Jet Aircraft Propulsion

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Lect-38

In this lecture...

- Thermodynamic cycle and performance parameters of ramjets and pulsejets

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Ramjet engines

- Ramjet is the simplest of all the airbreathing engines.
- It consists of a diffuser, combustion chamber and a nozzle.
- Ramjets are most efficient when operated at supersonic speeds.
- When air is decelerated from a high Mach number to a low subsonic Mach number, it results in substantial increase in pressure and temperature.
- Hence ramjets do not need compressors and consequently no turbines as well.

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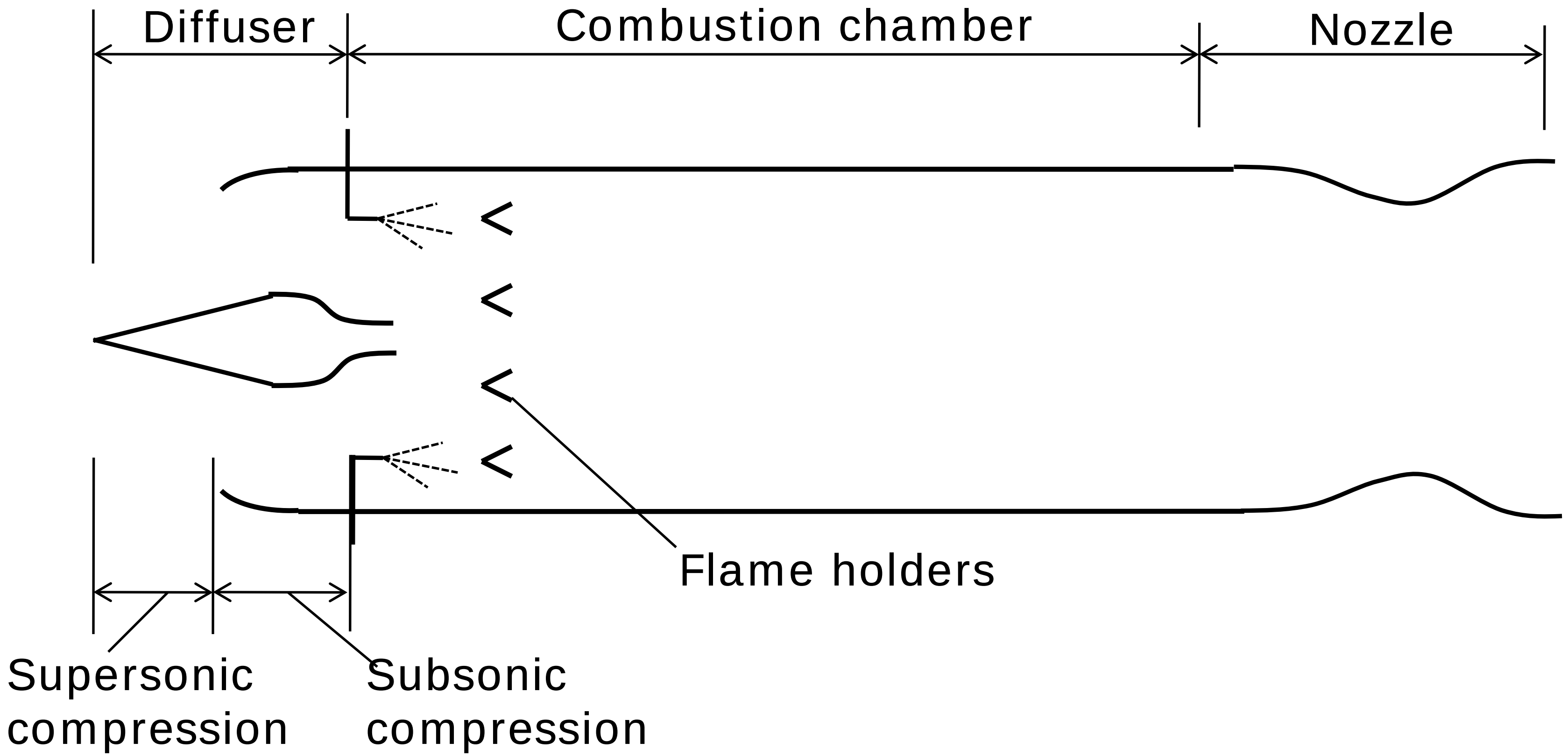
Ramjet engines



Schematic of typical ramjet engine

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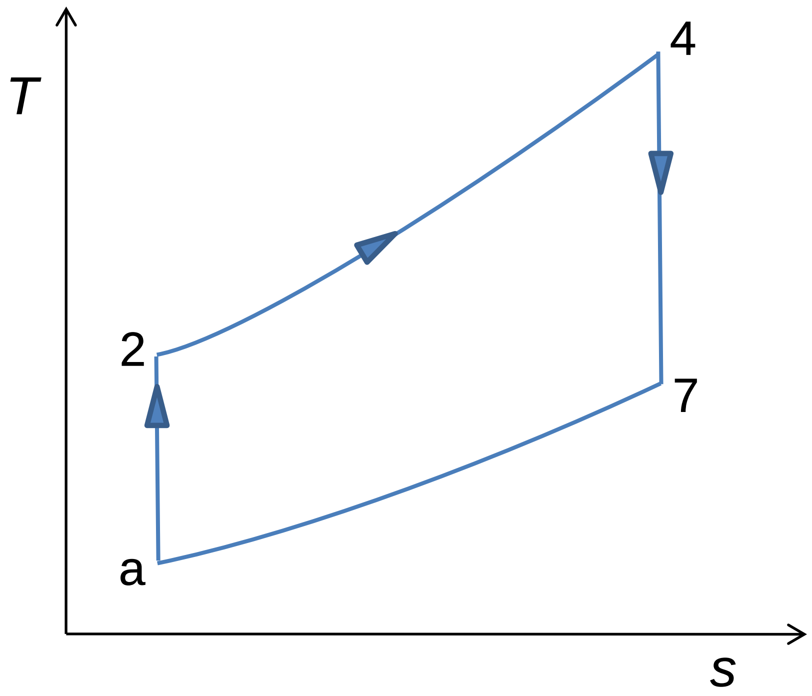
Ramjet engines



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

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Ramjet engines

- In an ideal ramjet cycle, there are no irreversibilities considered.
- Therefore there are no pressure drops or efficiencies of the components comprising a ramjet.
- If we assume complete expansion in the nozzle, $P_a = P_7 = P_e$
- We shall use the isentropic relations to determine the variation of pressure and temperature in the intake and nozzle.

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Ramjet engines

Intake :

$$\frac{T_{0a}}{T_a} = 1 + \frac{\gamma - 1}{2} M^2 = \frac{T_{02}}{T_a} \quad \text{Also,} \quad \frac{T_{0e}}{T_a} = \frac{T_{06}}{T_6} = 1 + \frac{\gamma - 1}{2} M_e{}^2 = \frac{T_{04}}{T_a}$$

Similarly, $\frac{P_{0a}}{P_a} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)}$ and, $\frac{P_{07}}{P_e} = \left(1 + \frac{\gamma - 1}{2} M_e{}^2\right)^{\gamma/(\gamma-1)}$

From the above equations, $\frac{P_{07}}{P_e} = \frac{P_{0a}}{P_a}$

and therefore, $M_e = M$, or $u_e = \frac{a_e}{a} u = \sqrt{\frac{T_e}{T_a}} u = \sqrt{\frac{T_{04}}{T_{02}}} u$

Ramjet engines

Combustor :

Energy balance across the combustor gives,

$$\dot{m}h_{02} + \dot{m}_f Q = (\dot{m} + \dot{m}_f)h_{04}$$

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

$$c_p T_{02} + fQ = (1 + f)c_p T_{04}$$

$$\text{therefore, } f = \frac{(c_p T_{04} / c_p T_{0a}) - 1}{(Q / c_p T_{0a}) - (c_p T_{04} / c_p T_{0a})}$$

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Ramjet engines

Thrust developed is :

$$F = \dot{m}\{(1+f)u_e - u\} \text{ or } F/\dot{m} = (1+f)u_e - u$$

We know that, $u_e = u\sqrt{\frac{T_{04}}{T_{0a}}} = u\sqrt{\frac{T_{04}}{T_a}}\sqrt{\frac{1}{1+\frac{\gamma-1}{2}M^2}}$

The thrust equation can be re – written as

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

and $\text{TSFC} = \frac{\dot{m}_f}{F} = \frac{f}{F/\dot{m}}$

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Ramjet engines

- A real or actual ramjet cycle will have irreversibilities like pressure drop and efficiencies of intake, combustor and nozzle.

Pressure recovery of the intake, $\pi_d = \frac{P_{02}}{P_{0a}}$,

Pressure loss in the combustor, $\pi_b = \frac{P_{04}}{P_{02}}$

Stagnation pressure ratio in the nozzle, $\pi_n = \frac{P_{07}}{P_{04}}$

Overall pressure ratio, $\frac{P_{07}}{P_{0a}} = \pi_d \pi_b \pi_n$

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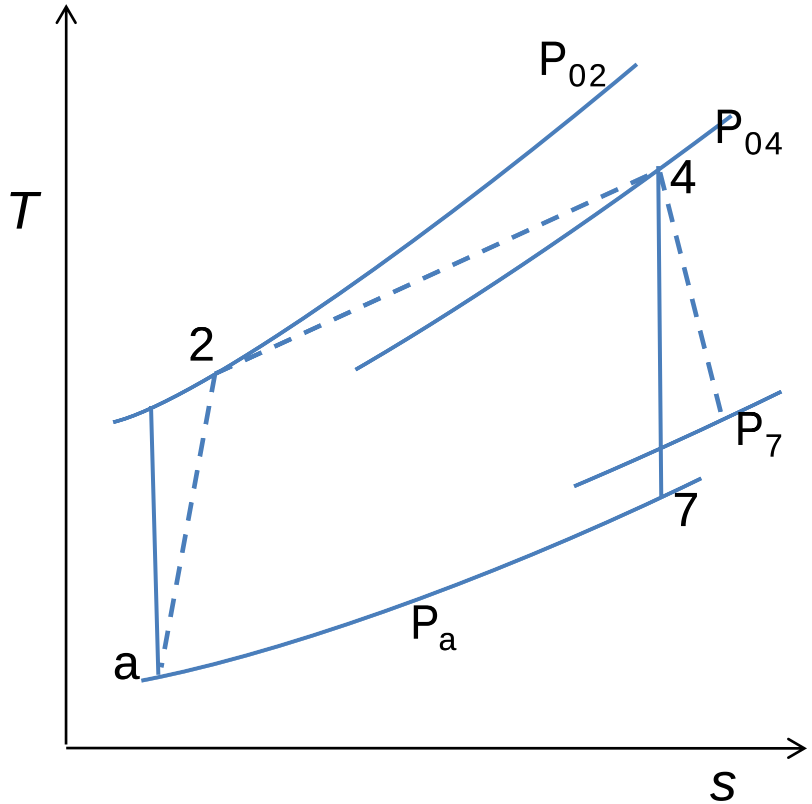
Ramjet engines



a-2: Compression in the intake
2-4: Combustion at constant pressure
4-7: Expansion through the nozzle

Real ramjet cycle on a T-s diagram

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Ramjet engines

The exhaust Mach number can be related to the inlet Mach number as

$$M_e^2 = \left(\frac{2}{\gamma-1}\right)\left[\left(1+\frac{\gamma-1}{2}M^2\right)\left(\pi_d\pi_b\pi_n\frac{P_a}{P_e}\right)^{(\gamma-1)/\gamma} - 1\right]$$

In the above expression, if $\pi_d = \pi_b = \pi_n = 1$ and $P_e = P_a$, then $M_e = M \rightarrow$ Ideal ramjet cycle.

We can determine, f, by energy balance,

$$f = \frac{\left(c_{pg}T_{04} / c_{pa}T_{02}\right) - 1}{(\eta_b Q / c_{pa}T_{02}) - \left(c_{pg}T_{04} / c_{pa}T_{02}\right)}$$

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Ramjet engines

$$\frac{T_{07}}{T_7} = \frac{T_{04}}{T_e} = \left(1 + \frac{\gamma-1}{2} M_e^2\right),$$

$$u_e = M_e\sqrt{\gamma R T_e} = M_e\sqrt{\gamma R T_{04}\frac{T_e}{T_{04}}} = M_e\sqrt{\frac{\gamma R T_{04}}{\left(1 + \frac{\gamma-1}{2} M_e^2\right)}}$$

The specific thrust and SFC can be calculated in a manner similar to that adopted for the ideal ramjet.

$$\frac{F}{\dot{m}} = \left[(1+f)u_e - u\right] + \frac{A_e}{\dot{m}}(P_e - P_a)$$

and $\text{TSFC} = \dfrac{f}{F/\dot{m}}$

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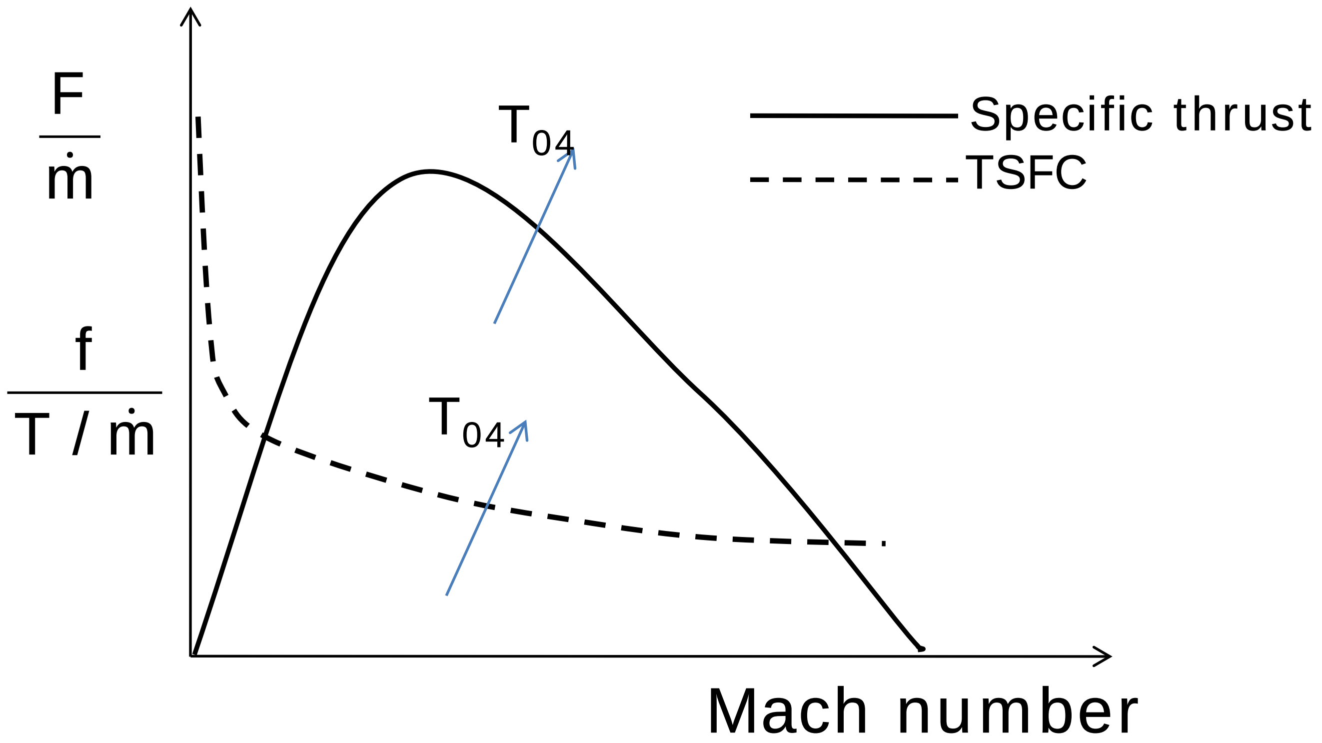
Ramjet engines



Variation of specific thrust and TSFC with Mach number

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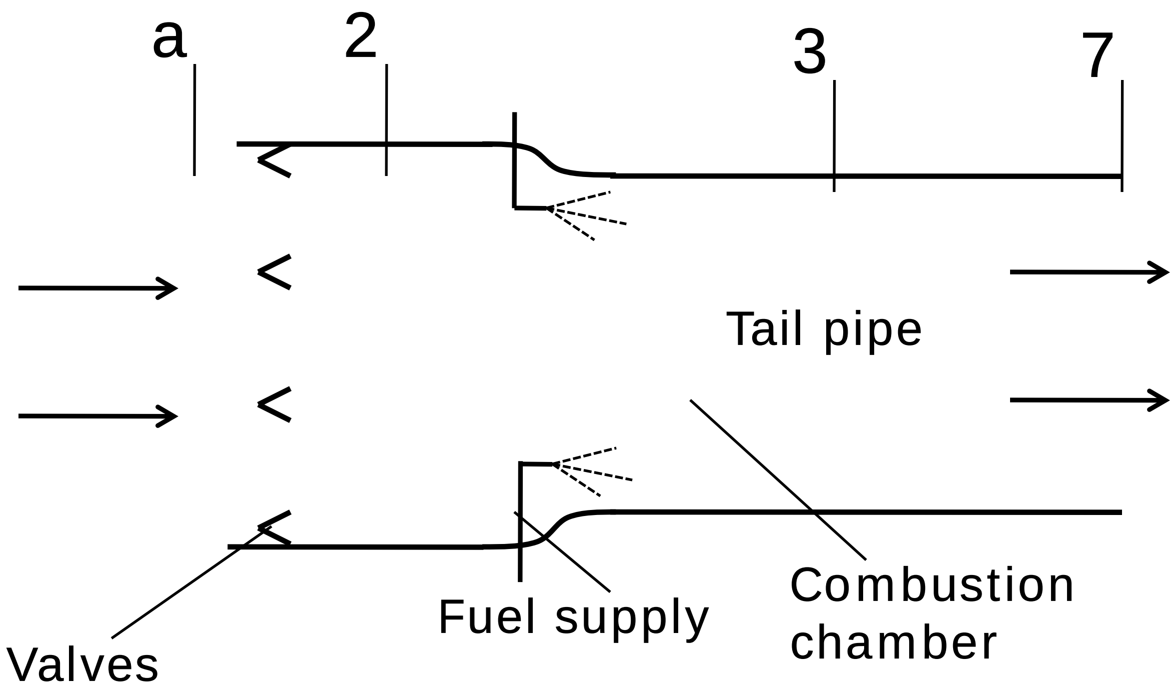
Pulsejet engines

- Pulsejet is a very simple engine like a ramjet.
- Comprises of an intake, combustion chamber and an acoustically resonating exhaust pipe.
- Combustion occurs in pulses resulting in a pulsating thrust.
- Two types of pulsejet engines: valved and valveless engines.
- Pulse Detonation Engines (PDE) is being evolved conceptually.

Pulsejet engines



Schematic of typical pulsejet engine

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Pulsejet engines

Intake :

$$P_{01} = P_{0a} = P_a\left(1+\frac{\gamma-1}{2}M^2\right)^{\gamma/(\gamma-1)}$$

Similarly, $T_{01} = T_{0a} = T_a\left(1+\frac{\gamma-1}{2}M^2\right)$

For an ideal pulsejet, $P_{02} = P_{01}$ and $T_{02} = T_{01}$

Combustor :

Combustion takes place at constant volume (ideal cycle).

Therefore, $P_{03} = P_{02}\left(\frac{T_{03}}{T_{02}}\right)$

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Pulsejet engines

Energy balance across the combustion chamber :

$$(\dot{m} + \dot{m}_f)c_p T_{03} = \dot{m} c_p T_{02} + \dot{m}_f Q$$

Simplifying, $f = \dfrac{c_p T_{03} - c_p T_{02}}{Q - c_p T_{03}}$

Tailpipe :

Assuming, $P_7 = P_a, \dfrac{T_{03}}{T_7} = \left(\dfrac{P_{03}}{P_7}\right)^{(\gamma-1)/\gamma}$

The exhaust velocity is calculated as :

$$u_e = \sqrt{2c_p T_{03}\left[1 - \left(\frac{P_a}{P_{03}}\right)^{(\gamma-1)/\gamma}\right]}$$

The thrust and TSFC can therefore be calculated.

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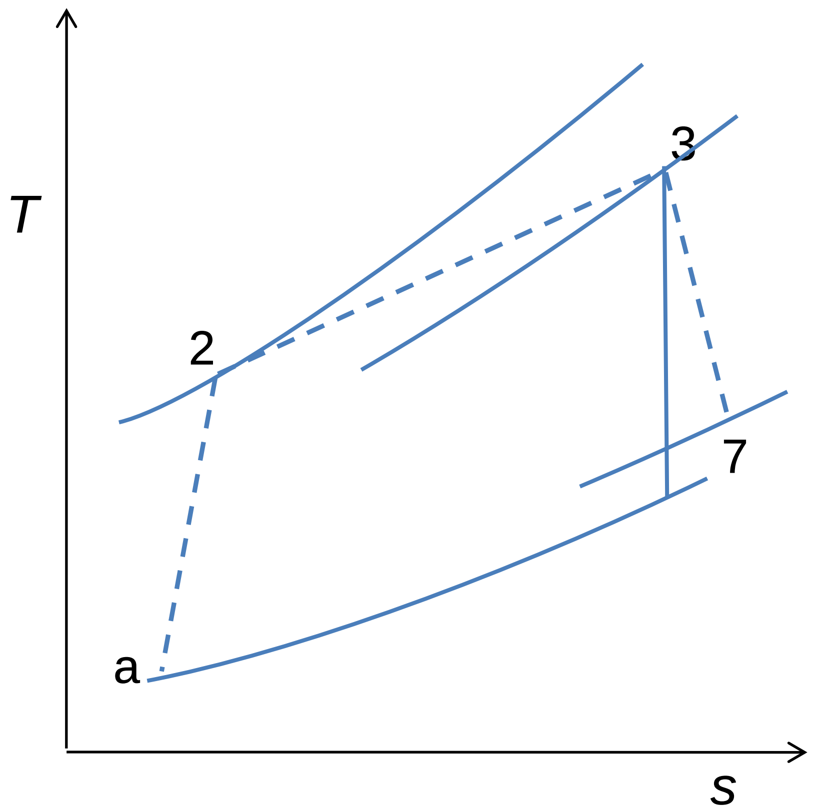
Pulsejet engines



a-2: Stagnation pressure loss
2-3: Non 2-3
3-7: Non-isentropic process

Real pulsejet cycle on a T-s diagram

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Pulsejet engines

- A real or actual pulsejet cycle will have irreversibilities like pressure drop and efficiencies of intake, combustor and nozzle.

Pressure recovery of the intake, $\pi_d = \frac{P_{02}}{P_{0a}}$,

Pressure loss in the combustor, $\pi_b = \frac{P_{04}}{P_{02}}$

Stagnation pressure ratio in the tailpipe, $\pi_n = \frac{P_{07}}{P_{04}}$

Overall pressure ratio, $\frac{P_{07}}{P_{0a}} = \pi_d \pi_b \pi_n$

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Pulsejet engines

- Besides this combustion process may have an efficiency associated with it.

$$f = \frac{c_p T_{03} - c_p T_{02}}{\eta_b Q - c_p T_{03}}$$

- The thrust and fuel consumption will be affected as a result of the irreversibilities.

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In this lecture...

- Thermodynamic cycle and performance parameters of ramjets and pulsejets

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In the next lecture…

- Components of ramjets and pulsejets

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