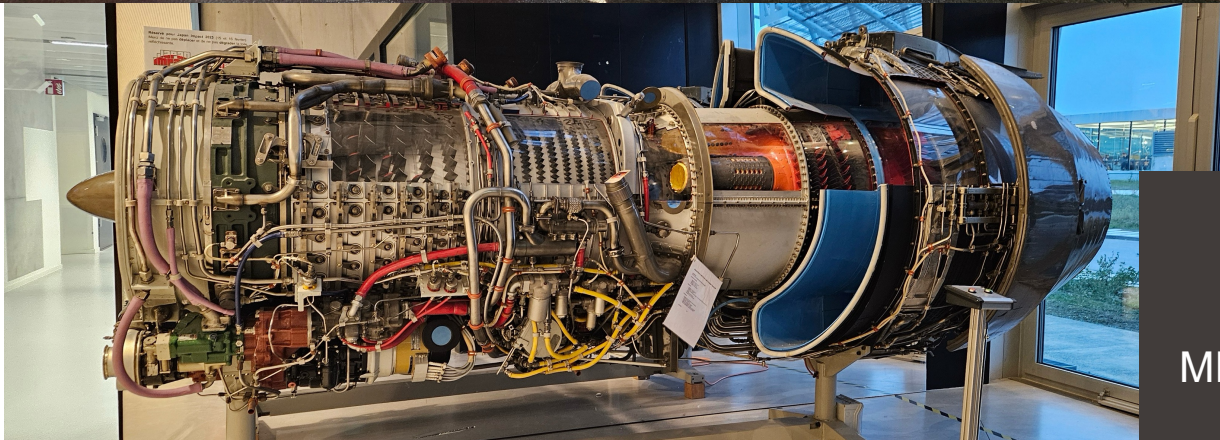




Chapter 11: Compressible machines



ME-342 Introduction to
turbomachinery

- 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)

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:

$$C_Q = \frac{Q}{\omega D^3}, \quad C_H = \frac{gh_a}{\omega^2 D^2}, \quad C_P = \frac{\dot{W}_{\text{shaft}}}{\rho \omega^3 D^5}$$

- Specific Speed (Dimensionless):

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

- Power Specific Speed (Hydraulic Turbines):

$$N'_s = \frac{\omega \sqrt{\dot{W}_{\text{shaft}} / \rho}}{(gh_a)^{5/4}}$$

- (static) Enthalpy and Stagnation enthalpy:

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

- Degree of Reaction:

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

- 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

- Similar in principle to incompressible pumps and turbines
- **Key difference:** Fluid **density** 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 **increase**
- **Turbines:**
 - Extract energy from the gas
 - Cause **pressure, density, and temperature** to **decrease**

(static) Enthalpy: internal energy and flow work

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


 $\text{Pa} \cdot \text{m}^3/\text{kg} \equiv \text{J/kg}$
 Internal energy

Ideal gas law → when can we use this?

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

- Low pressure/high-temperature gases
- Superheated steam ($T > 200^\circ\text{C}$)

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

Side note..

$$pV = nR'T \quad R': \text{universal gas constant, } n: \text{number of mols}$$

$$pV = mRT \quad R: \text{specific gas constant, } m: \text{mass}$$

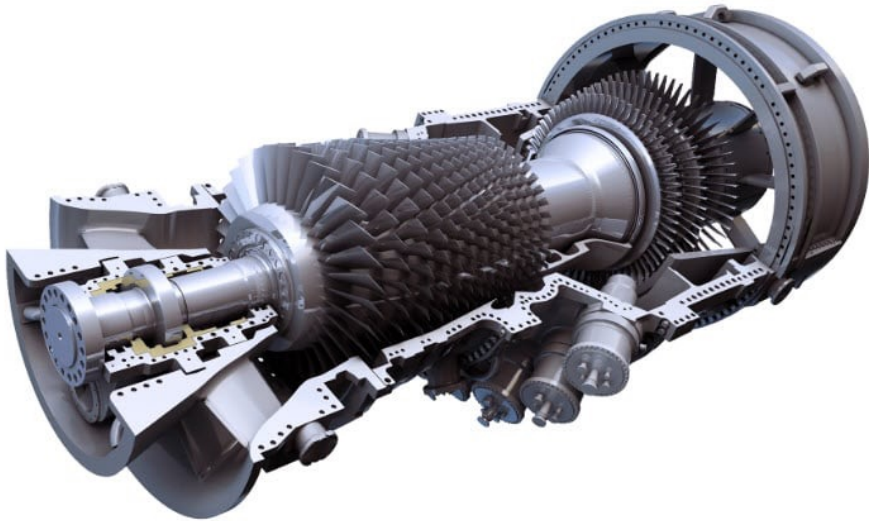
Reaction

$$R = \frac{\text{static enthalpy change in **rotor**}}{\text{stage static enthalpy change}}$$

$$= \frac{\check{h}_2 - \check{h}_3}{\check{h}_1 - \check{h}_3}$$

Compressor and Turbine

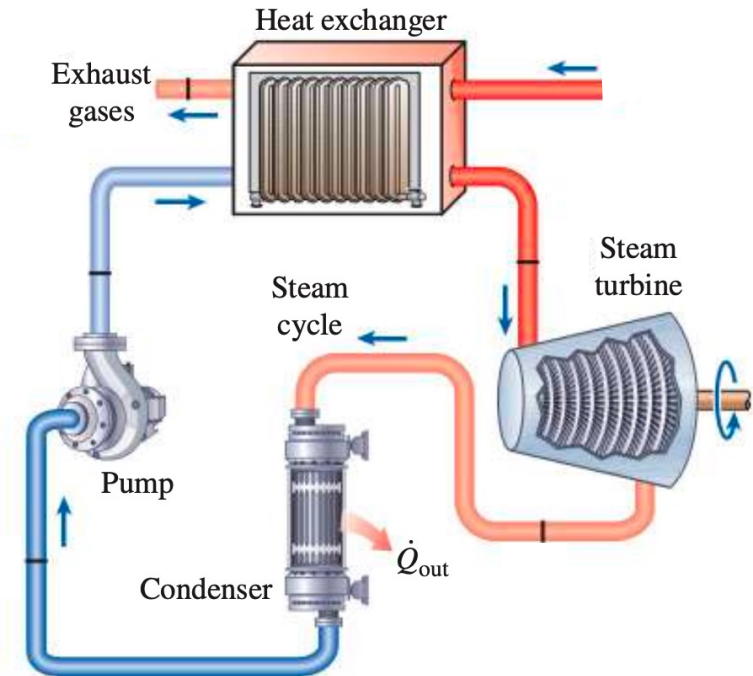
- “**Gas turbine**” usually refers to a **full** gas turbine engine:
 - Includes **compressor**, **combustor**, and **turbine**
 - Common in **aircraft propulsion** and **power generation**
- “**Steam turbine**” usually refers to a turbine driven by high-pressure steam:
 - **Part of the steam cycle** (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)



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 $\sim 620^{\circ}\text{C}$
- **Efficiency:** $\sim 30\text{--}40\%$ (on its own)

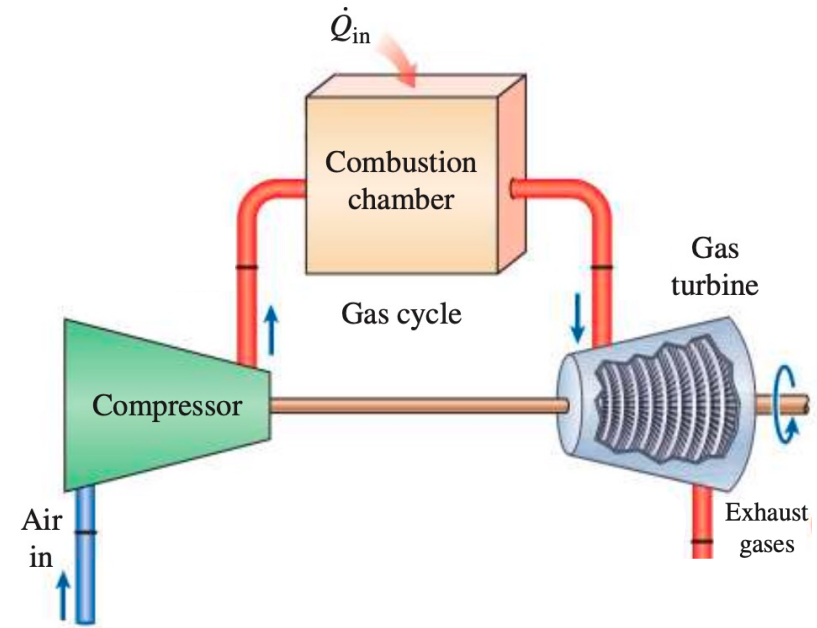
Key idea: Steam run a turbine to extract energy



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 $\sim 1425^\circ\text{C}$
- **Real-world example:** Jet engines, gas turbines
- **Efficiency:** $\sim 30\text{--}40\%$

Key idea: High-temperature gas spins the turbine $\rightarrow$ generates electricity/thrust.



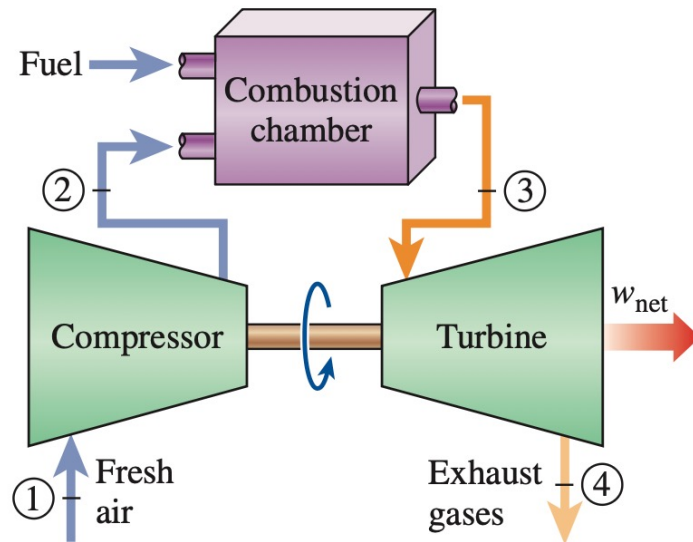
Combined Cycle = Brayton + Rankine

- **How it works:**
 - Burn fuel $\rightarrow$ gas turbine (Brayton) $\rightarrow$ electricity
 - Use the hot exhaust $\rightarrow$ heat water $\rightarrow$ steam turbine (Rankine) $\rightarrow$ more electricity
- **Total efficiency:** $\sim 55\text{--}60\%$, much higher than either cycle alone.

Brayton Cycle

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

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

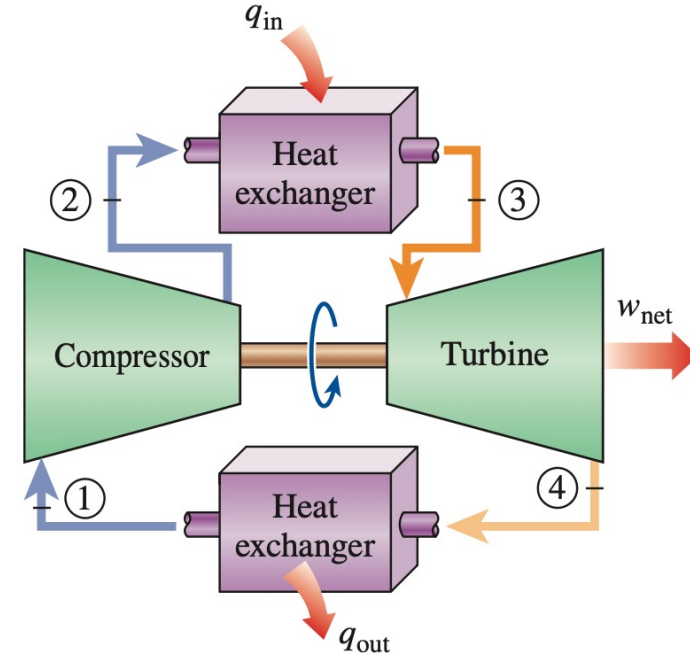


Isentropic: adiabatic and reversible ($\Delta s=0$)

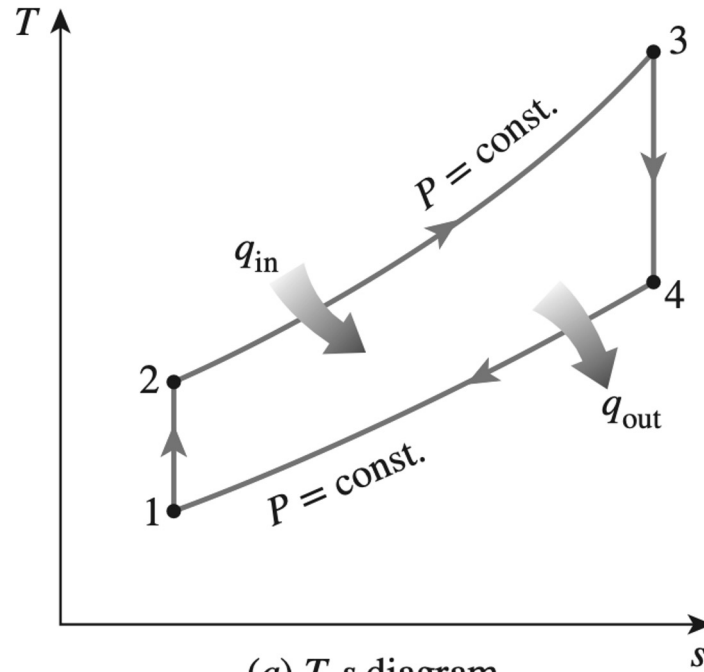
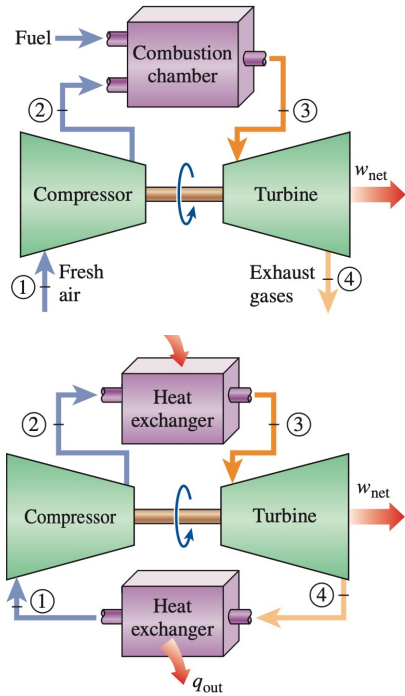
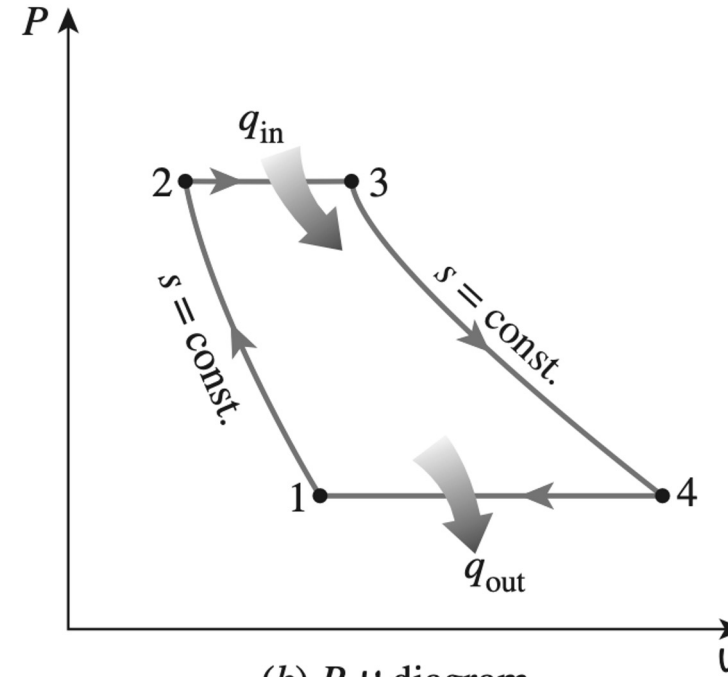
$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}}$$

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

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



- 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

(a) $T-s$ diagram(b) $P-v$ diagram

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

- 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

- 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 for radial compressors:
 - **High pressure rise**
 - **Low flowrate**
 - **Axially compact**
- **Total Pressure Ratio (PR):** $PR = \frac{p_{T2}}{p_{T1}}$ in absolute pressure

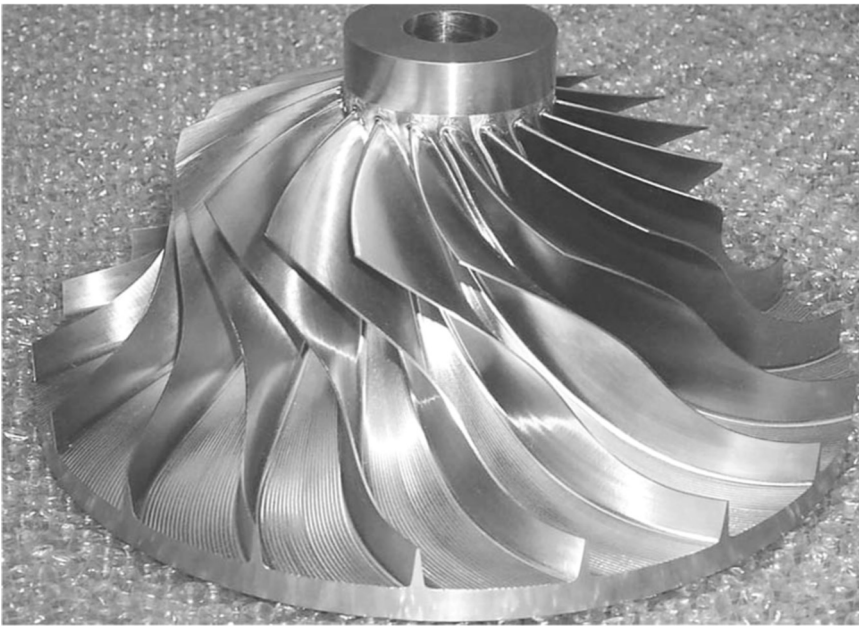
Total pressure:

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

- Example: $PR = 3.0 \rightarrow$ Air compressed from 101.3 kPa to ~304 kPa
Accompanied temperature rise? $k=1.4$ air 25°C

Isentropic compression $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = PR^{\frac{k-1}{k}} = 3^{\frac{0.4}{1.4}} = 1.364$

$$T_2 = (25^\circ\text{C} + 273.15) 1.365 \rightarrow \underline{T_2 = 408.17\text{K}}$$



Multi-Stage Compression

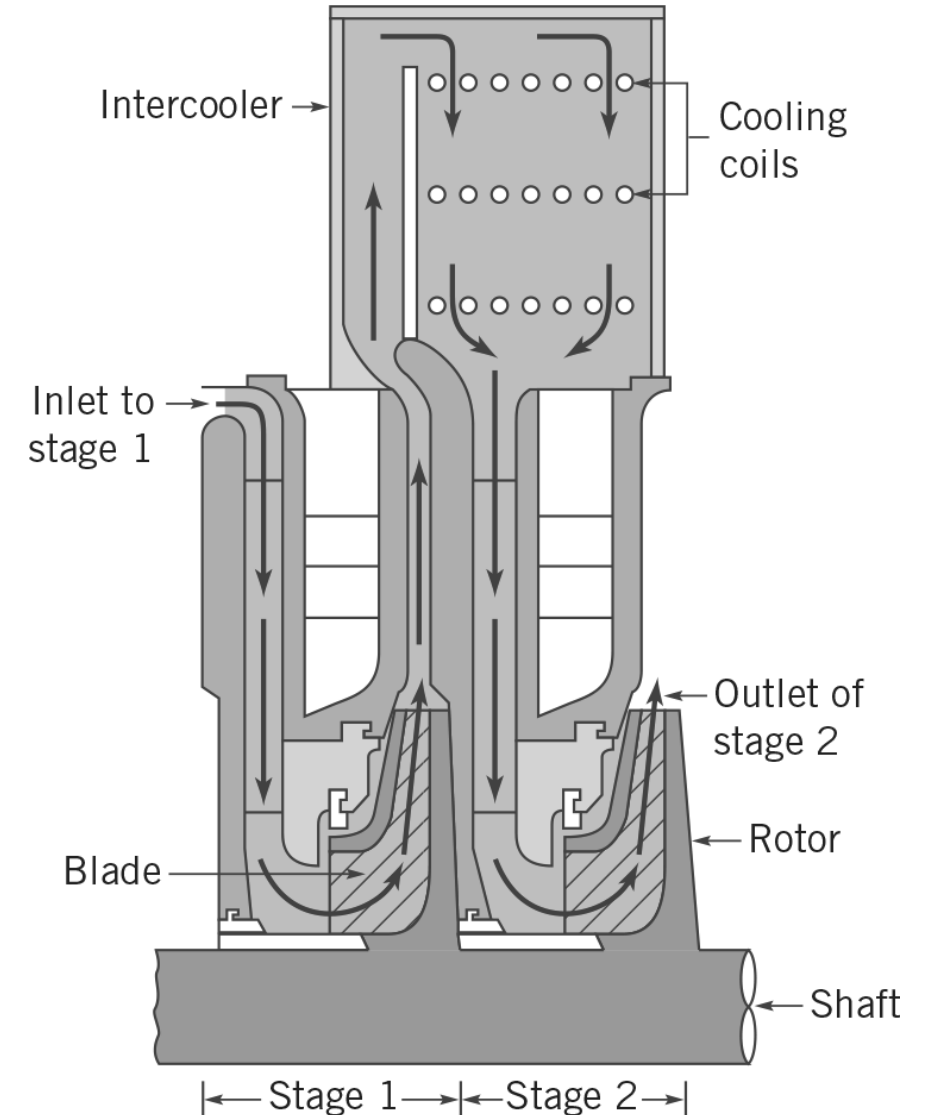
- Higher compression ratio
- For similar PR per stage,

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

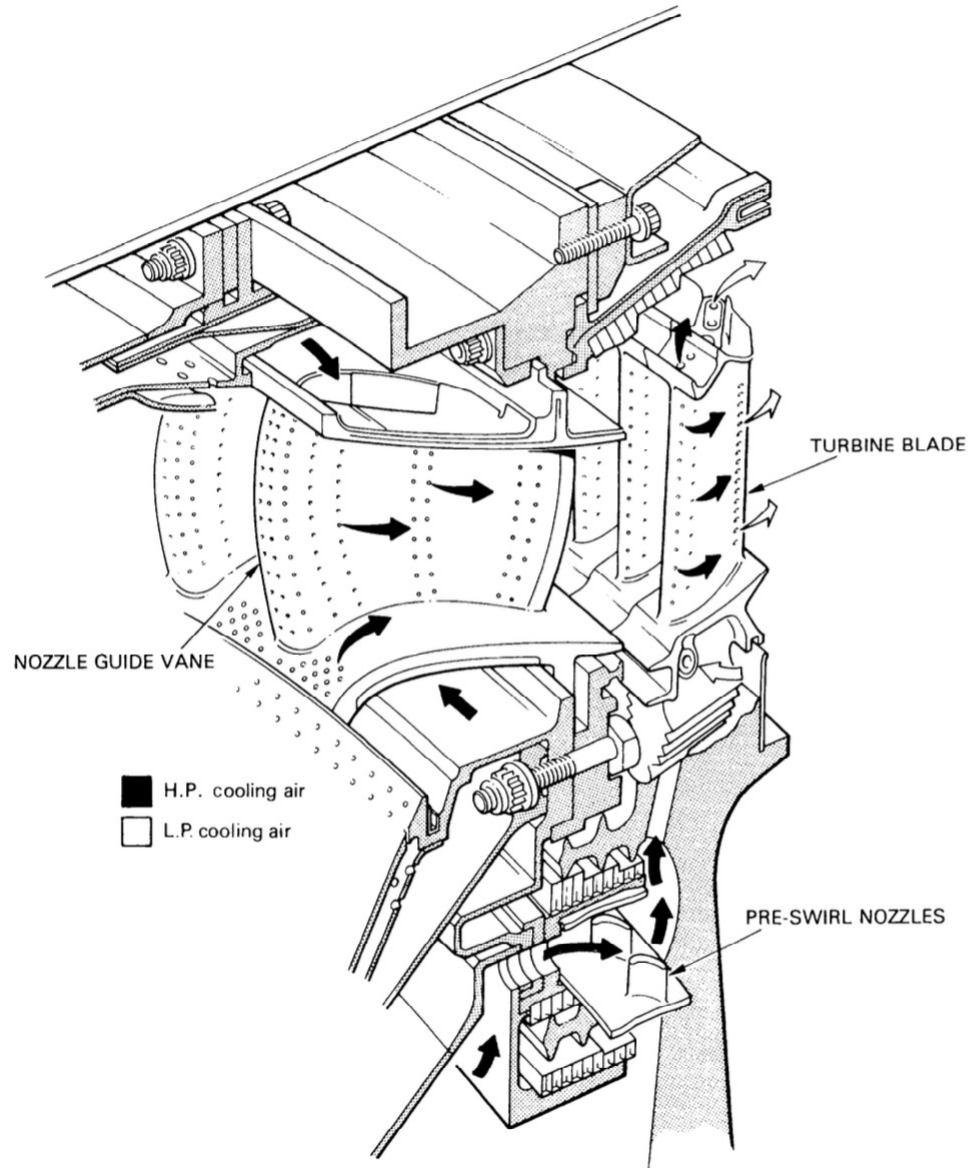
- Example: 4 stages with $PR_{\text{stage}} = 2.0 \rightarrow PR_{\text{overall}} = 2^4 = 16$
 $\rightarrow$ Compress air from 101.3 kPa to 1620 kPa

Thermodynamic Considerations

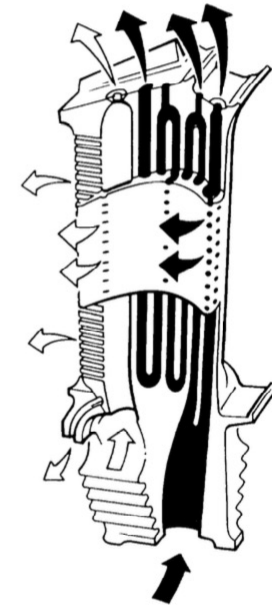
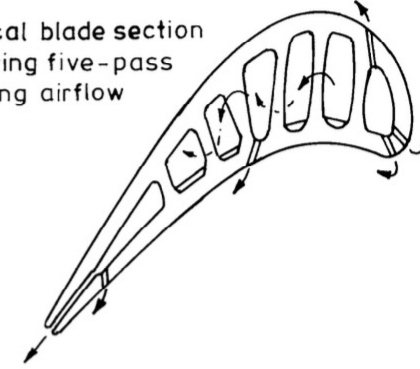
- **Adiabatic compression** (Brayton cycle)
 $\rightarrow$ temperature increases, more work needed
- **Isothermal compression** (ideal)
 $\rightarrow$ less work
- **Intercooler** between stages:
 - **Reduces temperature** before next stage
 - **Lowers required compression work**



Blade cooling



Typical blade section showing five-pass cooling airflow

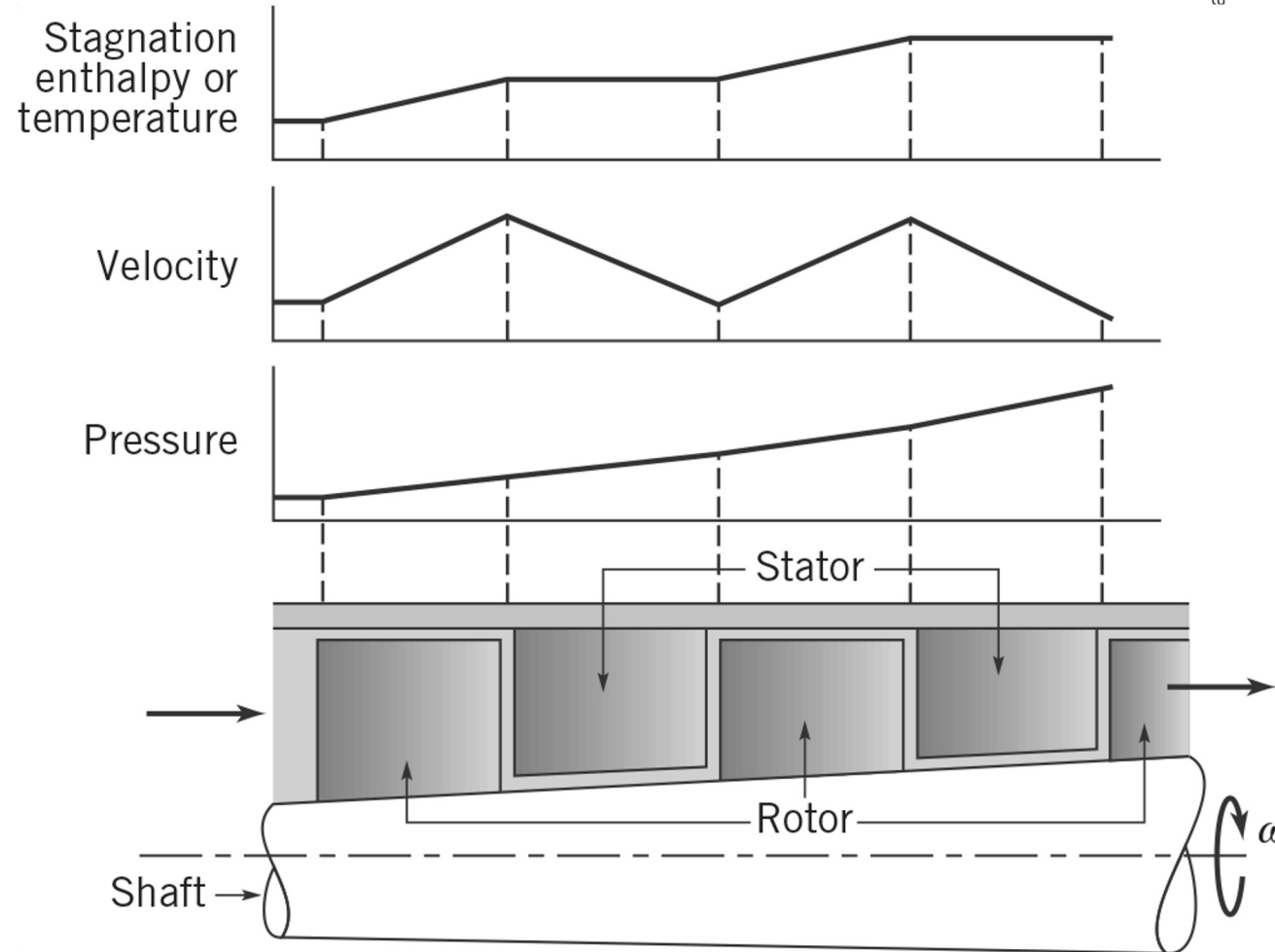


QUINTUPLE PASS, MULTI-FEED INTERNAL COOLING WITH EXTENSIVE FILM COOLING

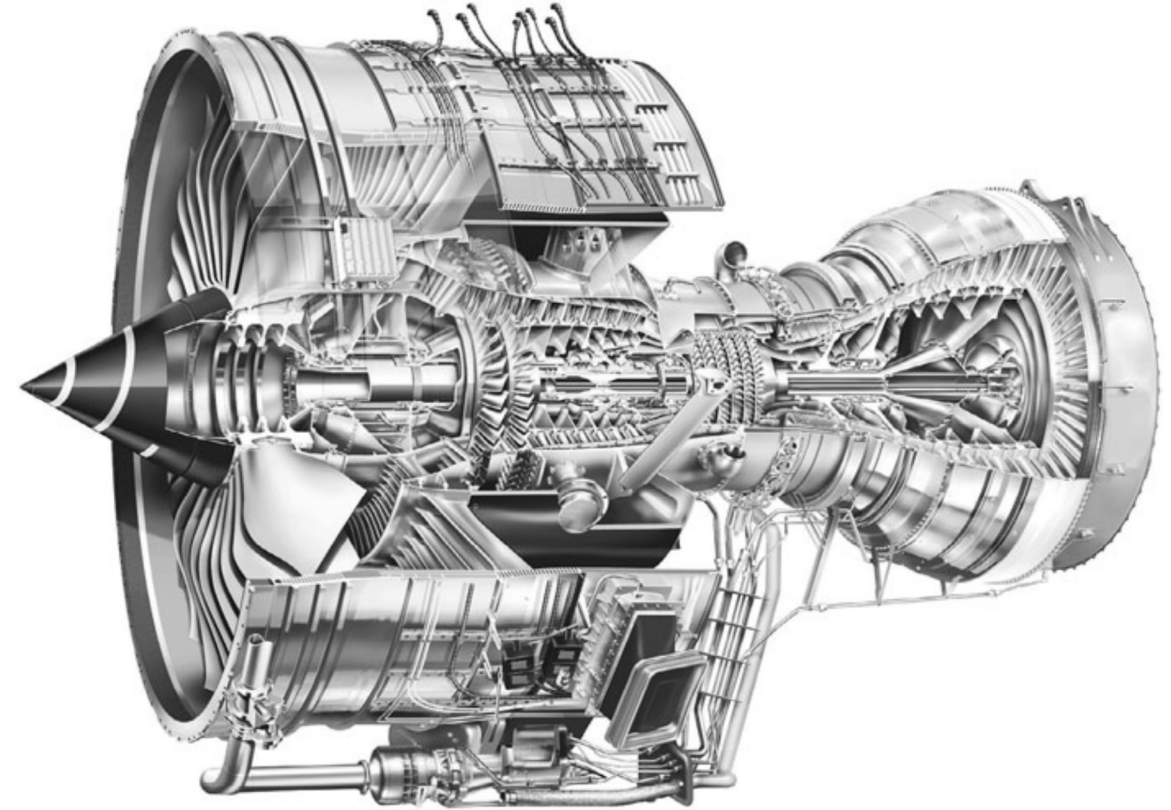
- Widely used **compressor type** in turbomachinery
- Compared to centrifugal compressors:
 - Lower pressure rise per stage**
 - Higher flowrate**
 - More radially compact**
- Usually **multiple stages**
 - Usually, PR_{stage} varies across the stages
 $\rightarrow PR_{\text{overall}} = PR_{\text{st1}} \times PR_{\text{st2}} \cdots PR_{\text{stn}}$
- As gas is compressed:
 - Density increases**
 - Cross-sectional area decreases**
 - Blade height reduces** from inlet to outlet

$\rightarrow$ Why do compressor blades shrink?

$$\dot{m} = \rho AV = \text{constant}$$

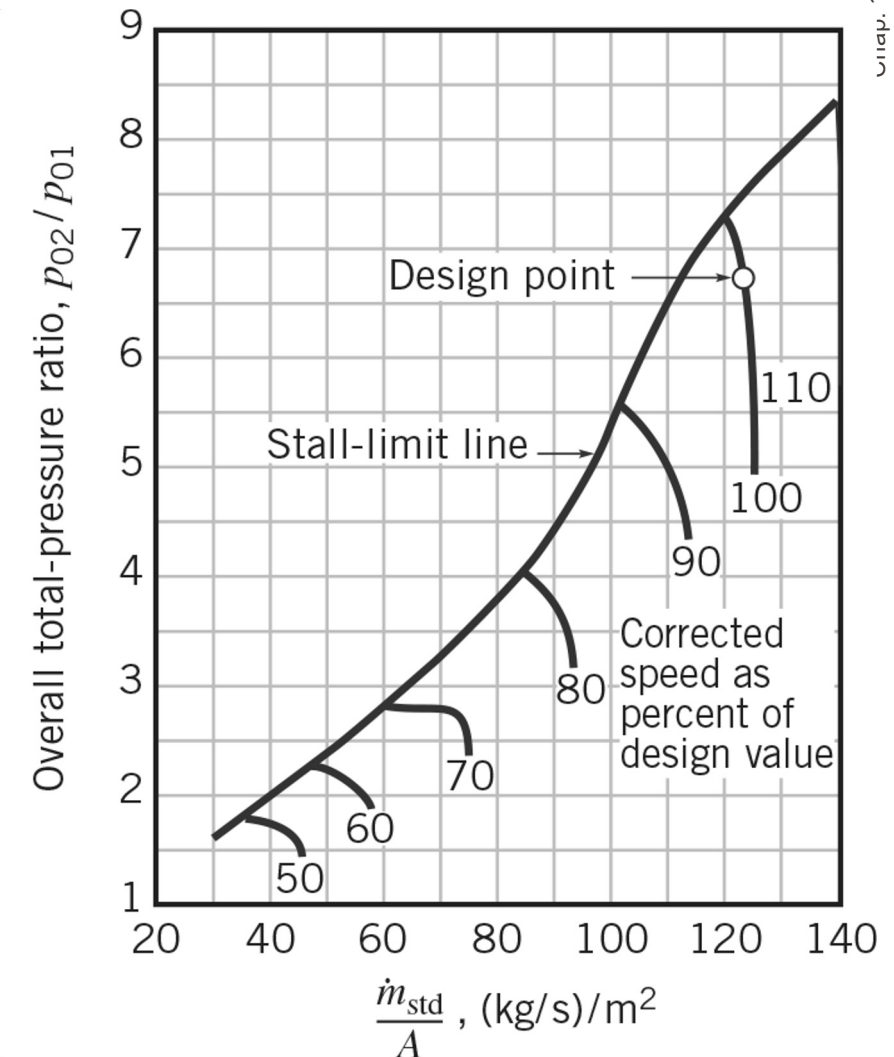


- **Inlet Guide Vanes (IGVs):**
 - Located **before the first rotor**
 - **Redirect flow** away from purely axial direction
 - Optimize **relative velocity** into rotor blades
- **Rotor Blades:**
 - **Rotate**, pushing gas **rearward and outward**
 - **Add energy** to the flow (like an axial pump)
 - 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)

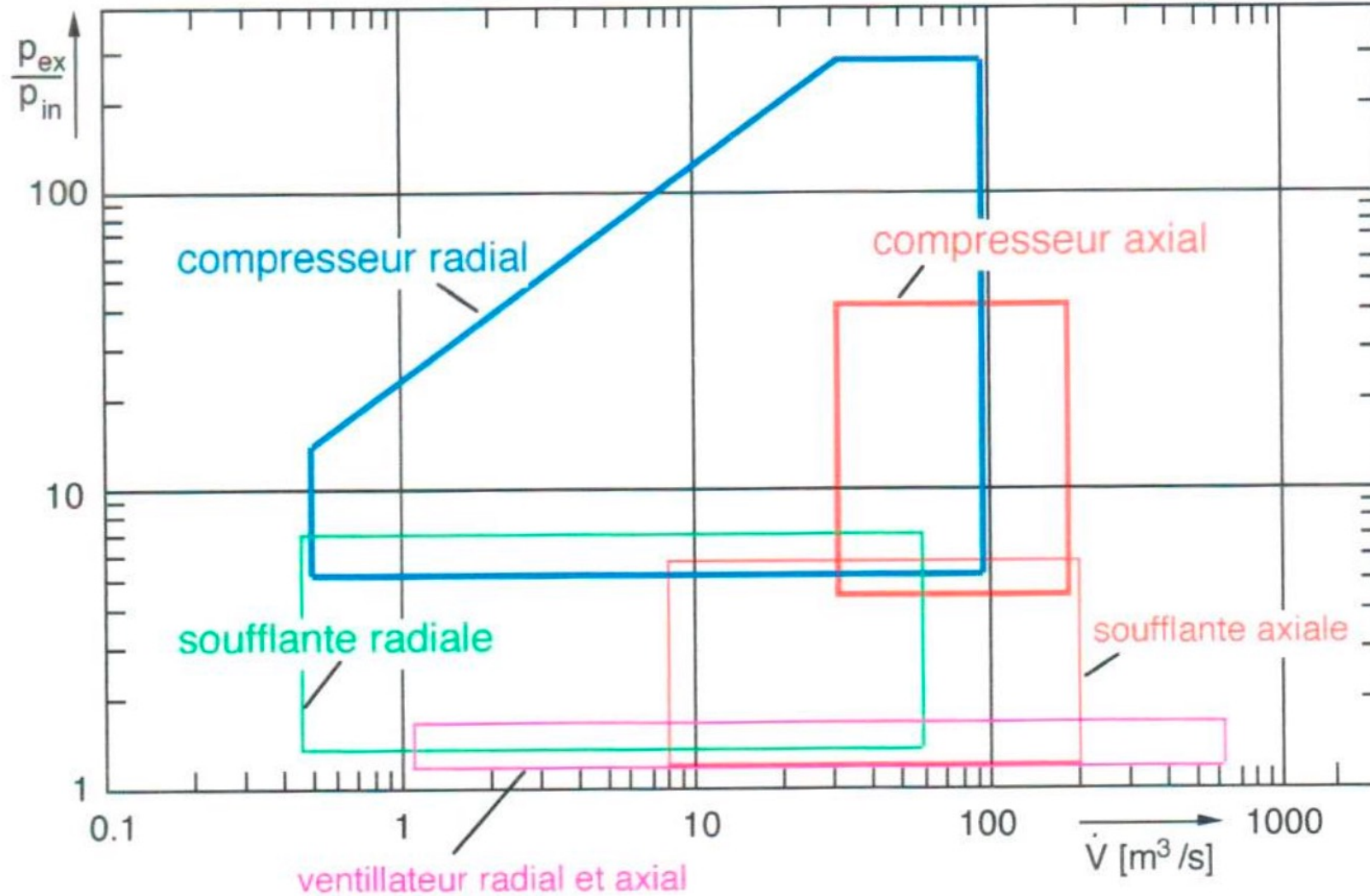


Axial-flow compressor multistaging requires less frontal area but more length than centrifugal compressors.

- **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**

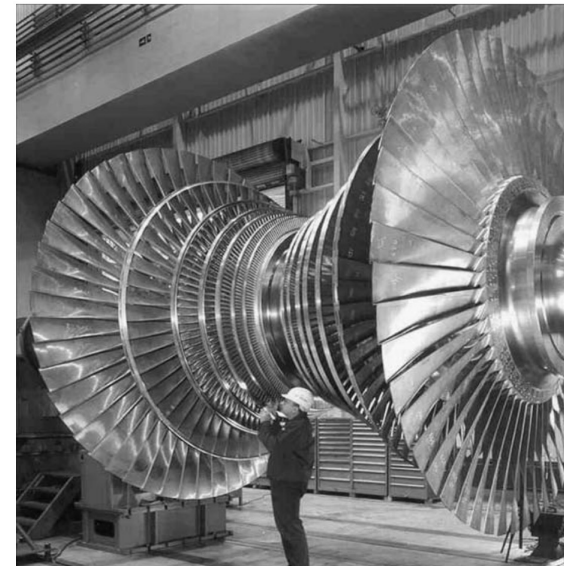
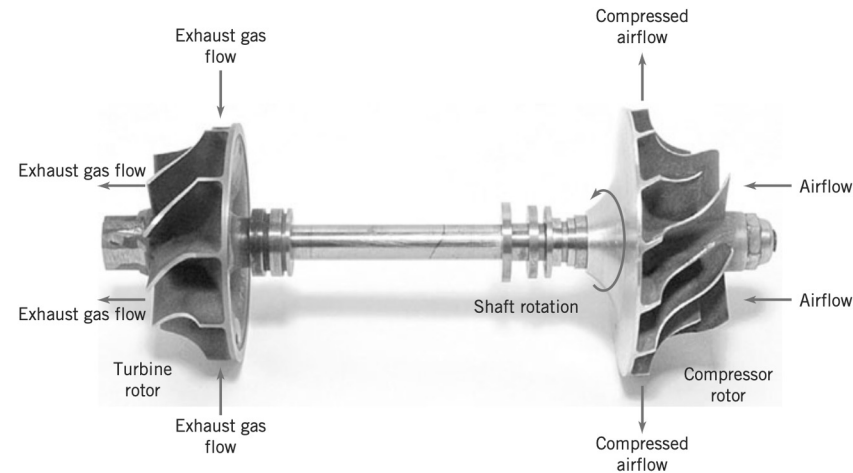


Compressor map



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

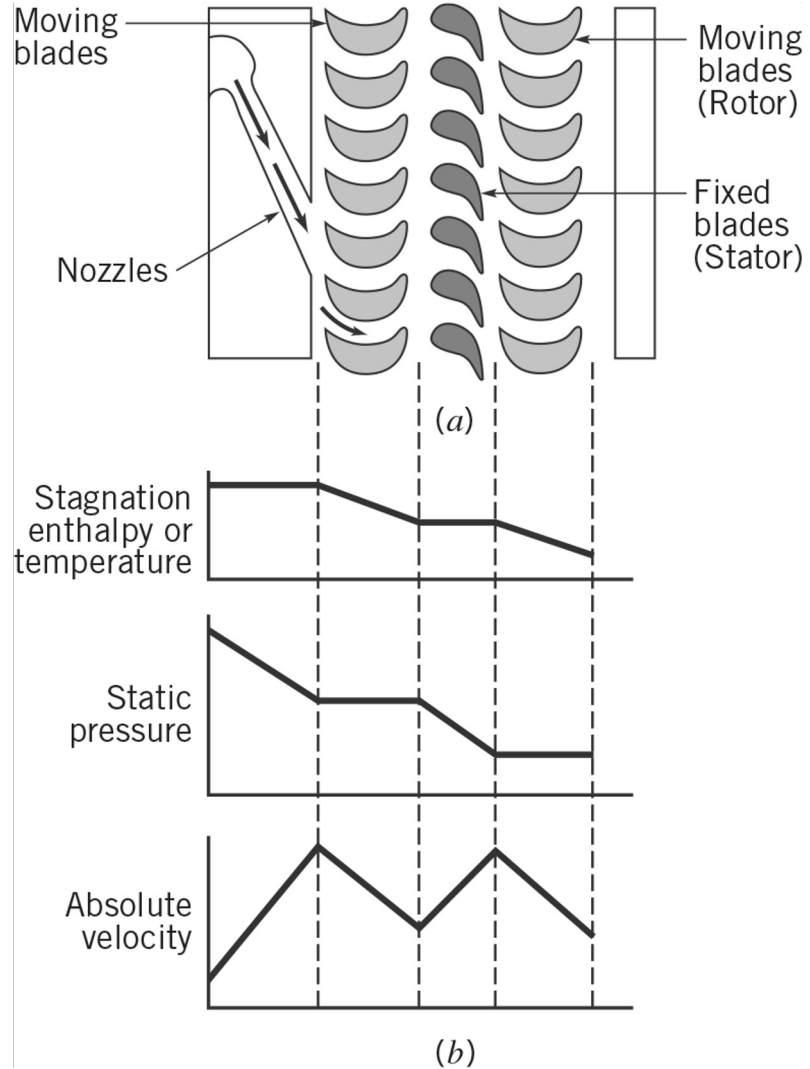
- Example: **Turbocharger** turbine (automotive)
- Advantages:
 - **Robust & durable**
 - **Axially compact**
 - **Cost-effective**
- Disadvantages:
 - Generally **lower efficiency** than axial-flow turbines

Axial-Flow Turbines

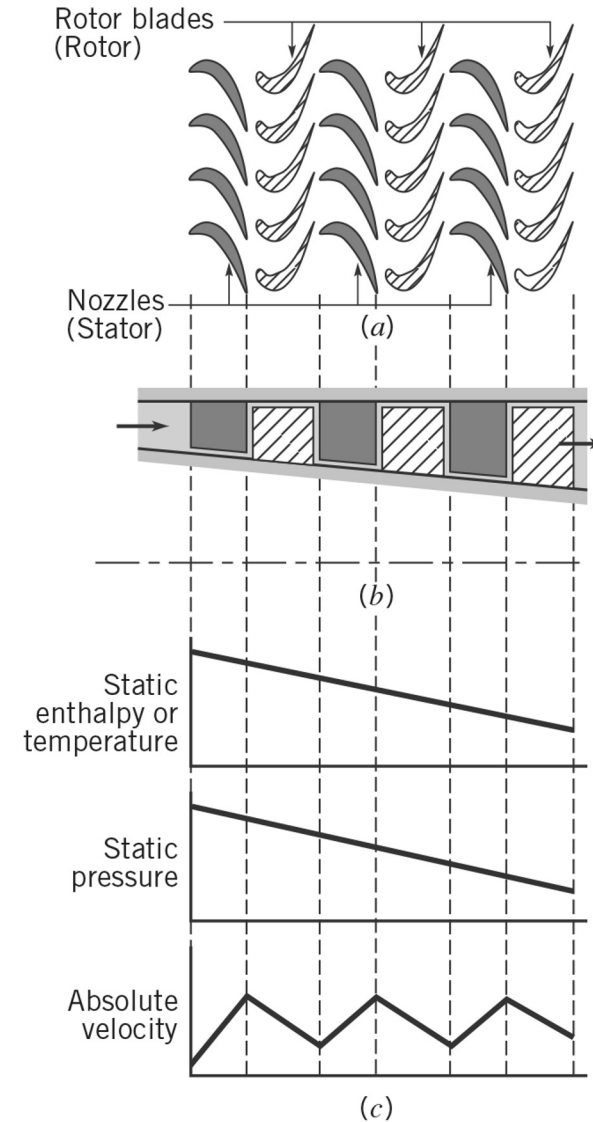
- **Steam and gas power plants**
- **Marine propulsion**
- **Gas turbine engines**
- Can be:
 - **Single-stage** or **multistage**
 - **Impulse** or **reaction** type

Impulse or Reaction?

Two-stage impulse turbine

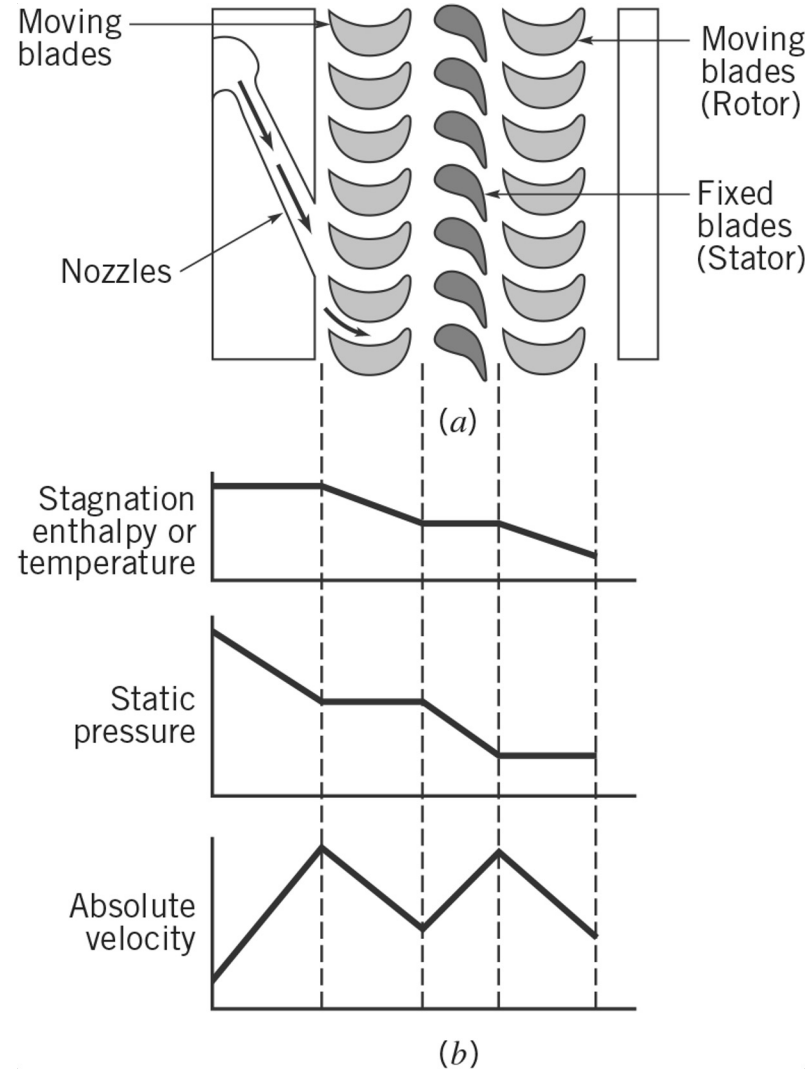


Three-stage reaction turbine



Impulse turbine

Two-stage impulse turbine

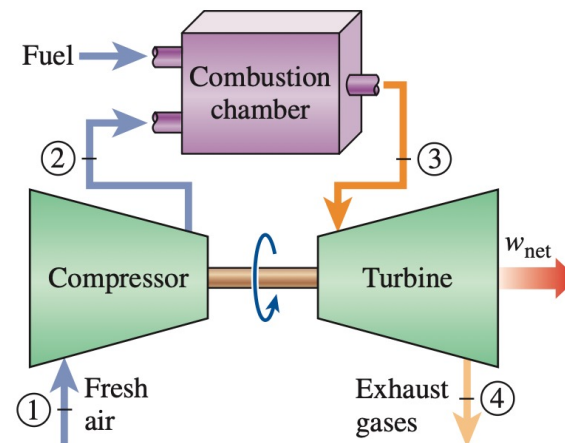


- Pressure drop happens mostly across **nozzles (stators)**
- Rotor blades operate at nearly constant pressure

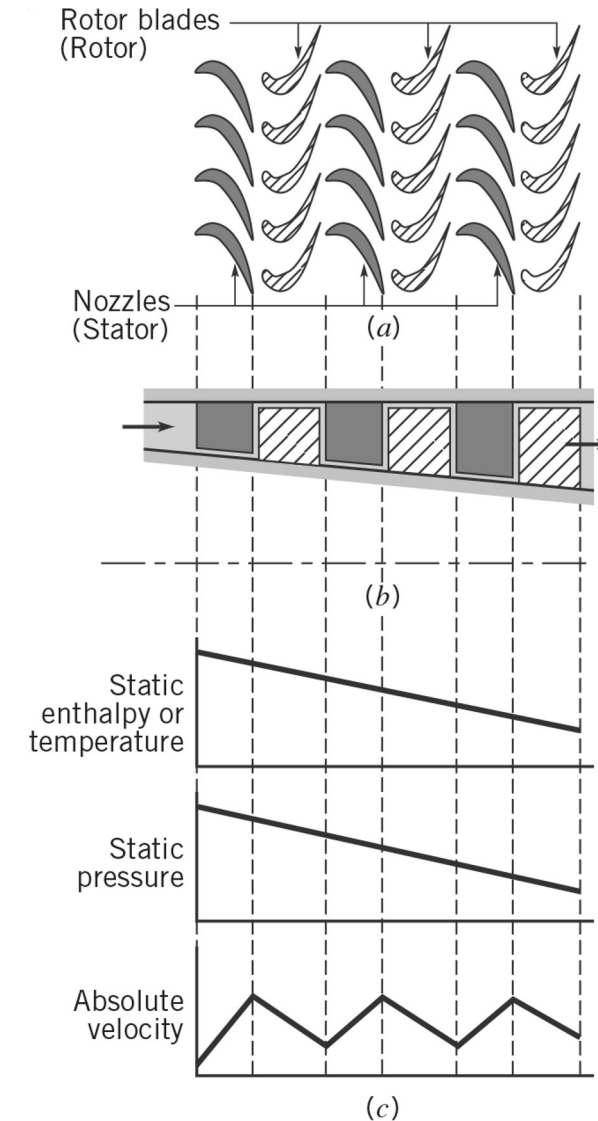
- **Stators only guide and accelerate flow** (adiabatic $\rightarrow$ no energy loss)
- **Stagnation enthalpy (or temperature) remains constant** across stators
- Due to **gas expansion** (pressure $\downarrow$), **density** $\downarrow$
- To maintain mass flow, **passage area increases** from inlet to outlet
- Seen clearly in reaction turbine geometries

$\rightarrow$ Why Do **Turbine Blades Expand**?

$$\dot{m} = \rho AV = \text{constant}$$

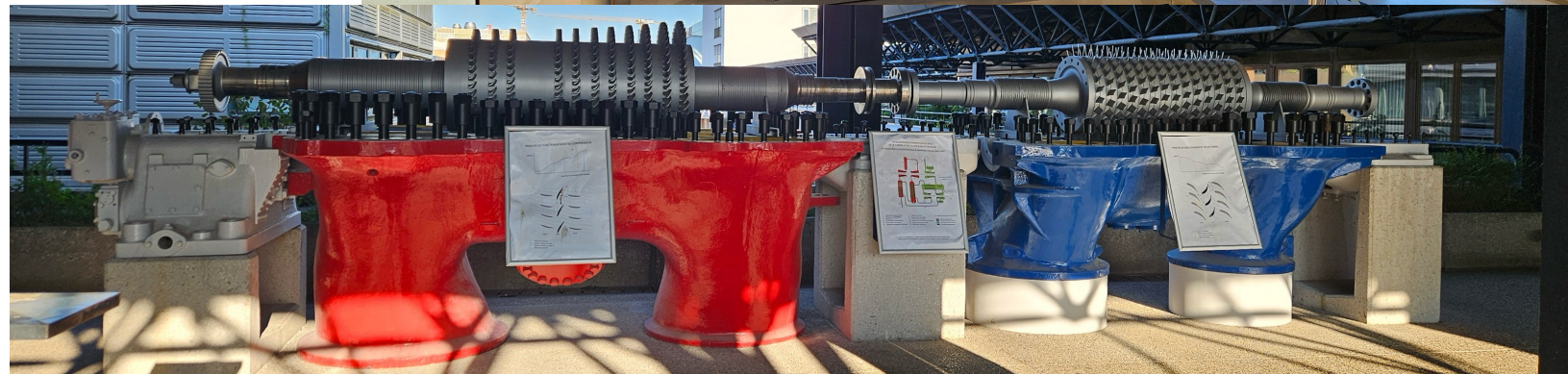
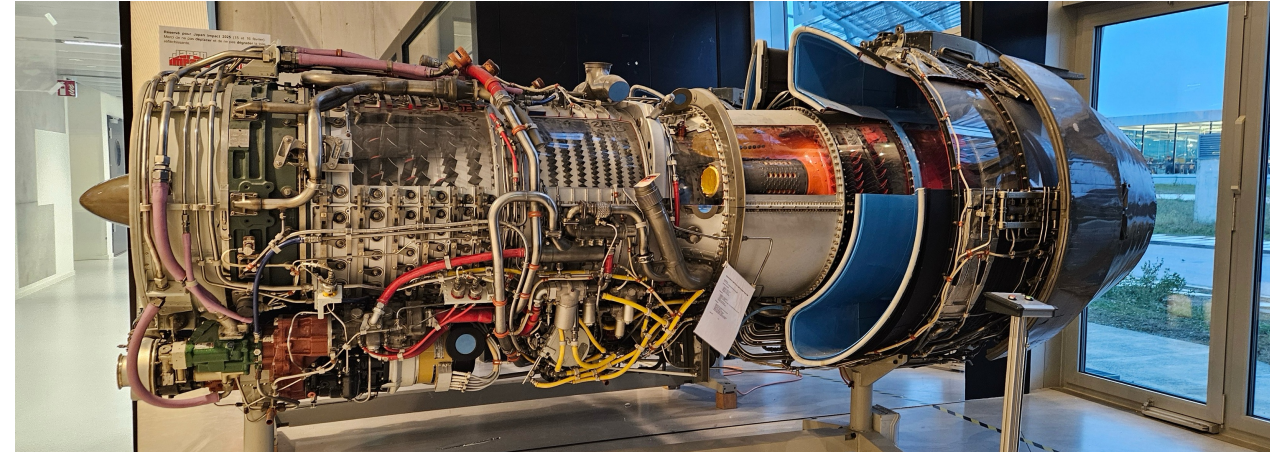


Three-stage reaction turbine

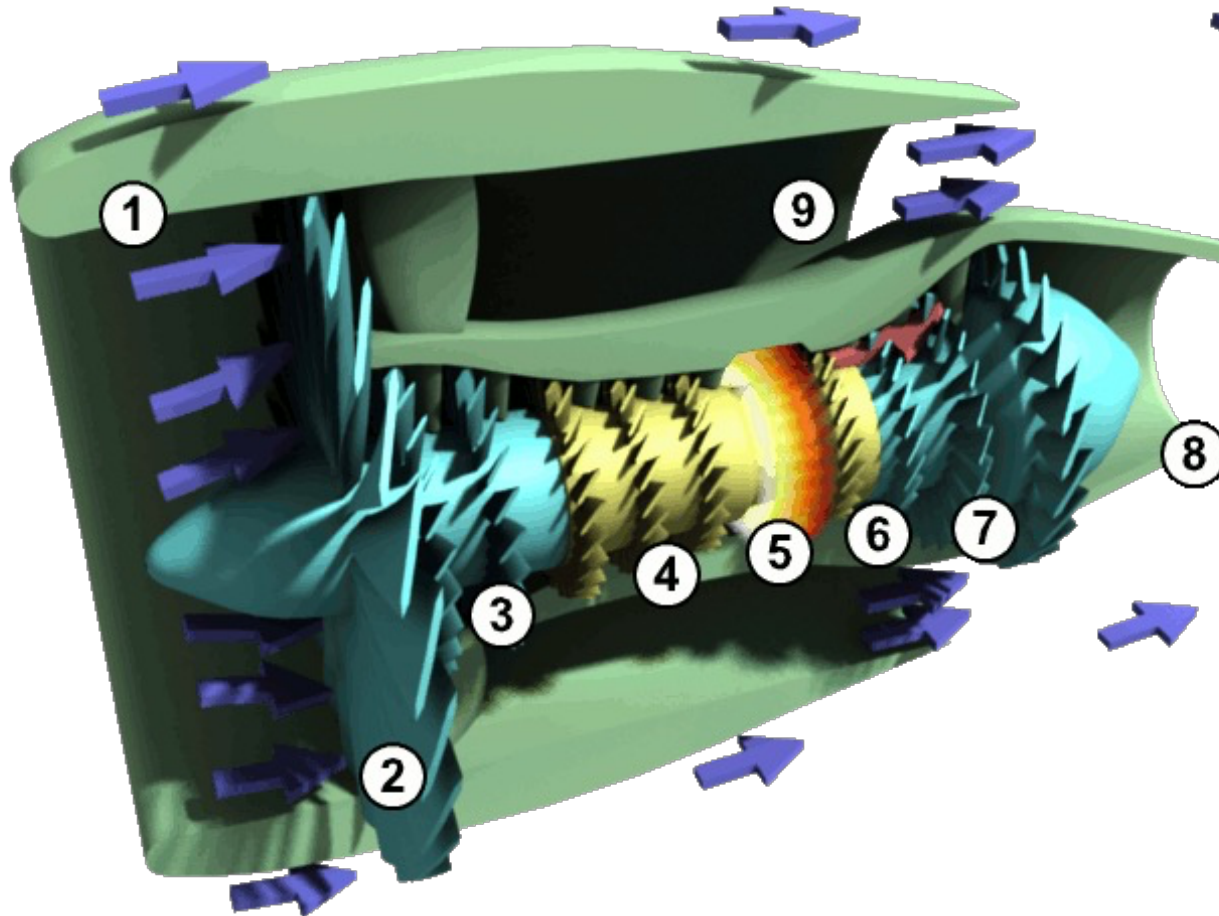


Our Compressible Turbomachines - next week!

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



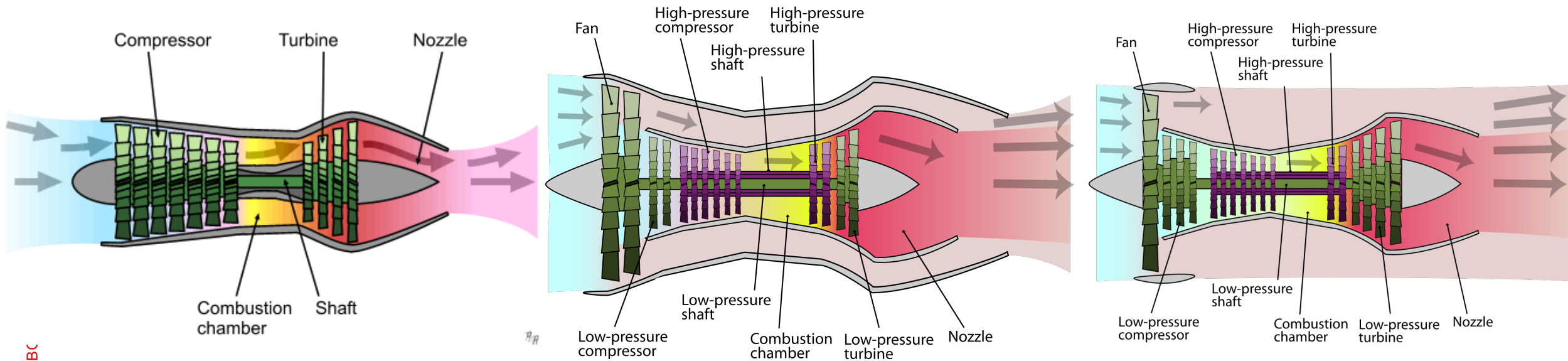
Multiple spools (shafts)



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

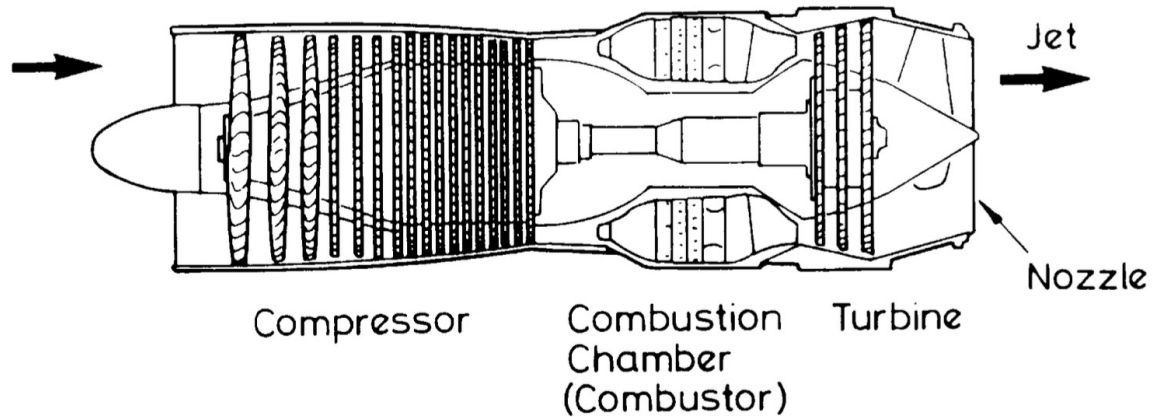
- A** Low-pressure spool
- B** High-pressure spool
- C** Stationary components

- **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.



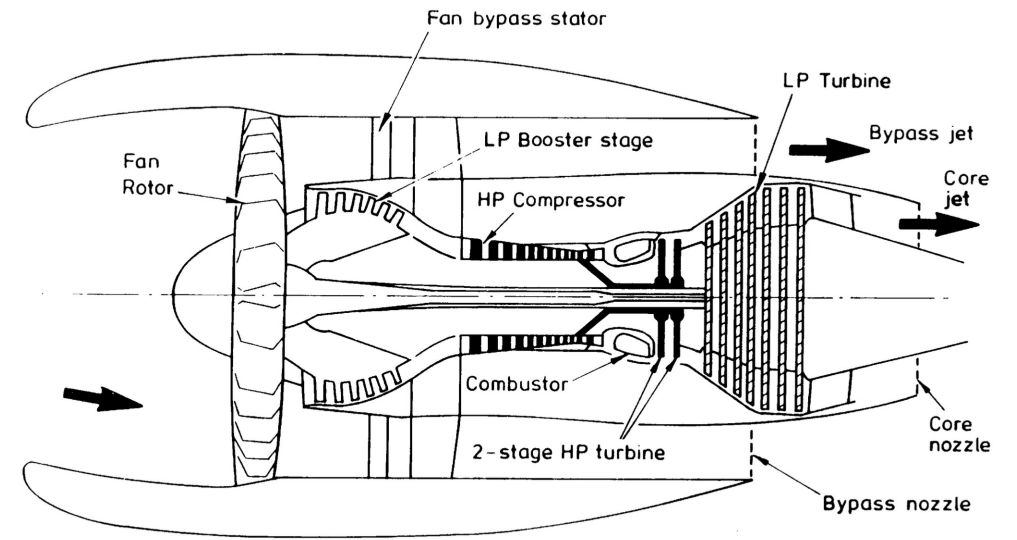
- Multiple shafts system is also required
 - Large diameter of fan, slow speed (Low pressure compressors, LP turbines)
 - Small diameter, faster speed (High pressure compressors, HP turbines)

Turbofan: Bypass ratio

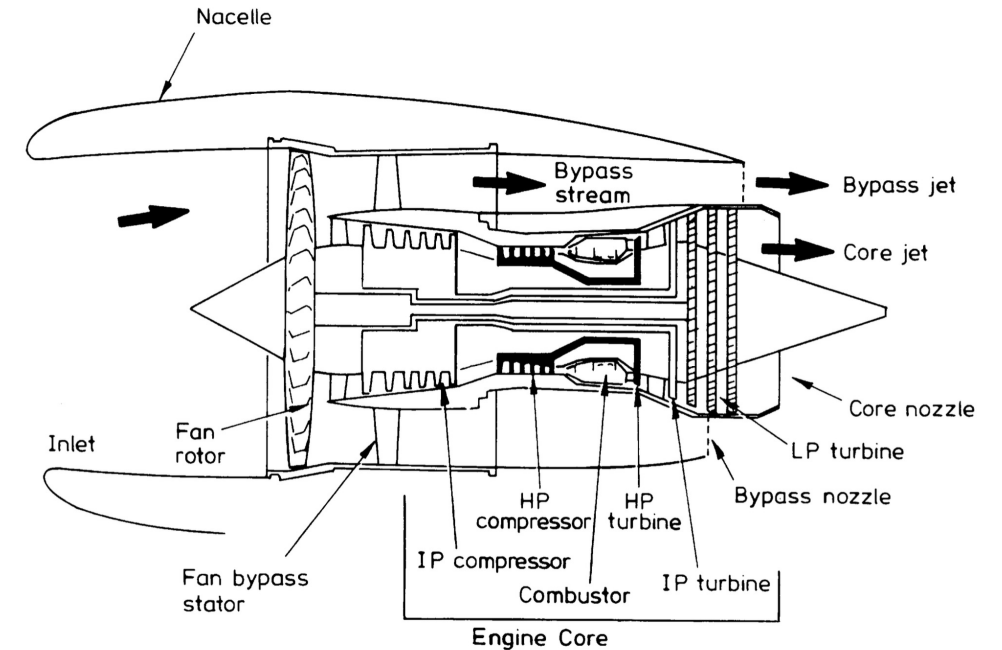


A single-shaft turbojet engine (no bypass)

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



A two-shaft high bypass engine



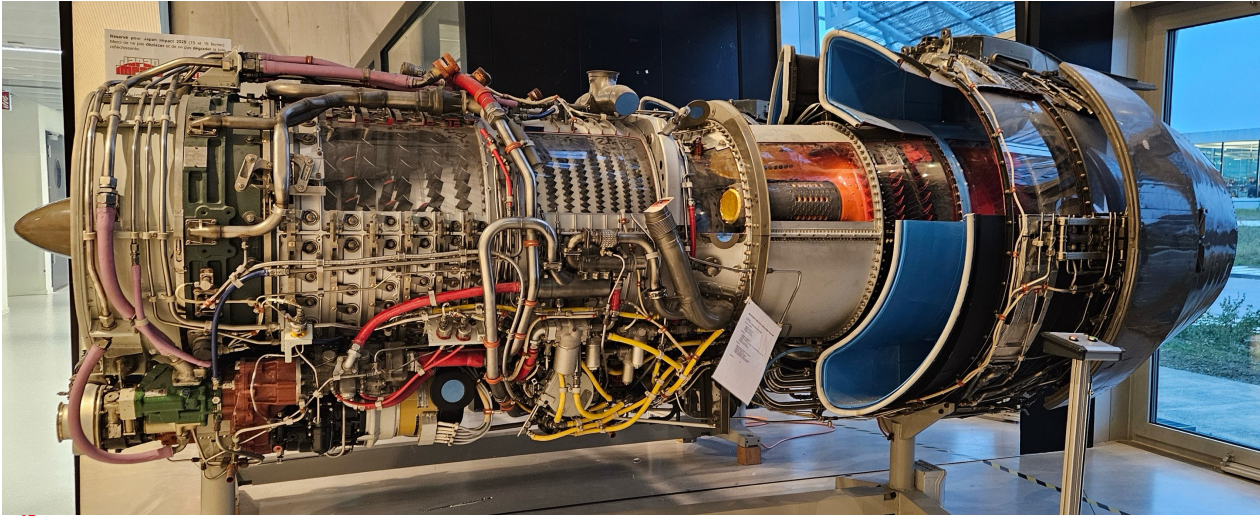
A three-shaft high bypass engine

Bypass ratio

GE CJ805-23

Bypass ratio 1.46

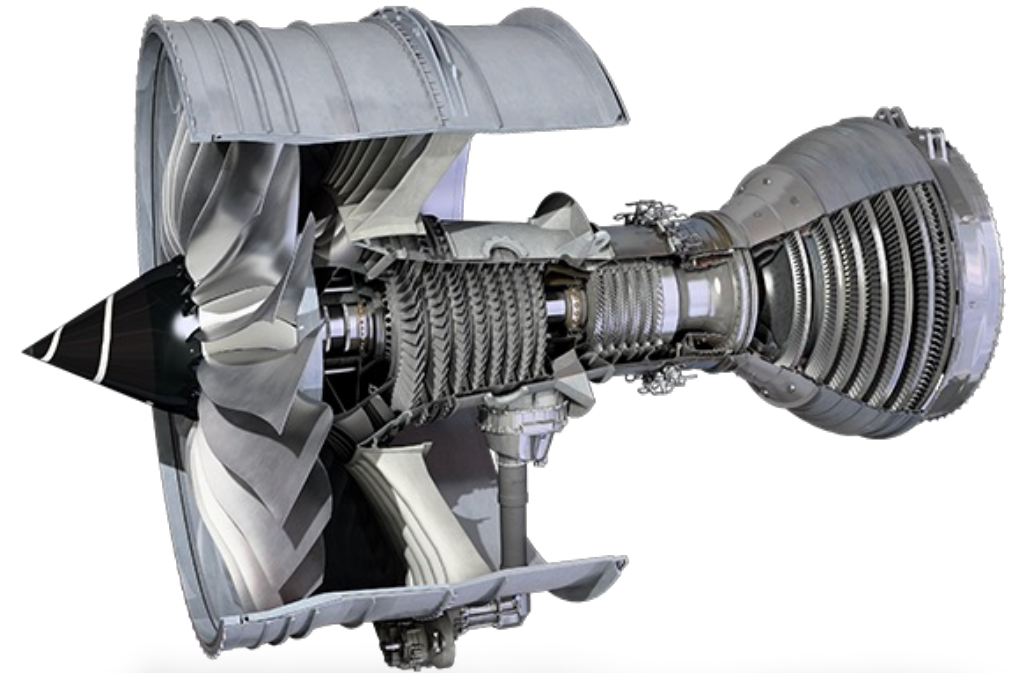
Overall Pressure ratio 13



Rolls-Royce Trent 1000

Bypass ratio 9.0–12.5

Overall Pressure ratio 50





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Anna Sophia Wallerand
and
Prof. François Maréchal