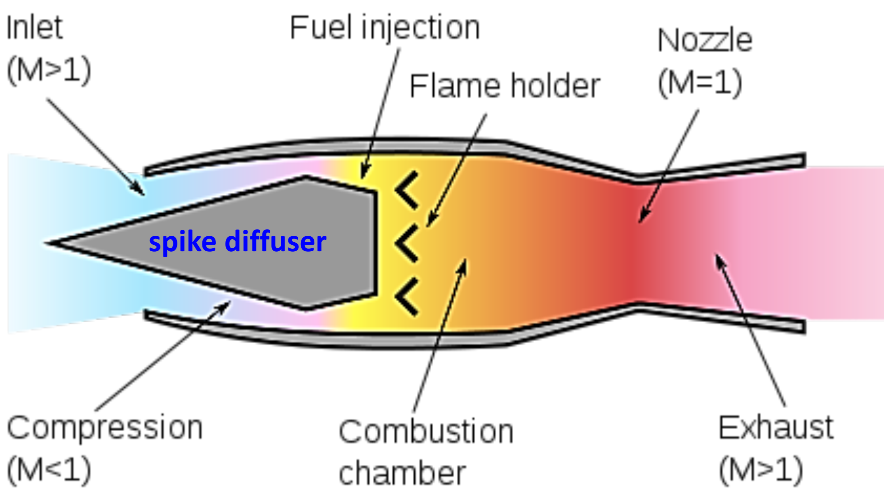
Lecture 10

Ramjet Introduction

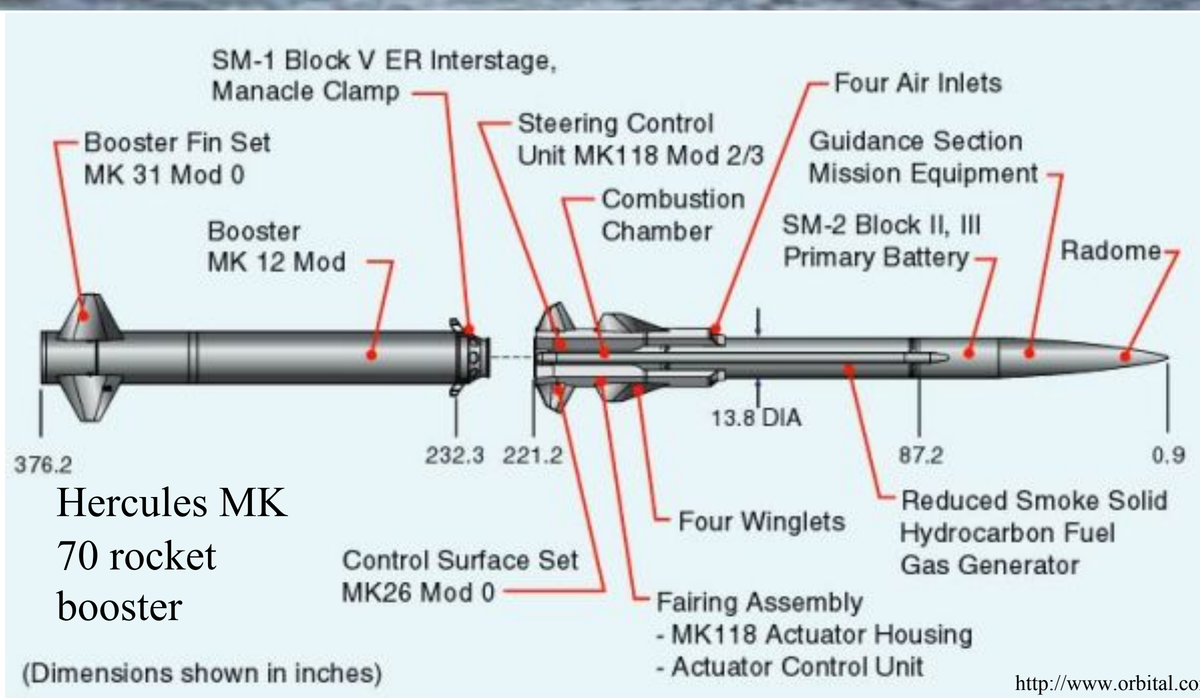
Ideal Performance Analysis

Ramjets : Introduction



- High thrust for reaching high supersonic speeds
- Ramjet has no moving parts - high reliability
- Simple construction – low weight
- Achieves compression of intake air by forward speed of vehicle – Cannot start from rest, needs a booster propulsion system – which reduces payload

Ramjet Missile Concept



Hercules MK 70 rocket booster

Orbital Sciences GQM-163 Coyote:
Ducted rocket/ramjet engine,
Flight speed up to Mach 2.8 at sea-level

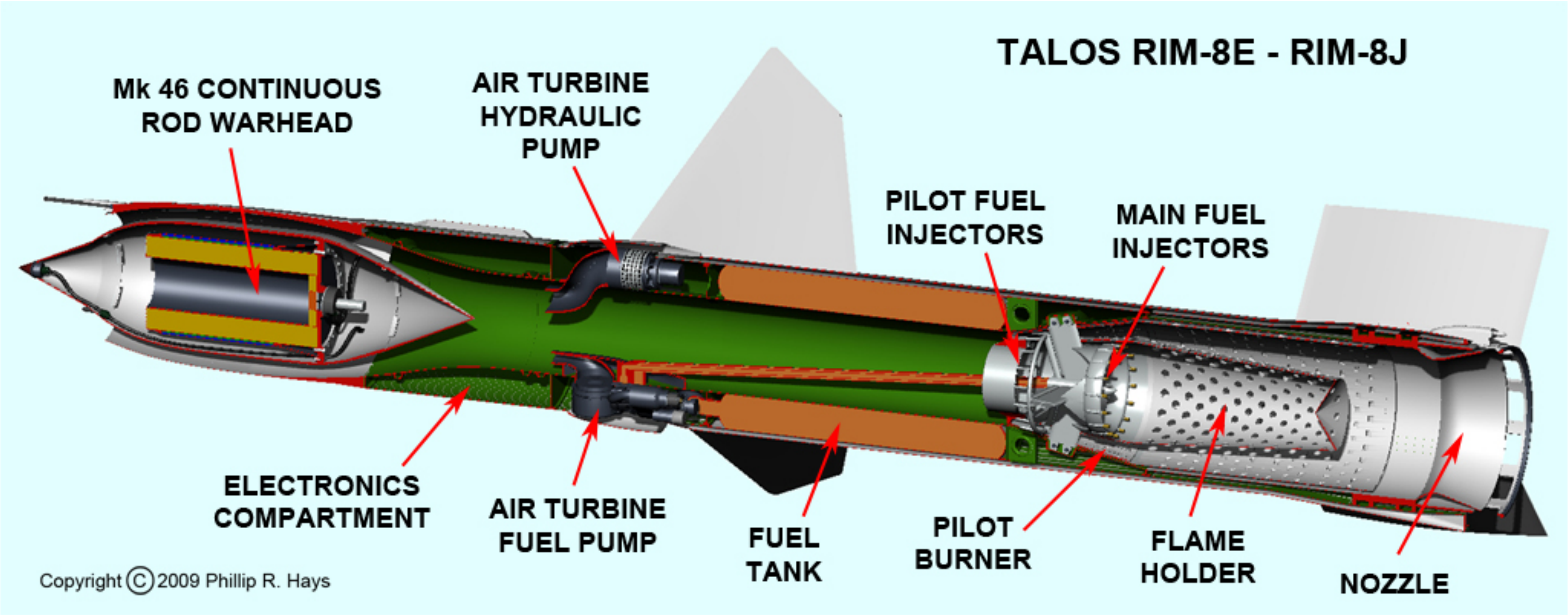
http://www.orbital.com/

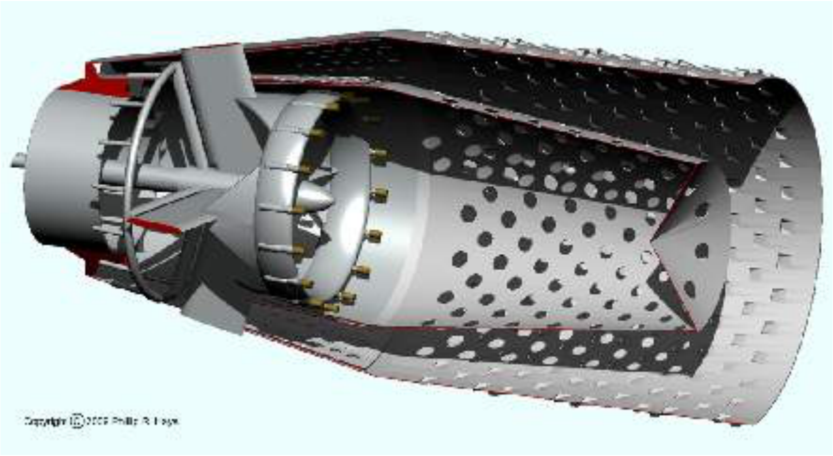
Talos RIM-8 Surface-Air Missile

- **Weight** 3,538 kg (missile: 1,542 kg, booster: 1,996 kg
- **Length** 11.6 m
- **Diameter** 0.7m
- **Warhead** 136 kg continuous-rod HE warhead or W30 nuclear warhead
- **Engine** Stage1: MK 11 solid-fueled rocket booster, Stage2: Bendix ramjet sustainer, 89kN
- **Wingspan** 2.80 m
- **Operational range** 185 km
- **Flight ceiling** 80,000 ft
- **Speed** Mach 2.5
- **Guidance system** Radar beam riding
- **Launch platform** Surface Ship

https://www.okieboat.com/Talos%20missile.html

Unified Talos Ramjet Propulsion System

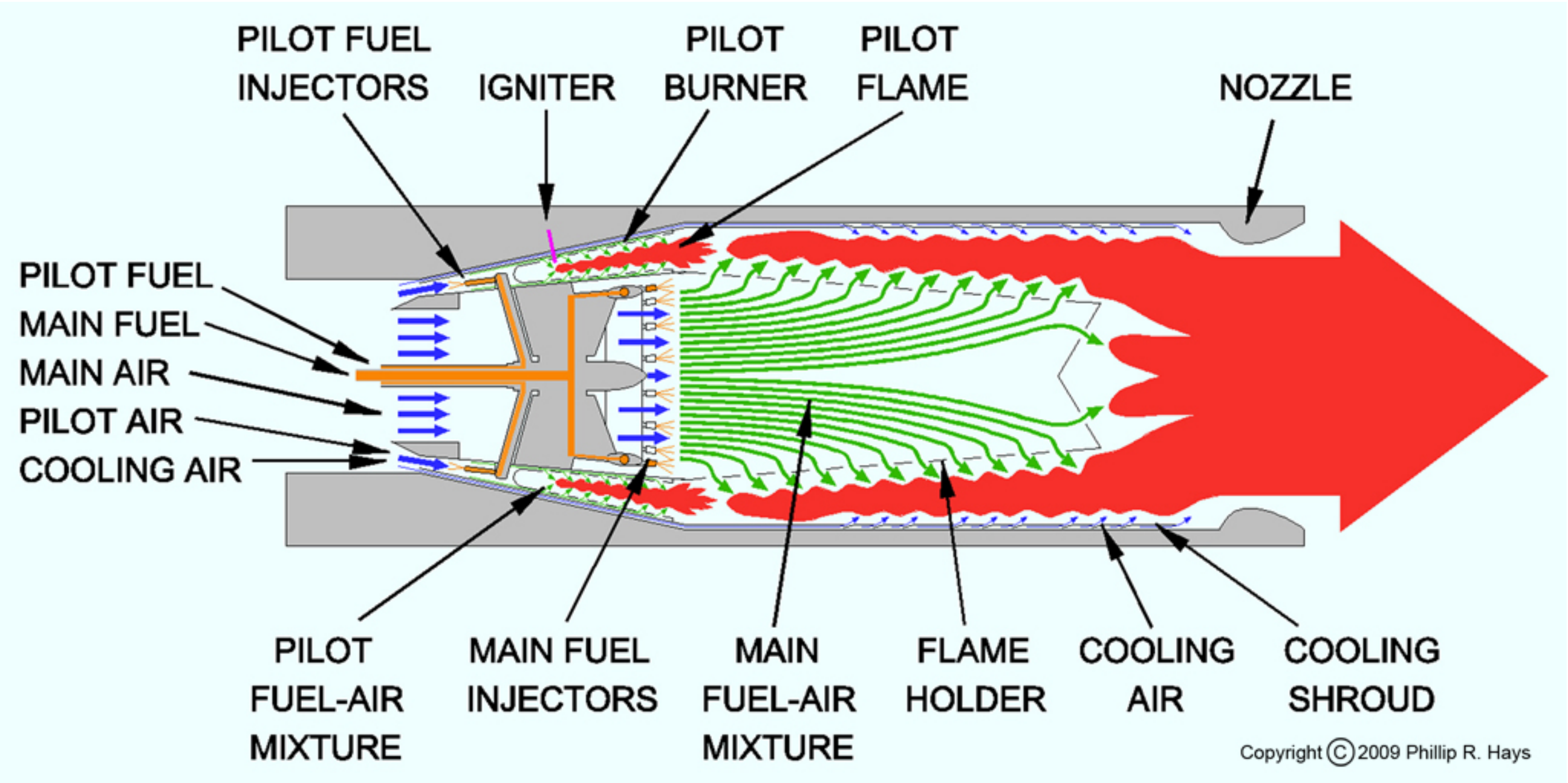




- Designed to fly Mach 2.5 at 60K ft altitude
- 1349 Missiles flown over 25 years
- Combustion Chamber pictured on the right

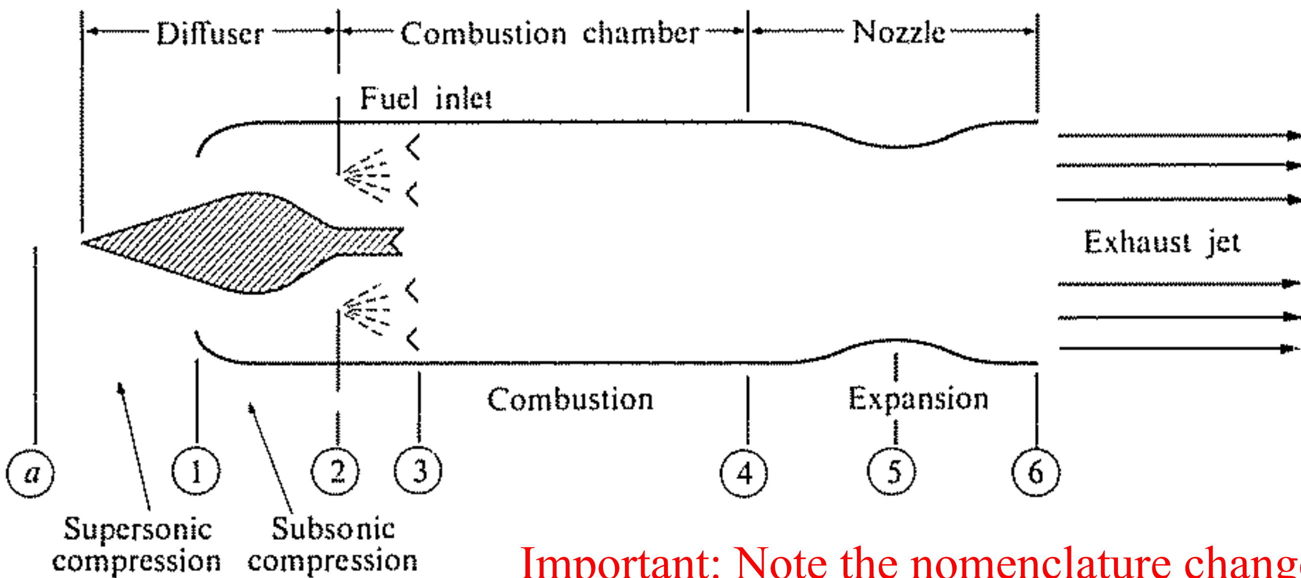
https://www.okieboat.com/Talos%20missile.html

Ramjet Combustion Detail

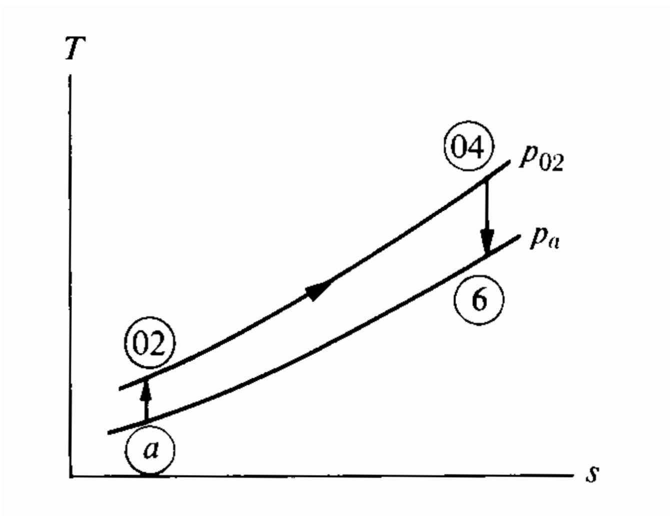


https://www.okieboat.com/Talos%20missile.html

Ideal Ramjet

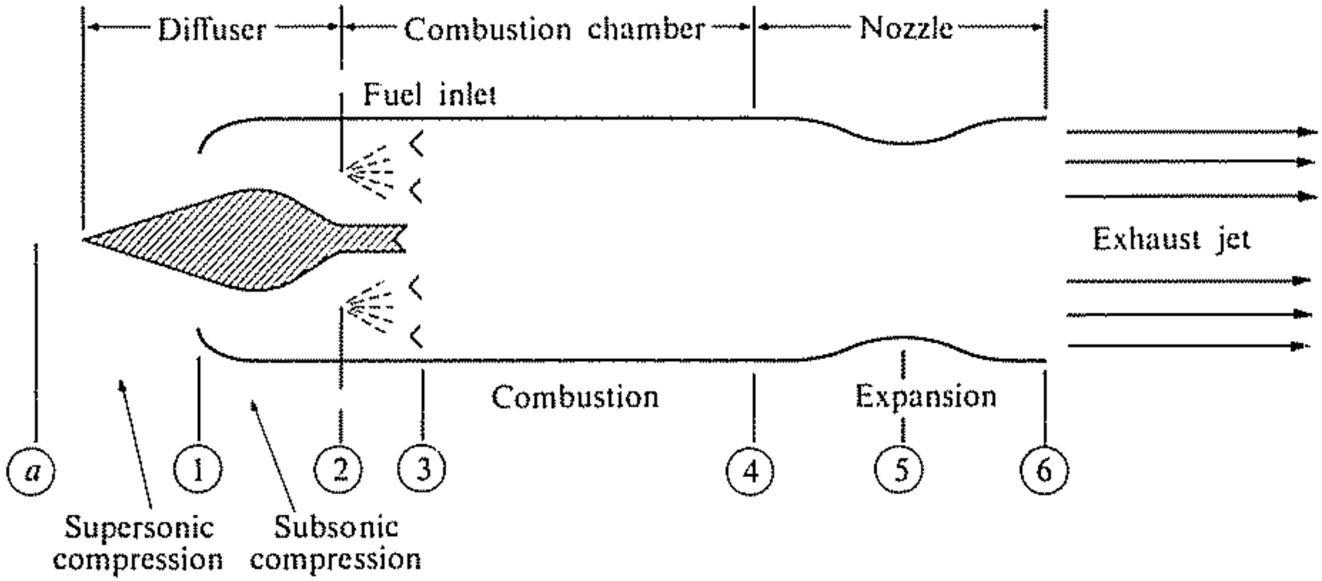


Important: Note the nomenclature change compared to the Brayton Cycle



- We are starting to look at stagnation properties
- Assume heat addition at near zero velocity (otherwise have to look at flow with heat addition, Rayleigh Flow
- So station 2 to 4 is at stagnation conditions (follow the 02, 04 terminology)

Ideal Ramjet Performance Analysis

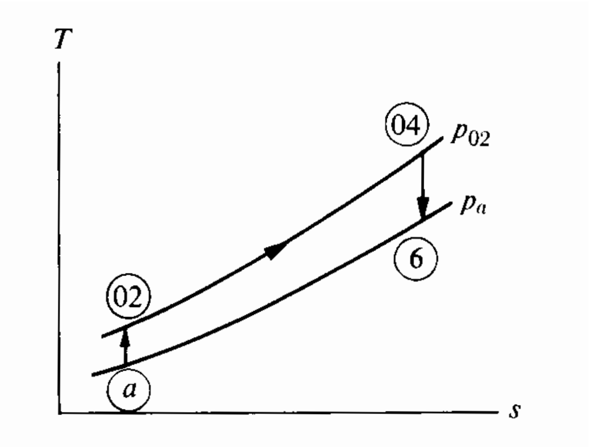


- We start with the assumption of isentropic flow in the inlet and nozzle and constant pressure heat addition in the combustion chamber, so $p_{0a} = p_{06}$
- Ignore variations in fluid properties like Cv, Cp, R, γ

$$\frac{p_{0a}}{p_a} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)} \quad \text{and} \quad \frac{p_{06}}{p_e} = \left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{\gamma/(\gamma-1)}$$

Ideal Ramjet Performance Analysis

- If we assume $p_e = p_a$ (perfectly expanded nozzle)



$$\frac{p_{0a}}{p_a} = \left(1 + \frac{\gamma - 1}{2}\mathrm{M}^2\right)^{\gamma/(\gamma-1)} \quad \text{and} \quad \frac{p_{06}}{p_e} = \left(1 + \frac{\gamma - 1}{2}\mathrm{M}_e^2\right)^{\gamma/(\gamma-1)}$$

$$\frac{p_{0a}}{p_a} = \frac{p_{06}}{p_e} \quad \text{and} \quad \mathrm{M}_e = \mathrm{M}_a .$$

$$u_e = \frac{a_e}{a_a} u ,$$

where a is the speed of sound. Since $a = \sqrt{\gamma RT}$, then $a_e/a_a = \sqrt{T_e/T_a}$. However, for the case $\mathrm{M}_e = \mathrm{M}_a$, $T_e/T_a = T_{06}/T_{0a}$ and, since $T_{04} = T_{06}$, then

$$u_e = \sqrt{T_{04}/T_{0a}}\, u .$$

Ideal Ramjet Performance

- Applying the energy equation to the idealized combustion process, neglecting the enthalpy of the incoming fuel, (mass flow and velocity of incoming fuel is small)

$$(1 + f)h_{04} = h_{02} + fQ_R$$

- Rewrite, and use constant specific heat values across the engine

$$f = \frac{(T_{04}/T_{0a}) - 1}{(Q_R/c_p T_{0a}) - T_{04}/T_{0a}}$$

- How much fuel you can add is related to :
  - T04 (Maximum combustor exit temperature)
  - Specific Heat of Fuel
  - Incoming Stagnation Temperature

Example Problem

- A Ramjet is flying at Mach 2.5 and 60000 ft, where the air temperature is -56C and density is 0.12kg/m^3. The inlet area of the ramjet is 0.3m^2 . It burns Kerosene for fuel, which has a Q_R = 46 MJ/kg and density of 810 kg/m^3. Assume air has a specific heat of 1005 J/kg.K. The combustor/nozzle walls can handle a temperature of 3400K. For a range of 185km, assuming an annular fuel tank of inner dia 0.5m and outer dia 0.7m, what is the length of the fuel tank?

Solution

- We are trying to find the volume of fuel that needs to be stored.
- Volume of fuel = mass of fuel/ density
- Mass of fuel = mass flow rate of fuel * time of flight

- Time of flight = Range/incoming speed
  - Incoming speed = Mach No * Speed of Sound = 2.5 * sqrt(1.4*287*217) = 2.5 * 295 = 738 m/s
  - Therefore time of flight = 185000/738 = 250 secs

- Mass flow rate of fuel = f * mass flow rate of air
  - Mass flow rate of air = density * Area * incoming speed
    - = 0.12*0.3*738 = 26.58 kg/s

Solution

- Lets calculate fuel air ratio, f

$$f = \frac{(T_{04}/T_{0a}) - 1}{(Q_R/c_p T_{0a}) - T_{04}/T_{0a}}$$

- For the freestream, T_{0a} is related to Ta by the isentropic relation,
  - » $T_{0a} = Ta\ (1 + 0.5 * (\gamma - 1) * M^2)$
  - » $T_{0a} = 217 * (1 + 0.5 * 0.4 * 2.5\text{^}2) = 488K$
  - » $T_{04} = 3400K$
  - Therefore, f = (3400-488)/(46000000/1005-3400)=0.063
  - So, mass flow rate of fuel = 0.063*26.58 = 1.69 kg/s
  - Total mass of fuel stored = 1.69 * 250 = 422kg
  - Volume of fuel = 422/810 = 0.52cu.m
  - Length of tank = 0.52/((0.7^2-0.5^2)*3.14/4) = 0.52/0.188
    - » = 2.77m

Ideal Ramjet Performance Equations

Fuel Air Ratio

$$f = \frac{(T_{04}/T_{0a}) - 1}{(Q_R/c_p T_{0a}) - T_{04}/T_{0a}}$$

Thrust

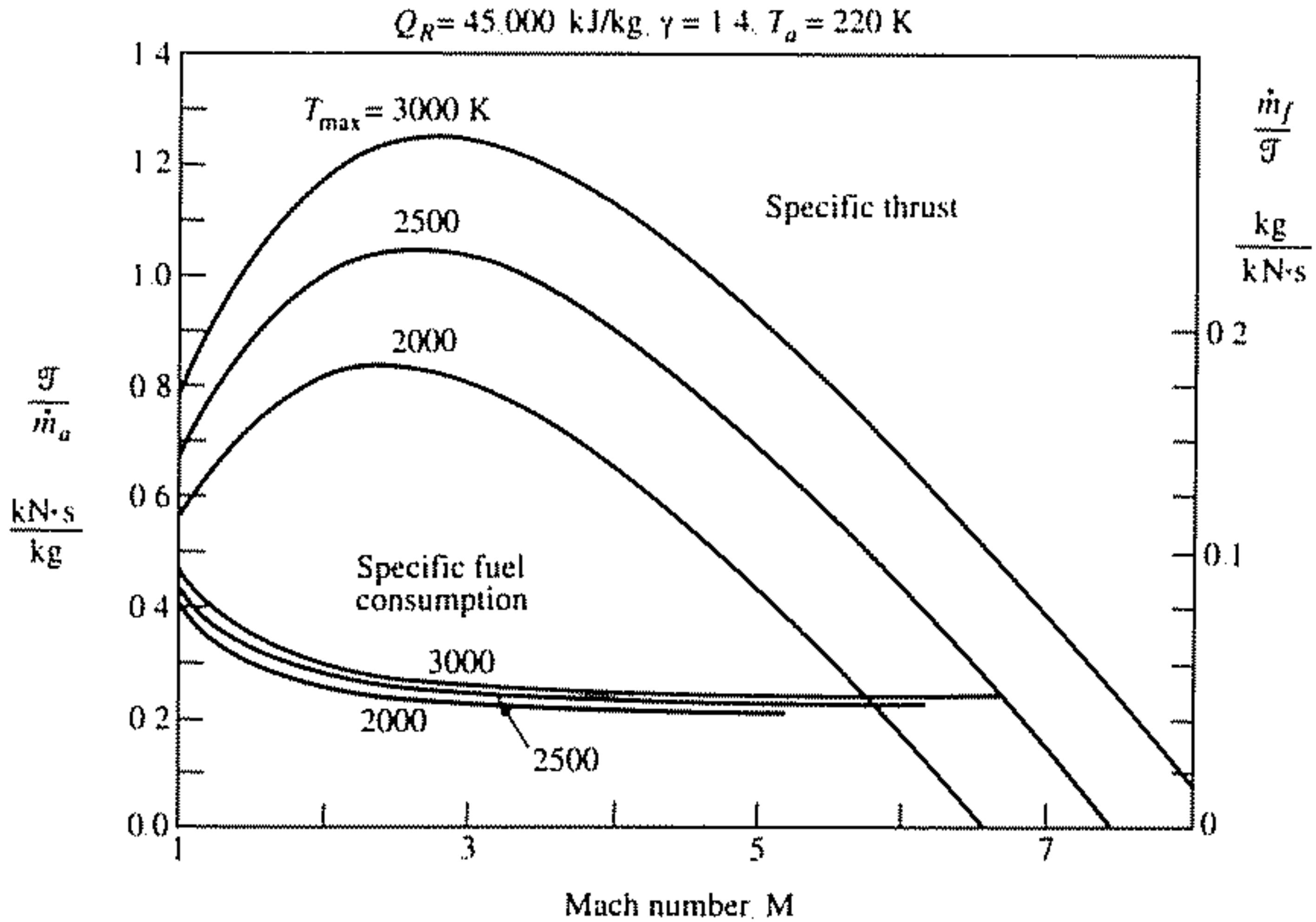
$$\mathcal{T} = \dot{m}_a[(1 + f)u_e - u]$$

Combine the above

Specific Thrust

$$\frac{\mathcal{T}}{\dot{m}_a} = \mathrm{M}\sqrt{\gamma R T_a}\left[(1 + f)\sqrt{T_{04}/T_a}\left(1 + \frac{\gamma - 1}{2}\mathrm{M}^2\right)^{-1/2} - 1\right]$$

Thrust and TSFC Performance Summary



- Ramjet performance parameters vs. flight Mach number
- Specific thrust has peak value for set T_{max} and Ta
- Specific thrust increases as maximum allowable combustor exit temperature increases
- Specific fuel consumption decreases with increasing flight Mach number

Thrust per unit Mass vs Efficiency Summary

- Ramjet performance parameters vs. flight Mach number
- Specific thrust has peak value for set T_{max} and Ta. Peak is around Mach 2.5
- Propulsive, thermal and overall efficiencies increase continually with increasing Flight Mach number