Jet engine

A Pratt and Whitney turbofan engine for the F-15 Eagle is tested at Robins Air Force Base, Georgia, USA. The tunnel behind the engine muffles noise and allows exhaust to escape. The mesh cover at the front of the engine (left of photo) prevents debris—or people—from being pulled into the engine by the huge volume of air rushing into the inlet.

A **jet engine** is any engine that accelerates and discharges a fast moving jet of fluid to generate thrust in accordance with Newton's third law of motion. This broad definition of jet engines includes turbojets, turbofans, rockets and ramjets, but in common usage, the term generally refers to a gas turbine used to produce a jet of high speed exhaust gases for propulsive purposes.

Turbojet engines

A turbojet engine is a type of internal combustion engine often used to propel aircraft. Air is drawn into the rotating compressor via the intake and is compressed to a higher pressure before entering the combustion chamber. Fuel is mixed with the compressed air and ignited by flame in the eddy of a flame holder. This combustion process significantly raises the temperature of the gas. Hot combustion products leaving the combustor expand through the turbine, where power is extracted to drive the compressor. Although this expansion process reduces both the gas temperature and pressure at exit from the turbine, both parameters are usually still well above ambient conditions. The gas stream exiting the turbine expands to ambient pressure via the propelling nozzle, producing a high velocity jet in the exhaust plume. If the jet velocity exceeds the aircraft flight velocity, there is a net forward thrust upon the airframe.

Under normal circumstances, the pumping action of the compressor prevents any backflow, thus facilitating the continuous flow process of the engine. Indeed, the entire process is similar to a four-stroke cycle, but with induction, compression, ignition, expansion and exhaust taking place simultaneously. The efficiency of a jet engine is strongly dependent upon the Overall Pressure Ratio (Combustor Entry Pressure/Intake Delivery Pressure) and the Turbine Inlet Temperature of the cycle.

It is also perhaps instructive to compare turbojet engines with propeller engines. Turbojet engines take a relatively small mass of air and accelerate it by a large amount, whereas a propeller takes a large mass of air and accelerates it by a small amount. The high-speed exhaust of a jet engine makes it efficient at high speeds (especially supersonic speeds) and high altitudes. On slower aircraft and those required to fly short stages, a gas turbine-powered propeller engine, commonly known as a turboprop, is more common and much more efficient. Very small aircraft generally use conventional piston engines to drive a propeller but small turboprops are getting smaller as engineering technology improves.

The turbojet described above is a single spool design, where a single shaft connects the turbine to the compressor. Higher Overall Pressure Ratio designs often have two concentric shafts, to improve compressor stability during engine throttle movements. The outer (HP) shaft connects the High Pressure (HP) Compressor to the HP turbine. This HP Spool, with the combustor, forms the core or gas generator of the engine. The inner shaft connects the Low Pressure (LP) Compressor to the LP Turbine to create the LP Spool. Both spools are free to operate at their optimum shaft speed.

Turbofan engines

Most modern jet engines are actually turbofans, where the LP Compressor acts as a fan, supplying supercharged air to not only the engine core, but to a bypass duct. The bypass airflow either passes to a separate Cold Nozzle or mixes with LP Turbine exhaust gases, before expanding through a Mixed Flow Nozzle.

Forty years ago there was little difference between civil and military jet engines, apart from the use of afterburning in some (supersonic) applications. Turbofans, today, have a low specific thrust (net thrust/airflow) to keep jet noise to a minimum and to improve fuel efficiency. Consequently the bypass ratio (bypass flow/core flow) is relatively high (a ratio of 8-12:1 is common). Only a single fan stage is required, because a low specific thrust implies a low fan pressure ratio.

Today's military turbofans, however, have a relatively high specific thrust, to maximize the thrust for a given frontal area, jet noise being of little consequence. Multi-stage fans are normally required to achieve the relatively high fan pressure ratio needed for a high specific thrust. Although high Turbine Inlet Temperatures are frequently employed, the bypass ratio tends to be low (usually significantly less than 2.0).

An approximate equation for calculating the net thrust of a jet engine is:

$$F_n = m(V_{jfe} - V_a)$$

where:

$m =$ intake mass flow

$V_{jfe} =$ fully expanded jet velocity (in the exhaust plume)

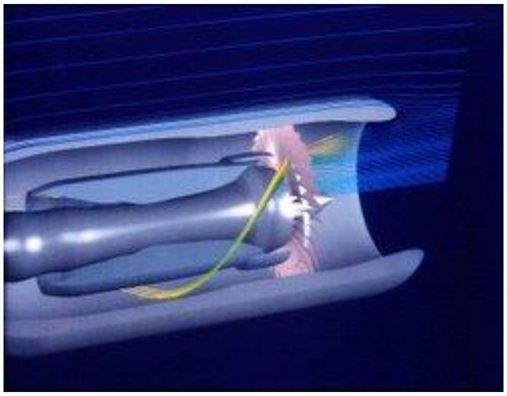
$V_a =$ aircraft flight velocity

While the $m \cdot v_{jfe}$ term represents the gross thrust of the nozzle, the $m \cdot v_a$ term represents the ram drag of the intake. Most types of jet engine have an air intake, which provides the bulk of the gas exiting the exhaust. There is, however, a penalty for picking this air up and this is known as the ram drag. Conventional rocket motors, however, do not have an air intake, the oxidizer being carried within the airframe. Consequently, rocket motors do not have ram drag; the gross thrust of the nozzle is the net thrust of the engine. Consequently, the thrust characteristics of a rocket motor are completely different from that of an air breathing jet engine; at full throttle, the thrust of a rocket motor improves slightly with increasing altitude (because the back pressure from the atmosphere falls), whereas with a turbojet (or turbofan) the falling density of the air entering the intake causes the net thrust to decrease with increasing altitude.

History

Before the advent of the jet engine, the reciprocating piston engine in its different forms (rotary and static radial, aircooled and liquid-cooled inline) had been the only type of powerplant available to aircraft designers. This was understandable so long as low aircraft performance parameters were considered acceptable, and indeed inevitable. However, by approximately the late 1930s, engineers were beginning to realize that conceptually the piston engine was self-limiting in terms of the maximum performance which could be obtained from it; the limit was essentially one of propeller efficiency, which seemed to peak as blade tips approached supersonic tangential velocity. If engine, and thus aircraft, performance were ever to increase beyond such a barrier, a way would have to be found to radically improve the design of the piston engine, or a wholly new type of powerplant would have to be conceived. The latter would prove to be the case. The gas turbine (**turbojet**, or simply **jet**) engine, as subsequently developed, would become almost as revolutionary to aviation as the Wright brothers' first flight.

The gas turbine was not an idea developed in the 1930s: the patent for a stationary turbine was granted to John Barber in England in 1791. The earliest attempts at jet engines were hybrid designs in which an external power source supplied the compression. In this system (called a thermojet by Secondo Campini) the air is first compressed by a fan driven by a conventional piston engine, then it is mixed with fuel and burned for jet thrust. The examples of this type of design were the Henri Coanda's Coanda-1910 aircraft, and the much later Campini Caproni CC.2, and the Japanese Tsu-11 engine intended to power Ohka kamikaze planes towards the end of World War II. None were entirely successful and the CC.2 ended up being slower than the same design with a traditional engine and propeller combination.



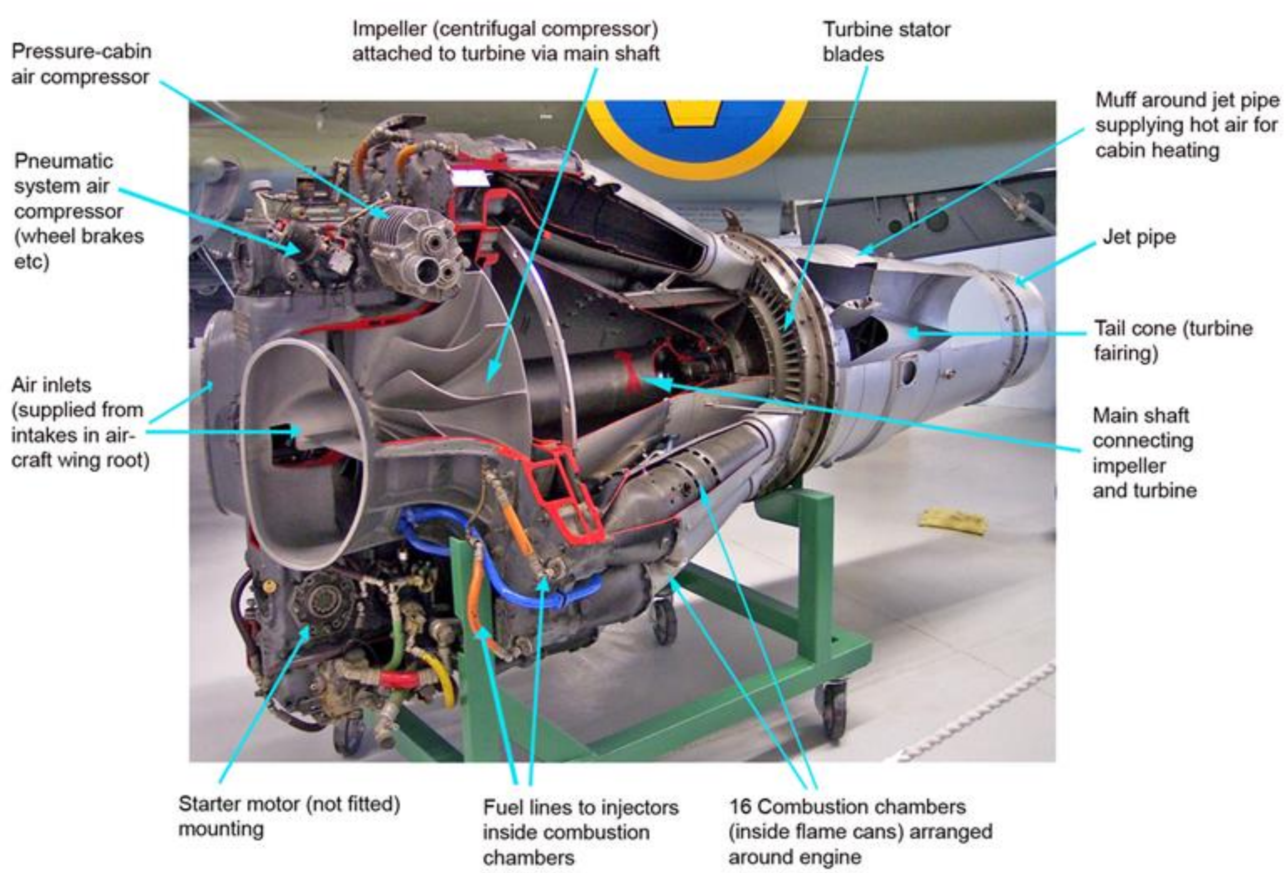
Jet engine airflow simulation

The key to the useful jet engine was the gas turbine, used to extract energy to drive the compressor from the engine itself. The first gas turbine to successfully run self-sustaining was built in 1903 by Norwegian engineer Aegidius Elling. The first patents for jet propulsion were issued in 1917. Limitations in design and practical engineering and metallurgy prevented such engines reaching manufacture. The main problems were safety, reliability, weight and, especially, sustained operation.

On January 16, 1930, in England Frank Whittle submitted patents for his own design for a full-scale aircraft engine (granted in 1932). In 1935 Hans von Ohain started work on a similar design in Germany, seemingly unaware of Whittle's work.

Ohain approached Ernst Heinkel, one of the larger aircraft industrialists of the day, who immediately saw the promise of the design. Heinkel had recently purchased the Hirth engine company, and Ohain and his master machinist Max Hahn were set up there as a new division of the Hirth company. They had their first HeS 1 engine running by September 1937. Unlike Whittle's design, Ohain used hydrogen as fuel, which he credits for the early success. Their subsequent designs culminated in the gasoline-fuelled HeS 3 of 1,100 lbf (5 kN), which was fitted to Heinkel's simple and compact He 178 airframe and flown by Erich Warsitz in the early morning of August 27, 1939, from Marienehe aerodrome, an impressively short time for development. The He 178 was the **world's first jetplane.**

The engine was starting to look useful, and Whittle's **Power Jets Ltd.** started receiving Air Ministry money. In 1941 a flyable version of the engine called the **W.1**, capable of 1000 lbf (4 kN) of thrust, was fitted to the Gloster E28/39 airframe, and first flew on May 15, 1941 at RAF Cranwell.



A picture of an early centrifugal engine (the *DH Goblin II*) sectioned to show its internal components

One problem with both of these early designs, which are called **centrifugal-flow** engines, was that the compressor works by "throwing" (accelerating) air outward from the central intake to the outer periphery of the engine where the air is then compressed by a divergent duct setup—thus converting velocity into pressure. The advantage was that such compressor designs were well understood in centrifugal superchargers but this leads to a very large cross section for the engine at rotational speeds that were usable at the time. A further disadvantage is that the air flow has to be "bent" to flow rearwards through the combustion section and to the turbine and tailpipe. With improvements to bearings, the shaft speed of the engine was increased and the diameter of the centrifugal compressor was greatly reduced. The shortness of this engine is one advantage. The strength of this type of compressor is another advantage over the later axial-flow compressors that are still liable to foreign object damage (**FOD** in aviation parlance).

Austrian Anselm Franz of Junkers' engine division (*Junkers Motoren* or **Jumo**) addressed this problem with the introduction of the axial-flow compressor. Essentially, this is a turbine in reverse. Air coming in the front of the engine is blown to the rear of the engine by a fan stage (convergent ducts), where it is crushed against a set of non-rotating blades called *stators* (divergent ducts). The process is nowhere near as powerful as the centrifugal compressor, so a number of these pairs of fans and stators are placed in series to get the needed compression. Even with all the added complexity, the resulting engine is much smaller in diameter. Jumo was assigned the next engine number, 4, and the result was the Jumo 004 engine. After many lesser technical difficulties were solved, mass production of this engine started in 1944 as a powerplant for the world's first jet-fighter aircraft, the Messerschmitt Me 262. Because Hitler wanted a new bomber the Me 262 came too late to decisively impact Germany's position in World War II, but it will be remembered as the first use of jet engines in service. After the end of the war the German Me 262 aircraft were extensively studied by the victorious allies and contributed to work on early Soviet and US jet fighters.

British engines also were licensed widely in the US (see Tizard Mission). Their most famous design, the Nene would also power the USSR's jet aircraft also after a technology exchange. American designs would not come fully into their own until the 1960s.

Types

There are a large number of types of jet engines, which get propulsion from a high speed exhaust jet. Some examples are as follows:

Type	**Description**	**Advantages**	**Disadvantages**
Water jet	Squirts water out the back of a boat	Can run in shallow water, powerful, less harmful to wildlife	Can be less efficient than a propeller, more vulnerable to debris
Thermojet	Most primitive airbreathing jet engine		Very inefficient and underpowered
Turbojet	Generic term for simple turbine	Simplicity of design	Basic design, misses many improvements in efficiency

	engine		and power
Turbofan	First stage compressor greatly enlarged to provide bypass airflow around engine core	Quieter due to greater mass flow and lower total exhaust speed, more efficient for a useful range of subsonic airspeeds for same reason	Greater complexity (additional ducting, usually multiple shafts), large diameter engine, need to contain heavy blades. More subject to FOD and ice damage. Different degrees of bypass are possible - this is the design most commonly used on commercial airliners
Rocket	Carries all propellants onboard, emits jet for propulsion	Very few moving parts, Mach 0 to Mach 25+, efficient at very high speed (> Mach 10.0 or so), thrust/weight ratio over 100, relatively simple, no complex air inlet, high compression ratio, very high speed exhaust, good cost/thrust ratio, works best exoatmospheric which is kinder on vehicle structure at high speed.	Needs lots of propellant- very low specific impulse- typically 100-450 seconds. Extreme thermal stresses of combustion chamber can make reuse harder. Typically requires carrying oxidiser onboard which increases risks.
Ramjet	Intake air is compressed entirely by speed of oncoming air and duct shape (divergent)	Very few moving parts, Mach 0.8 to Mach 5+, efficient at high speed (> Mach 2.0 or so), lightest of all airbreathing jets (thrust/weight ratio up to 30 at optimum speed)	Must have a high initial speed to function, inherently inefficient at slow speeds due to poor compression ratio, difficult to arrange shaft power for accessories, difficult to engineer to be efficient over a wide range of airspeeds.
Turboprop (Turboshaft similar)	Strictly not a jet at all- a gas turbine engine is used as powerplant to drive (propeller) shaft	High efficiency at lower subsonic airspeeds(300 knots plus), high shaft power to weight	Limited top speed (aeroplanes), somewhat noisy, complexity of propeller drive, very large yaw (aeroplane) if engine fails
Propfan	Turboprop engine drives one or more propellers. much like a turbofan but without ductwork	Higher fuel efficiency, some designs are less noisy than turbofans, could lead to higher-speed commercial aircraft, popular in the 1980s during fuel shortages,	Development of propfan engines has been very limited, typically more noisy than turbofans, complexity
Pulsejet	Air enters a divergent-duct inlet, the front of the combustion area is shut, fuel injected into the air ignites,	Very simple design, commonly used on model aircraft	Noisy, inefficient (low compression ratio), works best at small scale, valves need to be replaced very often

	exhaust vents from other end of engine		
Pulse detonation engine	Similar to a pulsejet, but combustion occurs as a detonation instead of a deflagration, may or may not need valves	Maximum theoretical engine efficiency	Extremely noisy, parts subject to extreme mechanical fatigue, hard to start detonation, not practical for current use
Integral rocket ramjet	Essentially a ramjet where intake air is compressed and burnt with the exhaust from a rocket	Mach 0 to Mach 4.5+ (can also run exoatmospheric), good efficiency at Mach 2 to 4	Similar efficiency to rockets at low speed or exoatmospheric, inlet difficulties, a relatively undeveloped and unexplored type, cooling difficulties
Scramjet	Intake air is compressed but not slowed to below supersonic, intake, combustion and exhaust occur in a single constricted tube	can operate at very high Mach numbers (Mach 8 to 15)[1]	still in development stages, must have a very high initial speed to function (Mach >6), cooling difficulties, inlet difficulties, very poor thrust/weight ratio (~2), airframe difficulties, testing difficulties
Turborocket	An additional oxidizer such as oxygen is added to the airstream to increase max altitude	Very close to existing designs, operates in very high altitude, wide range of altitude and airspeed	Airspeed limited to same range as turbojet engine, carrying oxidizer like LOX can be dangerous
Precooled jets / LACE	Intake air is chilled to very low temperatures at inlet	Very high thrust/weight ratios are possible (~14) together with good fuel efficiency over a wide range of airspeeds, mach 0-5+	Exists only at the lab protoyping stage. Examples include RB545, SABRE, ATREX

[edit]

Components

The components of a jet engine are standard across the different types of engines, although not all engine types have all components. The parts include:

- **Air Induction**
  The standard reference frame for a jet engine is the aircraft itself. For subsonic aircraft, the air intake to a jet engine presents no special difficulties, and consists essentially of an opening which is designed to minimise drag, as with any other aircraft component. However, the air reaching the compressor of a normal jet engine must be travelling below the speed of sound, even for supersonic aircraft, to sustain the flow mechanics of the compressor and turbine

blades. At supersonic flight speeds, shockwaves form in the intake system and reduce the recovered pressure at inlet to the compressor. So some supersonic intakes use devices, such as a cone or ramp, to increase pressure recovery, by making more efficient use of the shock wave system.

- **Compressor** or **Fan**
  In many cases, the compressor is a series of fans that are spaced very closely together. Each fan compresses the air a little more. Energy is derived from the **turbine** (see below), passed along the **shaft**.
- **Shaft**
  This carries power from the **turbine** to the **compressor**, and runs most of the length of the engine. There may be as many as three concentric shafts, rotating at independent speeds, with as many sets of turbines and compressors. Other services, like a bleed of cool air, may also run down the shaft.
- **Combustor** or **Can** or **Flameholders** or **Combustion Chamber**
  This is a chamber where fuel is continuously burned in the compressed air.
- **Turbine**
  The turbine acts like a windmill, extracting energy from the hot gases leaving the **combustor**. This energy is used to drive the **compressor** through the **shaft**, or bypass fans, or props, or even (for a gas turbine-powered helicopter) converted entirely to rotational energy for use elsewhere.
- **Afterburner** or **reheat** (chiefly UK)
  (mainly military) Produces extra thrust by burning extra fuel, usually inefficiently, to significantly raise Nozzle Entry Temperature at the **exhaust**. Owing to a larger volume flow (i.e. lower density) at exit from the afterburner, an increased nozzle flow area is required, to maintain satisfactory engine matching, when the afterburner is alight.
- **Exhaust** or **Nozzle**
  Hot gases leaving the engine exhaust to atmospheric pressure via a nozzle, the objective being to produce a high velocity jet. In most cases, the nozzle is convergent and of fixed flow area.
- **Supersonic Nozzle**
  If the Nozzle Pressure Ratio (Nozzle Entry Pressure/Ambient Pressure) is very high, to maximize thrust it may be worthwhile, despite the additional weight, to fit a convergent-divergent (de Laval) nozzle. As the name suggests, initially this type of nozzle is convergent, but beyond the throat (smallest flow area), the flow area starts to increase to form the divergent portion. The expansion to atmospheric pressure and supersonic gas velocity continues downstream of the throat, whereas in a convergent nozzle the expansion beyond sonic velocity occurs externally, in the exhaust plume. The former process is more efficient.

Design considerations

The various components named above have constraints on how they are put together to generate the most efficiency or performance. Important here is air intake design, overall size, number of compressor stages (sets of blades), fuel type, number of exhaust stages, metallurgy of components, amount of bypass air used, where the bypass air is introduced, and many other factors. For instance, let us consider design of the air intake.

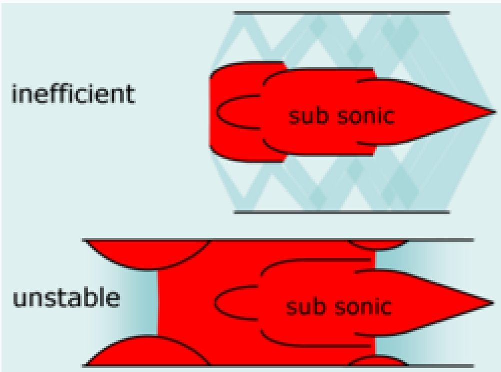
Air intakes

See also: Inlet cone

Subsonic inlets

At low speeds a subsonic inlet is little more than a hole, with an aerodynamic fairing around it. However, from around mach 0.85, the air entering the inlet can start to experience shock waves, and then careful radiusing is required for optimum performance at all speeds.

Supersonic inlets



Supersonic inlets: Normal shock is not isentroph

For aircraft travelling at supersonic speeds, a design complexity arises, since the air ingested by the engine must be below supersonic speed, otherwise the engine will "choke" and cease working. This subsonic air speed is achieved by passing the approaching air through a deliberately generated shock wave (since one characteristic of a shock wave is that the air flowing through it is slowed). Therefore, some means is needed to create a shockwave ahead of the intake.

The earliest types of supersonic aircraft featured a central shock cone, called an inlet cone, which was used to form the shock wave. This type of shock cone is clearly seen on the English Electric Lightning and MiG-21 aircraft, for example. The same approach can be used for air intakes mounted at the side of the fuselage, where a half cone serves the same purpose with a semicircular air intake, as seen on the F-104 Starfighter and BAC TSR-2. A more sophisticated approach is to angle the intake so that one of its edges forms a leading blade. A shockwave will form at this blade, and the air ingested by the engine will be behind the shockwave and hence subsonic. The Century series of US jets featured a number of variations on this approach, usually with the leading blade at the outer vertical edge of the intake which was then angled back inwards towards the fuselage. Typical examples include the Republic F-105 Thunderchief and F-4 Phantom.

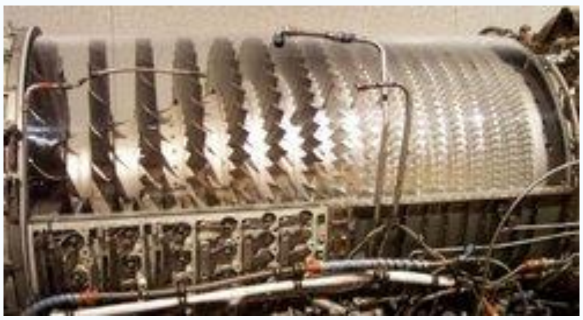
Later this evolved so that the leading edge was at the top horizontal edge rather than the outer vertical edge, with a pronounced angle downwards and rearwards. This approach simplified the construction of the intakes and permitted the use of variable ramps to control the airflow into the engine. Most designs since the early 1960s now feature this style of intake, for example the F-14 Tomcat, Panavia Tornado and Concorde.

SR 71

The SR-71's engines were rather unusual in that a variable air intake design was used to convert the engine from a turbojet to a ramjet, in flight. To get good efficiency over a wide range of speeds the Pratt & Whitney J58 could move a conical spike fore and aft within the engine nacelle, to keep the supersonic shock wave just in front of the inlet. In this manner, the airflow behind the shock wave, and more importantly, through the engine, was kept subsonic at all times. At high mach, the compressor for the J58 was unable to carry the high air flow entering the inlet without stalling its blades, and so the engine directed the excess air through 6 bypass pipes straight to the afterburner. At high speeds the engine actually obtained 80% of its thrust, versus 20% through the turbines itself, in this way. Essentially, this allowed the engine to operate as a ramjet, actually improving specific impulse (fuel efficiency) by 10%–15%.

Heat exchangers

For engines that may need to operate at almost hypersonic speeds (mach 0 to 6), there is strong theoretical and experimental support for using a heat-exchanger to cool the air at the intake. This can increase the density of the air and thus reduce the necessary compression. The lower temperatures also permit lighter alloys to be used hence reducing the engine's weight by several times. This leads to plausible designs like SABRE and ATREX that might permit jet engined vehicles to be used to launch to space.



Compressor stage GE J79

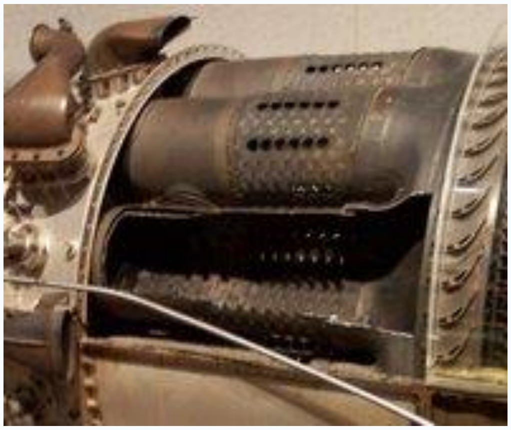
Compressors

Each design of compressor has an operating map or characteristic peculiar to that unit. At a given throttle condition, the compressor operates somewhere along the steady state running line. Unfortunately, this operating line is displaced during transients and under extreme conditions can cross the surge or stall line (see compressor map), causing, in some cases, the compressor flow to reverse direction violently. Many compressors are fitted with anti-stall systems in the form of bleed bands or variable geometry stators to decrease the likelihood of surge. Another ploy is to split the compressor into two or more units, operating on separate concentric shafts.

Another design consideration is the average stage loading. This can be kept at a sensible level either by increasing the number of compression stages (more weight/cost) or the mean blade speed (more blade/disc stress).

Although large flow compressors are usually all-axial, the rear stages on smaller units are too small to be robust. Consequently, these stages are often replaced by a single centrifugal (CF) unit. Very small flow compressors often employ two centrifugal compressors, connected in series. Although in isolation centrifugal compressors are capable of running at quite high pressure ratios (e.g. 10:1), impeller stress considerations (i.e. T3, NH implications) limit the CF pressure ratio that can be employed in high overall pressure ratio engine cycles.

Increasing overall pressure ratio implies a higher (HP) compressor exit temperature (i.e. T3). This implies a higher HP shaft speed, to maintain the datum blade tip Mach number on the rear compressor stages. Stress considerations, however, may limit shaft speed increases, leading to a reduction in the pressure ratio of the rear stages.


Combustion chamber GE J79

Combustors

Care must be taken to keep the flame burning in a moderately fast moving airstream, at all throttle conditions, as efficiently as possible. Since the turbine cannot withstand stoichiometric temperatures, resulting from the optimum combustion process, some of the compressor air is used to quench the exit temperature of the combustor to an acceptable level. Air used for combustion is considered to be primary airflow, while excess air used for cooling is called secondary airflow. Combustor configurations include can, annular, and can-annular.

Turbines


Turbine Stage GE J79

Because a turbine expands from high to low pressure, there is no such thing as turbine surge or stall. Designers must, however, prevent the turbine blades and vanes from melting in a very high temperature and stress environment. Consequently bleed air extracted from the compression system is often used to cool the turbine blades/vanes internally. Other solutions are improved materials and/or special insulating coatings.

The discs must be specially shaped to withstand the huge stresses imposed by the rotating blades. They take the form of impulse, reaction, or combination impulse-reaction shapes. Improved materials help to keep disc weight down.

Nozzles


Afterburner GE J79

Most jet engines use a simple convergent nozzle, which is relatively easy to design.

However, afterburning engines require a variable area nozzle, to maintain sensible engine matching when the afterburner is alight. This is usually accommodated by using a series of interlocking petals (driven by pneumatic or hydraulic rams) to adjust the throat area.

Even more complexity is introduced if a convergent-divergent nozzle is fitted, especially if the throat and exit areas are adjusted independently.


Afterburner nozzle

Rocket motors also employ convergent-divergent nozzles, but these are usually of fixed geometry, to minimize weight. Because of the much higher nozzle pressure ratios experienced, rocket motor con-di nozzles have a much greater area ratio (exit/throat) than those fitted to jet engines.

At the other extreme, some high bypass ratio civil turbofans use an extremely low area ratio (less than 1.01 area ratio), convergent-divergent, nozzle on the bypass (or mixed exhaust) stream, to control the fan working line. The nozzle acts as if it has variable geometry. At low flight speeds the nozzle is unchoked (less than a Mach number of unity), so the exhaust gas speeds up as it approaches the throat and then slows down slightly as it reaches the divergent section. Consequently, the nozzle exit area controls the fan match and, being larger than the throat, pulls the fan working line slightly away from surge. At higher flight speeds, the ram rise in the intake increases nozzle pressure ratio to the point where the throat becomes choked (M=1.0).

Under these circumstances, the throat area dictates the fan match and being smaller than the exit pushes the fan working line slightly towards surge. This is not a problem, since fan surge margin is much better at high flight speeds.

[See also

- Jet Engine Performance
- Jet aircraft
- Jetboat
- Turbofan
- Turbojet
- Turboprop
- Turboshaft
- Ramjet
- Spacecraft propulsion
- Supercharger
- Turbocharger
- Gas turbine
- Kurt Schreckling who built practical jet engines for model aircraft

- Wikibooks: Jet propulsion

External links

Turbofan

CFM56-3 turbofan, lower half, side view.

Boeing 747 jet engine up close

The **turbofan** is a type of airplane engine which has evolved from the axial-flow turbojet engine, essentially by increasing the relative size of the Low Pressure (LP) Compressor to the point where some (or in some cases, most) of the air exiting the unit actually bypasses the core (or gas generator). This bypass air either expands through a separate propelling nozzle, or is mixed with the hot gases leaving the Low Pressure (LP) Turbine, before expanding through a Mixed Stream Propelling Nozzle.

If the turboprop is better at moderate flight speeds and the turbojet is better at very high speeds, it might be imagined that at some speed range in the middle a mixture of the two is best. Such an engine is the turbofan (originally termed *bypass turbojet* by the inventors at Rolls Royce). Another term used is ducted fan.

The difference between a ducted fan and a propeller is that the duct slows the air before it arrives at the fan. As both propeller and fan blades must operate subsonically to be efficient, ducted fans allow efficient operation at higher vehicle speeds.

Depending on specific thrust (i.e. net thrust/intake airflow), ducted fans operate best from about 250 to 1300 mph (400 to 2000 km/h), which is why turbofans are the most common type of engine for aviation use today.

In a turbofan, the LP Compressor is often called a fan. Civil turbofans usually have a single fan stage, whereas most military turbofans have multi-stage fans.

Bypass ratio (the ratio of bypassed air mass to combustor air mass) is a parameter often used for classifying turbofans, although specific thrust is a better parameter.

The noise of any type of jet engine is strongly related to the velocity of the exhaust gases. High bypass ratio (i.e. low specific thrust) turbofans are relatively quiet compared to turbojets and low bypass ratio (i.e. high specific thrust) turbofans. A low specific thrust engine has a low jet velocity almost by definition, as the following approximate equation for net thrust implies:

$$F_n = m \cdot (V_{jfe} - V_a)$$

where:

$m =$ intake mass flow

$V_{jfe} =$ fully expanded jet velocity (in the exhaust plume)

$V_a =$ aircraft flight velocity

Rearranging the above equation, specific thrust is given by:

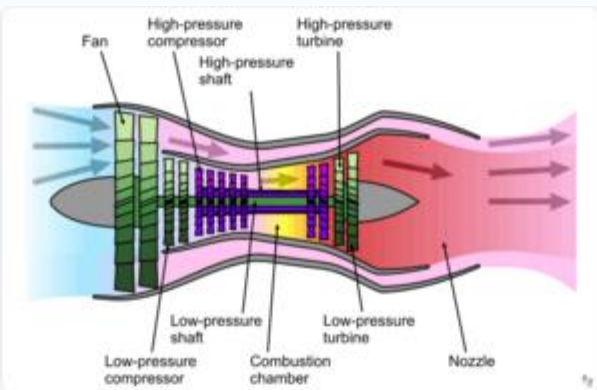
$$\frac{F_n}{m} = (V_{jfe} - V_a)$$

So for zero flight velocity, specific thrust is directly proportional to jet velocity.

Jet aircraft are often considered loud, but a conventional piston engine or a turboprop engine delivering the same power would be much louder. (NASA has a web page with details on jet noise.)

[edit]

Low-bypass turbofans



Schematic diagram illustrating a 2-spool, low-bypass turbofan engine with a mixed exhaust. The low-pressure spool is coloured green and the high-pressure one purple. The fan is driven by the low-pressure spool

Early turbojet engines were very fuel-inefficient, as their overall pressure ratio and turbine inlet temperature were severely limited by the technology available at the time. Improved materials, and the introduction of twin compressors such as in the Pratt & Whitney JT3C engine, increased the overall pressure ratio and thus the thermodynamic efficiency of engines, but led to a poor propulsive efficiency, as pure turbojets have a low mass flow, high velocity exhaust.

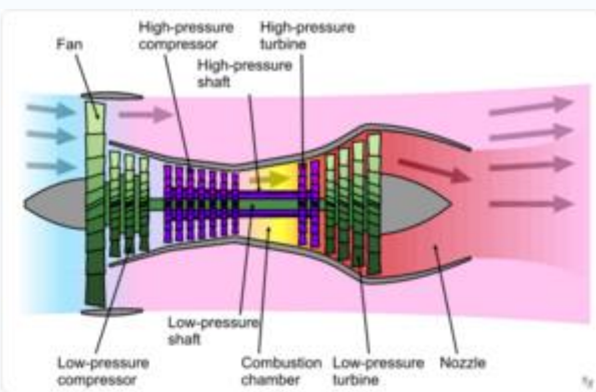
The original **low-bypass turbofan** engines were designed to improve propulsive efficiency by reducing the exhaust speed to a value closer to aircraft speeds. The Rolls-Royce Conway, the first turbofan, had a bypass ratio of 0.3, similar to the modern General Electric F404 fighter engine. Civil turbofan engines of the 1960s, such as the Pratt & Whitney JT8D and the Rolls-Royce Spey had bypass ratios close to unity. Since the 1970s, most jet fighter engines have been low-bypass turbofans with a mixed exhaust and afterburners – the first afterburning turbofan was the Pratt & Whitney TF30. A few low-bypass ratio military turbofans (e.g. F404) have Variable Inlet Guide Vanes, with piano-style hinges, to direct air onto the first rotor stage. This improves the fan surge margin (see compressor map) in the mid-flow range.

Imagine a retrofit situation where a new low bypass ratio, mixed exhaust, turbofan is replacing an old turbojet, in a particular military application. Say the new engine is to have the same airflow and net thrust (i.e. same specific thrust) as the one it is replacing. A bypass flow can only be introduced if the turbine inlet temperature is allowed to increase, to compensate for a correspondingly smaller core flow. Improvements in turbine cooling/material technology would facilitate the use of a higher turbine inlet temperature, despite increases in cooling air temperature, resulting from a probable increase in overall pressure ratio.

Efficiently done, the resulting turbofan would probably operate at a higher nozzle pressure ratio than the turbojet, but with a lower exhaust temperature to retain datum net thrust. Since the temperature rise across the whole engine (intake to nozzle) would be lower, the (dry power) fuel flow would also be reduced, resulting in a better specific fuel consumption (SFC).

Modern low-bypass military turbofans include the Pratt & Whitney F119, the Eurojet EJ200 and the General Electric F110, all of which feature a mixed exhaust, afterburner and variable area propelling nozzle. Non-afterburning engines include the Rolls-Royce/Turbomeca Adour and the unmixed, vectored thrust, Rolls-Royce Pegasus.

High-bypass turbofan engines



Schematic diagram illustrating a 2-spool, high-bypass turbofan engine with an unmixed exhaust. The low-pressure spool is coloured green and the high-pressure one purple. The fan is driven by the low-pressure spool.

The introduction of variable compressor stators enabled high pressure ratio compressors to work surge-free at all throttle settings. This innovation made its debut in the General Electric J79, a single-shaft turbojet for supersonic military aircraft. When variable stators were combined with multiple compressors, dramatic increases in overall pressure ratio became possible. Higher turbine inlet temperatures (through improvements in turbine cooling/material technology) enabled relatively small mass flow gas generators to be employed. Coupling this with significant increases in fan mass flow, made the *high-bypass turbofan'* engine feasible. Bypass ratios of 5 or more are now common.

The first high-bypass turbofan engine was the General Electric TF39, built to power the Lockheed C-5 Galaxy military transport aircraft. The civil General Electric CF6 engine used a related design. Other high-bypass turbofans are the Pratt & Whitney JT9D, the three-shaft Rolls-Royce RB211 and the CFM International CFM56. More recent large high-bypass turbofans include the Pratt & Whitney PW4000, the three-shaft Rolls-Royce Trent, the General Electric GE90, and the General Electric GEnx.

The tremendously higher thrust provided by high-bypass turbofan engines also made civil wide-body aircraft practical and economical. In addition to the vastly increased thrust, these engines are also generally quieter. This is not so much due to the higher bypass ratio, but as to the use of low pressure ratio, single stage, fans, which significantly reduce specific thrust and, thereby, jet velocity. The combination of a higher overall pressure ratio and turbine inlet temperature improves thermal efficiency. This, together with a lower specific thrust (better propulsive efficiency), leads to a lower specific fuel consumption.

For reasons of fuel economy, and also of reduced noise, almost all of today's jet airliners are powered by high-bypass turbofans. Although modern military aircraft tend to use low bypass ratio turbofans, military transport aircraft (e.g. C17) mainly use high bypass ratio turbofans (or turboprops) for fuel efficiency.

The Soviet Union's engine technology was less advanced than the West's and its first wide-body aircraft, the Ilyushin Il-86, was powered by low-bypass engines. The Yakovlev Yak-42, a medium-range, rear-engined aircraft seating up to 120 passengers was the first Soviet aircraft to use high-bypass engines.

Cycle improvements

Consider a mixed turbofan with a fixed bypass ratio and airflow. Increasing the overall pressure ratio of the compression system raises the combustor entry temperature. Therefore, at a fixed fuel flow there is an increase in turbine inlet temperature. Although the higher temperature rise across the compression system, implies a larger temperature drop over the turbine system, the mixed nozzle temperature is unaffected, because the same amount of heat is being added to the system. There is, however, a rise in nozzle pressure, because overall pressure ratio increases faster than the turbine expansion ratio, causing an increase in the hot mixer entry pressure. Consequently, net thrust increases, whilst specific fuel consumption (fuel flow/net thrust) decreases. A similar trend occurs with unmixed turbofans.

So turbofans can be made more fuel efficient by raising overall pressure ratio and turbine inlet temperature in unison. However, better turbine materials and/or improved vane/blade cooling are required to cope with increases in both turbine inlet temperature and compressor delivery temperature. Increasing the latter may require better compressor materials.

Technical Discussion

1) Specific Thrust (net thrust/intake airflow) is an important parameter for turbofans and jet engines in general. Imagine a fan (driven by an appropriately sized electric motor) operating within a pipe, which is connected to a propelling nozzle. Fairly obviously, the higher the Fan Pressure Ratio (discharge pressure/inlet pressure), the higher the jet velocity and the corresponding specific thrust. Now imagine we replace this set-up with an equivalent turbofan - same airflow and same fan pressure

ratio. Obviously, the core of the turbofan must produce sufficient power to drive the fan via the Low Pressure (LP) Turbine. If we choose a low (HP) Turbine Inlet Temperature for the gas generator, the core airflow needs to be relatively high to compensate. The corresponding bypass ratio is therefore relatively low. If we raise the Turbine Inlet Temperature, the core airflow can be smaller, thus increasing bypass ratio. Raising turbine inlet temperature tends to increase thermal efficiency and, therefore, improve fuel efficiency.

2) Naturally, as altitude increases there is a decrease in air density and, therefore, the net thrust of an engine. There is also a flight speed effect, termed Thrust Lapse Rate. Consider the approximate equation for net thrust again:

$$F_n = m \cdot (V_{jfe} - V_a)$$

With a high specific thrust (e.g. fighter) engine, the jet velocity is relatively high, so intuitively one can see that increases in flight velocity have less of an impact upon net thrust than a medium specific thrust (e.g. trainer) engine, where the jet velocity is lower. The impact of thrust lapse rate upon a low specfic thrust (e.g. civil) engine is even more severe. At high flight speeds, high specific thrust engines can pick-up net thrust through the ram rise in the intake, but this effect tends to diminish at supersonic speeds because of shock wave losses.

3) Thrust growth on civil turbofans is usually obtained by increasing fan airflow, thus preventing the jet noise becoming too high. However, the larger fan airflow requires more power from the core. This can be achieved by raising the Overall Pressure Ratio (combustor inlet pressure/intake delivery pressure) to induce more airflow into the core and by increasing turbine inlet temperature. Together, these parameters tend to increase core thermal efficiency and improve fuel efficiency.

4) Some high bypass ratio civil turbofans use an extremely low area ratio (less than 1.01), convergent-divergent, nozzle on the bypass (or mixed exhaust) stream, to control the fan working line. The nozzle acts as if it has variable geometry. At low flight speeds the nozzle is unchoked (less than a Mach Number of unity), so the exhaust gas speeds up as it approaches the throat and then slows down slightly as it reaches the divergent section. Consequently, the nozzle exit area controls the fan match and, being larger than the throat, pulls the fan working line slightly away from surge. At higher flight speeds, the ram rise in the intake increases nozzle pressure ratio to the point where the throat becomes choked (M=1.0). Under these circumstances, the throat area dictates the fan match and, being smaller than the exit, pushes the fan working line slightly towards surge. This is not a problem, since fan surge margin is much better at high flight speeds.

5) The off-design behaviour of turbofans is illustrated under compressor map and turbine map.

Recent developments in blade technology

The turbine blades in a turbofan engine are subject to high heat and stress, and require special fabrication. New material construction methods and material science have allowed blades, which were originally polycrystalline (regular metal), to be made from lined up metallic crystals and more recently mono-crystalline (i.e. single crystal) blades, which can operate at higher temperatures with less distortion.

Although turbine blade (and vane) materials have improved over the years, much of the increase in (HP) turbine inlet temperatures is due to improvements in blade/vane cooling technology.

Relatively cool air is bled from the compression system, bypassing the combustion process, and enters the hollow blade or vane. After picking up heat from the blade/vane, the cooling air is dumped into the main gas stream. If the local gas temperatures are low enough, downstream blades/vanes are uncooled and solid.

Strictly speaking, the HP Turbine Rotor Inlet Temperature (after the temperature drop across the HPT stator) is more important than the (HP) turbine inlet temperature. Although some modern military and civil engines have peak RIT's of the order of 3300R (2840F), such temperatures are only experienced for a short time (during Take-off) on civil engines.

Turbofan engine manufacturers

The turbofan engine market is dominated by General Electric, Rolls-Royce plc and Pratt & Whitney, in order of market share.

[edit]

General Electric

GE Aircraft Engines, part of the General Electric Conglomerate, currently has the largest share of the turbofan engine market. Through joint ventures CFM International and Engine Alliance, they have created the very successful CFM56 series and the new GP7200.

[edit]

Rolls-Royce

Rolls-Royce plc is the second largest manufacturer of turbofans and is most noted for their RB211 and Trent series, as well as their joint venture engines for the Airbus A320 and Boeing MD-90 families (IAE V2500), the Panavia Tornado (Turbo-Union RB199) and the Boeing 717 (BR700). As owners of the Allison Engine Company, their engines power the C-130 Hercules and several Embraer regional jets.

[edit]

Pratt & Whitney

Pratt & Whitney is behind GE and Rolls-Royce, the JT9D has the proud distinction of being chosen by Boeing to power the original 747 "Jumbo jet".

[edit]

Extreme bypass jet engines

In the 1970's Rolls-Royce/SNECMA tested a M45SD-02 turbofan fitted with variable pitch fan blades to improve handling at ultra low fan pressure ratios and to provide thrust reverse down to zero aircraft speed. The engine was aimed at ultra quiet STOL aircraft operating from city center airports.

In a bid for increased efficiency with speed, a development of the *turbofan* and *turboprop* , known as a propfan engine, was created that had an unducted fan. The fan blades are situated outside of the duct, so that it appears like a turboprop with wide scimitar-like blades. Both General Electric and Pratt & Whitney/Allison demonstrated propfan engines in the 1980's. Excessive cabin noise and relatively cheap jet fuel prevented the engines being put into service.

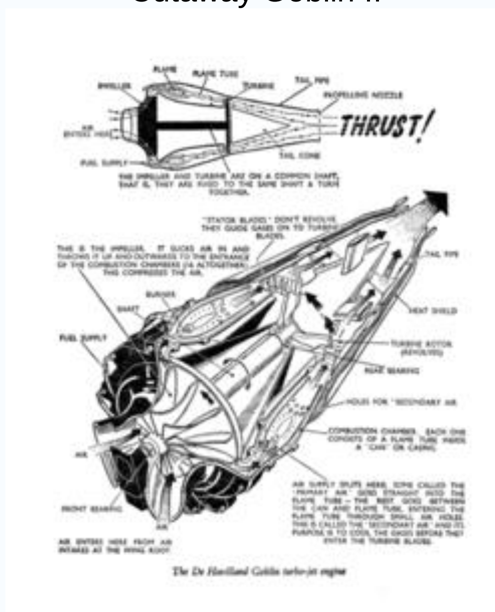
[See also

- Jet Engine Performance
- Jet aircraft
- Jetboat
- Jet Engine
- Turbojet
- Turboprop
- Turboshaft
- Ramjet
- Spacecraft propulsion
- Supercharger
- Turbocharger
- Gas turbine
- Kurt Schreckling who built practical jet engines for model aircraft

- Wikibooks: Jet propulsion

De Havilland Goblin

Cutaway Goblin II



A cutaway diagram of the internal workings of the *de Havilland Goblin*, as fitted to the *Vampire.*

The **Goblin**, originally the **Halford H-1**, was an early turbojet engine designed by Frank Halford and built by de Havilland. It was the second British engine to fly, and the first to pass tests and receive a "Gas Turbine" class type rating. It was the primary engine of the de Havilland Vampire, and was to have been the engine for the F-80 Shooting Star (as the Allis-Chalmers J36) before that design switched engines due to production delays. The Goblin also powered the SAAB 21, Fiat G.80 and De Havilland Swallow. The Goblin was later expanded into the larger De Havilland Ghost, with the model numbers continuing from the last marks of the Goblin.

Design of the engine was carried out by Frank Halford at his London consulting firm starting in April 1941. It was based on the basic layout pioneered by Frank Whittle, using a centrifugal compressor and sixteen individual flame cans. Compared to the Whittle designs it was "cleaned up" in that it used a single-sided compressor with the inlet at the front, and used a "straight through" design with the flame cans exhausting straight onto the turbine. Whittle's designs used a "reverse flow" layout that piped the hot air back to the middle of the engine, in order to "fold" it and reduce its length. Halford's changes made his engine somewhat simpler than Whittle's designs, notably allowing one of the main bearings to be removed. Nevertheless it was a fairly compact design, even without the Whittle-style "folding".

The H-1 first ran on 13 April 1942, and quickly matured to produce its full design thrust within two months. It first flew on 5 March 1943 on the Gloster Meteor, and on 20 September on the de Havilland Vampire. It was around this time that the name was changed to "Goblin".

In July 1943 an H-1 was sent to the United States, where it was selected to become the primary engine of the F-80. This engine was fitted to the prototype and first flew on 8 January, 1944. The engine was later accidentially destroyed in testing, and replaced by another H-1 from the prototype Vampire. Allis-Chalmers was selected to produce the engine in the US as the **J36**, but ran into lengthy delays. Instead General Electric was forced to give the I-40, their greatly improved 4,000 lbf version of the Rolls-Royce Derwent to Allison Engine, becoming the Allison J33.

Axial compressor

Axial compressors are compressors in which the fluid flows mainly parallel to the rotation axis. Axial flow compressors have large mass flow capacity and high efficiencies, but have a smaller pressure rise per stage than centrifugal compressors. Axial compressors are widely used in gas turbines, notably jet engines. Engines using an axial compressor are known as **axial-flow**. Almost all modern engines are axial-flow, the notable exception being those used in helicopters, where the centrifugal compressor's smaller size is useful.

Description

Axial compressors are essentially a steam turbine reversed; instead of high-pressure gas flowing into the turbine and forcing it to rotate to provide power, in the compressor role power is provided from an external source in order to spin the system and compress the gas.

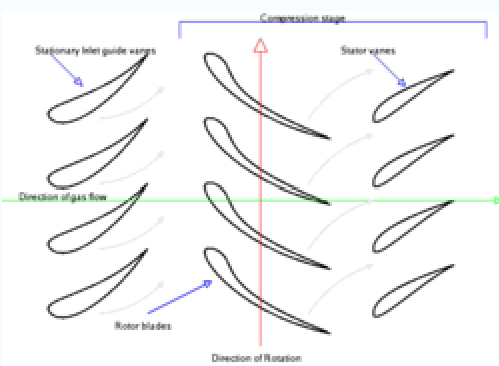


Diagram of an axial flow compressor

A typical axial compressor has a *rotor* which looks like a fan with contoured blades followed by a stationary set of blades, called a *stator*. As the diagram illustrates, compressor blades/vanes are relatively flat in section. Turbine blades/vanes, on the other hand, have significant curvature. Each pair of rotors and stators is referred to as a *stage*, and most axial compressors have a number of such stages placed in a row along a common power shaft in the center. The stator blades are required in order needed to ensure reasonable efficiency, without them the gas would rotate with the rotor blades resulting in a large drop in efficiency. Improvements can be made by replacing the stators with a second set of fans rotating in the opposite direction, but these designs have generally proven to be too complex to be worthwhile.

Each stage is smaller than the last, as the volume of air is reduced by the compression of the preceding stage. Axial compressors therefore generally have a conical shape, widest at the inlet. Compressors typically have between 9 and 15 stages.

In a jet engine the compressor is powered by a turbine placed in the hot exhaust, using up some of its energy. In such a system axial compressors typically use between 60% and 65% of the engine's power in order to run. This explains why jet engines are not used in cars; even standing still at a red light the engine would be running almost full out just to idle. In aircraft this is not an issue, as the engine is running almost full out for the entire trip.

Development

Early axial compressors offered poor efficiency, so poor that in the early 1920s a number of papers claimed that a practical jet engine would be impossible to construct. Things changed dramatically after A. A. Griffith published a seminal paper in 1926, noting that the reason for the poor performance was that existing compressors used flat blades and were essentially "flying stalled". He showed that the use of airfoils instead of the flat blades would dramatically increase efficiency, to the point where a practical jet engine was a real possibility. He concluded the paper with a basic diagram of such an engine, which included a second turbine that was used to power a propeller.

Although Griffith was well known due to his earlier work on metal fatigue and stress measurement, little work appears to have started as a direct result of his paper. The only obvious effort was a test-bed compressor built by Griffith's colleague at the RAE, Haine Constant. Other early jet efforts, notably those of Frank Whittle and Hans von Ohain, were based on the much better understood centrifugal compressor which was widely used in superchargers. Griffith had seen Whittle's work in 1929 and pooh-poohed it, noting an error in the math and going on to claim that the frontal size of the engine would make it useless on a high-speed aircraft.

Real work on axial-flow engines started in the late 1930s, in several efforts that all started at about the same time. In England, Haine Constant reached an agreement with the steam turbine company Metropolitan Vickers (Metrovick) in 1937, starting their turboprop effort based on the Griffith design in 1938. In 1940, after the successful run of Whittle's centrifugal-flow design, their effort was re-designed as a pure jet, the Metrovick F.2. In Germany, von Ohain had produced several working centrifugal engines, some of which had flown, but all short-term development efforts had moved on to Junkers and BMW, who used axial-flow designs. In the United States, both Lockheed and General Electric were awarded contracts in 1941 to develop axial-flow engines, the former a pure jet, the later a turboprop. Northrop also started their own project to develop a turboprop, which the US Navy eventually contracted in 1943. Westinghouse also entered the race in 1942, their project proving to be the only successful one of the US efforts, later becoming the J30.

By the 1950s every major engine development had moved on to the axial-flow type. As Griffith had originally noted in 1929, the large frontal size of the centrifugal compressor caused it to have higher drag than the narrower axial-flow type. Additionally the axial-flow design could improve its compression ratio simply by adding additional stages and making the engine slightly longer. In the centrifugal-flow design the compressor itself had to be larger in diameter, which was much more difficult to "fit" properly on the aircraft. On the other hand, centrifugal-flow designs remained much less complex (the major reason they "won" in the race to flying examples) and therefore have a role in places where size and streamlining are not so important. For this reason they remain a major solution for helicopter engines, where the compressor lies flat and can be built to any needed size without upsetting the streamlining to any great degree.

Axial-flow jet engines

In the jet engine application, the compressor faces a wide variety of operating conditions. On the ground at takeoff the inlet pressure is high, inlet speed zero, and the compressor spun at a variety of speeds as the power is applied. Once in flight the inlet pressure drops, but the inlet speed increases (due to the forward motion of the aircraft) to recover some of this pressure, and the compressor tends to run at a single speed for long periods of time.

There is simply no "perfect" compressor for this wide range of operating conditions. Fixed geometry compressors, like those used on early jet engines, are limited to a design pressure ratio of about 4 or 5:1. As with any heat engine, fuel efficiency is strongly related to the compression ratio, so there is very strong financial need to improve the compressor stages beyond these sorts of ratios.

Additionally the compressor may stall if the inlet conditions change abruptly, a common problem on early engines. In some cases, if the stall occurs near the front of the engine, all of the stages from that point on will stop compressing the air. In this situation the energy required to run the compressor drops suddenly, and the remaining hot air in the rear of the engine allows the turbine to speed up whole engine dramatically. This condition, known as **surging**, was a major problem on early engines and often led to the turbine or compressor breaking and shedding blades.

For all of these reasons, axial compressors on modern jet engines are considerably more complex than those on earlier designs.

Spools

All compressors have a sweet spot relating rotational speed and pressure, with higher compressions requiring higher speeds. Early engines were designed for simplicity, and used a single large compressor spinning at a single speed. Later designs added a second turbine and divided the compressor into "low pressure" and "high pressure" sections, the later spinning faster. This **two-spool** design resulted in increased efficiency. Even more can be squeezed out by adding a third spool, but in practice this has proven to be too complex to make it generally worthwhile. That said, there are several three-spool engines in use, perhaps the most famous being the Rolls-Royce RB.211, used on a wide variety of commercial aircraft.

Bleed air, variable stators

As an aircraft changes speed or altitude, the pressure of the air at the inlet to the compressor will vary. In order to "tune" the compressor for these changing conditions, designs starting in the 1950s would "bleed" air out of the middle of the compressor in order to avoid trying to compress too much air in the final stages. This was also used to help start the engine, allowing it to be spun up without compressing much air by bleeding off as much as possible. Bleed systems were already commonly used anyway, to provide airflow into the turbine stage where it was used to cool the turbine blades, as well as provide pressurized air for the air conditioning systems inside the aircraft.

A more advanced design, the **variable stator**, used blades that can be individually rotated around their axis, as opposed to the power axis of the engine. For startup they are rotated to "open", reducing compression, and then are rotated back into the airflow as the external conditions require. The General Electric J79 was the first major example of a variable stator design, and today it is a common feature of most military engines.

Closing the variable stators progressively, as compressor speed falls, reduces the slope of the surge (or stall) line on the operating characteristic (or map), improving the surge margin of the installed unit. By incorporating variable stators in the first five stages, General Electric Aircraft Engines has developed a ten-stage axial compressor capable of operating at a 23:1 design pressure ratio.

Bypass

For jet engine applications, the "whole idea" of the engine is to move air to provide thrust. In most cases the engine can actually provide much more energy than it can air; the inlet into the compressor is simply too small to move the amount of air that the engine could, in theory, heat and use.

A number of engine designs had experimented with using some of the turbine power to drive a secondary "fan" for added air flow, starting with the Metrovick F.3, which placed a fan at the rear of a late-model F.2 engine. A much more practical solution was created by Rolls-Royce in their early 1950's Conway engine, which enlarged the first compressor stage to be larger than the engine itself. This allowed the compressor to blow cold air past the interior of the engine, somewhat similar to a propeller. This technique allows the engine to be designed to produce the amount of energy needed, and any air that cannot be blown through the engine due to its size is simply blown around it. Since that air is not compressed to any large degree, it is being moved without using up much energy from the turbine, allowing a smaller core to provide the same mass flow, and thrust, as a much larger "pure jet" engine. The resultant engine is called a "turbofan."

This technique also has the added benefit of mixing the cold bypass air with the hot engine exhaust, greatly lowering the exhaust temperature. Since the sound of a jet engine is strongly related to the exhaust temperature, bypass also dramatically reduces the sound of the engine. Early jetliners from the 1960s were famous for their "screaming" sound, whereas modern engines of greatly higher power generally give off a much less annoying "whoosh" or even buzzing.

Mitigating this savings is the fact that drag increases exponentially at high speeds, so while the engine is able to operate far more efficiently, this typically translates into a smaller real-world effect. For instance, the latest Boeing 737's with high-bypass CFM56 engines operates at an overall efficiency about 30% better than the earlier models. Military turbofans, on the other hand, especially those used on combat aircraft, tend to have so low a bypass ratio that they are sometimes referred to as "leaky turbojets."

Turbine cooling

The limiting factor in jet engine design is not the compressor, but the temperature at the turbine. It is fairly easy to build an engine that can provide enough compressed air that when burnt will melt the turbine; this was a major cause of failure in early German engines. Improvements in air cooling and materials have dramatically improved the temperature performance of turbines, allowing the compression ratio of jet engines to increase dramatically. Early test engines offered perhaps 3:1 and production engines like the Jumo 004 were about 6:1, about the same as contemporary piston engines. Improvements started immediately and have not stopped; the latest Rolls-Royce Trent operates at about 40:1, far in excess of any piston engine.

Since compression ratio is strongly related to fuel economy, this eightfold increase in compression ratio really does result in an eightfold increase in fuel economy for any given amount of power, which is the reason there is strong pressure in the airline industry to use only the latest designs.

Design notes

Energy Exchange between rotor and fluid

The relative motion of the blades relative to the fluid adds velocity or pressure or both to the fluid as it passes through the rotor. The fluid velocity is increased through the rotor, and the stator converts kinetic energy to pressure energy. Some diffusion also occurs in the rotor in most practical designs.

The increase in velocity of the fluid is primarily in the tangential direction (swirl) and the stator removes this angular momentum.

The pressure rise results in a stagnation temperature rise. For a given geometry the temperature rise depends on the square of the tangential Mach number of the rotor row. Current turbofan engines have fans that operate at Mach 1.7 or more, and require significant containment and noise suppression structures to reduce blade loss damage and noise.

Velocity diagrams

The blade rows are designed at the first level using velocity diagrams. The velocity diagram shows the relative velocities of the blade rows and the fluid.

The axial flow through the compressor is kept as close as possible to Mach 1 to maximize the thrust for a given compressor size. The tangential Mach number determines the attainable pressure rise.

The blade rows turn the flow through and angle ß and larger turning allows a higher temperature ratio, but requires higher solidity.

Modern blades rows have lower aspect ratios and higher solidity.

Compressor maps

A compressor map shows the performance of a compressor and allows determination of optimal operating conditions. It shows the mass flow along the horizontal axis, typically as a percentage of the design mass flow rate, or in actual units. The pressure rise is indicated on the vertical axis as a ratio between inlet and exit stagnation pressures.

A surge or stall line identifies the boundary to the left of which the compressor performance rapidly degrades and identifies the maximum pressure ratio that can be achieved for a given mass flow. Contours of efficiency are drawn as well as performance lines for operation at particular rotational speeds.

Compression stability

Operating efficiency is highest close to the stall line. If the downstream pressure is increased beyond the maximum possible the compressor will stall and become unstable.

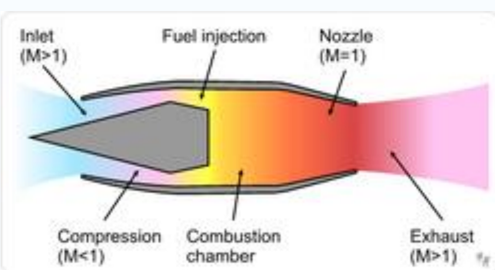
Typically the instability will be at the Helmholtz frequency of the system, taking the downstream plenum into account.

Ramjet

Small ramjet engine

A **ramjet**, sometimes referred to as a **stovepipe jet**, is a type of jet engine. The idea was patented as early as 1908 by René Lorin, but it only became reality with the works of René Leduc in France (whose work was greatly slowed down by the need to evade occupation authorities during World War II) and William Avery in the United States. Leduc's Model 010 was the first-ever ramjet-powered aircraft to fly, in 1949.

Design



Schematic diagram showing simple ramjet operation, with Mach numbers of flow shown.

In its simplest form a turbojet consists of an air intake, compressor, combustor, turbine and nozzle. In a ramjet, owing to the high flight speed, the ram compression is sufficient to dispense with the need for a compressor and a turbine to drive it. So a ramjet is virtually a 'flying stovepipe', a very simple device comprising an air intake, combustor and nozzle. Normally, the only moving parts are those within the turbopump, which pumps the fuel to the combustor.

Ramjets try to exploit the very high stagnation pressure within the streamtube approaching the air intake lip. A reasonably efficient intake will recover much of the freestream stagnation pressure, to support the combustion and expansion processes. Most ramjets operate at supersonic flight speeds and use one or more conical (or oblique) shock waves, terminated by a strong normal shock, to decelerate the airflow to a subsonic velocity at intake exit. Further diffusion is then required to get the air velocity down to level suitable for the combustor.

Since there is no downstream turbine, a ramjet combustor can safely operate at stoichiometric fuel:air ratios, which implies a combustor exit stagnation temperature of the order of 2400K for kerosene. Normally the combustor must be capable of operating over a wide range of throttle settings, for a range of flight speeds/altitudes. Usually a sheltered pilot region enables combustion to continue when the vehicle intake undergoes high yaw/pitch, during turns. Other flame stabilization techniques make use of flame holders, which vary in design from combustor cans to simple flat plates, to shelter the flame and improve fuel mixing. Overfuelling the combustor can cause the normal shock within a supersonic intake system to be pushed forward beyond the intake lip, resulting in a substantial drop in engine airflow and net thrust.

Because nozzle pressure ratios are relatively high, ramjet engines are normally fitted with a convergent/divergent propelling nozzle. Given sufficient initial flight velocity, a ramjet will be self-sustaining. Indeed, unless the vehicle drag is extremely high, the engine/airframe combination will tend to accelerate to higher and higher flight speeds, substantially increasing the air intake temperature. As this could have a detrimental effect on the integrity of the engine and/or airframe, the fuel control system must reduce engine fuel flow to stabilize the flight Mach number and, thereby, air intake temperature to sensible levels.

As a ramjet contains no (major) moving parts, it is lighter than a turbojet and can be particularly useful in applications requiring a small and simple engine for high speed use; such as missiles. They have also been used successfully, though not efficiently, as tipjets on helicopter rotors.

Flight speed

Ramjets generally give little or no thrust below about half the speed of sound, and they are inefficient (less than 600 seconds due to low compression ratios) until the airspeed exceeds 1000 km/h (600 mph). Even above the minimum speed a wide flight envelope (range of flight conditions), such as low to high speeds and low to high altitudes, can force significant design compromises, and they tend to work best optimised for one designed speed and altitude (point designs). However, ramjets tend to outperform traditional jet engine designs at supersonic speeds (mach 2-4), and although inefficient at the slower speeds, are still more fuel-efficient than rockets within the atmosphere.

Applications

They are found almost exclusively in missiles, where they are boosted to operating speeds by a rocket engine, or by being attached to another aircraft (typically a fighter).

Ramjet propulsion is used in the British Bloodhound (no longer in service) and Sea Dart surface-to-air missiles.

The Bomarc missile in the U.S. used two body pylons underneath the wings each housing a Marquardt ramjet engine capable of producing 10,000 pounds of thrust in the A version and 14,000 pounds thrust in the B version. The Bomarc served as part of the North American Defense System between 1959 and 1972.

A number of missile projects currently under development use ramjet engines to achieve better fuel efficiency (and thus longer range) at supersonic speeds than a rocket-driven approach. These include the British MBDA Meteor air-to-air missile and the Russian-Indian BrahMos supersonic cruise missile.

Related engines

Ramjets always slow the incoming air to a subsonic velocity within the combustor. Scramjets, or "supersonic combustion ramjet" are similar to Ramjets, but the air goes through the entire engine at supersonic speeds, eliminating the strong normal shock wave in the intake. This increases the stagnation pressure recovered from the freestream and improves net thrust. Owing to the hypersonic (rather than supersonic) flight speeds experienced, scramjet air intake temperatures are too high for burning kerosene, so hydrogen is normally used as the fuel. Thermal choking of the exhaust is avoided by having a relatively high supersonic air velocity at combustor entry. Fuel injection is often into a sheltered region below a step in the combustor wall. Although scramjet engines have been studied for many decades it is only recently that small experimental units have been flight tested and then only very briefly.

A variant of the pure ramjet is the 'combined cycle' engine, intended to overcome the limitations of the pure ramjet. One example of this is the SABRE engine. Another example of this is the Air Turbo Ramjet (ATR) which operates as a conventional turbojet at subsonic speeds and a fan assisted ramjet at speeds below Mach 6.

The ATREX engine developed in Japan is an experimental implementation of this concept. It uses liquid hydrogen fuel in a fairly exotic single-fan arrangement. The liquid hydrogen fuel is pumped through a heat exchanger in the air-intake, simultaneously heating the liquid hydrogen, and cooling the incoming air. This cooling of the incoming air is critical in achieving a reasonable efficiency. The hydrogen then continues through a second heat exchanger positions after the combustion section, where the hot exhaust is used to further heat the hydrogen, turning it in a very high pressure gas. This gas is then passed through the tips of the fan providing driving power to the fan at sub-sonic speeds. After mixing with the air, it's then combusted in the combustion chamber.

During the cold war, the United States designed and ground-tested a nuclear-powered ramjet called Project Pluto. This system used no combustion - instead, a nuclear reactor heated the air. The project was ultimately canceled because ICBMs seemed to serve the purpose better, and because a low-flying missile would have been highly radioactive.

The SR-71's Pratt & Whitney J58 engines act as ramjets at high-speeds (Mach 3.2).

Aircraft using ramjets

- D-21 Tagboard
- Leduc experimental aircraft
- Lockheed X-7
- Nord 1500 Griffon

See also

- Ram accelerator
- Aircraft engines
- Scramjet
- Jet Engine Performance
- Jet aircraft
- Jetboat
- Turbofan
- Turbojet
- Turboprop
- Turboshaft
- Jet engine
- Spacecraft propulsion
- Supercharger
- Turbocharger
- Gas turbine
- Kurt Schreckling who built practical jet engines for model aircraft

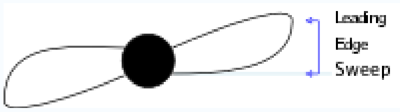
Propfan

General Electric GE-36 UDF Unducted Fan engine on a McDonnell Douglas MD-81 testbed

A **propfan** is a modified turbofan engine, with the fan placed outside of the engine nacelle on the same axis as the compressor blades. Propfans are also known as ultra-high by-pass (UHB) engines. The design is intended to offer the speed and performance of a turbofan, with the fuel economy of a turboprop.

Turboprops have a fairly strict sweet spot at speeds below about 450 mph. The reason is that all propellers lose efficiency at high speed, due to an effect known as wave drag that occurs just below supersonic speeds. This powerful form of drag has a sudden onset, and led to the concept of a sound barrier when it was first encountered in the 1940s. In the case of a propeller this effect can happen any time the prop is spun fast enough that the tips of the prop start travelling near the speed of sound, even if the plane is sitting still.

This can be controlled to some degree by adding more blades to the prop, using up more power at a lower rotational speed. This is why most WWII fighters started with two-blade props and were using five-blade designs by the end of the war. The only downside to this approach is that adding blades makes the propeller harder to balance and maintain. At some point though the forward speed of the plane combined with the rotational speed of the propeller will once again result in wave drag problems. For most aircraft this will occur at speeds over about 450 mph.



A method of decreasing wave drag was discovered by German researchers in WWII: sweeping the wing backwards. Today almost all aircraft designed to fly much above 450 mph (700 km/h) use a swept wing. In the 1970s, NASA started researching propellers with similar sweep. Since the inside of the prop is moving more slowly than the outside, the blade became progressively more swept toward the outside, leading to a curved shape similar to a scimitar.


Progress propfan on the Antonov An-70.

The propfan concept was intended to deliver 35% better fuel efficiency than contemporary turbofans, and in this they succeeded. In static and air tests on a modified DC-9, propfans reached a 30% improvement. This efficiency comes at a price, as one of the major problems with the propfan is noise, particularly in an era where aircraft are required to comply with increasingly strict Stage III and Stage IV noise requirements.

General Electric's **Unducted Fan** (**UDF**) is a variation on NASA's original propfan concept, and appears similar to a pusher propeller-driven piston engine. GE's UDF has a novel direct drive arrangement, where the reduction gearbox is replaced by a low speed 7 stage turbine. The turbine rotors drive one prop, whilst the other prop is connected to the 'unearthed' turbine stators and rotates in the opposite direction. Boeing intended to offer GE's pusher UDF engine on the 7J7 platform, and McDonnell Douglas were going to do likewise on their MD-94X airliner. Both airliners were to use rear-fuselage mounted General Electric GE-36 engines. Similar was the Antonov An-180, also powered by two rear-mounted engines, this time Progress D-27 propfans, planned for a 1995 introduction. None of the projects came to fruition, mainly because of:

a) excessive cabin noise

b) fuel prices remained low, in real terms

Antonov developed the Antonov An-70 with four Progress D-27s for Ukrainian air forces. Russian air forces ordered 164 aircraft in 2003.

Pulse jet engine

A **pulse jet engine** (or **pulsejet**) is a very simple form of internal combustion engine wherein the combustion occurs in pulses and the propulsive effort is a reaction to the rearward flow of hot gases.

A typical pulsejet comprises an air intake fitted with a one-way valve, a combustion chamber, and an acoustically resonant exhaust pipe. The valving is accomplished though the use of reed valves or, in a valveless pulse jet engine, through aerodynamics. Fuel in the form of a gas or liquid aerosol is either mixed with the air in the intake or injected into the combustion chamber. Once the engine is running it requires only an input of fuel, but it usually requires forced air and an ignition method for the fuel-air mix. Once running, the engine is self-sustaining.

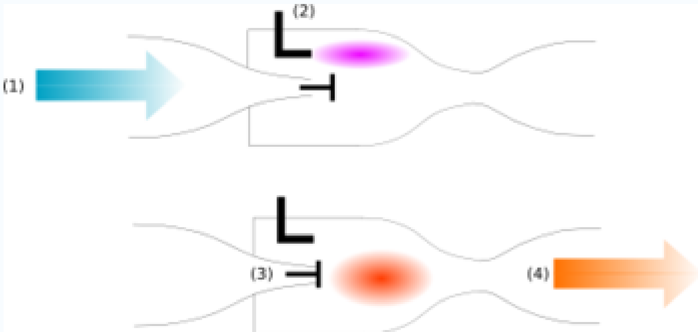
History

Martin Wiberg (1826-1905) developed the first pulse jet in Sweden.

Pulsejet engines are characterized by extreme simplicity, low cost of construction, poor fuel economy and very high noise levels. The high noise levels make them impractical for other than military applications and similarly restricted applications. Pulsejets have been used to power experimental helicopters, the engines being attached to the extreme ends of the rotor blades. One proposed design during WWII was the Focke-Wulf Fw Triebflugel, although the craft was never built. In this application they have the distinct advantage of not producing the usual reaction torque upon the fuselage and the helicopter may be built without a tail rotor and its associated transmission and drive shaft, greatly simplifying the aircraft (though it is still necessary to rotate the fuselage relative to the rotors in order to keep it pointing in one direction). Pulsejets have also been used in both tethered and radio-control model aircraft. The speed record for tethered model aircraft is 186 miles per hour (299 km/h), set in the early 1950s.

The principal military use of the pulsejet engine was in the V-1 flying bomb, the engine's characteristic droning noise earning it the nicknames "buzz bomb" or "doodlebug". The V-1 was a German cruise missile used in World War II, most famously in the bombing of London after mid-1943. Pulsejet engines, being cheap and easy to construct, were the obvious choice for the V-1's designers given the Germans' materials shortages and over-stretched industry at that stage of the war. Modern cruise missiles do not generally use pulsejet engines but true rocket or gas turbine engines.

Functioning



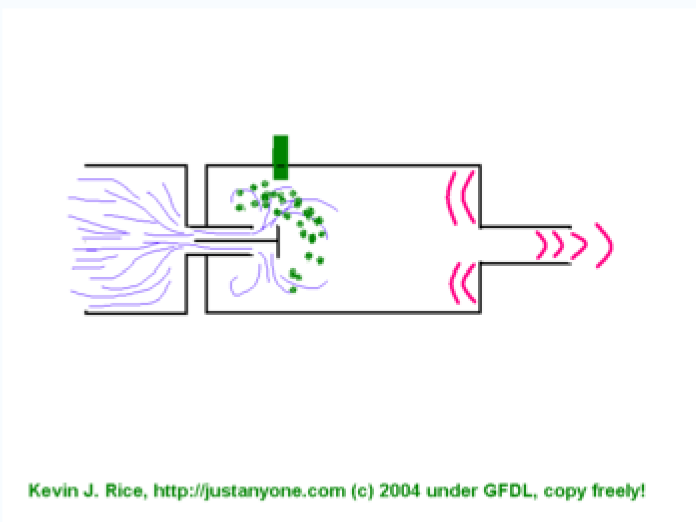
Pulse jet schematic. First part of the cycle: air intake (1), mixed with fuel (2). Second part: the valve (3) is closed and the ignited fuel-air mix (4) propels the craft.

The combustion cycle comprises six phases: Ignition, Combustion, Exhaust, Induction, Compression, and (in some engines) Fuel Injection.

Starting at ignition within the combustion chamber, a high pressure is raised by the combustion of the fuel/air mixture. The pressurized gas from combustion cannot exit forward through the one way intake valve and so exits only to the rear through the exhaust tube.

It is the inertial reaction of this gas flow that causes the engine to provide thrust, this force being used to propel an airframe or a rotor blade. The inertia of the traveling exhaust gas causes a low pressure in the combustion chamber. This pressure is less than the inlet pressure (upstream of the one-way valve), and so the induction phase of the cycle begins.

In the most simple of pulsejet engines this intake is through a venturi which causes fuel to be drawn from a fuel supply. In more complex engines the fuel may be injected directly into the combustion chamber. When the induction phase is complete a reflected high pressure wave from the tailpipe compresses the charge, which is ignited by residual heat from the previous cycle.



Pulse Jet diagram 2

There are two basic types of pulsejets. The first is known as a valved or traditional pulsejet and it has a set of one-way valves through which the incoming air passes. When the air/fuel is ignited, these valves slam shut which means that the hot gases can only leave through the engine's tailpipe, thus creating forward thrust.

The second type of pulsejet is the known as the valveless pulsejet. This name is really a misnomer. These engines have no mechanical valves, but they do have aerodynamic valves, which, for the most part, restrict the flow of gases to a single direction just as their mechanical counterparts. Indeed they have no mechanically moving parts at all and in that respect they are similar to a ramjet.

With these engines, the intake and exhaust pipes usually face the same direction. This necessitates bending the engine into a "U" shape (the Lockwood-Hiller design is made this way) or placing a 180 degree bend in the intake tube. When the air/fuel mixture inside the engine ignites, hot gases will rush out both the intake tube and the exhaust tube, since the aerodynamic valves "leak". If both tubes weren't facing in the same direction, less thrust would be generated because the reactions from the intake and exhaust gas flows would partially cancel each other. This idea was the brainchild of a French propulsion research group named S.N.E.C.M.A.

The advantage of the aerodynamically valved pulsejet is simplicity. Since there are no moving parts to wear out, they are easier to maintain and simpler to construct. However, they are more difficult to optimize.

The cycle frequency is primarily dependent on the length of the engine. For a small model-type engine the frequency may be typically around 250 pulses per second — whereas for a larger engine such as the one used on the German V1 flying bomb, the frequency was closer to 45 pulses per second.

Pulsejets survive today in target drone aircraft, model airplanes, fog generators and home heating equipment. Some experimenters continue to work on improved designs. The engines are difficult to integrate into manned aircraft design due to high fuel consumption, noise, and vibration.

See also

- Pulse detonation engine
- Valveless pulse jet

Pulse detonation engine

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A **pulse detonation engine**, or **PDE**, is a type of propulsion system that is designed primarily to be used in high-speed, high-altitude regimes. To date no practical PDE engine has been put into production, but several testbed engines have been built that have proven the basic concept. In theory the design can produce an engine with the efficiency far surpassing gas turbine with almost no moving parts.

All regular jet engines and most rocket engines operate on the *deflagration* of fuel - that is, the rapid but subsonic combustion of fuel. The pulse detonation engine is a concept currently in active development to create a jet engine that operates on the supersonic *detonation* of fuel.

The basic operation of the PDE is similar to that of the pulse jet engine; air is mixed with fuel to create a flammable mixture that is then ignited. The resulting combustion greatly increases the pressure of the mixture, which then expands through a nozzle for thrust. To ensure that the mixture exits to the rear, thereby pushing the aircraft forward, the pulsejet uses a series of shutters or careful tuning of the inlet to force the air to travel only in one direction through the engine.

The main difference between a PDE and traditional pulsejet is the way in which the airflow and combustion in the engine is controlled. In the PDE the combustion process is supersonic, effectively an explosion instead of burning, and the shock wave of the combustion front inside the fuel serves the purpose of the shutters of a pulsejet. When the shock wave reaches the rear of the engine and exits the combustion products are ejected in "one go", the pressure inside the engine suddenly drops, and air is pulled in the front of the engine to start the next cycle. Some designs require valves to make this process work properly.

The main side effect of the change in cycle is that the PDE is considerably more efficient. In the pulsejet the combustion pushes a considerable amount of the fuel/air mix (the *charge*) out the rear of the engine before it has had a chance to burn (thus the trail of flame seen on the V-1 flying bomb), and even while inside the engine the mixture's volume is continually changing, an inefficient way to burn fuel. In contrast the PDE deliberately uses a high-speed combustion process that burns all of the charge while it is still inside the engine at a constant volume, a much more efficient process. Detonation is inherently more efficient than deflagration, thus while the maximum energy efficiency of most types of jet engines is around 30%, a PDE can attain an efficiency theoretically near 50%.

Another side effect, not yet demonstrated in practical use, is the cycle time. A traditional pulsejet tops out at about 250 pulses per second, but the aim of the PDE is thousands of pulses per second, so fast that it is basically continual from an engineering perspective. This should help smooth out the otherwise highly vibrational pulsejet engine -- many small pulses will create less volume than a smaller number of larger ones for the same net thrust. Unfortunately, detonations are many times louder than deflagrations.

The major difficulty with a pulse detonation engine is starting the detonation. While it is possible to start a detonation directly with a large spark, the amount of energy input is very large and is not practical for an engine. The typical solution is to use a Deflagration-to-Detonation Transition (DDT) - that is, start a high-energy deflagration, and have it accelerate down a tube to the point where it becomes fast enough to become a detonation.

This process is far more complicated than it sounds, due to the resistance the advancing wavefront encounters (similar to wave drag). DDTs occur far more readily if there are obstacles in the tube. The most widely used is the "Shchelkin spiral", which is designed to create the most useful eddies with the least resistance to the moving fuel/air/exhaust mixture. The eddies lead to the flame separating into multiple fronts, some of which go backwards and collide with other fronts, and then accelerate into fronts ahead of them.

The behavior is difficult to model and to predict, and research is ongoing. As with conventional pulsejets, there are two main types of designs: valved and valveless. Designs with valves encounter the same hard-to-resolve wear issues encountered with their pulsejet equivalents. Valveless designs typically rely on abnormalities in the air flow to ensure a one-way flow, and are very hard to achieve a regular DDT in.

NASA maintains a research program on the PDE, which is aimed at high-speed, about mach 5, civilian transport systems. However most PDE research is military in nature, as the engine could be used to develop a new generation of high-speed, long-range reconnaissance aircraft that would fly high enough to be out of range of any current anti-aircraft defenses, while offering range considerably greater than the SR-71, which required a massive tanker support fleet to use in operation. (See Aurora aircraft)

While most research is on the high speed regime, newer designs with much higher pulse rates in the hundreds of thousands appear to work well even at subsonic speeds. Whereas traditional engine designs always include tradeoffs that limit them to a "best speed" range, the PDE appears to outperform them at all speeds. Both Pratt & Whitney and General Electric now have active PDE research programs in an attempt to commercialize the designs.

Key difficulties in pulse detonation engines are achieving DDT without requiring a tube long enough to make it impractical and drag-imposing on the aircraft; reducing the noise (often described as sounding like a jackhammer); and damping the severe vibration caused by the operation of the engine.

Scramjet

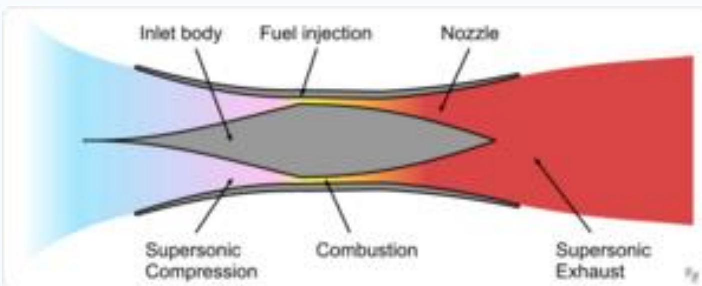


Diagram illustrating the principle of scramjet operation

A **scramjet** (**s**upersonic **c**ombustion **ramjet**) is a variation of a ramjet where the flow of the air and combustion of the fuel air mixture through the engine is done at supersonic speeds. This allows the scramjet to achieve greater speeds than a conventional ramjet which slows the incoming air to subsonic speeds before entering the combustion chamber. Projections for the top speed of a scramjet engine (without additional oxidiser input) vary between Mach 12 and Mach 24 (orbital velocity). By way of contrast, the fastest conventional air-breathing, manned vehicles, such as the U.S. Air Force SR-71, achieve slightly more than Mach 3.2.

Like a ramjet, a scramjet essentially consists of a constricted tube through which inlet air is compressed by the high speed of the vehicle, fuel is combusted, and then the exhaust jet leaves at higher speed than the inlet air. Also like a ramjet, there are few or no moving parts. In particular there is no high speed turbine as in a turbofan or turbojet engine that can be a major point of failure.

A scramjet requires supersonic airflow through the engine, thus, similar to a ramjet, scramjets have a minimum functional speed. This speed is uncertain due to the low number of working scramjets, relative youth of the field, and the largely classified nature of research using complete scramjet engines. However it is likely to be at least Mach 5 for a pure scramjet, with higher Mach numbers 7-9 more likely. Thus scramjets require acceleration to hypersonic speed via other means. A hybrid ramjet/scramjet would have a lower minimum functional Mach number, and some sources indicate the NASA X-43A research vehicle is a hybrid design. Recent tests of prototypes have used a booster rocket to obtain the necessary velocity. Air breathing engines should have significantly better specific impulse while within the atmosphere than rocket engines. However scramjets have weight and complexity issues that must be considered.

History

During and after World War II, tremendous amounts of time and effort were put into researching high-speed jet- and rocket-powered aircraft. The Bell X-1 attained supersonic flight in 1947, and by the early 1960s, rapid progress towards faster aircraft suggested that operational aircraft would be flying at "hypersonic" speeds within a few years. Except for specialized rocket research vehicles like the North American X-15 and other rocket-powered spacecraft, aircraft top speeds have remained level, generally in the range of Mach 1 to Mach 2.

In the realm of civilian air transport, the primary goal has been reducing operating cost, rather than increasing flight speeds. Because supersonic flight requires significant amounts of fuel, airlines have favored subsonic jumbo jets rather than supersonic transports. The production supersonic airliners, the Concorde and Tupolev Tu-144 operated at a financial loss (with the possible exception of British Airways that never opened the accounts). Military aircraft design focused on maneuverability and stealth, features thought to be incompatible with hypersonic aerodynamics.

Hypersonic flight concepts haven't gone away, however, and low-level investigations have continued over the past few decades. Presently, the US military and NASA have formulated a "National Hypersonics Strategy" to investigate a range of options for hypersonic flight. Other nations such as Australia, France, and Russia have also progressed in hypersonic propulsion research.

Different U.S. organizations have accepted hypersonic flight as a common goal. The U.S. Army desires hypersonic missiles that can attack mobile missile launchers quickly. NASA believes hypersonics could help develop economical, reusable launch vehicles. The Air Force is interested in a wide range of hypersonic systems, from air-launched cruise missiles to orbital spaceplanes, that the service believes could bring about a true "aerospace force."

The University of Queensland, Australia reported in 1995 the first development of a scramjet that achieved more thrust than drag[1] and in 2002 successfully tested the HyShot Scramjet system.

Simple description

A scramjet is a type of engine which is designed to operate at the high speeds normally associated with rocket propulsion. It is different from a rocket because it uses air collected from the atmosphere to burn its fuel, rather than carrying oxidiser in tanks. Normal jet engines and ramjet engines also use air collected from the atmosphere in this way. The problem is that collecting air from the atmosphere causes drag, which increases quickly as the speed increases. Also, at high speed, the air collected becomes so hot that the fuel doesn't burn properly any more.

A scramjet tries to solve both of these problems by changing the design of a ramjet. The main change is that the blockage inside the engine is reduced, so that the air isn't slowed down as much.

This means that the air is cooler, so that the fuel can burn properly. Unfortunately the higher speed of the air means that the fuel has to mix and burn in a very short time, which is difficult to achieve.

To keep the combustion of the fuel going at the same rate, the pressure and temperature in the engine need to be kept constant. Unfortunately, the blockages which were removed from the ramjet were useful to control the air in the engine, and so the scramjet is forced to fly at a particular speed for each altitude. This is called a "constant dynamic pressure path" because the wind that the scramjet feels in its face is constant, making the scramjet fly faster at higher altitude and slower at lower altitude.

The inside of a very simple scramjet would look like two kitchen funnels attached by their small ends. The first funnel is the intake, and the air is pushed through, becoming compressed and hot. In the small section, where the two funnels join, fuel is added, and the combustion makes the gas become even hotter and more compressed. Finally, the second funnel is a nozzle, like the nozzle of a rocket, and thrust is produced.

Theory

All scramjet engines have an inlet, which compresses the incoming air, fuel injectors, a combustion chamber and a thrust nozzle. Typically engines also include a region which acts as a flame holder, although the high stagnation temperatures mean that an area of focused waves may be used, rather than a discrete engine part as seen in turbine engines. An isolator between the inlet and combustion chamber is often included to improve the homogeneity of the flow in the combustor and to extend the operating range of the engine.

A scramjet is reminiscent of a ramjet. In a typical ramjet, the supersonic inflow of the engine is decelerated at the inlet to subsonic speeds and then reaccelerated through a nozzle to supersonic speeds to produce thrust. This deceleration, which is produced by a normal shock, creates a total enthalpy loss which limits the upper operating point of a ramjet engine.

Changing from subsonic to supersonic combustion, the kinetic energy of the freestream air entering the scramjet engine is large compared to the energy released by the reaction of the oxygen content of the air with a fuel (say hydrogen). Thus the heat released from combustion at Mach 25 is around 10% of the total enthalpy of the working fluid. Depending on the fuel, the kinetic energy of the air and the potential combustion heat release will be equal at around Mach 8. Thus the design of a scramjet engine is as much about minimising drag as maximising thrust.

This high speed makes the control of the flow within the combustion chamber more difficult. Since the flow is supersonic, no upstream influence propagates within the freestream of the combustion chamber. Thus throttling of the entrance to the thrust nozzle is not a usable control technique. In effect, a block of gas entering the combustion chamber must mix with fuel and have sufficient time for initiation and reaction, all the while travelling supersonically through the combustion chamber, before the burned gas is expanded through the thrust nozzle. This places stringent requirements on the pressure and temperature of the flow, and requires that the fuel injection and mixing be extremely efficient. Usable dynamic pressures lie in the range 0.2-2 bar, where (Dynamic pressure)=0.5 x (density) x (velocity)^2

The minimum Mach number at which a scramjet can operate is limited by the fact that the compressed flow must be hot enough to burn the fuel, and of high enough pressure that the reaction is finished before the air moves out the back of the engine. Additionally, in order to be called a scramjet, the compressed flow must still be supersonic after combustion. Here two limits must be observed: Firstly, since when a supersonic flow is compressed it slows down, the level of compression must be low enough (or the initial speed high enough) not to slow down the gas below Mach 1. If the gas within a scramjet goes below Mach 1 the engine will "choke", transitioning to subsonic flow in the combustion chamber. This effect is well known amongst experimenters on scramjets since the waves caused by choking are easily observable. Additionally, the sudden increase in pressure and temperature in the engine can lead to an acceleration of the combustion, leading to the combustion chamber exploding.

Secondly, the heating of the gas by combustion causes the speed of sound in the gas to increase (and the Mach number to decrease) even though the gas is still travelling at the same speed. Forcing the speed of air flow in the combustion chamber under Mach one in this way is called "thermal choking". It is clear that a pure scramjet can operate at Mach numbers of 6-8 (e.g [1]), but in the lower limit, it depends on the definition of a scramjet. Certainly there are designs where a ramjet transforms into a scramjet over the Mach 3-6 range[5] (Dual-mode scramjets). In this range however, the engine is still receiving significant thrust from subsonic combustion of "ramjet" type.

The high cost of flight testing and the unavailability of ground facilities have hindered scramjet development. A large amount of the experimental work on scramjets has been undertaken in cryogenic facilities, direct-connect tests, or burners, each of which simulates one aspect of the engine operation. Further, vitiated facilities, storage heated facilities, arc facilities and the various types of shock tunnels each have limitations which have prevented perfect simulation of scramjet operation. The HyShot flight test showed the relevance of the 1:1 simulation of conditions in the T4 and HEG shock tunnels, despite having cold models and a short test time. The NASA-CIAM tests provided similar verification for CIAM's C-16 V/K facility and the Hyper-X project is expected to provide similar verification for the Langley AHSTF, CHSTF and 8 Ft HTT.

Computational fluid dynamics has only recently reached a position to make reasonable computations in solving scramjet operation problems. Boundary layer modeling, turbulent mixing, two-phase flow, flow separation, and real-gas aerothermodynamics continue to be problems on the cutting edge of CFD. Additionally, the modeling of kinetic-limited combustion with very fast-reacting species such as hydrogen makes severe demands on computing resources. Reaction schemes are numerically stiff, having typical times as low as 10^{-19} seconds, requiring reduced reaction schemes.

Much of scramjet experimentation remains classified. Several groups including the US Navy with the SCRAM engine between 1968-1974, and the Hyper-X program with the X-43A have claimed successful demonstrations of scramjet technology. Since these results have not been published openly, they remain unverified and a final design method of scramjet engines still does not exist.

The final application of a scramjet engine is likely to be in conjunction with engines which can operate outside the scramjet's operating range. Dual-mode scramjets combine subsonic combustion with supersonic combustion for operation at lower speeds, and rocket-based combined cycle (RBCC) engines supplement a traditional rocket's propulsion with a scramjet, allowing for additional oxidizer to be added to the scramjet flow.

Applications

Seeing its potential, organizations around the world are researching scramjet technology. Scramjets will likely propel missiles first, since that application requires only cruise operation instead of net thrust production. Much of the money for the current research comes from governmental defence research contracts.

Space launch vehicles may or may not benefit from having a scramjet stage. A scramjet stage of a launch vehicle theoretically provides a specific impulse with 1000 to 4000 s whereas a rocket provides less than 600 s while in the atmosphere[23], potentially permitting much cheaper access to space. However, a scramjet's specific impulse decreases rapidly with speed, as the vehicle exhibits increased drag.

One issue is that scramjet engines are predicted to have exceptionally poor thrust to weight ratio- around 2 [4]. This compares **very** unfavourably with the 50-100 of a typical rocket engine. This is compensated for in scramjets partly because the weight of the vehicle would be carried by aerodynamic lift rather than pure rocket power (giving reduced 'gravity losses'), but scramjets would take much longer to get to orbit due to lower thrust which greatly offsets the advantage. The takeoff weight of a scramjet vehicle is significantly reduced over that of a rocket, due to the lack of onboard oxidiser, but increased by the structural requirements of the larger and heavier engines.

Whether this vehicle would be reusable or not is still a subject of debate and research.

An aircraft using this type of jet engine could dramatically reduce the time it takes to travel from one place to another, potentially putting any place on Earth within a 90 minute flight. However, there are questions about whether such a vehicle could carry enough fuel to make useful length trips, and there are obvious issues with sonic booms and acceptable g-loads on passengers.

Recent progress

In recent years, significant progress has been made in the development of hypersonic technology, particularly in the field of scramjet engines. While American efforts are probably the best funded, the first to demonstrate a scramjet working in an atmospheric test was a shoestring project by an Australian team at the University of Queensland. The university's HyShot project demonstrated scramjet combustion in 2002. This demonstration was somewhat limited, however; while the scramjet engine worked effectively and demonstrated supersonic combustion in action, the engine was not designed to provide thrust to propel a craft.

The US Air Force and Pratt and Whitney have cooperated on the Hypersonic Technology (HyTECH) scramjet engine, which has now been demonstrated in a wind-tunnel environment. NASA's Marshall Space Propulsion Center has introduced an Integrated Systems Test of an Air-Breathing Rocket (ISTAR) program, prompting Pratt & Whitney, Aerojet, and Rocketdyne to join forces for development.

To coordinate hypersonic technology development, the various factions interested in hypersonic research have formed two integrated product teams (IPTs): one to consolidate Army, Air Force, and Navy hypersonic weapons research, the other to consolidate Air Force and NASA space transportation and hypersonic aircraft work. Current funding levels are relatively low, no more than US $85 million per year in total, but are expected to rise.

The most advanced US hypersonics program is the US $250 million NASA Langley Hyper-X X-43A effort, which flew small test vehicles to demonstrate hydrogen-fueled scramjet engines. NASA is working with contractors Boeing, Microcraft, and the General Applied Science Laboratory (GASL) on the project.

The NASA Langley, Marshall, and Glenn Centers are now all heavily engaged in hypersonic propulsion studies. The Glenn Center is taking leadership on a Mach 4 turbine engine of interest to the USAF. As for the X-43A Hyper-X, three follow-on projects are now under consideration:

- X-43B: A scaled-up version of the X-43A, to be powered by the ISTAR engine. ISTAR will use a hydrocarbon-based liquid-rocket mode for initial boost, a ramjet mode for speeds above Mach 2.5, and a scramjet mode for speeds above Mach 5 to take it to maximum speeds of at least Mach 7. A version intended for space launch could then return to rocket mode for final boost into space. ISTAR is based on a proprietary Aerojet design called a "strutjet", which is currently undergoing wind-tunnel testing.

- X-43C: NASA is in discussions with the Air Force on development of a variant of the X-43A that would use the HyTECH hydrocarbon-fueled scramjet engine.

While most scramjet designs to date have used hydrogen fuel, HyTech runs on conventional kerosene-type hydrocarbon fuels, which are much more practical for support of operational vehicles. A full-scale engine is now being built, which will use its own fuel for cooling. Using fuel for engine cooling is nothing new, but the cooling system will also act as a chemical reactor, breaking long-chain hydrocarbons down into short-chain hydrocarbons that burn more rapidly.

- X-43D: A version of the X-43A with a hydrogen-powered scramjet engine with a maximum speed of Mach 15.

Hypersonic development efforts are also in progress in other nations. The French are now considering their own scramjet test vehicle and are in discussions with the Russians for boosters that would carry it to launch speeds. The approach is very similar to that used with the current NASA X-43A demonstrator.

Several scramjet designs are now under investigation with Russian assistance. One of these options or a combination of them will be selected by ONERA, the French aerospace research agency, with the EADS conglomerate providing technical backup. The notional immediate goal of the study is to produce a hypersonic air-to-surface missile named "Promethee", which would be about 6 meters (20 ft) long and weigh 1,700 kilograms (3,750 lb).

Scramjet programmes

HyShot

On July 30, 2002, the University of Queensland's HyShot team conducted the first ever test successful flight of a scramjet.

The team took a unique approach to the problem of accelerating the engine to the necessary speed by using an Terrier-Orion sounding rocket to take the aircraft up on a parabolic trajectory to an altitude of 314 km. As the craft re-entered the atmosphere, it dropped to a speed of Mach 7.6. The scramjet engine then started, and it flew at about Mach 7.6 for 6 seconds. [1]. This was achieved on a lean budget of just A$1.5 million (US $1.1 million), a tiny fraction of NASA's US $250 million to develop the X-43A.

NASA has partially explained the tremendous difference in cost between the two projects by pointing out that the American vehicle has an engine fully incorporated into an airframe with a full complement of flight control surfaces available.

No net thrust was achieved. (The thrust was less than the drag.)

Hyper-X

NASA's Hyper-X program is the successor to the National Aerospace Plane (NASP) program which was cancelled in November 1994. This program involves flight testing through the construction of the X-43 vehicles. NASA first successfully flew its X-43A scramjet test vehicle on March 27, 2004 (an earlier test, on June 2, 2001 went out of control and had to be destroyed). Unlike the University of Queensland's vehicle, it took a horizontal trajectory. After it separated from its mother craft and booster, it briefly achieved a speed of 5,000 miles per hour (8,000 km/h), the equivalent of Mach 7, easily breaking the previous speed record for level flight of an air-breathing vehicle. Its engines ran for eleven seconds, and in that time it covered a distance of 15 miles (24 km). The *Guinness Book of Records* certified the X-43A's flight as the current Aircraft Speed Record holder on 30 August 2004. The third X-43 flight set a new speed record of 6,600 mph (10,621 km/h), nearly Mach 10 on 16 November 2004. It was boosted by a modified Pegasus rocket which was launched from a Boeing B-52 at 13,157 meters (40,000 feet). After a free flight where the scramjet operated for about ten seconds the craft made a planned crash into the Pacific ocean off the coast of southern California. The X-43A craft were designed to crash into the ocean without recovery. Duct geometry and performance of the X-43 are classified.

Russia and France (and NASA)

On November 17, 1992, Russian scientists with some additional French support successfully launched a scramjet engine in Kazakhstan[5]. From 1994 to 1998 NASA worked with the Russian central institute of aviation motors (CIAM) to test a dual-mode scramjet engine. Four tests took place, reaching Mach numbers of 5.5, 5.35, 5.8, and 6.5. The final test took place aboard a modified SA-5 surface to air missile launched from the Sary Shagan test range in the Republic of Kazakhstan on 12 February 1998. Data regarding whether the internal combustion took place in supersonic air streams was inconclusive, according to NASA. No net thrust was achieved.

GASL projectile

At a test facility at Arnold Air Force Base in the U.S. state of Tennessee, GASL fired a projectile equipped with a hydrocarbon-powered scramjet engine from a large gun. On July 26, 2001, the four inch (100 mm) wide projectile covered a distance of 260 feet (79 m) in 30 milliseconds (roughly 5,900 mph or 9,500 km/h). The projectile is supposedly a model for a missile design. Many do not consider this to be a scramjet "flight," as the test took place near ground level. However, the test environment was described as being very realistic.

Scramjet in the movies

The movie "Starflight: The Plane That Couldn't Land" (see cross reference under "Airport") explores the concept of a hypersonic jetliner for passenger transportation, developed by the fictional company Thornwall Aviation. The jetliner uses scramjet engines to reach a point high in the stratosphere for a quick two-hour jump from Los Angeles to Sydney, Australia, and the engines are powered with hydrogen. NASA is accustomed to handling this fuel, and a NASA space shuttle handles a refuelling job while the jetliner is (accidentally) stuck in orbit.

In the 2005 movie "Stealth" the UCAV (Unmanned Combat Aerial Vehicle) named "EDI" (Extreme deep invader) is powered by two Scramjets as booster engines.

Specific impulse

The **specific impulse** (commonly abbreviated I_{sp}) of a propulsion system is the impulse (change in momentum) per unit of propellant.

Depending on whether the amount of propellant is expressed in mass or in weight (by convention weight on the Earth) the dimension of specific impulse is that of speed or time, respectively, differing by a factor of g, the gravitational acceleration at the surface of the Earth.

General considerations

Essentially, the higher the specific impulse, the less propellant is needed to gain a given amount of momentum. In this regard a propulsion method is more fuel-efficient if the specific impulse is higher. This should not in any way be confused with energy-efficiency, which can even decrease as specific impulse increases, since many propulsion systems that give high specific impulse require high energy to do so.

In addition it is important that thrust and specific impulse not be confused with one another. The specific impulse is a measure of the *thrust per unit of propellant* that is expelled, while thrust is a measure of the momentary or peak force supplied by a particular engine. In fact, propulsion systems with very high specific impulses (such as ion thrusters: 3,000 seconds) are power limited to producing low thrusts, due to the relatively high weight of power generators.

When calculating specific impulse, only propellant that is carried with the vehicle before use is counted. For a chemical rocket the propellant mass therefore would include both fuel and oxidizer; for air-breathing engines only the mass of the fuel is counted, not the mass of air passing through the engine.

Examples

Specific impulse of various propulsion technologies

Engine	"C" eff. exhaust velocity (N·s/kg or m/s)	**Specific impulse** (s)	Fuel mass (kg)	Energy expended (GJ)
Jet engine	30,000	3,000	50,000	2135
Solid rocket	2,000	200	190,000	95
Bipropellant rocket	4,500	450	8,200	103
Ion thruster	30,000	3,000	620	775
VASIMR	300,000	30,000	100	4,500

An example of a specific impulse measured in time is 459 seconds, or, equivalently, an effective exhaust velocity of 4500 m/s, for the Space Shuttle Main Engines when operating in vacuum.

An air-breathing engine typically has a much larger specific impulse than a rocket: a jet engine may have a specific impulse of 2000-3000 seconds or more at sea level.

In some ways, comparing specific impulse seems unfair in the case of jet engines and rockets. However in rocket or jet powered aircraft, specific impulse is approximately proportional to range, and rockets do indeed perform much worse than jets at sea level.

The highest specific impulse for a chemical propellant ever test-fired in a rocket engine was lithium, fluorine, and hydrogen (a tripropellant): 542 seconds (5320 m/s). However, the combination is impractical, see rocket fuel.

Nuclear thermal rocket engines differ from conventional rocket engines in that thrust is created strictly through thermodynamic phenomena, with no chemical reaction. The nuclear rocket typically operates by passing hydrogen gas over a superheated nuclear core. Testing in the 1960s yielded specific impulses of about 850 seconds (8340 m/s), about twice that of the Space Shuttle engines.

A variety of other non-rocket propulsion methods, such as ion thrusters, give much higher specific impulse but with much lower thrust; for example the Hall effect thruster on the Smart 1 satellite has a specific impulse of 1640 s (16100 m/s) but a maximum thrust of only 68 millinewtons. The hypothetical Variable specific impulse magnetoplasma rocket(VASIMR) propulsion should yield a minimum of 10,000-300,000 m/s but will probably require a great deal of heavy machinery to confine even relatively diffuse plasmas, so they will be unusable for very-high-thrust applications such as launch from planetary surfaces.

Specific impulse in seconds

For all vehicles specific impulse (impulse per unit weight-on-Earth of propellant) in seconds can be defined by the following equation:

$$\text{Thrust} = I_{\text{sp}} \cdot \frac{dm}{dt} \cdot g_0$$

where:

Thrust is the thrust obtained from the engine.

I_{sp} is the specific impulse measured in seconds.

$\frac{dm}{dt}$ is the mass flow rate, which is minus the time-rate of change of the vehicle's mass, since fuel is being expelled.

g_0 is the acceleration at the Earth's surface.

This I_{sp} in seconds value is somewhat physically meaningful - it is the number of seconds a unit weight of fuel would last if the engine would apply a unit force (if an engine could be scaled proportionately). As such it is a value that can be used to compare engines; much like 'miles per gallon' is for cars.

The advantage that this formulation has is that it may be used for rockets, where all the reaction mass is carried onboard, as well as aeroplanes, where most of the reaction mass is taken from the atmosphere. In addition, it gives a result that is independent of units used (provided the unit of time used is the second).

Rocketry - specific impulse in seconds

In rocketry, where the only reaction mass is the propellent, an equivalent way of calculating the specific impulse in seconds is also frequently used. In this sense, specific impulse is defined as the change in momentum per unit weight-on-Earth of the propellent:

$$I_{\text{sp}} = \frac{v_{\text{e}}}{g_0}$$

where

I_{sp} is the specific impulse measured in seconds

v_e is the average exhaust speed along the axis of the engine

g_0 is the acceleration at the Earth's surface

It may seem odd that the acceleration or weight at the Earth's surface is in the definition, while the rocket may be far from the Earth. However, accelerations are often measured in terms of $\mathbf{g_0}$; for example, astronauts should not be subjected to an acceleration more than a few times this value. Additionally, in Imperial units the relationship between force and mass is defined to involve the acceleration due to gravity. Thus pounds (force) and pounds (mass), both used in rocketry, when divided, must be additionally multiplied by $\mathbf{g_0}$ to get the acceleration in more usual units.

The official Imperial unit of mass the *slug*, which is not popular for obvious reasons, was introduced to make Imperial units more like the SI units and avoid this multiplication. This, the common use of pounds for both force and mass, is in fact the chief reason $\mathbf{g_0}$ enters so often into rocketry definitions, and is likely the reason two definitions of specific impulse are in common use.

When expressed in units of seconds, the specific impulse can be interpreted in the following ways:

- the impulse divided by the sea-level weight of a unit mass of propellant
- the time one kilogram of propellant lasts if a force equal to the weight of one kilogram is produced, for example for a hypothetical hovering over the Earth (imagine the fuel to be supplied from outside, so that the mass on which the thrust is applied does not reduce by spending fuel)
- the time one pound mass of propellant lasts if a force of one pound is produced, for example for a hypothetical hovering vehicle over the Earth (imagine the fuel to be supplied from outside, so that the mass on which the thrust is applied does not reduce by spending fuel)
- alternatively, for engines that can not produce a large thrust: approximately the time one kilogram of propellant lasts if an acceleration of 0.01 *g* of a mass of one 100 kilogram is produced
- 100 times the time an acceleration *g* can be produced (i.e. a thrust equal to the weight on Earth of the current mass) with a propellant mass of 1 % of the current total mass (100 times the time it takes in this case to reduce the total mass by 1 %)
- the time an acceleration *g* can be produced with a propellant mass of 63.2 % of the initial total mass (the time it takes in this case to reduce the total mass by a factor e, to 36.8 %)
- twice the net power to produce an acceleration of 1 m/s^2 to a mass which at Earth has a weight of 1 N (i.e. a mass of 102 grams)

e.g. for hydrogen/oxygen, with a specific impulse of 460 seconds (4500 m/s):

- one kilogram of propellant lasts 460 seconds if an acceleration *g* of a mass of one kilogram is produced
- one kilogram of propellant lasts 460 seconds if an acceleration of 0.01 *g* of a mass of 100 kilogram is produced
- it takes 4.6 seconds to reduce the total mass by 1 % if an acceleration *g* is produced
    - an acceleration *g* during 460 seconds can be produced with a propellant mass of 63.2 % of the initial total mass (it is the time it takes in this case to reduce the total mass by a factor e, to 36.8 %)
- the net power to produce an acceleration of 1 m/s^2 to a mass of 102 grams is 230 W.

The reason why the specific impulse of a turbo fan is so large is because the atmosphere provides the oxidant, so the plane does not carry it. A very simplified example can make this point clear: Lets look at a hydrogen based engine:

The ideal reaction is: $2H_2+O_2 \longrightarrow 2H_2O$ +467kJ/mol If the O_2 came from a tank in a rocket the specific gives (again over-simplificated)

$\frac{mv^2}{2} = 467kJ$. Where the mass is 18g (2*H+O, 2g/mole+16g/mole)

Solving for **v** , we get: 5093m/s about 5000 under ideal conditions (ejection temperature 0K) In case that we don't have to carry the oxygen the mass is now 2g, but energy **still** is 467kJ, so we know get: 15280m/s. We can improve that by pushing great amounts of non-combustion air. This is possible because the Energy is proportional to the square power of the ejection speed but the "force" is proportional to the speed. The presence of nitrogen makes things even better. If we see the diagrams of big, efficient turbo fans we will see that this is important part of the optimization guides. (http://anirudh.net/seminar/ge90.pdf by example)

Rocketry - specific impulse as a speed (effective exhaust velocity)

In rocketry the specific impulse as the impulse per unit mass of propellant used is simply the effective exhaust velocity:

$$I_{\mathrm{sp}} = v_{\mathrm{e}}$$

where

I_{sp} is the specific impulse, as defined above, and measured in metres per second (in the U.S. feet/second).

v_e is the effective exhaust velocity measured in metres per second.

It is related to the thrust, or forward force on the rocket by the equation:

$$\mathrm{Thrust} = I_{\mathrm{sp}} \cdot \frac{dm}{dt}$$

where

$\frac{dm}{dt}$ is the mass flow rate, which is minus the time-rate of change of the vehicle's mass, since fuel is being expelled.

A rocket must carry all its fuel with it, so the mass of the unburned fuel must be accelerated along with the rocket itself. Minimizing the mass of fuel required to achieve a given push is crucial to building effective rockets. Using Newton's laws of motion it is not difficult to verify that for a fixed mass of fuel, the total change in velocity (in fact, momentum) it can accomplish can only be increased by increasing the exhaust velocity.

A spacecraft without propulsion follows an orbit determined by the gravitational field. Deviations from the corresponding velocity pattern (these are called delta-v) are achieved by sending exhaust mass in the direction opposite to that of the desired velocity change.

Due to the law of conservation of momentum, to change the speed of the spacecraft by an amount equal to 1% of the exhaust speed, approximately requires an exhaust mass equal to 1% of the mass of the spacecraft, including the fuel that has not yet been spent.

As a useful rule of thumb the delta-v that can be produced with a propellant mass of 63.2 % of the initial total mass is equal to the exhaust velocity (see Rocket equation.)

The speed is also approximately twice the power per unit thrust

For a delta-v that is much smaller than the specific impulse, the fuel required is approximately proportional to the delta-v. For a delta-v that is larger than the specific impulse, this requirement of carrying the fuel and spending much of the fuel on accelerating the fuel, gives rise to an exponential increase in fuel requirement (and larger tanks which also add to the mass). See spacecraft propulsion calculations and Tsiolkovsky rocket equation for details.

e.g for hydrogen/oxygen, with a specific impulse of 4500 m/s (460 seconds):

- the effective exhaust speed is 4,500 m/s
- the impulse produced per unit mass of propellant used is 4,500 N·s per kg
- the thrust is 4,500 N if the propellant mass flow rate is 1 kg/s
- the delta-v that can be produced with a propellant mass of 1 % of the current total mass (the delta-v that reduces the mass by 1%) is 45 m/s
- the delta-v that can be produced with a propellant mass of 63.2 % of the initial total mass (the delta-v that reduces the total mass by a factor e, to 36.8 %) is 4,500 m/s
- the power-thrust ratio is 2,250 W/N

Mach number

Mach number (*Ma*) (pronounced "mack" in British English and "mock" in American English) is defined as a ratio of speed to the speed of sound in the medium in case. The Mach number is commonly used both with objects travelling at high speed in a fluid, and with high-speed fluid flows inside channels such as nozzles, diffusers or wind tunnels. As it is defined as a ratio of two speeds, it is a dimensionless number. At standard sea level conditions, Mach 1 is 1,225 km/h (761.2 MPH) in the atmosphere.

Since the speed of sound increases as the temperature increases, the actual speed of an object travelling at Mach 1 will depend on the fluid temperature around it.

It can be shown that the Mach number is also the ratio of inertial forces (also referred to aerodynamic forces) to elastic forces.

The Mach number is named after Austrian physicist and philosopher Ernst Mach.

High-speed flow around objects

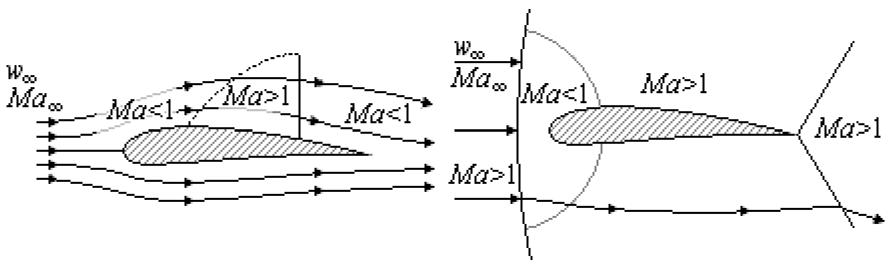
High speed flight can be classified in five categories:

- **Subsonic:** Ma < 1
- **Sonic:** Ma = 1
- **Transonic:** 0.8 < Ma < 1.3
- **Supersonic:** 1.2 < Ma < 5
- **Hypersonic:** Ma > 5

(For comparison: the required speed for low Earth orbit is ca. 7.5 km/s = Ma 22.06 in air at sea level)

At transsonic speeds, the flow field around the object includes both sub- and supersonic parts. The transsonic regime begins when first zones of Ma>1 flow appear around the object. In case of an airfoil (such as an aircraft's wing), this typically happens above the wing. Supersonic flow can decelerate back to subsonic only in a normal shock; this typically happens before the trailing edge. (Fig.1a)

As the velocity increases, the zone of *Ma*>1 flow increases towards both leading and trailing edges. As *Ma*=1 is reached and passed, the normal shock reaches the trailing edge and becomes a weak oblique shock: the flow decelerates over the shock, but remains supersonic. A normal shock is created ahead of the object, and the only subsonic zone in the flow field is a small area around the object's leading edge. (Fig.1b)



(a) (b)

Fig. 1. *Mach number in transsonic airflow around an airfoil; Ma<1 (a) and Ma>1 (b).*

When an aircraft exceeds Mach 1 (i.e. the sound barrier) a large pressure difference is created just in front of the aircraft. This abrupt pressure difference, called a shock wave, spreads backward and outward from the aircraft in a cone shape (a so-called Mach cone). It is this shock wave that causes the sonic boom heard as fast moving aircraft travels overhead. A person inside the aircraft will not hear this. The higher the speed, the more narrow the cone; at just over *Ma*=1 it is hardly a cone at all, but closer to a slighly concave plane.

At fully supersonic velocity the shock wave starts to take its cone shape, and flow is either completely supersonic, or (in case of a blunt object), only a very small subsonic flow area remains between the object's nose and the shock wave it creates ahead of itself. (In the case of a sharp object, there is no air between the nose and the shock wave: the shock wave starts from the nose.)

As the Mach number increases, so does the strength of the shock wave and the Mach cone becomes increasingly narrow. As the fluid flow crosses the shock wave, its speed is reduced and temperature, pressure, and density increase. The stronger the shock, the greater the changes. At high enough Mach numbers the temperature increases so much over the shock that ionization and dissociation of gas molecules behind the shock wave begin. Such flows are called hypersonic.

It is clear that any object travelling at hypersonic velocities will likewise be exposed to the same extreme temperatures as the gas behind the nose shock wave, and hence choice of heat-resistant materials becomes important.

High-speed flow in a channel

As a flow in a channel crosses *Ma*=1 becomes supersonic, one significant change takes place. Common sense would lead one to expect that contracting the flow channel would increase the flow speed and at subsonic speeds this holds true. However, once the flow becomes supersonic, the relationship of flow area and speed is reversed: expanding the channel actually increases the speed.

The obvious result is that in order to accelerate a flow to supersonic, one needs a convergent-divergent nozzle, where the converging section accelerates the flow to *Ma*=1, and the diverging section continues the acceleration to supersonic. Such nozzles are called De Laval nozzles.

Afterburner (engine)

An afterburner injects fuel into the path of the hot exhaust gases to provide extra thrust.

Pratt & Whitney J58 engine on testbed with full afterburner

SR-71 in flight with J58 on full afterburner

SR-71 in flight without afterburner

An **afterburner** is an additional component added to some jet engines, primarily those on military aircraft. In British English, it is sometimes called a **reheat jetpipe**.

Design

A jet engine afterburner is an extended exhaust section containing extra fuel injectors, and since the jet engine upstream will use little of the oxygen it ingests, the afterburner is, at its simplest, a type of ramjet. When the afterburner is turned on, fuel is injected, which ignites readily, owing to the relatively high temperature of the incoming gases. The resulting combustion process increases the afterburner exit (nozzle entry) temperature significantly, resulting in a steep increase in engine net thrust. It should be noted that the nozzle throat area must be increased to accommodate the resulting increase in afterburner exit volume flow, otherwise the upstream turbomachinery will rematch (probably causing fan surge in a turbofan application).

Limitations

Due to their high fuel consumption, afterburners are not used for extended periods (a notable exception is the Pratt & Whitney J58 engine used in the SR-71 Blackbird). Thus, they are only used when it is important to have as much thrust as possible. This includes takeoffs from short runways (as on an aircraft carrier) and air combat situations.

Efficiency

One should note that since the exhaust gas already has reduced oxygen due to previous combustion, and since the fuel is not burning in a highly compressed air column, it is fairly inefficient compared with that of the main combustor. Afterburner efficiency also declines significantly as the tailpipe pressure decreases with increasing altitude.

Afterburners do, however, produce markedly enhanced thrust as well as (typically) a very large, impressive flame at the back of the engine. This exhaust flame may show *shock-diamonds*, which are caused by shock waves being formed due to the turbulent exhaust stream being ejected at a velocity greater than the speed of sound.

Influence on cycle choice

Afterburning has a significant influence upon engine cycle choice.

Lowering fan pressure ratio decreases specific thrust (both dry and afterburning), but results in a lower temperature entering the afterburner. Since the afterburning exit temperature is effectively fixed, the temperature rise across the unit increases, raising the afterburner fuel flow. The total fuel flow tends to increase faster than the net thrust, resulting in a higher afterburning specific fuel consumption (SFC). However, the corresponding dry power SFC improves (i.e. lower specific thrust). The high temperature ratio across the afterburner results in a good thrust boost.

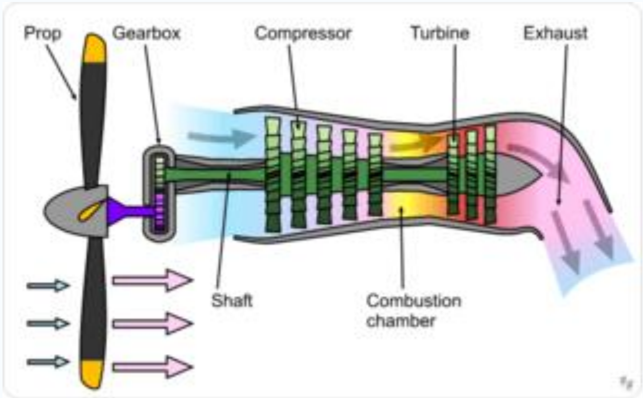
If the aircraft burns a large percentage of its fuel with the afterburner alight, it pays to select an engine cycle with a high specific thrust (i.e. high fan pressure ratio/low bypass ratio). The resulting engine is relatively fuel efficient with afterburning (i.e. Combat/Take-off), but thirsty in dry power. If, however, the afterburner is to be hardly used, a low specific thrust (low fan pressure ratio/high bypass ratio) cycle will be favored. Such an engine has a good dry SFC, but a poor afterburning SFC at Combat/Take-off.

Often the engine designer is faced with a compromise between these two extremes.

Usage

The only civilian aircraft to use afterburners were Concorde and the Tupolev Tu-144 supersonic passenger aircraft. The development of supercruise engines has lessened the need for afterburner use. A turbojet engine equipped with an afterburner is called an "afterburning turbojet," whereas a turbofan engine similarly equipped is called an "augmented turbofan."

Turboprop



A schematic diagram showing the operation of a turboprop engine.

A **Turboprop** (*Turbo-propeller*) or turboshaft engine is a type of gas turbine engine. It differs from a Turbojet in that the design is optimized to produce rotating shaft power to drive a propeller, instead of thrust from the exhaust gas.

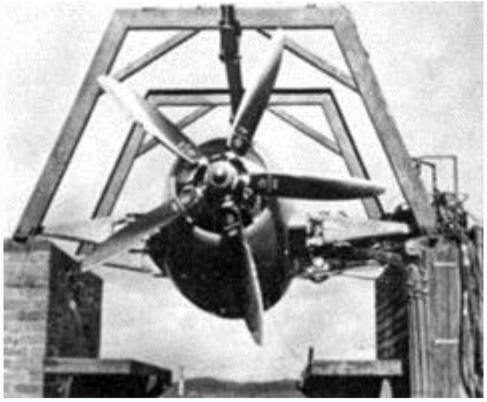
Basically, a turbojet consists of an intake, compressor, combustor, turbine and a propelling nozzle. Air drawn into the intake is compressed by the compressor. Fuel is burnt with the compressed air in the combustor. The hot combustion gases expand through the turbine, to provide power to the compressor. Further expansion of the gases occurs in the propelling nozzle; the high velocity jet produced providing forward thrust.

In a turboprop much of the jet thrust is sacrificed in favor of shaftpower, which is obtained by extracting additional power (to that necessary to drive the compressor) from the turbine expansion process. Whilst the power turbine may be integral with the gas generator section, many turboprops today feature a Free Power Turbine, on a separate coaxial shaft. This enables the propeller to rotate freely, independent of compressor speed. Owing to the additional expansion in the turbine system, the residual energy in the jet is fairly low (<10% of total thrust, including that of the propeller).

Because the propeller is very much larger in diameter than the power turbine, the tip speed of the propeller can become supersonic. Consequently, to prevent this, a speed reduction gearbox is inserted between the power turbine and propeller shafts. The gearbox is part of the engine, whereas in a turboshaft the (helicopter) rotor reduction gearbox is remote from the engine.

Turboprops are very efficient at modest flight speeds (below 724 km/h or 450mph), because the jet velocity of the propeller (and exhaust) is relatively low. Consequently, small commuter aircraft and military transports tend to feature turboprop engines. Although turboprops are used in some General Aviation applications, their high price deters more widespread acceptance.

While most modern turbojet and turbofan engines use axial-flow compressors, turboprop engines usually contain at least one stage of centrifugal compression, because of the small size of the engines.


A Rolls-Royce RB.50 *Trent* on a test rig at Hucknall, in March 1945

Propellers lose efficiency as aircraft speed increases, which is why turboprops are not used on higher-speed aircraft. However, turboprops are far more efficient than piston-driven propeller engines.

The world's first Turboprop was the 'Jendrassik CS-1' designed by Gyorgy Jendrassik. It was produced and flown briefly in Czecho-Slovakia between 1939 and 1942. The aircraft it was fitted to was the Varga XG/XH twin-engined Recconaisance bomber. Not surprisingly the engines proved very unreliable. For more info. visit "Podklady", a Czech Aircraft drawing site (Czech text). Jendrassik had also produced a small scale turboprop of 75 kW in 1937. (Added By Peter Butt 03/12/05)

The first British turboprop engine was the Rolls-Royce RB.50 Trent, a converted Derwent II fitted with reduction gear and a Rotol 7' 11" five-bladed propeller. Two Trents were fitted to Gloster Meteor EE227 - the sole "Trent-Meteor" - which became the first relataively reliable turboprop powered aircraft. From their experience with the Trent, Rolls-Royce developed the Dart, which became one of the most reliable turbprop engines ever built. Dart production continued for more than fifty years. For info on Trent go to Rolls-Royce Heritage Trust)

The first American Turboprop was the General-Electric T-31.

A European consortium is currently developing the 11000shp TP400-D6 turboprop for the Airbus A400M military transport. The engine is all-axial and has a two shaft core, with a free power turbine mounted on a third coaxial shaft.

Residual thrust on a turboshaft is avoided by:

a) further expansion in the turbine system

and/or

b) truncating and turning the exhaust through 90degrees, to produce two opposing jets.

Apart from the above and the remote location of the gearbox, there is very little difference between a turboprop and a turboshaft.