to mechanical work, turbines take advantage of this fact: As steam expands, or drops in pressure, through a small opening or nozzle, it accelerates and forms a high-speed jet. Harnessing this momentum in a rotating blade provides mechanical work at the shaft.

Turbines are fundamentally classified as impulse or reaction type by how the steam expands through a nozzle and impacts a blade. Impulse stages are often compared to a waterwheel, reaction stages to a rotary lawn sprinkler.

Impulse nozzles organize the steam so it flows in well-formed high-speed jets (Fig. 3.1.6). Moving blades, also called buckets, absorb the jet's kinetic energy and convert it to shaft rotation. When the blade is stationary, the jet enters and leaves with equal speed, developing the maximum force, but no mechanical work is done. But as the blade speeds up, the jet slows down relatively and the force shrinks. Under ideal conditions, the steam jet does the most work when the blade speed is one-half the steam speed (see Fig. 3.1.7). Steam pressure and speed vary through the true impulse stage.

Impulse designed stages are capable of handling the highest pressure drop per stage and potentially produce more usable power than a reaction stage. Because of the high steam velocity and larger kinetic energy losses, the impulse stage is usually less efficient than an equivalent reaction stage.

In a reaction stage, steam enters the fixed-blade passages and leaves as a steam jet that fills the entire rotor periphery (Fig. 3.1.9). Steam flows between moving blades that, in turn, form moving nozzles. There it drops in pressure, and its speed rises relative to that of the blades. This creates reactive pressure that does work. Despite the rising relative speed, the overall effect reduces the absolute steam speed through one stage.

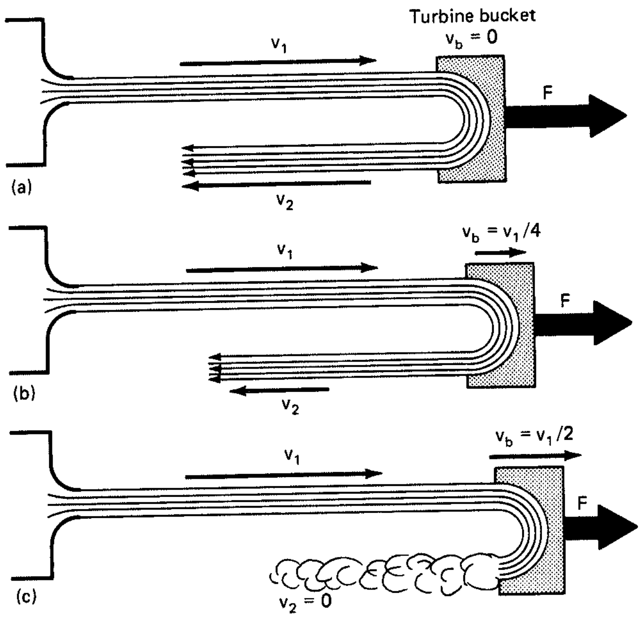

FIGURE 3.1.6 In a steam turbine: (*a*) The steam jet exerts maximum force on the locked impulse bucket, but no work is done since the bucket does not move. (*b*) When the bucket moves with one-quarter the speed of the steam jet, the force diminishes and steam leaves the bucket at lower speed but first does work by moving the bucket. (*c*) When the bucket speed equals one-half the steam jet speed, the force drops to one-half of that of the locked condition. Steam leaves the bucket with zero speed and does maximum work.

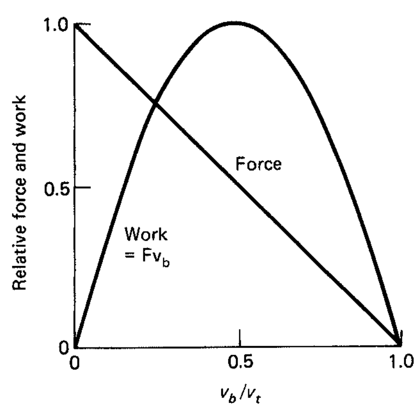

FIGURE 3.1.7 Curves show how the reactive forces and work vary with bucket speed.

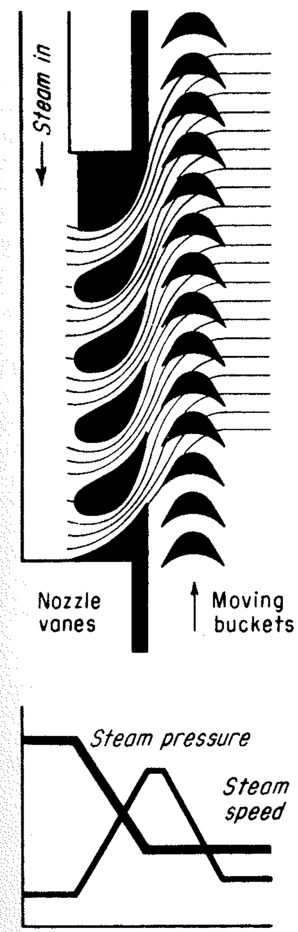

FIGURE 3.1.8 In an impulse turbine, the nozzles direct steam into buckets mounted on the rim of a rotating disk. The steam flow changes to an axial direction as it goes through the moving passages. The pressure drops only across the nozzle.

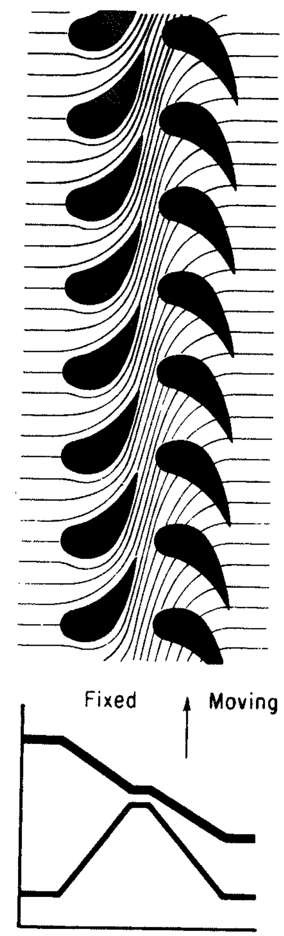

FIGURE 3.1.9 In a reaction turbine, stationary blades direct steam into passages between moving blades; pressure drops across both the fixed and moving blades.

When the enthalpy drop is about equal in the moving and stationary blades, it is called a 50 percent reaction stage.

Reaction designed blades are more efficient than other designs, but more stages are required to efficiently extract the same amount of work compared to pure impulse designs. Additional stages are necessary due to lower pressure-drop limits across each stage and to minimize leakage losses.

While individual turbine manufacturers may favor one type of stage design over another, in practice, steam-turbine manufacturers combine impulse and reaction concepts into their blading design. Most all manufacturers use an impulse or velocity compound stage as their inlet stage. Even this stage may contain some (5 to 15 percent) reaction component to improve stage efficiency. As the steam flows through the turbine, the reaction component increases such that the last stage of a condensing turbine is usually 90 percent reaction at the outer blade end. This stage design is found on most all recent turbines, regardless of the manufacturer.

Steam flowing through nozzles can be pressure-compounded or velocity-compounded (Fig. 3.1.10). In the former, for an impulse design, exhaust steam from one stage flows through similar impulse stages. In the latter, steam energy is absorbed in a series of constant-pressure steps. The velocity energy in the steam emerging from the nozzles is applied to two or more sets of moving blades. Velocity compounding uses a

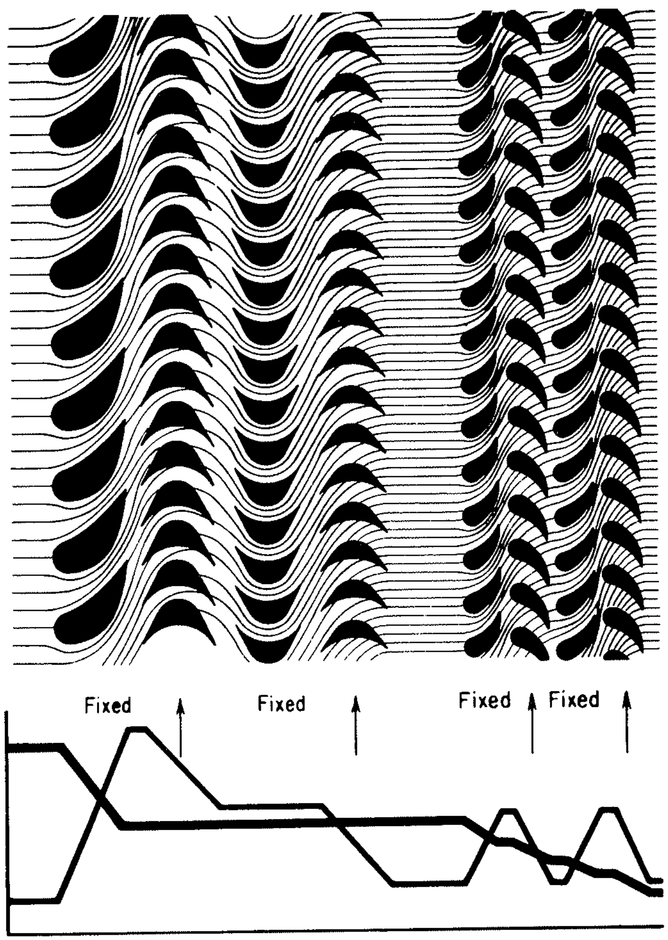

FIGURE 3.1.10 In the velocity-compounded turbine, steam is discharged into two reaction stages. The velocity stage uses a large pressure drop to develop the high-speed jet. Part of the kinetic energy is absorbed in the first moving bucket row. Fixed buckets turn partly slowed steam before it enters a second row of moving buckets, where most of the remaining energy is absorbed. In pressure compounding, there are multiple nozzles, each followed by one row of moving buckets. Each stage is essentially designed as a single-stage impulse turbine.

set of stationary blades between sets of rotating blades to reverse the flow of steam.

In the reaction design example, a velocity-compounded control stage (also known as the *Curtis stage*) is used at the inlet and is followed by two reaction stages. The inlet high-speed steam jet gives up only part of its kinetic energy in the first row of moving blades. Then come reversing blades that redirect the slowed steam in the second row of moving blades, where most of its remaining kinetic energy is absorbed. Steam then enters the series of typical reaction stages.

TURBINE ROTATING SPEED

The rotational speed of power-generating turbines is determined by electric frequency needs. The frequency typically varies from 25 to 60 Hz (cycles per second). The number of magnetic poles of the generator rotor also influences the output speed.

A two-pole generator runs at 3000 and 3600 rpm for 50 and 60 Hz, respectively. A four-pole generator rotor runs at one-half of the above speeds. Typically, the turbine rotor turns at the same speed as the generator rotor, but some turbines run at a higher speed and a reduction gear is connected between them.

Turbines used to drive mechanical equipment may be required to operate at variable speeds. Gearing can also be used to increase or decrease the turbine output shaft speed by a fixed rate. Since blading is designed to have maximum efficiency at one rotor speed, a variable-speed turbine will be less efficient at other speeds. Typical variable-speed turbine rotor speeds range from 3000 to 8000 rpm.

KEY TURBINE COMPONENTS

See Figs. 3.1.11 and 3.1.12.

Blading

Each axial-flow turbine stage is made up of two components: stationary blades and rotating blades. Depending on the stage location in the turbine and the manufacturer's terminology, these two components can have different names. But in general:

- *Nozzle*—first stationary blade row of a turbine. The nozzle can be made in different forms—a bolted-on flat plate that has angled drill holes or inserted blade vanes, or a semicircular pipe (nozzle box) with attached blade vanes. The nozzle takes the highest-stage pressure drop in the turbine. The nozzle is restrained by the casing to counteract steam exit forces.
- *Bucket*—a moving vane attached to the rim of a rotor disk or wheel. Typically it is found on impulse turbine stages.
- *Blade*—a moving vane typically attached to a drum-type rotor. A drum rotor has blades that attach to the outer surface of the shaft or with short wheels. Typically it is found on a reaction turbine.
- *Diaphragm*—two 180° rings that hold inserted stationary blade vanes for one stage (Fig. 3.1.13). Typically it is found on impulse-type turbines. The diaphragms are anchored into the turbine casings and resist torque opposite to the direction of rotor rotation.

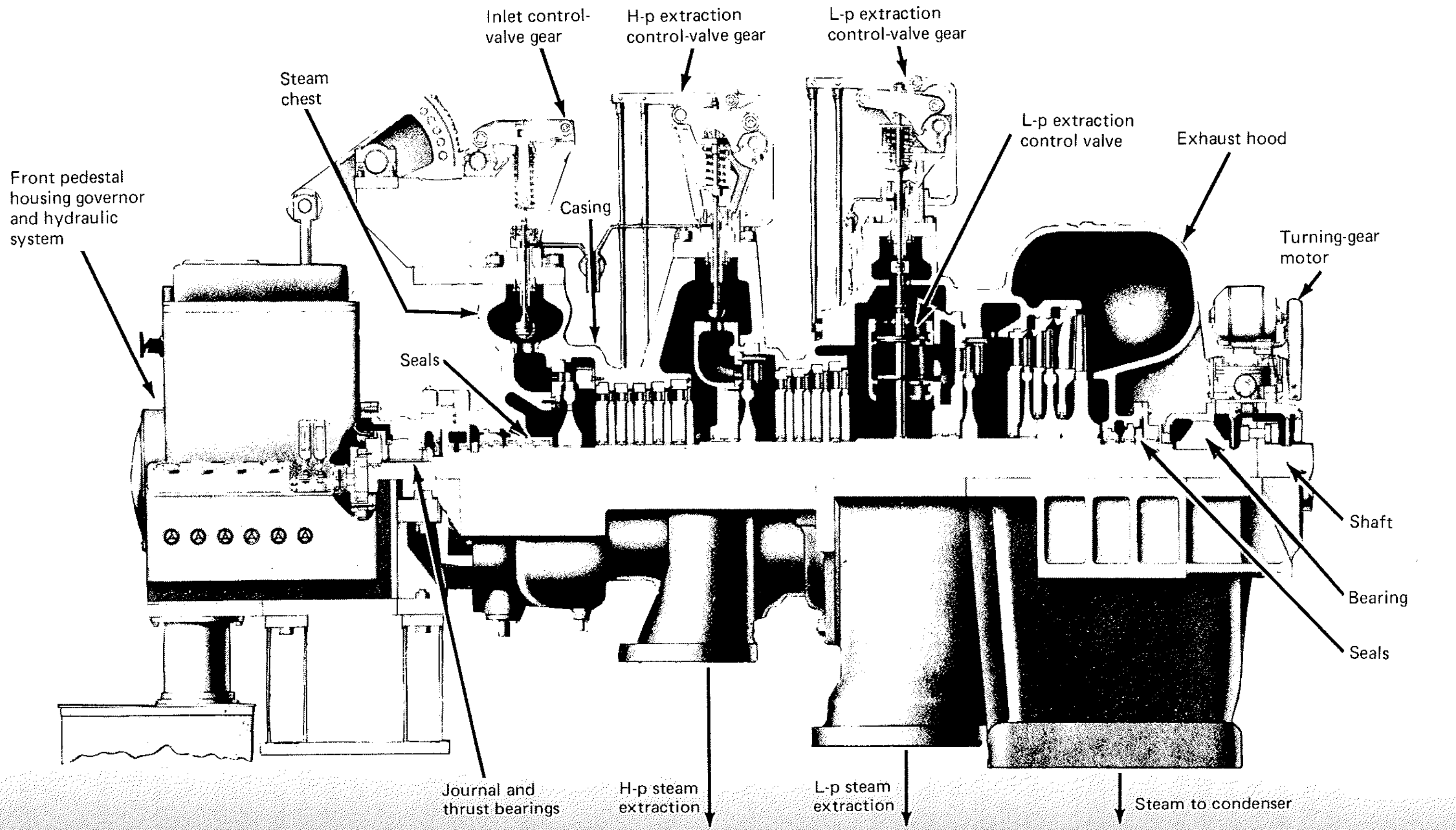

FIGURE 3.1.11 Impulse-type double-automatic-extraction condensing turbine.

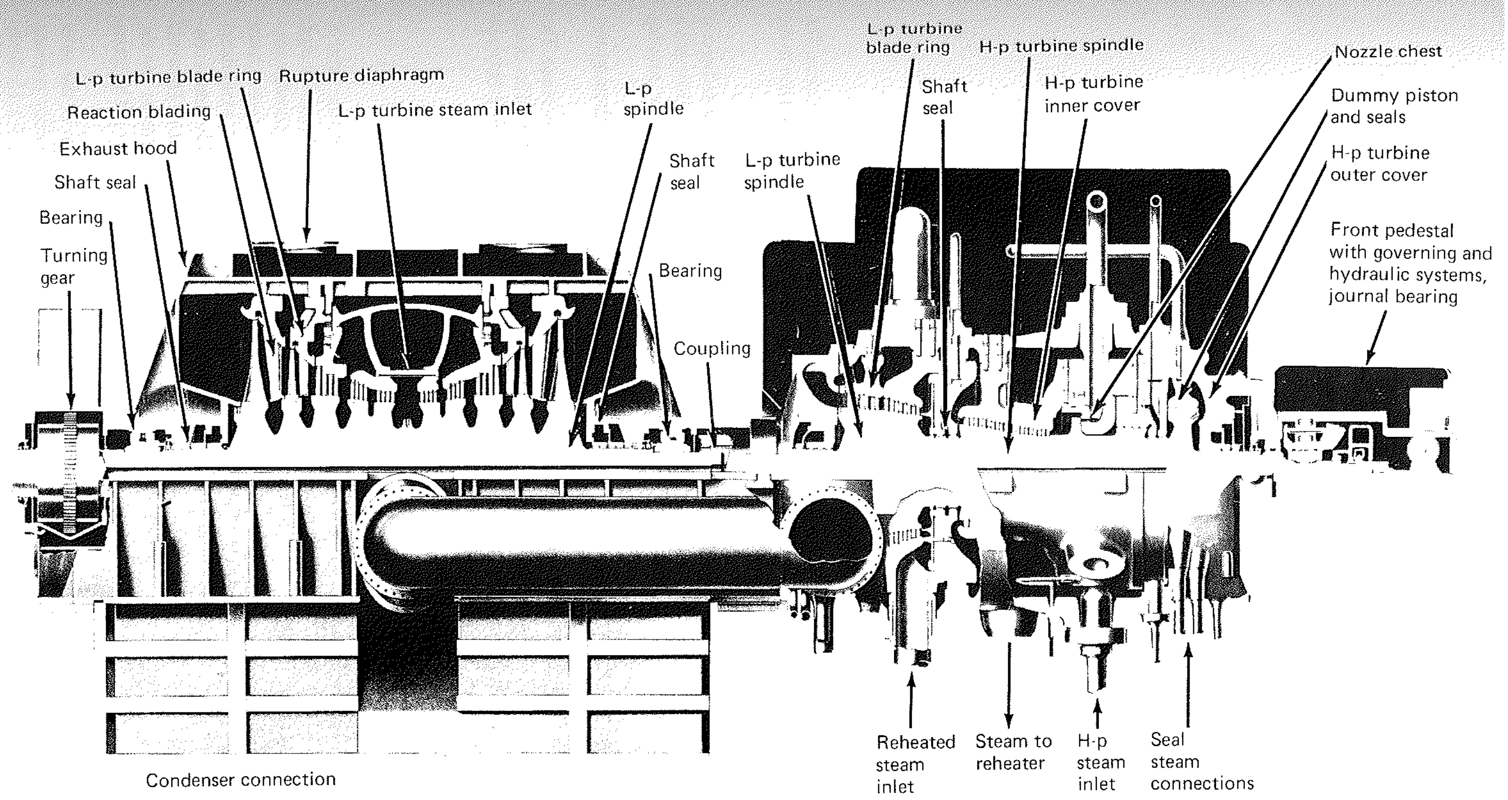

FIGURE 3.1.12 Reaction-type (drum) turbine with two main casings.

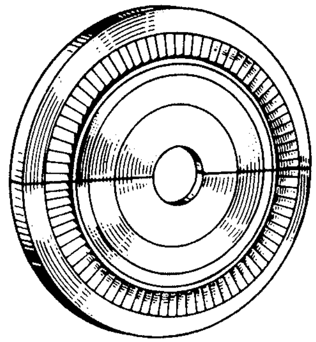

FIGURE 3.1.13 Impulse-type diaphragm.

- *Blade ring*—two 180° casings that hold multiple stages of stationary blade vanes. The blade ring anchors the blading into the outer casing and resists torque opposite to the direction of rotor rotation. Typically it is found on reaction turbines.

The general function of stationary blades is to take axial steam flow and redirect it upon leaving the blade, into a vortex flow (Fig. 3.1.14). The vortex steam flow has a rotational component, and the flow is then directed at the inlet side of the rotating blades.

When the rotating blades are moving at design speed, the exiting steam then returns to an axial flow. This process continues for each stage.

As steam expands through the stages, its energy level and density level decrease. The volume of the steam increases, necessitating a larger blade flow annulus. The blade lengths increase to provide a larger annulus, and/or the steam flow is divided between two or more stages of equal size to enlarge the annulus.

Rotating-Blade (Bucket) Geometry

When blade height becomes a significant part of the total stage diameter, the ratio of steam to bucket speed changes over the length of the bucket. To counteract this change, warped buckets are installed (Fig. 3.1.15). An exploded view (Fig. 3.1.14) shows a nozzle diaphragm, steam vortex flow, a bladed or bucketed wheel, and the leaving exhaust steam. Ideally, steam enters the nozzle diaphragm or stationary blade in an axial direction and leaves in a circumferential direction, forming a vortex flow or eddy that is contained by the turbine casing before steam enters the moving buckets. To avoid cross-currents in the vortex flow, the product of the linear velocity of steam and the radius of the circle in which it travels must be constant, that is, $v_1r_1 = v_2r_2$. The steam pressure must also be higher at the outer rather than the inner radius.

Steam leaves nozzles at the inner radius with higher linear speed than at the outer radius. But the bucket's linear speed increases with the radius. So a steadily growing ratio of blade to steam speed occurs as one moves from root to tip. Figure 3.1.15 shows

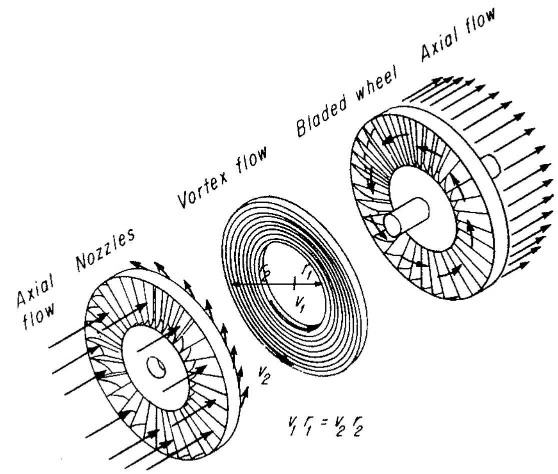

FIGURE 3.1.14 Steam flows axially in entering stages, nozzles, or diaphragms and leaves as a vortex flow. A twisted-blade design on the rotor returns the flow to axial for inlet to the next stage.

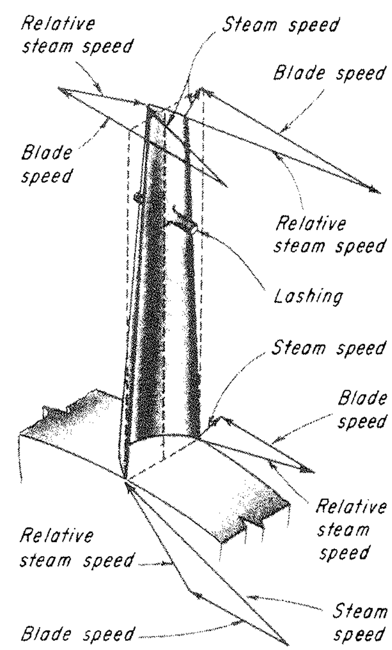

FIGURE 3.1.15 This twisted condensing-stage rotor blade works with impulse flow at the root and reaction flow at the tip.

velocity diagrams at the root and tip of a blade that receives a steam jet moving in vortex flow. The blade root has been designed for impulse flow, which is equivalent to 0 percent reaction and no pressure drop.

The blade's entrance angle is fixed by the angle of approach of the steam's relative speed, so steam slides smoothly over the blade. In the ideal situation, the absolute steam speed should be just about double the blade speed. At the blade's exit edge, the vector difference of relative steam and blade speeds shows that steam has a residual absolute speed in an axial direction.

Since the blade speed at its tip is about double the absolute steam speed, the steam must approach the blade from a direction almost opposite to its motion. The blade section must be twisted to receive the steam smoothly all the way up the blade. But since entering steam pressure is higher at the tip than at the root, there will be a pressure drop through the blade. Thus a reaction blade section must be used with the relative steam speed higher at the blade exit. A pure reaction force acts at the blade tip, a pure impulse force at the root. At the tip exit, the vector difference of relative steam speed and blade speed indicates that steam leaves with low velocity in an axial direction, just as at the root.

The number of blades per stage depends on several factors including blade strength requirements and the number of upstream stationary blades (to prevent excess harmonic stimuli). Examples of impulse and reaction stages are shown in Figs. 3.1.16 and 3.1.17.

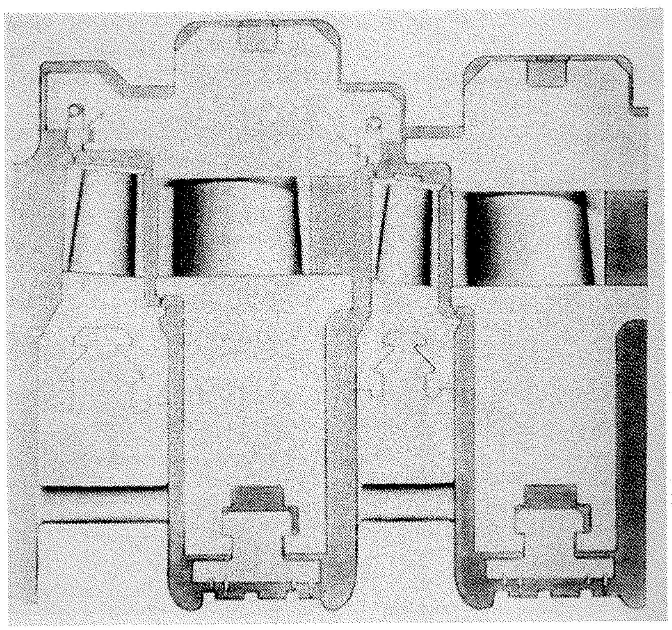

FIGURE 3.1.16 Impulse stages with two rotating bucket rows with diaphragms between them. Single seal on shroud around buckets and labyrinth packing ring in diaphragms control steam leakage. Buckets are attached to rims of rotor wheels.

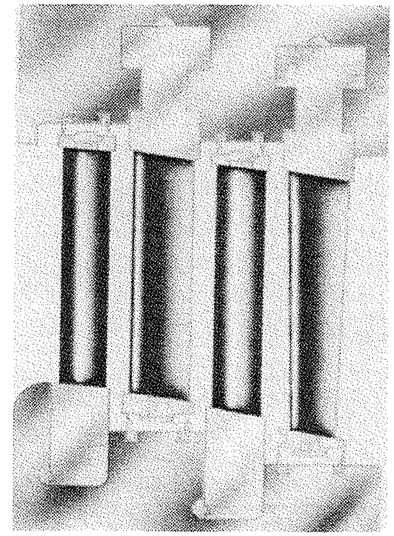

FIGURE 3.1.17 Reaction stages with two rotating rows of blades with stationary blades between them. Double seals are on blading shrouds.

Rotors, Shafts, and Drums

The rotating blades are attached to the outer perimeter of the rotating shaft (Fig. 3.1.18). Some manufacturers call the rotating shaft a *spindle* while others call it a *rotor* or a *drum*. Smaller industrial drive rotors are typically built up with disks shrunk onto a slender shaft. The blades fit onto or into machined grooves at the outer diameter of the disks. The disks are keyed onto the shaft to transmit torque. This design is simpler to manufacture and is not limited by available maximum forging size. Some older and larger utility units had low-pressure rotors that were also constructed by this method.

Due to recent advances in steelmaking and forging capacity, today, most all larger utility turbine rotors are made from a single piece forging (Mono-block) or are constructed from several forged rings welded together. These are also machined to accept rows of blades.

Large rotors may or may not have a central bore, as shown in the top two rotors of Fig. 3.1.18. Before the mid-1970s, bored-out rotor and shaft forgings were necessary to remove center-area imperfections. Recent steelmaking is more controlled, and bores are not usually required with shrunk-on disk or solid rotor designs.

Casings

Casings are also called *shells,* or *cylinders,* depending on the turbine manufacturer. Casings contain the high steam pressure from leaking out as well as prevent air from leaking into the condenser. They also position the nozzles, diaphragms, blade rings, shaft end seals, and, on smaller turbines, even the bearings. The casings must control the position of most of these parts so that they do not contact the spinning rotor. The sta-

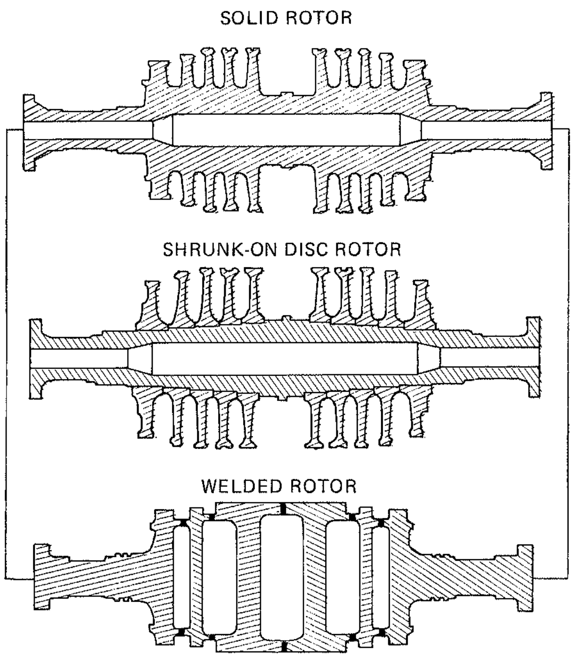

FIGURE 3.1.18 Key types of rotors for large and small turbines.

tionary blading thrust and torque forces are offset by the casing and turbine foundation supports.

On larger high-temperature units, there are usually multiple inner and outer casings. This reduces temperature and pressure gradients to better accommodate thermal expansion of the components relative to the rotor. Typically, the center section of the high and intermediate (reheat) casing contains the hottest inlet steam on larger turbines. The casings on most designs are split horizontally, and the two halves are bolted together. Some less common types are split at a 45° angle, and the two halves are held together by shrink rings that are fitted around the outside of the casings. Other less common designs use a casing that opens on one end so the rotor and stages can be removed. This design is called a *barrel-type casing.*

High-pressure and high-temperature casings are usually made from two halves of low-alloy steel castings. They may be up to 20 ft (6 m) long by 12 ft (3.6 m) in diameter and weigh 100 tons (90,700 kg). Lower-temperature and lower-pressure turbines are presently weld-fabricated from steel plate, while older designs may have included cast inner casings.

Exhaust Hood

An exhaust hood guides the flowing steam from the last stage of the turbine to the point of disposal—a pipeline, condenser, etc. This hood must be designed to minimize pressure loss, which otherwise would reduce the turbine's thermal efficiency. In highly refined central station units, the hood may act as a diffuser to develop pressure at the outlet of the last-stage buckets lower than that at the hood outlet. It does this by converting leaving kinetic energy of the last stage to internal energy.

Rupture diaphragms in the exhaust hood prevent excessive steam pressure buildup should the condenser lose its vacuum. On larger noncondensing turbines, a safety valve on the exhaust piping protects the exhaust casing from excess pressure.

Steam Valves

Valves are used to control steam flow through the turbine. There are two types of valves. *Stop valves* are either open or closed to admit or interrupt steam flow. The other type is called a *control, governor,* or *intercept valve.* The later valves are used to regulate turbine rotor speed load or mechanical output.

When the turbine is started, the stop valve is opened wide and the control valves are slowly opened until the desired speed is attained. Control valves admit more steam through the first-stage nozzles to increase the load. On electric generating turbines, the control valves continue to open after the generator is synchronized with the grid.

Reheat turbines need both intercept and stop valves between the boiler reheater and the reheat turbine inlet. Steam energy in the boiler reheater and its connecting steam lines can seriously overspeed the unit during a large load drop or loss. The intercept valve closes partway during rapid load changes; both valves shut on overspeed. Similarly, the stop valve slams shut to stop steam flow to the inlet turbine rotor.

On smaller mechanical drive turbines, the stop and control valve functions may be handled by a single valve attached to the turbine (Fig. 3.1.19). On larger units, a separate stop valve is usually installed in the steam line adjacent to the turbine. The control valves may be installed in a steam chest attached to the turbine casing or in a separate valve casing adjacent to the turbine.

In automatic extraction turbines, a controlling valve is placed at the extraction points to control pressure or flow into the extraction steam lines.

While older turbines had their controlling valves operated by mechanical governors, mechanical linkages, and cams, recent designs may use an electronic governor and individual hydraulic servo-controlled hydraulic cylinders.

Shaft and Casing Seals

Seals are used on all turbines to contain the steam from leaking out where the shaft must pass through. No seal is perfect, and some steam will leak out or air will leak in at the exhaust end of a condensing turbine.

On smaller turbines, carbon (or similar material) packing rings ride directly on the shaft to seal the shaft to the casing (Fig. 3.1.20). Tension springs hold the ring segments in place and against the shaft. The small amount of steam that leaks past the rings is usually vented to a low-pressure turbine stage, the condenser, or the atmosphere. Condensed steam is collected at the outer seal and is usually drained to waste.

On some older but larger units, the shaft end areas may be sealed by using pressurized water (glands). The water is admitted to an annulus around the shaft prior to starting the turbine. The water seals the shaft against air in-leakage when a condensing turbine casing is put under a vacuum. An impeller is attached to the shaft inside the annulus. When operating, the impeller creates a positive pressure in the annulus and reduces the amount of water flow needed for the seal. Modern larger units have stepped labyrinth gland seals to control shaft leakage (Fig. 3.1.21). Intermediate leak-offs direct the steam to lower-pressure turbine stages. The outboard leak-off collects final steam

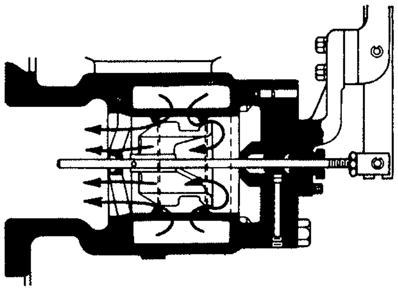

FIGURE 3.1.19 Balanced stop and control valves for small turbine.

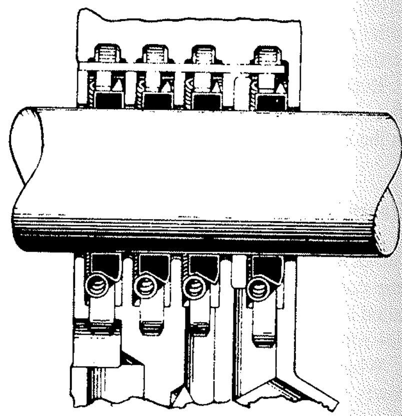

FIGURE 3.1.20 Carbon packing.

leakage and outside air in-leakage and is then directed to a small gland vacuum condenser. The steam is condensed, and the condensate is reused. The noncondensable air is vented to the atmosphere.

The labyrinth seals have alternating high and low teeth that match steps machined on the shaft. The seals have sharpened teeth that are positioned near the shaft to create high flow resistance. Enough axial distance is needed between steps to avoid contact when the shaft and gland casing expand or contract at different rates. When differential movement is large, the shaft is made smooth and the seal teeth are all of equal length. The seal teeth may be angled to add additional flow resistance.

Bearings

Bearing types range from pressure-lubricated babbitted journal bearings for large turbines (Fig. 3.1.22) through ball or roller bearings for small turbines. The larger bearings are configured with slightly elliptical bores and relief grooves in their top halves, to build an oil wedge that presses the shaft downward to increase shaft stability. To further increase shaft stabilization on large units, the circular bearing may be segmented into three to six tilting pads.

The stages of turbines are arranged to offset steam forces and reduce shaft thrust loading. The net thrust must be restrained to keep the rotor in proper position. Figure 3.1.23 shows a Kingsbury-type thrust bearing, in which individual swiveling shoes (pads) bear on leveling plates (left). A thrust collar on the shaft rides against the shoes from the right with a film of oil.

Auxiliaries

To support the sealing and bearing functions on larger units, separate lube oil and shaft seal systems are used. The lube oil system contains pumps, coolers, filters, and a storage tank. These are typically contained in one tank which is located below the turbine elevation to facilitate gravity oil returns from the bearings.

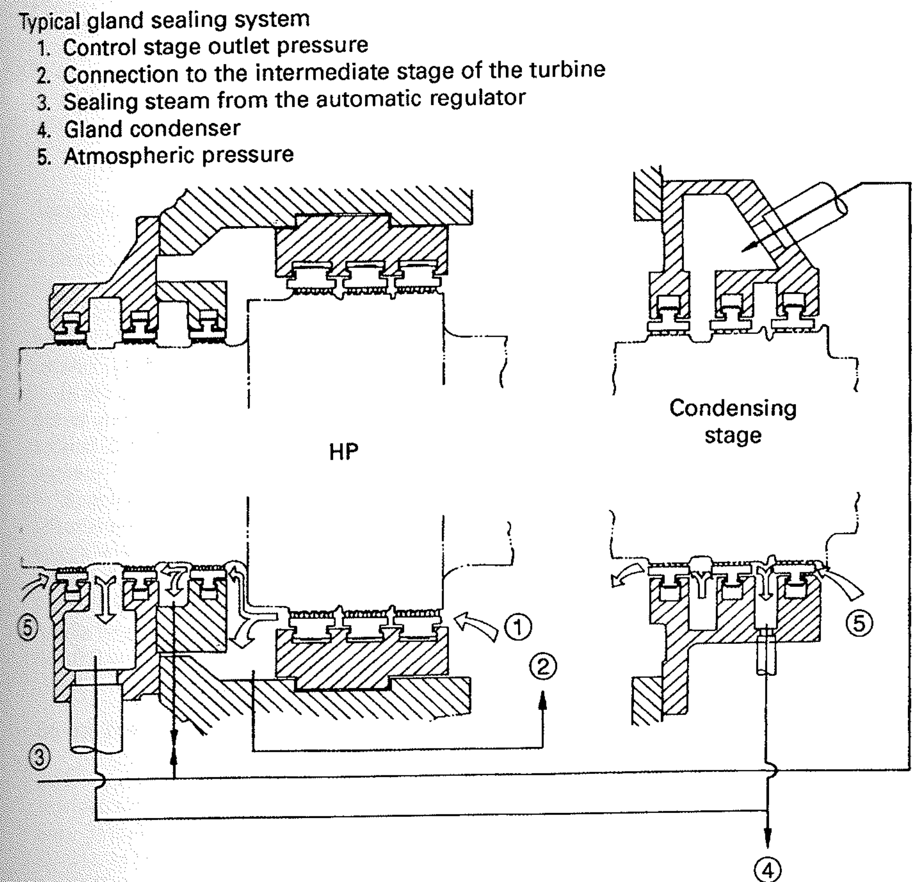

FIGURE 3.1.21 Typical gland sealing system: (1) Control stage outlet pressure, (2) connection to the intermediate stage of the turbine, (3) sealing steam from the automatic regulator, (4) gland condenser, and (5) atmospheric pressure.

The lube oil may also be used to position the steam valves. On larger units, electric oil pumps are used for start-up and as backup to the main shaft pump, which is coupled to the main turbine rotor.

On larger units, the steam sealing system regulates the steam pressure inside the gland housings. The system consists of a pressure-regulating valve, a condenser, and an exhaust blower. The system ties to a boiler steam line for a steam source on start-up and a dump valve for controlling leak-off pressure when the unit is in service.

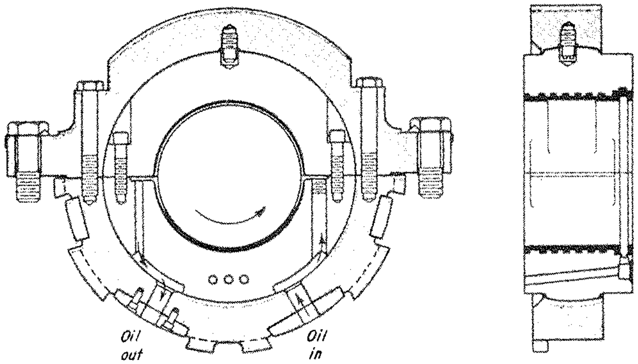

FIGURE 3.1.22 Journal bearing has a spherical seat for self-alignment. Oil builds a wedge at the bottom to lubricate shaft, and oil pressure builds at the top to keep shaft stabilized in bearing.

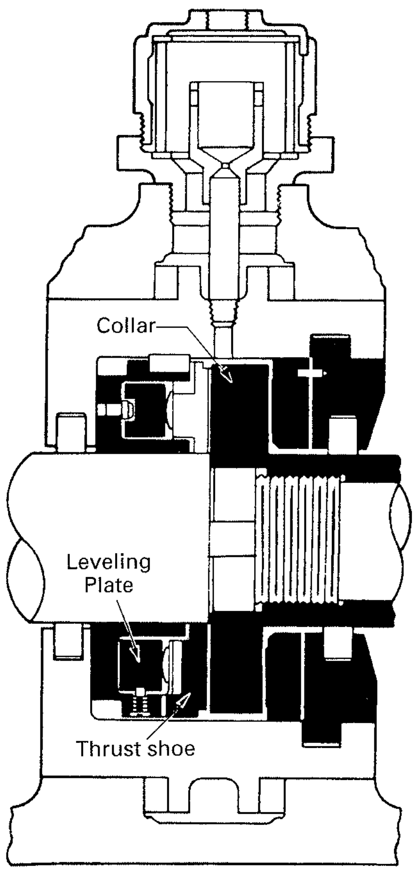

FIGURE 3.1.23 In a Kingsbury-type thrust bearing, the tilting shoes form oil wedges.

PRIMARY TURBINE TYPES

Steam turbines can be divided into two basic categories: condensing turbines, which exhaust steam at less than atmospheric pressure, and noncondensing or back-pressure turbines, which exhaust steam at higher than atmospheric pressure.

Condensing versus Noncondensing

A steam turbine has no means of controlling its exhaust pressure, which is determined by the system it services. With back-pressure turbines, the exhaust pressure usually is controlled by using a reducing station, with an outlet pressure set to maintain the desired level. If the exhaust system or process requires more steam than is flowing through the turbine, the reducing station makes up the difference.

In the case of a condensing turbine, the vacuum generally is maintained with a condenser and air ejectors of the steam jet or mechanical pump type. Shaft-sealing steam is applied to the turbine glands to prevent air from entering the seals and destroying the vacuum.

Noncondensing turbines have their widest application in process plants and may be either single-stage or multistage machines (Figs. 3.1.24 and 3.1.25) that can be built to meet a wide range of output requirements. Properly applied, these units permit designers to achieve a high overall level of steam cycle efficiency. Condensing turbines are found most often in central stations and generally are multistage machines designed to handle large volumes of steam. Noncondensing turbines cost less to purchase than condensing units, but their efficiency often is lower, too.

Steam Flow Patterns

Both condensing and noncondensing turbines may be categorized further by the manner in which steam flows through the machine—straight flow, reheat, extraction, and induction. Straight-flow turbines use full-throttle steam flow from inlet to exhaust (Fig. 3.1.26). In reheat turbines, virtually all of which serve in utility powerplants, the main steam flow exhausts from the unit at one (single-reheat, Fig. 3.1.27) or two (double-reheat, Fig. 3.1.28) intermediate stages. The temperature of this steam is then increased, usually in the boiler furnace, before the steam is returned to the turbine at the next-lower stage for further expansion.

Extraction turbines see service in both industrial and utility powerplants. The automatic-extraction units typical of industrial plants bleed off part of the main steam flow

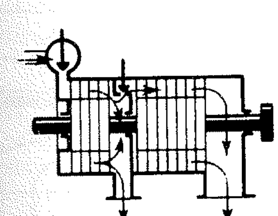

FIGURE 3.1.24 Single automatic-extraction turbine, noncondensing type.

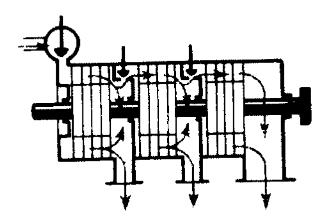

FIGURE 3.1.25 Double automatic-extraction turbine, noncondensing type.

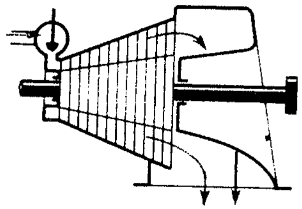

FIGURE 3.1.26 Straight-through design, condensing type.

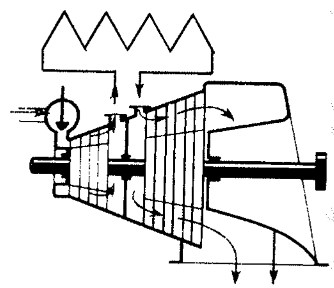

FIGURE 3.1.27 Single-reheat design, condensing type.

at one, two, or three points (Figs. 3.1.29, 3.1.30, and 3.1.31). Valved partitions between selected turbine stages control the extracted steam for process use at various points which can be maintained at any rate within design limitations.

When extracted steam flow through the turbine does not produce enough shaft power to meet the demand, more steam flows through to exhaust. Extraction turbines are located between steam supply and process steam heaters. Automatic governing systems correlate steam flows, pressures, shaft speed, and shaft output for any one unit.

Turbines driving generators in central stations usually combine condensing, reheating, and nonautomatic extraction. Large units can have over a dozen bleed points for

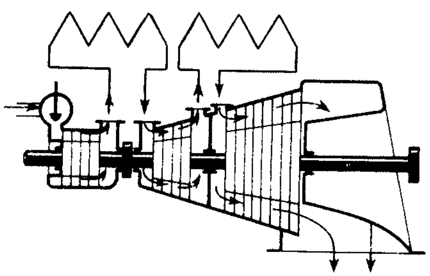

FIGURE 3.1.28 Double-reheat design, condensing type.

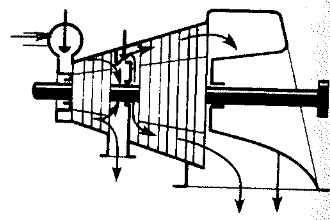

FIGURE 3.1.29 Single automatic-extraction unit, condensing type.

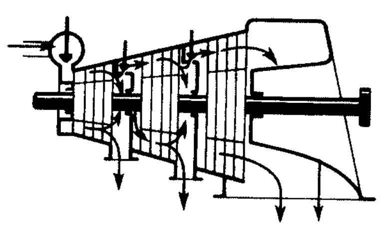

FIGURE 3.1.30 Double automatic-extraction unit, condensing type.

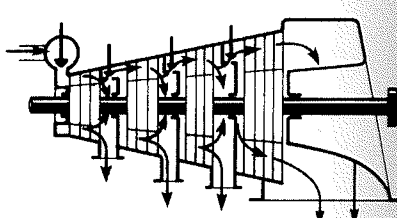

FIGURE 3.1.31 Triple automatic-extraction unit, condensing type.

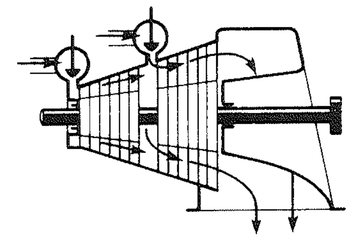

FIGURE 3.1.32 Induction-type turbine, condensing.

feedwater heating. In these non-automatic-extraction turbines, the pressure of extracted steam at each point varies with the turbine shaft load. Although such variations can seldom be tolerated for process work, they are acceptable for feedwater heating service.

Induction turbines work as extraction turbines—except in reverse (Fig. 3.1.32). That is, steam at lower than throttle pressure is injected into the unit downstream of the throttle valve to produce a portion of the total output. Combination units incorporate both functions: extraction and induction. Induction machines generally are found in process plants, although at least one manufacturer also specifies them for utility combined-cycle service.

Most importantly, although the simplicity of straight-through machines keeps the first cost low, operating flexibility and efficient use of steam dictate the selection of extraction or induction units in many process applications and reheat, non-automatic-extraction turbines in central station service.

Tandem Compounding versus Cross-Compounding

Simple, small multistage turbines are generally built with all the stages on a single shaft that is housed in one casing. As turbine sizes increase beyond 40 MW, however, single casings become impractical. To avoid long casing runs, the different stages may be split among two or more casings on separate rotors; as many as six different casings may see service today.

If all the rotors of the different casings are bolted together in line to drive the same generator, it is called a *tandem-compound turbine* (Fig. 3.1.33). In other installations, the sections may be arranged with two shafts, or groups of shafts, side by side, driving two separate generators. This is called a *cross-compound turbine* (Fig. 3.1.34). Cross-compounding for large units has the advantage of making it easier to construct two half-sized generators than one large unit.

Nearly all larger turbines built in the last 25 years are condensing, single or double reheat, with simple multiple extraction for regenerative feedwater heating, and nearly all are compound units, with most being tandem-compound rather than cross-compound machines. Steam conditions for modern turbines have also largely been standardized at 1800, 2400, and 3600 psia (12,400, 18,600, and 24,800 kPa). Initial and reheat steam temperatures range between 950 and 1050°F (510 and 566°C). Exhaust pressures, while limited by the temperature of the cooling water available, range from about 1 to $3\frac{1}{2}$ inHg (3.38 to 11.83 kPa). Recently, there has been considerable interest in high-back-pressure condensing turbines for pairing with dry-cooling towers and condensers. It requires a special design of the last-stage blading.

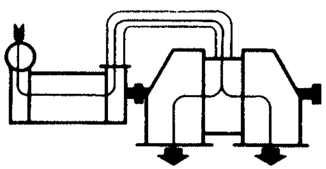

FIGURE 3.1.33 Tandem-compound, nonreheat unit in a two-casing, double-flow, low-pressure turbine.

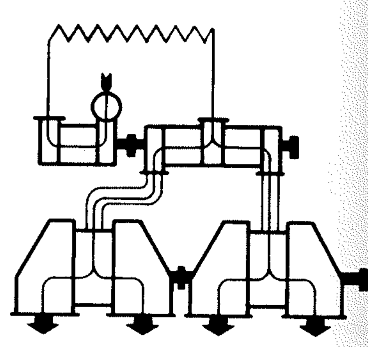

FIGURE 3.1.34 Cross-compound unit. This is a four-casing, quadruple-flow, low-pressure design with reheat.

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SECTION 3.2
STEAM-TURBINE DESIGN

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INTRODUCTION

The function of the steam turbine is the conversion of stored thermal energy to mechanical work by controlled expansion of the steam through stationary nozzles and rotating blades. Steam turbines can be classified in a number of ways: Rankine cycle, Rankine regenerative cycle, reheat cycle, condensing or noncondensing, and so on. The turbine can be classified according to the number and arrangement of the shafts and casings. When there are two or more casings, the designs are designated as *tandem compound* (all casings on the same shaft) or *cross-compound* (casings on two or more shafts). The smaller units using a nonreheat cycle accomplish the expansion from the initial steam (throttle) conditions to the condenser in a single casing, as shown in Fig. 3.2.1.

As the unit size increases, the last-stage annulus area necessitates two parallel-flow paths, or double flow, resulting in a separate low-pressure (LP) casing (Fig. 3.2.2) and a separate high-pressure (HP) casing. For reheat turbines the expansion of the steam occurs in three stages: HP (Fig 3.2.3), intermediate-pressure (IP) (Fig. 3.2.4), and LP with the IP element expanding the steam from the hot reheat to the LP element inlet. Moreover, for unit ratings up to about 600 MW, the HP and IP expansions may be accomplished in a combined HP-IP element (Fig. 3.2.5), with a common outer shell or casing with appropriate subdivisions in the inner shell.

Turbines can also be characterized by the level of the throttle steam temperature and pressure. Fossil-fuel steam conditions are typified by high pressure and high temperature (high superheat). Nuclear turbine conditions are essentially dry and saturated steam or modest superheat with pressures in the range of 700 to 1100 psia (4823 to 7579 kPa). For nuclear turbines rated at 800 MW and above, the turbine configuration consists of a double-flow HP element and two or more double-flow LP elements, as illustrated in Fig. 3.2.6.