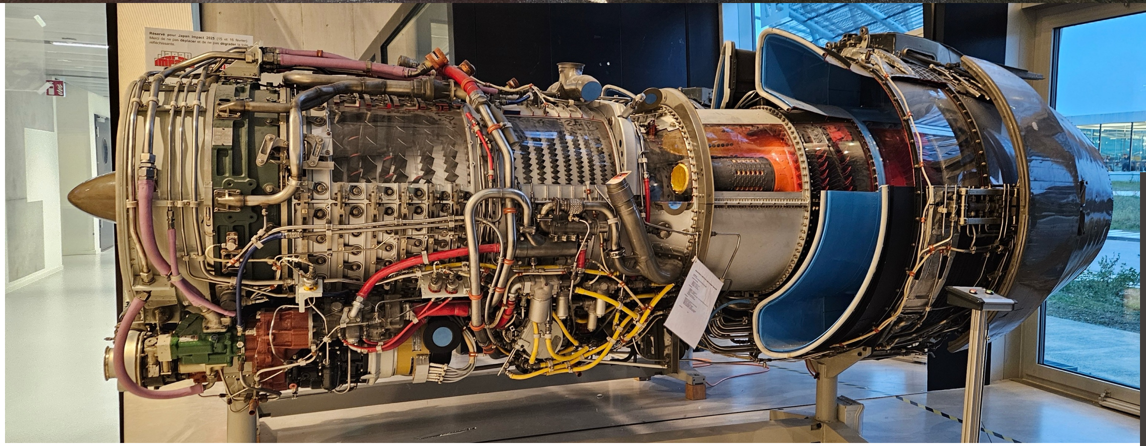
EPFL



Chapter 11: Compressible machines

ME-342 Introduction to turbomachinery

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About the exam

- 17th June 9:15-12:15
- The **equation sheet** will be available in Moodle **this week**
  - You should still learn what it means and how they are derived
  - Do **Not** Bring it to the exam → You will get the same copy in the exam
- You need to know the concepts and definitions
- Based on the exercises (in-class/exercise sessions)
- Bring a calculator!

- Lecture notes from Chap. 2 – Chap. 12 (next week included)

 You will receive the same copy in the exam.

Euler equation, Pumps and Turbines

- Shaft Work per Unit Mass:

$$w_s = U_2 V_{\theta 2} - U_1 V_{\theta 1}$$

- Shaft Power:

$$\dot{W}_{\text{shaft}} = -\dot{m}_1 (U_1 V_{\theta 1}) + \dot{m}_2 (U_2 V_{\theta 2})$$

- Euler Turbomachine Equation (Torque form):

$$T_{\text{shaft}} = -\dot{m}_1 (r_1 V_{\theta 1}) + \dot{m}_2 (r_2 V_{\theta 2})$$

- Total Head:

$$H = \frac{U_2 V_{\theta 2} - U_1 V_{\theta 1}}{g}$$

- Power gained by/from fluid:

$$P = \gamma Q H$$

- Ideal head rise pump:

$$h_i = \frac{U_2 V_{\theta 2} - U_1 V_{\theta 1}}{g}$$

- Actual head rise pump:

$$h_a = \frac{p_2 - p_1}{\gamma} + z_2 - z_1 + \frac{V_2^2 - V_1^2}{2g}$$

- Available Net Positive Suction Head (NPSH$_A$):

$$\text{NPSH}_A = \frac{p_{\text{atm}} - p_v}{\gamma} - z_s + \sum h_L$$

- Flow, Head and Power Coefficients:

$$C_Q = \frac{Q}{\omega D^3}, \quad C_H = \frac{g h_a}{\omega^2 D^2}, \quad C_{\mathscr{P}} = \frac{\dot{W}_{\text{shaft}}}{\rho \omega^3 D^5}$$

- Specific Speed (Dimensionless):

$$N_s = \frac{\omega \sqrt{Q}}{(g h_a)^{3/4}}$$

- Power Specific Speed (Hydraulic Turbines):

$$N_s' = \frac{\omega \sqrt{\dot{W}_{\text{shaft}} / \rho}}{(g h_a)^{5/4}}$$

- (static) Enthalpy and Stagnation enthalpy:

$$\check{h} = \check{u} + \frac{p}{\rho}, \quad \check{h}_0 = \check{h} + \frac{V^2}{2} + gz$$

- Degree of Reaction:

$$R = \frac{\check{h}_{\text{rotor}}}{\check{h}_{\text{stage}}}$$

- Head available at the turbine inlet relative to the surface of the tailrace:

$$H_E = h_g - h_{LP}$$

- Turbine Efficiency:

$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{shaft}}}{\gamma Q H_E}$$

$$\eta_h = \frac{|w_{\text{shaft}}|}{g H_E} = \frac{|-U_1 V_{\theta 1} + U_2 V_{\theta 2}|}{g H_E}$$

- Pump Efficiency:

$$\eta_{\text{pump}} = \frac{\gamma Q h_a}{\dot{W}_{\text{shaft}}}$$

- Thoma Cavitation Factor:

$$\sigma = \frac{\text{NPSH}_A}{H_E}$$

Compressible turbomachines

- Ideal gas law

$$\rho = \frac{p}{RT}$$

Compressible Flow Turbomachines

Compressible Flow Turbomachines

- Similar in principle to incompressible pumps and turbines
- **Key difference:** Fluid ______ **changes significantly** from inlet to the outlet
  → **unique consequences, benefits, and challenges**

- **Energy and angular momentum** principles still apply
- **Thermodynamics** is essential for understanding compressible flow behaviour
- Unlike liquids, **temperature change matters greatly** in gases/vapours

Compressor vs. Turbine Behaviour

- **Compressors** (like pumps):
  - Add energy to the gas
  - Cause **pressure**, **density**, and **temperature** to ______
- **Turbines**:
  - Extract energy from the gas
  - Cause **pressure**, **density**, and **temperature** to ______

Recall?

(static) Enthalpy: internal energy and flow work

$$\check{h} = \check{u} + \frac{p}{\rho} \quad \text{[J/kg]}$$

$\check{u}$: Internal energy

$\frac{p}{\rho}$: $\mathrm{Pa} \cdot \mathrm{m}^3/\mathrm{kg} \equiv \mathrm{J/kg}$

Ideal gas law → when can we use this?

$$\rho = \frac{p}{RT}$$

- Low pressure/high-temperature gases
- Superheated steam (T>200 °C)

R is the specific gas constant (not Reaction)
T in Kelvin, [K]

Side note..

$p\cancel{V} = nR'T$ R': universal gas constant, n: number of mols

$p\cancel{V} = mRT$ R: specific gas constant, m: mass

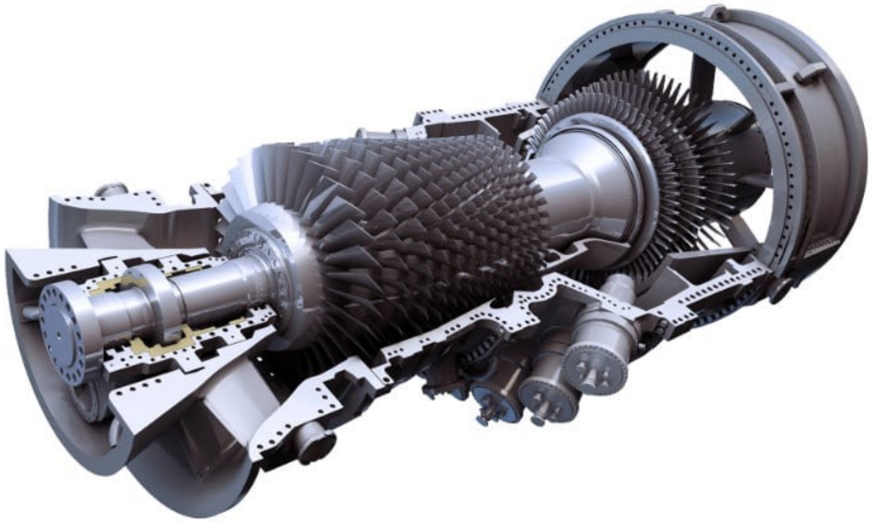
Reaction

$$R = \frac{\text{static enthalpy change in } \textbf{rotor}}{\textbf{stage} \text{ static enthalpy change}} = \frac{\check{h}_2 - \check{h}_3}{\check{h}_1 - \check{h}_3}$$

Compressor and Turbine

- **“Gas turbine”** usually refers to a **full** gas turbine engine:
  - Includes **compressor**, **combustor**, and **turbine**
  - Common in **aircraft propulsion** and **power generation**

- **“Steam turbine”** usually refers to a turbine driven by high-pressure steam:
  - **Part of the steam cycle** (usually Rankine cycle)
  - Steam is generated in a boiler, then expanded in the turbine
  - **Only includes the turbine itself**, not the boiler or condenser
  - Common in thermal power plants (coal, nuclear, solar thermal, and combined cycle)

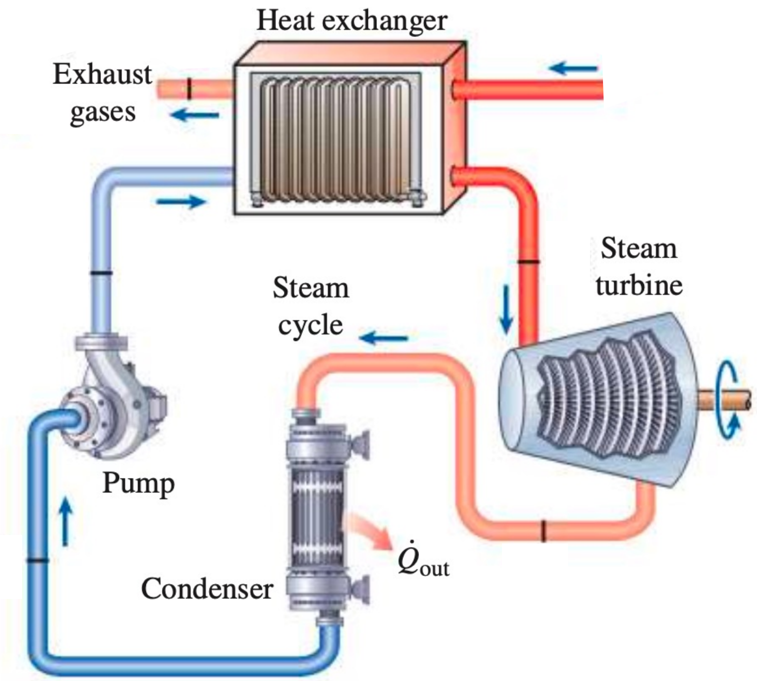


Thermodynamic cycle

Rankine Cycle — Steam Turbine

- **Working fluid**: water/steam
- **Main components**:
  - **Boiler/Heat Recovery Steam Generator (HRSG)**: uses heat from gas turbine exhaust to create steam
  - **Steam turbine**: expands steam to produce power
  - **Condenser**: condenses steam back to water
  - **Pump**: returns water to the boiler
- The maximum fluid temperature at the turbine inlet ~620°C
- **Efficiency**: ~30–40% (on its own)

Key idea: Steam run a **turbine to extract energy**

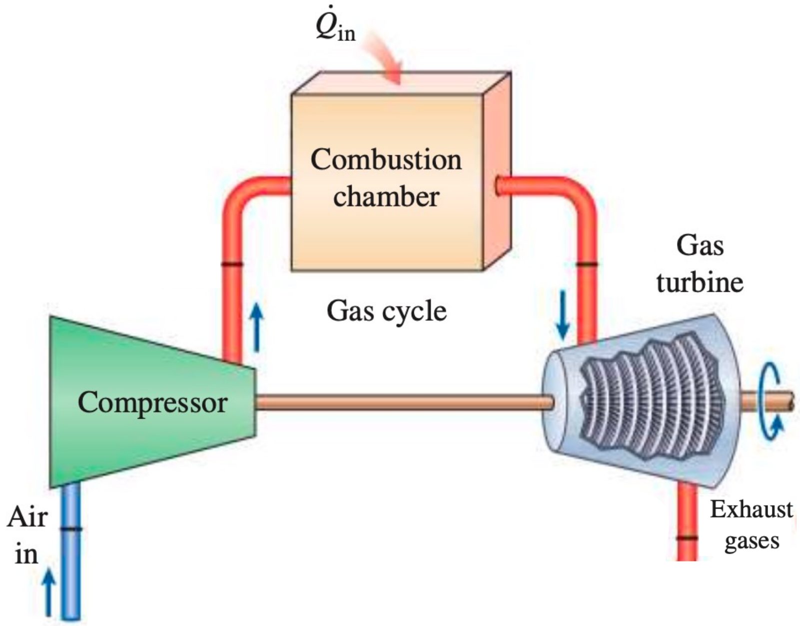


Thermodynamic cycle

Brayton Cycle (a.k.a. Joule Cycle) — Gas Turbine

- **Working fluid**: air (and combustion gases)
- **Main components**:
  - **Compressor** (compresses air)
  - **Combustor** (burns fuel to heat air)
  - **Turbine** (expands hot gases to generate power)
- The maximum fluid temperature at the turbine inlet ~1425°C
- **Real-world example**: Jet engines, gas turbines
- **Efficiency**: ~30–40%

Key idea: High-temperature gas spins the turbine → generates electricity/thrust.



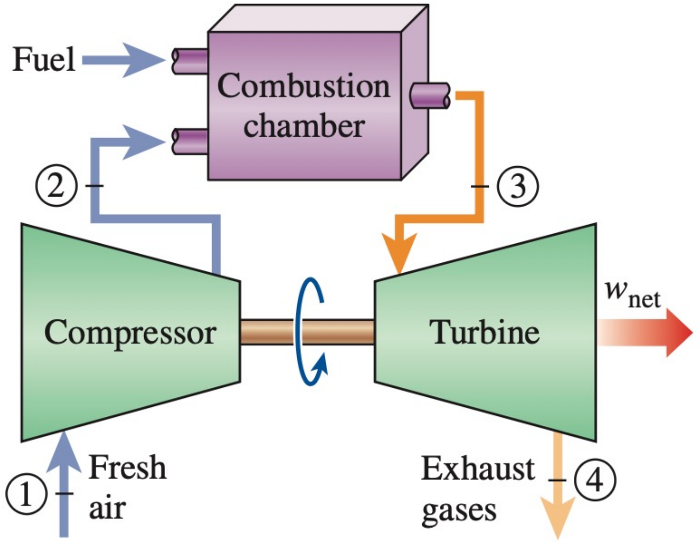
Combined Cycle = Brayton + Rankine

- **How it works**:
  - Burn fuel → gas turbine (Brayton) → electricity
  - Use the hot exhaust → heat water → steam turbine (Rankine) → more electricity
- **Total efficiency**: ~55–60%, much higher than either cycle alone.

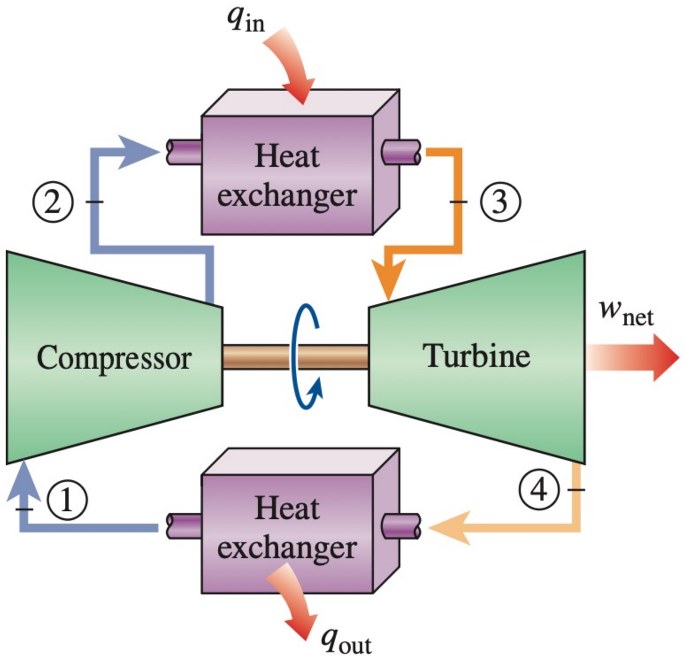
Brayton Cycle

- **THE IDEAL CYCLE FOR GAS-TURBINE ENGINES**

An **open-cycle** gas-turbine engine



A **closed-cycle** gas-turbine engine



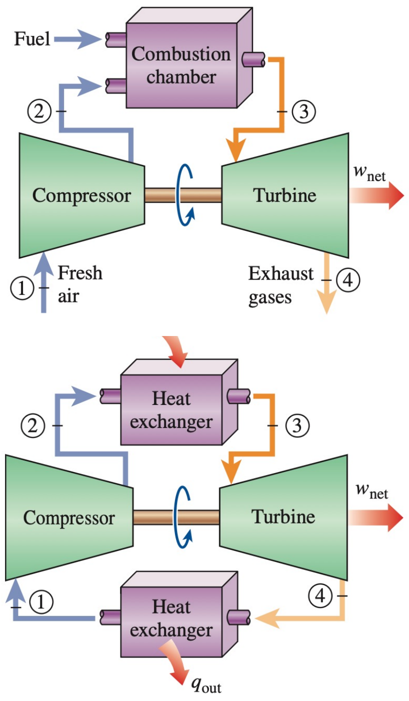
Isentropic: adiabatic and reversible (Δs=0)

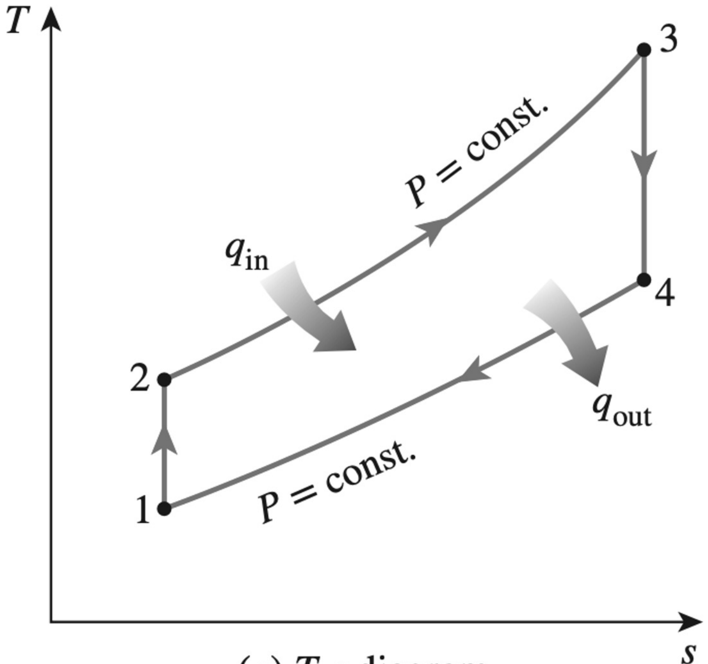
$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

Specific heat ratio: $k = c_p/c_v$, (air ~1.4)

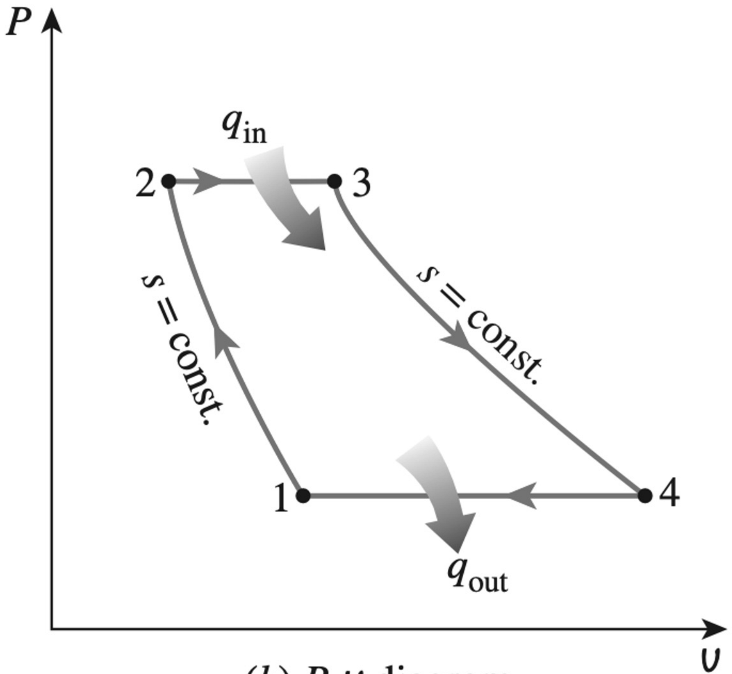
1→2 Isentropic compression (in a compressor)
2→3 Constant-pressure heat addition
3→4 Isentropic expansion (in a turbine)
4→1 Constant-pressure heat rejection

Brayton Cycle





(a) T-s diagram



(b) P-υ diagram

P = pressure, v = volume, T = temperature, s = entropy, q = the heat added to or rejected by the system

Compressors – Radial (Centrifugal)

Radial-Flow (Centrifugal) Compressors

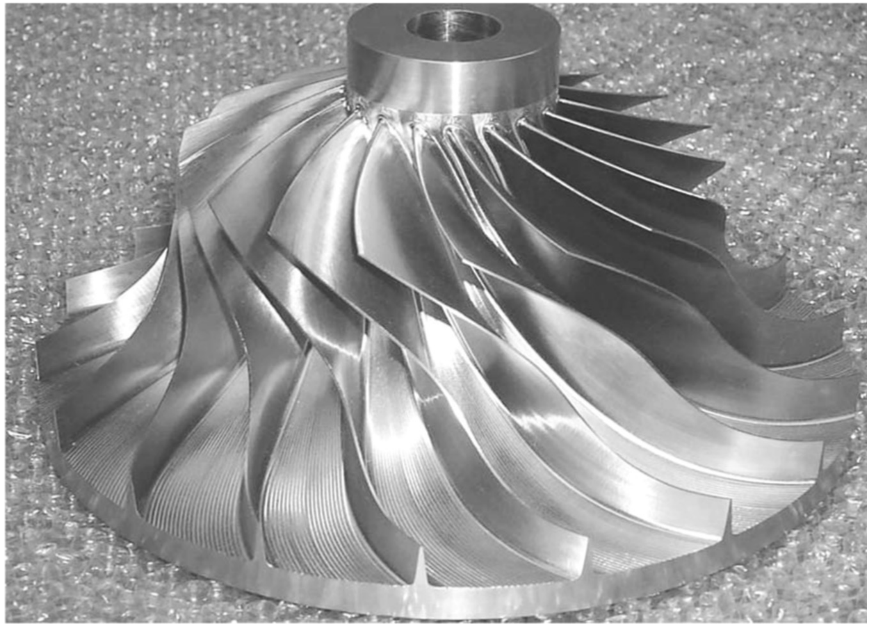
- Turbocompressors **continuously compress** flowing gas
- Compression leads to significant **increases in pressure, density, and temperature**
- Operate like centrifugal pumps, but with **gas instead of liquid**

- Typical features:
  - **High pressure rise**
  - **Low flowrate**
  - **Axially compact**

- **Total Pressure Ratio (PR):** $\mathrm{PR} = \frac{p_{T2}}{p_{T1}}$ in absolute pressure

Total pressure:

$$p_T = p + \frac{1}{2}\rho V^2 + \gamma z \simeq p + \frac{1}{2}\rho V^2$$



- Example: PR = 3.0 → Air compressed from 101.3 kPa to ~304 kPa
  Accompanied temperature rise?

Isentropic compression $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = PR^{\frac{k-1}{k}}$

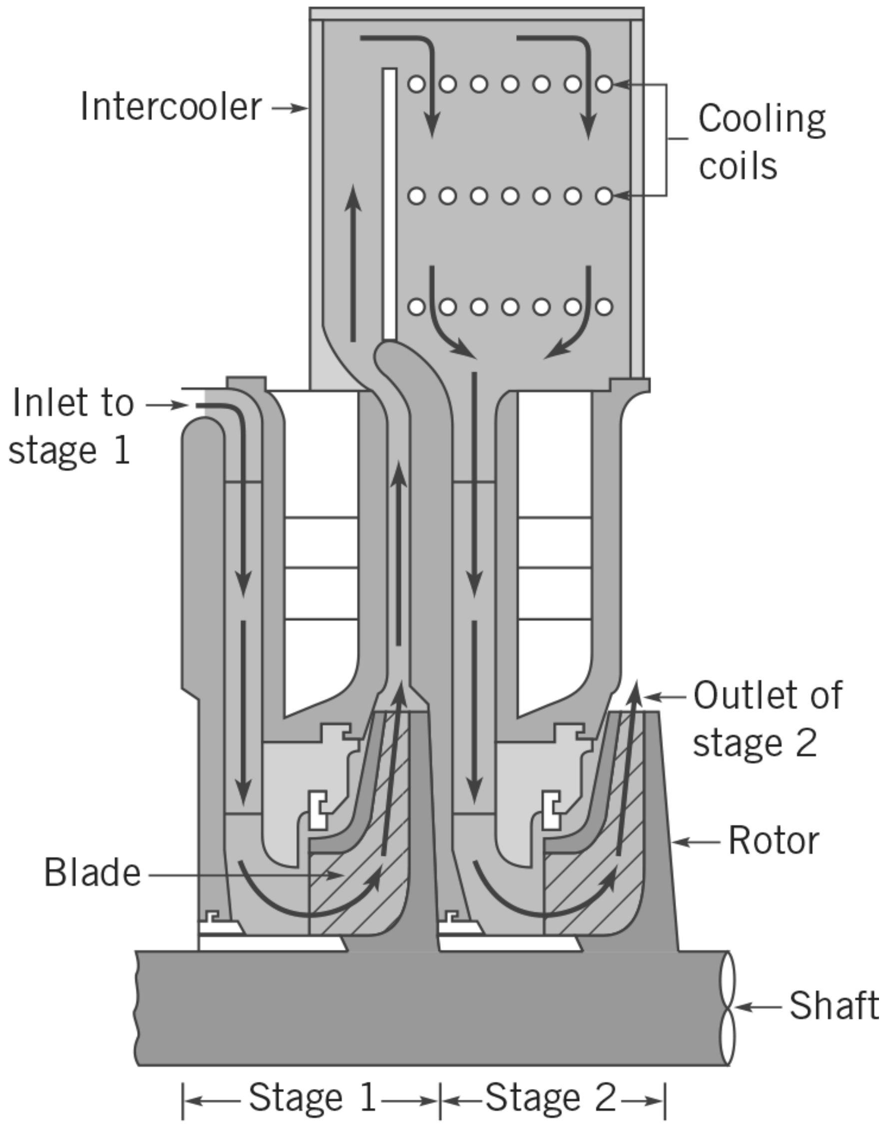
Compressors – Radial

Multi-Stage Compression

- Higher compression ratio
- For similar PR per stage,

$$\text{Overall PR} = (PR_{\text{stage}})^n$$

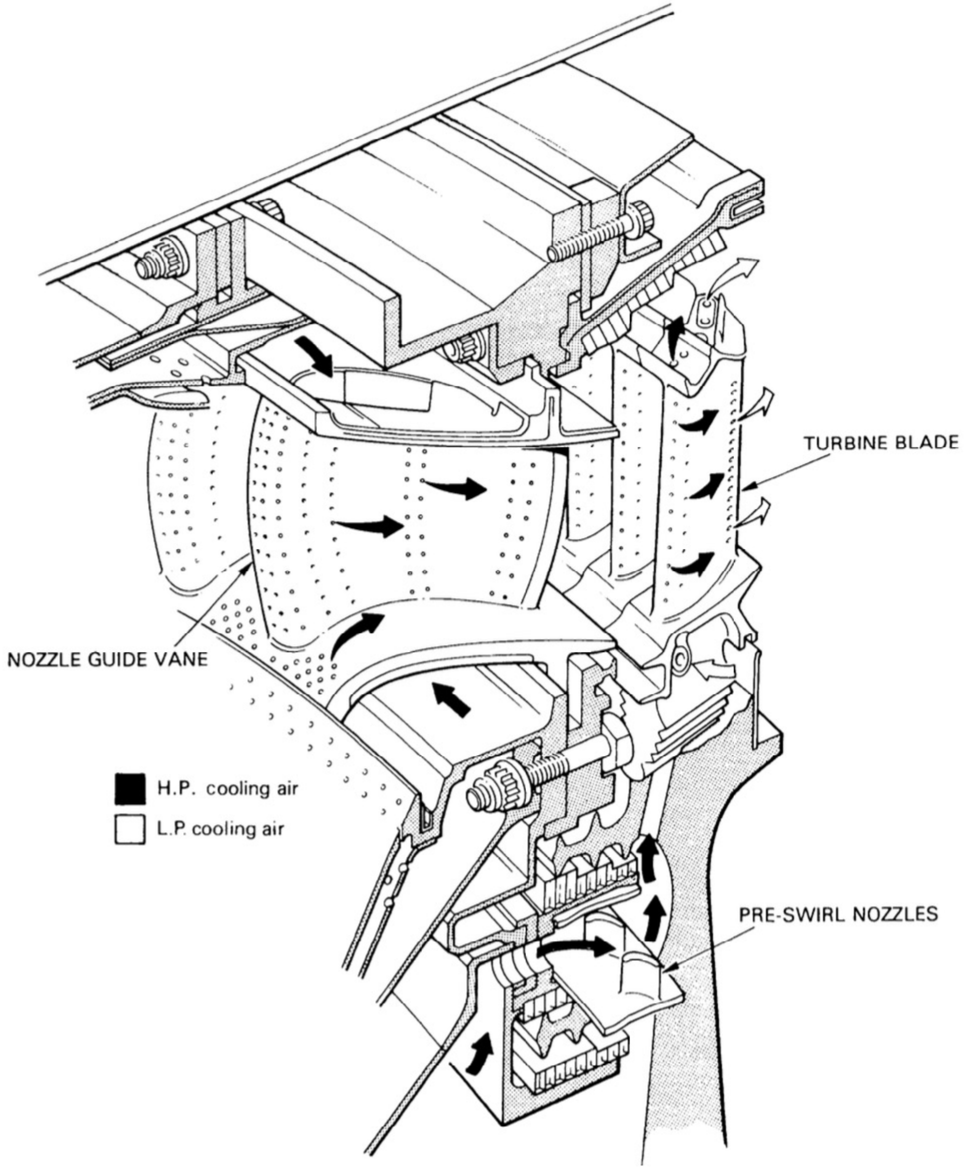
- Example: 4 stages with $PR_{stage} = 2.0 \rightarrow PR_{overall} = 2^4 = 16$
  → Compress air from 101.3 kPa to 1620 kPa

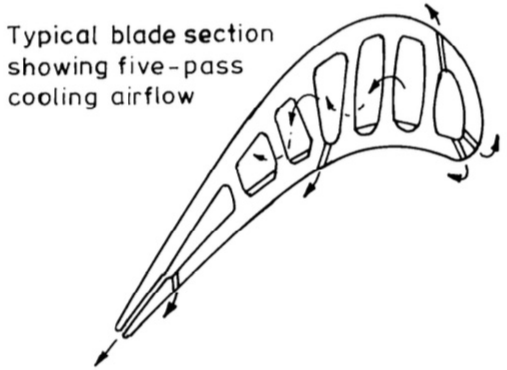


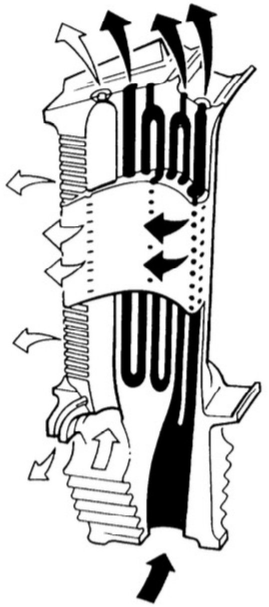
Thermodynamic Considerations

- **Adiabatic compression** (Brayton cycle)
  → temperature increases, more work needed
- **Isothermal compression** (ideal)
  → less work
- **Intercooler** between stages:
  - **Reduces temperature** before next stage
  - **Lowers required compression work**

Blade cooling







Compressors – Axial

- Widely used **compressor type** in turbomachinery

- Compared to centrifugal compressors:
  - **Lower pressure rise per stage**
  - **Higher flowrate**
  - More **radially compact**

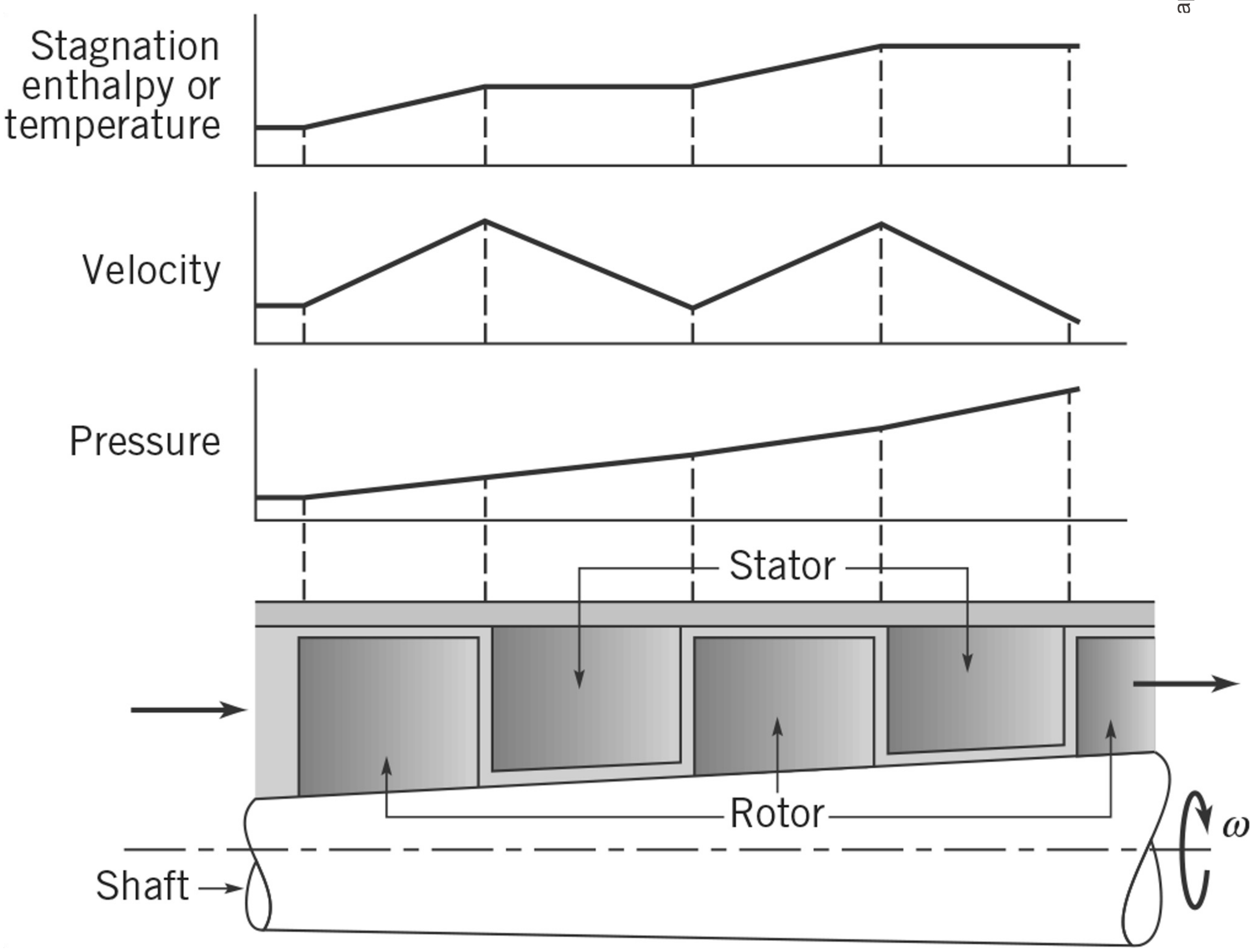
- Usually **multiple stages**
  - Usually, PR_{stage} varies across the stages

    → $\mathrm{PR}_{\mathrm{overall}} = \mathrm{PR}_{\mathrm{st1}} \times \mathrm{PR}_{\mathrm{st2}} \cdots \mathrm{PR}_{\mathrm{stn}}$

- As gas is compressed:
  - **Density increases**
  - **Cross-sectional area decreases**
  - **Blade height reduces** from inlet to outlet

→ Why do compressor blades shrink?

$$\dot{m} = \rho A V = \text{constant}$$

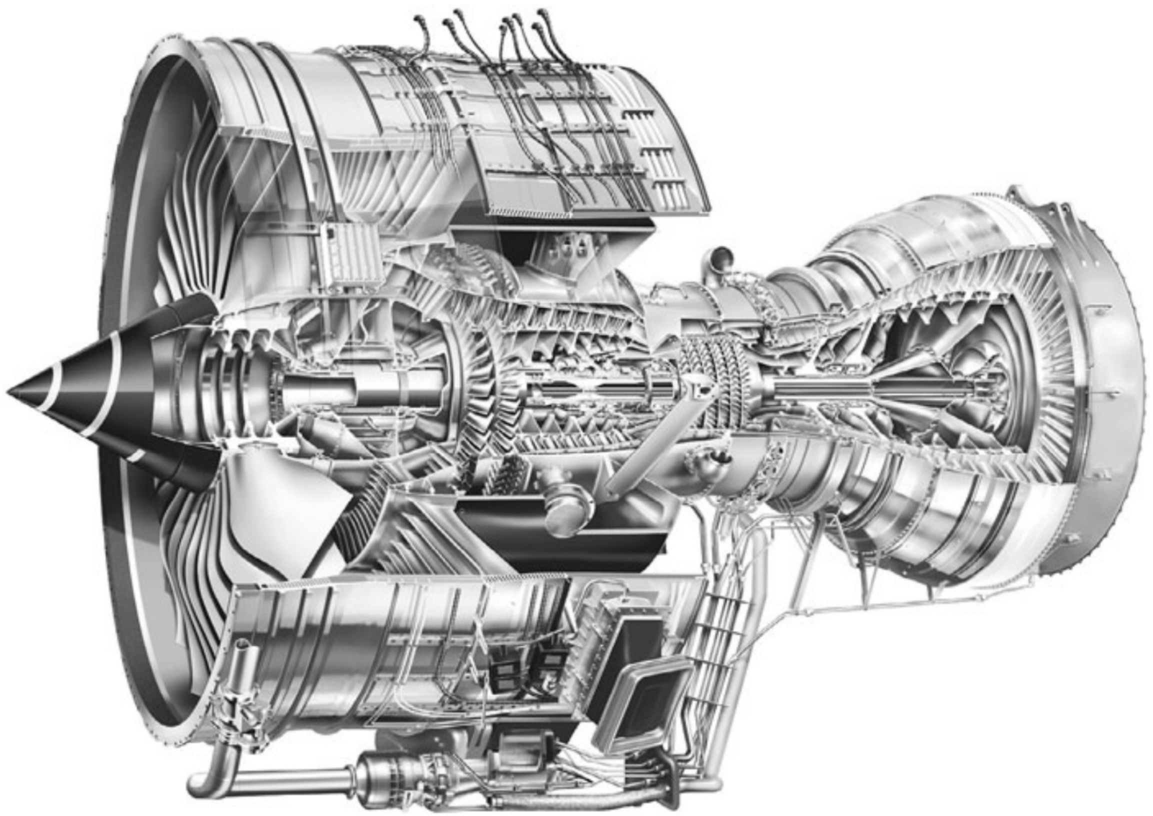


Compressors – Axial

- **Inlet Guide Vanes (IGVs)**:
  - Located **before the first rotor**
  - **Redirect flow** away from purely axial direction
  - Optimize **relative velocity** into rotor blades

- **Rotor Blades**:
  - **Rotate**, pushing gas **rearward and outward**
  - **Add energy** to the flow (like an axial pump)
  - Increase **total pressure and enthalpy**

- **Stator Blades**:
  - **Stationary**, act as **diffusers**
  - **Turn flow back** toward axial direction
  - Increase **static pressure**
  - Cannot add energy (no rotation)



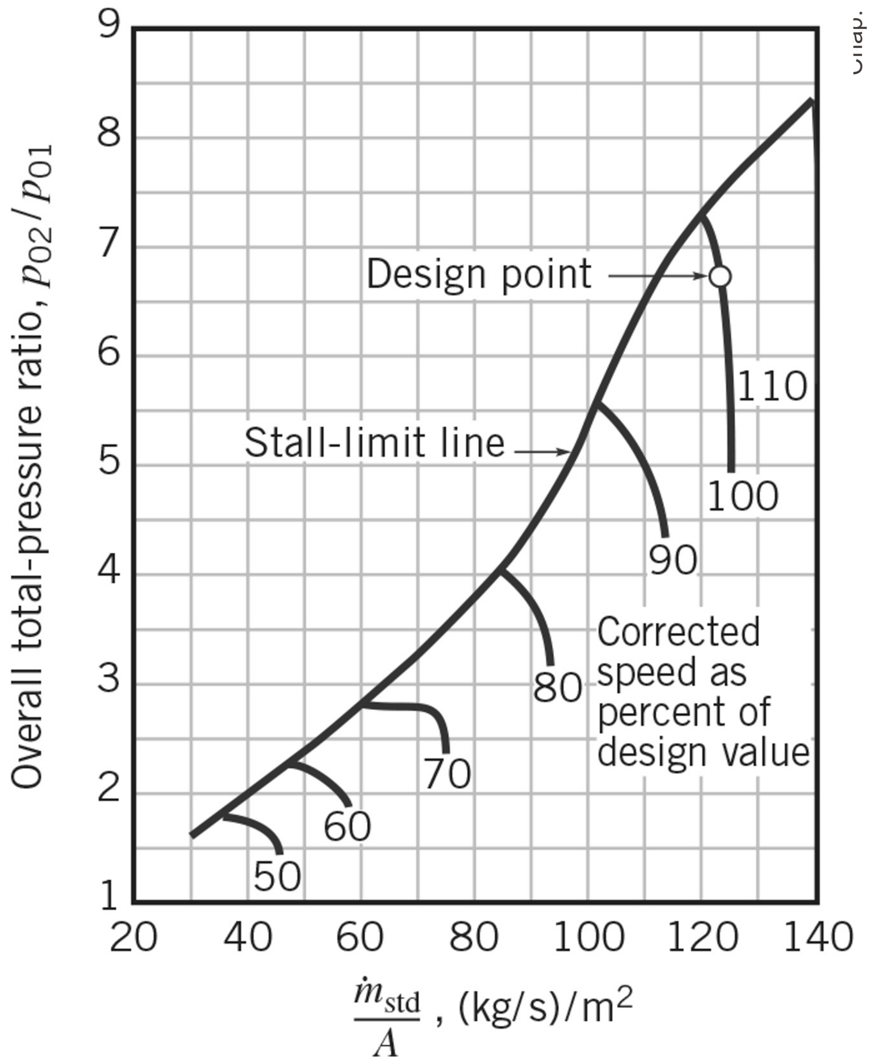
Axial-flow compressor multistaging requires less frontal area but more length than centrifugal compressors.

Compressors

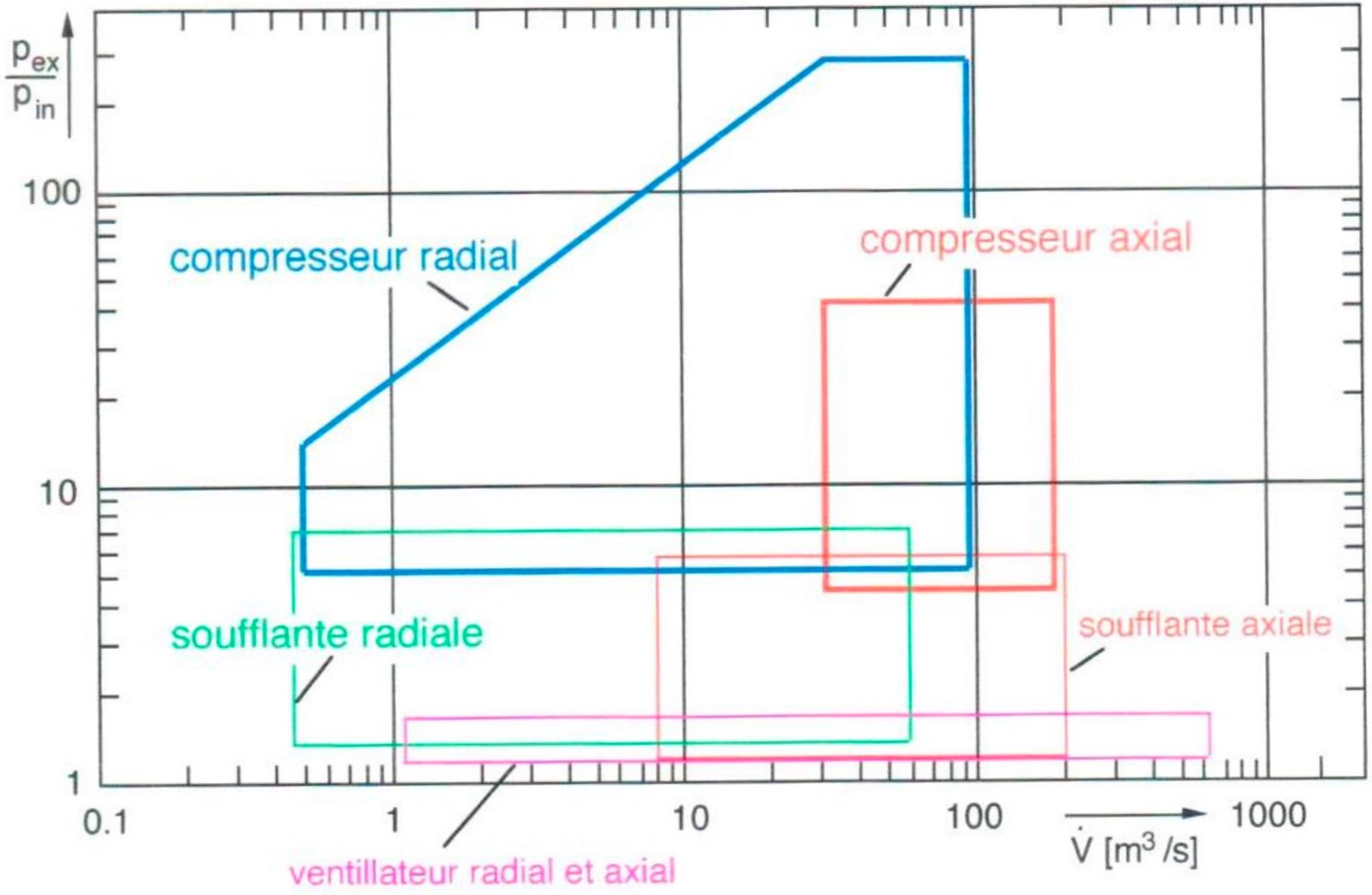
- **Axial-Flow Compressor Blade Behavior**
  - Blades are shaped like **airfoils** (like airplane wings)
    - Designed to generate **lift** and manage **drag**
  - Operate best at **design flowrate**

- **Compressor Stall and Surge**
  - At reduced flowrate:
    - **Angle of incidence** (between flow and blade) **increases**
    - **Relative flow hits blade at a steeper angle**
  - If incidence is too large:
    - **Blade stall** occurs (like wing stall in aircraft)
    - Leads to **compressor surge or stall**:
      - **Unstable flow**
      - Can cause:
        - **Excessive vibration**
        - **Noise**
        - **Performance loss**
        - **Mechanical damage**

- **Operating Limits**
  - **Lower flowrate bound** is set by **onset of stall/surge**

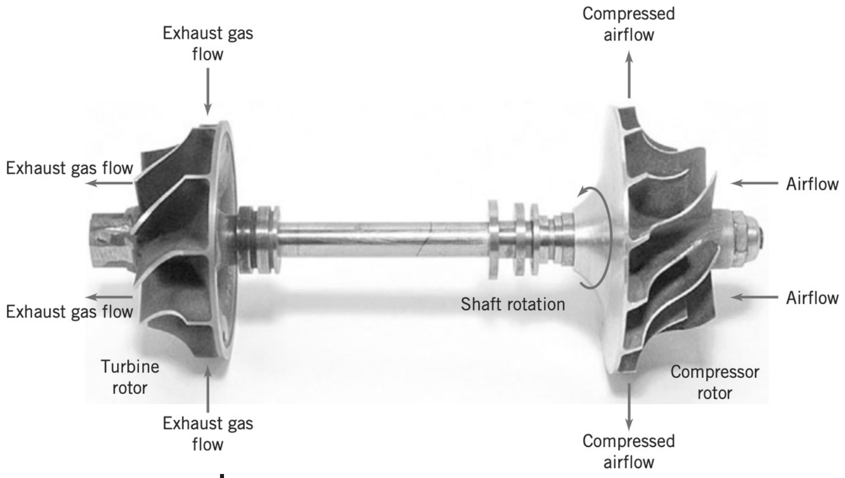


Compressor map



Compressible Flow Turbines

- Similar in principle to **hydraulic turbines**
- Use a **gas** or **vapor** as a working fluid → **fluid expands** during flow
- Can be:
  - **Impulse** or **reaction** type
  - **Axial**, **radial**, or **mixed-flow**



Radial-Inflow Turbines

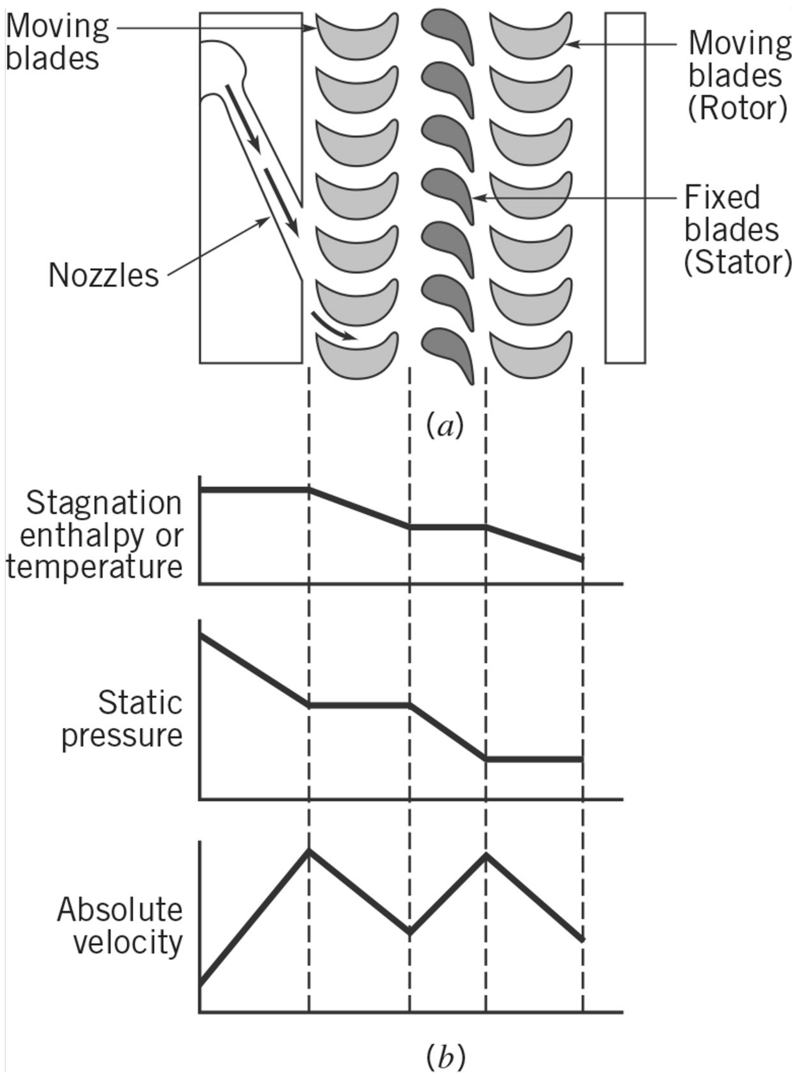
- Example: **Turbocharger** turbine (automotive)
- Advantages:
  - **Robust & durable**
  - **Axially compact**
  - **Cost-effective**
- Disadvantages:
  - Generally **lower efficiency** than axial-flow turbines

Axial-Flow Turbines

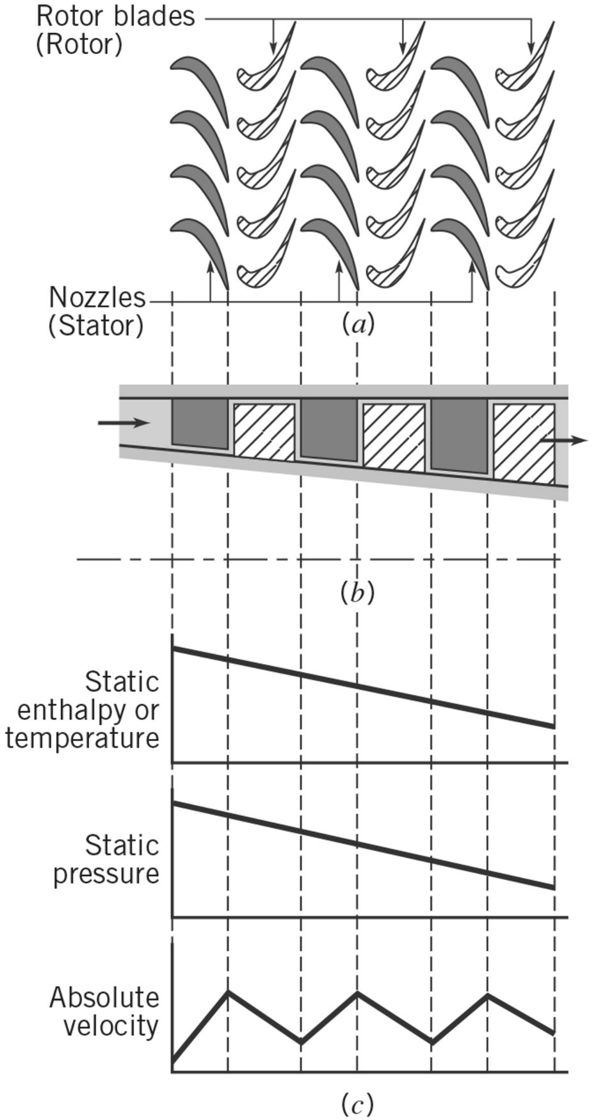
- **Steam and gas power plants**
- **Marine propulsion**
- **Gas turbine engines**
- Can be:
  - **Single-stage** or **multistage**
  - **Impulse** or **reaction** type

Impulse or Reaction?

Two-stage turbine

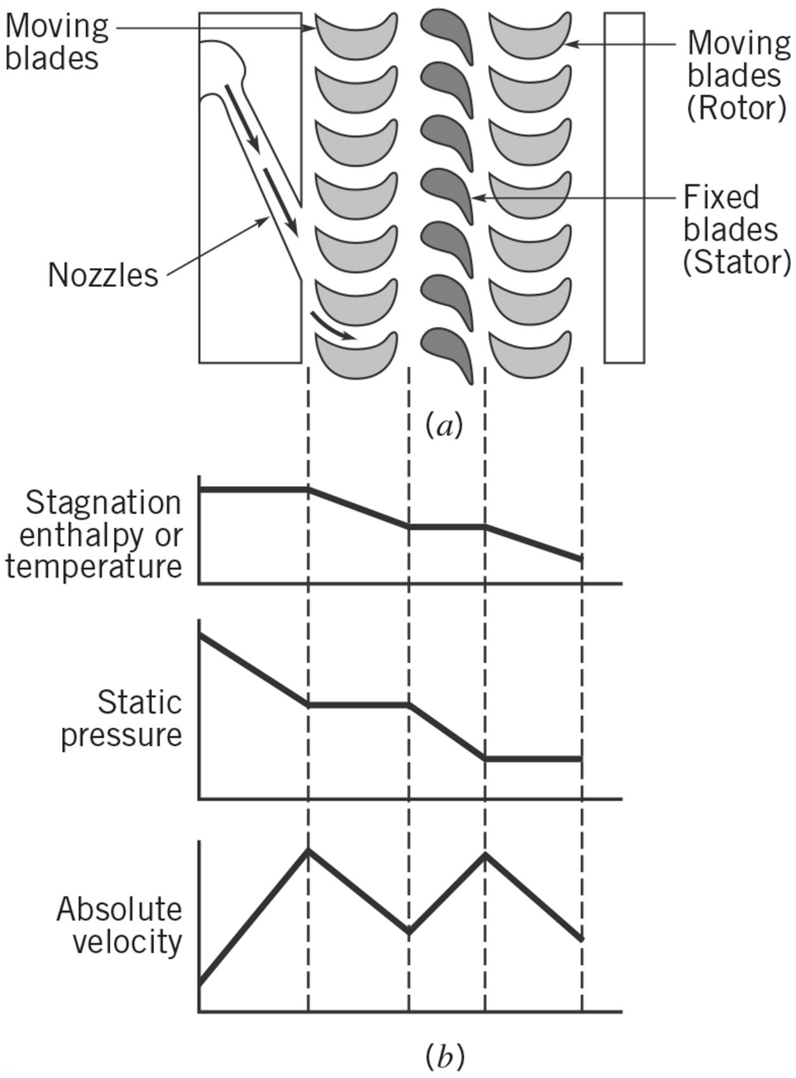


Three-stage turbine



Impulse turbine

Two-stage impulse turbine



- Pressure drop happens mostly across **nozzles (stators)**
- Rotor blades operate at nearly constant pressure

Reaction turbine

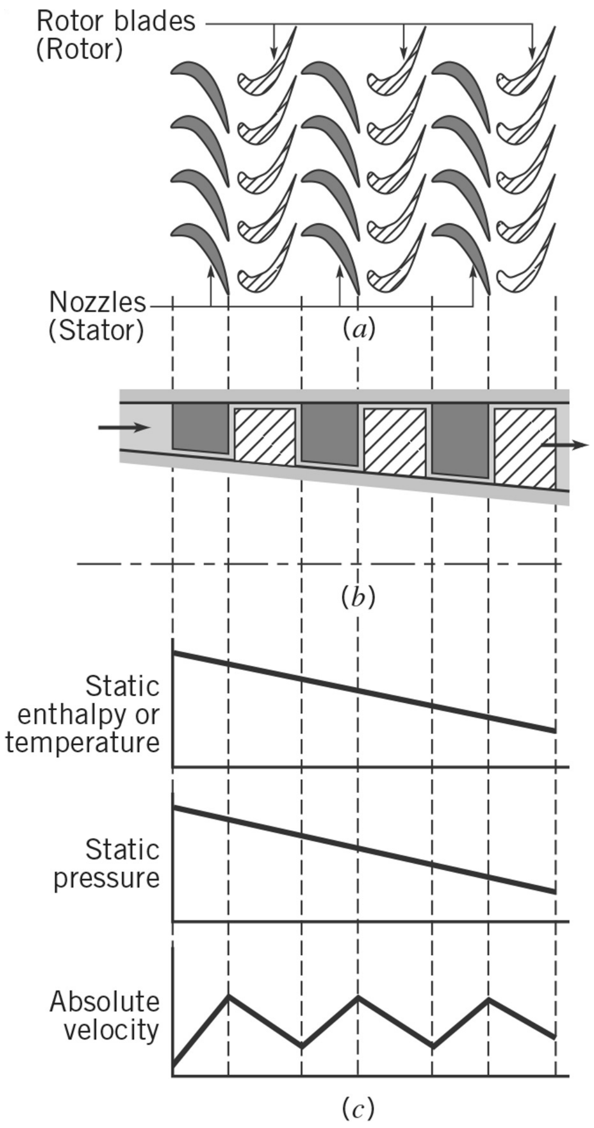
- **Stators only guide** and **accelerate** flow (adiabatic → no energy loss)
- **Stagnation enthalpy (or temperature) remains constant** across stators

- Due to **gas expansion** (pressure ↓), **density** ↓
- To maintain mass flow, **passage area increases** from inlet to outlet
- Seen clearly in reaction turbine geometries

→ Why Do **Turbine** Blades **Expand**?

$$\dot{m} = \rho A V = \text{constant}$$

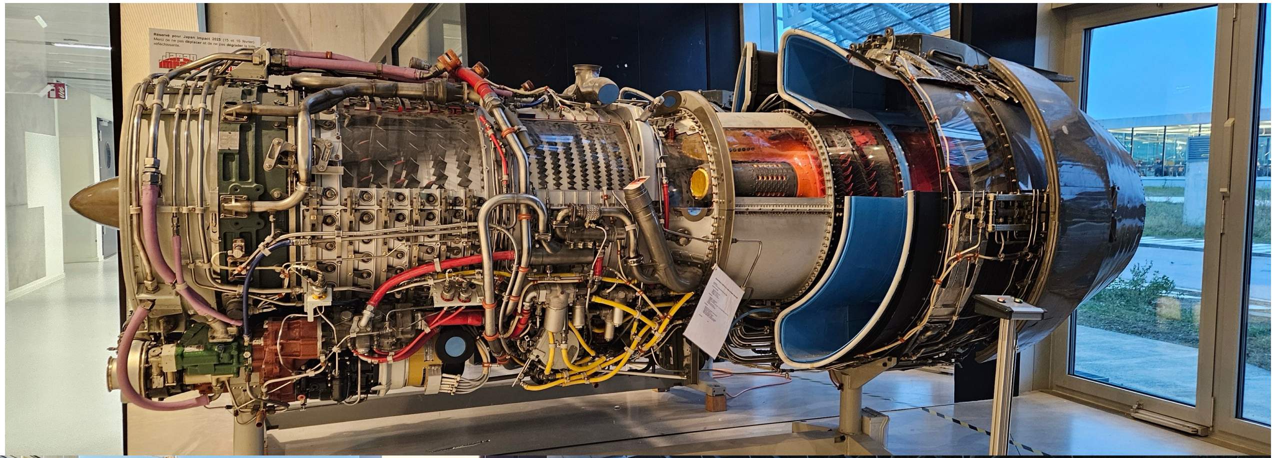
Three-stage reaction turbine

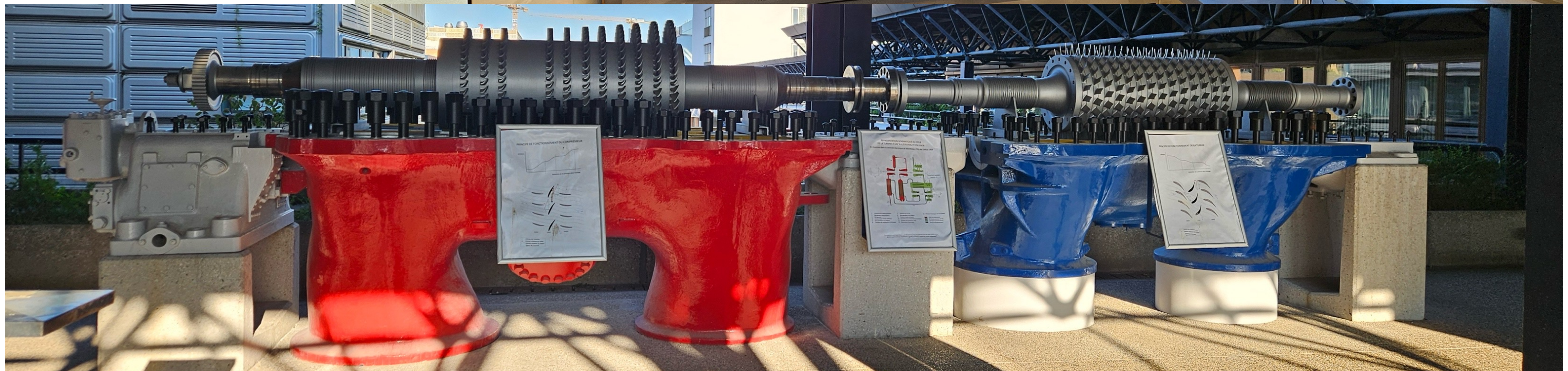


Our Compressible Turbomachines - next week!

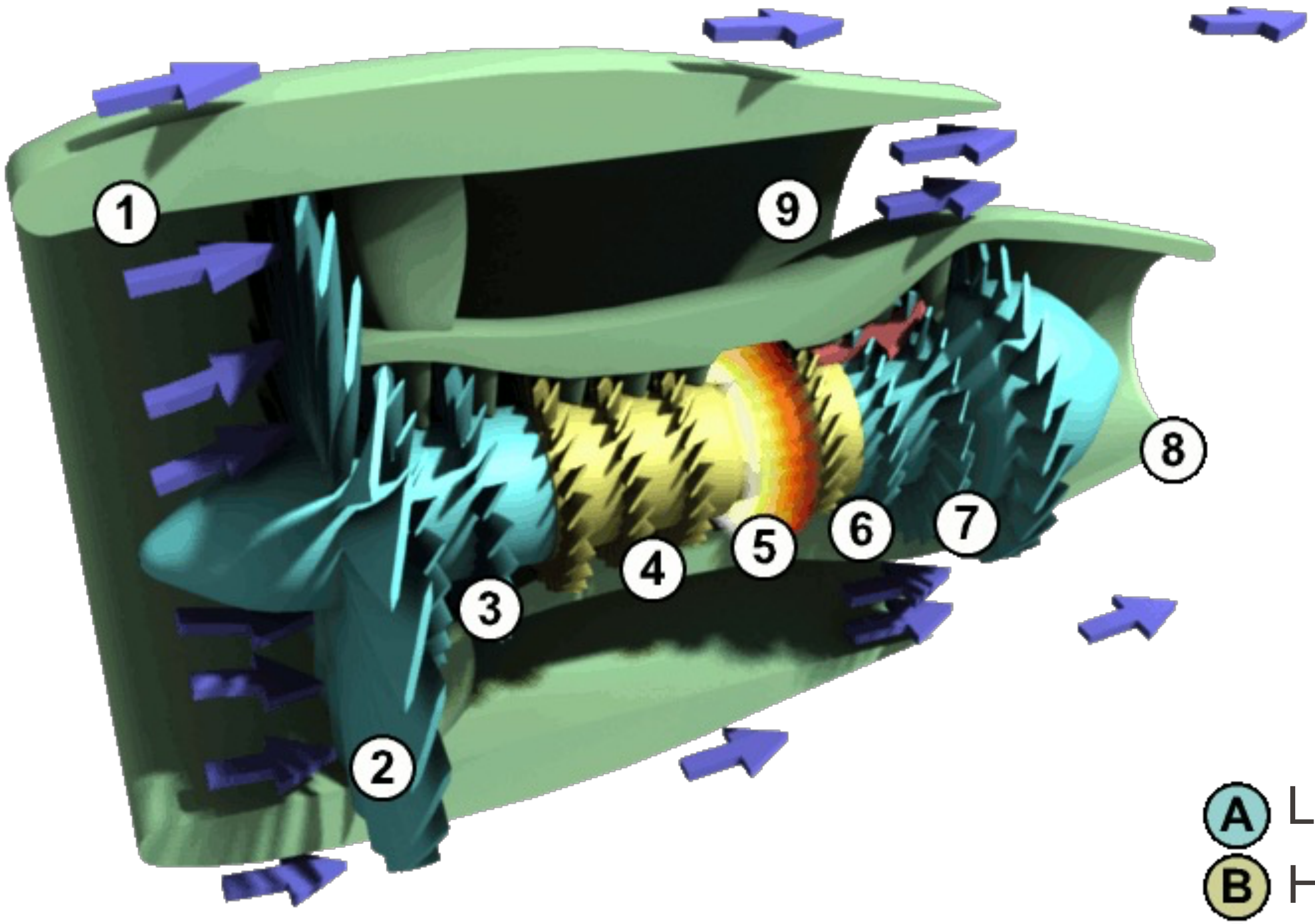
Next Week

- Guided tour + exercise
  - Lecture on our turbomachines
    - Visit together the machines
  - Two groups
    - Group 1: exercise + tour
    - Group 2: tour + exercise





Multiple spools (shafts)

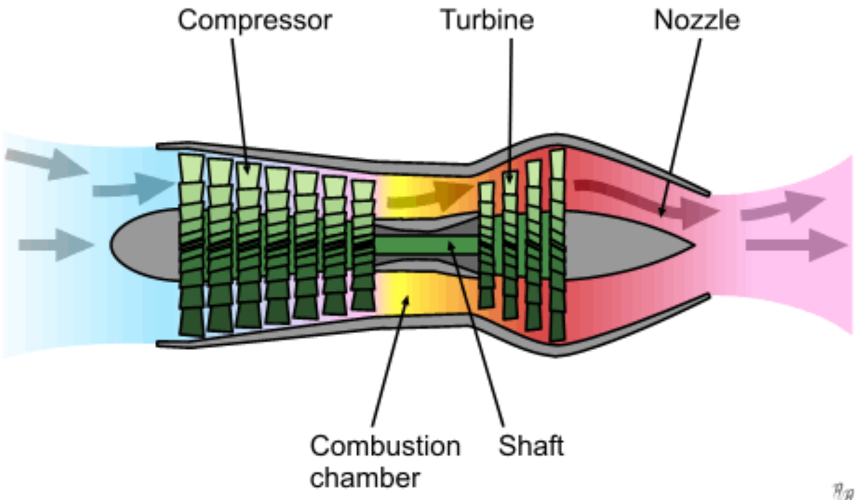


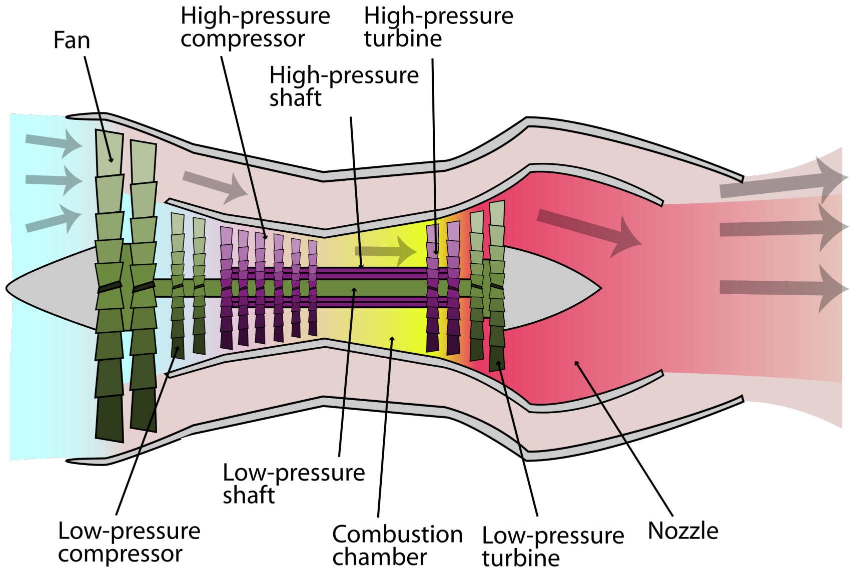
1. Nacelle
2. Fan
3. Low-pressure compressor
4. High-pressure compressor
5. Combustion chamber
6. High-pressure turbine
7. Low-pressure turbine
8. Core nozzle
9. Fan nozzle

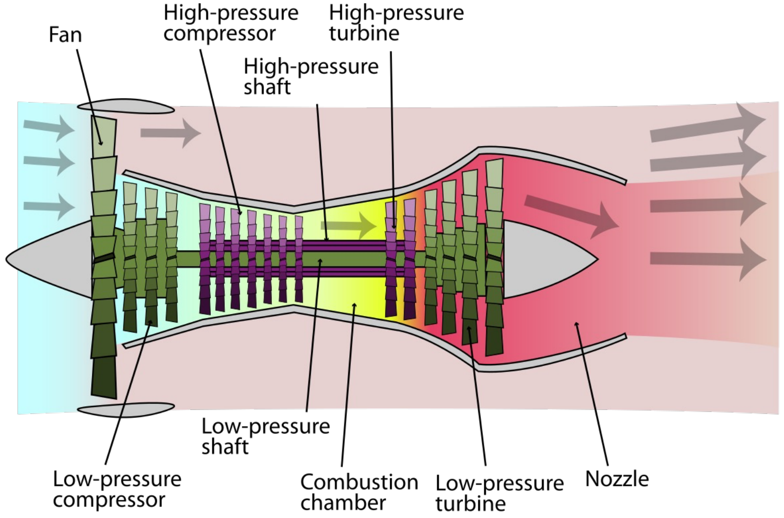
(A) Low-pressure spool
(B) High-pressure spool
(C) Stationary components

Turbojet and turbofan

- **turbofan** a jet engine with a bypass stream.
- **turbojet** a jet engine with no bypass stream – these were the earliest type of jet engines and are still used for very highspeed propulsion.

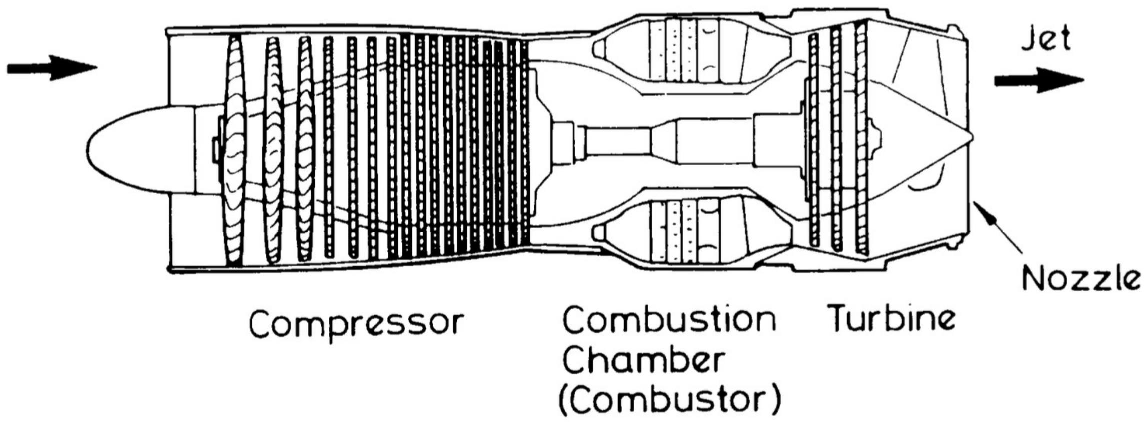




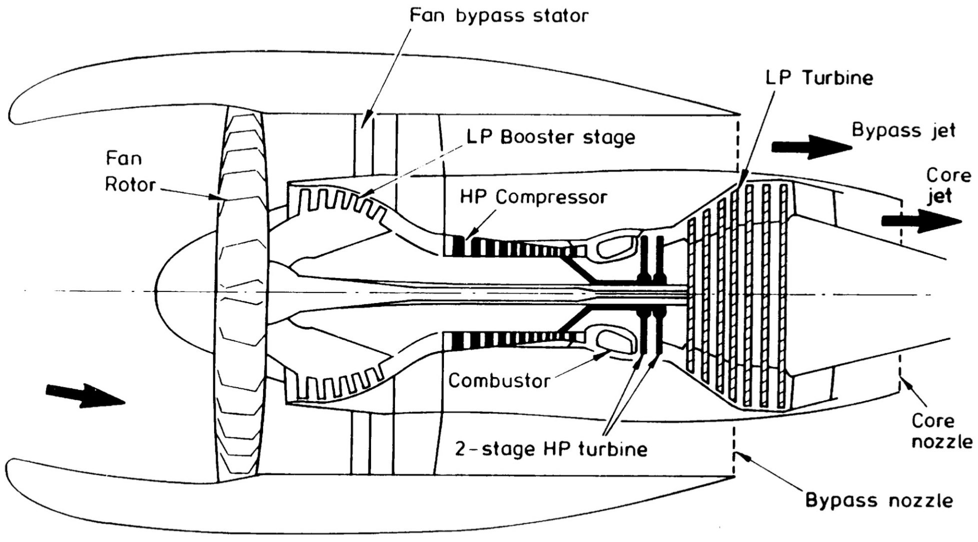


- Multiple shafts system is also required
  - Large diameter of fan, slow speed (Low pressure compressors, LP turbines)
  - Small diameter, faster speed (High pressure compressors, HP turbines)

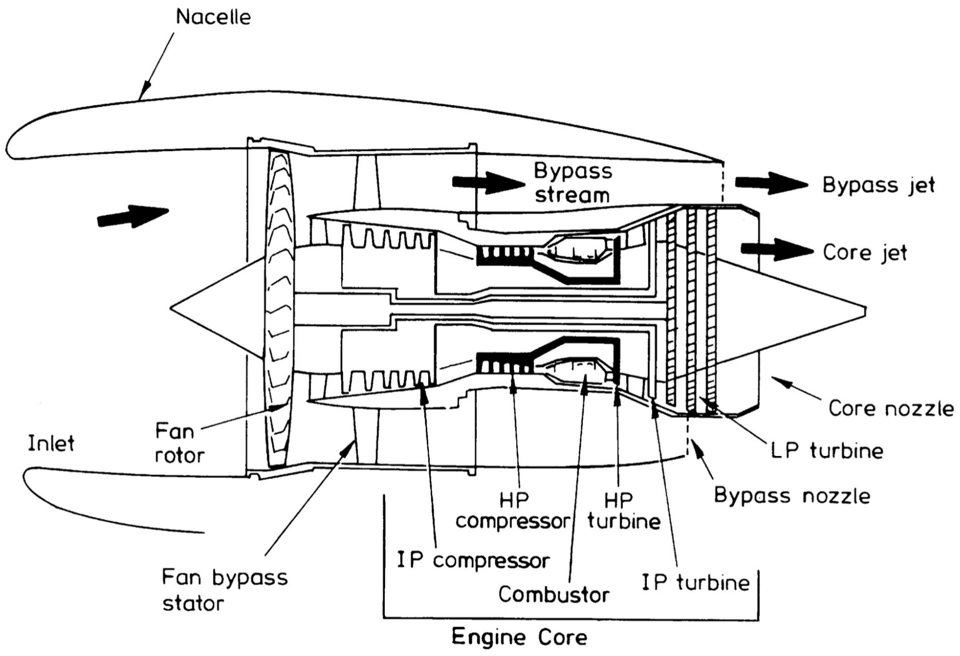
Turbofan: Bypass ratio



A single-shaft turbojet engine (no bypass)



A two-shaft high bypass engine



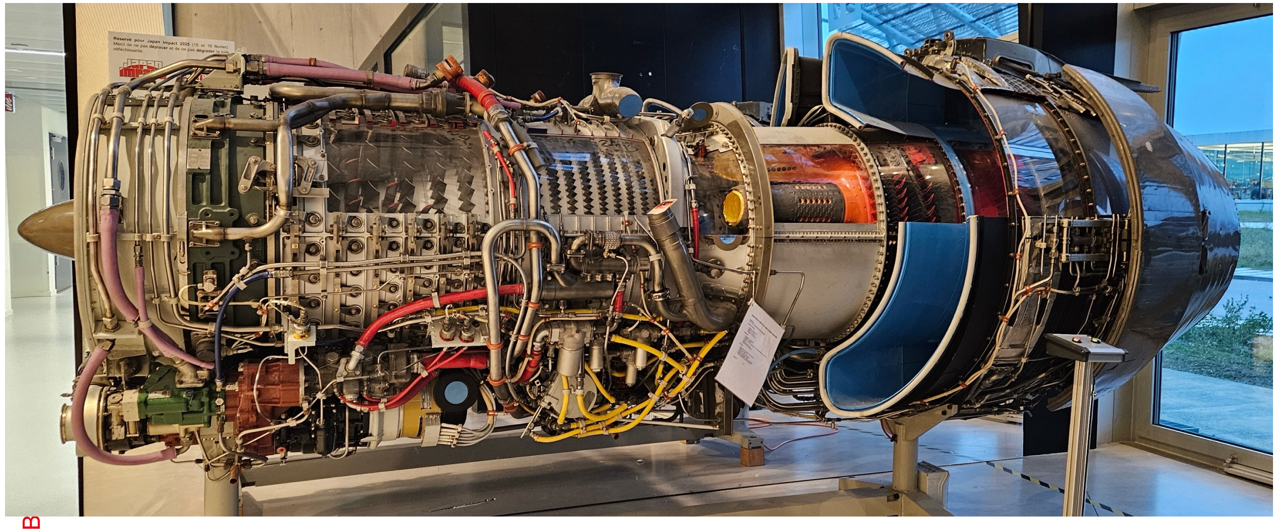
A three-shaft high bypass engine

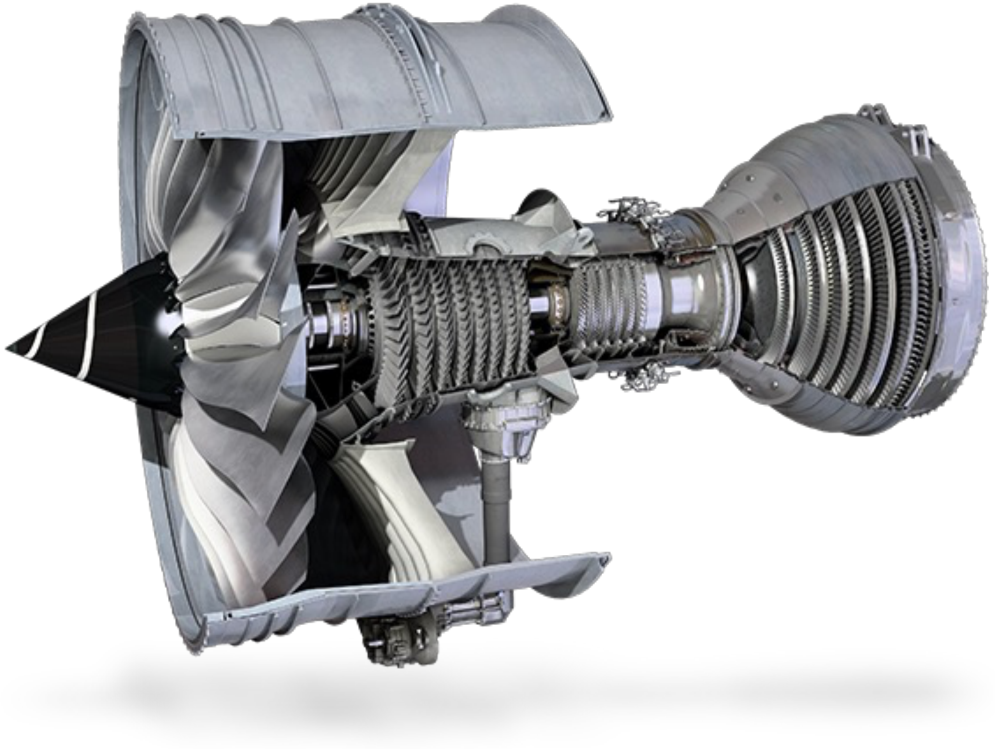
Low-Pressure (LP)	First compression from ambient to intermediate
Intermediate (IP)	Compression to medium pressure
High-Pressure (HP)	Final compression before combustion

Bypass ratio

GE CJ805-23
Bypass ratio 1.46
Overall Pressure ratio 13

Rolls-Royce Trent 1000
Bypass ratio 9.0–12.5
Overall Pressure ratio 50





Next Week - High-Pressure Sulzer Gas Turbine