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Jet and Rocket Propulsion

AE4451

LECTURE 12

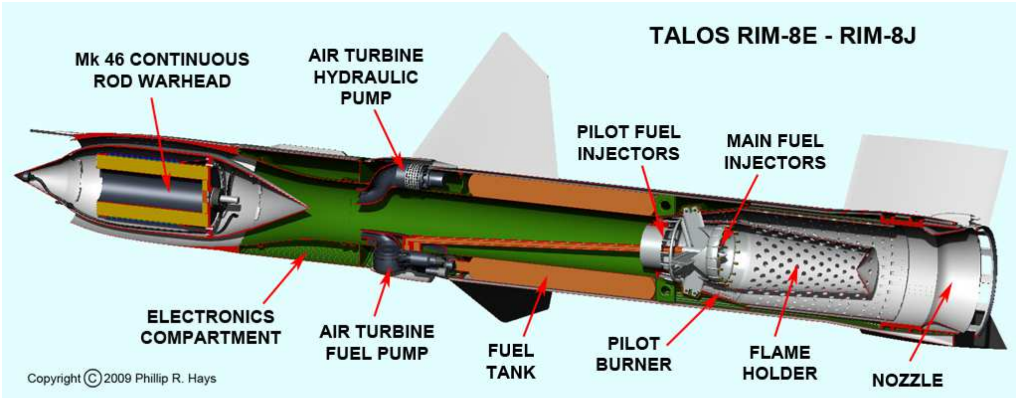
Sedina Tsikata – February 6, 2023

Ramjets

Overview

- original idea for ramjets predates the turbojet
  - 1913: French patent (René Lorin)
  - 1930's and early 1940's: development work in Soviet Union and Germany, including engine flight tests
  - late 1940's: first flight of ramjet powered winged aircraft (Leduc 0.10, France), 1949

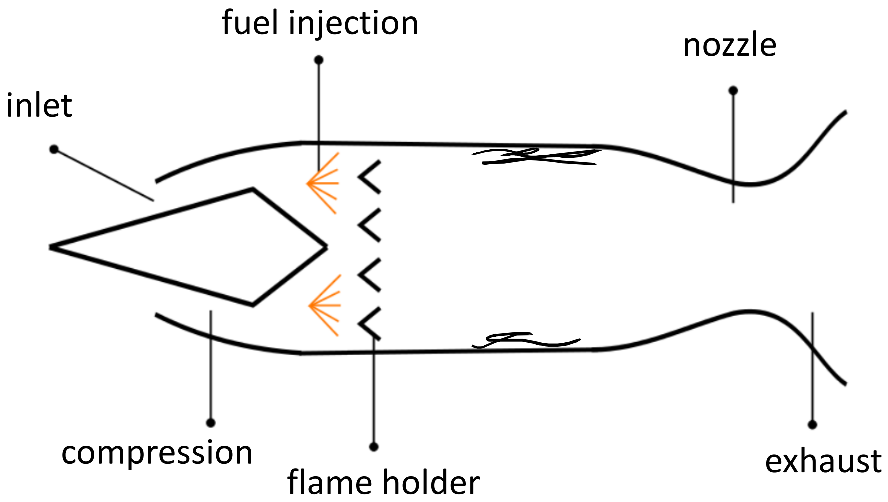
Leduc 0.10, Musée de l'Air et de l'Espace



early application: 1950s, US Navy SAM

Ramjets

Structure and operation



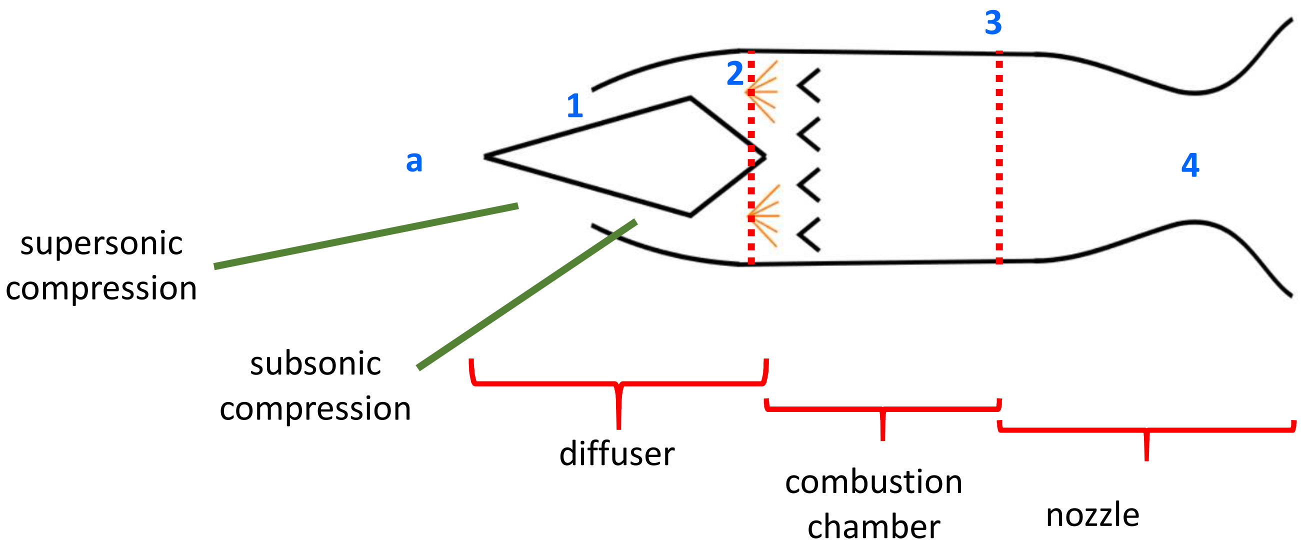
- simple configuration with no moving parts
- cannot produce thrust at zero speed
  - requires booster/staging with another vehicle or propulsion system
- pressure rise accomplished using diffuser
  - e.g. p_2/p_1 = 34 for Mach 3

- can operate at high combustion temp. (~2200-2500K)
  - no downstream turbine
  - higher maximum flight *M* than turbine engines
  - flame holder: improves stability, mixing

- protection of combustor and nozzle walls from hot gases
  - cooling air, thermal barrier coatings

Ramjets

Structure and operation



Ramjets

Performance (cycle) analysis

- goal: calculate performance of a ramjet as a function of input parameters

- performance parameters are outputs, e.g.

  specific thrust, thrust specific fuel consumption, efficiencies~~Inputs~~

- inputs include:

  flight conditions: Mach number, altitude (pa,Ta), fuel

  design choices: component performance, fuel choice, structural or thermal limitations

- simplest version is ideal cycle analysis

- key assumptions:

  (i) all components are ideal

  (ii) working fluid is thermally and calorically perfect gas

  (iii) fluid properties (γ, MW, …) do not change due to combustion

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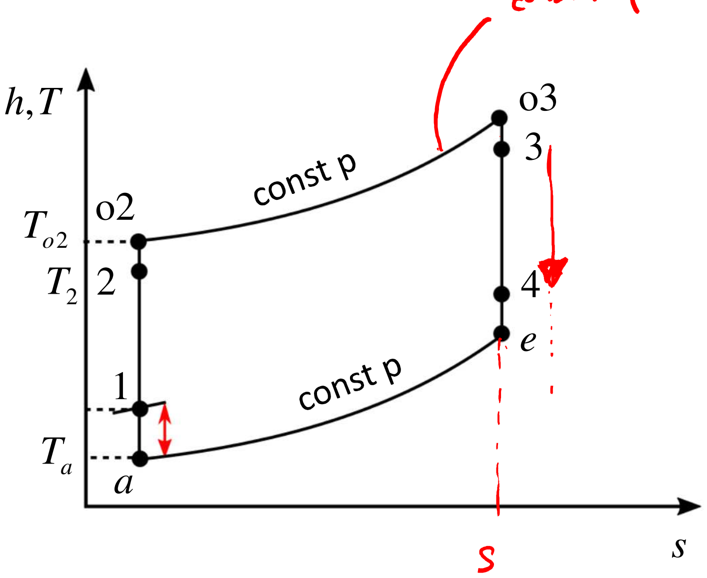
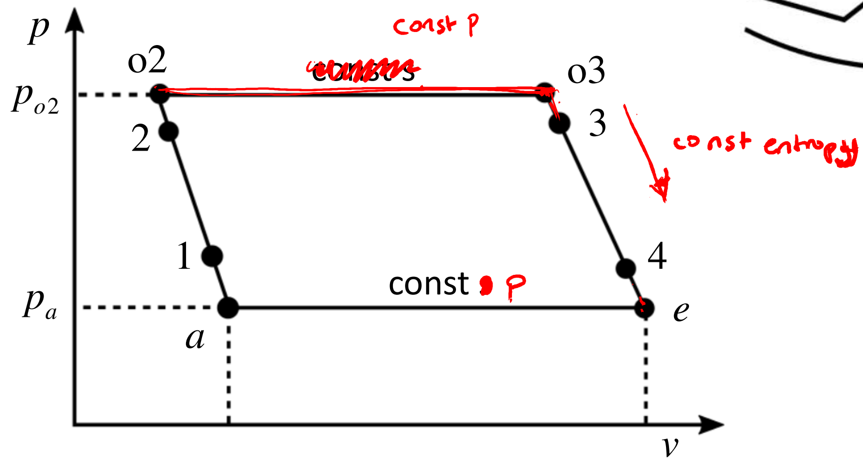
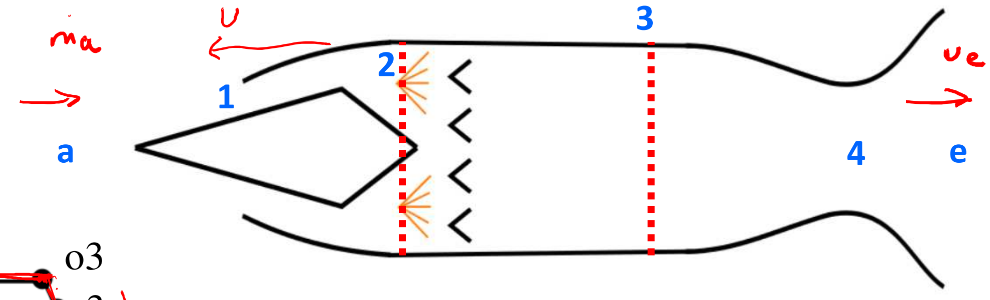
Ideal cycle analysis: (h,s) and (p,v) diagrams







a - 1: "ram effect", pressure increase due to deceleration

- consider our original expression for thrust τ

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

engine size

operator choice, materials

flight conditions

$f=$ fuel/air

- we need u_e

Ramjets

Relationship between stagnation and M (thermally and calorically perfect gases)

- recall expression for stagnation/total enthalpy h_0 from energy conservation

$$h_0 = h + \frac{v^2}{2} \qquad c_p = \frac{dh}{dT}$$

, and assuming calorically perfect gas, $T_0 = T + \dfrac{v^2}{2c_p}$

$$\frac{T_0}{T} = 1 + \frac{v^2}{2c_pT}$$

, and using the relation $c_p = \dfrac{\gamma R}{\gamma - 1}$, and sound speed a: $a = \gamma RT$ $\qquad M = \dfrac{v}{a}$

$\frac{v^2}{a^2}$ $\qquad \gamma$

we obtain: $\boxed{\dfrac{T_0}{T} = 1 + \dfrac{\gamma - 1}{2}M^2}$ T_0 and h_0 constant for adiabatic flow

- also recall from entropy conservation (conditions reversible and adiabatic) isentropic

from isentropic state equation $\dfrac{P_0}{P} = \left(\dfrac{T_0}{T}\right)^{\frac{\gamma}{\gamma - 1}}$

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

p_0 (stagnation pressure) and s_0 (stagnation enthalpy) constant if process also reversible

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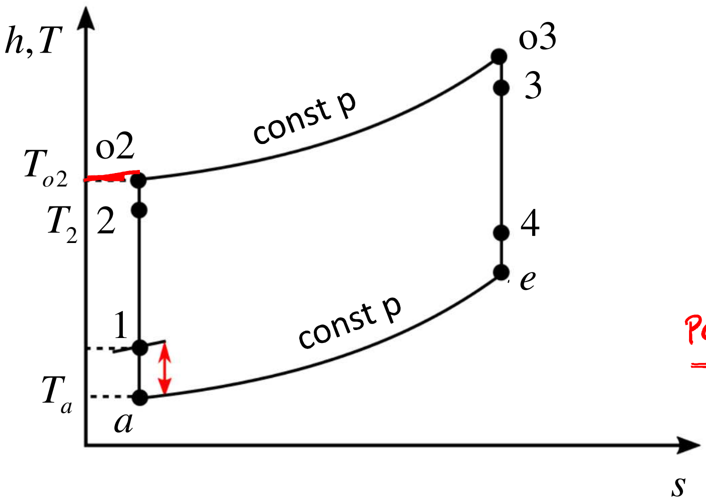
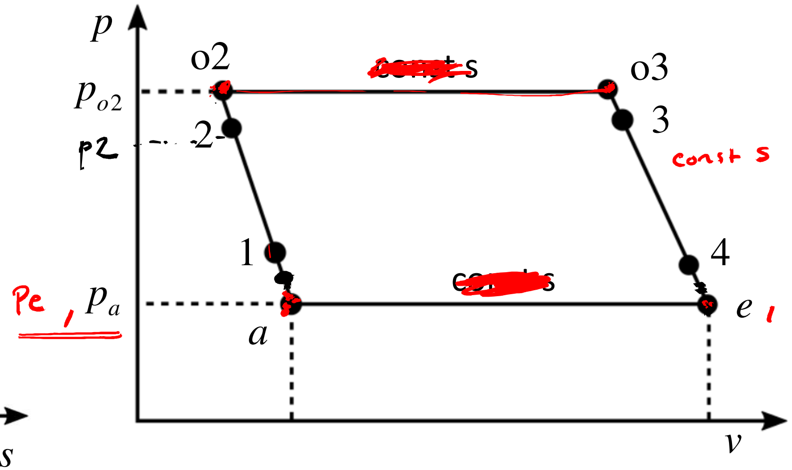
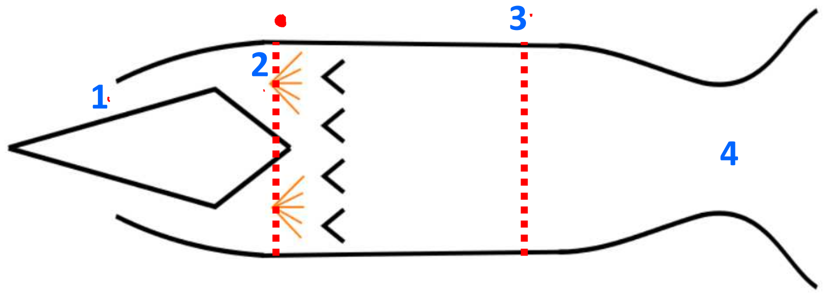
Ideal cycle analysis: (h,s) and (p,v) diagrams

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







- short cut method to find u_e assuming *ideal* cases (isentropic compression and expansion, reversible heating)

$$\frac{p_{oe}}{p_e} = \frac{p_{o3}}{p_e} = \frac{p_{o2}}{p_a} = \frac{p_{oa}}{p_a}$$

$$\frac{p_{oe}}{p_e} = \frac{p_{oa}}{p_a} \Rightarrow M_e = M$$

$$\Rightarrow \frac{u_e}{u} = \sqrt{\frac{T_e}{T_a}}$$

and

$$\frac{p_{o3}}{p_e} = \frac{p_{oa}}{p_a} \Rightarrow \frac{T_{o3}}{T_e} = \frac{T_{oa}}{T_a}$$

thus

$$\frac{u_e}{u} = \sqrt{\frac{T_{o3}}{T_{oa}}}$$

$$p_a = p_e$$

$$p_{o3} = p_{o2}$$

$U_e = U,\ T_{o3},\ T_{oa}$

Ramjets

Specific thrust

$$\frac{\tau}{\dot m_a} = \left[(1+f)u_e - u\right] + \cancel{\frac{(p_e - p_a)A_e}{\dot m_a}}$$

$$= u\left[(1+f)\frac{u_e}{u} - 1\right] = M\sqrt{\gamma R T_a}\left[(1+f)\overbrace{\sqrt{\frac{T_{o3}}{\underbrace{T_a\left(1+\frac{\gamma-1}{2}M^2\right)}_{T_{o2}=T_{oa}}}}}^{u_e/u} - 1\right]$$

u

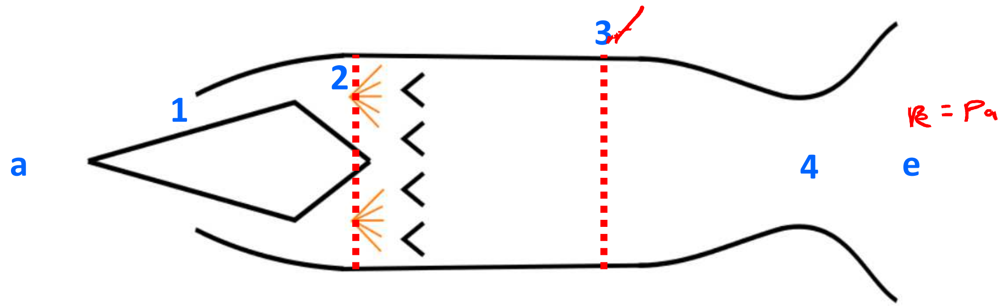
u/a

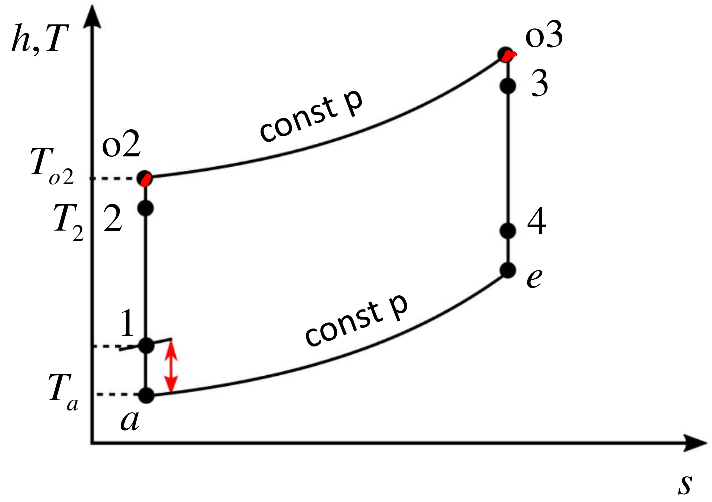
$\dot m_f/\dot m_a$

$$f = \frac{T_{o3} - T_{o2}}{\Delta h_R/c_p - T_{o3}} = \frac{T_{o3}/T_a - \left(1+\frac{\gamma-1}{2}M^2\right)}{\Delta h_R/c_pT_a - T_{o3}/T_a}$$

choose T_{o3} (e.g., $=T_{max\ matl}$)

so ST = ST(M, T_a, T_{o3}, $\Delta h_R/c_p$)





Ramjets

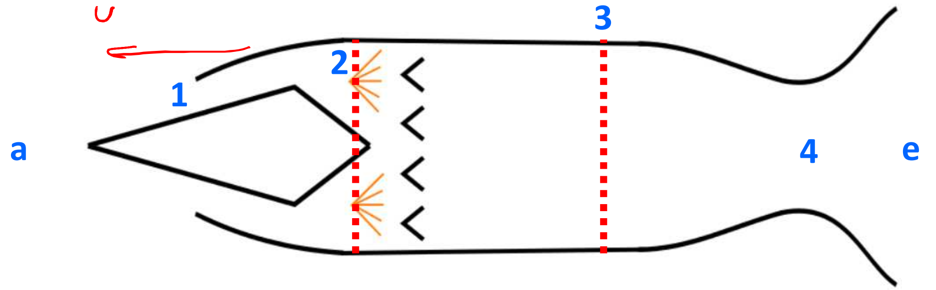
Other parameters

$$TSFC = \frac{f}{ST}$$

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

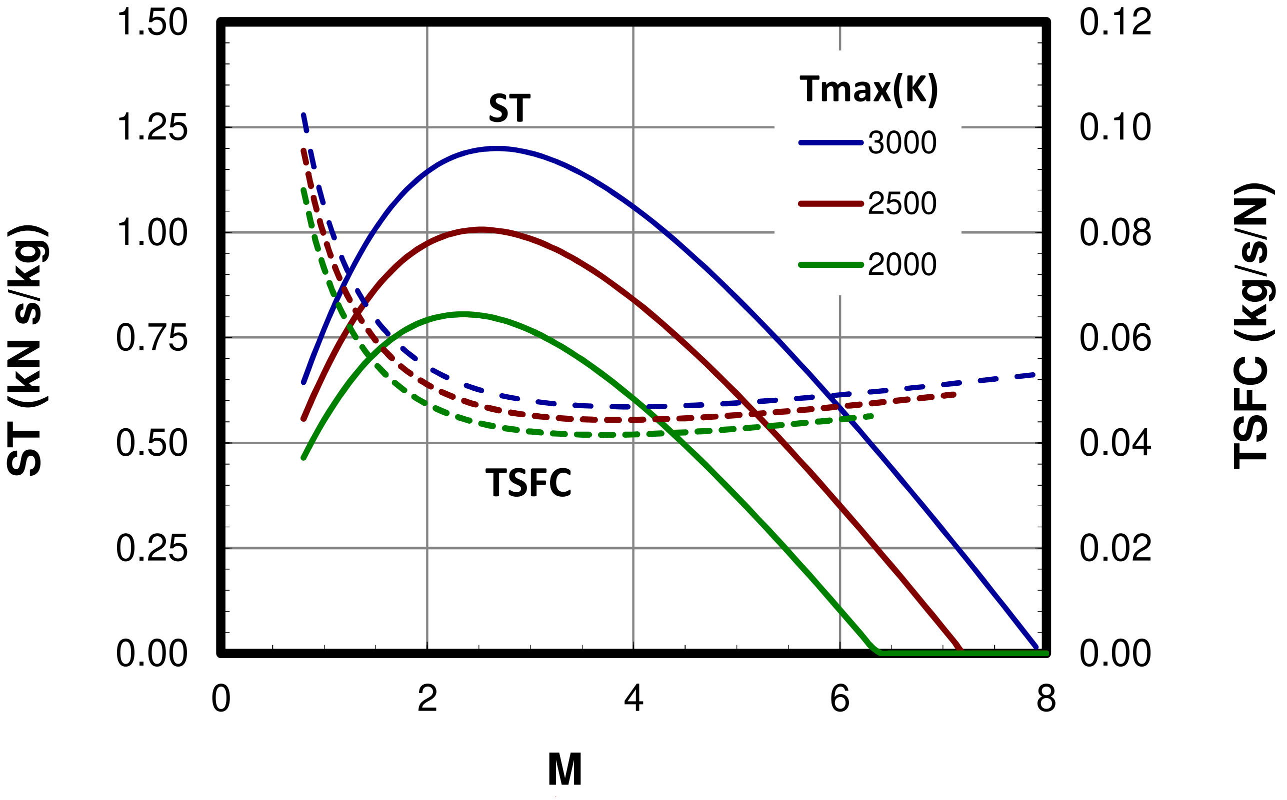
$$\eta_p = \frac{\tau u}{\Delta \dot{K}E} = \frac{\tau u}{\frac{1}{2}\dot{m}_a\left[(1+f)u_e^2 - u^2\right]} = 2\frac{ST}{u\left[(1+f)(u_e/u)^2 - 1\right]}$$

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



Ramjets

Ideal ramjet performance



Δh_R=45MJ/kg

γ=1.4

T_a=220K

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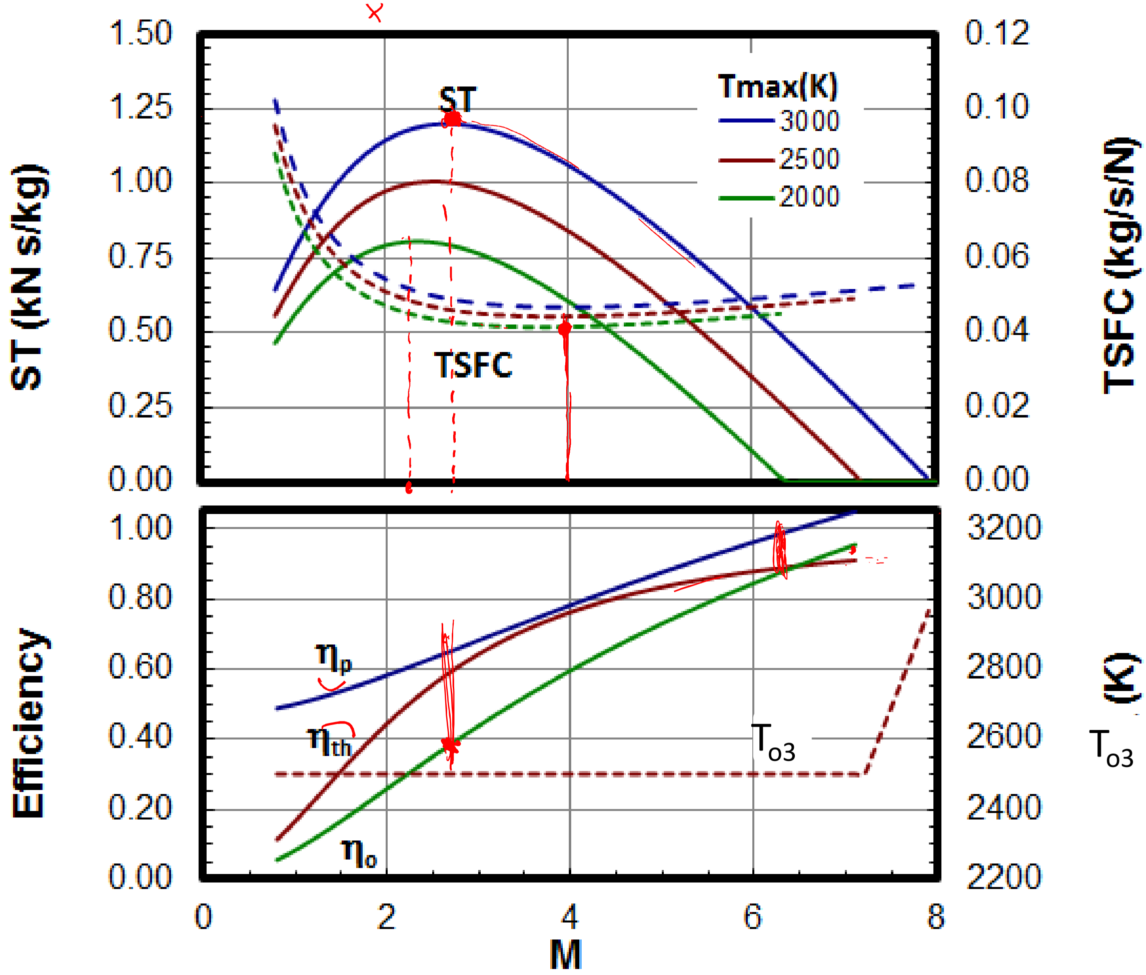
Ideal ramjet performance



γ=1.4

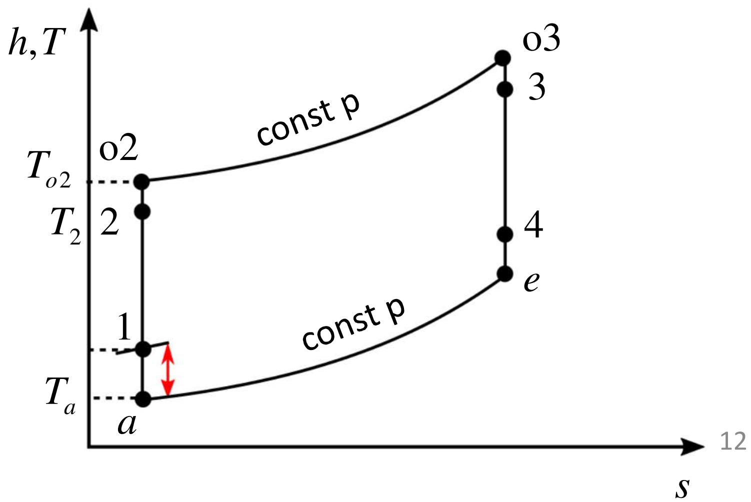
T_a=220K

Δh_R=45MJ/kg heat of reaction

Poor subsonic performance

ST_{max} @ M~2.6 but SFC_{min} @ M~4

- for given M, $T_{max}\downarrow \Rightarrow SFC\downarrow$ but $ST\downarrow$
- for given T_{max}, there is max M



Ramjets

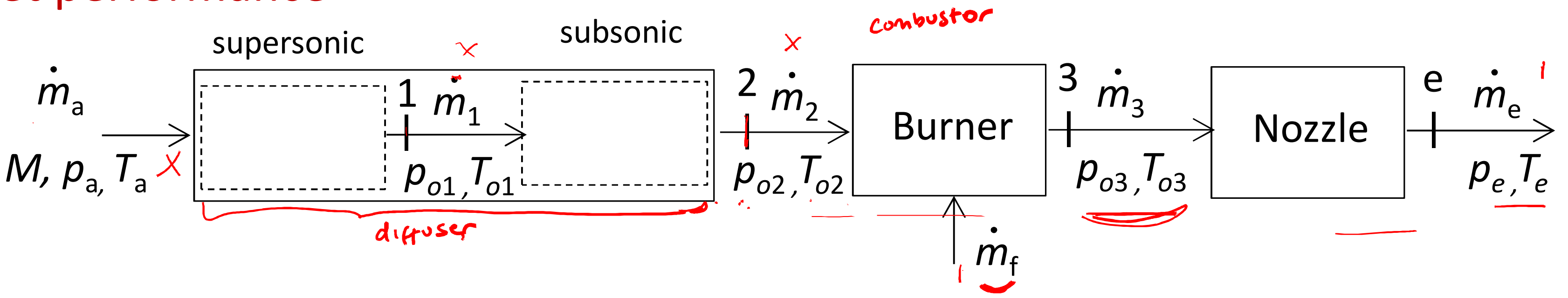
Real ramjet performance

Now we want to remove some of the idealizations in the previous analysis:

- inlet/diffuser, combustor and nozzle are no longer reversible
  - pressure losses will result
- combustor does not achieve ideal heat release
- some of the fuel is unburned and/or the combustion is "incomplete" (e.g., CO instead of CO_2)
- nozzle not perfectly expanded
- some idealizations maintained:
  - no heat losses, c_p= constant

Ramjets

Real ramjet performance



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

Energy $\dot{m}_a h_{oa} = \dot{m}_a h_{o1} = \dot{m}_a h_{o2}$ $\Rightarrow T_{o2} = T_{oa} = T_a\left(1 + \frac{\gamma - 1}{2} M^2\right)$

$\frac{T_{oa}}{T_a}$

Entropy to get stagnation pressure, use adiabatic efficiency to compare to isentropic case