Advances in Aerospace Science and Applications.
Volume 1, Number 1 (2011), pp. 7-22

http://www.ripublication.com/aasa.htm

Analysis of an After Burner in a Jet Engine

A.P. Haran[1], C. Lindon Robert Lee[2], S. Antony Raja[3] and D. Raja Joseph[4]

*[1]Professor of Aeronautical Engineering,
Park Engineering College of Technology, Coimbatore, Tamil Nadu, India
[2]Assistant Professor, School of Mechanical Sciences,
Karunya University, Coimbatore, Tamil Nadu, 641114, India
[3]Assistant Professor, School of Mechanical Sciences,
Karunya University, Coimbatore, Tamil Nadu, 641114, India
[4]Assistant Professor, Aeronautical Engineering,
Indian Engineering College, Tirunelveli, Tamil Nadu, India*

Abstract

A jet engine is a reaction engine that discharges a fast moving jet of fluid to generate thrust in accordance with Newton's laws of motion. An afterburner (or reheat) is an additional component added to some jet engines, primarily those on military supersonic aircraft. Its purpose is to provide a temporary increase in thrust, both for supersonic flight and for takeoff. A jet engine can produce more thrust by either accelerating the gas to a higher velocity or by having a greater mass (quantity) of gas. There are a large number of different types of jet engines, all of which achieve forward thrust from the principle of jet propulsion. A common form of jet engine is the rocket engine. Rocket engines are used for high altitude flights because they give very high thrust and their lack of reliance on atmospheric oxygen allows them to operate at arbitrary altitudes. Afterburning has a significant influence upon engine cycle choice. Jet engines are usually run on fossil fuel propellant, and are thus a source of carbon dioxide in the atmosphere. Jet engines can use biofuels or hydrogen, although the production of the latter is usually made from fossil fuels.

Keywords: Jet engine, after burner, and fuel.

Introduction

A jet engine is a reaction engine that discharges a fast moving jet of fluid to generate thrust in accordance with Newton's laws of motion. This broad definition of jet engines includes turbojets. Turbo fans, rockets, ramjets, pulse jets and pump-jets. In general, most jet engines are internal combustion engines but non-combusting forms also exist. An afterburner (or reheat) is an additional component added to some jet engines, primarily those on military supersonic aircraft. Its purpose is to provide a temporary increase in thrust, both for supersonic flight and for takeoff (as the high wing loading typical of supersonic aircraft designs means that take-off speed is very high). On military aircraft the extra thrust is also useful for combat situations. This is achieved by injecting additional fuel into the jet pipe downstream of (i.e. after) the turbine. The advantage of afterburning is significantly increased thrust; the disadvantage is its very high fuel consumption and inefficiency, though this is often regarded as acceptable for the short periods during which it is usually used. Jet engines are referred to as operating wet when afterburning is being used and dry when the engine is used without afterburning. An engine producing maximum thrust wet is at maximum power (this is the maximum power the engine can produce); an engine producing maximum thrust dry is at military power.

Principle

Jet engine thrust is governed by the general principle of mass flow rate. Simply put, thrust depends on two things: first, the velocity of the exhaust gases; second, the mass of those gases. A jet engine can produce more thrust by either accelerating the gas to a higher velocity or by having a greater mass (quantity) of gas. In the case of a basic turbojet, focusing on the second principle produces the turbofan, which creates slower gas but more of it. Turbofans are efficient and can deliver high thrust for long periods of time but have large sizes for unit power. To create the same power in a compact engine for short periods of time, an engine requires an afterburner. The afterburner increases thrust primarily by the first method: it accelerates the exhaust. The fuel added to the exhaust does also add to the total mass of flow, but this effect is small compared to the increased exhaust velocity, which also helps to increase thrust.

The temperature of the gas in the engine is highest just before the turbine, known as the TIT (Turbine Inlet Temperature), one of the critical engine operating parameters. Then while the gas passes the turbine, it expands at near constant entropy, thus losing temperature. The afterburner subsequently injects fuel downstream of the turbine and reheats the gases. (Thus the more correct name from a thermodynamic standpoint is reheated.) In conjunction with the added heat, the pressure rises in the tailpipe and the gases are ejected through the nozzle at a higher velocity while the mass flow is only slightly increased (by the mass flow of the added fuel).

A jet engine afterburner is an extended exhaust section containing extra fuel injectors, and since the jet engine upstream (i.e., before the turbine) 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. In addition to the increase in afterburner exit stagnation temperature, there is also an increase in nozzle mass flow (i.e. afterburner entry mass flow plus the effective afterburner fuel flow), but a decrease in afterburner exit stagnation pressure (owing to a fundamental loss due to heating plus friction and turbulence losses).

The resulting increase in afterburner exit volume flow is accommodated by increasing the throat area of the propulsion nozzle. Otherwise, the upstream turbo machinery rematches (probably causing a compressor stall or fan surge in a turbofan application).

To a first order, the gross thrust ratio (afterburning/dry) is directly proportional to the root of the stagnation temperature ratio across the afterburner (i.e. exit/entry).

Types

There are a large number of different types of jet engines, all of which achieve forward thrust from the principle of jet propulsion.

Water jet

For propelling water rockets and jet boats; squirts water out the back through a nozzle

Motor jet

Works like a turbojet but instead of a turbine driving the compressor a piston engine drives it.

Turbojet

A tube with a compressor and turbine sharing a common shaft with a burner in between and a propelling nozzle for the exhaust. Uses a high exhaust gas velocity to produce thrust. Has a much higher core flow than bypass type engines

Low-bypass Turbofan

One- or two-stage fan added in front bypasses a proportion of the air through a bypass duct straight to the nozzle/afterburner, avoiding the combustion chamber, with the rest being heated in the combustion chamber and passing through the turbine. Compared with its turbojet ancestor, this allows for more efficient operation with somewhat less noise. This is the engine of high-speed military aircraft, some smaller private jets, and older civilian airliners such as the Boeing 707, the McDonnell Douglas DC-8, and their derivatives.

Ramjet

Intake air is compressed entirely by speed of oncoming air and duct shape (convergent), and then it goes through a burner section where it is heated and then passes through a propelling nozzle

Rocket

Carries all propellants and oxidants on-board, emits jet for propulsion

Turboprop
Strictly not a jet at all — a gas turbine engine is used as a power plant to drive a propeller shaft (or rotor in the case of a helicopter)

Prop fan/Unducted Fan
Turbojet engine that also drives one or more propellers. Similar to a turbofan without the fan cowling.

Pulsejet
Air is compressed and combusted intermittently instead of continuously. Some designs use valves.

Pulse detonation engine
Similar to a pulsejet, but combustion occurs as a detonation instead of a deflagration, may or may not need valves

Air-augmented rocket
Essentially a ramjet where intake air is compressed and burnt with the exhaust from a rocket

Scramjet
Similar to a ramjet without a diffuser; airflow through the entire engine remains supersonic

Turbo rocket
A turbojet where an additional oxidizer such as oxygen is added to the airstream to increase maximum altitude

Precooled jets / LACE
Intake air is chilled to very low temperatures at inlet in a heat exchanger before passing through a ramjet and/or turbojet and/or rocket engine.

Engine design considerations
The process of developing an engine is one of compromises. Engineers design specific attributes into engines to achieve specific goals. Aircraft are one of the most demanding applications for an engine, presenting multiple design requirements, many of which conflict with each other. An aircraft engine must be:

- Reliable, as losing power in an airplane is a substantially greater problem than in an automobile. Aircraft engines operate at temperature, pressure, and speed extremes, and therefore need to perform reliably and safely under all reasonable conditions.
- Light weight, as a heavy engine increases the empty weight of the aircraft and reduces its payload.
- Powerful, to overcome the weight and drag of the aircraft.
- Small and easily streamlined; large engines with substantial surface area,

when installed, create too much drag.

- Field repairable, to keep the cost of replacement down. Minor repairs should be relatively inexpensive and possible outside of specialized shops.
- Fuel efficient to give the aircraft the range the design requires.
- Capable of operating at sufficient altitude for the aircraft

Unlike automobile engines, aircraft engines are often operated at high power settings for extended periods of time. In general, the engine runs at maximum power for a few minutes during taking off, then power is slightly reduced for climb, and then spends the majority of its time at a cruise setting—typically 65 percent to 75 percent of full power. In contrast, an automobile engine might spend 20 percent of its time at 65 percent power while accelerating, followed by 80 percent of its time at 20 percent power while cruising.

The power of an internal combustion reciprocating or turbine aircraft engine is rated in units of power delivered to the propeller (typically horsepower) which is torque multiplied by crankshaft revolutions per minute (RPM). The propeller converts the engine power to thrust horsepower or thp in which the thrust is a function of the blade pitch of the propeller relative to the velocity of the aircraft. Jet engines are rated in terms of thrust, usually the maximum amount achieved during takeoff.

The design of aircraft engines tends to favor reliability over performance. Long engine operation times and high power settings, combined with the requirement for high-reliability means that engines must be constructed to support this type of operation with ease. Aircraft engines tend to use the simplest parts possible and include two sets of anything needed for reliability. Independence of function lessens the likelihood of a single malfunction causing an entire engine to fail. For example, reciprocating engines have two independent magneto ignition systems, and the engine's mechanical engine-driven fuel pump is always backed-up by an electric pump.

Aircraft spend the vast majority of their time travelling at high speed. This allows an aircraft engine to be air cooled, as opposed to requiring a radiator. With the absence of a radiator, aircraft engines can boast lower weight and less complexity. The amount of air flow an engine receives is usually carefully designed according to expected speed and altitude of the aircraft in order to maintain the engine at the optimal temperature.

Aircraft operate at higher altitudes where the air is less dense than at ground level. As engines need oxygen to burn fuel, a forced induction system such as turbocharger or supercharger is especially appropriate for aircraft use. This does bring along the usual drawbacks of additional cost, weight and complexity.

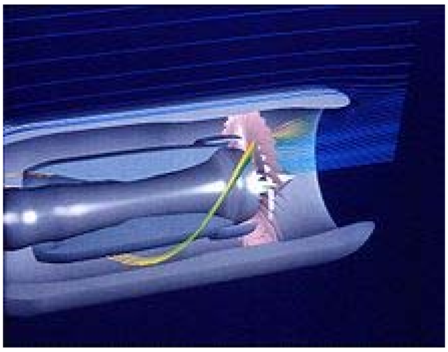
Fuel

All aviation fuel is produced to stringent quality standards to avoid fuel-related engine failures. Aviation standards are much stricter than those for road vehicle fuel because an aircraft engine must meet a strictly defined level of performance under known conditions. These high standards mean that aviation fuel costs much more than fuel used for road vehicles.

Aircraft reciprocating (piston) engines are typically designed to run on aviation gasoline. Avgas has a higher octane rating as compared to automotive gasoline, allowing the use of higher compression ratios, increasing power output and efficiency at higher altitudes. Currently the most common Avgas is 100LL, which refers to the octane rating (100 octane) and the lead content (LL = low lead).

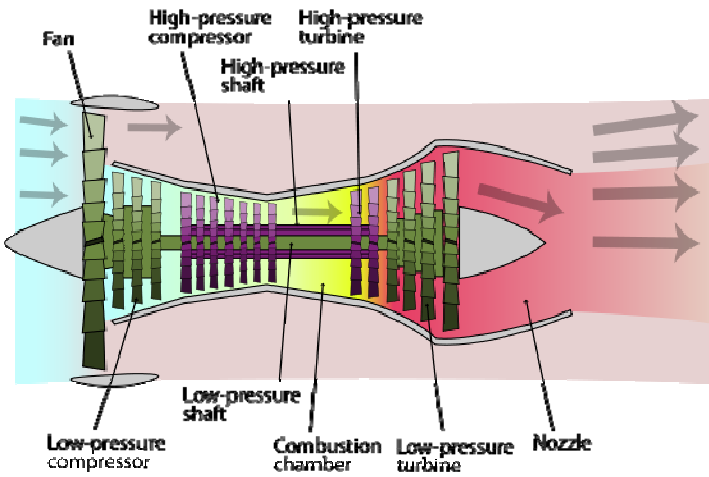
Avgas is blended with tetra-ethyl lead (TEL) to achieve these high octane ratings, a practice no longer permitted with road vehicle gasoline. The shrinking supply of TEL, and the possibility of environmental legislation banning its use, has made a search for replacement fuels for general aviation aircraft a priority for pilot's organizations.[1].

Turbine engines burn various grades of jet fuel, a relatively heavy and less volatile petroleum derivative similar to diesel fuel.



Simulation of a low bypass turbofan's airflow

Major components



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

Cold Section

Air intake (Inlet) — For subsonic aircraft, the air intake to a jet engine consists essentially of an opening which is designed to minimize drag. The air reaching the compressor of a normal jet engine must be travelling below the speed of sound, even for supersonic aircraft, to allow smooth flow through compressor and turbine blades. At supersonic flight speeds, shockwaves form in the intake system, these help compress the air, but also there is some inevitable reduction in the recovered pressure at inlet to the compressor. Some supersonic intakes use devices, such as a cone or a ramp, to increase pressure recovery.

Compressor or Fan — The compressor is made up of stages. Each stage consists of vanes which rotate, and stators which remain stationary. As air is drawn deeper through the compressor, its heat and pressure increases. Energy is derived from the turbine (see below), passed along the shaft.

Bypass ducts — Much of the thrust of essentially all modern jet engines comes from air from the front compressor that bypasses the combustion chamber and gas turbine section that leads directly to the nozzle or afterburner (where fitted).

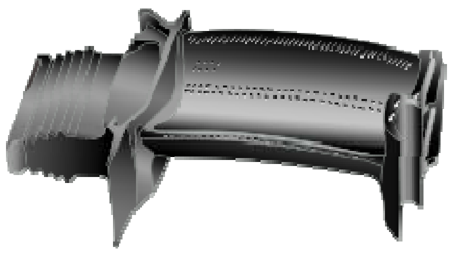
Common

Shaft — The shaft connects 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.

Diffuser section: - This section is a divergent duct that utilizes Bernoulli's principle to decrease the velocity of the compressed air to allow for easier ignition. And, at the same time, continuing to increase the air pressure before it enters the combustion chamber.

Hot section

Combustor or Can or Flame holders or Combustion Chamber — This is a chamber where fuel is continuously burned in the compressed air.



A blade with internal cooling as applied in the high-pressure turbine

Turbine — The turbine is a series of bladed discs that act like a windmill, gaining energy from the hot gases leaving the combustor. Some of this energy is used to drive the compressor, and in some turbine engines (ie turboprop, turbo shaft or turbofan engines), energy is extracted by additional turbine discs and used to drive devices such as propellers, bypass fans or helicopter rotors. One type, a free turbine, is configured such that the turbine disc driving the compressor rotates independently of the discs that power the external components. Relatively cool air, bled from the compressor, may be used to cool the turbine blades and vanes, to prevent them from melting.

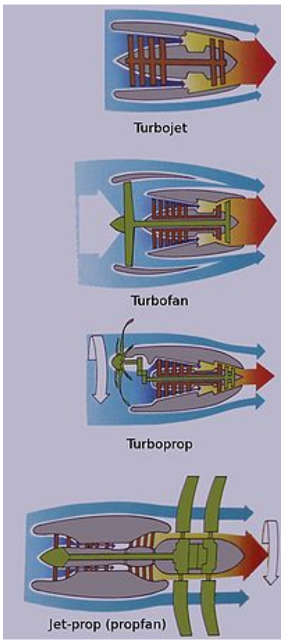
Afterburner or reheat (chiefly UK) — (mainly military) Produces extra thrust by burning extra fuel, usually inefficiently, to significantly raise Nozzle Entry Temperature at the exhaust. Owing to a larger volume flow (i.e. lower density) at exit from the afterburner, an increased nozzle flow area is 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 than the latter.

The various components named above have constraints on how they are put together to generate the most efficiency or performance. The performance and efficiency of an engine can never be taken in isolation; for example fuel/distance efficiency of a supersonic jet engine maximizes at about mach 2, whereas the drag for the vehicle carrying it is increasing as a square law and has much extra drag in the transonic region. The highest fuel efficiency for the overall vehicle is thus typically at Mach ~0.85.

For the engine optimization for its intended use, 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.



Rocket engines

A common form of jet engine is the rocket engine.

Rocket engines are used for high altitude flights because they give very high thrust and their lack of reliance on atmospheric oxygen allows them to operate at arbitrary altitudes.

This is used for launching satellites, space exploration and manned access, and permitted landing on the moon in 1969.

However, the high exhaust speed and the heavier, oxidizer-rich propellant results in more propellant use than turbojets, and their use is largely restricted to very high altitudes, very high speeds, or where very high accelerations are needed as rocket engines themselves have a very high thrust-to-weight ratio.

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

$$F = \dot{m} g_0 I_{sp-vac} - A_e P$$

Where F is the thrust, $I_{sp(vac)}$ is the specific impulse, g_0 is a standard gravity, $\dot{m}$ is the propellant flow in kg/s, Ae is the area of the exhaust bell at the exit, and P is the atmospheric pressure.

Thrust

The motion impulse of the engine is equal to the fluid mass multiplied by the speed at which the engine emits this mass:

$$I = mc$$

where m is the fluid mass per second and c is the exhaust speed. In other words, a vehicle gets the same thrust if it outputs a lot of exhaust very slowly or a little exhaust very quickly. (In practice parts of the exhaust may be faster than others, but it is the average momentum that matters, and thus the important quantity is called the effective exhaust speed - c here.)

However, when a vehicle moves with certain velocity v, the fluid moves towards it, creating an opposing ram drag at the intake:

$$mv$$

Most types of jet engine have an intake, which provides the bulk of the fluid exiting the exhaust. Conventional rocket motors, however, do not have an intake, the oxidizer and fuel both being carried within the vehicle. Therefore, 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 different from that of an air breathing jet engine, and thrust is independent of speed.

The jet engine with an intake duct is only useful if the velocity of the gas from the engine, c, is greater than the vehicle velocity, v, as the net engine thrust is the same as if the gas were emitted with the velocity c − v. So the thrust is actually equal to

$$S = m(c - v)$$

This equation shows that as v approaches c, a greater mass of fluid must go through the engine to continue to accelerate at the same rate, but all engines have a designed limit on this. Additionally, the equation implies that the vehicle can't accelerate past its exhaust velocity as it would have negative thrust.

Energy efficiency

Dependence of the energy efficiency (η) upon the vehicle speed/exhaust speed ratio (v/c) for air-breathing jet and rocket engines

Energy efficiency (η) of jet engines installed in vehicles has two main components, cycle efficiency (η_c)- how efficiently the engine can accelerate the jet, and propulsive efficiency (η_p)-how much of the energy of the jet ends up in the vehicle body rather than being carried away as kinetic energy of the jet.

Even though overall energy efficiency η is simply:

$$\eta = \eta_p \eta_c$$

For all jet engines the propulsive efficiency is highest when the engine emits an exhaust jet at a speed that is the same as, or nearly the same as, the vehicle velocity as this gives the smallest residual kinetic energy. The exact formula for air-breathing engines moving at speed v with an exhaust velocity c is given in the literature as: is

$$\eta_p = \frac{2}{1 + \frac{c}{v}}$$

And for a rocket:

$$\eta_p = \frac{2\frac{v}{c}}{1 + (\frac{v}{c})^2}$$

In addition to propulsive efficiency, another factor is cycle efficiency; essentially a jet engine is typically a form of heat engine. Heat engine efficiency is determined by the ratio of temperatures that are reached in the engine to that they are exhausted at from the nozzle, which in turn is limited by the overall pressure ratio that can be achieved. Cycle efficiency is highest in rocket engines (~60+ %), as they can achieve extremely high combustion temperatures and can have very large, energy efficient nozzles. Cycle efficiency in turbojet and similar is nearer to 30%, the practical combustion temperatures and nozzle efficiencies are much lower

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, the afterburner is generally inefficient compared with the main combustor. Afterburner efficiency also declines significantly if, as is usually the case, the tailpipe pressure decreases with increasing altitude.

However, as a counter-example, the SR-71 had reasonable efficiency at high altitude in afterburning mode ("wet") due to its high speed (mach 3.2) and hence high pressure due to ram effect.

Afterburners do produce markedly enhanced thrust as well as (typically) a very large flame at the back of the engine. This exhaust flame may show shock-diamonds, which are caused by shock waves being formed due to slight differences between ambient pressure and the exhaust pressure. These imbalances cause oscillations in the exhaust jet diameter over distance and cause the visible banding where the pressure and temperature is highest.

Influence on cycle choice

Afterburning has a significant influence upon engine cycle choice. Lowering fan pressure ratio decreases specific thrust (both dry and when 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 higher 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.

MiG-23 afterburner

Afterburners are generally only used in military aircraft and are considered standard equipment for fighter aircraft. The handfuls of civilian planes that have used them include some NASA research aircraft, the Tupolev Tu-144 and Concorde, and the White Knight of Scaled Composites. Concorde and the Tu-144 had this capability and flew long distances at supersonic speeds. This would be impossible with the high fuel consumption of reheat, and these aircraft used afterburners at takeoff and to minimize time spent in the high drag transonic flight regime. Supersonic flight without afterburners is referred to as super cruise.

A turbojet engine equipped with an afterburner is called an "afterburning turbojet", whereas a turbofan engine similarly equipped is sometimes called an "augmented turbofan".

A "dump-and-burn" is a fuel dumping procedure where dumped fuel is intentionally ignited using the plane's afterburner. A spectacular flame combined with high speed makes this a popular display for air shows or as a finale to fireworks.

Thrust-to-weight ratio

The thrust to weight ratio of jet engines of similar principles varies somewhat with scale, but mostly is a function of engine construction technology. Clearly for a given engine, the lighter the engine, the better the thrust to weight is, the less fuel is used to compensate for drag due to the lift needed to carry the engine weight, or to accelerate the mass of the engine.

As can be seen in the following table, rocket engines generally achieve very much higher thrust to weight ratios than duct engines such as turbojet and turbofan engines. This is primarily because rockets almost universally use dense liquid or solid reaction mass which gives a much smaller volume and hence the pressurization system that supplies the nozzle is much smaller and lighter for the same performance. Duct engines have to deal with air which is 2-3 orders of magnitude less dense and this gives pressures over much larger areas, and which in turn results in more engineering materials being needed to hold the engine together and for the air compressor.

Comparison of types

Turboprops obtain little thrust from jet effect, but are useful for comparison. They are gas turbine engines that have a rotating fan that takes and accelerates the large mass of air but by a relatively small change in speed. This low speed limits the speed of any propeller driven airplane. When the plane speed exceeds this limit, propellers no longer provide any thrust ($c - v < 0$). However, because they accelerate a large mass of air, turboprops are very efficient.

Turbojets accelerate a much smaller mass of the air and burned fuel, but they emit it at the much higher speeds possible with a de Laval nozzle. This is why they are suitable for supersonic and higher speeds.

Low bypass turbofans have the mixed exhaust of the two air flows, running at different speeds (c1 and c2). The thrust of such engine is

$$S = m1\ (c1 - v) + m2\ (c2 - v)$$

where m1 and m2 are the air masses, being blown from the both exhausts. Such engines are effective at lower speeds, than the pure jets, but at higher speeds than the turbo shafts and propellers in general. For instance, at the 10 km altitude, turbo shafts are most effective at about Mach 0.4 (0.4 times the speed of sound), low bypass turbofans become more effective at about Mach 0.75 and turbojets become more effective than mixed exhaust engines when the speed approaches Mach 2-3.

Rocket engines have extremely high exhaust velocity and thus are best suited for high speeds (hypersonic) and great altitudes. At any given throttle, the thrust and efficiency of a rocket motor improves slightly with increasing altitude (because the back-pressure falls thus increasing net thrust at the nozzle exit plane), whereas with a turbojet (or turbofan) the falling density of the air entering the intake (and the hot gases leaving the nozzle) causes the net thrust to decrease with increasing altitude. Rocket engines are more efficient than even scramjets above roughly Mach 15.

Altitude and speed

With the exception of scramjets, jet engines, deprived of their inlet systems can only accept air at around half the speed of sound. The inlet system's job for transonic and supersonic aircraft is to slow the air and perform some of the compression.

The limit on maximum altitude for engines is set by flammability- at very high altitudes the air becomes too thin to burn, or after compression, too hot. For turbojet engines altitudes of about 40 km appear to be possible, whereas for ramjet engines 55 km may be achievable. Scramjets may theoretically manage 75 km. Rocket engines of course have no upper limit.

Flying faster compresses the air in at the front of the engine, but ultimately the engine cannot go any faster without melting. The upper limit is usually thought to be about Mach 5-8, except for scramjets which may be able to achieve about Mach 15 or more, as they avoid slowing the air.

Noise

Noise is due to shockwaves that form when the exhaust jet interacts with the external air. The intensity of the noise is proportional to the thrust as well as proportional to the fourth power of the jet velocity. Generally then, the lower speed exhaust jets emitted from engines such as high bypass turbofans are the quietest, whereas the fastest jets are the loudest.

Although some variation in jet speed can often be arranged from a jet engine (such as by throttling back and adjusting the nozzle) it is difficult to vary the jet speed from an engine over a very wide range. Therefore since engines for supersonic vehicles such as Concorde, military jets and rockets inherently need to have supersonic exhaust at top speed, so these vehicles are especially noisy even at low speeds.

Advanced designs

J-58 combined ramjet/turbojet

The SR-71 Blackbird's Pratt & Whitney J58 engines were rather unusual. They could convert in flight from being largely a turbojet to being largely a compressor-assisted ramjet. At high speeds (above Mach 2.4), the engine used variable geometry vanes to direct excess air through 6 bypass pipes from downstream of the fourth compressor stage into the afterburner. 80% of the SR-71's thrust at high speed was generated in this way, giving much higher thrust, improving specific impulse by 10-15%, and permitting continuous operation at Mach 3.2. The name coined for this setup is turbo-ramjet.

Hydrogen fuelled air-breathing jet engines

Jet engines can be run on almost any fuel. Hydrogen is a highly desirable fuel, as, although the energy per mole is not unusually high, the molecule is very much lighter than other molecules. The energy per kg of hydrogen is twice that of more common fuels and this gives twice the specific impulse. In addition, jet engines running on hydrogen are quite easy to build—the first ever turbojet was run on hydrogen. Also, although not duct engines, hydrogen-fueled rocket engines have seen extensive use.

However, in almost every other way, hydrogen is problematic. The downside of hydrogen is its density; in gaseous form the tanks are impractical for flight, but even in the form of liquid hydrogen it has a density one fourteenth that of water. It is also deeply cryogenic and requires very significant insulation that precludes it being stored in wings. The overall vehicle would end up being very large, and difficult for most airports to accommodate. Finally, pure hydrogen is not found in nature, and must be manufactured either via steam reforming or expensive electrolysis. Nevertheless, research is ongoing and hydrogen-fueled aircraft designs do exist that may be feasible.

Precooled jet engines

An idea originated by Robert P. Carmichael in 1955 is that hydrogen-fueled engines could theoretically have much higher performance than hydrocarbon-fueled engines if a heat exchanger were used to cool the incoming air. The low temperature allows lighter materials to be used, a higher mass-flow through the engines, and permits combustors to inject more fuel without overheating the engine.

This idea leads to plausible designs like Reaction Engines SABRE, that might permit single-stage-to-orbit launch vehicles, and ATREX, which could permit jet engines to be used up to hypersonic speeds and high altitudes for boosters for launch vehicles. The idea is also being researched by the EU for a concept to achieve non-stop antipodal supersonic passenger travel at Mach 5 (Reaction Engines A2).

Nuclear-powered ramjet

Project Pluto was a nuclear-powered ramjet, intended for use in a cruise missile. Rather than combusting fuel as in regular jet engines, air was heated using a high-temperature, unshielded nuclear reactor. This dramatically increased the engine burn time, and the ramjet was predicted to be able to cover any required distance at supersonic speeds (Mach 3 at tree-top height).

However, there was no obvious way to stop it once it had taken off, which would be a great disadvantage in any non-disposable application. Also, because the reactor was unshielded, it was dangerous to be in or around the flight path of the vehicle (although the exhaust itself wasn't radioactive). These disadvantages limit the application to warhead delivery system for all-out nuclear war, which it was being designed for.

Scramjets

Scramjets are an evolution of ramjets that are able to operate at much higher speeds than any other kind of air breathing engine. They share a similar structure with ramjets, being a specially-shaped tube that compresses air with no moving parts through ram-air compression. Scramjets, however, operate with supersonic airflow through the entire engine. Thus, scramjets do not have the diffuser required by ramjets to slow the incoming airflow to subsonic speeds.

Scramjets start working at speeds of at least Mach 4, and have a maximum useful speed of approximately Mach 17. Due to aerodynamic heating at these high speeds, cooling poses a challenge to engineers.

Economic considerations

In 2007, the cost of jet fuel, while highly variable from one airline to another averaged 26.5% of total operating costs, making it the single largest operating expense for most airlines.

Environmental considerations

Jet engines are usually run on fossil fuel propellant, and are thus a source of carbon dioxide in the atmosphere. Jet engines can use biofuels or hydrogen, although the production of the latter is usually made from fossil fuels.

About 7.2% of the oil used in 2004 was consumed by jet engines.

Some scientists believe that jet engines are also a source of global dimming due to the water vapor in the exhaust causing cloud formations.

Nitrogen compounds are also formed from the combustion process from atmospheric nitrogen. At low altitudes this is not thought to be especially harmful, but for supersonic aircraft that fly in the stratosphere some destruction of ozone may occur.

Sulphates are also emitted if the fuel contains sulphur.

Safety and reliability

Jet engines are usually very reliable and have a very good safety record. However, failures do sometimes occur.

Compressor blade containment

The most likely failure is compressor blade failure, and modern jet engines are designed with structures that can catch these blades and keep them contained within the engine casing. Verification of a jet engine design involves testing that this system works correctly.

Conclusion

Jet engines are usually used as aircraft engines for jet aircraft. They are also used for cruise missiles and unmanned aerial vehicles. In the form of rocket engines they are used for fireworks, model rocketry, spaceflight, and military missiles. Jet engines have also been used to propel high speed cars, particularly drag racers, with the all-time record held by a rocket car. A turbofan powered car Thrust SSC currently holds the land speed record.

Jet engine designs are frequently modified to turn them into gas turbine engines which are used in a wide variety of industrial applications. These include electrical power generation, powering water, natural gas, or oil pumps, and providing propulsion for ships and locomotives. Industrial gas turbine can create up to 50,000 shaft horsepower.

Due to their high fuel consumption, afterburners are not used for extended periods. Afterburners are generally used only 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.

References

[1] Gyorgy, Nagy Istvan, "Albert Fono: A Pioneer of Jet Propulsion", International Astronautical Congress, 1977, IAF/IAA.
[2] Dugger, Gordon L. (1969). Ramjets. American Institute of Aeronautics and Astronautics, p. 15.
[3] Frank Whittle, "Improvements relating to the propulsion of aircraft and other vehicles," British patent no. 347,206 (filed: 16 January 1930).
[4] Warsitz, Lutz: The first jet pilot - The Story of German Test Pilot Erich Warsitz (p. 125), Pen and Sword Books Ltd., England, 2009.
[5] John Golley (1997). Genesis of the Jet: Frank Whittle and the Invention of the Jet Engine. Crowood Press. ISBN 1-85310-860-X.
[6] David S Brooks (1997). Vikings at Waterloo: Wartime Work on the Whittle Jet Engine by the Rover Company. Rolls-Royce Heritage Trust. ISBN 1-872922-08-2.
[7] Lutz Warsitz (2009): The first jet pilot - The Story of German Test Pilot Erich Warsitz, Pen and Sword Books Ltd., England, ISBN 978-1-84415-818-8, English Edition.
[8] Ronald D. Flack (2005). Fundamentals of jet propulsion with applications. Cambridge, UK: CambridgeUniversityPress.ISBN 0-521-81983-0.
[9] Gengel YA and Boles MA,Thermodynamics - an engineering approach, McGraw Hill, 2006.
[10] Theoretical investigation of thrust augmentation of turbojet engines by tail-pipe burning, Bohanon, H R; Wilcox, E C.