AIRCRAFT PROPULSION and GAS TURBINE ENGINES

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El-Sayed, Ahmed F.
Aircraft propulsion and gas turbine engines
Dedication

To

My wife Amany, and sons Mohamed, Abdallah, and Khaled
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5 Turbofan Engines

5.1 INTRODUCTION

Turbofan engines were first termed by Rolls-Royce as bypass turbojet. Boeing Company sometimes identifies them as fanjets [1]. Turbofan engines are the most reliable engines ever developed. Fundamentally, turbofan engines are fuel-efficient and quiet turbine engines. They feature continuous combustion and smooth rotation, unlike the internal combustion engine of an automotive. Similar to the turbojet engines, the gas generator in turbofan engines has three sections:

- Fan unit and compressor section
- Combustion chamber
- Turbine section

The compressors pressurize air and feed it aft. Most of the air goes around the engine core through a nozzle-shaped chamber. The rest goes through the engine core where it mixes with fuel and ignites. The hot expanding combustion efflux passes through the turbine section, spinning the turbine as it exits the engine.

The spinning turbine turns the engine shaft. The rotating shaft spins the fan on the front of the engine. The fan compresses more air and keeps this continuous cycle going.

Although during 1936–1946 the two companies Power Jet and Metropolitan-Vickers pioneered various kinds of ducted-fan jet engines, nobody had an interest in these engines and looked at them as rather complicated turbojet engines. Ten years later Rolls-Royce introduced such bypass turbojet engines having a bypass ratio (BPR) of three and more [2]. General Electric (GE) led the way in 1965 with the TF39 (BPR of 8) and still leads with GE90 (BPR nearly 9).

The turbofan engine has several advantages over both the turboprop and the turbojet engines. The fan is not as large as the propeller, so the increase of speeds along the blade is less. Thus, a turbofan engine can power a civil transport flying at transonic speeds up to Mach 0.9. In addition, by enclosing the fan inside a duct or cowling, the aerodynamics is better controlled. There is less flow separation at higher speeds and less trouble with shock developing. The turbofan may suck in more airflow than a turbojet, thus generating more thrust. Like the turboprop engine, the turbofan has low fuel consumption compared with the turbojet. The turbofan engine is the best choice for high-speed, subsonic commercial airplanes. Advantages of turbofan engines are as follows:

- The fan is not as large as the propeller; therefore, higher aircraft velocities can be reached before vibrations occur. The aircraft is able to reach transonic speeds of Mach 0.9.
- The fan is more stable than a single propeller and therefore, if the vibration velocity is reached, vibrations are less apparent and do not disrupt the airflow as significantly.
- The fan is encased in a duct or cowling; therefore, the aerodynamics of the airflow is controlled a lot better providing greater efficiency.
- For geared turbofan engines, the gearbox required to translate the energy from the compressor/fan to the turbine is relatively small and less complex as the fan is smaller. This reduces the weight and aerodynamic drag loss that are present on the turboprop design.
• The smaller fan is more efficient and takes in air at a greater rate than the propeller allowing the engine to produce greater thrust.
• The turbofan engine is a much more fuel-efficient design than the turbojet and is able to equal some of the high performance velocities.

As described in the classification section of Chapter 1, numerous types of turbofan exist. A detailed analysis of these types will be given in the following sections.

5.2 FORWARD FAN UNMIXED SINGLE-SPOOL CONFIGURATION

The main components here are the intake, fan, fan nozzle, compressor, combustion chamber, turbine, and turbine nozzle. The turbine drives both the fan and compressor. A schematic diagram of the fan as well as the cycle (successive processes) is illustrated in Figures 5.1 and 5.2. Here the BPR is defined as

\[ \beta = \frac{\text{Bypass airflow}}{\text{Primary airflow}} = \frac{\dot{m}_{\text{cold}}}{\dot{m}_{\text{hot}}} = \frac{\dot{m}_{\text{fan}}}{\dot{m}_{\text{core}}} \]

![Figure 5.1 Schematic diagram of a single-spool turbofan engine.](image)

![Figure 5.2 Temperature-entropy (T-S) diagram for the single-spool turbofan engine.](image)
Thus if the air mass through the core (compressor) is \( \dot{m}_a \), then the bypass air mass flow rate is \( \beta \dot{m}_a \). Sometimes the core mass flow rate is identified as the gas generator mass flow rate \( \dot{m}_{GG} \). However, this designation will not be used in this text.

Now the successive elements will be examined.

1. **Intake:** The inlet conditions of the air entering the intake are the ambient temperature and pressure \( (P_a, T_a) \) respectively. The intake has an isentropic efficiency \( \eta_d \). For a flight Mach number \( (M_a) \), then the temperature and pressure at the outlet of the intake are \( T_{02} \) and \( P_{02} \) given by the relations

\[
P_{02} = P_a \left( 1 + \frac{\gamma_e - 1}{2} M_a^2 \right)^{\gamma_e/(\gamma_e - 1)}
\]

\[
T_{02} = T_{0a} = T_a \left( 1 + \frac{\gamma_e - 1}{2} M_a^2 \right)
\]

where \( \eta_d \) is the diffuser isentropic efficiency and \( \gamma_e \) is the specific heat ratio for air (cold stream).

2. **Forward fan:** For a known fan pressure ratio \( (\pi_f) \) and isentropic efficiency \( (\eta_f) \), then the temperature and pressure at the outlet of the fan are given by the following relations:

\[
P_{08} = (P_{02}) (\pi_f)
\]

\[
T_{08} = T_{02} \left[ 1 + \frac{1}{\eta_f} \left( \pi_f^{\gamma_e - 1}/\gamma_e - 1 \right) \right]
\]

3. **Compressor:** Similarly, both the compressor pressure ratio \( (\pi_c) \) and its isentropic efficiency \( (\eta_c) \) are known. Thus, the temperature and pressure at the outlet of the compressor are given by the following relations:

\[
P_{03} = (P_{08}) (\pi_c)
\]

\[
T_{03} = T_{08} \left[ 1 + \frac{1}{\eta_c} \left( \pi_c^{\gamma_e - 1}/\gamma_e - 1 \right) \right]
\]

4. **Combustion chamber:** The temperature at the end of combustion process \( T_{04} \) is generally known. The maximum temperature in the cycle, which is frequently identified as the turbine inlet temperature (TIT) occurs here. The pressure at the end of combustion depends on the pressure drop in the combustion process itself. Thus, depending on the known expression for the pressure drop in the combustion chamber it may be expressed as

\[
P_{04} = P_{03} - \Delta P_{cc}
\]
or

\[ P_{04} = P_{03} (1 - \Delta P_{Tc\%}) \]  \hspace{1cm} (5.8)

The energy balance for the combustion chamber yields the following relation for the fuel-to-air ratio \( f \), defined as the ratio between the mass of fuel burnt and the air mass flow rate through the core (hot)

\[ f = \frac{\dot{m}_f}{\dot{m}_a} \]

\[ \dot{m}_a (1 + f) C_p h T_{04} = \dot{m}_a C_p c T_{03} + \eta_b \dot{m}_t Q_R \]

\[ f = \frac{(C_p h/C_p c) (T_{04}/T_{03}) - 1}{\eta_b (Q_R/C_p c T_{03}) - (C_p h/C_p c) (T_{04}/T_{03})} \]  \hspace{1cm} (5.9)

5. Turbine: Since the turbine drives both the compressor and turbine, then the energy balance for this spool per unit air mass flow rate is given by the following relation:

\[ W_t = W_c + W_f \]

From the above relation, the temperature ratio across the turbine is deduced as follows:

\[ \dot{m}_a (1 + f) C_p h (T_{04} - T_{05}) = \dot{m}_a C_p c (T_{03} - T_{05}) + (1 + \beta) \dot{m}_a C_p c (T_{08} - T_{02}) \]

\[ T_{04} - T_{05} = \frac{C_p c [[(T_{03} - T_{08})] + (1 + \beta) [(T_{08} - T_{02})]]}{C_p h (1 + f)} \]

\[ \therefore \frac{T_{05}}{T_{04}} = 1 - \frac{[(T_{03} - T_{08})] + (1 + \beta) [(T_{08} - T_{02})]}{(T_{04}) (C_p h/C_p c) (1 + f)} \]  \hspace{1cm} (5.10a)

The above relation can be rewritten as

\[ \frac{T_{05}}{T_{04}} = 1 - \frac{[(T_{03} - T_{08})] + \beta [(T_{08} - T_{02})]}{(T_{04}) (C_p h/C_p c) (1 + f)} \]  \hspace{1cm} (5.10b)

This temperature ratio can be further expressed as follows:

\[ \frac{T_{05}}{T_{04}} = \left\{ 1 - \left(\frac{1/\eta_t}{(1 + f)(C_p h/C_p c)}\right) \left(\frac{(P_{03}/P_{02})^{(\gamma_t-1)/\gamma_t} - 1}{(P_{08}/P_{02})^{(\gamma_t-1)/\gamma_t} - 1} \right) \right\} \]  \hspace{1cm} (5.10c)

The expansion ratio through the turbine can now be evaluated as long as its adiabatic efficiency \( \eta_t \) and the ratio of specific heats \( \gamma_t \) of the turbine working fluid are known.

\[ \frac{P_{05}}{P_{04}} = \left[ 1 - \frac{1}{\eta_t} \left(1 - \frac{T_{05}}{T_{04}}\right) \right]^{\gamma_t/(\gamma_t-1)} \]  \hspace{1cm} (5.11a)

\[ \frac{P_{05}}{P_{04}} = \left[ 1 - \frac{1}{\eta_t} \left((1/\eta_t) \left(\frac{(P_{03}/P_{02})^{(\gamma_t-1)/\gamma_t} - 1}{(1 + f)(C_p h/C_p c)}\right) \left(T_{04}/T_{02}\right) \right) \right]^{\gamma_t/(\gamma_t-1)} \]  \hspace{1cm} (5.11b)
6. **Turbine nozzle:** Assume that there are no changes in the total pressure and total temperature in the jet pipe between the turbine and nozzle. Thus \( P_{05} = P_{06} \) and \( T_{05} = T_{06} \). Next, a check for nozzle choking is performed. Thus for a nozzle isentropic efficiency of \( \eta_n \), the critical pressure is calculated from the relation

\[
\frac{P_{06}}{P_c} = \frac{1}{\left[ 1 - \frac{1}{\eta_n} \right] \left( \gamma_h - 1 \right) \left( \gamma_h + 1 \right)}^{1/\left( \gamma_h - 1 \right)}
\]

Now if the nozzle is an ideal, then \( \eta_n = 1 \), the above equation is reduced to

\[
\frac{P_{06}}{P_c} = \left( \frac{\gamma_h + 1}{2} \right)^{1/\left( \gamma_h - 1 \right)}
\]

If \( P_c \geq P_a \) then the nozzle is choked. The temperature of the gases leaving the nozzle is obtained from the relation

\[
\frac{T_{06}}{T_7} = \left( \frac{\gamma_h + 1}{2} \right)
\]

In this case, the gases leave the nozzle at a speed equal to the sonic speed or

\[
V_7 = \sqrt{\gamma_h R T_7}
\] (5.12a)

If the nozzle is unchoked \( (P_7 = P_a) \), then the speed of the gases leaving the nozzle is now given by

\[
V_7 = \sqrt{2 C_p R T_0 \eta_n \left[ 1 - \left( P_a / P_{06} \right) \left( \gamma_h - 1 \right) \right]}
\] (5.12b)

The pressure ratio in the nozzle is obtained from the relation

\[
\frac{P_{06}}{P_a} = \frac{P_{06}}{P_{05}} \frac{P_{05}}{P_{04}} \frac{P_{04}}{P_{03}} \frac{P_{03}}{P_{02}} \frac{P_{02}}{P_{01}} \frac{P_{01}}{P_a}
\]

7. **Fan nozzle:** The fan nozzle is also checked to determine whether choked or unchoked. Thus, the critical pressure is calculated from the relation

\[
\frac{P_{08}}{P_c} = \frac{1}{\left[ 1 - \frac{1}{\eta_{fn}} \right] \left( \gamma_c - 1 \right) \left( \gamma_c + 1 \right)}^{1/\left( \gamma_c - 1 \right)}
\]

Now if the nozzle is an ideal, then \( \eta_{fn} = 1 \) and the above equation will be reduced to

\[
\frac{P_{08}}{P_c} = \left( \frac{\gamma_c + 1}{2} \right)^{1/\left( \gamma_c - 1 \right)}
\]
Appendix A

GLOSSARY

Absolute pressure The total pressure measured from absolute zero (i.e., from an absolute vacuum).

Absolute temperature The temperature of a body with reference to the absolute zero, at which point the volume of an ideal gas theoretically becomes zero. (Fahrenheit scale is -459.67°F/Celsius scale is -273.15°C).

Adiabatic efficiency Ratio between measured shaft power and the adiabatic compression power, referring to measured mass flow.

Afterburner The afterburner is a second combustion chamber; afterburning (or reheat) is a method of augmenting the basic thrust of an engine to improve the aircraft takeoff, climb, and (for military aircraft) combat performance. Afterburning consists of the introduction and burning of fuel between the engine turbine and the jet pipe-propelling nozzle; utilizing the unburned oxygen in the exhaust gas increases the velocity of the jet leaving the propelling nozzle and therefore increases the engine thrust.

ATFI The abbreviation ATFI stands for Advance Technology Fan Integrator, a revolutionary propulsion concept for future aircraft that features a reduction gearbox between the low-pressure turbine and the fan.

Augmenter Augmenters are afterburners on low-bypass turbofan engines. Core airflow and bypass (fan) airflow are mixed aft of the turbines, in the exhaust. Fuel nozzles supply atomized fuel into the airflow and an igniter ignites the fuel-air mixture. Augmenters are used on low-bypass turbofan engines to increase thrust for short periods during takeoff, climb, and combat flight.

Augmenter exhaust nozzles Augmenter exhaust nozzles make up the aft end of augmented low-bypass turbofan engines. It has a flame holder, fuel nozzles, an igniter, and a variable exhaust nozzle. The fuel nozzles supply atomized fuel into the exhaust airflow and the igniter makes the fuel-air mixture burn. Augmenter exhaust nozzles are used on low-bypass turbofan engines to increase thrust.

Axial-flow compressor A compressor through which the air passes mostly in axial direction, that is, along the engine axis; in a centrifugal-flow compressor the air flow direction is transverse to the engine axis. Both variants are still in use today. Their application depends on the engine concept in each case.

Blade load Blade load is the ratio between the static pressure differential upstream and downstream of the cascade and the dynamic inlet pressure or, more generally, the total of aerodynamic loads acting on the airfoil.

Booster compressor Machine for compressing air or gas from an initial pressure, which is above atmospheric pressure, to a still higher pressure.

Brake horse power (BHP) The maximum rate at which an engine can do work as measured by the resistance of an applied brake, expressed in horsepower.

Bypass ratio (BPR) With commercial engines the ratio between cold and hot airflow is very high. A BPR of 6:1, for example, means that the air volume flowing through the fan and bypassing the core engine is six times the air volume flowing through the core engine.

Can-type combustion chamber Can-type combustion chambers are particularly suitable for engines with centrifugal-flow compressors as the airflow is already divided by the compressor outlet diffusers. Each flame tube has its own secondary air duct. The separate flame tubes are all
interconnected. Ignition problems may occur, particularly at high altitudes. The entire combustion section consists of 8–12 cans that are arranged around the engine. Individual cans are also used as combustion chambers for small engines or auxiliary power units.

**Cascade spacing** Distance between the skeleton lines of two adjacent airfoils.

**Centrifugal flow compressor** The direction of the flow of compressed air discharges outward at 90° to the spool axis. The centrifugal compressor consists of a rating impellor, a fixed diffuser, and a manifold that collects and turns the compressed air.

**Centrifugal flow turbojet** A turbojet engine with a centrifugal compressor rather than an axial flow compressor.

**Cogeneration** (1) Any of several processes that either use waste heat produced by electricity generation to satisfy thermal needs, or process waste heat to electricity, or produce mechanical energy or (2) the use of a single prime fuel source in a reciprocating engine or gas turbine to generate both electrical and thermal energy to optimize fuel efficiency. The dominant demand for energy may be either electrical or thermal. Usually it is thermal with excess electrical energy, if any, being transmitted into the local power supply lines.

**Combustion chamber** The purpose of the combusting chamber is to provide a stream of hot gas that releases its energy to the turbine and nozzle sections of the engine. There are three types of combustion chambers.

**Component efficiency** Component efficiency is the efficiency of individual engine components, such as compressor, combustion chamber, or turbine. One constituent of the component efficiency is the mechanical efficiency, which takes bearing losses and friction between gas and air flows and engine components into account.

**Compressor** The compressor is the first component in the engine core. The compressor squeezes the air that enters it into smaller areas, resulting in an increase in the air pressure. This results in an increase in the energy potential of the air. The normal parts of a compressor include compressor front frame, compressor casing with stator vanes, a rotor with rotor blades, and a compressor rear frame.

**Core** The core engine module is aft of the fan module and forward of the turbine stator case and is made up of three components; compressor rotor and stator, combustion liner, and stage 1 HPT nozzle. The core is responsible for supplying approximately 20% of the total engine thrust and the torque for operation of all accessories.

**Cowling** A removable metal covering placed over and around an airplane’s engine(s).

**Degree of reaction** The degree of reaction is the ratio between the specific flow in the rotor (static change over rotor) and the specific flow work between inlet and outlet of the stage (static change over stage).

**3D Design** Today, 3D methods are used to design the blading of turbomachinery components (compressors and turbines). This means that the airfoils are no longer designed section by section to obtain the necessary deflection of the gas flow but over their entire radial height so that a rather uniform load distribution is achieved and local flow separations and excessive losses are prevented.

**Diffuser** A stationary passage surrounding an impeller in which velocity pressure imparted to the flow medium by the impeller is converted into static pressure.

**Engine 3E** Engine 3E is a German Government–sponsored research program where 3E stands for environment, efficiency, and economy. Under this program, Motoren- und Turbinen-Union (MTU) is maturing technologies to reduce noise levels by 10%, carbon dioxide emissions by 20%, and NOx emissions by 85% by the year 2010.

**Engine price** The price of a production engine for the Airbus A320 aircraft family, for example, amounts to approximately US $5.5 million and that of a jumbo jet engine is in the region of US $10 million.

**Exhaust** The exhaust section is located behind the turbine section and at the rear of the engine. It is made up of either a fixed or variable nozzle assembly, depending on the aircraft application. The exhaust section directs the exhaust gases aft and further accelerates the exhaust gases to
produce forward thrust. Variable nozzles are usually found on military engines while fixed ones are typically associated with commercial turbofans.

**Fan** The fan is the first component on the engine. The spinning fan sucks in large quantities of air. Most blades of the fan are made of titanium. It then speeds this air up and splits it into two parts. One part continues through the “core” or center of the engine, where it is acted upon by the other engine components. The fan module typically supplies approximately 80% of the engine thrust. The second part “bypasses” the core of the engine. It goes through a duct that surrounds the core to the back of the engine where it produces much of the force that propels the airplane forward. This cooler air helps quiet the engine as well as adding thrust to the engine.

**Fuel consumption** It is the fuel consumed in liters for traveling 100 km per passenger seat. For a medium range aircraft it is 5–6 liters while for a long range—like Airbus A340—it is 3.7 liters/seat.

**Gas generator** The combination of the compressor, combustion chamber, and the turbine.

**Gas turbine** The turbine converts gas energy into mechanical work to drive the compressor by a rigid shaft.

**Geared fan** Normally, the fan, the low-pressure compressor, and the low-pressure turbine are fitted on one shaft. In contrast, a geared fan is “uncoupled” from the low-pressure system by means of a reduction gearbox. Thus, the low-pressure turbine and the low-pressure compressor can be operated at their respective optimum high speeds whereas the fan rotates at a much lower speed (ratio approx. 3:1). Advantages of the geared fan concept include a markedly improved overall engine efficiency and significant noise reduction.

**High-pressure turbine (HPT)** The HPT module is aft of the compressor rear frame and forward of the LPT stator case. The HPT module is made up of the HPT rotor and HPT stator and it removes energy from the combustion gases to turn the high-pressure compressor and accessory gearbox.

**Horsepower (HP)** A unit of power equal to 33,000 ft-lb of work per minute.

**Hydrocarbons** Chemicals containing carbon and hydrogen.

**Hypersonic** Very fast speed of flight, 3500–7000 mph (or Mach 5–10). The space shuttle travels this fast, once it is in space.

**IGV** Inlet guide-vane valve: a valve assembly at the air inlet of a “blower” (single stage, low pressure, centrifugal air compressor) usually advised to be mounted in very close proximity to the “blower” impeller. Provides “pre-swirl” of airflow in same rotational direction as “blower” impeller. Proven to improve efficiency (reduced BHP) during throttled-down modulation of “blowers.” Effectiveness, when used with multistage centrifugal air compressors, degrades rapidly.

**Impeller** The part of the rotating element of a dynamic compressor that imparts energy to the flowing medium by means of centrifugal force. It consists of a number of blades mounted so as to rotate with the shaft.

**Impingement cooling** A high-velocity cold air jet is directed from a hole vertically onto the component surface to be cooled. As the cooling air jet hits the surface, it is diverted in all directions parallel to the impingement surface. The cooling effect is high, but decreases continuously as the distance from the point of impingement increases.

**Industrial gas turbine** The operating principle of an individual gas turbine is essentially the same as that of an aero engine. However, a so-called power turbine is used in place of the low-pressure turbine of an aero engine that drives the fan. This power turbine delivers the necessary power—directly or via a gearbox—to a generator or pump, and so forth. Nearly all industrial gas turbines of the lower and intermediate power classes are aero engine derivatives.

**Jet engine** An of a class of reaction engines that propel aircraft by means of the rearward discharge of a jet of fluid, usually hot exhaust gases generated by burning fuel with air drawn in from the atmosphere. The aircraft engine provides a constant source of thrust to give the airplane forward movement.

**Low-pressure compressor** To achieve pressure ratios of over 30 in present-day engines, two different types of compressors are used: low-pressure compressors and high-pressure compressors.
These compressors that rotate at different speeds are driven by their counterparts in the turbine via concentric shafts.

**Low-pressure turbine**  The LPT module is in the rear of the engine, aft of the HPT stator case. LPT components include the LPT rotor, LPT nozzle stator case, and turbine rear frame. The LPT removes energy from the combustion gases to drive the low-pressure compressor (N1) rotor assembly.

**Mixer**  A mixer is a sheet-metal cone at the rear end of some engines which, owing to its special wavy form, ensures intensive mixing of the high velocity and, thus, loud exhaust gases exiting the low-pressure turbine with the slowly flowing bypass air. This results in a marked reduction of noise levels.

**Multistage centrifugal compressor**  A machine having two or more impellers operating in series on a single shaft and in a single casing.

**Multistage compressor**  A machine employing two or more stages.

**Normal turbine stage**  The normal turbine stage consists of a stator and a rotorator, with the rotor being arranged downstream of the stator.

**Nozzle**  The nozzle is the exhaust duct of the engine. This is the engine part that actually produces the thrust for the plane. The energy depleted airflow that passed the turbine, in addition to the colder air that bypassed the engine core, produces a force when exiting the nozzle that acts to propel the engine, and therefore the airplane, forward. The combination of the hot air and cold air is expelled and produces an exhaust, which causes a forward thrust.

**Pressure ratio**  The pressure ratio indicates the ratio between the pressure of the air entering the engine and the pressure of the air leaving the compressor. A pressure ratio of 30:1 (1 being the pressure of the inlet air) or just 30 thus means that the air pressure at the compressor exit (just upstream of the combustion chamber inlet) is 30 times the pressure value at the compressor inlet (first compressor stage or, in most engines, fan).

**Principle of energy transfer**  To allow the transfer of energy in a turbomachine the flow of the working fluid must be deflected in bladed rotors. This means that the generation of energy (compressor) and absorption of energy (turbine) take place in the rotors only, with the absolute flow being unsteady.

**Propeller spinner**  A cone-shaped piece of an airplane, mounted on a propeller, which reduces air resistance or drag.

**Propfan**  The propfan features a huge fan propeller that is driven by a turbine and allows bypass ratios of 15:1 or more to be achieved. Fuel consumption, noise, and emissions are significantly reduced.

**Propulsion**  (As a field of study in relation to aeronautics.) Is the study of how to design an engine that will provide the thrust that is needed for a plane to take off and fly through the air.

**Propulsion efficiency**  The external efficiency—also called propulsion efficiency—is a measure of the quality of an engine. It depends on the outlet velocity/flight velocity ratio, that is, the smaller this ratio the higher is the propulsion efficiency.

**Pusher engine**  A turboprop engine with a propeller mounted behind the engine and thus the generated thrust forces pushes the airplane. The engine is then identified as pusher, while if the propeller is in front of the engine it is called puller as it pulls the airplane.

**Radial-flow machine**  The flow direction is predominantly radial. Radial-flow machines feature centrifugal stages (flow from inside to outside) and centripetal stages (flow from outside to inside). With a view to ensuring the necessary energy transfer, the centrifugal principle is used in the compressor and the centripetal principle in the turbine.

**Ram**  The amount of pressure buildup above ambient pressure at the engine's compressor inlet, due to forward motion of the engine through the air—air's initial momentum.

**Ramjet**  A jet engine with no mechanical compressor, consisting of specially shaped tubes or ducts open at both ends. The air necessary for combustion is shoved into the duct and compressed by the forward motion of the engine.
Ram ratio  The ability of an engine’s air inlet duct to take advantage of ram pressure.


Reheaters  Heat exchangers for raising the temperature of compressed air to increase its volume.

Reverse-flow annular combustion chamber  The advantages and disadvantages of reverse-flow annular combustion chambers are the same as with annular combustion chambers. They reduce the length of the engine, however, at the expense of a larger cross-section. Reverse-flow annular combustion chambers are used mainly in engines whose last compressor stage is a centrifugal-flow compressor.

Single-crystal turbine blades  Single-crystal turbine blades have been developed for use in the high-temperature environment of advanced aero engines. With single-crystal blades the cooling process is controlled such that a single crystal is produced.

Slip  The internal leakage within a rotary compressor. It represents gas at least partially compressed but not delivered. It is experimentally determined and expressed in CFM to be deducted from the displacement to obtain capacity.

Solar-powered aircraft  Solar-powered aircraft, such as the pathfinder; use photovoltaic cells to convert energy from the sun into electricity to power electric motors that drive the aircraft.

SPC  Specific power consumption.

Specific fuel consumption  The ratio of fuel consumption to compressor capacity.

Specific work of a stage  The mechanical work of a stage per 1 kg mass flow is the specific work of a stage.

Speed of sound  When a plane travels faster than at 760 mph, a sound barrier forms in front of the plane. If a plane is going at the speed of sound it is traveling at Mach 1.

Stage  A stage is the combination of a stator and a rotor.

Stall  A flight condition wherein the airflow separates from the airfoil surface, or the airflow around the airfoil becomes turbulent, causing the airfoil to lose lift. It is usually a result of insufficient airspeed or excessive angle of attack.

Straight cascade  Blades/vanes arranged at regular intervals along a straight line, that is, the cascade axis (two-dimensional geometry).

Surge  The reversal of flow within a dynamic compressor that takes place when the capacity being handled is reduced to a point where insufficient pressure is being generated to maintain flow (also known as pumping).

Thermal barrier coatings  During operation, engine components are subjected to a combination of mechanical, thermal, and chemical loads. They must therefore be protected by high-temperature-resistant coatings capable of withstanding temperatures as high as 2500°C. Thermal barrier coatings are mainly used in combustion chambers and on turbine blades and vanes.

Thermal efficiency  The thermal or internal efficiency of an aero engine is the ratio between the amount of heat converted to work and the total amount of heat supplied. The thermal efficiency is a measure of the quality of an engine.

Thrust  The forward force that pushes the engine and, therefore, the airplane forward. Sir Isaac Newton discovered that for “every action there is an equal and opposite reaction.” Aircraft engine uses this principle.

Thrust class  Turbojet engines are grouped into three thrust classes: engines with a thrust of up to 20,000 lbs; engine with a thrust between 20,000 lbs and ~ 50,000 lbs, and engines with a thrust in excess of 50,000 lbs.

Thrust, gross  The thrust developed by the engine, not taking into account any presence of initial-air-mass momentum.

Thrust, net  The effective thrust developed by the engine during the flight, taking into consideration the initial momentum of the aircraft speed mass before entering the influence of the engine.

Thrust reverser  Thrust reversers serve as an aircraft’s main brakes on landing. There are three types of thrust reversers: translating cowl, clamshell, and turboprop reverse pitch. All three literally
reverse the engine's thrust by closing in when deployed by the pilot pushing the air out the front of the engine rather than the back. This motion decreases the speed of the aircraft and is the loud noise you hear when landing.

**Thrust, specific fuel consumption**  The fuel that the engine must burn to generate 1 lb of thrust.

**Thrust, static**  Thrust developed by engine, without any initial air—mass momentum due to engine's static state.

**Thrust-to-weight ratio**  The thrust-to-weight ratio is a characteristic value indicating the technical standard of an engine. The thrust-to-weight ratio of present-day military engines, for example, is 10:1.

**Turbine**  The high-energy gas flow coming out of the combustor goes into the turbine, causing the turbine blades to rotate. This rotation extracts some energy from the high-energy flow that is used to drive the fan and the compressor. The gases produced in the combustion chamber move through the turbine and spin its blades. The task of a turbine is to convert gas energy into mechanical work to drive the compressor.

**Turbofan engine**  In turbofan engines only a small part of the thrust is generated in the core engine. The major part is produced by the bypass flow through the fan. The fan feeds large air volumes downstream that surround the engine like an envelope and thus reduce the engine noise. With increasing bypass ratio, that is, ratio between internal and external airflow, operating cost, emissions, and noise are reduced. Bypass ratios of turbofans for modern airlines are now about 6:1, that is, the bypass flow through the fan and around the engine is six times the airflow through the core engine.

**Turbojet engine**  Turbojet engines, the first jet engine generation, are single-flow engines in which the total volume of air ingested flows through the compressor, the combustion chamber, and the turbine. The thrust is then produced by the exhaust gases exiting the engine at high velocities. Because of the low efficiency and the high noise levels, turbojet engines are no longer produced today.

**Turboprop**  A turboprop is a jet engine attached to a propeller. The turbine at the back is turned by the hot gases generated by the engine, and this turns a shaft that drives the propeller. A variety of smaller aircraft are powered by turboprops. Like the turbojet, the turboprop engine consists of a compressor, combustion chamber, and turbine, and the air and gas pressure is used to run the turbine, which then creates power to drive the compressor. Compared with a turbojet engine, the turboprop has better propulsion efficiency at flight speeds below about 500 mph. Modern turboprop engines are equipped with propellers that have a smaller diameter but a larger number of blades for efficient operation at much higher flight speeds. To accommodate the higher flight speeds, the blades are scimitar-shaped with swept-back leading edges at the blade tips. Engines featuring such propellers are called propfans.

**Turboshaft engine**  Turboshaft engines are mainly used to power helicopters. They may include an additional free power turbine with a gearbox to convert the thrust into driving power for the rotor.

**Two-stage compressor**  Machines in which air or gas is compressed from initial pressure to an intermediate pressure in one or more cylinders or casings.

**Variable-pitch propeller**  An engine-driven device, designed to drive an airplane forward, whose efficiency can be improved by turning its blades in midflight.

**Velocity triangle**  The velocity triangle is the geometric representation of the kinematics condition.

**Zeppelin**  Named after its German inventor, this airship craft is controllable, powered, and lighter than air, with a rigid structure.