Jet Aircraft Propulsion

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Lect-8

In this lecture...

- Cycle components and component performance
  - Intake
  - Compressor/fan
  - Combustion chamber
  - Turbine
  - Nozzle

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Cycle components

- Jet engine cycle has several salient components
  - Air intake/diffuser: decelerates air and delivers it to the compressor
  - Fan: present in turbofan engines, drives the bypass mass flow
  - Compressor: compresses ingested air to high pressure and temperature
  - Combustion chamber: fuel is added here, combustion results in high temperature and pressure at turbine inlet

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Cycle components

- Turbine: Combustion products are expanded through the turbine, generates shaft power to drive the compressor
- Nozzle: Turbine exhaust is further expanded through the nozzle, generates thrust
- Afterburner: used in afterburning turbojets, function similar to combustion chamber

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Air intake performance

- Inlet losses arise due to wall friction and shock waves (in a supersonic inlet).
- These result in a reduction in total pressure.
- The flow is usually adiabatic as it flows through the intake.
- Performance of intakes are characterised using total pressure ratio and isentropic efficiency.

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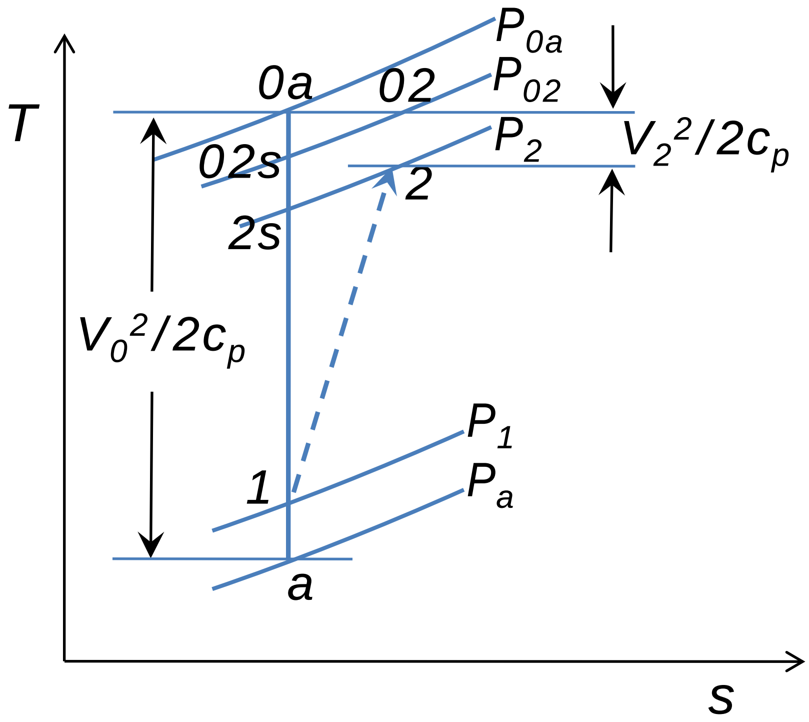
Air intake performance



Actual and ideal intake processes

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Air intake performance

- Isentropic efficiency, η_d, of the diffuser is

$$\eta_d = \frac{h_{02s} - h_a}{h_{0a} - h_a} \cong \frac{T_{02s} - T_a}{T_{0a} - T_a}$$

- This efficiency can be related to the total pressure ratio (π_d) and Mach number

$$\eta_d = \frac{\left(1 + \frac{\gamma - 1}{2} M^2\right) \pi_d^{(\gamma-1)/\gamma} - 1}{\left[(\gamma - 1)/2\right] M^2}$$

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Air intake performance

- During cycle analysis, the value of isentropic efficiency is often calculated based on the Mach number.
- The isentropic efficiency drops drastically as Mach number increases.
- This is because of the presence of shocks and the resultant total pressure losses.
- There are empirical correlations available for estimating the diffuser efficiency as a function of Mach number.

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Compressor/fan performance

- Compressors are to a high degree of approximation, adiabatic.
- Compressor performance is evaluated using the isentropic efficiency, η_c

$$\eta_C = \frac{\text{Ideal work of compression for given pressure ratio}}{\text{Actual work of compression for given pressure ratio}}$$

$$= \frac{w_{ci}}{w_c} = \frac{h_{03s} - h_{02}}{h_{03} - h_{02}}$$

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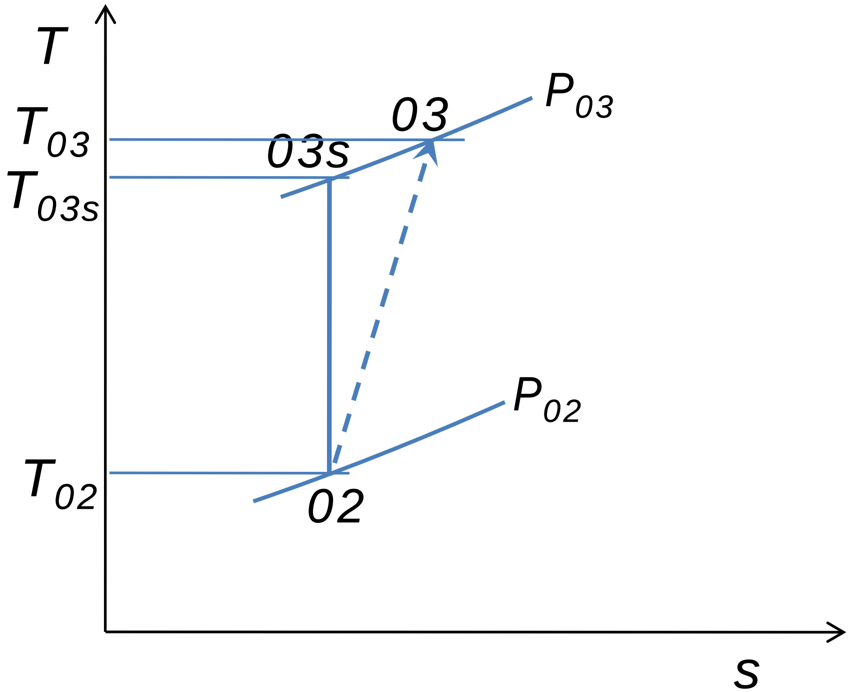
Compressor / fan performance



Actual and ideal compression processes

Compressor/fan performance

$$\eta_C = \frac{h_{03s} - h_{02}}{h_{03} - h_{02}} \cong \frac{T_{03s} - T_{02}}{T_{03} - T_{02}}$$

$$= \frac{T_{03s}/T_{02} - 1}{T_{03}/T_{02} - 1} = \frac{\left(P_{03}/P_{02}\right)^{(\gamma-1)/\gamma} - 1}{\tau_C - 1}$$

$$= \frac{\left(\pi_C\right)^{(\gamma-1)/\gamma} - 1}{\tau_C - 1}$$

- The isentropic efficiency is thus a function of the total pressure ratio and the total temperature ratio.

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Compressor / fan performance

- Besides isentropic efficiency, there are other efficiency definitions, stage efficiency and polytropic efficiency that are used in assessing the performance of multistage compressors.
- Stage efficiency will be discussed in detail during the lectures on compressors.
- The three efficiency terms can be related to one another.

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Compressor / fan performance

- The polytropic efficiency, η_{poly}, is defined as

$$\eta_{poly} = \frac{\text{Ideal work of compression for a differential pressure change}}{\text{Actual work of compression for a differential pressure change}}$$

$$= \frac{dw_i}{dw} = \frac{dh_{0i}}{dh_0} = \frac{dT_{0i}}{dT_0}$$

For an ideal compressor, the isentropic relation gives,

$T_{0i} = P_{0i}^{(\gamma-1)/\gamma} \times \text{constant}$. Therefore,

$$\frac{dT_{0i}}{T_0} = \frac{\gamma-1}{\gamma}\frac{dP_{0i}}{P_0}$$

$$\eta_{poly} = \frac{dT_{0i}}{dT_0} = \frac{dT_{0i}/T_0}{dT_0/T_0} = \frac{\gamma-1}{\gamma}\frac{dP_{0i}/P_0}{dT_0/T_0}$$

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Compressor / fan performance

Rewriting the above equation,

$$\frac{dT_0}{T_0} = \frac{\gamma - 1}{\gamma \eta_{poly}} \frac{dP_0}{P_0}$$

Integrating between states 02 and 03,

$$\tau_C = \pi_C^{(\gamma-1)/(\gamma \eta_{poly})}$$

$$or, \eta_C = \frac{(\pi_C)^{(\gamma-1)/\gamma} - 1}{\tau_C - 1} = \frac{(\pi_C)^{(\gamma-1)/\gamma} - 1}{\pi_C^{(\gamma-1)/(\gamma \eta_{poly})} - 1}$$

The above equation relates the isentropic efficiency with the pressure ratio assuming a constant polytropic efficiency.

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Combustion chamber performance

- In a combustion chamber (or burner), there are two possibilities of losses, incomplete combustion and total pressure losses.
- Combustion efficiency can be defined by carrying out an energy balance across the combustor.
- Two different values of specific heat at constant pressure: one for fluid upstream of the combustor and the other for fluid downstream of the combustor.

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Combustion chamber performance

Combustion efficiency, η_b

$$\eta_b = \frac{(\dot{m}+\dot{m}_f)h_{04} - \dot{m}h_{03}}{\dot{m}_f \dot{Q}_f} = \frac{(\dot{m}+\dot{m}_f)c_{p4}T_{04} - \dot{m}c_{p3}T_{03}}{\dot{m}_f \dot{Q}_f}$$

$$= \frac{(\dot{m}+\dot{m}_f)c_{pg}T_{04} - \dot{m}c_{pa}T_{03}}{\dot{m}_f \dot{Q}_f}$$

Where, c_{pg} is the average value for gases downstream of the burner and c_{pa} is the average value for air upstream of the burner.

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Combustion chamber performance

- Total pressure losses arise from two effects:
  - viscous losses in the combustion chamber
  - total pressure loss due to combustion at finite Mach number

Combustion chamber pressure loss,

$$\pi_b = \frac{P_{04}}{P_{03}} < 1$$

- Combustion efficiency is usually very high in gas turbine engines.
- In real cycle analysis both these parameters are used.

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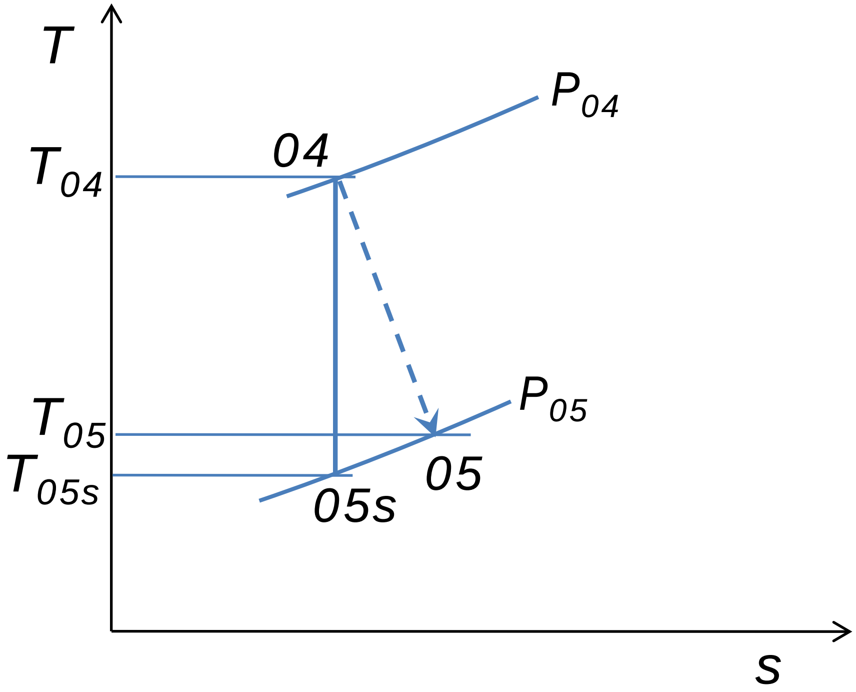
Turbine performance

- The flow in a turbine is also assumed to be adiabatic, though in actual engines there could be turbine blade cooling.
- Isentropic efficiency of the turbine is defined in a manner similar to that of the compressor.

$$\eta_t = \frac{\text{Actual work of compression for given pressure ratio}}{\text{Ideal work of compression for given pressure ratio}}$$

$$= \frac{w_t}{w_{ti}} = \frac{h_{04} - h_{05}}{h_{04} - h_{05s}} = \frac{1 - \tau_t}{1 - \pi_t^{(\gamma-1)/\gamma}}$$

Turbine performance



Actual and ideal turbine processes

Turbine performance

- The polytropic efficiency, η_{poly}, is defined as

$$\eta_{poly} = \frac{\text{Actual turbine work for a differential pressure change}}{\text{Ideal turbine work for a differential pressure change}}$$

$$= \frac{dw}{dw_i} = \frac{dh_0}{dh_{0i}} = \frac{dT_0}{dT_{0i}}$$

For an ideal turbine, the isentropic relation gives,

$T_{0i} = P_{0i}^{(\gamma-1)/\gamma} \times \text{constant}$. Therefore,

$$\frac{dT_{0i}}{T_0} = \frac{\gamma-1}{\gamma}\frac{dP_{0i}}{P_0}$$

$$\eta_{poly} = \frac{dT_0}{dT_{0i}} = \frac{dT_0/T_0}{dT_{0i}/T_0} = \frac{dT_0/T_0}{[(\gamma-1)/\gamma]dP_0/P_0}$$

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Turbine performance

Integrating between states 04 and 05,

$$\pi_t = \tau_t^{\gamma/\left[(\gamma-1)\eta_{poly}\right]}$$

$$or, \eta_t = \frac{1-\tau_t}{1-\tau_t^{1/\eta_{poly}}} = \frac{1-(\pi_t)^{(\gamma-1)\eta_{poly}/\gamma} - 1}{1-(\pi_t)^{(\gamma-1)/\gamma}}$$

The above equation relates the isentropic efficiency with the pressure ratio assuming a constant polytropic efficiency.

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Nozzle performance

- The flow in the nozzle is also adiabatic.
- However losses in a nozzle could occur due to incomplete expansion (under or over-expansion).
- Friction may reduce the isentropic efficiency.
- The efficiency is defined by

$$\eta_n = \frac{h_{06} - h_7}{h_{06} - h_{7s}}$$

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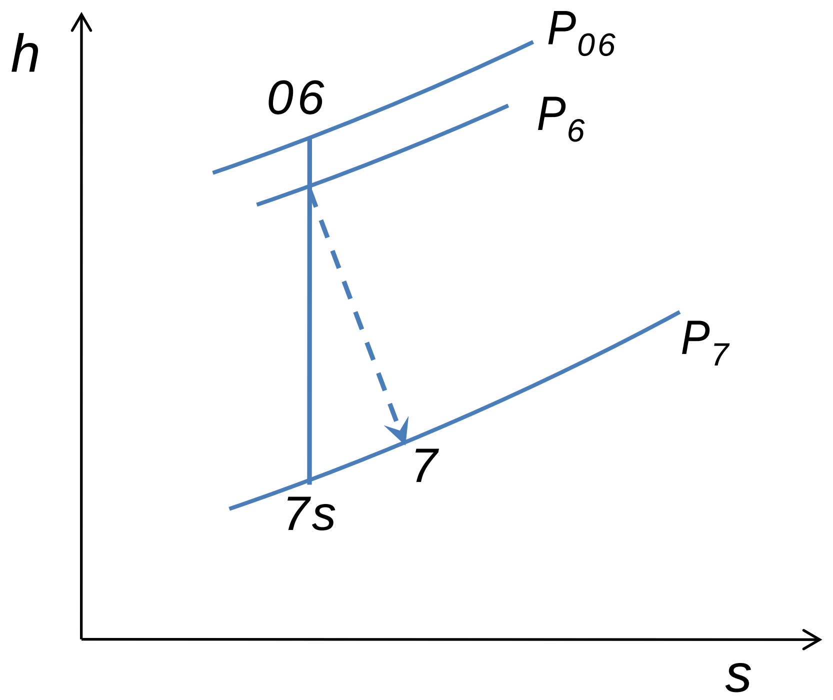
Nozzle performance



Actual and ideal nozzle processes

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Afterburner performance

- Afterburner is thermodynamically similar to a combustion chamber.
- The performance parameters for an afterburner is thus the combustion efficiency and the total pressure loss.
- In case of engines with afterburning, the corresponding performance parameters for an afterburner needs to be taken into account.

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Mechanical efficiency

- Mechanical efficiency is sometimes used to account for the loss or extraction of power on that shaft.
- Mechanical efficiency is defined as

$$\eta_m = \frac{\text{power leaving the shaft to compressor}}{\text{power entering the shaft from turbine}} = \frac{\dot{W}_C}{\dot{W}_t}$$

- Mechanical efficiency is less than one due to losses in power that occur from shaft bearings and also power extraction for driving accessories like oil and fuel pumps.

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Typical component efficiencies

Component	Figure of merit	Type	Value
Diffuser	π_d	Subsonic Supersonic	0.95-0.98 0.85-0.95
Compressor	η_c	-	0.85-0.90
Burner	η_b π_b	-	0.96-0.99 0.90-0.95
Turbine	η_t	Uncooled Cooled	0.85-0.92 0.84-0.90
Afterburner	η_{ab} π_{ab}	-	0.96-0.99 0.90-0.95
Nozzle	η_n	-	0.95-0.98
Mechanical	η_m	-	0.96-0.99

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In the next lecture...

- Tutorial on ideal cycles and component performance.

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