**Turbines, Gas**

LEE S. LANGSTON  
University of Connecticut  
Storrs, Connecticut, United States

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**Glossary**

Aeroderivative An aviation propulsion gas turbine (jet engine) used in a nonaviation application (e.g., an electric power plant) to provide shaft power.

Brayton Cycle Ideal gas cycle that is approximated by a gas turbine simple cycle.

Cogeneration A gas turbine operating to produce shaft power and to supply heat from its exhaust for some useful purpose.

Combined-Cycle Power Plant The combination of a gas turbine power plant and a steam turbine power plant. The gas turbine exhaust energy is used as heat input to generate steam.

Gas Generator The compressor, combustor, and turbine components of a gas turbine.

Isentropic A process that is reversible and adiabatic; having constant entropy.

Jet Engine An aviation gas turbine used for aircraft propulsion thrust power.

Rankine Cycle Ideal gas cycle that is approximated by a simple steam turbine power plant cycle.

Thermal Efficiency Useful output power divided by costly input energy rate, expressed as a percentage.

Working Fluid In the case of gas turbine, the gas (usually air) that flows through the machine to produce work or power.

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The first jet engine-powered aircraft flight and the first electric power produced by a land-based gas turbine both occurred in 1939, making the gas turbine one of the youngest energy conversion devices. A gas turbine consists of a rotating assembly of a compressor to draw in a gas (usually air) and a turbine to extract power from the gas flow. Energy (usually combusted fuel) is added in a combustor between the two rotating components to heat the gas flow and power the turbine. Gas turbines are used to produce either thrust power (e.g., an aircraft jet engine) or shaft power (e.g., to turn an electric generator). The thermal efficiency and power output of a gas turbine are dependent on the compressor pressure ratio and on the gas flow temperature at the inlet to the turbine. Gas turbines range in size from hand-held units to whale-size units, weighing from a few kilograms to 300,000 kg, and producing power from tens of kilowatts up to 250 MW.

1. INTRODUCTION

In the broad sense, a turbine is any kind of spinning device that uses the action of a fluid to produce work or power (work per unit time). Typical fluids are air, water, steam, gaseous combustion products, and helium. Windmill turbines, water turbines in hydroelectric dams, and steam turbines have been used for decades to turn electrical generators to produce electrical power for both industrial and residential consumption. Simple turbines date back centuries, with the first known appearance in ancient Greece (Hero's turbine).

In the history of energy conversion, the gas turbine is a relatively new energy converter, or prime mover. The first practical gas turbine used to generate electricity ran at Neuchatel, Switzerland, in 1939 and was developed by the Brown Boveri firm. The first gas turbine-powered airplane flight also took place in 1939 in Germany using the gas turbine developed by Hans P. von Ohain. In England in the 1930s, the invention and development of the aircraft gas turbine by Frank Whittle resulted in a similar British flight in 1941.

Table I presents a list of energy converters and the year in which a first working device was successfully
run. The gas turbine is by far the “youngest” of the energy converters listed. Note that the common automotive gasoline engine (Otto engine) has been around a long time (1876), as has the fuel cell (1839).

The name “gas turbine” is somewhat misleading, for it implies a simple turbine that uses gas as a working fluid. Actually, a gas turbine (as shown schematically in Fig. 1) has a compressor to draw in and compress gas (usually air), a combustor (or burner) to add combusted fuel to heat the compressed gas, and a turbine (or expander) to extract power from the hot gas flow. The gas turbine is an internal combustion (IC) engine employing a continuous combustion process, as distinct from the intermittent combustion occurring in a Diesel or Otto cycle IC engine.

Because the 1939 origin of the gas turbine lies both in the electric power field and in aviation, there has been a profusion of “other names” for the gas turbine. For land and marine applications, it is generally called a gas turbine, but also a combustion turbine, a turboshaft engine, and sometimes a gas turbine engine. For aviation applications, it is usually called a jet engine, and various other names (depending on the particular aviation configuration, or application), such as jet turbine engine, turbojet, turbofan, fanjet, and turboprop or prop jet (if it is used to drive a propeller) are also sometimes used. The compressor–combustor–turbine part of the gas turbine (Fig. 1) is commonly termed the gas generator.

2. GAS TURBINE APPLICATIONS

In an aircraft gas turbine, all of the turbine power is used to drive the compressor (which may also have an associated fan or propeller). The gas flow leaving the turbine is then accelerated to the atmosphere in an exhaust nozzle (Fig. 1A) to provide thrust or propulsion power. Gas turbine or jet engine thrust power is the mass flow momentum increase from engine inlet to exit, multiplied by the flight velocity.
A typical jet engine is shown in Fig. 2. Such engines can range from approximately 100 lbs of thrust (445 N) to as high as 100,000 lbs of thrust (445,000 N), with dry weights ranging from approximately 30 lbs (134 N) to 20,000 lbs (89,000 N). The jet engine shown in Fig. 2 is a turbofan engine, with a larger diameter compressor-mounted fan. Thrust is generated both by air passing through the fan (bypass air) and by air passing through the gas generator itself. With a large frontal area, the turbofan generates peak thrust at low (takeoff) speeds, making it most suitable for commercial aircraft. A turbojet does not have a fan and generates all of its thrust from air that passes through the gas generator. Turbojets have smaller frontal areas and generate peak thrusts at high speeds, making them most suitable for fighter aircraft.

In nonaviation gas turbines, part of the turbine power is used to drive the compressor. The remainder, the “useful power,” is used as output shaft power to turn an energy conversion device (Fig. 1B), such as an electrical generator or a ship’s propeller. As shown in Fig. 3, shaft power land-based gas turbines can become very large (as high as 240 MW). The unit in Fig. 3 is called an industrial or frame machine, used mostly for electric power generation. It is constructed for heavy duty, ruggedness, and long life, where weight is not a major factor as it is with a jet engine. Typically, frame machines are designed conservatively and have made use of jet engine technical advances when it has made sense to do so.

Lighter-weight gas turbines derived from jet engines (such as in Fig. 2) and used for nonaviation applications are called aeroderivative gas turbines. Aeroderivatives are used to drive natural gas pipeline compressors, to power ships, and to produce electric power. They are particularly used to provide peaking and intermediate power for electric utility applications. [Peaking power supplements a utility’s normal electric power output during high-demand periods (e.g. summer air conditioning in major cities).]

Some of the principle advantages of the gas turbine are as follows:

1. It is capable of producing large amounts of useful power for a relatively small size and weight.
2. Since motion of all its major components involves pure rotation (i.e., no reciprocating motion as in a piston engine), its mechanical life is long and the corresponding maintenance cost is relatively low.
(During its early development, the deceiving simplicity of the gas turbine caused problems, until aspects of its fluid mechanics, heat transfer, and combustion were better understood.)

3. Although the gas turbine must be started by some external means (a small external motor or other source, such as another gas turbine), it can be brought up to full-load (peak output) conditions in minutes, as contrasted to a steam turbine plant, whose startup time is measured in hours.

4. A wide variety of fuels can be utilized. Natural gas is commonly used in land-based gas turbines, whereas light distillate (kerosene-like) oils power ship and aircraft gas turbines. Diesel oil or specially treated residual oils can also be used, as can combustible gases derived from blast furnaces, refineries, land fills, sewage, and the gasification of solid fuels such as coal, wood chips, and bagasse.

5. The usual working fluid is atmospheric air. As a basic power supply, the gas turbine requires no coolant (e.g., water).

In the early days of its development, one of the major disadvantages of the gas turbine was its lower efficiency (hence higher fuel usage) when compared to other IC engines and to steam turbine power plants. However, during the past 50 years, continuous engineering development work has pushed the thermal efficiency (18% for the 1939 Neuchatel gas turbine) to approximately 40% for simple-cycle operations and up to 60% for combined-cycle operations (i.e., when combined with a heat-recovery steam-generation unit and a steam turbine). Even more fuel-efficient gas turbines are in the planning stages, with simple-cycle efficiencies predicted as high as 45–47% and combined-cycle machines in the >60% range. These projected values are significantly higher than those for other prime movers, such as steam power plants.

3. GAS TURBINE CYCLES

The ideal gas Brayton cycle (1876, and also proposed by Joule in 1851), shown in graphic form in Fig. 4A as a pressure–volume diagram, is an idealized representation of the properties of a fixed mass of gas (working fluid) as it passes through a gas turbine in operation (Fig. 4B).

A unit mass of ideal gas (e.g., air) is compressed isentropically from point 1 to point 2. This represents the effects of an ideal adiabatic (isentropic) compressor (Figs. 1 and 4B) and any isentropic gas flow deceleration for the case of an aviation gas turbine in flight (Fig. 1A). The ideal work necessary to cause the compression is represented by the area between the pressure axis and the isentropic curve 1–2.

The unit gas mass is then heated at constant pressure from 2 to 3 in Fig. 4 by the exchange of heat input, $Q_{23}$. This isobaric process is the idealized representation of heat addition caused by the combustion of injected fuel into the combustor in Figs. 1A, 1B, and 4B. The mass flow rate of the fuel is very much lower than that of the working fluid (approximately 1:50), so the combustion products can be neglected as a first approximation.
The unit gas mass is then isentropically expanded (lower pressure and temperature and higher volume) from 3 to 4 in Fig. 4, where \( P_4 = P_1 \). In Fig. 4B, this represents flow through the turbine (to point 3’) and then flow through the exit nozzle in the case of the jet engine (Fig. 1A) or flow through the power turbine in Fig. 1B (point 4). In Fig. 4, the area between the pressure axis and the isentropic curve 3–3’ represents the ideal work, \( W_{33} \), derived from the turbine. This work must be equal to the ideal compressor work \( W_{12} \) (the area bounded by curve 1–2). The ideal “useful work,” \( W_{3’4} \), in Fig. 4 (the area bounded by the isentropic curve 3’–4) is that which is available to cause output shaft power (Figs. 1B and 4B) or thrust power (Fig. 1A).

The Brayton cycle is completed in Fig. 4 by a constant pressure process in which the volume of the unit gas mass is decreased (temperature decrease) as heat \( Q_{41} \) is rejected. Most gas turbines operate in an open cycle mode, in which, for instance, air is taken in from the atmosphere (point 1 in Figs. 1 and 4) and discharged back into the atmosphere (point 4), with exiting working fluid mixing to reject \( Q_{41} \). In a closed-cycle gas turbine facility, the working fluid is continuously recycled by ducting the exit flow (point 4) through a heat exchanger (shown schematically in Fig. 5) to reject heat \( Q_{41} \) at (ideally) constant pressure and back to the compressor inlet (point 1).

Because of its confined, fixed-mass working fluid, the closed-cycle gas turbine is not an internal combustion engine. The combustor (shown in Fig. 1) is replaced with an input heat exchanger, supplied by an external source of heat. Closed-cycle designs were developed in the 1960s for providing power to space satellites on deep space missions, using a radioisotope heat source to heat helium gas.

**FIGURE 4** (A) Brayton cycle pressure-volume diagram for a unit mass of working fluid (e.g., air), showing work (W) and heat (Q) inputs and outputs. (B) Gas turbine schematic showing relative points from the diagram for the Brayton cycle.
as the gas turbine working fluid and a space radiator for cycle heat rejection. Development work to use a nuclear reactor (e.g., a pebble bed reactor) to heat helium gas in a closed-cycle gas turbine to be used for electric utility power generation in the 100 MW range is in progress.

The ideal Brayton cycle thermal efficiency, $\eta_B$, can be shown to be

$$\eta_B = 1 - \frac{T_4}{T_3} = 1 - \frac{1}{r^{(k-1)/k}},$$

(1)

where the absolute temperatures $T_3$ and $T_4$ correspond to points 3 and 4 in Fig. 4, $k = c_p/c_v$ is the ratio of specific heats for the ideal gas, and $r$ is the compressor pressure ratio,

$$r = \frac{P_2}{P_1}.$$  

(2)

Thus, the Brayton-cycle thermal efficiency increases with both the turbine inlet temperature, $T_3$, and compressor pressure ratio, $r$. Modern gas turbines have pressure ratios as high as 30:1 and turbine inlet temperatures approaching 3000°F (1649°C).

The effect of real (nonisotropic) compressor and turbine performance can be easily seen in the expression for the net useful work $W_{net} = W_{3'4}$

$$W_{net} = \eta_T c_p T_3 \left[ 1 - \frac{1}{r^{(k-1)/k}} \right] - \frac{c_p T_1}{\eta_C} \left[ r^{(k-1)/k} - 1 \right],$$

(3)

where $c_p$ is the specific heat at constant pressure, and $\eta_T$ and $\eta_C$ are the thermal (adiabatic) efficiencies of the turbine and compressor, respectively. This expression shows that for large $W_{net}$ one must have high values for $\eta_T$, $\eta_C$, $r$, and $T_3$. For modern gas turbines, $\eta_T$ can be as high as 0.92–0.94 and $\eta_C$ can reach 0.88.

A gas turbine that is configured and operated to closely follow the ideal Brayton cycle (Figs. 4 and 5) is called a simple-cycle gas turbine. Most aircraft gas turbines operate in a simple-cycle configuration since attention must be paid to engine weight and frontal area. However, in land or marine applications, additional equipment can be added to the simple-cycle gas turbine, leading to increases in thermal efficiency and/or the net work output of a unit. Three such modifications are regeneration, intercooling, and reheating.

Regeneration involves the installation of a heat exchanger (shown in Fig. 6A) through which the turbine exhaust gases (point 4 in Fig. 6A) pass. The compressor exit flow (point 2 in Fig. 6A) is then heated in the exhaust gas heat exchanger (regenerator, and also called a recuperator) before the flow enters the combustor. If the regenerator is well designed—that is, if the heat exchanger effectiveness is high and the pressure drops are small—the cycle efficiency will be increased over the simple-cycle value. However, its relatively high cost must also be taken into account. Regenerated gas turbines can increase efficiency by 5–6 percentage points and are even more beneficial for part-load operation.

Intercooling also involves the use of a heat exchanger. An intercooler, as shown in Fig. 6B, is a heat exchanger that cools compressor gas during the compression process. For instance, if the compressor consists of a high-pressure unit and a low-pressure unit, the intercooler can be mounted between them (Fig. 6B) to cool the flow and decrease the work necessary for compression in the high-pressure
compressor. The cooling fluid could be atmospheric air or water (e.g., sea water in the case of a marine gas turbine). The net work output of a given gas turbine is increased with a well-designed intercooler. Studies of gas turbines equipped with extensive turbine convective and film cooling show that intercooling can also allow increases in thermal efficiency by providing cooling fluid at lower temperatures, thereby allowing increased turbine inlet temperatures \[ T_3 \] in Eq. (1).

Reheating, as shown in Fig. 6C, occurs in the turbine and increases turbine work without changing compressor work or exceeding the material temperature limits in the turbine. If a gas turbine has a high-pressure turbine and a low-pressure turbine, a re heater (as shown in Fig. 6C, usually another combustor) can be used to “reheat” the flow between the two turbines. Reheat in a jet engine is accomplished by adding an afterburner at the turbine exhaust, thereby increasing thrust, with a greatly increased fuel consumption rate.

A combined-cycle gas turbine (CCGT) power plant, shown schematically in Fig. 7, is essentially an electrical power plant in which a gas turbine provides useful work \( W_B \) to drive an electrical generator. The gas turbine exhaust energy \( Q_{BR} \) is then used to produce steam in a heat exchanger (called a heat recovery steam generator) to supply a steam turbine whose useful work output \( W_R \) provides the means to generate more electricity. [If the steam is used for heat (e.g., heating buildings), the unit would be called a cogeneration plant.] Figure 7 is a simplified thermodynamic representation of a CCGT and shows it to be two heat engines (Brayton and Rankine) coupled in series. The “upper” engine is the gas turbine (represented as a Brayton-cycle heat
engine), whose energy input is $Q_{\text{in}}$. It rejects heat ($Q_{\text{BR}}$) as the input energy to the “lower” engine (the steam turbine, represented as a Rankine-cycle heat engine). The Rankine heat engine then rejects unavailable energy (heat) as $Q_{\text{Out}}$ by means of a steam condenser. The combined thermal efficiency ($\eta_{\text{CC}}$) can be derived fairly simply and is given as

$$\eta_{\text{CC}} = \eta_B + \eta_R - \eta_B \eta_R,$$  \hspace{1cm} (4)

where $\eta_B = W_B/Q_{\text{in}}$ and $\eta_R = W_R/Q_{\text{BR}}$ are the thermal efficiencies of the Brayton and Rankine cycles, respectively. Taking $\eta_B = 40\%$ (a good value for modern gas turbines) and $\eta_R = 30\%$ (a reasonable value under typical CCGT conditions), the sum minus the product in Eq. (4) yields $\eta_{\text{CC}} = 58\%$, a value of combined-cycle efficiency greater than either of the individual efficiencies.

This remarkable equation gives insight into why CCGTs are so efficient. The calculated value of $\eta_{\text{CC}}$ represents an upper bound on an actual CCGT, since Eq. (4) does not account for efficiencies associated with transferring $Q_{\text{BR}}$ (duct losses, irreversibilities due to heat transfer, etc.). Actual efficiency values as high as 52 to 57\% have been attained with CCGT units during the past few years, thus coming close to values given by Eq. (4).

4. GAS TURBINE COMPONENTS

A greater understanding of the gas turbine and its operation can be gained by considering its three major components (Figs. 1, 2, and 3): the compressor, the combustor, and the turbine. The features and characteristics of these components are briefly examined here.

4.1 Compressors and Turbines

The turbine and compressor components are mated by a shaft, since the former powers the latter. A single-shaft gas turbine has but one shaft connecting the compressor and turbine components. A twin-spool gas turbine has two concentric shafts, a longer one connecting a low-pressure compressor to a low-pressure turbine (the low spool), which rotates inside a shorter, larger-diameter shaft (e.g., see Figs. 6B and 6C). The latter connects the high-pressure turbine with the higher pressure compressor (the high spool), which rotates at higher speeds than the low spool. A triple-spool engine would have a third, intermediate-pressure compressor-turbine spool.

Gas turbine compressors can be centrifugal, axial, or a combination of both. Centrifugal compressors (radial outflow) are robust, generally cost less, and are limited to pressure ratio of 6 or 7 to 1. They are found in early gas turbines or in modern, smaller gas turbines. The more efficient, higher capacity axial flow compressor is used on most gas turbines (e.g., Figs. 2 and 3). An axial compressor is made up of a number of stages, with each stage consisting of a row of rotating blades (airfoils) and a row of stationary blades (called stators) configured so the gas flow is compressed (adverse or unfavorable pressure gradient) as it passes through each stage. It has been said that compressor operation can founder on a metaphoric rock, and that rock is called stall. Care must be taken in compressor operation and design to avoid the conditions that lead to blade stall, or flow separation. The collective behavior of blade separation can lead to compressor stall or surge, which manifests itself as an instability of gas flow through the entire gas turbine.
Turbines are generally easier to design and operate than compressors, since the flow is expanding in an overall favorable pressure gradient. Axial flow turbines (Figs. 2 and 3) will require fewer stages than an axial compressor for the same pressure change magnitude. There are some smaller gas turbines that utilize centrifugal turbines (radial inflow) but most utilize axial turbines (e.g., Figs. 2 and 3).

Turbine design and manufacture are complicated by the need to ensure turbine component life in the hot gas flow. The problem of ensuring durability is especially critical in the first turbine stage, where temperatures are highest. Special materials and elaborate cooling schemes must be used to allow metal alloy turbine airfoils that melt at 1800 to 1900°F (982 to 1038°C) to survive in gas flows with temperatures as high as $T_3 = 3000°F$ (1649°C).

4.2 Combustors

High-pressure air leaves the compressor (Figs. 1, 2, and 3) and enters the gas turbine combustor, where, in a very short space and at high flow rates, heat is added to it by the combustion of fuel (gas or liquid). Modern gas turbine combustors are of three types: cans (individual cylindrical chambers arranged circumferentially), annular (consisting of a cylindrical single inner and single outer shroud), and can–annular (a fusion of the can and annular geometrics). Because of the high temperatures in the combustors, combustor parts are regularly inspected and will require repair and/or replacement during the lifetime of the gas turbine.

Compared to some other energy converters [such as the Diesel or Otto (gasoline) engines listed in Table I], gas turbines produce very low levels of combustion pollution, such as unburned fuel, carbon monoxide, oxides of nitrogen ($NO_x$), and smoke. New electric power plants using gas turbines drastically reduce area pollution when they replace older steam- or diesel-powered plants. For instance, due to new strict environmental restrictions being placed on Alaskan cruise vessels, new cruise ships are installing gas turbines, as the only means available to comply with the emission levels that have been put in place.

Gas turbine combustion systems must have very low pressure losses and be carefully designed to provide a stable flow, free of pressure pulsations and characterized by uniform exit temperatures (flow “hot spots” can damage turbine gas path parts, such as stationary vanes). New electric power gas turbines have experienced serious pressure oscillations with new “lean premixed” combustion systems designed to meet lower $NO_x$ emission regulations. System pressure oscillations brought about by combustion mechanisms that not yet fully understood have been given descriptive names ranging from humming to hooting, screech, chub, buzz, and rumble. Manufacturers have taken a number of paths to deal with this problem (which, if left unattended, can shake a machine apart), such as the use of catalysis, resonators, fuel schedule timing, active controls, or simple cutting back on power output levels.

5. GAS TURBINE USAGE

Although they are used in an ever-increasing variety of applications, gas turbines are used extensively in two areas: aviation and electric power generation.

It is difficult to remember a time when the aviation gas turbine—the jet engine—was not part of aviation. Before jet engines, an aviation piston engine manufacturer could expect to sell 20–30 times the original cost of piston engines, in aftermarket parts. With the advent of the jet engine, this aftermarket value dropped to 3–5 times the original cost (an important reduction that made air travel affordable and reliable, and airlines profitable). Technology and airline/military demands made on jet engine manufacturers have resulted in even longer lasting engine components, dropping the aftermarket value even lower.

A well-managed airline will regularly try to keep a jet-powered plane in the air as much as 18 h per day, 365 days a year, to produce revenue. The airline expects the engines, if well-maintained, to remain in service and on the wing for up to 15,000–20,000 h of operation, depending on the number of takeoffs and landings experienced by the plane. After this period (or time between overhauls), the jet engine will be taken off of the wing and overhauled and usually hot-section (combustor and turbine) parts will be replaced as needed. (An experienced air traveler can generally believe the numbers presented here, by reflecting how few (if any) times he or she has experienced an in-flight shutdown of a jet engine while flying.)

The life of electric power gas turbines are much longer than those of their aviation counterparts, because they run at constant speeds and are not usually subjected to the wide range of power settings experienced by jet engines. Modern power plant operators expect trouble-free units to run as long as 30,000–50,000 h, depending on load conditions, maintenance procedures, and the level of turbine
inlet temperatures. Overhauls usually involve replacement or refurbishment of hot-section parts in the combustor and turbine sections. Normally, these will take place approximately three or more times during the life of a gas turbine unit.

In summary, the power spectrum of the gas turbine units produced is larger than that of most other prime movers, spanning a range that varies by a factor of 10,000. New microturbines [weighing little more than 100 pounds (45 kg)] are being produced in the range of ~25 kW to provide electrical power and heat for fast-food restaurants. Base-load electric power gas turbines as large as 250 MW [weighing as much as 330 tons (300,000 kg)] are being installed to drive electric generators and to supply heat for steam turbines in combined-cycle operations, with resultant thermal efficiencies approaching 60%. In an evolving role as the engineer’s most versatile energy converter, gas turbines produce thrust power [as much as 120,000 pounds thrust (534,000 N) for the largest commercial jet engines] to propel most of the world’s military and commercial aircraft. In closing, it can be noted that at the time this article is being written, the annual worldwide value of production of gas turbines for shaft power applications (electric power, ship propulsion, natural gas pipeline compression) is approximately equal to that for aviation thrust power applications.

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