PS41 Propulsion – Chapter 4

Performance & Thermodynamics Cycles of Aircraft Gas Turbine Engine

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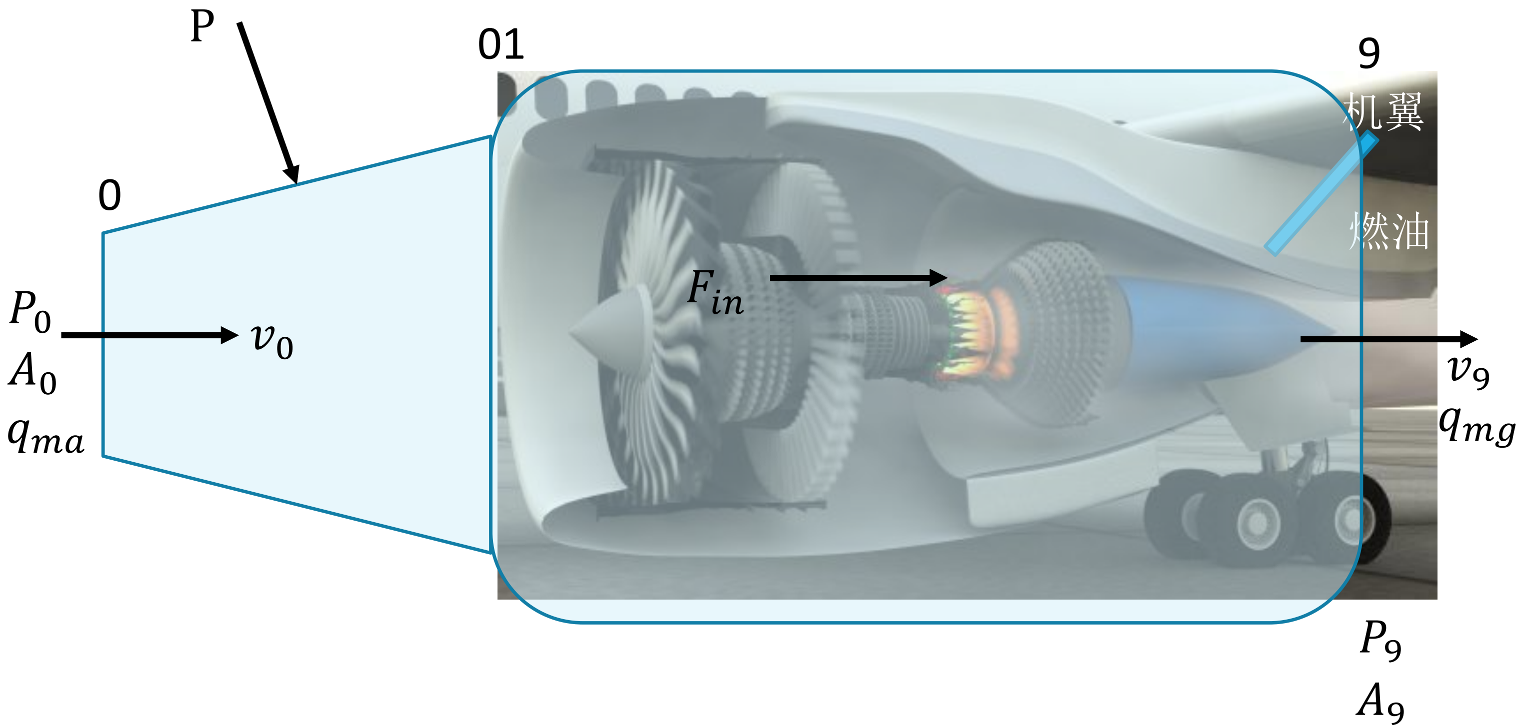
Objectives

- Jet engine thrust and other performance parameters.
- Performance of a basic jet engine.
- Brayton cycles
  - Ideal Brayton cycle
  - Variants of Brayton cycle
  - Actual/real Brayton cycle
- Jet engine cycles for aircraft propulsion
  - Turbojet engine
  - Turbojet engine with afterburning
  - Turbofan and its variants
  - Turboprop and turboshaft engines
  - Ramjet engines

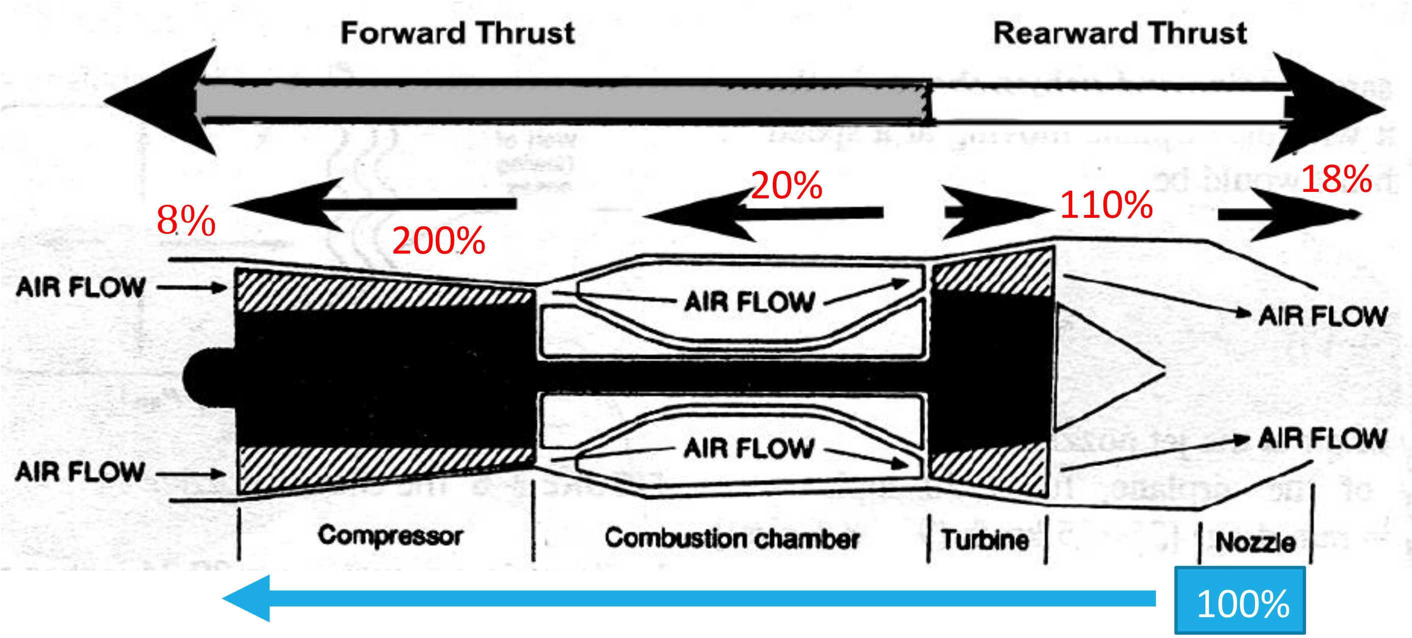
Thrust



$$F_e = F_{in} + F_{out}$$

$$F_{in} = q_{mg}v_9 - q_{ma}v_0 - P_0A_0 - \int_0^{01} PdA + P_9A_9$$

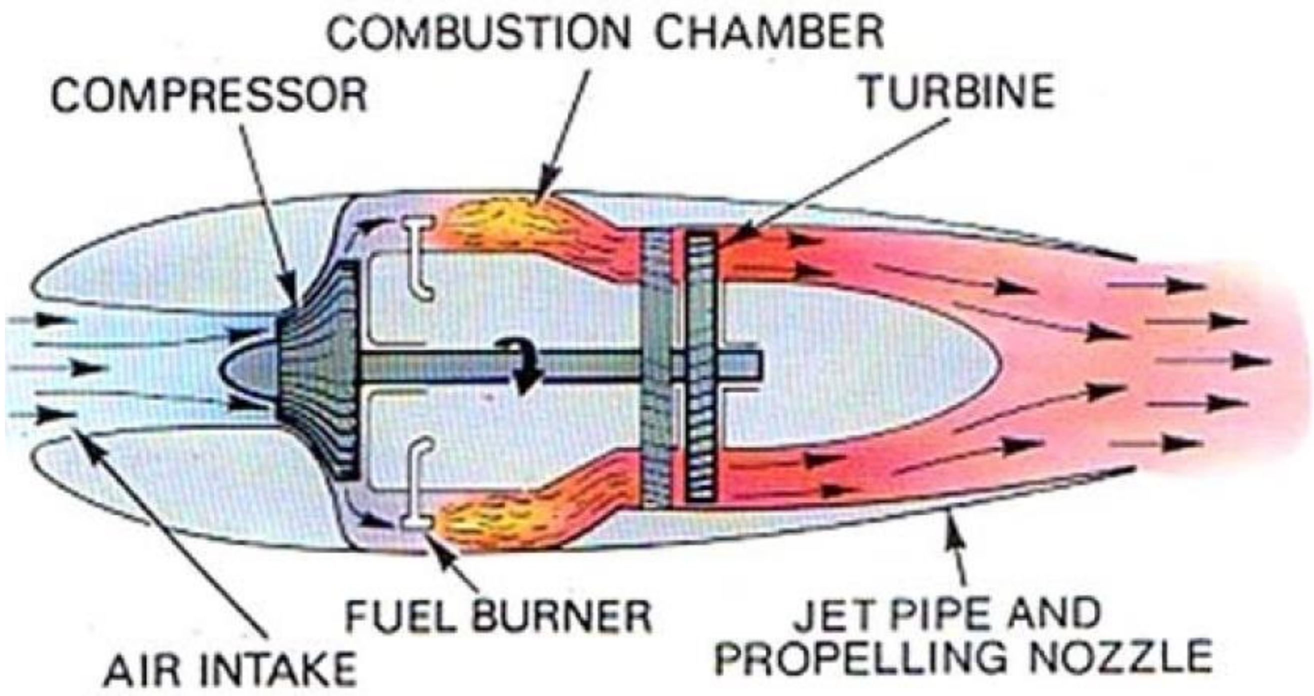
Thrust



$$F_{out} = -\int_{01}^{9} PdA - X_f$$

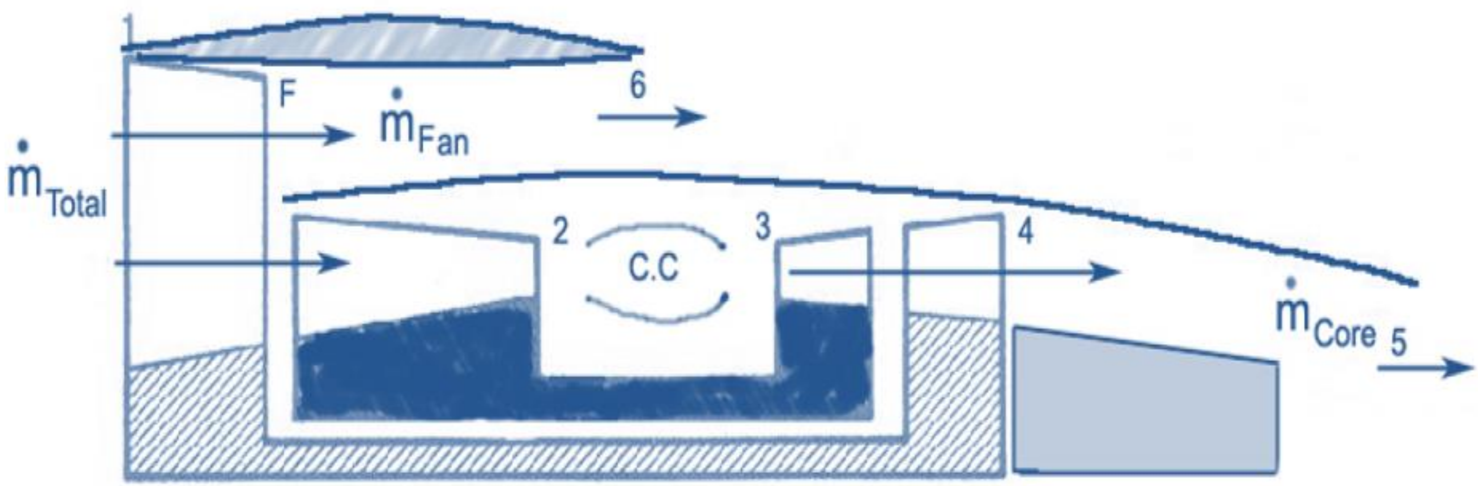
$$F_e = \boxed{q_{mg}v_9 + (P_9 - P_0)A_9} - q_{ma}v_0 - \int_{0}^{01}(P - P_0)dA - \int_{01}^{9}(P - P_0)dA - X_f$$

Thrust of a Jet Engine

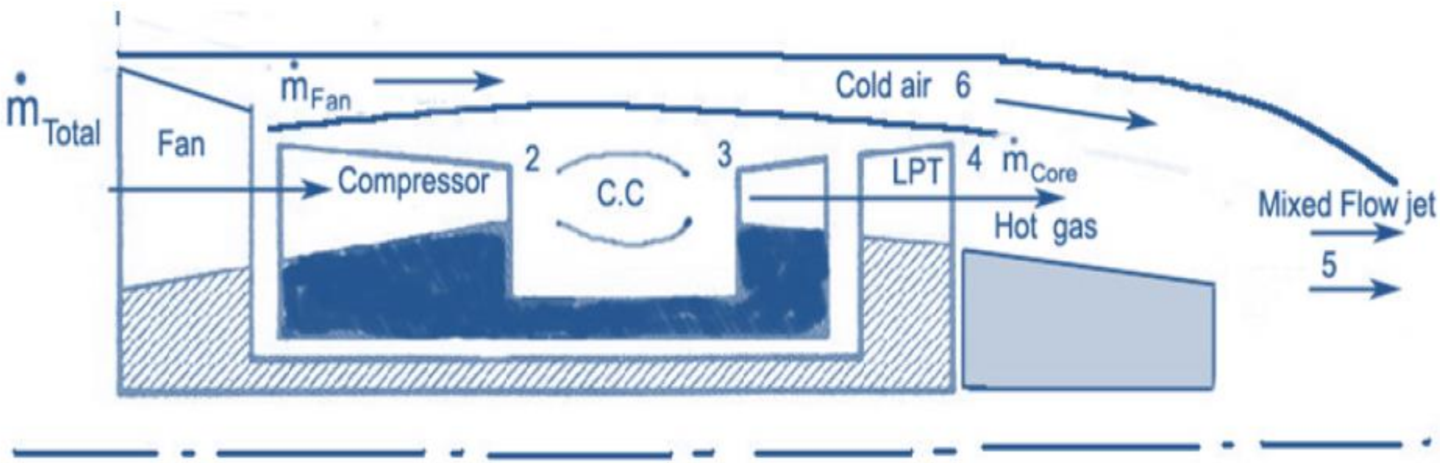


A Whittle-type turbo-jet engine

Thrust of a unmixed Turbo-fan engine

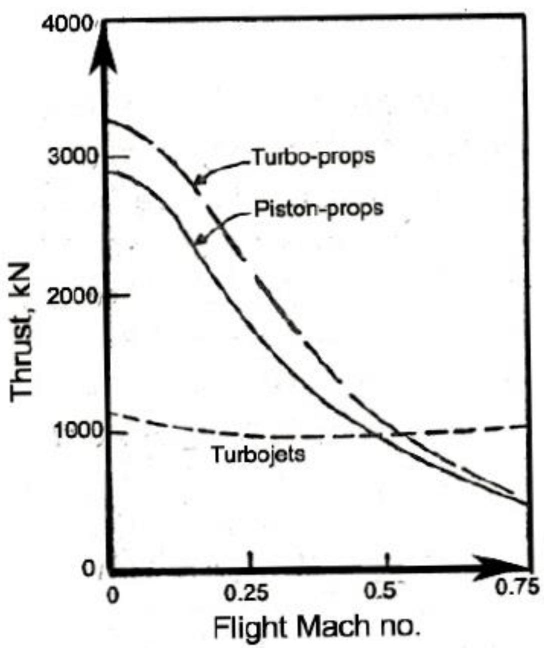


Thrust of a mixed Turbo-fan engine



Thrust

- $F_s = \frac{F}{q_{ma}}$
- Thrust to weight ratio
- Power to weight ratio



Typical thrust generation capability of small aircraft engines of similar power

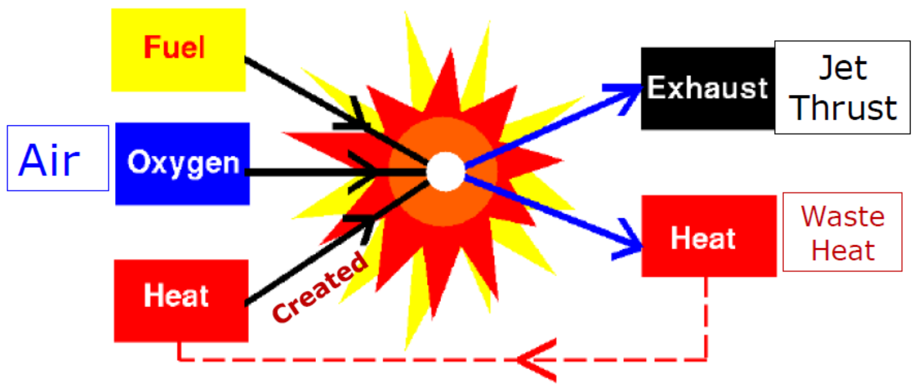
Fuel consumption

- Fuel consumption for turbojet and other jet engines is normally presented in terms of thrust specific fuel consumption (TSFC).

$$SFC = \frac{3600 q_{mf}}{F} = \frac{3600 f}{F_s} \text{ (kg/N-hr)}$$

- The thrust specific fuel consumption varies with engine rpm, Mach number and altitude.
- For jet engines with reheat or afterburning, the fuel consumption would be quite high, and SFC would show up as high value. In such operation sheer thrust requirement outweighs the high SFC.
- Turbo-props have lower SFC. This fact has proposed development of Prop-fans.

Jet Engine fundamentally is a Heat Engine



***Combustion** is the energy input in to the engine and is key to the operation of a jet engine*

燃油化学能 $q_{mf}H_u$ → 燃油放热量 $q_{mf}H_u\eta_b$ → 可用功率 $0.5\left(q_{mg}v_9^2 - q_{ma}v_0^2\right) + q_{mg}l_{Te}$ → 推进功率 Fv_0

燃油化学能 → 燃烧不完全损失

燃油放热量 → 热能形式损失（排热损失） $q_{mg}\left(c_p'T_9 - c_pT_0\right)$

可用功率 → 动能形式损失 $0.5q_{mg}(v_9 - v_0)^2$

Efficiency

- The efficiency of energy conversion (Thermal efficiency) is given by

$$\eta_t = \frac{l_e}{q_0}$$

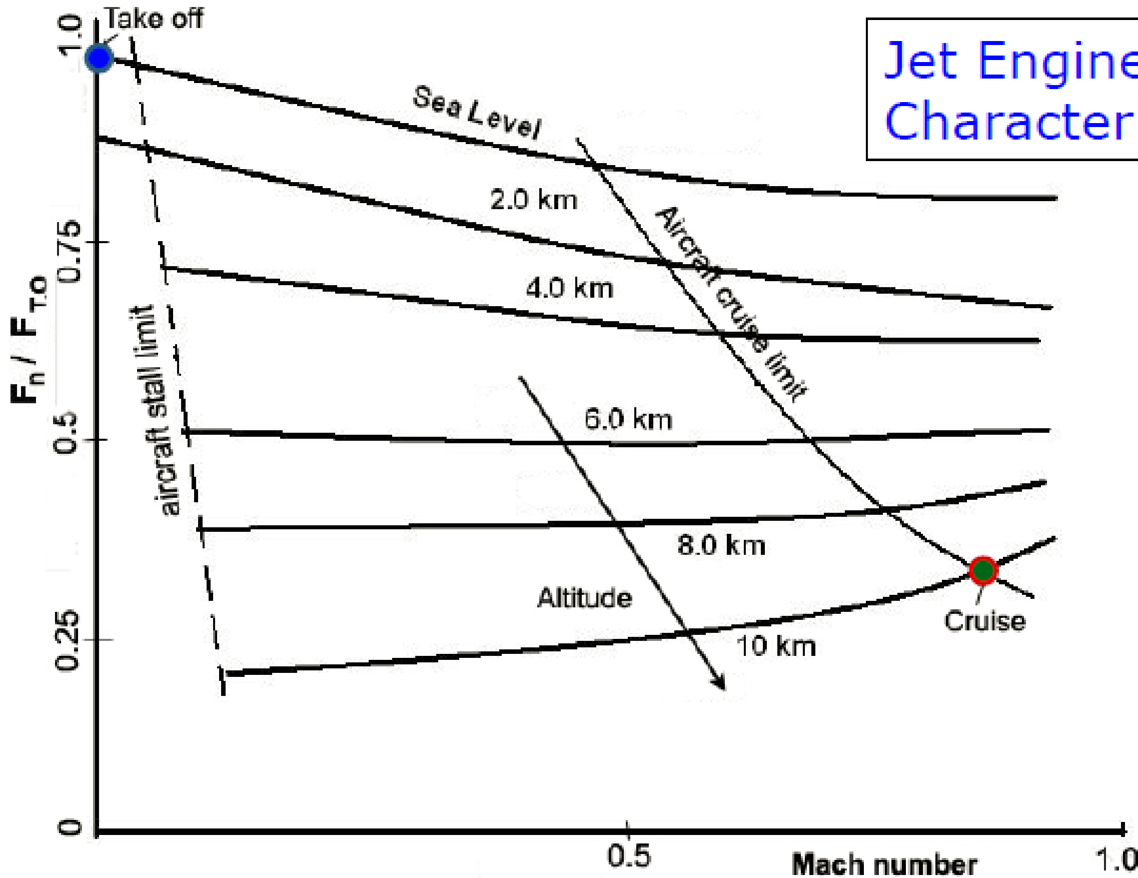
- The propulsive efficiency η_p can be written as

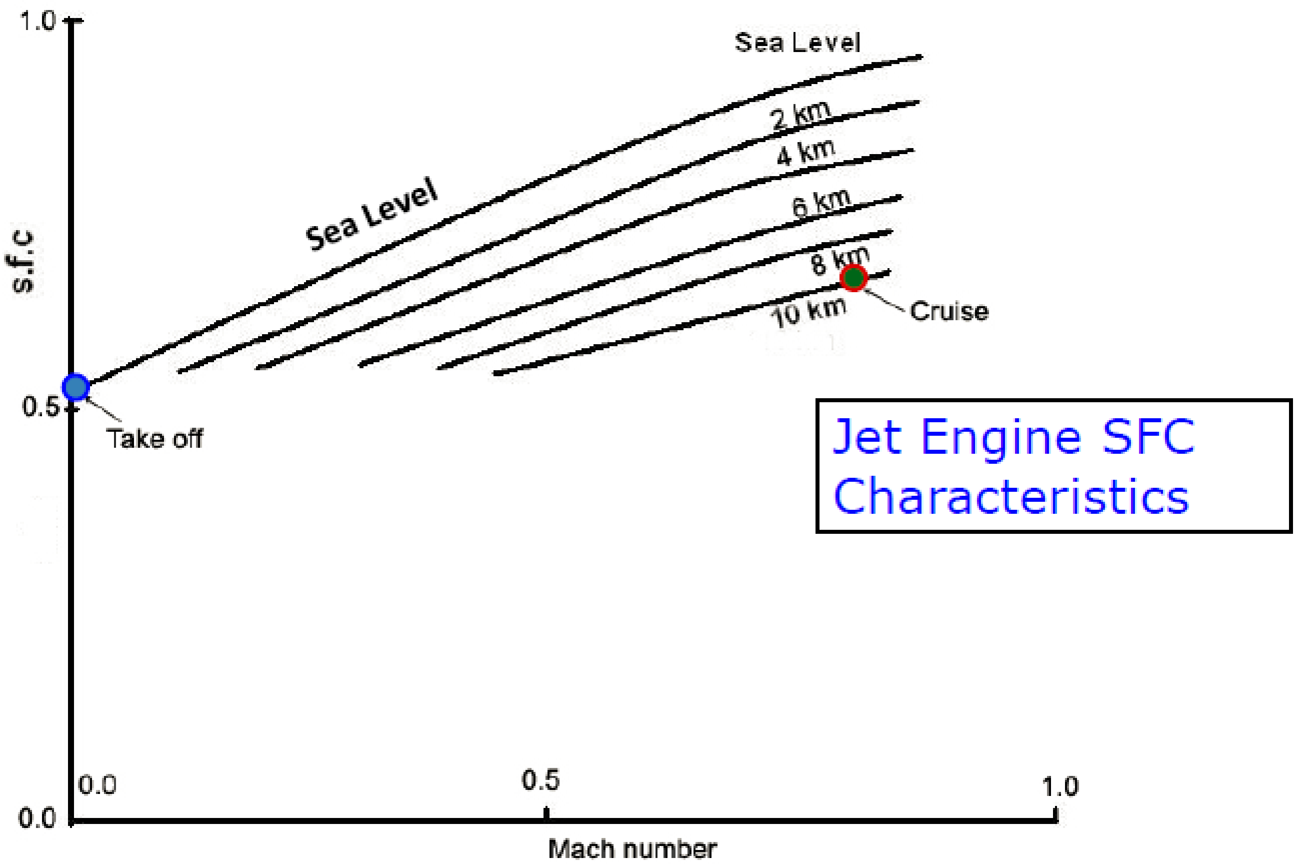
$$\eta_p = \frac{F_s v_0}{l_e}$$

- Total efficiency:

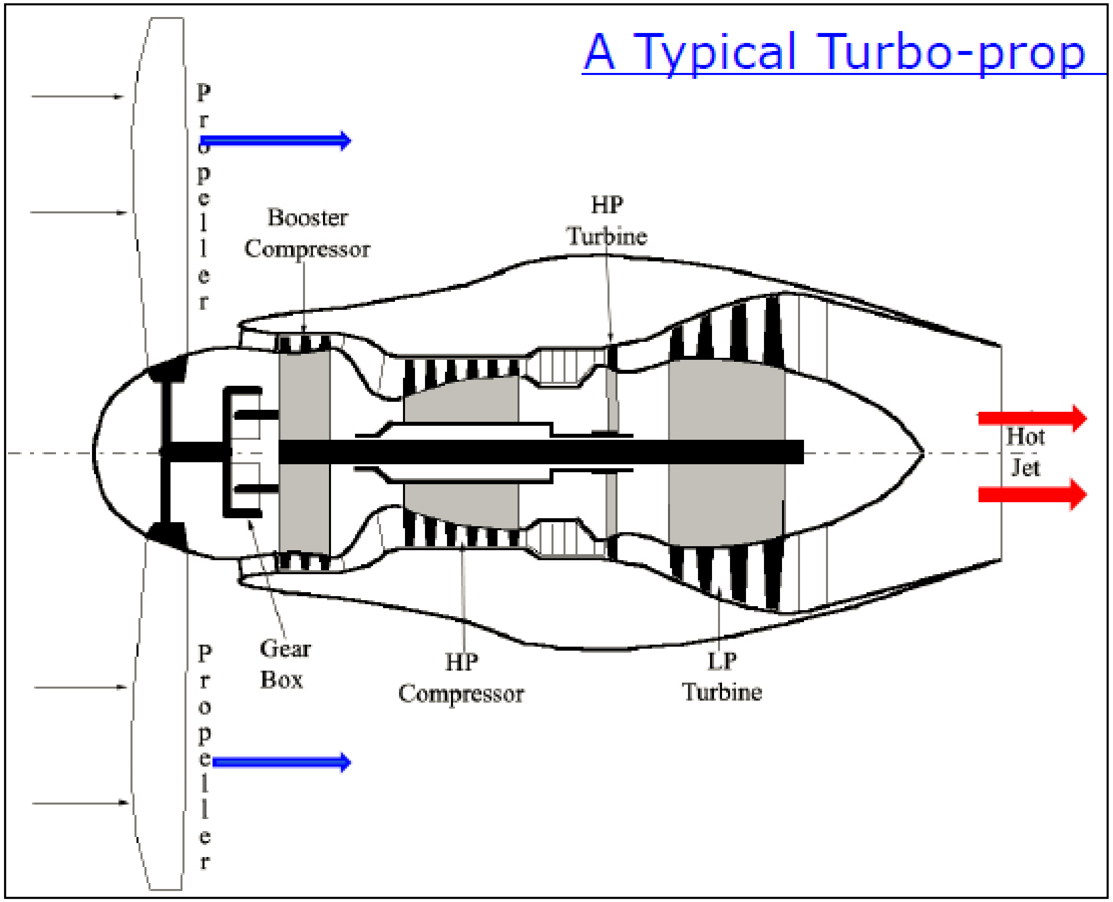
$$\eta_0 = \eta_t \cdot \eta_p$$

Jet Engine Thrust Characteristics



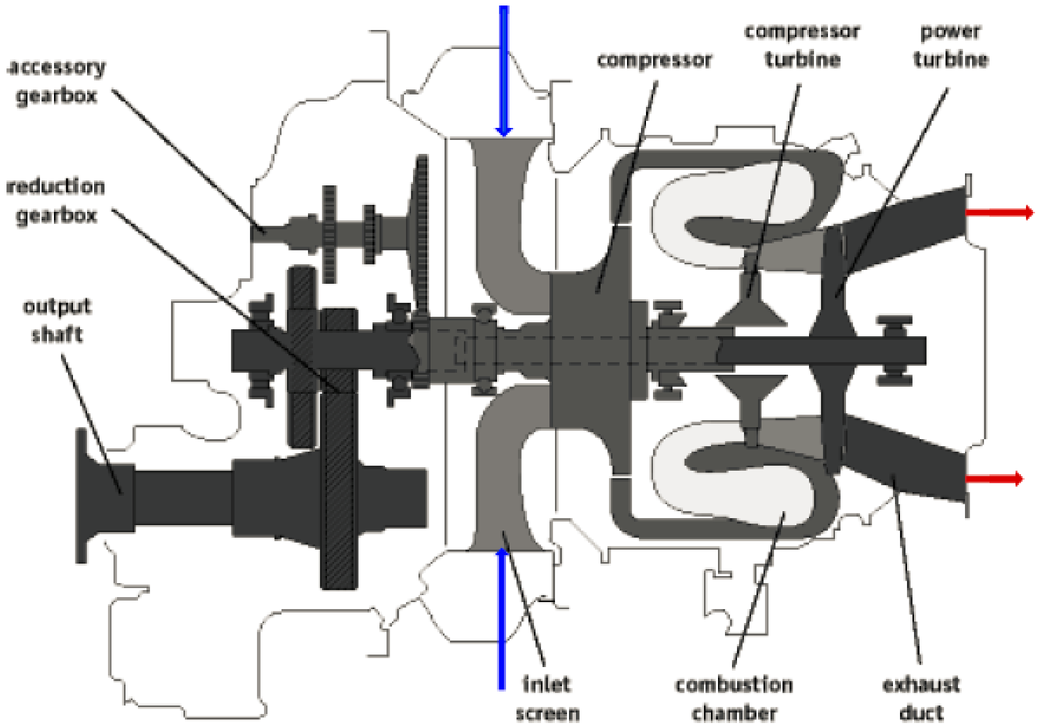

1.0
0.5
0.0
s.f.c
Sea Level
Sea Level
2 km
4 km
6 km
8 km
10 km
Cruise
Take off
0.0
0.5
1.0
Mach number
Jet Engine SFC Characteristics

A typical turbo-prop engine



- $P_e = q_{mg} l_{Te}$
- $P_P = P_e \eta_m$
- P'_P
- η_P
- F_P
- F_9, F
- sfc

A typical turbo-shaft engine



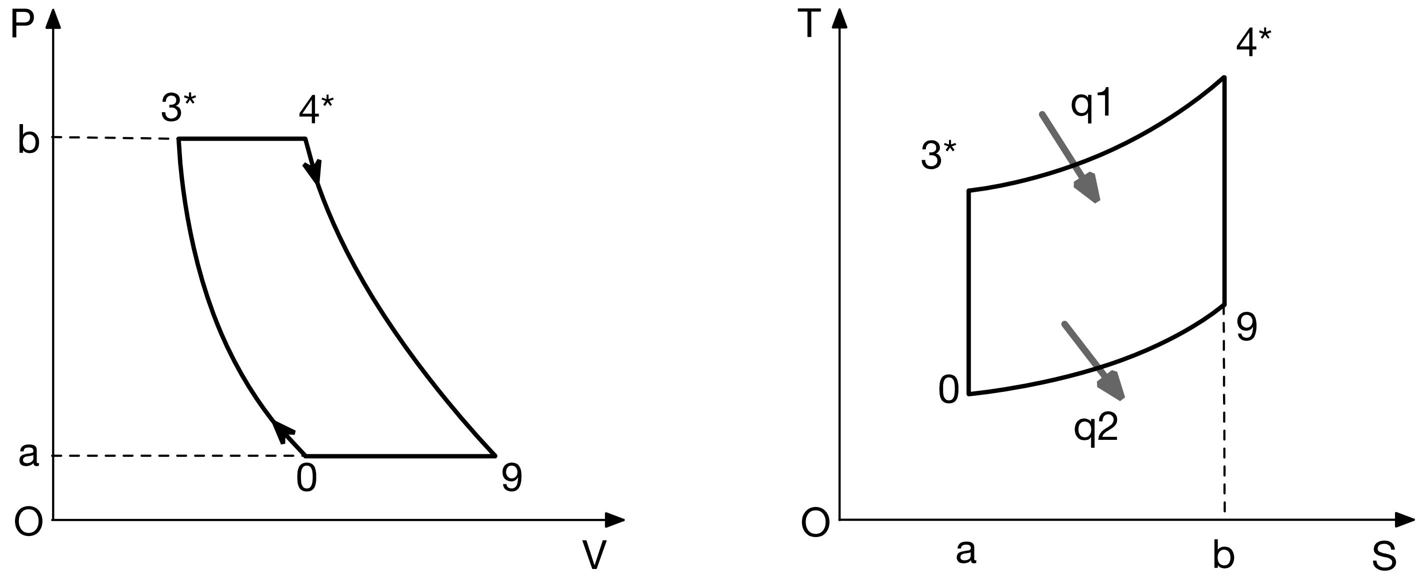
- P、P_s、sfc

Thermodynamic Cycles

Brayton cycle

- Modern day gas turbines operate on Brayton cycle and work with rotating machinery.
- Ideal Brayton cycle

Ideal Brayton cycle for turbo-jet



Brayton cycle on P-V and T-S diagrams

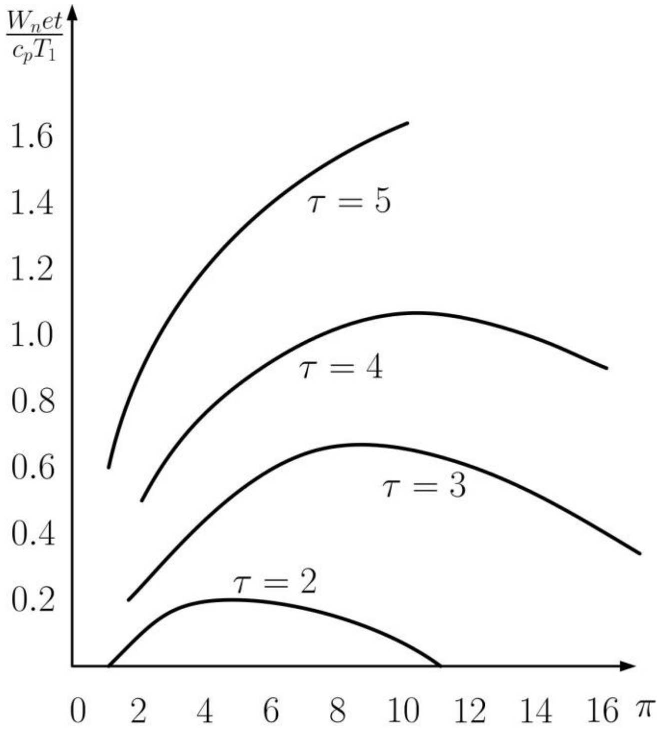
0-3: Isentropic compression
3-4: Constant-pressure heat addition
4-9: Isentropic expansion (in a turbine)
9-0: Constant-pressure heat rejection

Ideal Brayton cycle for turbo-jet

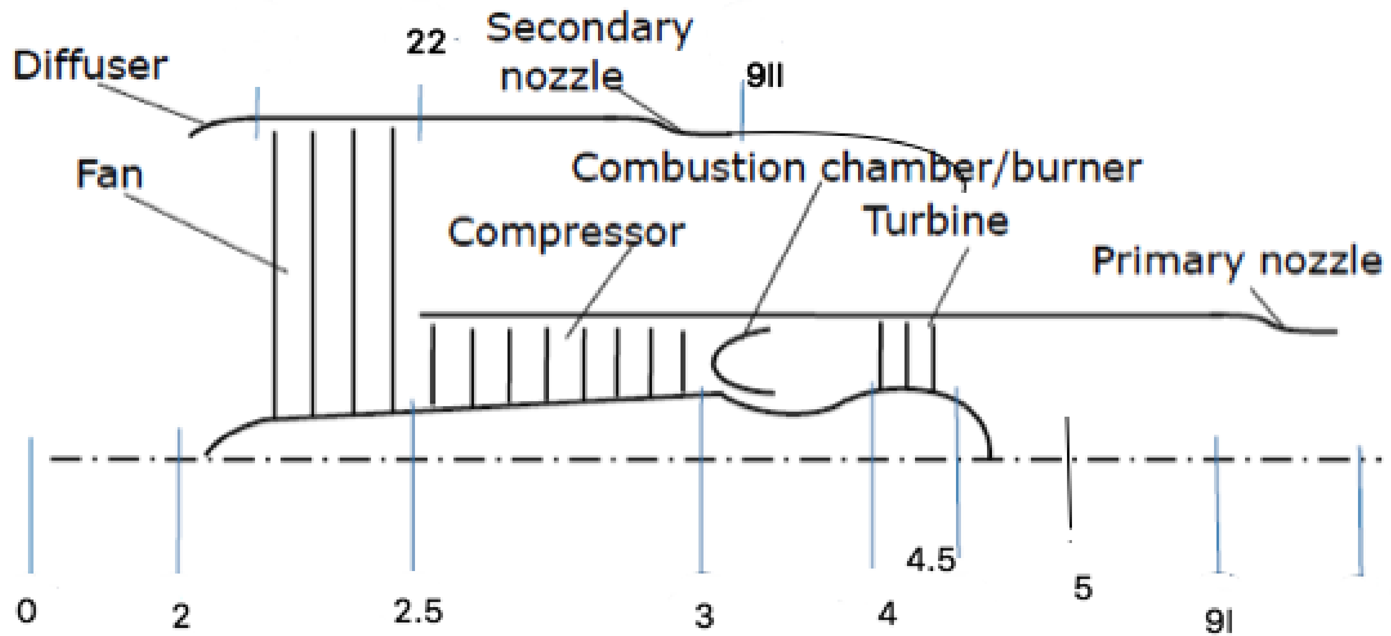
- Substituting these equations into the thermal efficiency relation and simplifying:

$$\eta_{th,Brayton} = 1 - \frac{1}{\pi^{(\gamma-1)/\gamma}}$$

- The thermal efficiency of a Brayton cycle is therefore a function of the cycle pressure ratio and the ratio of specific heats.

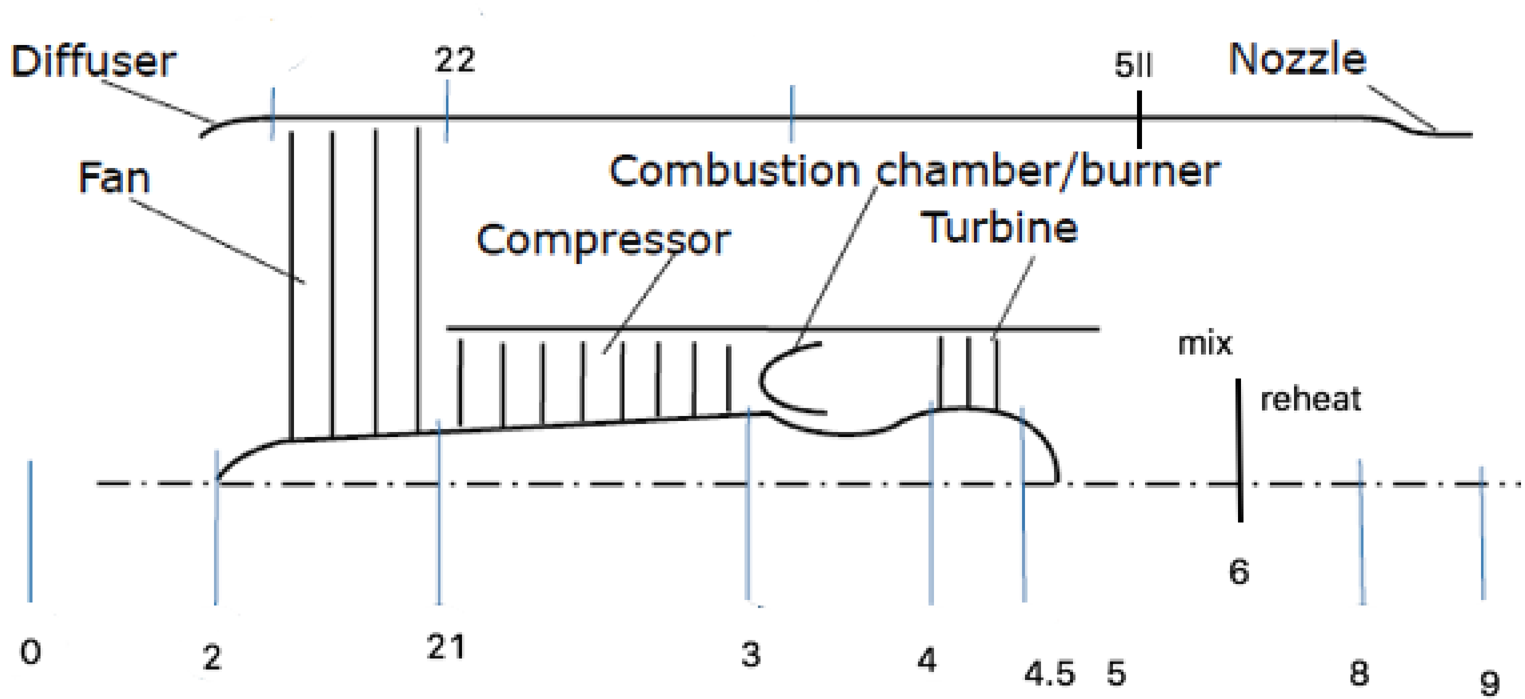


Ideal Brayton cycle for turbofan engine



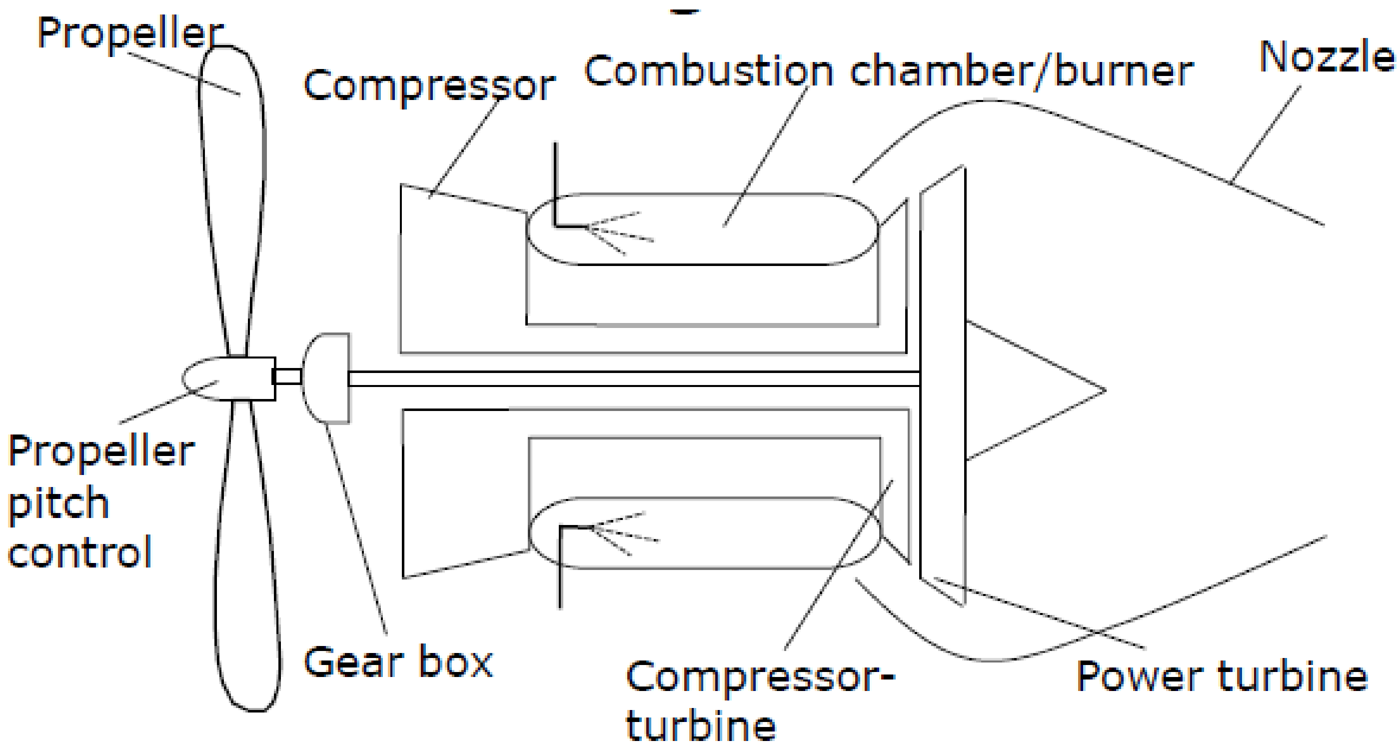
Schematic of an unmixed turbofan engine and station numbering scheme

Ideal Brayton cycle for turbofan engine



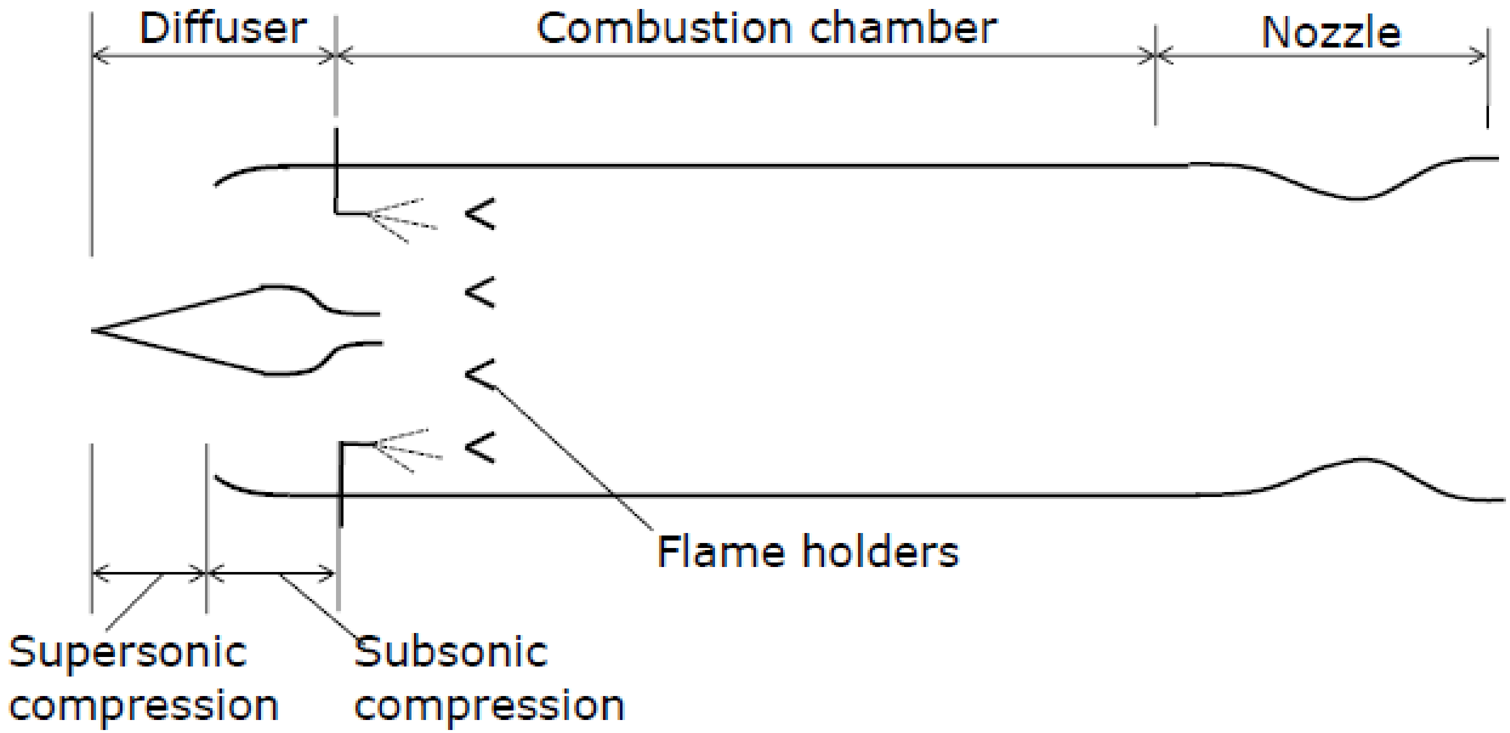
Schematic of an mixed turbofan engine and station numbering scheme

Ideal turboprop and turboshaft engines



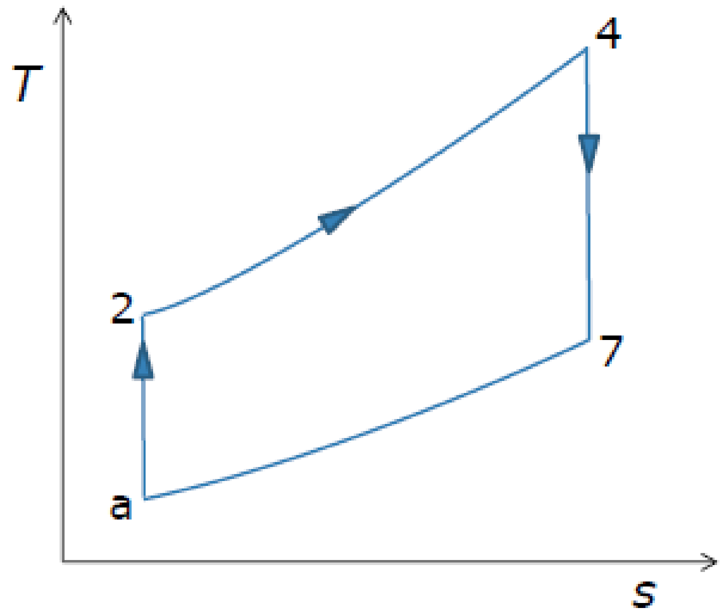
Schematic of typical turboprop engine

Ideal ramjet engines



Schematic of typical ramjet engine

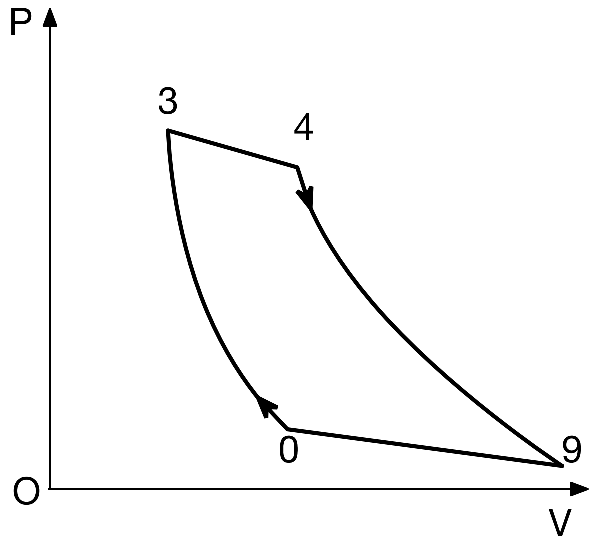
Ideal ramjet engines

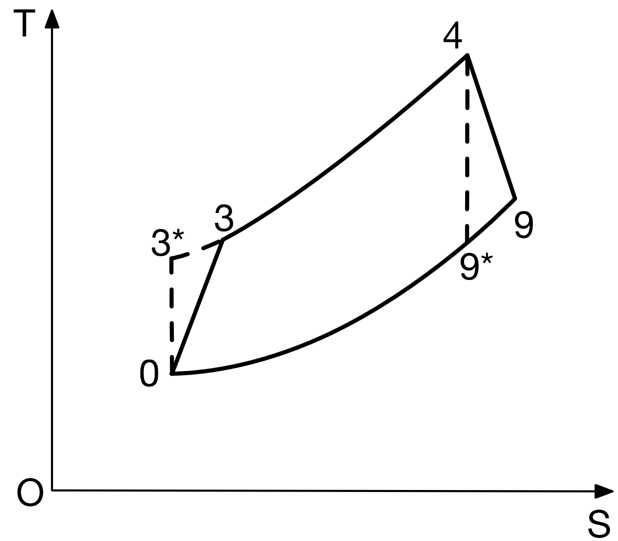


a-2: Isentropic compression in the intake
2-4: Combustion at constant pressure
4-7: Isentropic expansion through the nozzle

Ideal ramjet cycle on a T-S diagram

Actual/Real Brayton cycle



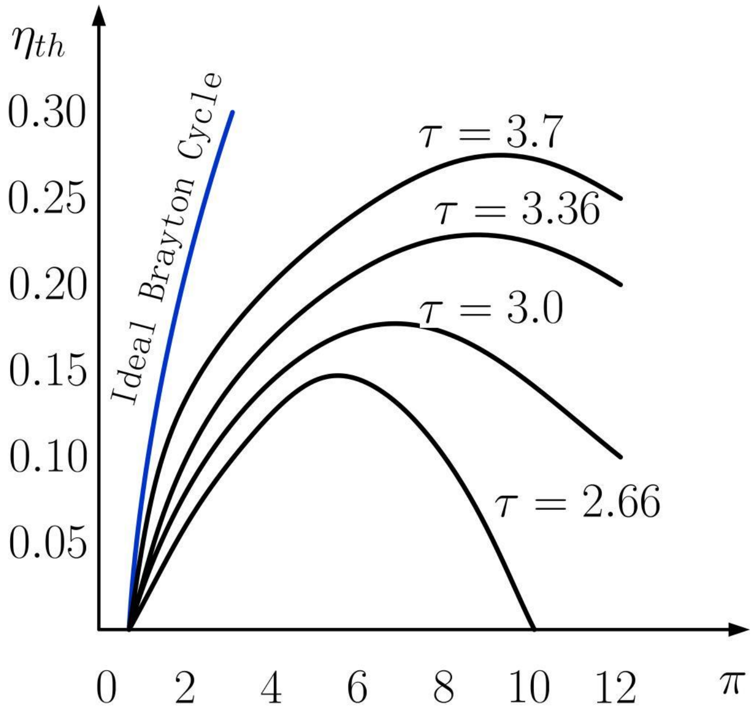


The deviation of actual compressors and turbines from the isentropic versions can be accounted for by using the isentropic efficiencies.

$$\eta_C = \frac{Isentropic\ work}{Actual\ work} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{Actual\ work}{Isentropic\ work} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

Actual/Real Brayton cycle



$\eta_{C,s} = \eta_T = 0.85,$
$T_1 = 290K, \gamma = 1.4$

- $\sigma_b = \frac{P_4^* - \Delta P_b^*}{P_3^*}$
- $\sigma = \sigma_1 \sigma_b \sigma_9$