Jet and Rocket Propulsion

AE4451

LECTURE 14

Sedina Tsikata – February 10, 2023

Overview

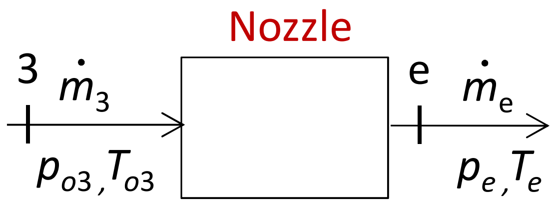
what we saw last time:

- real ramjet cycle analysis
    - component analysis
    - differences with respect to ideal cycle

today:

- turbojets and turbojet cycle analysis

Comment on efficiency



- last lecture, introduced nozzle efficiency (η_N) for ramjet

$$T_{e_s} = T_{o3}\left({p_e}/{p_{o3}} \right)^{\gamma-1/\gamma}$$

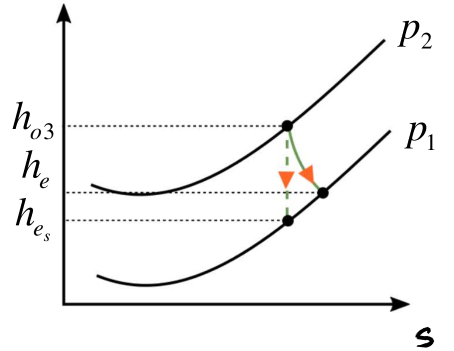
if isentropic expansion: just relating temperatures and pressures

$$T_e = T_{o3}\left\{1 - \eta_N \left[1 - \left(\frac{p_e}{p_{o3}}\right)^{\gamma-1/\gamma}\right]\right\}$$

considering non-isentropic case, where now

$$\eta_N = \frac{h_{o3} - h_e}{h_{o3} - h_{e_s}}$$

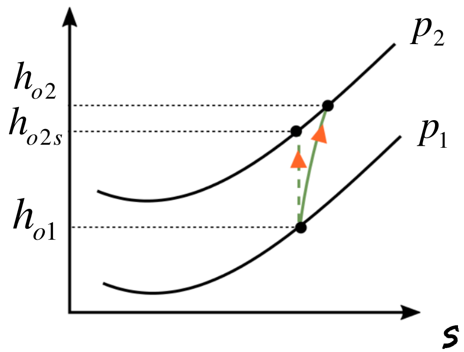
high to low pressure (p_2 to p_1)



this differs from the other efficiency we introduced earlier

$$\eta_d = \frac{h_{o_{2_s}} - h_{o_1}}{h_{o_2} - h_{o_1}}$$

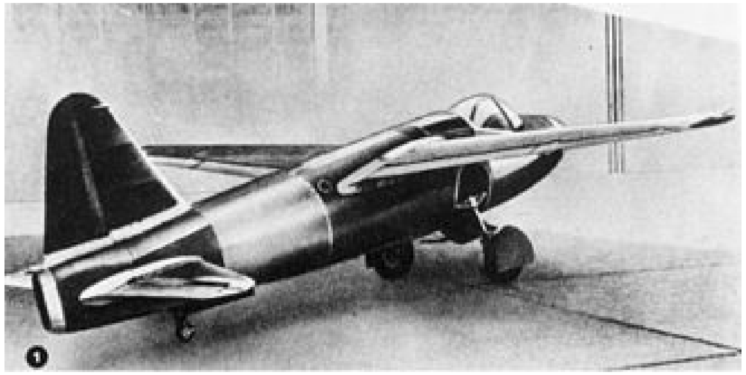
compressor adiabatic efficiency
low to high pressure



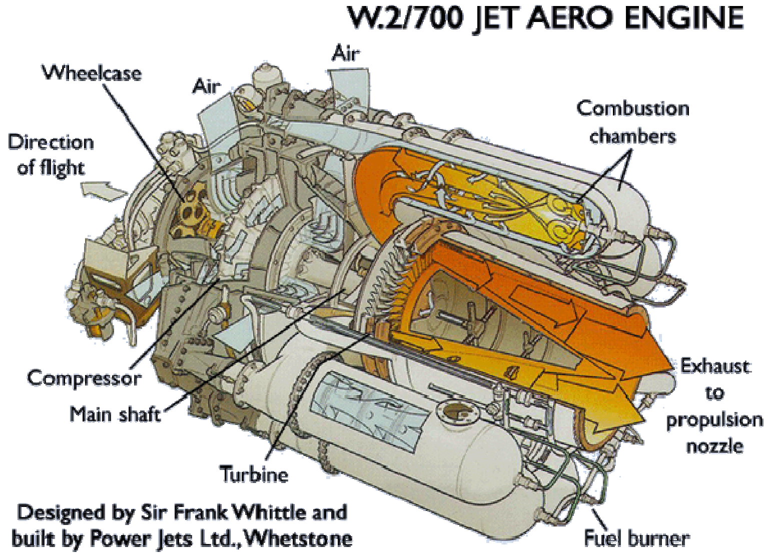
Turbojets

Overview

- idea for turbine-assisted propulsion emerged early
  - 1921: French patent (Maxime Guillaume)
- practical turbojets were implemented in the 1930's
  - inventors Frank Whittle and Hans von Ohain
- first turbojet engine to power an aircraft:
  Heinkel HeS 3 (von Ohain) in 1939

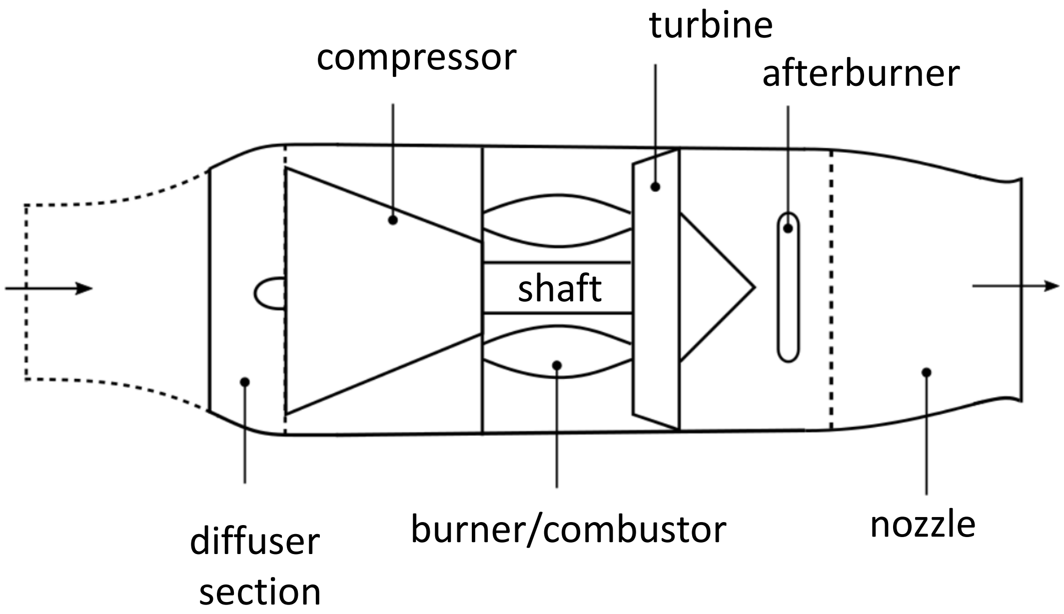


Heinkel He 178 aircraft



Turbojets

Structure and operation

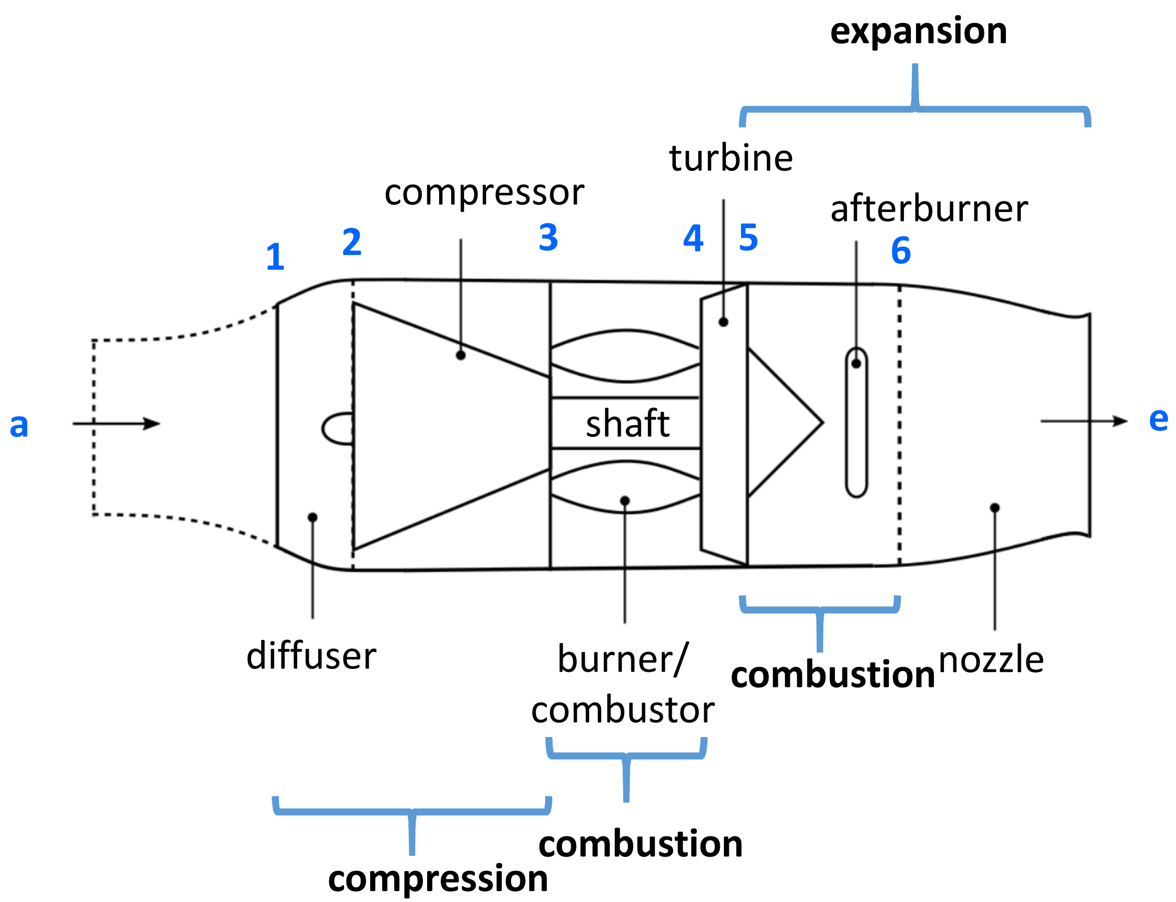


General Electric J85

- more complex configuration and more "stations" than a ramjet
- key advantage: can now produce thrust at zero speed
- operation at lower M than ramjet

Turbojets

Structure and operation

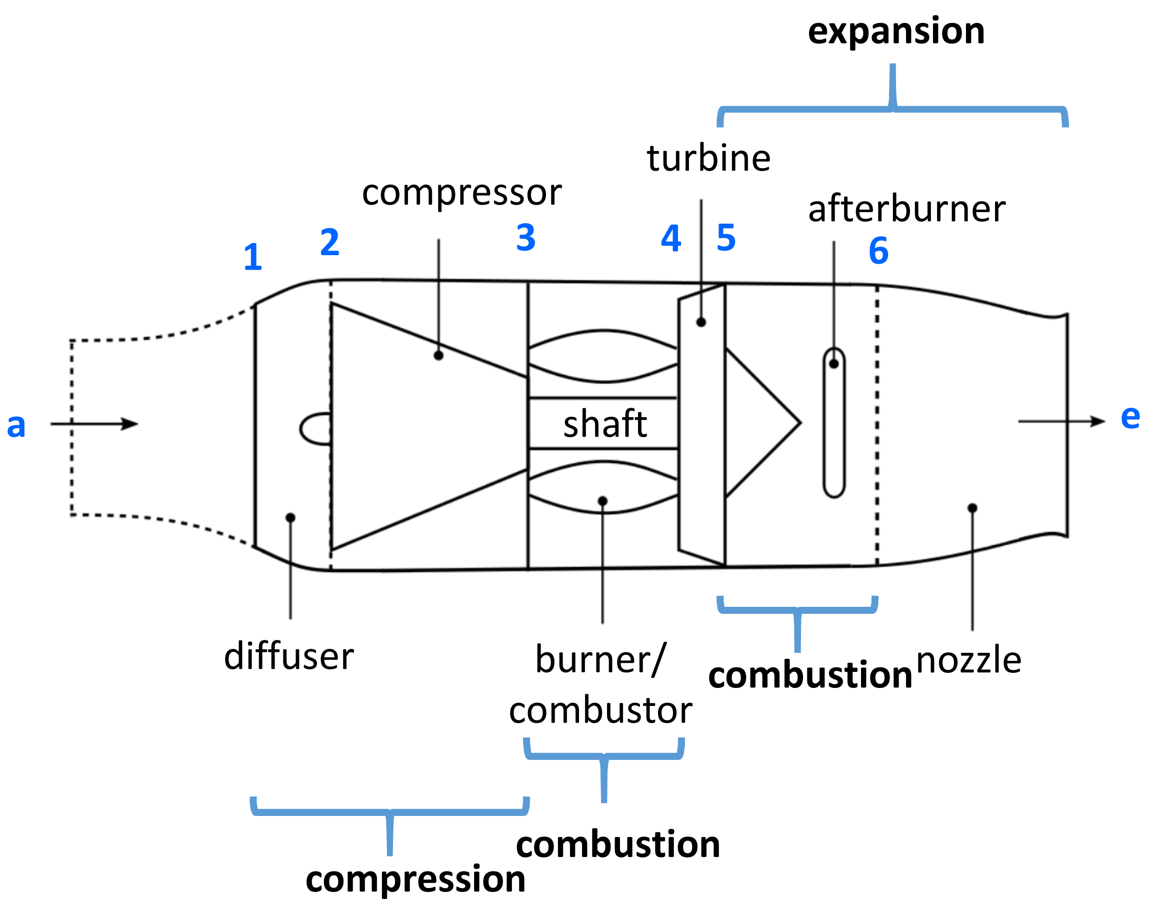


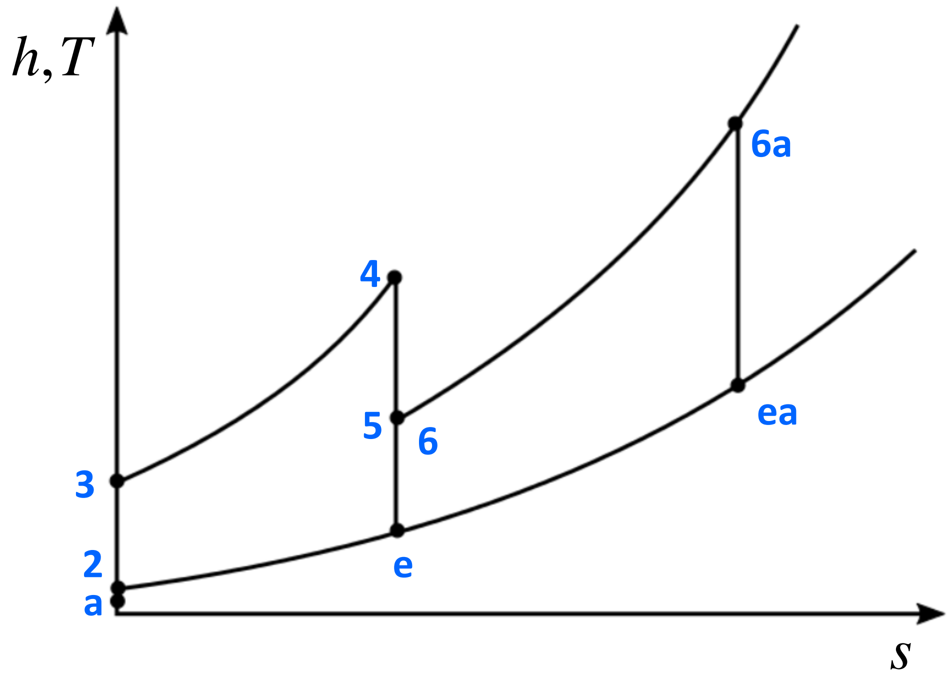
- axial flow compressor with multiple stages (10 – 15 is common) to progressively increase pressure
  - alternative: centrifugal/annular compressor (but less air flow)

- use of afterburner/augmentation device
  - normally, limitation of acceptable turbine blade temperature (< 50% of adiabatic flame temperature achieved with stoichiometric fuel-air ratio)
  - plenty of leftover oxygen
  - burn with additional fuel
  - provide extra thrust, acceleration

Turbojets

Cycle analysis: ideal turbojet





- isentropic compression (2-3)
- isentropic expansion (5-e) or with afterburner, (6a-ea)
- frictionless components
- components reversible, adiabatic

Turbojets

Cycle analysis: real turbojet

- we'll now assume non-reversible components
  - pressure losses possible

- for expansion and compression
  - use adiabatic effiency to characterize real processes (like non-ideal ramjet analysis)

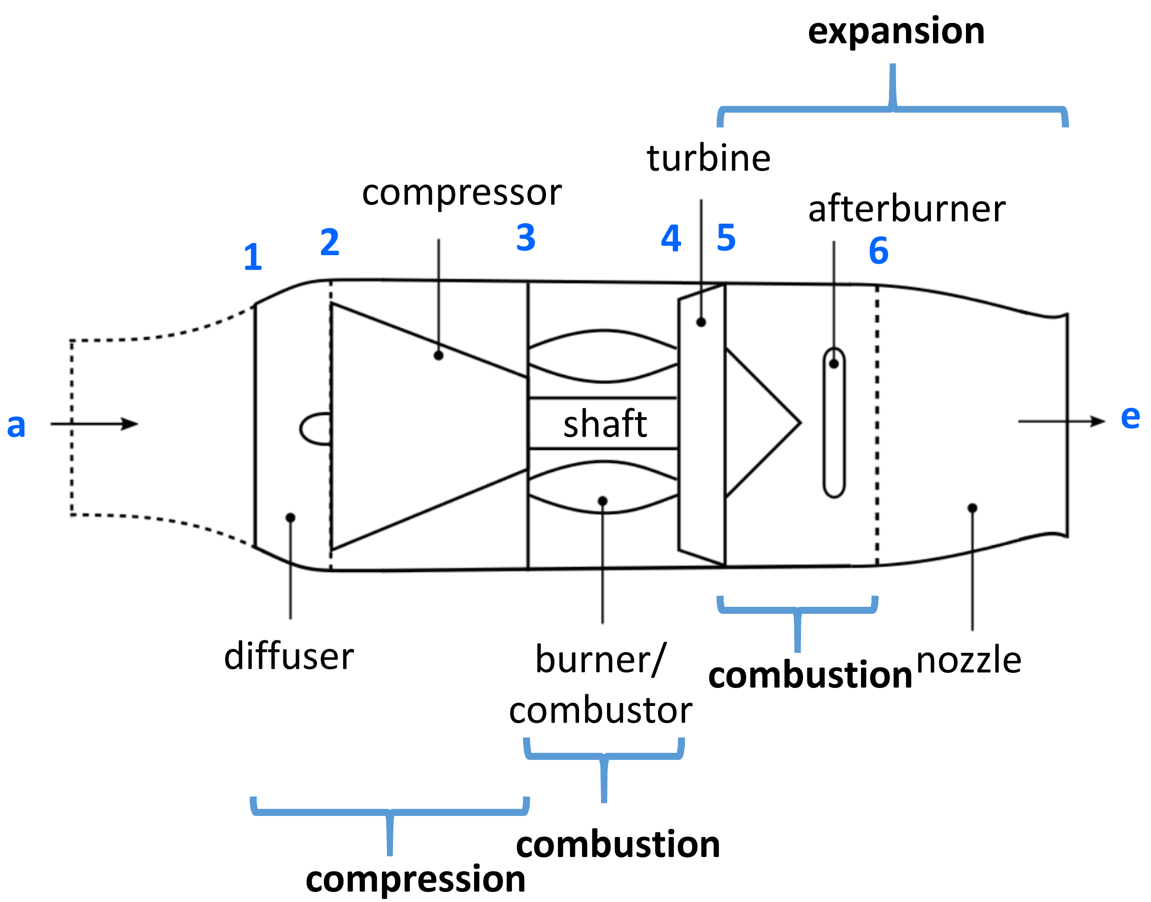
- for burners/combustors
  - use stagnation pressure ratios

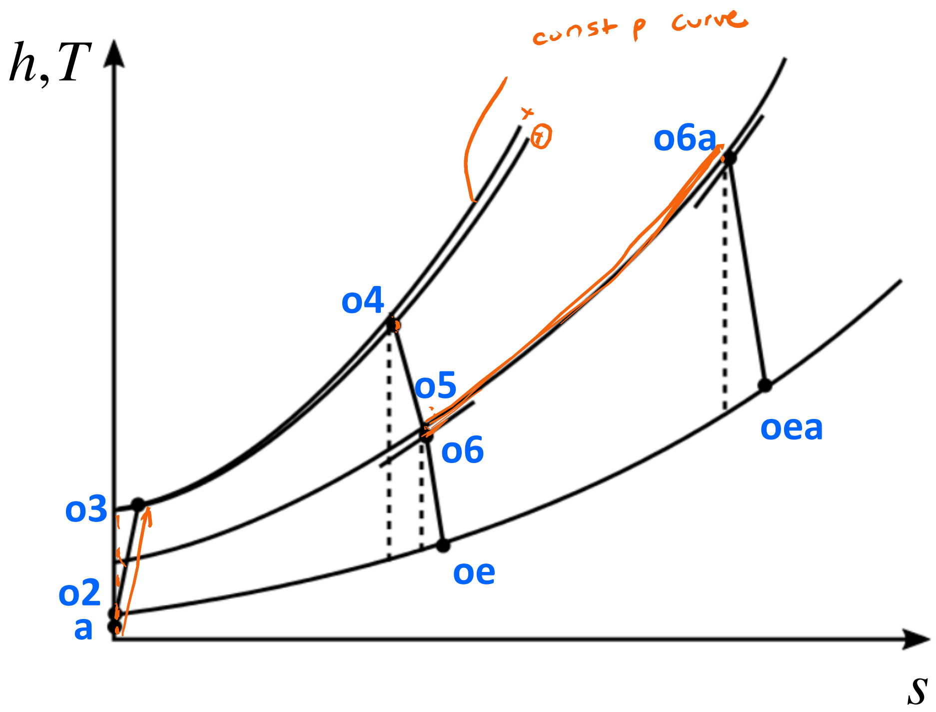
- assume burners/combustors do not achieve ideal heat release
  - use burner efficiencies

- assume c_p not constant throughout cycle, but averaged c_p can be assumed for each component

Turbojets

Cycle analysis: real turbojet

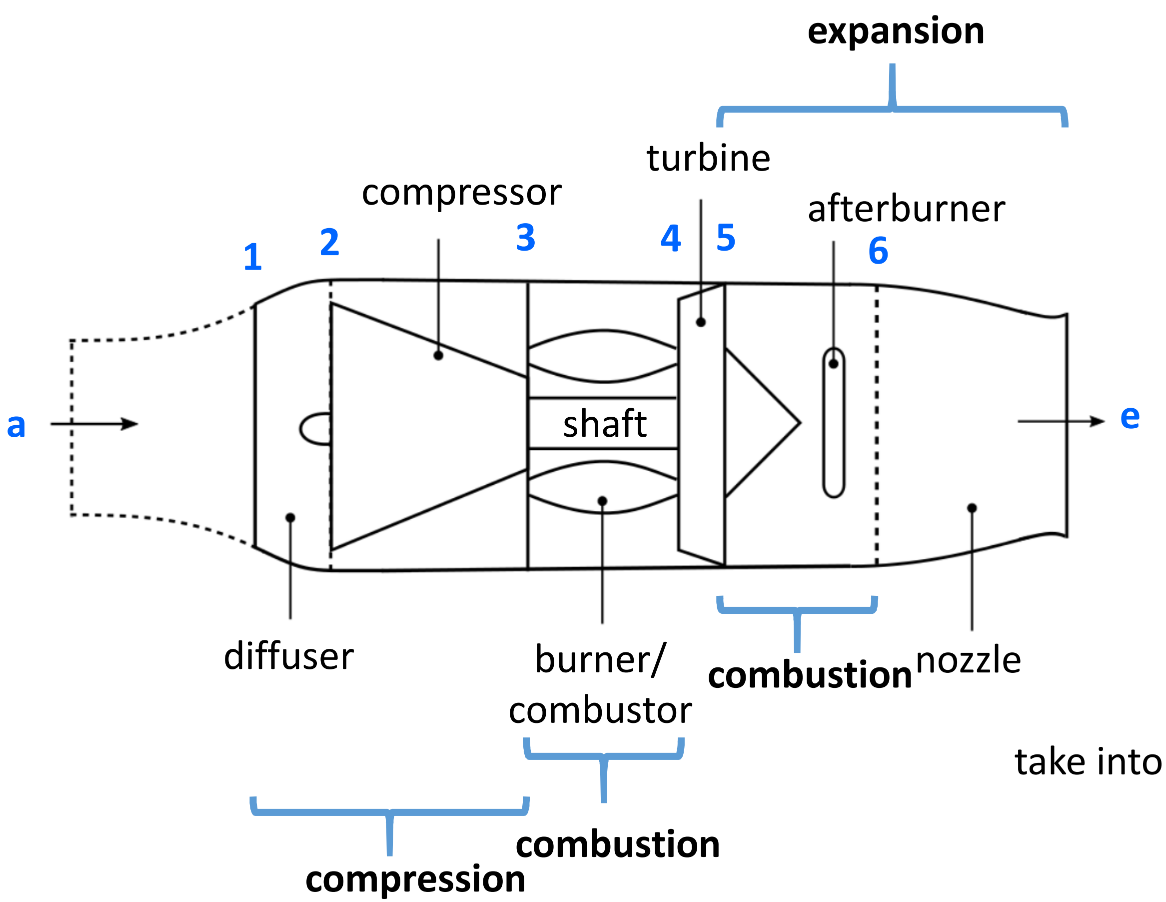




Turbojets

Real turbojet: diffuser

$\gamma_d = c_{p\gamma}/c_{v\gamma}$



Mass $\dot{m}_a = \dot{m}_1 = \dot{m}_2$

Energy $\dot{m}_a h_{oa} = \dot{m}_a h_{o1} = \dot{m}_a h_{o2}$

$$\Rightarrow T_{oa} = T_{o1} = T_{o2} \qquad \Rightarrow T_{o2} = T_a\left(1 + \frac{\gamma_d - 1}{2} M^2\right)$$

introduction of γ_d (due to our new treatment of cp)

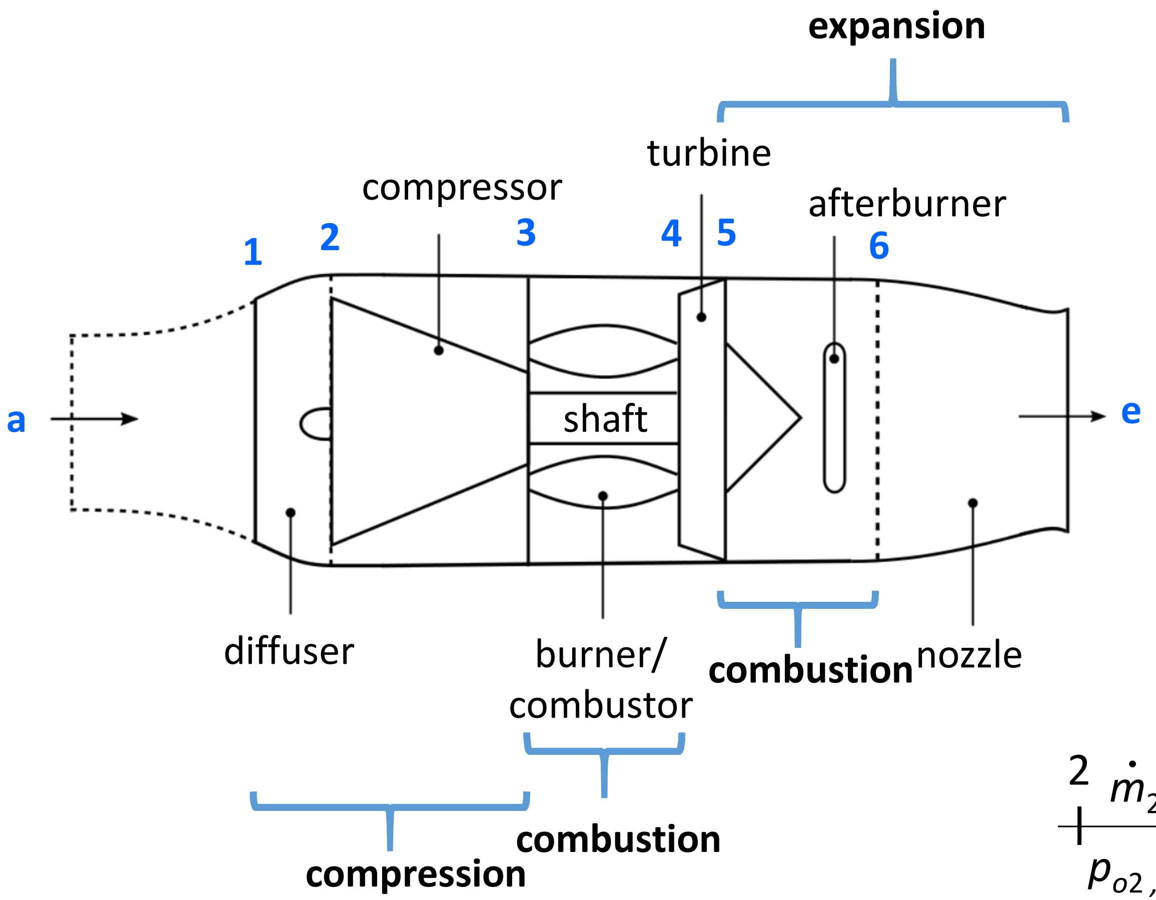
recall $$\frac{P_0}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

take into account ram recovery factor, diffuser efficiency

r_d

$$p_{o2} = p_a r_d \left(1 + \eta_d \frac{\gamma_d - 1}{2} M^2\right)^{\gamma_d / \gamma_d - 1}$$

Real turbojet: compressor



Mass $\dot{m}_3 = \dot{m}_2$

Energy $T_{o3} = T_{o2}\left\{1 + \frac{1}{\eta_c}\left[\left(\frac{p_{o3}}{p_{o2}}\right)^{\frac{\gamma_c - 1}{\gamma_c}} - 1\right]\right\}$

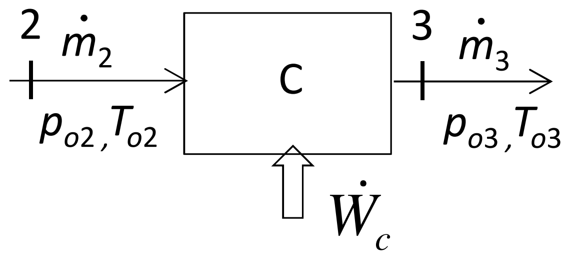
$\dot{W}_c = \dot{m}_3 c_{p_c}\left(T_{o3} - T_{o2}\right)$ work on compressor

take into account compressor efficiency η_c

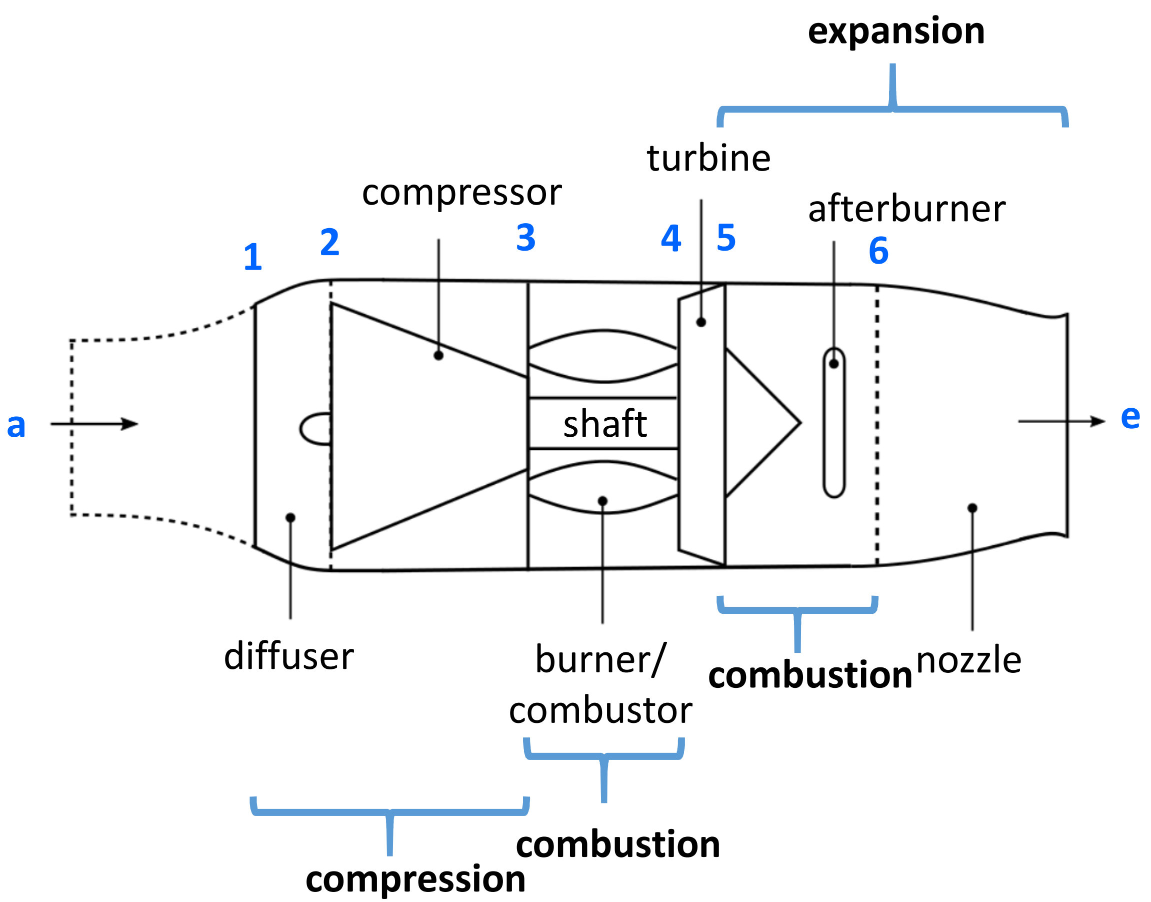
introduction of γ_c //

compressor ratio

$\frac{p_{o3}}{p_{o2}} = \text{design choice} = P_{rc}$



Real turbojet: burner/combustor



$\dot{m}_3 = \dot{m}_2 = \dot{m}_1$

Mass

$$\dot{m}_a + \dot{m}_f = \dot{m}_4$$

$$\dot{m}_4 = \dot{m}_a (1 + f)$$

Energy

$$f = \frac{T_{o4}/T_{o3} - 1}{\left(\eta_b \Delta h_R / c_{pb} T_{o3}\right) - T_{o4}/T_{o3}}$$

burner efficiency (η_b)

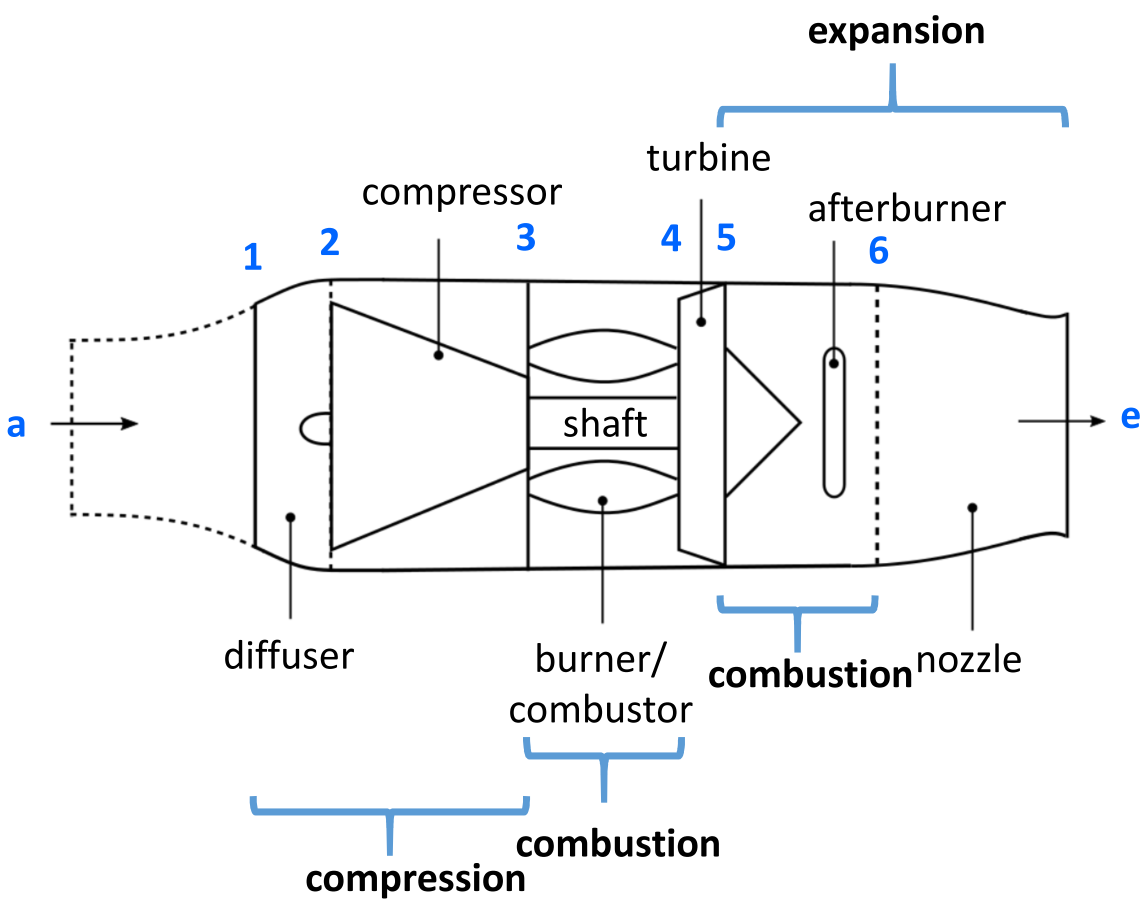
as we saw for ramjet

$$\frac{p_{o4}}{p_{o3}} = P_{rb}$$ burner pressure ratio

Turbojets

Georgia Tech

Real turbojet: turbine



Mass $\dot{m}_5 = \dot{m}_4$

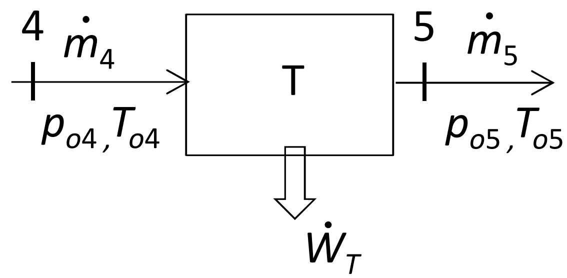
$\dot{W}_T = \dot{W}_C$

Energy

$$T_{o5} = T_{o4} - \frac{\dot{W}_T / \dot{m}_a}{c_{p_t}(1+f)}$$

$$p_{o5} = p_{o4}\left\{1 - \frac{1}{\eta_t}\left(1 - \frac{T_{o5}}{T_{o4}}\right)\right\}^{\frac{\gamma_t}{(\gamma_t - 1)}}$$

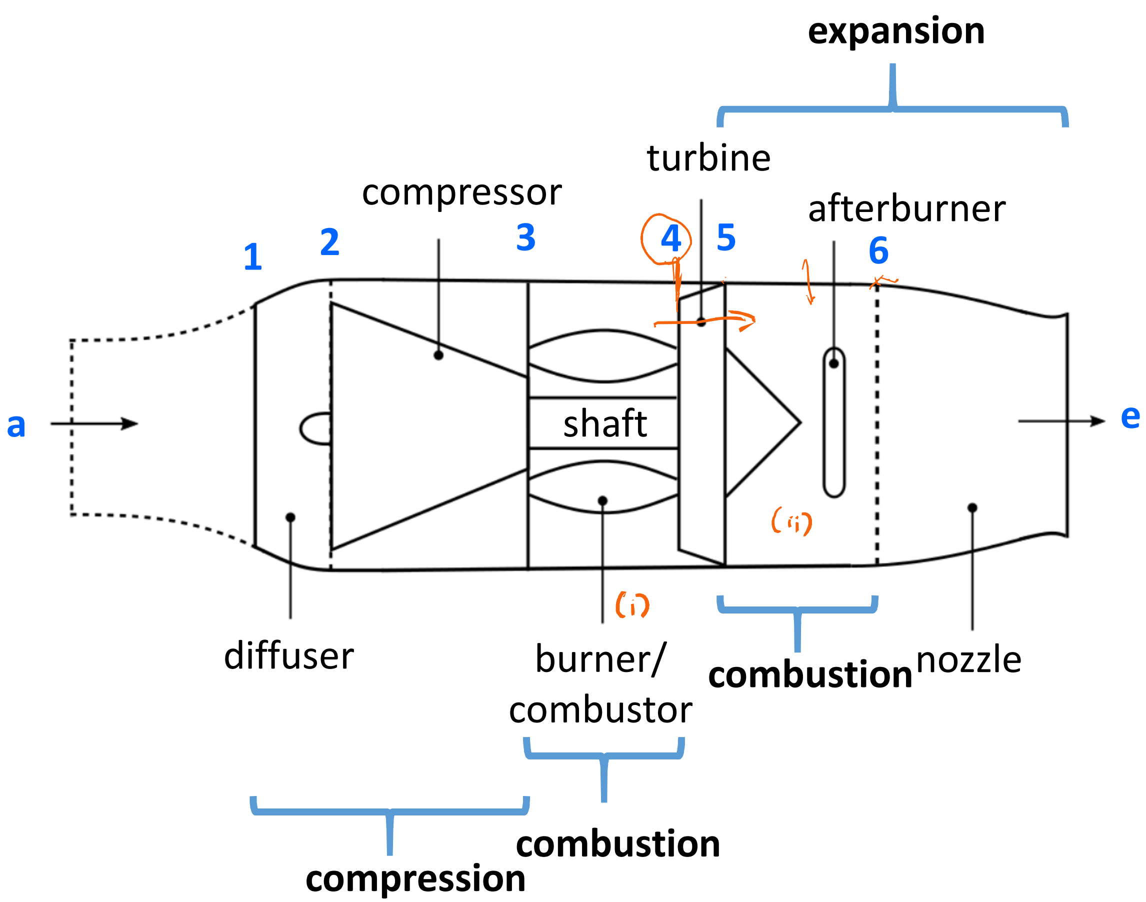
turbine efficiency

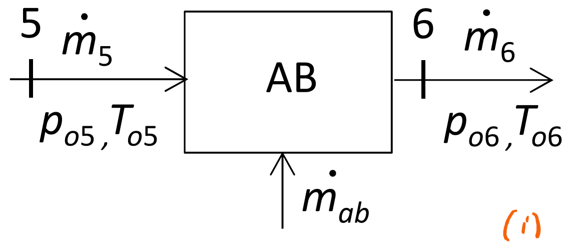


Turbojets

Real turbojet: afterburner

AB = afterburner





(i) (ii)

Mass $$\dot{m}_6 = \dot{m}_5 + \dot{m}_{fuel_{ab}} = \dot{m}_a\left(1 + f + f_{ab}\right)$$

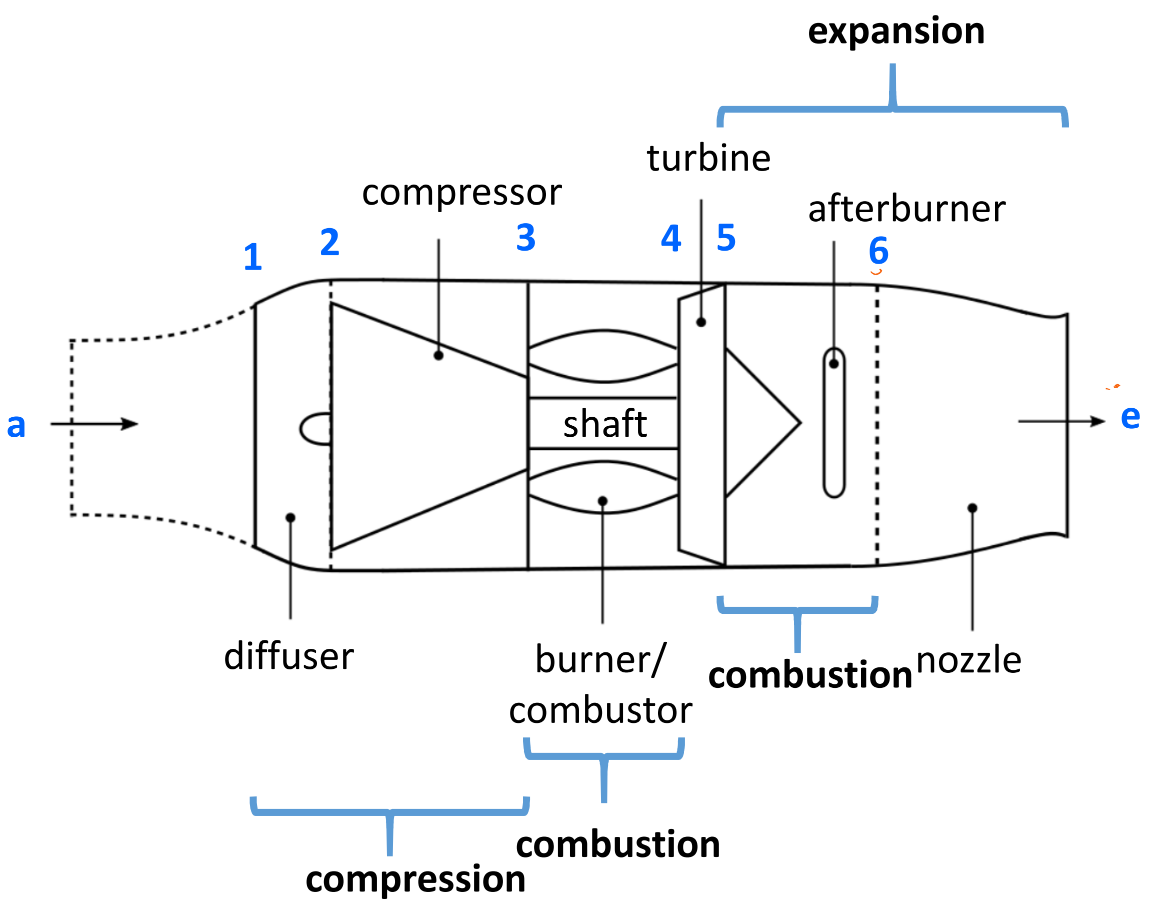
i.e. we have two sources of added fuel

Energy $$f_{ab} = \left(1+f\right)\frac{T_{o6}/T_{o5} - 1}{\left(\eta_{ab}\Delta h_R / c_{p_{ab}} T_{o5}\right) - T_{o6}/T_{o5}}$$

$$T_{o6} = \frac{\eta_{ab} f_{ab}\,\Delta h_r / c_{p_{ab}} + \left(1+f\right)T_{o5}}{1 + f + f_{ab}}$$

Turbojets

Real turbojet: nozzle



Mass $$\dot{m}_e = \dot{m}_6$$

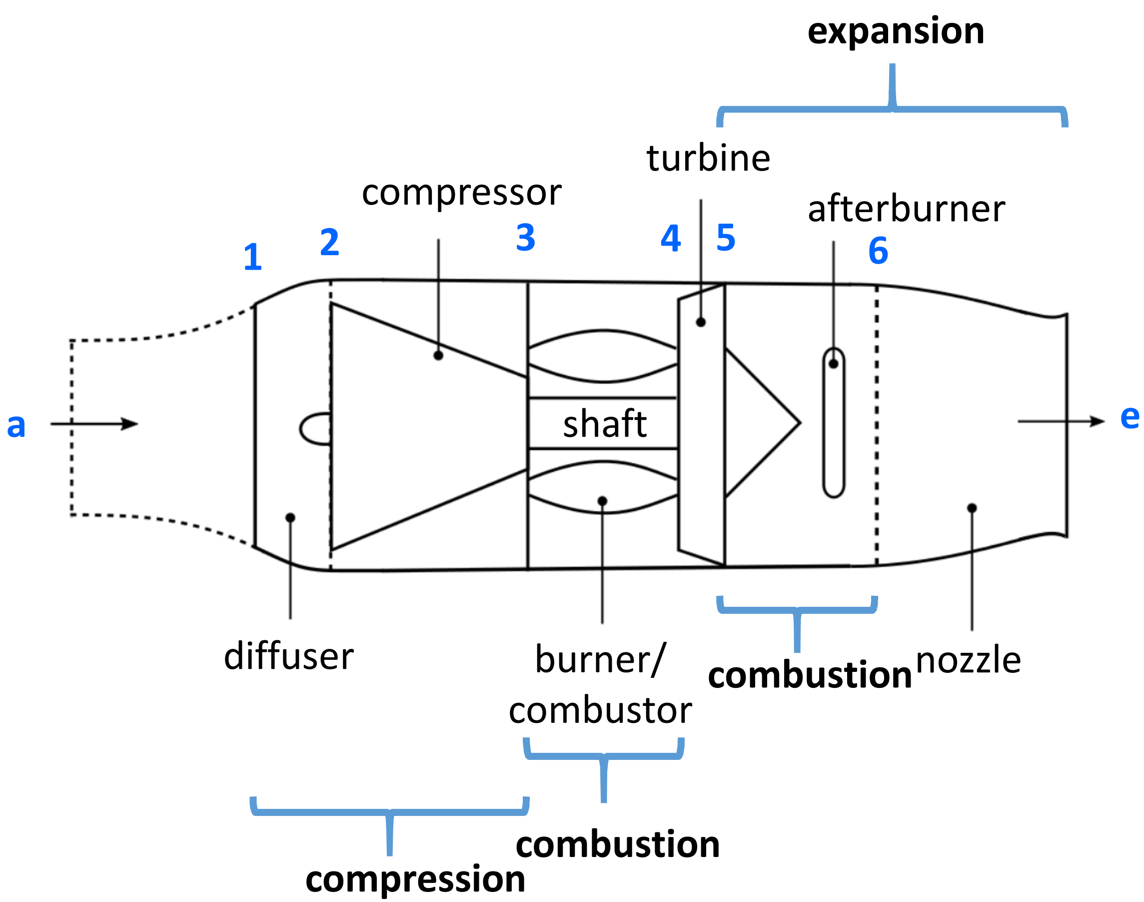
Energy $$T_e = T_{o6}\left\{1-\eta_n\left[1-\left(\frac{p_e}{p_{o6}}\right)^{\frac{\gamma_n-1}{\gamma_n}}\right]\right\}$$

$$u_e = \sqrt{2c_{p_n}\left(T_{o6}-T_e\right)}$$

notice how we've been able to arrive at the ejection velocity simply by doing a component-by-component analysis

Turbojets

Real turbojet performance



- only modification compared to ramjet is addition of the afterburner; main definitions unchanged

$$ST = \frac{\tau}{\dot{m}_a} = \left[(1+f+f_{ab})u_e - u\right] + \frac{(p_e - p_a)A_e}{\dot{m}_a}$$

$$TSFC = \frac{\dot{m}_f + \dot{m}_{f_{ab}}}{\tau} = \frac{f + f_{ab}}{ST}$$

$$\eta_o = \frac{1}{TSFC}\frac{u}{\Delta h_R}$$

$$\eta_{th} = \frac{\Delta \dot{KE}}{\left(\dot{m}_f + \dot{m}_{f_{ab}}\right)\Delta h_R} = \frac{(1+f+f_{ab})u_e^2 - u^2}{\left(f + f_{ab}\right)\Delta h_R}$$

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

Turbojets

Real turbojet performance

from Hill and Peterson

$T_{max}\uparrow \Rightarrow ST\uparrow$ but $SFC\uparrow$

as with ramjet

- can choose Pr_c for "optimum" performance
- optimum $Pr_c \downarrow$ as $M\uparrow$

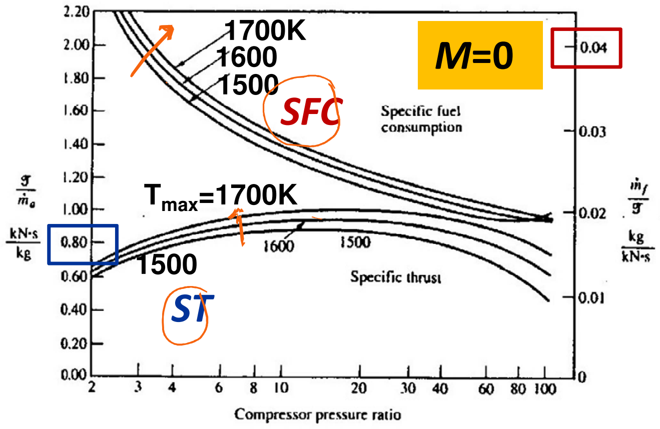


FIGURE 5.19 Turbojet static thrust and fuel consumption (M = 0).

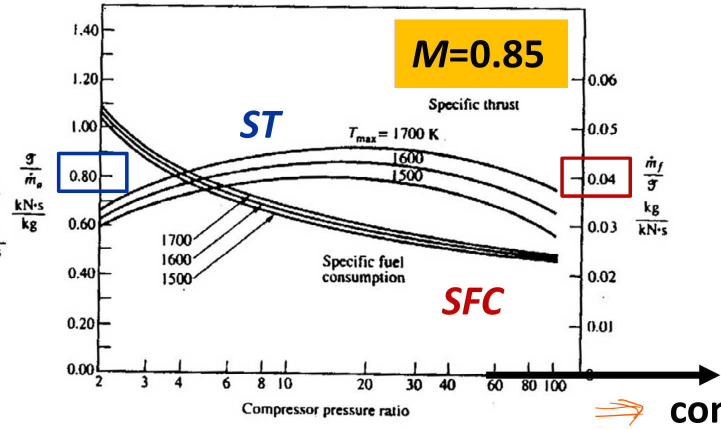


FIGURE 5.20 Turbojet cruise thrust and fuel consumption (M = 0.85).

compressor pressure ratio Pr_c

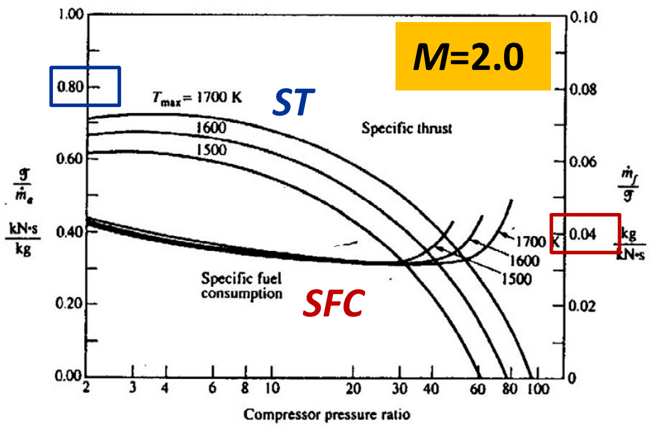


FIGURE 5.21 Turbojet cruise thrust and fuel consumption (M = 2).

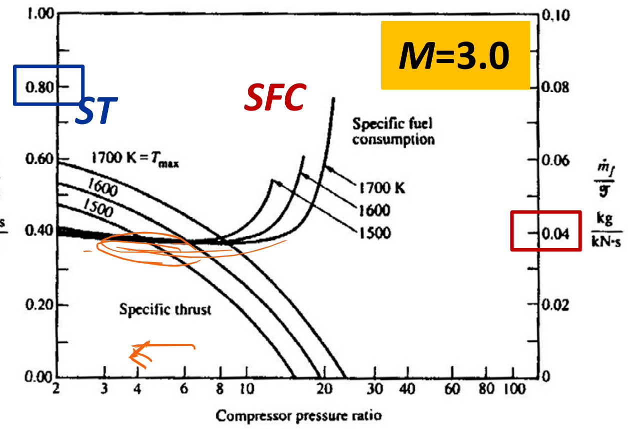


FIGURE 5.22 Turbojet cruise thrust and fuel consumption (M = 3).

Turbojets

Real turbojet performance: possible gains

- 3D printed turbine blades

  - GE Aviation for GE9X turbofan engine used in Boeing 777X jets since 2016
  - welding of layers of titanium aluminide powder (TiAl)
  - advantages:

  (i) weight: 50% lighter than conventional alloys

  (ii) can remove residual stress by pre-heating powder: reduce brittleness

10% gain in fuel efficiency

- Ceramic matrix composites (CMCs) since 2016, GE Aviation

- silicon fibers in silicon carbide matrix

(i) 1/3 weight of metals, less brittle than pure ceramics

(ii) less cooling needed

GE Aviation