Engine performance parameters

The engine performance is described by different efficiency definitions, thrust and the fuel consumption. The efficiency definitions that we shall now be discussing are applicable to an engine with a single propellant stream (turbojets or ramjets). For other types of jet engines (turbofan, turboprop) the equations need to be appropriately modified.

Thermal efficiency: The ratio of the rate of production of propellant kinetic energy to the totalenergy consumption rate.

$$\eta_{th} = \frac{\dot{m}_a\left[(1+f)(u_e^2/2) - u^2/2\right]}{\dot{m}_f Q_R} = \frac{\left[(1+f)(u_e^2/2) - u^2/2\right]}{f Q_R}$$

For a turboprop or turboshaft engine, the output is largely shaft power. In this case,

$$\eta_{th} = \frac{P_s}{\dot{m}_f Q_R}$$

Propulsion efficiency: The ratio of thrust power to the rate of production of propellant kinetic energy. The propulsive efficiency η_p can be defined as the ratio of the useful propulsive energyor thrust power (F. u) to the sum of that energy and the unused kinetic energy of the jet.

$$\eta_P = \frac{\Im u}{\dot{m}_a\left[(1+f)(u_e^2/2) - u^2/2\right]}$$

If we assume that f«1 and the pressure thrust term is negligible

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$$\eta_P = \frac{(u_e - u)u}{u_e^2/2 - u^2/2} = \frac{2u/u_e}{1 + u/u_e}$$

Overall efficiency: The product of thermal efficiency and propulsion efficiency.

$$\eta_o = \eta_p \eta_{th}$$

Specific Thrust

Specific thrust is a term used in gas turbine engineering to show the relative thrust per air mass flow rate of a jet engine (e.g. turbojet, turbofan, etc.) and is defined as the ratio: net thrust/total intake airflow.

Why are we interested in specific thrust?

First, it is an indication of engine efficiency. Two different engines have different values of specific thrust. The engine with the higher value of specific thrust is more efficient because it produces more thrust for the same amount of airflow**.**

It gives us an easy way to "size" an engine during preliminary analysis. The result of our thermodynamic analysis is a certain value of specific thrust. The aircraft drag defines the required value of thrust. Dividing the thrust required by the specific thrust tells us how much airflow our engine must produce and this determines the physical size of the engine.

Specific impulse

Specific impulse (usually abbreviated Isp) is a measure of how effectively a rocket uses propellant or jet engine uses fuel. By definition, it is the total impulse (or change in momentum) delivered per unit of propellant consumed.

$$I_{sp} \equiv \frac{F}{\dot{m}_p g}$$

Thrust Specific fuel consumption

TSFC or SFC for thrust engines (e.g. turbojets, turbofans, ramjets, rocket engines, etc.) is the mass of fuel needed to provide the net thrust for a given period.SFC varies with throttle setting,altitude and climate. For jet engines, flight speed also has a significant effect upon SFC; SFC isroughly proportional to air speed.

$$TSFC = \frac{\dot{m}_f}{\Im} \approx \frac{\dot{m}_f}{\dot{m}_a\left[(1+f)u_e - u\right]}$$

Component

performanceAir intake

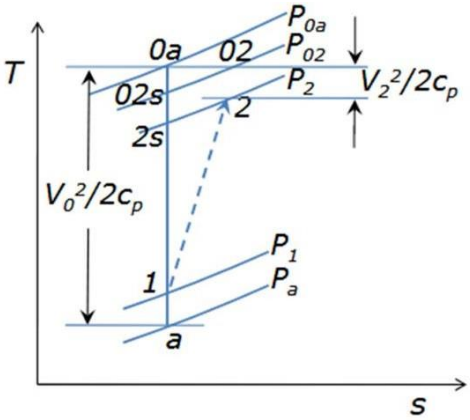
performance

Inlet losses arise due to wall friction and shock waves (in a supersonic inlet).
•These result in a reduction in total pressure.
•The flow is usually adiabatic as it flows through the intake.
•Performance of intakes arecharacterized using total pressure ratio and isentropic efficiency.Isentropic efficiency, η_d, of the diffuser is

$$\eta_d = \frac{h_{02s} - h_a}{h_{0a} - h_a} \cong \frac{T_{02s} - T_a}{T_{0a} - T_a}$$

$$\eta_d = \frac{\left(1+\frac{\gamma-1}{2}M^2\right)\pi_d^{(\gamma-1)/\gamma} - 1}{[(\gamma-1)/2]M^2}$$

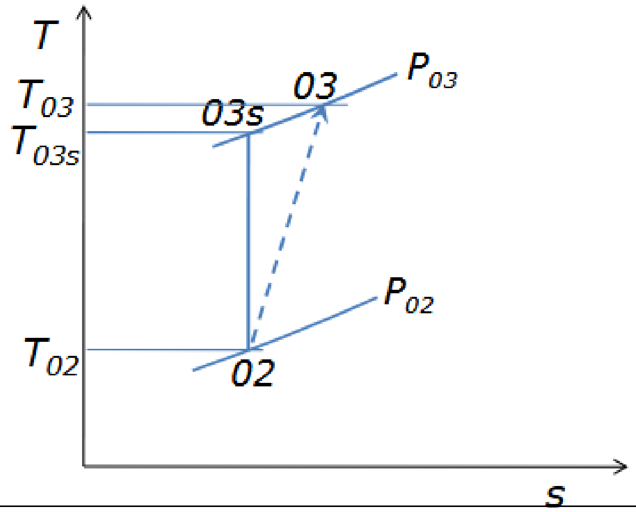
This efficiency can be related to the total pressure ratio (π_d) and Mach number



Compressor/fan performance

Compressors are to a high degree of approximation, adiabatic. Compressor performance is evaluated using the isentropic efficiency.

$$\eta_C = \frac{\text{Ideal work of compression for given pressure ratio}}{\text{Actual work of compression for given pressure ratio}}$$
$$= \frac{w_{ci}}{w_c} = \frac{h_{03s} - h_{02}}{h_{03} - h_{02}}$$



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$$\eta_C = \frac{h_{03s} - h_{02}}{h_{03} - h_{02}} \cong \frac{T_{03s} - T_{02}}{T_{03} - T_{02}}$$

$$= \frac{T_{03s}/T_{02} - 1}{T_{03}/T_{02} - 1} = \frac{(P_{03}/P_{02})^{(\gamma-1)/\gamma} - 1}{\tau_C - 1}$$

$$= \frac{(\pi_C)^{(\gamma-1)/\gamma} - 1}{\tau_C - 1}$$

The isentropic efficiency is thus a function of the total pressure ratio and the total temperature ratio.

Combustion chamber performance

In a combustion chamber (or burner), there are two possibilities of losses, incomplete combustion and total pressure losses.

- Combustion efficiency can be defined by carrying out an energy balance across thecombustor.
- Two different values of specific heat at constant pressure: one for fluid upstream of thecombustor and the other for fluid downstream of the combustor

Combustion efficiency, η_b

$$\eta_b = \frac{(\dot{m} + \dot{m}_f)h_{04} - \dot{m}h_{03}}{\dot{m}_f \dot{Q}_f} = \frac{(\dot{m} + \dot{m}_f)c_{p4}T_{04} - \dot{m}c_{p3}T_{03}}{\dot{m}_f \dot{Q}_f}$$

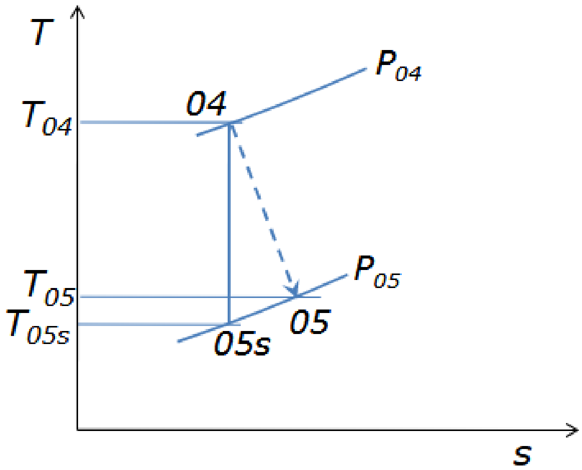
$$= \frac{(\dot{m} + \dot{m}_f)c_{pg}T_{04} - \dot{m}c_{pa}T_{03}}{\dot{m}_f \dot{Q}_f}$$

Total pressure losses arise from two effects:

- viscous losses in the combustion chamber
- total pressure loss due to combustion at finite Mach number.

Turbine performance

The flow in a turbine is also assumed to be adiabatic, though in actual engines there could be turbine blade cooling.Isentropic efficiency of the turbine is defined in a manner similar to thatof the compressor.

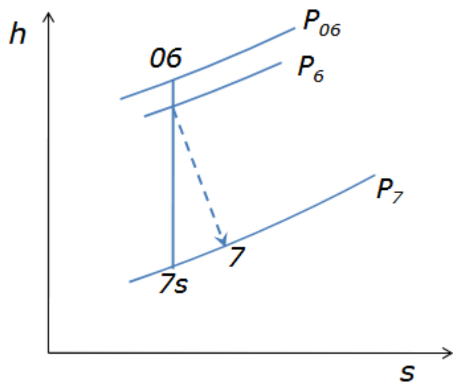


$$\eta_t = \frac{\text{Actual work of compression for given pressure ratio}}{\text{Ideal work of compression for given pressure ratio}}$$

$$= \frac{w_t}{w_{ti}} = \frac{h_{04} - h_{05}}{h_{04} - h_{05s}} = \frac{1-\tau_t}{1-\pi_t^{(\gamma-1)/\gamma}}$$

Nozzle performance

The flow in the nozzle is also adiabatic,however losses in a nozzle could occur due to incomplete expansion process (under or over-expansion). Friction may reduce the isentropic efficiency.



The efficiency is defined by

$$\eta_n = \frac{h_{06} - h_7}{h_{06} - h_{7s}}$$

Afterburner performance

Afterburner is thermodynamically similar to a combustion chamber. The performance parameters for an afterburner are thus the combustion efficiency and the total pressure loss. In case of engines with afterburning, the corresponding performance parameters for an afterburnerneed to be taken into account.
As stated above the propeller rotates at very low speed compared to its driving turbine. The speed reduction may be 1:15. This speed reduction is necessary owing to two reasons:

1. A large centrifugal force arises from the rotation of the large diameter (2–4 m or even more) propeller blades. These blades are fixed to the propeller hub in a cantilever fixed end configuration. Consequently, such a centrifugal force generates a large tensile stress at blade root. Stress limitations require that the large diameter propeller rotates ata much slow speed. It is a fact that no propeller can withstand the tensile force (and stress) that is generated when it is turned at the same speed of the turbine.
2. Owing to the rotation of the propeller, the relative velocity at the propeller tip will approach the speed of sound before the aircraft approaches the speed of sound. This compressibility effect when approaching the speed of sound limits the design of propellers. At high subsonic flight speeds ($M > 0.7$), the tips of blades may approach supersonic speeds. If this happens, the flow may separate and shock waves may form. As a consequence, the performance of turboprop engine deteriorates due to both the poor propeller efficiency and the decrease in air flow rate into the engine.

The propeller is pitch controlled to be suitable for a wider range of satisfactory applications.
If the shaft of a free turbine is used to drive something other than an aircraft propeller, the engine is called a turboshaft engine. This is one of the turboshaft engines that will be discussed later in this chapter. Turboshaft engines are similar to turboprop engines, except that the hot gases are expanded to a lower pressure in the turbine, thus providing greater shaft power andlow exhaust velocity.
Examples of turboshaft engines are those used in helicopters.Now, let us discuss the advantages of turboprop engines:

1. Turboprops have high fuel efficiency, even greater than turbofan engines. This is due to the small amount of air flow burned inside the engine. Turboprop engines can then generate a lot of thrust at low fuel consumption.
2. Turboprop engines may find application in vertical takeoff and landing (VTOL). The Osprey V-22 aircraft as shown in Figure 6.5 is one of the

famous VTOL aircraft that is powered by a turboprop engine.

3. Turboprop engines have high takeoff thrust that enables aircraft to have a short field takeoff.
4. They have the highest propulsive efficiency for flight speeds of 400 mph compared to turbo fan and turbojet engines.

However, turboprop engines have several disadvantages:

1. The noise and vibration produced by the propeller is a significant drawback.
1. Turboprop engines are limited to subsonic flights (< 400 mph) and low altitudes (below30,000 ft).

The propeller and its pitch control mechanism as well as the power turbine contribute additional weight, so the turboprop engine may be 1.5 times as heavy as a conventional turbojet of the same gas generator.