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TECHNISCHE THERMODYNAMIK

OTTO VON GUERICKE
UNIVERSITÄT
MAGDEBURG

# Industrial Energy Management
# Gas turbines

Jun.-Prof. Benoit Fond
fond@ovgu.de

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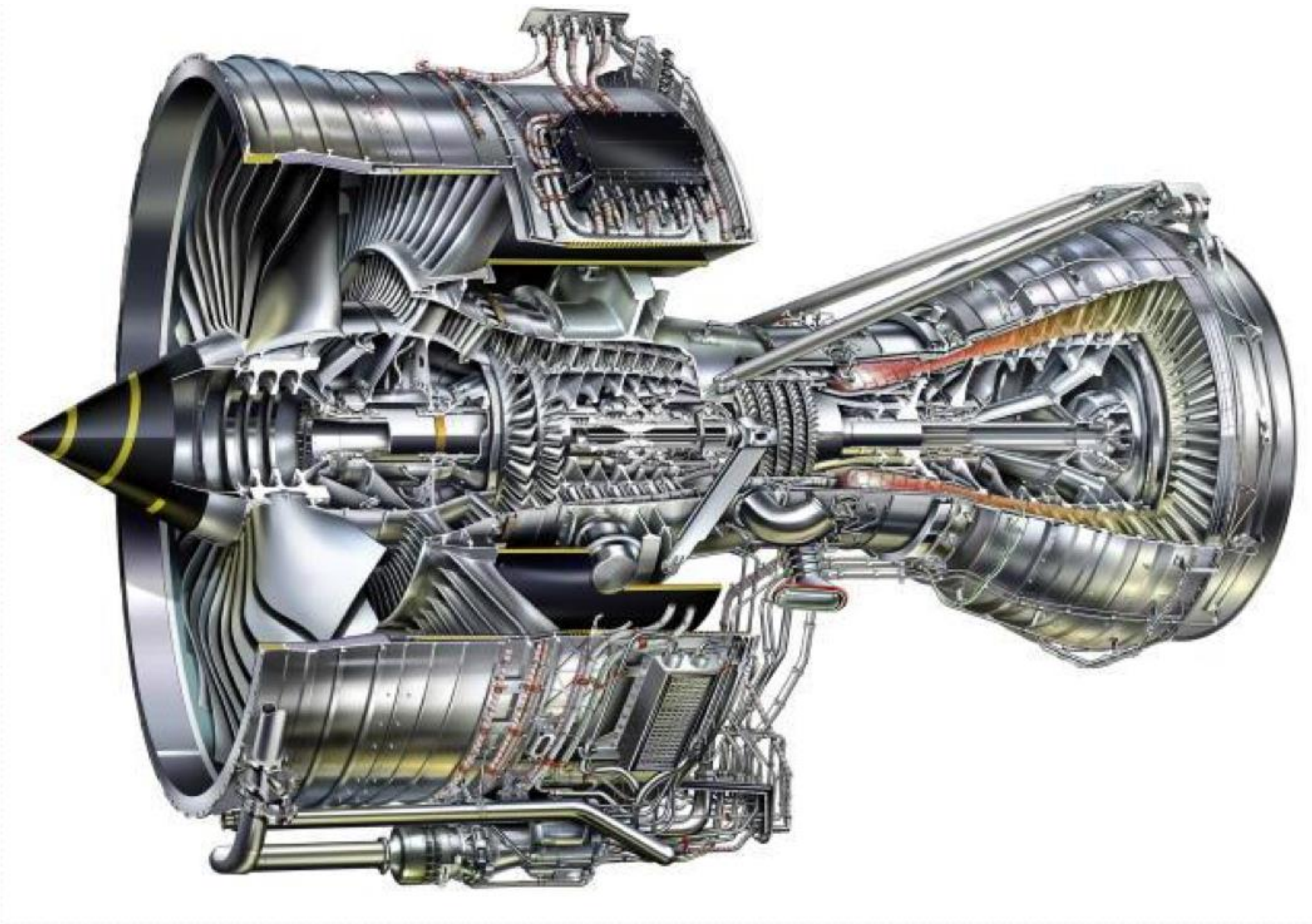
# Introduction to Gas Turbines

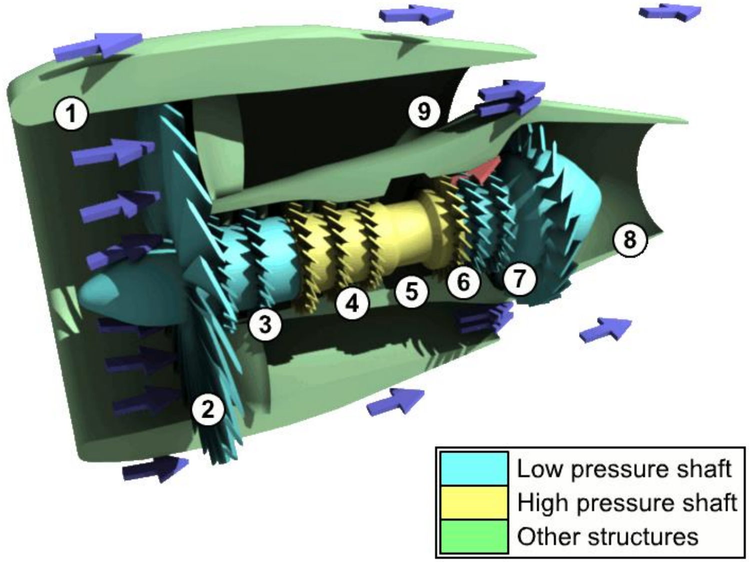


Rolls Royce Trent 900 (Airbus A 380)

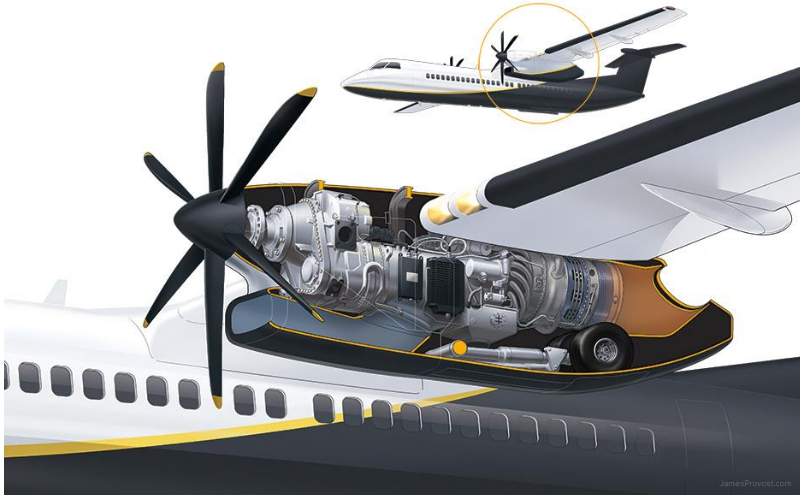
# Gas turbines

## Types of gas turbines

- Aero Engine Gas Turbines
  - Air breathing jet Engines
    - Turbojet
    - Turbofan
  - Turbo propeller




Turbofan engine - https://commons.wikimedia.org/wiki/File:Turbofan_Labelled.gif



Bombardier Q400

# Gas turbines

## Types of gas turbine

- Aero-derivative land-based gas-turbine (start-up time ~ 30 mins)
- Industrial power-generation gas turbine
    - Combined cycle power plant (start-up time ~ 1 day)
- Micro-gas turbines
- Powertrains for various vehicles (military and civil vessel, tanks, bus …)

Siemens SGT5-8000H gas turbine (400 MW)

# Gas turbines

## Layout

1. Gas Turbine cycles
    1. Joule cycle
    2. Effect of irreversibility
    3. Regenerative heat exchange
    4. Reheating
    5. Combined cycle
    6. Intercooling
2. Gas Turbine combustion
    1. Combustor design
    2. Conventional and Low $No_x$ combustors

# Gas Turbine

## Gas Turbine cycle

$$W_{net} \neq -\oint PdV$$

$$Q_{net} = -W_{net} = \oint TdS$$

- Continuous flow open cycle (Control volume Analysis)

- Processes :
  1. Compression (+ve work)
  2. Heat addition (Combustion + Dilution & Cooling)
  3. Expansion (-ve work)
  4. Heat rejection (Exhaust)

Each process is described by Steady Flow Energy Equation :

$$\dot{Q} + \dot{W} = \dot{m}\left(h + \frac{c^2}{2} + gz\right)_{out} - \dot{m}\left(h + \frac{c^2}{2} + gz\right)_{in}$$

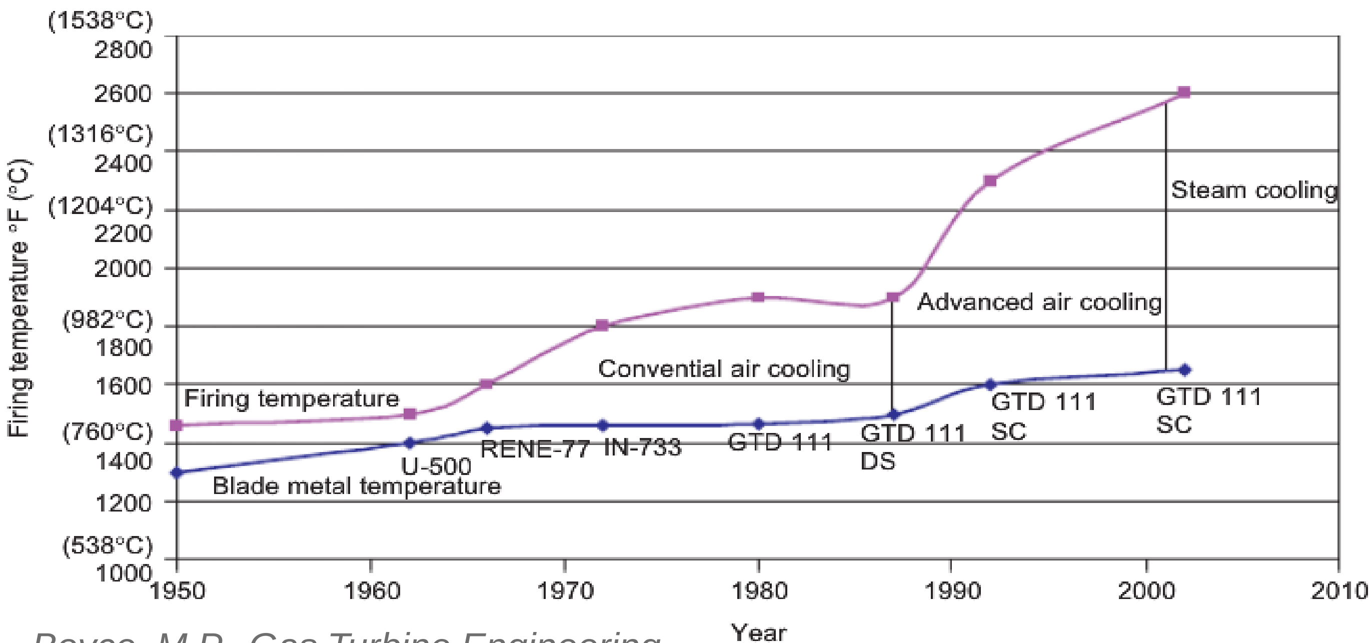
# Joule cycle

## Brayton (or Joule) cycle

$$\eta_{th} = 1 - \frac{1}{\left(r_p\right)^{\frac{\gamma - 1}{\gamma}}}$$

Efficiency function of pressure ratio and $\gamma$

$r_p$ limited by $T_3$ turbine inlet temperature




*Boyce, M.P., Gas Turbine Engineering Handbook. 4th ed. 2011: Burlington : Elsevier Science*

# Joule cycle optimisation

## Pressure ratio

- For fixed turbine inlet temperature:
  - $h_{th}$ increases with $r_p$
  - $\frac{\dot{W}_{net}}{\dot{m}}$ (net specific work) has a maximum

- Compromise between efficiency and specific work
  - Running cost (efficiency)
  - Capital investment (specific work)

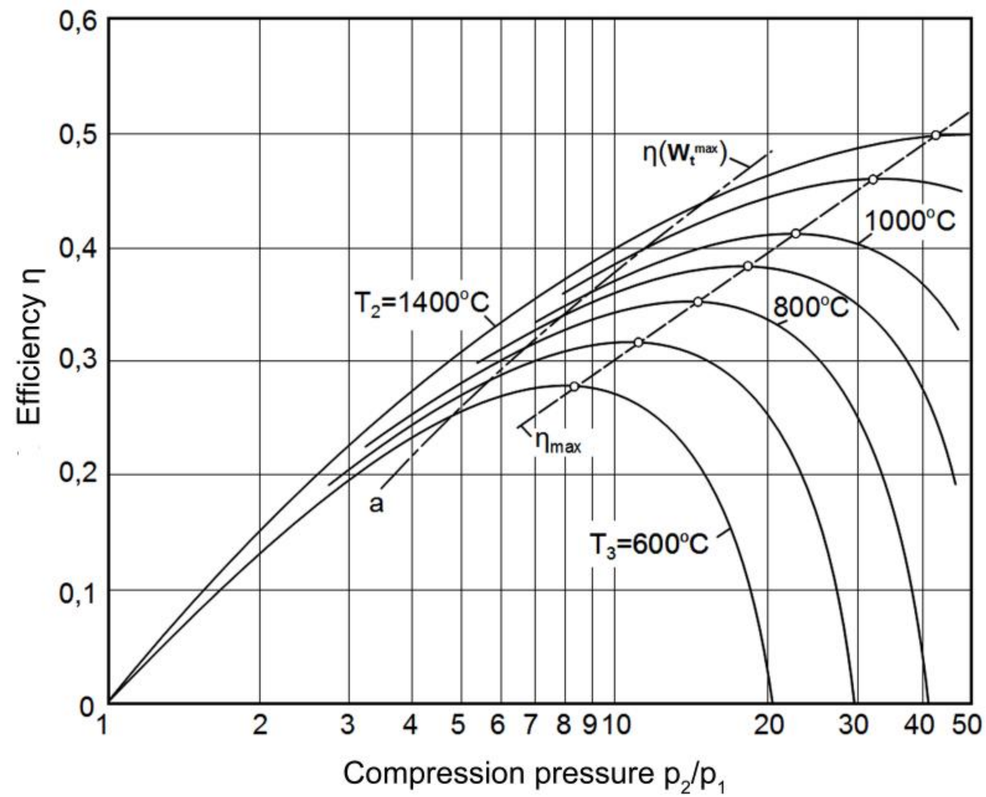
# Real cycle

## Isentropic efficiency

Irreversibilities :

- Increase compressor work
- Decrease turbine work

$\eta_{th} = f(r_p, T_3/T_1)$

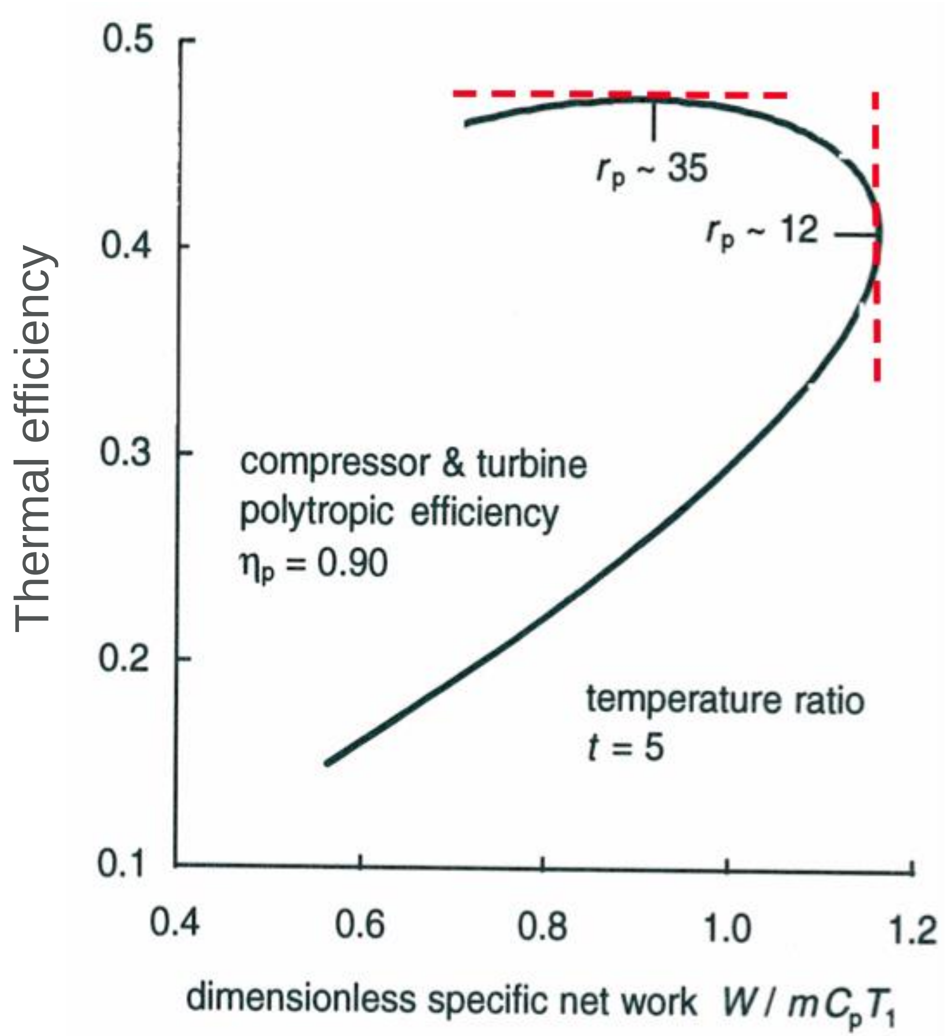



Thermal efficiency for $h_s = 90\%$

Source: Thermodynamics by Bähr & Kabelac

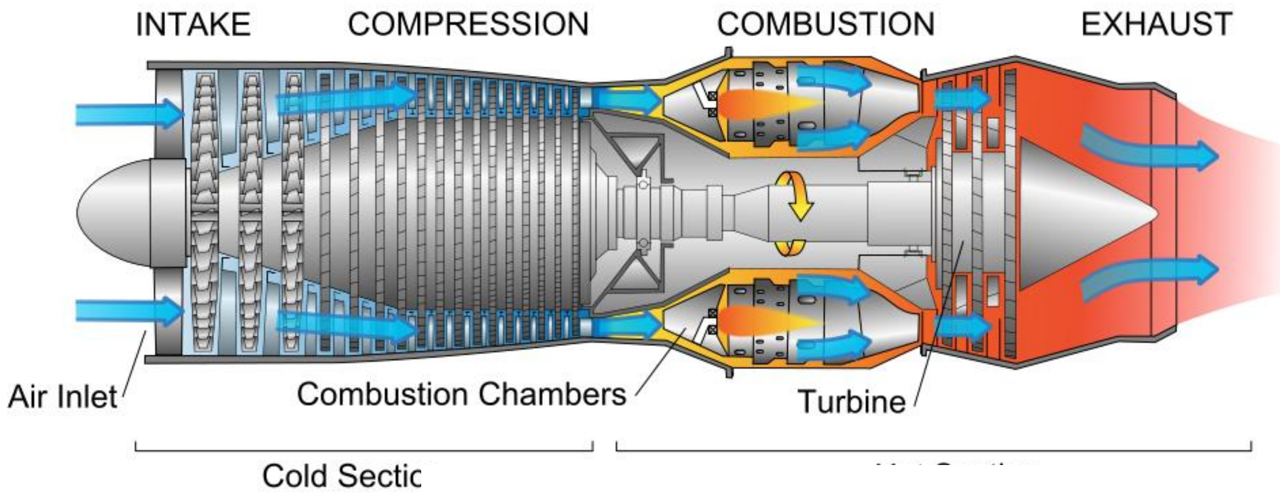
# Real cycle

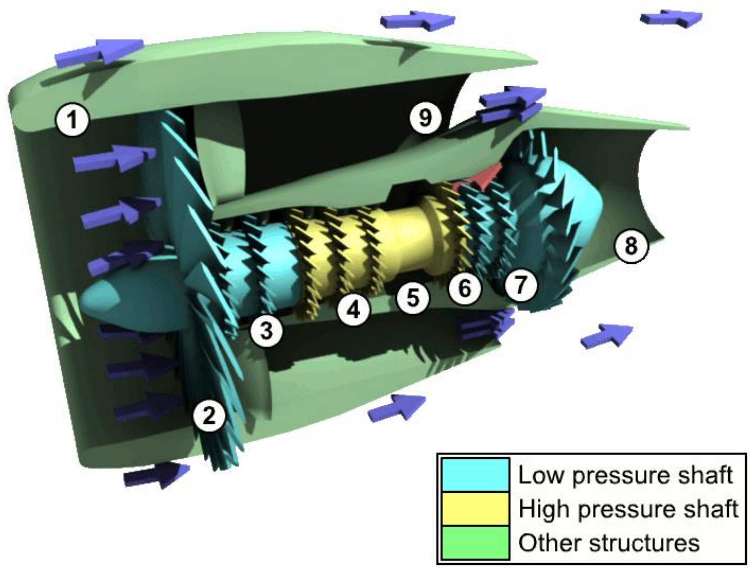
## Isentropic efficiency



# Real cycle

## Jet Engines

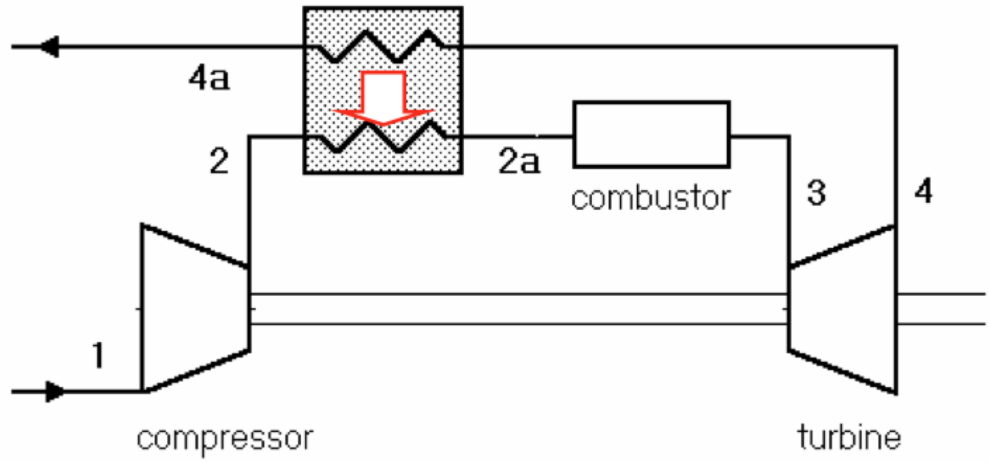


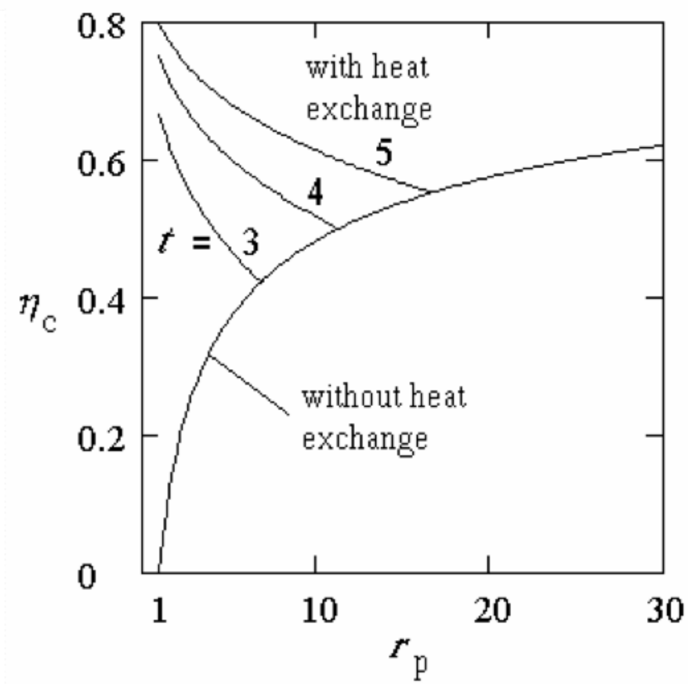

https://en.wikipedia.org/wiki/Turbojet
https://commons.wikimedia.org/wiki/File:Turbofan_Labelled.gif

# Gas turbine optimisation

## Regenerative heat exchange



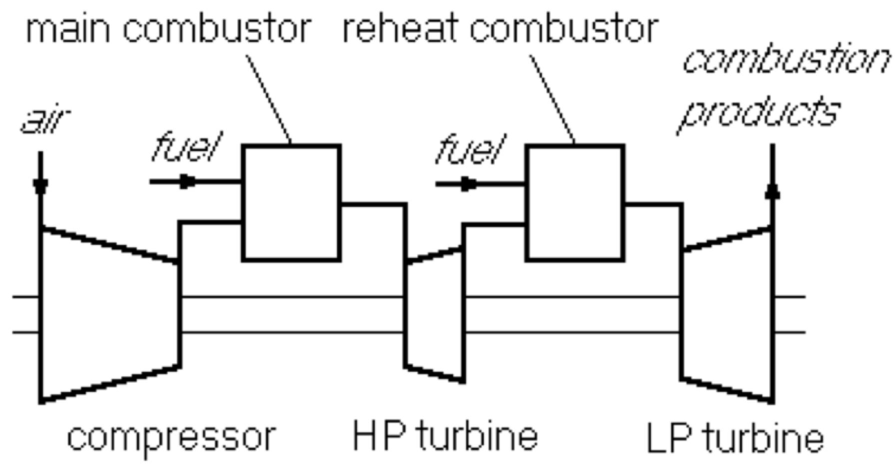

- Exhaust gases used to heat up compressed gases before combustion
- Heat exchanger -> Recuperator
- Efficiency improvement
- Improvement is only valid at low pressure ratio
- Limited scope (too bulky and non-standard)

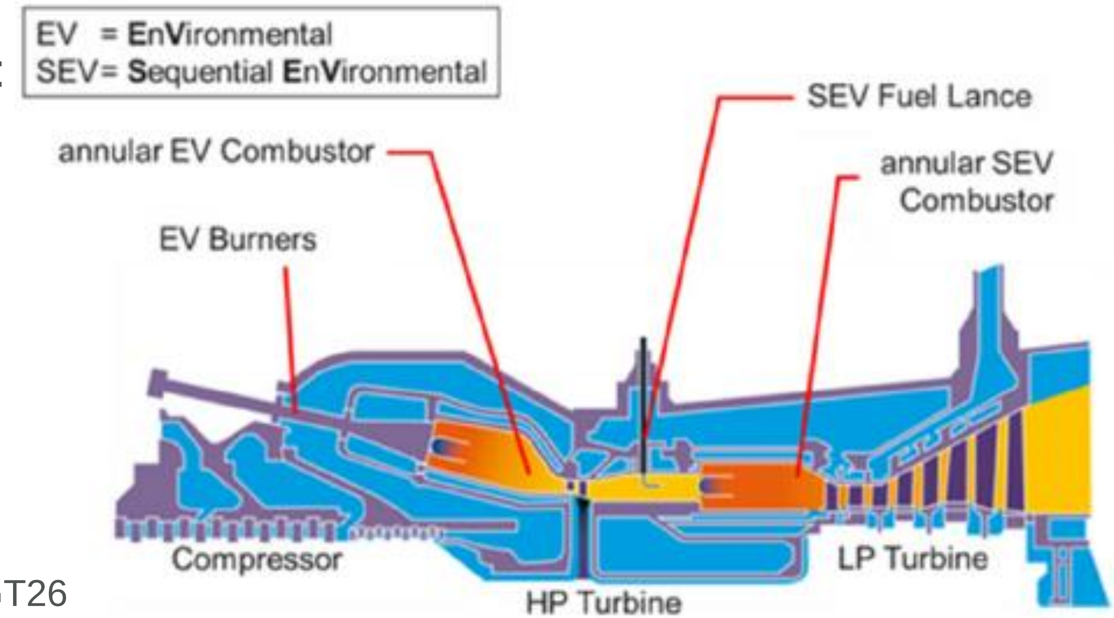


# Gas turbine optimisation

## Reheating

- Increase specific work output
- Decreases thermal efficiency
- High exhaust temperature : Especially suitable to combined cycle




Alstom GT26

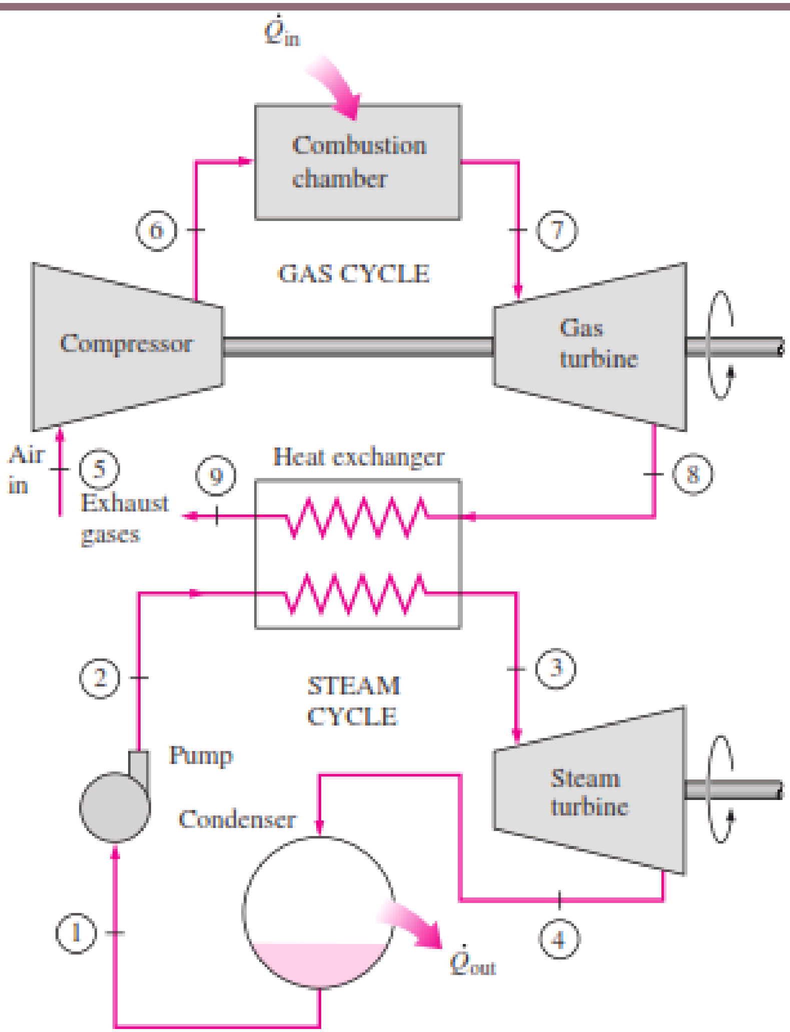
# Gas turbine optimisation

## Combined cycle

- Exhaust used as heat source for Rankine cycle
- Efficiency increases with gas turbine exhaust temperature

| SGT5-8000H in combined cycle | |
|---|---|
| Pressure ratio | 19.2 |
| Exhaust Temperature | 627°C |
| Efficiency | >60% |

Siemens Technical Data



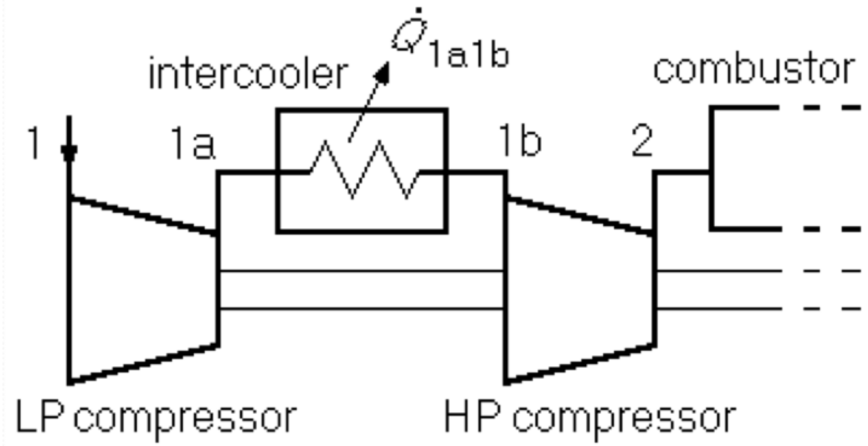

http://sounak4u.weebly.com/vapour--combined-power-cycle.html

# Gas turbine optimisation

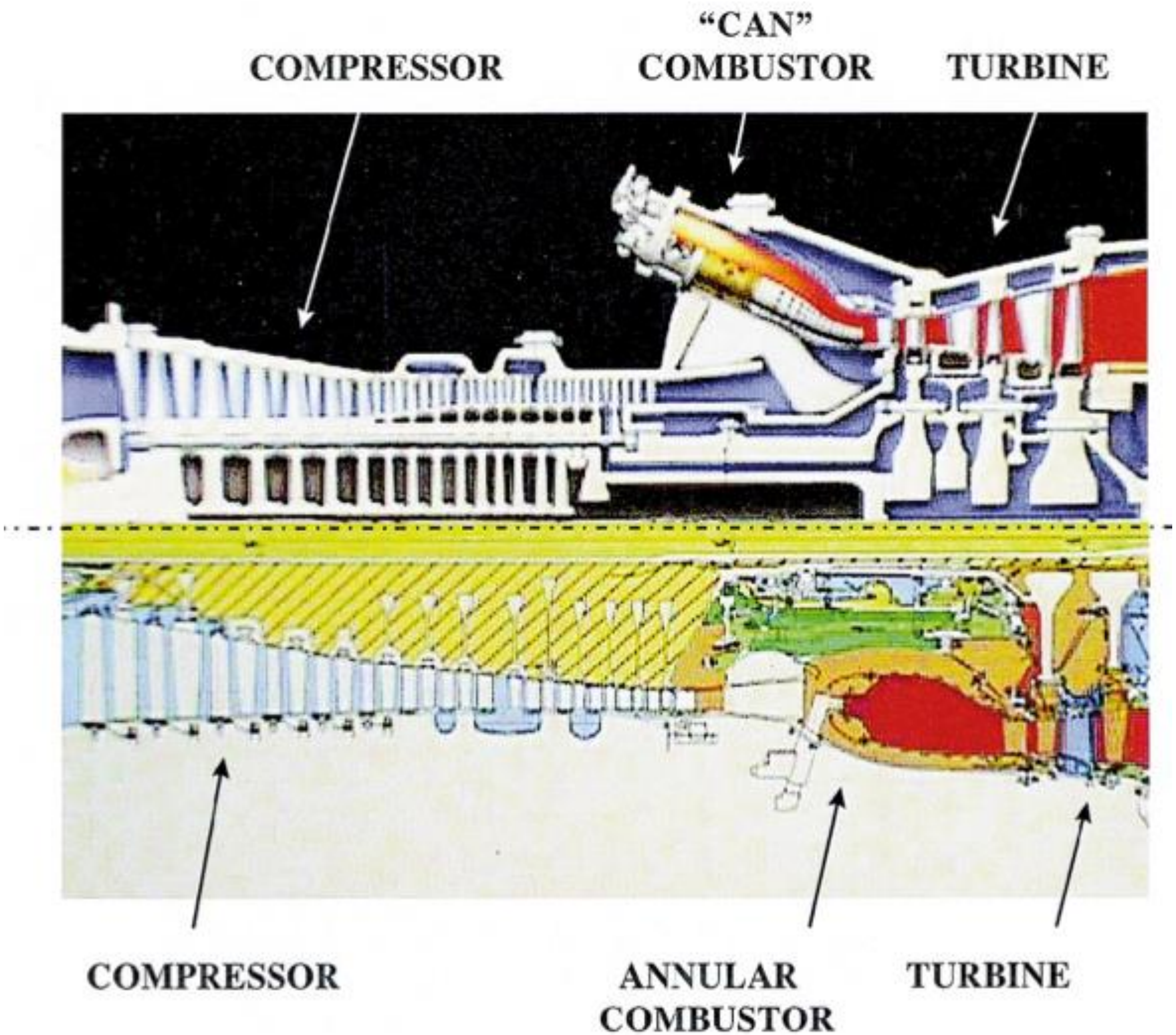
## Intercooling

- Reject heat between low and high pressure compressor
- Increases specific work
- Decreases efficiency

- Can be combined with heat regenerative heat exchanger (e.g. naval propulsion)



# 2. Gas turbine combustion




Can combustor (land based industrial GTs):

Easy access

Annular combustor (aero-engine GTs):

Compactness



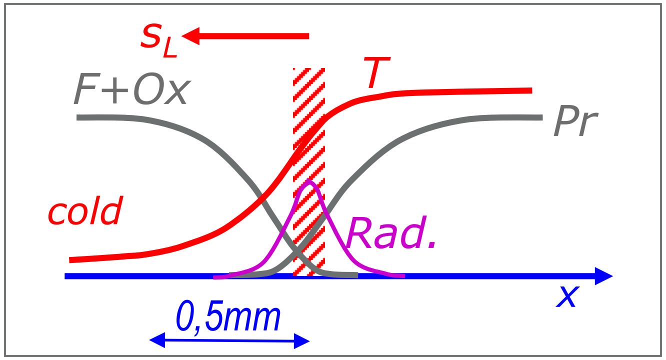
Correa, Proc. Comb. Inst. 1998

## Challenges of gas turbine combustion

- Low turbine inlet temperature (1500-1800 K) – dilution or lean premixed
- Fuel flexibility
- Load control
- High power density
- High altitude relight (aero-engines)
- Low emission (NOx and CO) – prevent hot spots

# Laminar and Diffusion flame

## Laminar premixed flame



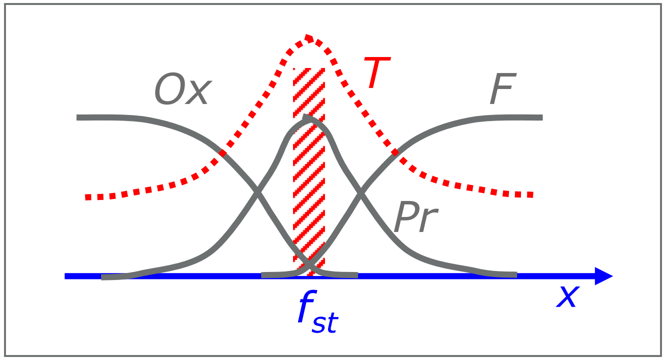

Premixed (but diffusion, heat conduction cannot be neglected)

Reaction progress variable $c = \frac{T - T_0}{T_{max} - T_0}$

Flame blue (CH, $C_2$)

$\lambda$ adjustable --> $T_{max}$ adjustable
--> low $NO_x$ possible

## Laminar non-premixed flame

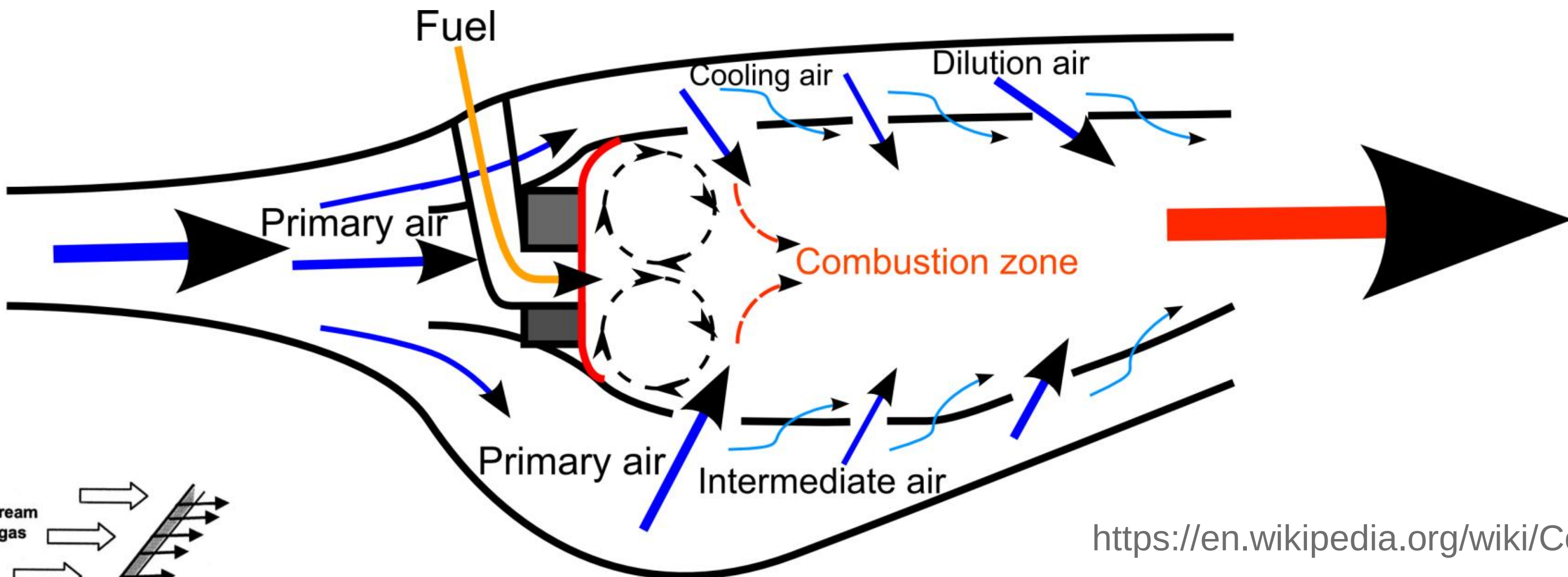



Diffusion --> Mixing

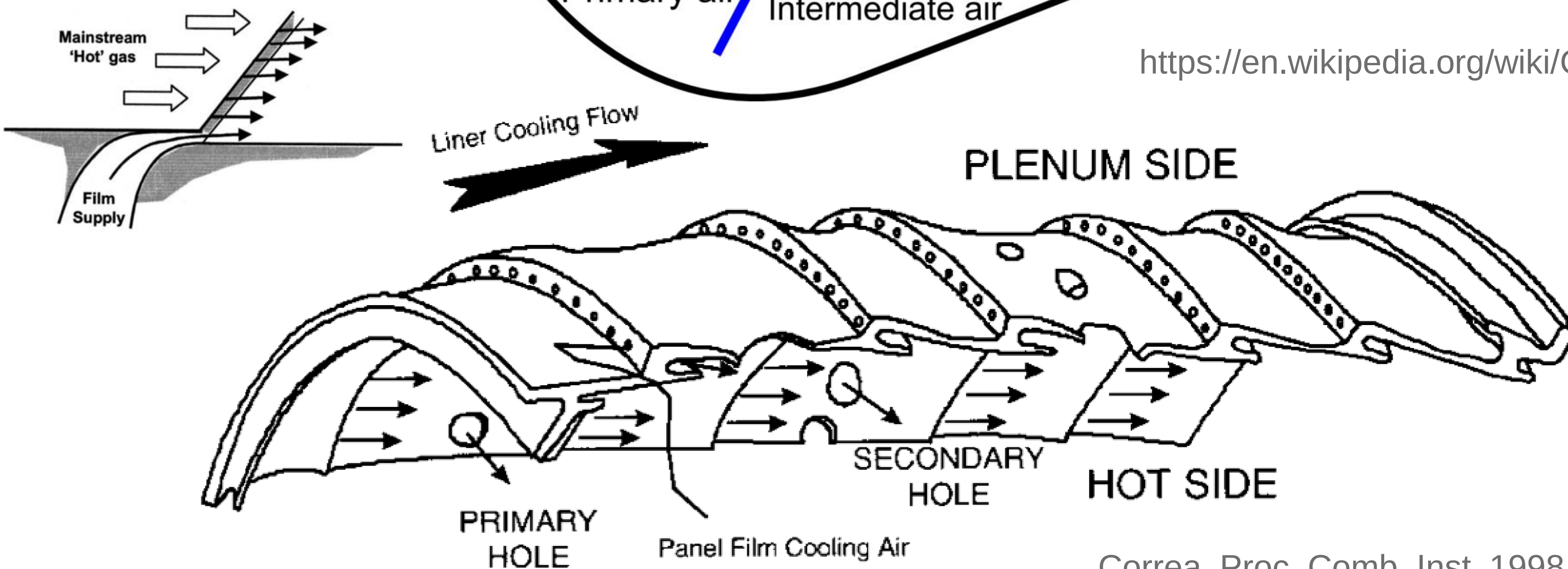
Mixture fraction variable f

Flame yellow (soot)

# Diffusion flame combustors




https://en.wikipedia.org/wiki/Combustor




Correa, Proc. Comb. Inst. 1998

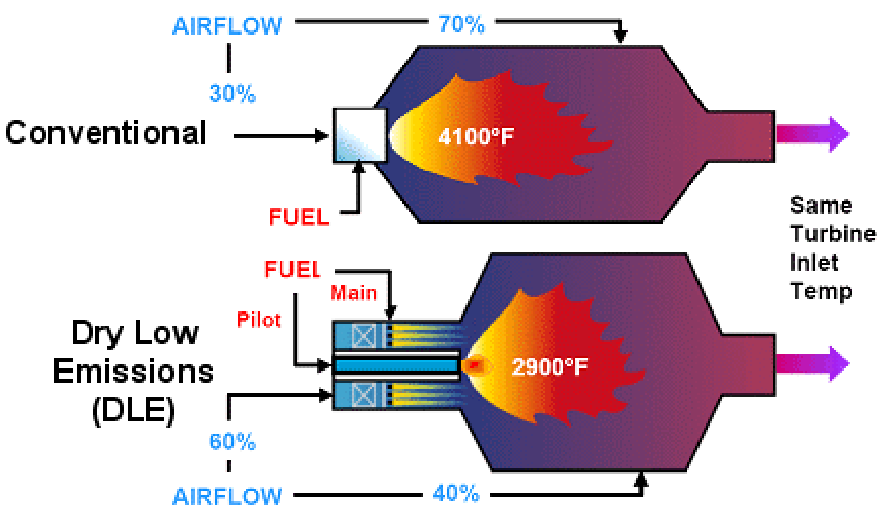
# Dry low NOx combustors

Traditional dilution cooled combustor :

- 30% primary combustion air
- High temperature in primary zone -> high NOx
- Load control by fuel mass flow

Dry-low-NOx combustion :

- Ideally premixed and lean (Φ~0.5)
- 80% primary combustion air
- At fixed Φ, load cannot be controlled by amount of fuel only -> complex schemes.
- 10 fold improvement in NOx emission
- Prone to instabilities (e.g. flashback)




*http://www.ramgen.com/tech_vortex_conventional.html*

# Stochiometry and flame temperature

## Flame temperature