

# FUNDAMENTALS OF GAS TURBINE ENGINES

## INTRODUCTION

The gas turbine is an internal combustion engine that uses air as the working fluid. The engine extracts chemical energy from fuel and converts it to mechanical energy using the gaseous energy of the working fluid (air) to drive the engine and propeller, which, in turn, propel the airplane.

## THE GAS TURBINE CYCLE

The basic principle of the airplane turbine engine is identical to any and all engines that extract energy from chemical fuel. The basic 4 steps for any internal combustion engine are:

1. Intake of air (and possibly fuel).
2. Compression of the air (and possibly fuel).
3. Combustion, where fuel is injected (if it was not drawn in with the intake air) and burned to convert the stored energy.
4. Expansion and exhaust, where the converted energy is put to use.

In the case of a piston engine, such as the engine in a car or reciprocating airplane engine, the intake, compression, combustion, and exhaust steps occur in the same place (cylinder head) at different times as the piston goes up and down.

In the turbine engine, however, these same four steps occur at the same time but in different places. As a result of this fundamental difference, the turbine has engine sections called:

1. The inlet section
2. The compressor section
3. The combustion section (the combustor)
4. The turbine (and exhaust) section.

The turbine section of the gas turbine engine has the task of producing usable output shaft power to drive the propeller. In addition, it must also provide power to drive the compressor and all engine accessories. It does this by expanding the high temperature, pressure, and velocity gas and converting the gaseous energy to mechanical energy in the form of shaft power.

A large mass of air must be supplied to the turbine in order to produce the necessary power. This mass of air is supplied by the compressor, which draws the air into the engine and squeezes it to provide high-pressure air to the turbine. The compressor

does this by converting mechanical energy from the turbine to gaseous energy in the form of pressure and temperature.

If the compressor and the turbine were 100% efficient, the compressor would supply all the air needed by the turbine. At the same time, the turbine would supply the necessary power to drive the compressor. In this case, a perpetual motion machine would exist. However, frictional losses and mechanical system inefficiencies do not allow a perpetual motion machine to operate. Additional energy must be added to the air to accommodate for these losses. Power output is also desired from the engine (beyond simply driving the compressor); thus, even more energy must be added to the air to produce this excess power. Energy addition to the system is accomplished in the combustor. Chemical energy from fuel as it is burned is converted to gaseous energy in the form of high temperatures and high velocity as the air passes through the combustor. The gaseous energy is converted back to mechanical energy in the turbine, providing power to drive the compressor and the output shaft.

## **SOME BASIC PRINCIPLES**

As air passes through a gas turbine engine, aerodynamic and energy requirements demand changes in the air's velocity and pressure. During compression, a rise in the air pressure is required, but not an increase in its velocity. After compression and combustion have heated the air, an increase in the velocity of gases is necessary in order for the turbine rotors to develop power. The size and shape of the ducts through which the air flows affect these various changes. Where a conversion from velocity to pressure is required, the passages are divergent. Conversely, if a conversion from pressure to velocity is needed, a convergent duct is used.

Before further discussion, an explanation of convergent ducts, divergent ducts, and the behavior of air within these ducts should be made. An understanding of the difference between static pressure ( $P_s$ ), impact pressure, ( $P_i$ ), and total pressure ( $P_t$ ) is also needed.

The difference between static, impact, and total pressures is as follows. Static pressure is the force per unit area exerted on the walls of a container by a stationary fluid. An example is the air pressure within a car tire. Impact pressure, on the other hand, is the force per unit area exerted by fluids in motion. Impact pressure is a function of the velocity of the fluid. An example of impact pressure is the pressure exerted on one's hand held outside a moving car's window. Total pressure is the sum of static and impact pressures.

Figure 2-1 illustrates the methods used to measure pressures. Part (a) illustrates the measurement of static pressure. Static pressure will not take into account the velocity of the air. Part (b) illustrates the measurement of total pressure, which accounts for both static pressure and the pressure due to the moving fluid (impact pressure). In

order to obtain impact pressure, the value of the static pressure is subtracted from the value of total pressure.

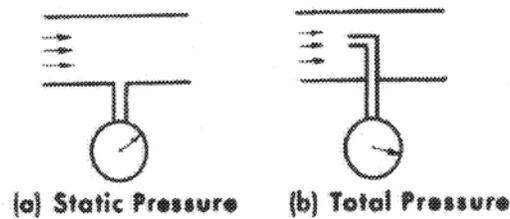


Figure 2-1. Pressure Measurement Techniques

Figure 2-2 shows the principle of divergent ducts, where energy is neither being added or taken away, but where the gaseous energy is being converted from velocity to pressure and temperature. There is a velocity decrease as air flows from a small inlet to a larger outlet. As velocity decreases, impact pressure ( $P_i$ ) also decreases. Since no energy is added or subtracted from the system, total pressure ( $P_t$ ) for the air remains constant and static pressure ( $P_s$ ) increases. One way of viewing this is that the impact pressure is converted to static pressure; thus, a static pressure rise is seen as air flows through a divergent duct and is compressed. A temperature rise is also noticed since compression is a heating process.

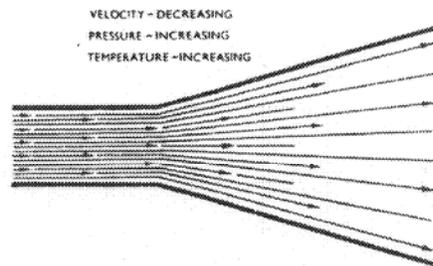


Figure 2-2. Divergent Duct

The convergent duct operates exactly in reverse of the divergent duct. Figure 2-3 shows the principle of convergent ducts, where energy is neither being added or taken away, but where the gaseous energy is being converted from pressure and temperature to velocity. There is a velocity increase as air flows from a large inlet to a smaller outlet. As velocity increases, impact pressure also increases. Since no energy is added or subtracted from the system, total pressure remains constant and static pressure decreases. One way of viewing this is that the static pressure is converted to impact pressure; thus, a static pressure decrease is seen as air flows through a convergent duct and goes through expansion. A temperature drop is associated with any expansion process.

NOTE: Even though the static and impact pressures are changing as fluids flow through either convergent or divergent ducts, the total pressure does not change. This is true if fluid friction is neglected and energy is not added or taken away from the fluid flow. In actuality, there will be a slight decrease in total pressure because of fluid frictional losses.

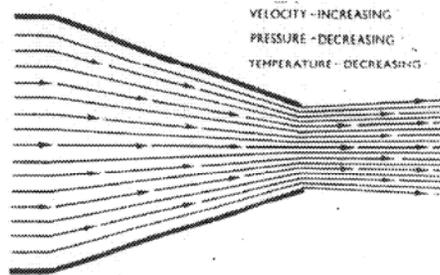


Figure 2-3. Convergent Duct

## PERFORMANCE AND EFFICIENCY

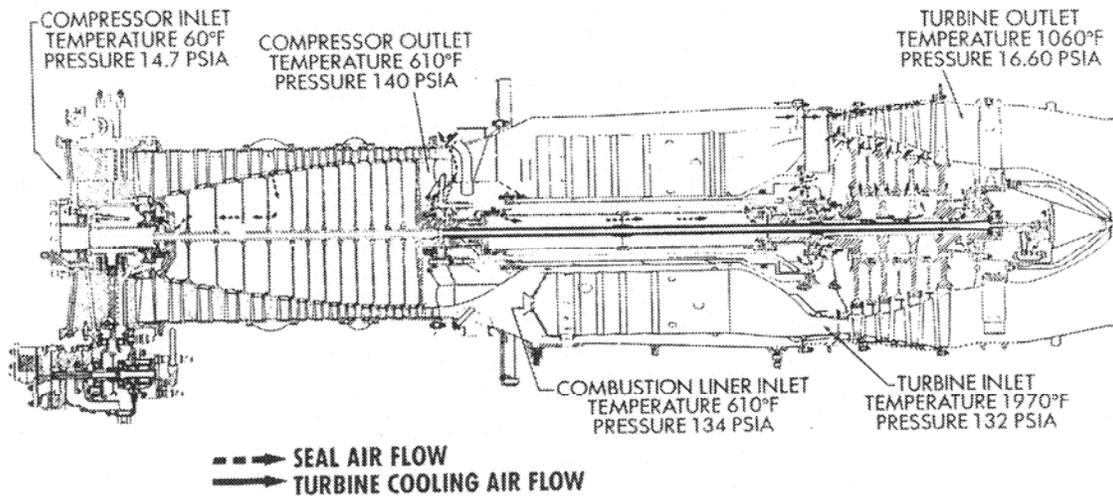
The type of operation for which the engine is designed dictates the performance requirement of a gas turbine engine. The performance requirement is mainly determined by the amount of shaft horsepower (s.h.p.) the engine develops for a given set of conditions. The majority of aircraft gas turbine engines are rated at standard day conditions of 59°F and 29.92 inches Hg. This provides a baseline to which gas turbine engines of all types can be compared.

The need for high efficiency in the engine becomes more important as fuels become more costly. Engine efficiency is primarily defined by the specific fuel consumption (s.f.c.) of the engine at a given set of conditions.

Many factors affect both the efficiency and the performance of the engine. The mass flow rate of air through the engine will dictate engine performance. Any restrictions acting against the smooth flow of air through the engine will limit the engine's performance. The pressure ratio of the compressor, the engine operating temperatures (turbine inlet temperature), and the individual component efficiencies will also influence both the performance and the efficiency of the overall engine. All these factors are considered during the design of the engine. An optimum pressure ratio, turbine inlet temperature, and air mass flow rate are selected to obtain the required performance in the most efficient manner. In addition, individual engine components are designed to minimize flow losses to maximize component efficiencies.

The following graphic shows the typical temperature and pressure rise through the gas flow path.

### Engine Temperature and Pressure Flow



## ENGINE SECTIONS

### Inlet

The air inlet duct must provide clean and unrestricted airflow to the engine. Clean and undisturbed inlet airflow extends engine life by preventing erosion, corrosion, and foreign object damage (FOD).

Consideration of atmospheric conditions such as dust, salt, industrial pollution, foreign objects (birds, nuts and bolts), and temperature (icing conditions) must be made when designing the inlet system. Fairings should be installed between the engine air inlet housing and the inlet duct to ensure minimum airflow losses to the engine at all airflow conditions.

The inlet duct assembly is usually designed and produced as a separate system rather than as part of the design and production of the engine.

### Compressor

The compressor is responsible for providing the turbine with all the air it needs in an efficient manner. In addition, it must supply this air at high static pressures. The example of a large turboprop axial flow compressor will be used. The compressor is

assumed to contain fourteen stages of rotor blades and stator vanes. The overall pressure ratio (pressure at the back of the compressor compared to pressure at the front of the compressor) is approximately 9.5:1. At 100% (>13,000) RPM, the engine compresses approximately 433 cubic feet of air per second. At standard day air conditions, this equals approximately 33 pounds of air per second. The compressor also raises the temperature of the air by about 550°F as the air is compressed and moved rearward. The power required to drive a compressor of this size at maximum rated power is approximately 7000 horsepower.

In an axial flow compressor, each stage incrementally boosts the pressure from the previous stage. A single stage of compression consists of a set of rotor blades attached to a rotating disk, followed by stator vanes attached to a stationary ring. The flow area between the compressor blades is slightly divergent. Flow area between compressor vanes is also divergent, but more so than for the blades.

In general terms, the compressor rotor blades convert mechanical energy into gaseous energy. This energy conversion greatly increases total pressure ( $P_t$ ). Most of the increase is in the form of velocity ( $P_i$ ), with a small increase in static pressure ( $P_s$ ) due to the divergence of the blade flow paths.

The stator vanes slow the air by means of their divergent duct shape, converting the accelerated velocity ( $P_i$ ) to higher static pressure ( $P_s$ ). The vanes are positioned at an angle such that the exiting air is directed into the rotor blades of the next stage at the most efficient angle. This process is repeated fourteen times as the air flows from the first stage through the fourteenth stage. Figure 2-4 shows one stage of the

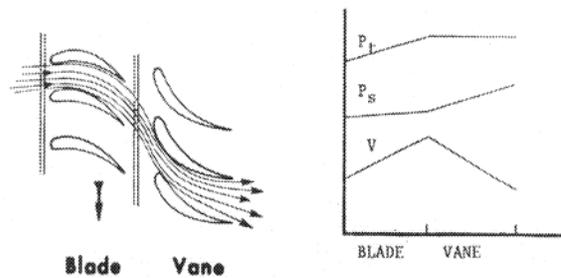


Figure 2-4. Compressor Flow Characteristics

compressor and a graph of the pressure characteristics as the air flows through the stage.

In addition to the fourteen stages of blades and vanes, the compressor also incorporates the inlet guide vanes and the outlet guide vanes. These vanes, located at the inlet and the outlet of the compressor, are neither divergent nor convergent. The inlet guide vanes direct air to the first stage compressor blades at the "best" angle. The outlet guide vanes "straighten" the air to provide the combustor with the proper airflow direction.

The efficiency of a compressor is primarily determined by the smoothness of the airflow. During design, every effort is made to keep the air flowing smoothly through the compressor to minimize airflow losses due to friction and turbulence. This task is a difficult one, since the air is forced to flow into ever-higher pressure zones.

Air has the natural tendency to flow toward low-pressure zones. If air were allowed to flow "backward" into the lower pressure zones, the efficiency of the compressor would decrease tremendously as the energy used to increase the pressure of the air was wasted. To prevent this from occurring, seals are incorporated at the base of each row of vanes to prevent air leakage. In addition, the tip clearances of the rotating blades are also kept at a minimum by the use of coating on the inner surface of the compressor case.

All components used in the flow path of the compressor are shaped in the form of airfoils to maintain the smoothest airflow possible. Just as is the case for the wings of an airplane, the angle at which the air flows across the airfoils is critical to performance. The blades and vanes of the compressor are positioned at the optimum angles to achieve the most efficient airflow at the compressor's maximum rated speed.

Any deviation from the maximum rated speed changes the characteristics of the airflow within the compressor. The blades and vanes are no longer positioned at their optimum angles. Many engines use bleed valves to unload the force of excess air in the compressor when it operates at less than optimum speed. The example engine incorporates four bleed valves at each of the fifth and tenth compressor stages. They are open until 13,000 RPM (~94% maximum) is reached, and allow some of the compressed air to flow out to the atmosphere. This results in higher air velocities over the blade and vane airfoils, improving the airfoil angles. The potential for airfoil stalling is reduced, and compressor acceleration can be accomplished without surge.

## **Diffuser**

Air leaves the compressor through exit guide vanes, which convert the radial component of the air flow out of the compressor to straight-line flow. The air then enters the diffuser section of the engine, which is a very divergent duct. The primary function of the diffuser structure is aerodynamic. The divergent duct shape converts most of the air's velocity ( $P_i$ ) into static pressure ( $P_s$ ). As a result, the highest static pressure and lowest velocity in the entire engine is at the point of diffuser discharge and combustor inlet. Other aerodynamic design considerations that are important in the diffuser section arise from the need for a short flow path, uniform flow distribution, and low drag loss.

In addition to critical aerodynamic functions, the diffuser also provides:

- Engine structural support, including engine mounting to the nacelle
- Support for the rear compressor bearings and seals

- Bleed air ports, which provide pressurized air for:
  - airframe "customer" requirements (air conditioning, etc.)
  - engine inlet anti-icing
  - control of acceleration bleed air valves
- Pressure and scavenge oil passages for the rear compressor and front turbine bearings.
- Mounting for the fuel nozzles.

## **Combustor**

Once the air flows through the diffuser, it enters the combustion section, also called the combustor. The combustion section has the difficult task of controlling the burning of large amounts of fuel and air. It must release the heat in a manner that the air is expanded and accelerated to give a smooth and stable stream of uniformly-heated gas at all starting and operating conditions. This task must be accomplished with minimum pressure loss and maximum heat release. In addition, the combustion liners must position and control the fire to prevent flame contact with any metal parts.

The engine in this example uses a can-annular combustion section. Six combustion liners (cans) are positioned within an annulus created by inner and outer combustion cases. Combustion takes place in the forward end or primary zone of the cans. Primary air (amounting to about one fourth of the total engine's total airflow) is used to support the combustion process. The remaining air, referred to as secondary or dilution air, is admitted into the liners in a controlled manner. The secondary air controls the flame pattern, cools the liner walls, dilutes the temperature of the core gasses, and provides mass. This cooling air is critical, as the flame temperature is above 1930°C (3500°F), which is higher than the metals in the engine can endure. It is important that the fuel nozzles and combustion liners control the burning and mixing of fuel and air under all conditions to avoid excess temperatures reaching the turbine or combustion cases. Maximum combustion section outlet temperature (turbine inlet temperature) in this engine is about 1070°C (>1950°F).

The rear third of the combustion liners is the transition section. The transition section has a very convergent duct shape, which begins accelerating the gas stream and reducing the static pressure in preparation for entrance to the turbine section.

## **Turbine**

This example engine has a four-stage turbine. The turbine converts the gaseous energy of the air/burned fuel mixture out of the combustor into mechanical energy to drive the compressor, driven accessories, and, through a reduction gear, the propeller. The turbine converts gaseous energy into mechanical energy by expanding the hot, high-pressure gases to a lower temperature and pressure.

Each stage of the turbine consists of a row of stationary vanes followed by a row of rotating blades. This is the reverse of the order in the compressor. In the compressor,

energy is added to the gas by the rotor blades, then converted to static pressure by the stator vanes. In the turbine, the stator vanes increase gas velocity, and then the rotor blades extract energy.

The vanes and blades are airfoils that provide for a smooth flow of the gases. As the airstream enters the turbine section from the combustion section, it is accelerated through the first stage stator vanes. The stator vanes (also called nozzles) form convergent ducts that convert the gaseous heat and pressure energy into higher velocity gas flow ( $P_i$ ). In addition to accelerating the gas, the vanes "turn" the flow to direct it into the rotor blades at the optimum angle.

As the mass of the high velocity gas flows across the turbine blades, the gaseous energy is converted to mechanical energy. Velocity, temperature, and pressure of the gas are sacrificed in order to rotate the turbine to generate shaft power. Figure 2-5 represents one stage of the turbine and the characteristics of the gases as it flows through the stage.

The efficiency of the turbine is determined by how well it extracts mechanical energy from the hot, high-velocity gasses. Since air flows from a high-pressure zone to a low-pressure zone, this task is accomplished fairly easily. The use of properly positioned airfoils allows a smooth flow and expansion of gases through the blades and vanes of the turbine.

All the air must flow across the airfoils to achieve maximum efficiency in the turbine. In order to ensure this, seals are used at the base of the vanes to minimize gas flow around the vanes instead of through the intended gas path. In addition, the first three stages of the turbine blades have tip shrouds to minimize gas flow around the blade tips.

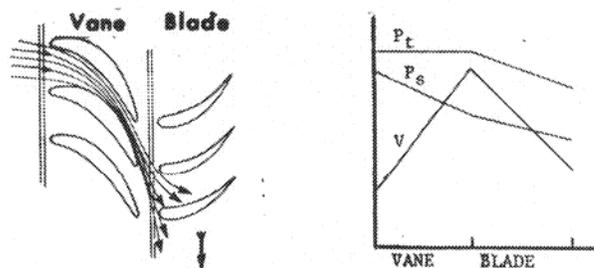


Figure 2-5. Turbine Flow Characteristics

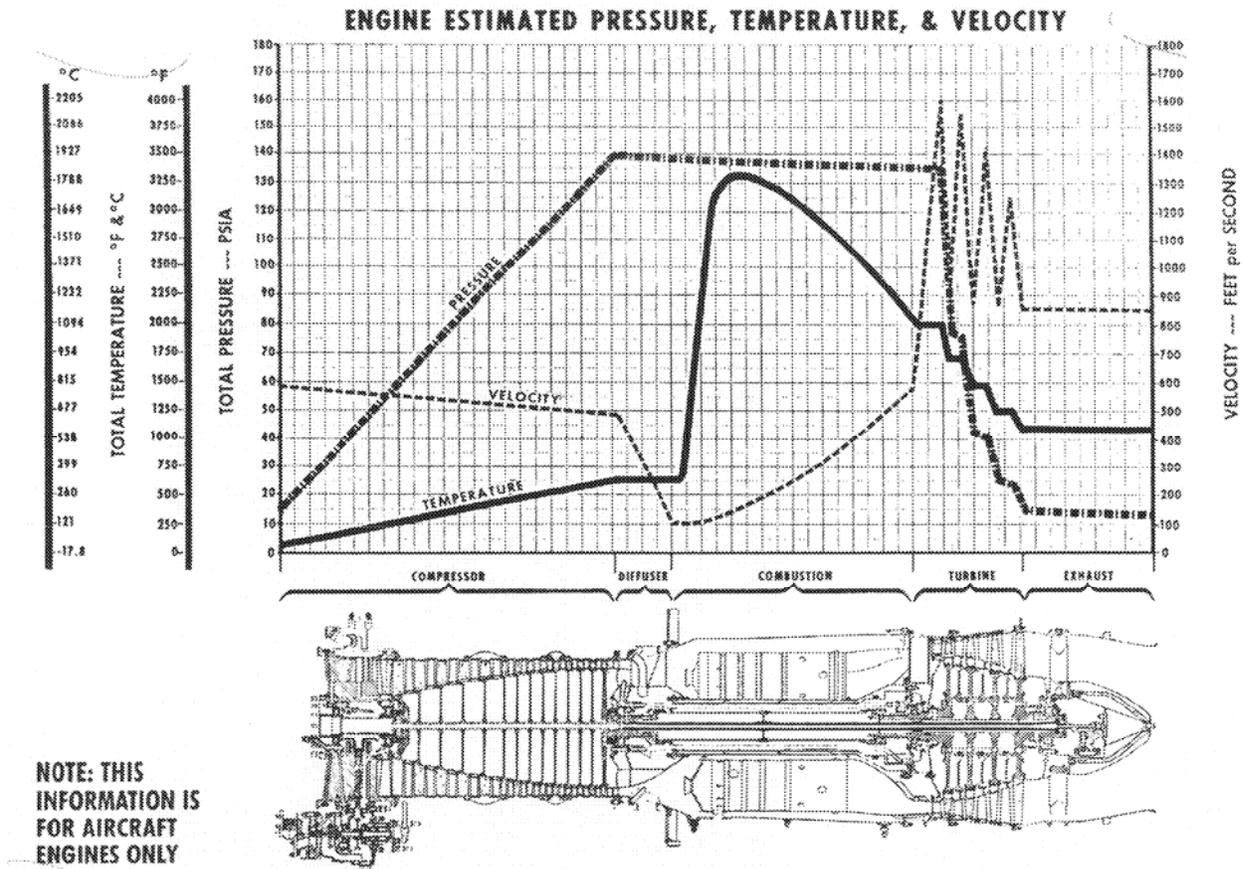
## Exhaust

After the gas has passed through the turbine, it is discharged through the exhaust. Though most of the gaseous energy is converted to mechanical energy by the turbine, a significant amount of power remains in the exhaust gas. This gas energy is accelerated through the convergent duct shape of the exhaust to make it more useful

as jet thrust - the principle of equal and opposite reaction means that the force of the exhausted air drives the airplane forward.

## EFFECTS OF TURBINE TEMPERATURE

The materials used in the turbine section of the engine limit the maximum temperature at which a gas turbine engine can operate. The first metal the hot gases from the combustion section strike is the turbine inlet. The temperature of the gas stream is carefully monitored to ensure that overtemperature does not occur.



Sample Engine Pressure, Temperature, and Velocity

Compromises are made in turbine design to achieve the optimum balance of power, efficiency, cost, engine life, and other factors. As an example, our sample engine can operate at a higher turbine inlet temperature than previous models due to improved materials and design. The higher temperature allows for increased power and improved efficiency while adding higher cost for the direct cooling of the first turbine stage airfoils and other components.

## **EFFECTS OF ATMOSPHERIC CONDITIONS**

The performance of the gas turbine engine is dependent on the mass of air entering the engine. At a constant speed, the compressor pumps a constant volume of air into the engine with no regard for air mass or density. If the density of the air decreases, the same volume of air will contain less mass, so less power is produced. If air density increases, power output also increases as the air mass flow increases for the same volume of air.

Atmospheric conditions affect the performance of the engine since the density of the air will be different under different conditions. On a cold day, the air density is high, so the mass of the air entering the compressor is increased. As a result, higher horsepower is produced. In contrast, on a hot day, or at high altitude, air density is decreased, resulting in a decrease of output shaft power.

## **COMPRESSOR STALL/SURGE**

### **Background information**

Compressor stall or surge is not peculiar to any one particular brand or type of engine. It may occur on any turbine engine if conditions are right. Stall has been encountered on two-stage or turbo-supercharged piston engines, so there is no need to look upon stall as some mysterious product of gas turbine engines.

Any number of mechanical defects, such as bad spark plugs, lean carburetion, poor timing, or sticking valves, can result in reciprocating engines backfiring. Similarly, for gas turbine engines, maintenance or flight conditions can influence the compressor stall or surge appreciably. The condition and operation of the bleed valve and fuel system components are of vital importance in maintaining surge-free operation.

Why are engines at risk of surge? As engines are designed to meet demands for higher power or lower specific fuel consumption, the engines must accommodate:

- Increased mass airflow.
- Increased pressure (compression) ratio.
- Increased maximum allowable turbine inlet and outlet temperatures.
- Improved efficiency of the compressor and turbine sections.

Quick engine starts and rapid accelerations are also desirable. To provide higher power with low specific fuel consumption and acceptable starting and acceleration characteristics, it is necessary to operate as close to the surge region as possible.

To prevent compressor stall or surge, fuel flow must be properly metered during the start and acceleration cycle of any gas turbine engine. To accomplish this, the example engine incorporates 5th and 10th stage acceleration bleed valves.

In general, there are fewer surge problems on centrifugal compressors than on axial flow compressors. There are several reasons for the difference; the primary reason is that centrifugal flow compressors operate at somewhat lower pressure ratios than axial flow compressors.

### **Explanation of stall/surge**

A surge from a turbine engine is the result of instability of the engine's operating cycle. As discussed earlier, the operating cycle of the turbine engine consists of intake, compression, combustion, and exhaust, which occur simultaneously in different places in the engine. The part of the cycle susceptible to instability is the compression phase. Compressor surge may be caused by engine deterioration, it may be the result of ingestion of birds or ice, or it may be the final sound from a "severe engine damage" type of failure.

In a turbine engine, compression is accomplished aerodynamically as the air passes through the stages of the compressor, rather than by confinement, as is the case in a piston engine. The air flowing over the compressor airfoils can stall just as the air over the wing of an airplane can. When this airfoil stall occurs, the passage of air through the compressor becomes unstable and the compressor can no longer compress the incoming air. The high-pressure air behind the stall further back in the engine escapes forward through the compressor and out the inlet.

This escape is sudden, rapid and often quite audible as a loud bang. Engine surge can be accompanied by visible flames forward out the inlet and rearward out the tailpipe. Instruments may show high EGT and EPR or rotor speed changes; but, in many stalls, the event is over so quickly that the instruments do not have time to respond.

Once the air from within the engine escapes, the reason (reasons) for the instability may self-correct and the compression process may re-establish itself. A single surge and recovery will occur quite rapidly, usually within fractions of a second. Depending on the reason for the cause of the compressor instability, an engine might experience:

1. A single self-recovering surge
2. Multiple surges prior to self-recovery
3. Multiple surges requiring pilot action in order to recover
4. A non-recoverable surge.

For complete, detailed procedures, flight crews must follow the appropriate checklists and emergency procedures detailed in their specific Airplane Flight Manual. In general, however, during a single self-recovering surge, the cockpit engine indications

may fluctuate slightly and briefly. The flight crew may not notice the fluctuation. (Some of the more recent engines may even have fuel-flow logic that helps the engine self-recover from a surge without crew intervention. The stall may go completely unnoticed, or it may be annunciated to the crew – for information only – via EICAS messages.) Alternatively, the engine may surge two or three times before full self-recovery. When this happens, there is likely to be cockpit engine instrumentation shifts of sufficient magnitude and duration to be noticed by the flight crew. If the engine does not recover automatically from the surge, it may surge continually until the pilot takes action to stop the process. The desired pilot action is to retard the power lever until the engine recovers. The flight crew should then SLOWLY re-advance the power lever. Occasionally, an engine may surge only once but still not self-recover.

The actual cause for the compressor surge is often complex and may or may not result from severe engine damage. Rarely does a single compressor surge CAUSE severe engine damage, but sustained surging will eventually over-heat the turbine, as too much fuel is being provided for the volume of air that is reaching the combustor. Compressor blades may also be damaged and fail as a result of repeated violent surges; this will rapidly result in an engine which cannot run at any power setting.