Introduction to Gas Turbines for Non-Engineers

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A turbine is any kind of spinning device that uses the action of a fluid to produce work. Typical fluids are: air, wind, water, steam and helium. Windmills and hydroelectric dams have used turbine action for decades to turn the core of an electrical generator to produce power for both industrial and residential consumption. Simpler turbines are much older, with the first known appearance dating to the time of ancient Greece.

In the history of energy conversion, however, the gas turbine is relatively new. The first practical gas turbine used to generate electricity ran at Neuchatel, Switzerland in 1939, and was developed by the Brown Boveri Company. 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, the 1930s' invention and development of the aircraft gas turbine by Frank Whittle resulted in a similar British flight in 1941.
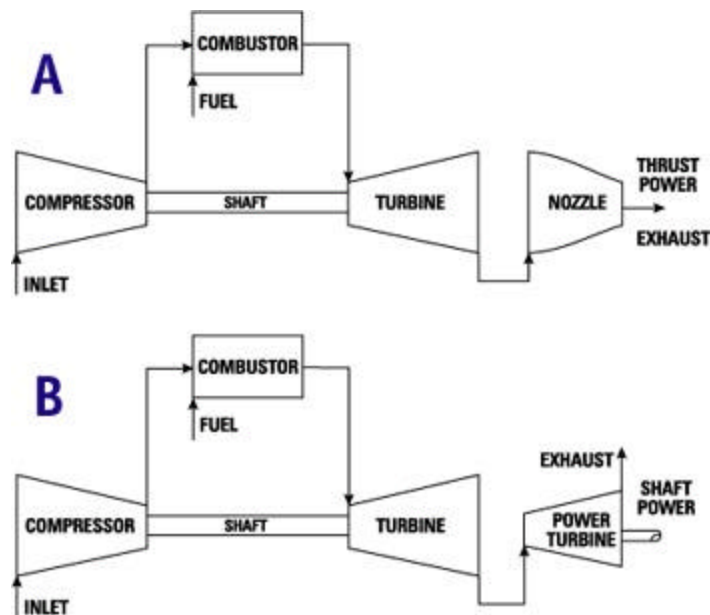

Figure 1. Schematic for a) an aircraft jet engine; and b) a land-based gas turbine

The name "gas turbine" is somewhat misleading, because to many it implies a turbine engine that uses gas as its fuel. Actually a gas turbine (as shown schematically in Fig. 1) has a *compressor* to draw in and compress gas (most usually air); a *combustor* (or burner) to add fuel to heat the compressed air; and a *turbine* to extract power from the hot air flow. The gas turbine is an internal combustion (IC) engine employing a continuous combustion process. This differs from the intermittent combustion occurring in Diesel and automotive IC engines.

Because the 1939 origin of the gas turbine lies simultaneously in the electric power field and in aviation, there have been a profusion of "other names" for the gas turbine. For electrical power generation and marine applications it is generally called a *gas turbine,* also a *combustion turbine (CT),* 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 engine configuration or application, such as: *jet turbine engine; turbojet; turbofan; fanjet;* and *turboprop* or *prop jet* (if it is used to drive a propeller). The compressor-combustor-turbine part of the gas turbine (Fig. 1) is commonly termed the *gas generator.*

Gas Turbine Usage

In an aircraft gas turbine the output of the turbine is used to turn the compressor (which may also have an associated fan or propeller). The hot air flow leaving the turbine is then accelerated into the atmosphere through an exhaust nozzle (Fig. la) to provide *thrust* or *propulsion power.*
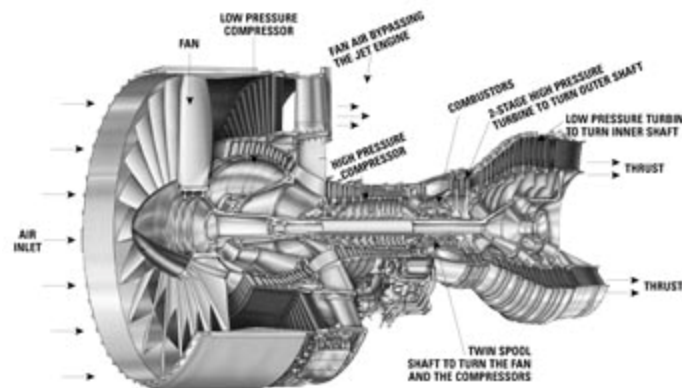

Figure 2. A modern jet engine used to power Boeing 777 aircraft. This is a Pratt & Whitney PW4084 turbofan which can produce 84000 pounds of thrust. It has a 112-inch diameter front-mounted fan, a length of 192 inches (4.87 m) and a weight of about 15,000 pounds (6804 kg). The nozzle has been disconnected from this engine.

A typical jet engine is shown in Fig. 2. Such engines can range from about 100 pounds of thrust (lbst.) to as high as 100,000 lbst. with weights ranging from about 30 lbs. to 20,000 lbs. The smallest jets are used for devices such as the cruise missile, the largest for future generations of commercial aircraft. The jet engine of Fig. 2 is a *turbofan* engine, with a large diameter compressor-mounted fan. Thrust is generated both by air passing through the fan (bypass air) and 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 non-aviation 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. lb) such as an electrical generator or a ship's propeller.

A typical land-based gas turbine is shown in Fig. 3. Such units can range in power output from 0.05 MW(Megawatts) to as high as 240 MW. The unit shown in Fig. 3 is an *aeroderivative* gas turbine; i.e., a lighter weight unit derived from an aircraft jet engine. Heavier weight units designed specifically for land use are called *industrial* or *frame*

machines. Although aeroderivative gas turbines are being increasingly used for base load electrical power generation, they are most frequently used to drive compressors for natural gas pipelines, power ships and provide peaking and intermittent power for electric utility applications. Peaking power supplements a utility's normal steam turbine or hydroelectric power output during high demand periods ... such as the summer demand for air conditioning in many major cities.
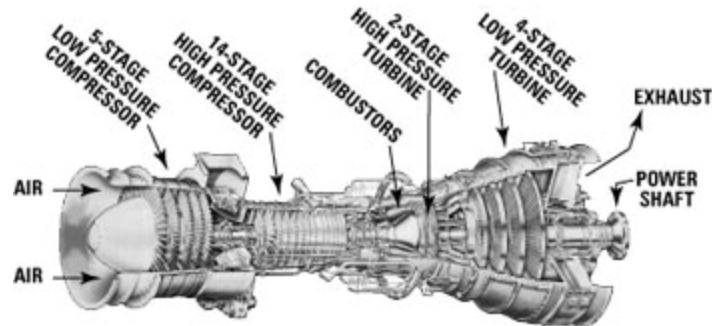

Figure 3. A modern land-based gas turbine used for electrical power production and for mechanical drives. This is a General Electric LM5000 machine with a length of 246 inches (6.2 m) and a weight of about 27,700 pounds (12,500 kg). It produces maximum shaft power of 55.2 MW (74,000 hp) at 3,600 rpm with steam injection. This model shows a direct drive configuration where the l.p. turbine drives both the l.p. compressor and the output shaft. Other models can be made with a power turbine.

Some of the principle advantages of the gas turbine are:

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 involve 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.
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 start up time is measured in hours.
4. A wide variety of fuels can be utilized. Natural gas is commonly used in land-based gas turbines while light distillate (kerosene-like) oils power aircraft gas turbines. Diesel oil or specially treated residual oils can also be used, as well as combustible gases derived from blast furnaces, refineries 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 past, 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 last fifty years, continuous engineering development work has pushed the thermal efficiency (18% for the 1939 Neuchatel gas turbine) to present levels of about 40% for simple cycle operation, and about 55% for combined cycle operation (see below). 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 other prime movers, such as steam power plants.

Gas Turbine Cycles

A cycle describes what happens to air as it passes into, through, and out of the gas turbine. The cycle usually describes the relationship between the space occupied by the air in the system (called volume, V) and the pressure (P) it is under. The Brayton cycle (1876), shown in graphic form in Fig. 4a as a pressure-volume diagram, is a representation of the properties of a fixed amount of air as it passes through a gas turbine in operation. These same points are also shown in the engine schematic in Fig. 4b.
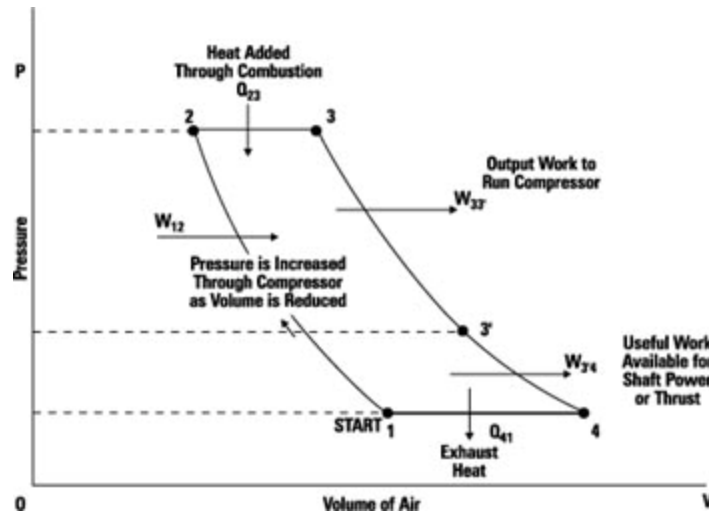

Figure 4a. Brayton cycle pressure-volume diagram for a unit mass of working fluid (e.g., air), showing work (W) and heat (Q) inputs and outputs.
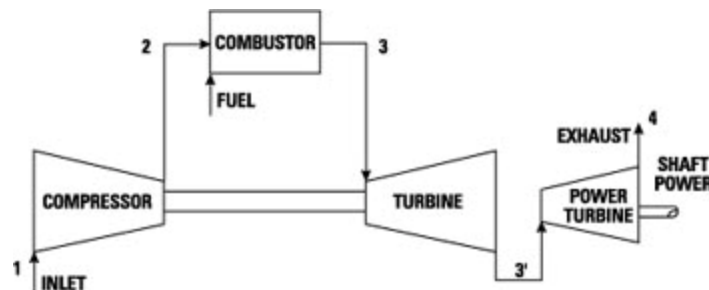

Figure 4b. Gas turbine schematic showing relative points from the Brayton Cycle diagram.

Air is compressed from point 1 to point 2. This increases the pressure as the volume of space occupied by the air is reduced.

The air is then heated at constant pressure from 2 to 3 in Fig. 4. This heat is added by injecting fuel into the combustor and igniting it on a continuous basis.

The hot compressed air at point 3 is then allowed to expand (from point 3 to 4) reducing the pressure and temperature and increasing its volume. In the engine in Fig. 4b, this represents flow through the turbine to point 3' and then flow through the power turbine to point 4 to turn a shaft or a ship's propeller. In Fig. 1a, the flow from point 3' to 4 is through the exit nozzle to produce thrust. The "useful work" in Fig. 4a is indicated by the curve 3'- 4. This is the energy available to cause output *shaft power* for a land-based gas turbine , or *thrust* for a jet aircraft.

The Brayton cycle is completed in Fig. 4 by a process in which the volume of the air is decreased (temperature decrease) as heat is absorbed into the atmosphere.
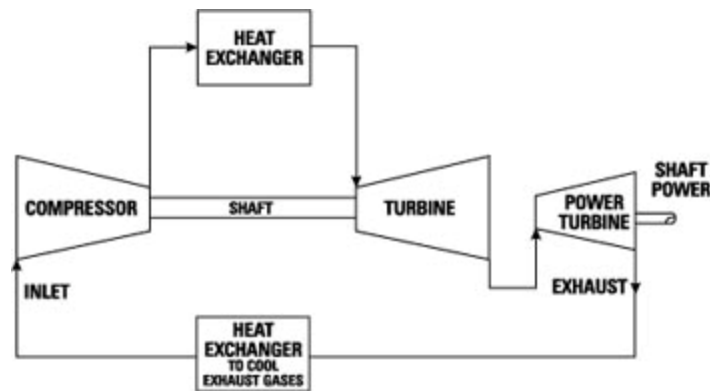

Figure 5. Closed Cycle System.

Most gas turbines operate in an *open-cycle* mode where, for instance, air is taken in from the atmosphere (point 1 in Figs. 4a and 4b) and discharged back into the atmosphere (point 4), with the hot air being cooled naturally after it exits the engine. In a *closed cycle* gas turbine facility the working fluid (air or other gas) is continuously recycled by cooling the exhaust air (point 4) through a heat exchanger (shown schematically in Fig. 5) and directing it back to the compressor inlet (point 1). Because of its confined, fixed amount of gas, the closed cycle gas turbine is *not* an internal combustion engine. In the closed cycle system, combustion cannot be sustained and the normal combustor is replaced with a second heat exchanger to heat the compressed air before it enters the turbine. The heat is supplied by an external source such as a nuclear reactor, the fluidized bed of a coal combustion process, or some other heat source. Closed cycle systems using gas turbines have been proposed for missions to Mars and other long term space applications.

A gas turbine that is configured and operated to closely follow the Brayton cycle (Fig. 4) is called a *simple cycle* gas turbine. Most aircraft gas turbines operate in a simple 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 efficiency and/or the output of a unit. Three such modifications are regeneration, intercooling and reheating.

Regeneration involves the installation of a heat exchanger (recuperator) through which the turbine exhaust gases (point 4 in Fig. 4b) pass. The compressed air (point 2 in Fig. 4b) is then heated in the exhaust gas heat exchanger, before the flow enters the combustor (Fig. 6a).

If the regenerator is well designed (i.e., the heat exchanger effectiveness is high and the pressure drops are small) the efficiency will be increased over the simple cycle value. However, the relatively high cost of

such a regenerator must also be taken into account. Regenerators are being used in the gas turbine engines of the M1 Abrams main battle tank of Desert Storm fame, and in experimental gas turbine automobiles. Regenerated gas turbines increase efficiency 5-6% and are even more effective in improved part-load applications.

Intercooling also involves the use of a heat exchanger. An intercooler is a heat exchanger that cools compressor gas during the compression process. For instance, if the compressor consists of a high and a low pressure unit, the intercooler could be mounted between them to cool the flow and decrease the work necessary for compression in the high pressure compressor (Fig. 6b). The cooling fluid could be atmospheric air or water (e.g., sea water in the case of a marine gas turbine). It can be shown that the output of a gas turbine is increased with a well-designed intercooler.

Reheating occurs in the turbine and is a way to increase turbine work without changing compressor work or melting the materials from which the turbine is constructed. If a gas turbine has a high pressure and a low pressure turbine at the back end of the machine, a reheater (usually another combustor) can be used to "reheat" the flow between the two turbines (Fig. 6c).This can increase efficiency by 1-3%. Reheat in a jet engine is accomplished by adding an afterburner at the turbine exhaust, thereby increasing thrust, at the expense of a greatly increased fuel consumption rate.
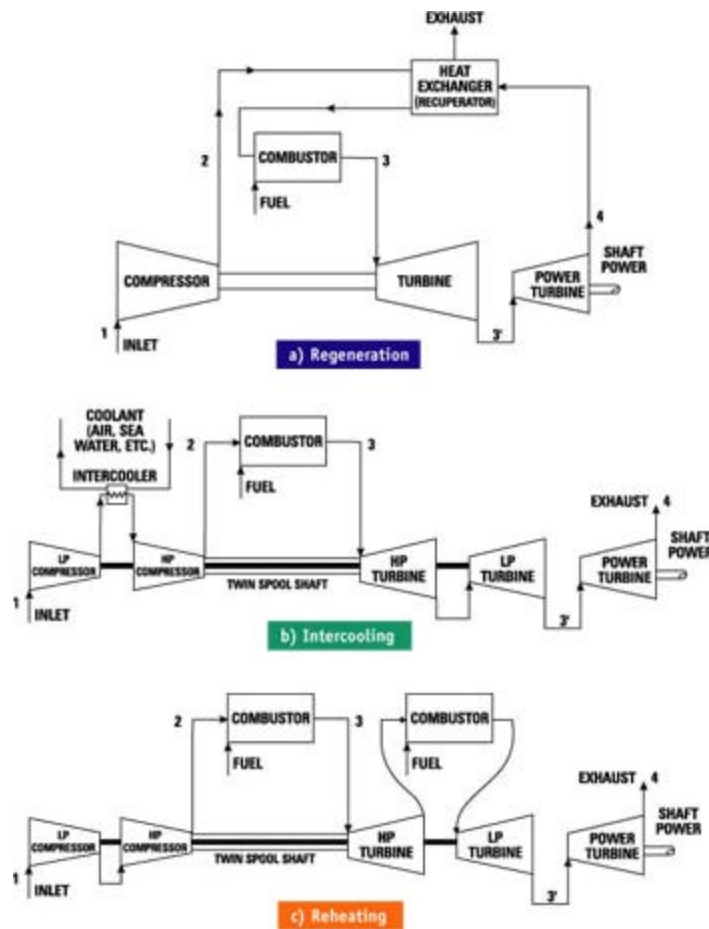

Figure 6. Modifications available for the simple Brayton Cycle.

A *combined cycle* gas turbine power plant, frequently identified by the abbreviation CCGT, is essentially an electrical power plant in which a gas turbine and a steam turbine are used in combination to achieve greater efficiency than would be possible independently. The gas turbine drives an electrical generator. The gas turbine exhaust is then used to produce steam in a heat exchanger (called a heat recovery steam generator) to supply a steam turbine whose output 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 or a CHP (Combined

Heat and Power) plant. Fig. 7 is a simplified representation of a CCGT and shows it to be two heat engines coupled in series. The "upper" engine is the gas turbine. It expels heat as the input to the "lower" engine (the steam turbine). The steam turbine then rejects heat by means of a *steam condenser.*
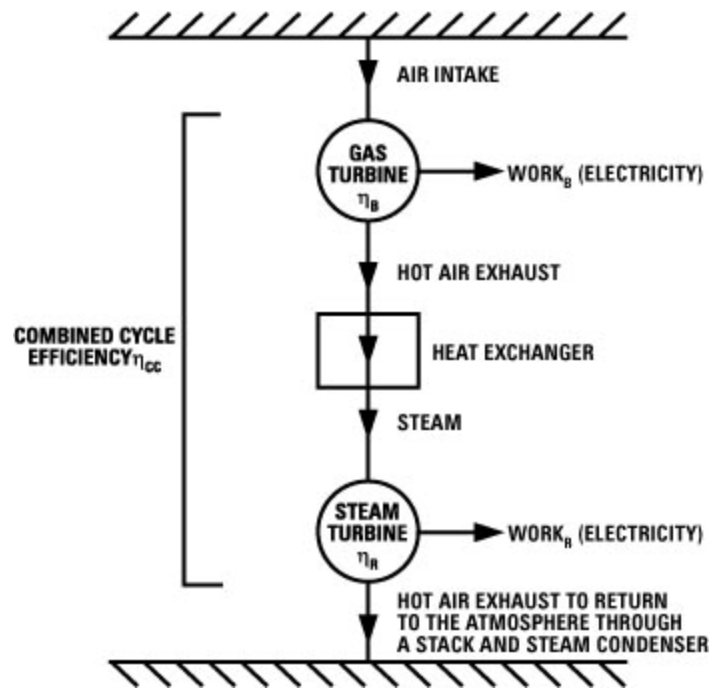

Figure 7. Schematic of Combined Cycle (CCGT) plant.

The combined cycle efficiency (η_{cc}) can be derived fairly simply by the equation $\eta_{cc} = \eta_B + \eta_R - \eta_B\eta_R$ ... in other words, the sum of the individual efficiencies, minus their product. This remarkable equation gives insight as to why CCGTs are so successful.

Suppose $\eta_B = 40\%$, which is a reasonable upper value for current high performance Brayton cycle gas turbines. A reasonable value for a Rankine cycle steam turbine operating at typical CCGT conditions would be $\eta_R = 30\%$. Thus, the sum minus the product of the individual efficiencies becomes

$$\eta_{cc} = 0.40 + 0.30 - 0.12$$
$$= 0.58$$
$$= 58\%$$

One can see that the combined efficiency $(\eta_{cc} = 58\%)$ is greater than the efficiency of either of the component engines taken separately ... 40%, 30%. The value given by the equation, however, represents an upper limit on the actual CCGT efficiency because there are losses in the system.

Actual efficiency values as high as 52-58% have been attained with CCGT units during the last few years. These units are particularly popular for gas turbine power plants constructed in developing countries.

Gas Turbine Components

A greater understanding of the gas turbine and its operation can be gained by considering its three major components (Fig. 1, Fig. 2 and Fig. 3): the compressor, the combustor and the turbine. The features and characteristics will be touched on here only briefly.

Compressors and Turbines: The compressor components are connected to the turbine by a shaft in order to allow the turbine to turn the compressor. A *single shaft* gas turbine (Fig. 1a and 1b) has only one shaft connecting the compressor and turbine components. A *twin spool* gas turbine (Fig. 6b, and 6c) 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. The shorter, larger diameter shaft 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 are either centrifugal or axial, or can be a combination of both. Centrifugal compressors (with compressed air output around the outer perimeter of the machine) are robust, generally cost less and are limited to pressure ratios 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 compressors (with compressed air output directed along the center line of the machine) are used in most gas turbines (e.g. Fig. 2 and Fig. 3). An axial compressor is made up of a relatively large number of stages, each stage, consisting of a row of rotating blades (airfoils) and a row of stationary blades (stators), arranged so that the air is compressed as it passes through each stage.

Turbines are generally easier to design and operate than compressors, since the hot air flow is expanding rather than being compressed. Axial flow turbines (e.g. Fig. 2 and Fig. 3) will require fewer stages than an axial compressor. There are some smaller gas turbines that utilize centrifugal turbines (radial inflow), but most utilize axial turbines.

Turbine design and manufacture is complicated by the need to extend turbine component life in the hot air 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 turbine airfoils that melt at 1800-1900°F to survive in air flows with temperatures as high as 3000°F.

Combustors: A successful combustor design must satisfy many requirements and has been a challenge from the earliest gas turbines of Whittle and von Ohain. The relative importance of each requirement varies with the application of the gas turbine, and of course, some requirements are conflicting, requiring design compromises to be made. Most design requirements reflect concerns over engine costs, efficiency, and the environment. The basic design requirements can be classified as follows:

1. High combustion efficiency at all operating conditions.
2. Low levels of unburned hydrocarbons and carbon monoxide, low oxides of nitrogen at high power and no visible smoke. (Minimized pollutants and emissions.)
3. Low pressure drop. Three to four percent is common.
4. Combustion must be stable under all operating conditions.

5. Consistently reliable ignition must be attained at very low temperatures, and at high altitudes (for aircraft).
6. Smooth combustion, with no pulsations or rough burning.
7. A low temperature variation for good turbine life requirements.
8. Useful life (thousands of hours), particularly for industrial use.
9. Multi-fuel use. Characteristically natural gas and diesel fuel are used for industrial applications and kerosene for aircraft.
10. Length and diameter compatible with engine envelope (outside dimensions).
11. Designed for minimum cost, repair and maintenance.
12. Minimum weight (for aircraft applications).

A combustor consists of at least three basic parts: a casing, a flame tube and a fuel injection system. The casing must withstand the *cycle pressures* and may be a part of the structure of the gas turbine. It encloses a relatively thin-walled flame tube within which combustion takes place, and a fuel injection system.

Compared to other prime movers (such as Diesel and reciprocating automobile engines), gas turbines are considered to produce very low levels of combustion pollution. The gas turbine emissions of major concern are unburned hydrocarbons, carbon monoxide, oxides of nitrogen (NO_x) and smoke. While the contribution of jet aircraft to atmospheric pollution is less than 1%, jet aircraft emissions injected directly into the upper troposphere have doubled between the latitudes of 40 to 60 degrees north, increasing ozone by about 20%. In the stratosphere, where supersonic aircraft fly, NO_x will deplete ozone. Both effects are harmful, so further NO_x reduction in gas turbine operation is a challenge for the 21st century.