Jet and Rocket Propulsion

AE4451

LECTURE 13

Sedina Tsikata – February 8, 2023

Overview

what we saw last time:

- ramjets
    - ideal cycle analysis
    - new expressions for performance metrics: specific thrust

today:

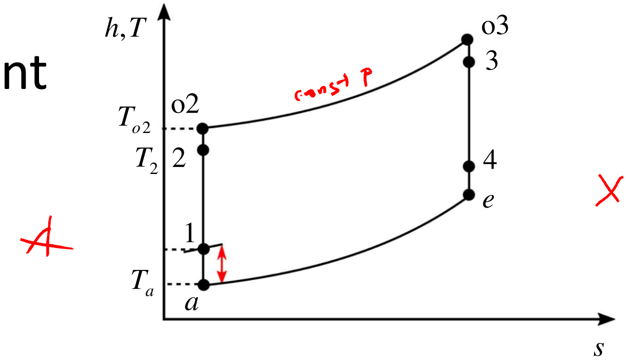
- real ramjet cycle analysis for different components

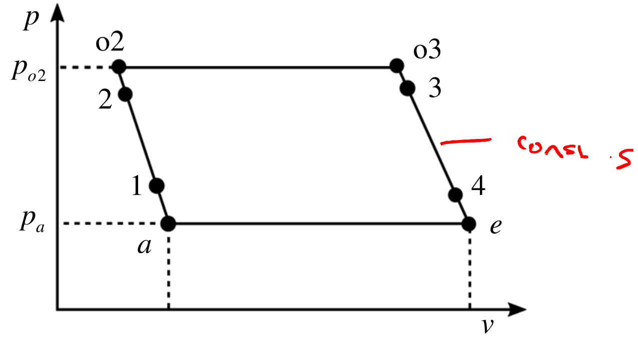
Ramjets

Real ramjet performance

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

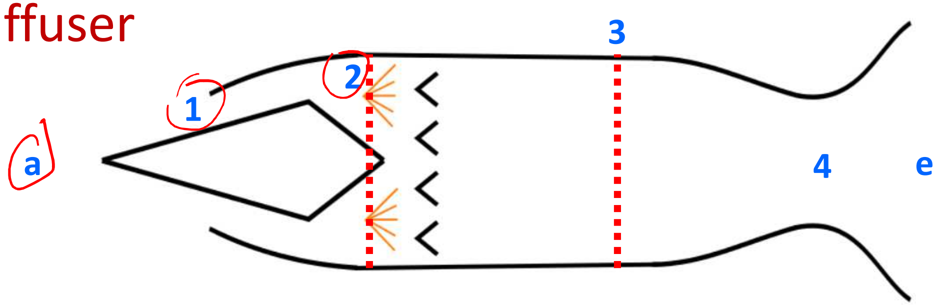




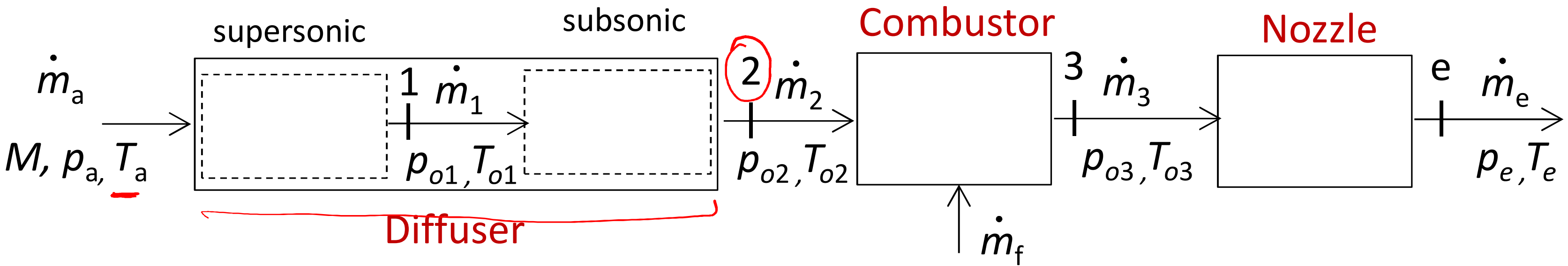
Ramjets

Real ramjet performance: diffuser

use same p_a, T_a,
M and T_{o3} as in ideal case



u_o, T_o, p_o, h_o ....
"stagnation"



Mass $\boxed{\dot m_a = \dot m_1 = \dot m_2}$ recall $\sum_{outlets} \dot m = \sum_{inlets} \dot m$

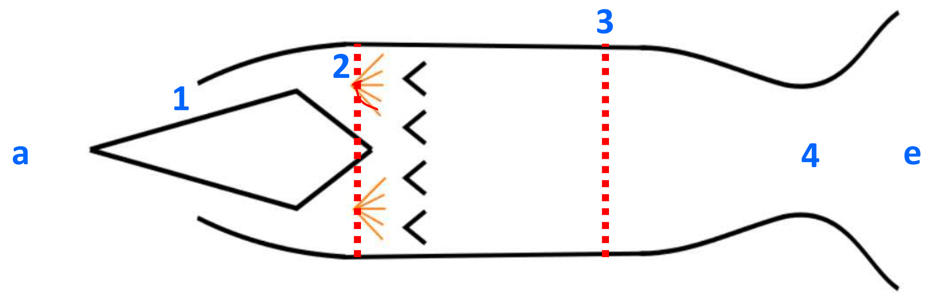
Energy * $\boxed{\dot m_a h_{oa} = \dot m_a h_{o1} = \dot m_a h_{o2}}$ recall $\dot Q_{in} - \dot W_{shaft} = \frac{d}{dt}\int_{CV} \rho e_o dV + \overset{\dot m(\Delta h_o)}{\int_{CS} \rho h_o (\vec u \cdot \hat n) dA}$ assumption is for no heat in

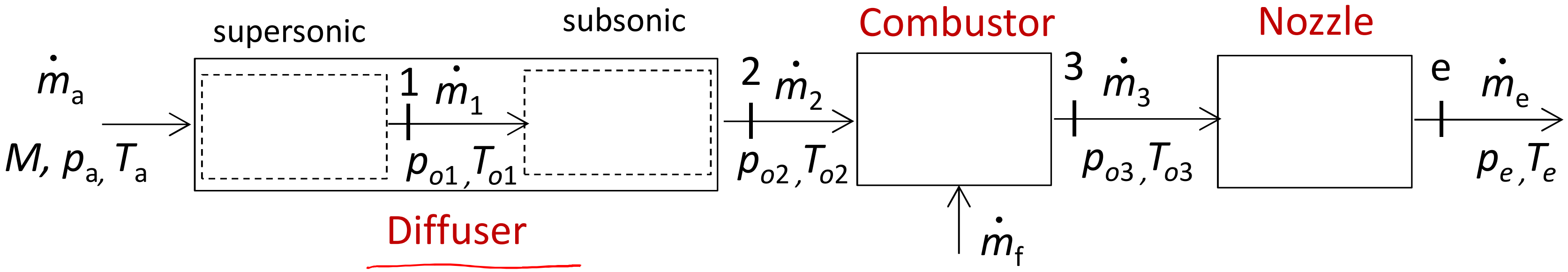
replacing enthalpy with T $\Rightarrow T_{oa} = T_{o1} = T_{o2}$ $\Rightarrow \boxed{T_{o2} = T_a\left(1 + \frac{\gamma - 1}{2} M^2\right)}$

$T_{oa} = T_a\left(1 + \frac{\gamma - 1}{2} M^2\right)$ ✗

Ramjets

Real ramjet performance



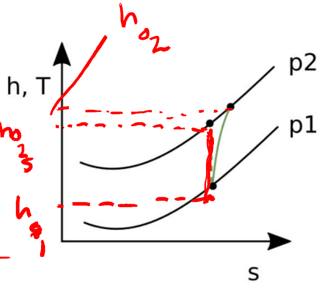


Entropy to get stagnation pressure, use adiabatic efficiency to compare to isentropic case

recall adiabatic efficiency form for compressor

isentropic

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



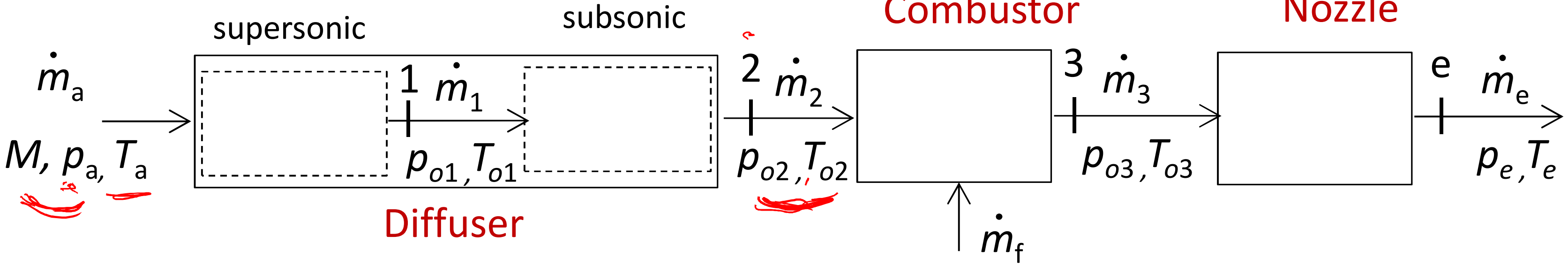
i.e. real work/isentropic work

or

isentropic enthalpy change/real enthalpy change

Ramjets

Real ramjet performance: diffuser



Entropy $$\eta_d = \frac{T_{o_{2s}} - T_{oa}}{T_{o_2} - T_{oa}} \Rightarrow \frac{T_{o_{2s}}}{T_{oa}} = \eta_d\left(\frac{T_{o_2}}{T_{oa}} - 1\right) + 1$$

recall $$\frac{P_0}{P} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\Rightarrow \frac{p_{o_{2s}}}{p_a} = \left[\eta_d\left(\frac{T_{o_{2s}}}{T_a} - 1\right) + 1\right]^{\gamma/(\gamma-1)}$$

modified by ram recovery factor (r_d (M) ≤ 1) to account for shock losses

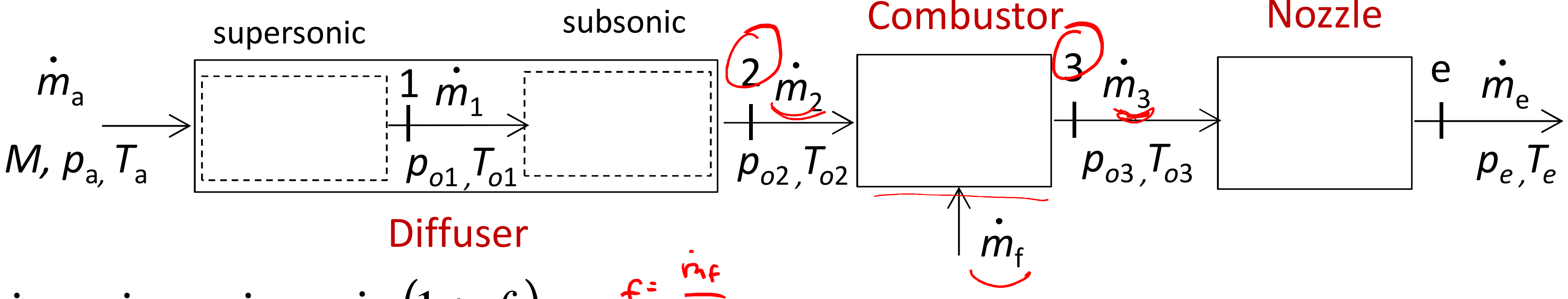
$$\Rightarrow \frac{p_{o2}}{p_a} = r_d\left\{1 + \eta_d\left(\frac{T_{o_2}}{T_a} - 1\right)\right\}^{\gamma/\gamma-1}$$

and using substitution $$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M^2$$

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

Ramjets

Real ramjet performance: combustor



Mass $$\dot m_a + \dot m_f = \dot m_3 = \dot m_a(1+f)$$

$f = \dfrac{\dot m_f}{\dot m_a}$

Energy

recall $$\dot m h_{o,in} = \dot m h_{o,exit} + \dot Q_{loss}$$

$$\dot Q_{loss} = \dot m(h_{o,in} - h_{o,exit}) = \dot m \Delta h_R$$

recall $$f = \frac{T_{o3} - T_{o2}}{\Delta h_R / c_p - T_{o3}}$$

combustion efficiency: how much available chemical energy is converted to thermal energy "η_b"

$$\Rightarrow \boxed{f = \frac{T_{o3} - T_{o2}}{\eta_b \Delta h_R / c_p - T_{o3}}}$$

$$f = \frac{T_{o3}/T_{o2} - 1}{(\eta_b \Delta h_R / c_p T_{o2}) - T_{o3}/T_{o2}}$$

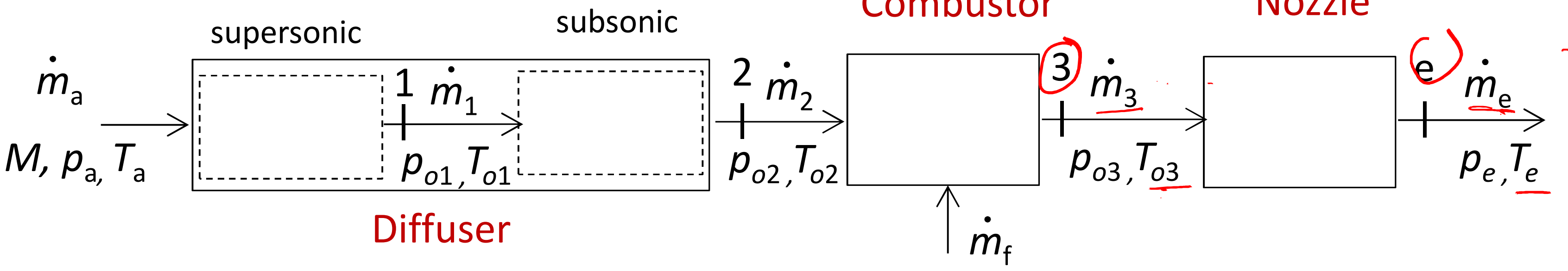
can now introduce the pressure burner ratio (< 1); i.e. pressure drops at exit of burner

$$\frac{p_{o3}}{p_{o2}} = p_{rb}$$

can only use efficiency to describe this if dealing with expansion/compression process

Ramjets

Real ramjet performance: nozzle



Mass $\dot m_3 = \dot m_e$

Energy $\dot m_3 h_{o3} = \dot m_e h_{oe} \Rightarrow h_{o3} = h_{oe} = h_e + \frac{u_e^2}{2}$

$$\Rightarrow u_e = [2(h_{o3} - h_e)]^{1/2} = [2c_p(T_{o3} - T_e)]^{1/2}$$

CpT

isentropic

Entropy

$$\eta_N = \frac{h_{o3} - h_e}{h_{o3} - h_{e_s}} = \frac{T_{o3} - T_e}{T_{o3} - T_{e_s}} \Rightarrow T_e = T_{o3}\{1 - \eta_N\} + \eta_N T_{e_s}$$

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

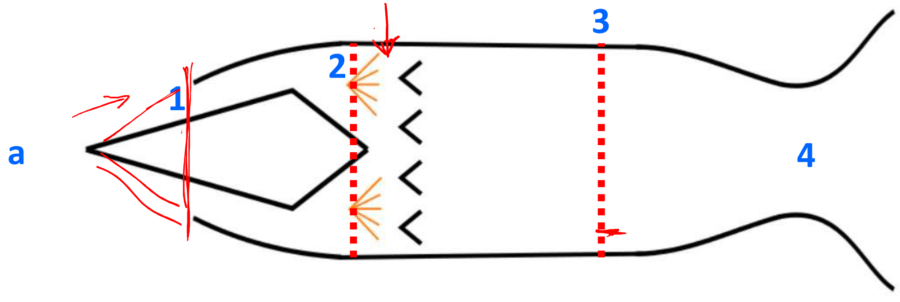
$$\boxed{T_e = T_{o3}\left\{1 - \eta_N\left[1 - \left(\frac{p_e}{p_{o3}}\right)^{\gamma-1/\gamma}\right]\right\}}$$ *

Ramjets

A closer look at performance: ideal ramjet

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

$$\eta_o = \frac{M\sqrt{\gamma R T_a}\left[(1+f)\sqrt{\dfrac{T_{o3}}{T_a\left(1+\frac{\gamma-1}{2}M^2\right)}}-1\right]}{\dfrac{T_{o3}/T_a-\left(1+\frac{\gamma-1}{2}M^2\right)}{\Delta h_R/c_pT_a-T_{o3}/T_a}}\frac{u}{\Delta h_R}$$

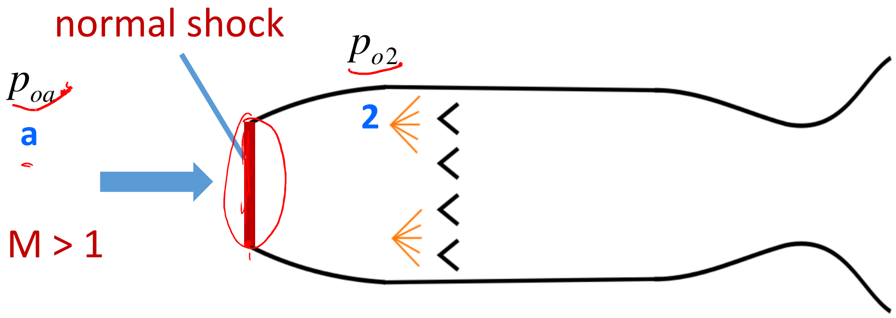


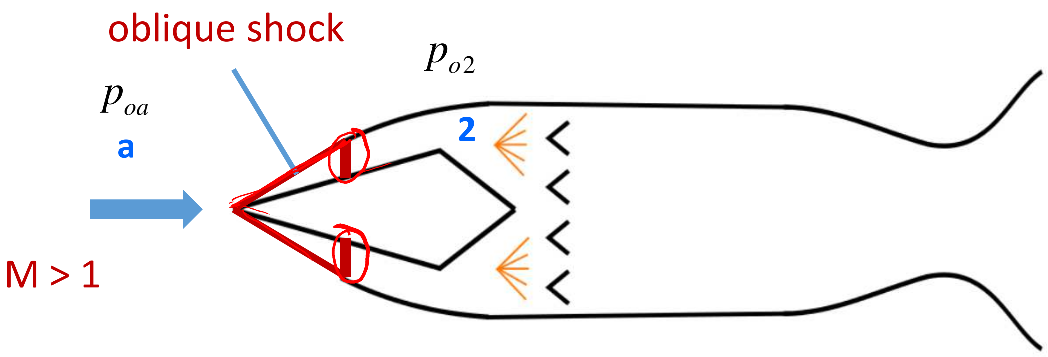
notice overall efficiency a function of:
- Mach number
- heat of reaction
- temperature ratio

at higher M, efficiency starts to drop, very inefficient for M > 5
- combustion should occur at subsonic speeds
- entering air must be slowed; happens thanks to shock waves at inlet
- these shocks will result in important losses

Ramjets

A closer look at performance: ideal ramjet





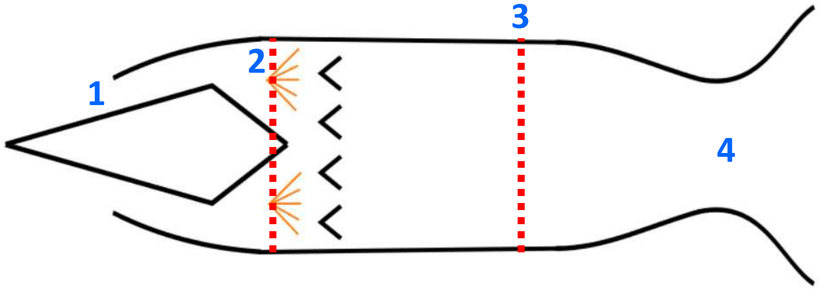
- ramjets use spikes to reduce shock pressure losses

$\underbrace{\dfrac{p_{o2}}{p_{oa}}}$ is lower without spike due to area of normal shock, i.e. "lower stagnation pressure recovery" or "lower ram recovery"

→ spike improves ramjet efficiency

Ramjets

A closer look at performance: real ramjet



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

$$ST = \frac{\tau}{\dot{m}_a} = \left[(1+f)u_e - \underbrace{M\sqrt{\gamma R T_a}}_{u}\right] + \frac{(p_e - p_a)A_e}{\dot{m}_a}$$

depends on nozzle design

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

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

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

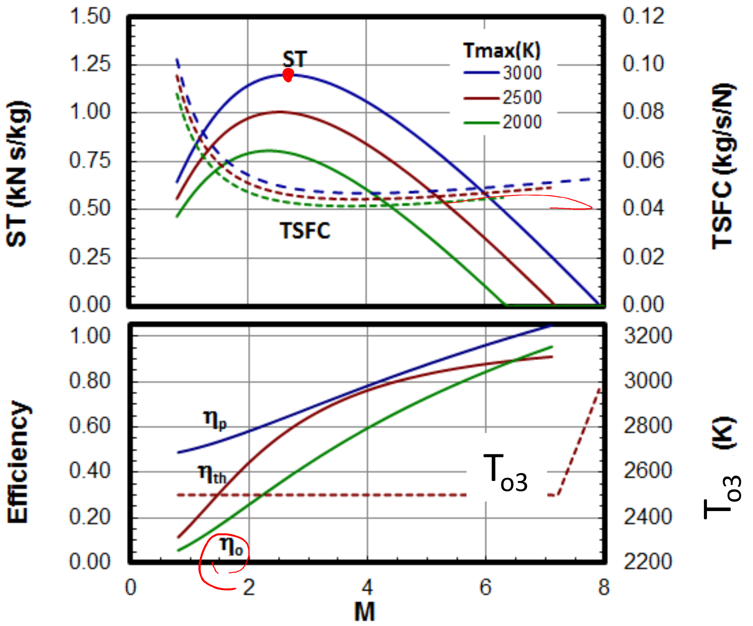
$$\eta_{th} = \frac{\eta_o}{\eta_p}$$

no change in these expressions compared to ideal case

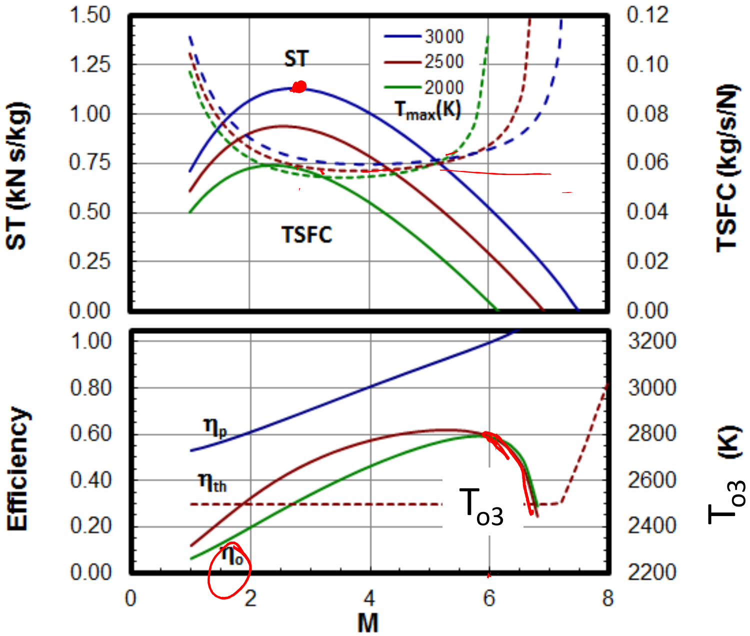
Ramjets

Real vs ideal ramjet performance

ideal

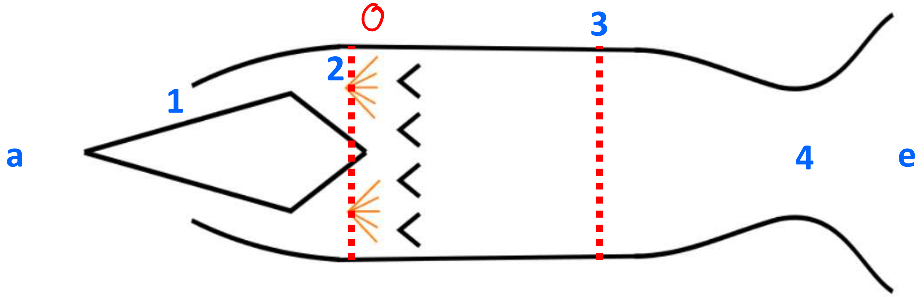


real



real ramjet has:

- lower specific thrust
- higher specific fuel consumption
- lower overall efficiency



$$\eta_{th} = \frac{\Delta \dot{KE}}{m_f \Delta h_R}$$

$$\eta_p = \frac{Tu}{\Delta \dot{KE}}$$

Ramjets

Scramjet = supersonic-combustion ramjet

NASA X-43: reached record speed of Mach 9.6

- melting of parts at high M avoided with water cooling from M > 3
- succeeded in 2006 by X-51 program

Boeing X-51A WaveRider (USAF graphic)
Mach 5.1

- 210 s powered flight time, 6 min total flight time
- longest hypersonic air-breathing flight

Hypersonic Air-breathing Weapons Concept (HAWC)
Mach 5

- scramjet-based hypersonic cruise missile
- first flight September 2021
- final successful test flight: end of Jan 2023