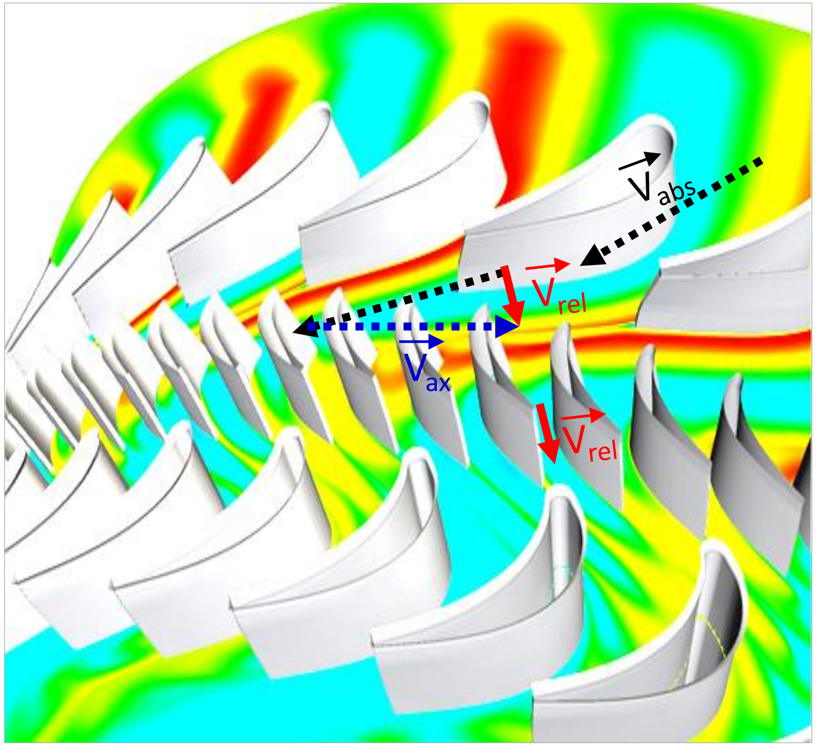
Journées Thématiques sur l'Exergie

Stationary Gas Turbines: A Brief Exergy Analysis of Part Load Operation



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Summary

- **Introduction**
- Some Key Points of Gas Turbine Technology
- Simplified Exergy Analysis of Part Load operation
- Discussion
- Conclusions & Prospects

Introduction

Stationary gas turbines ("GTs") are turbomachines comprising a compressor, combustors and expansion turbine (expander). Not to be confused with simple gas expanders. An alternative, better name is "***combustion turbine***".

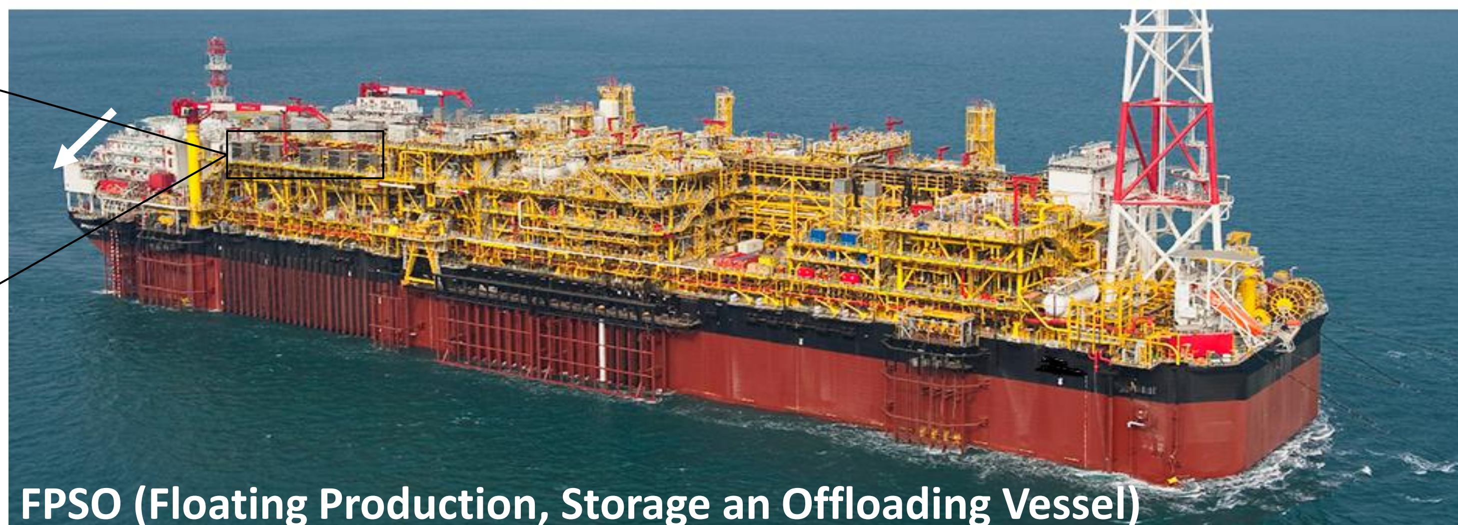
They can run in *simple cycle,* in *cogeneration* or in *combined cycle*.

Some specific applications, like power production in the *Oil & Gas sector* (e.g. *Exploration & Production* activities), require highly safe and reliable power units. Several units are then installed in simple cycle and run part load to secure a "spinning reserve" to be able to take over the load "on fly".

This presentation deals with the performances of gas turbines at part load.

Power island (5xGT):

Small but powerful !



FPSO (Floating Production, Storage an Offloading Vessel)

The different types of gas turbines ("GT")

Several families of gas turbines:

1- Aircraft gas turbines (or "jet engines")

They generate a thrust (for propulsion)

"Engine Alliance GP7200" jet engine

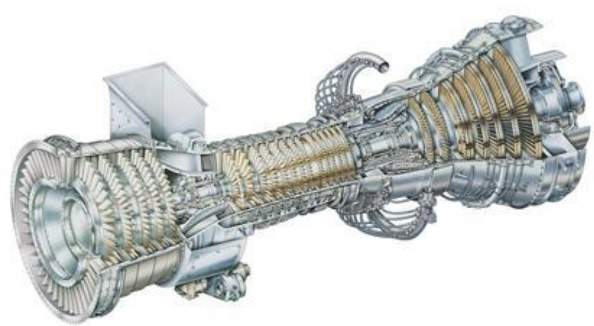
Jet engine (34 Tons of thrust)

2- Stationary GTs:

- They generate a torque and drive:
  - a generator: production of electricity
  - a process machine: pump or compressor drive

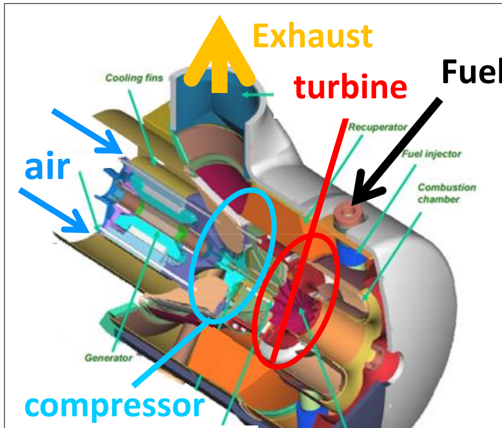
- They can be of various types:

- **Aeroderivative gas turbines** derive from jet engines and have two shafts
- **Industrial's or "Heavy Duty" gas turbines** derive from steam turbines: one shaft
- **Microturbines** range from a few kW to a few MW



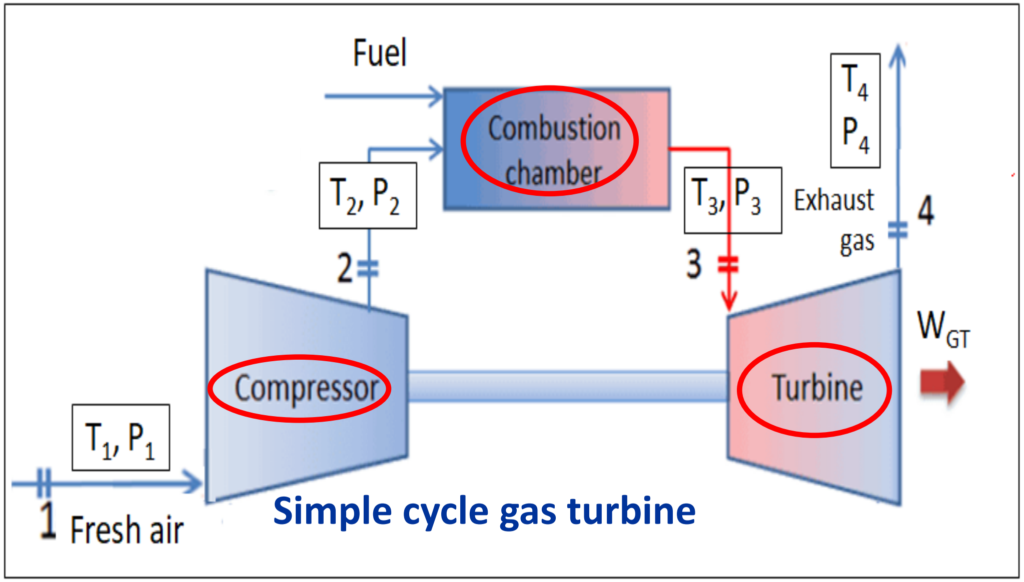
Aeroderivative LM6000-PC (50MWe) (2 shafts)

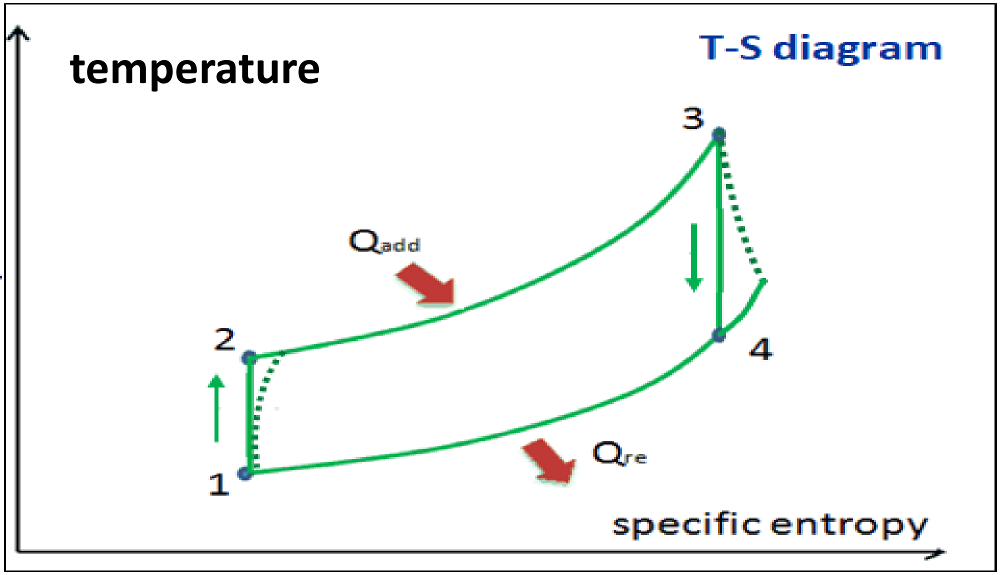
Heavy Duty GT 6F03 (80 MWe) (1 shaft)



Microturbine

Reminders: The Brayton cycle





Summary

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- **Some Key Points of Gas Turbine Technology**
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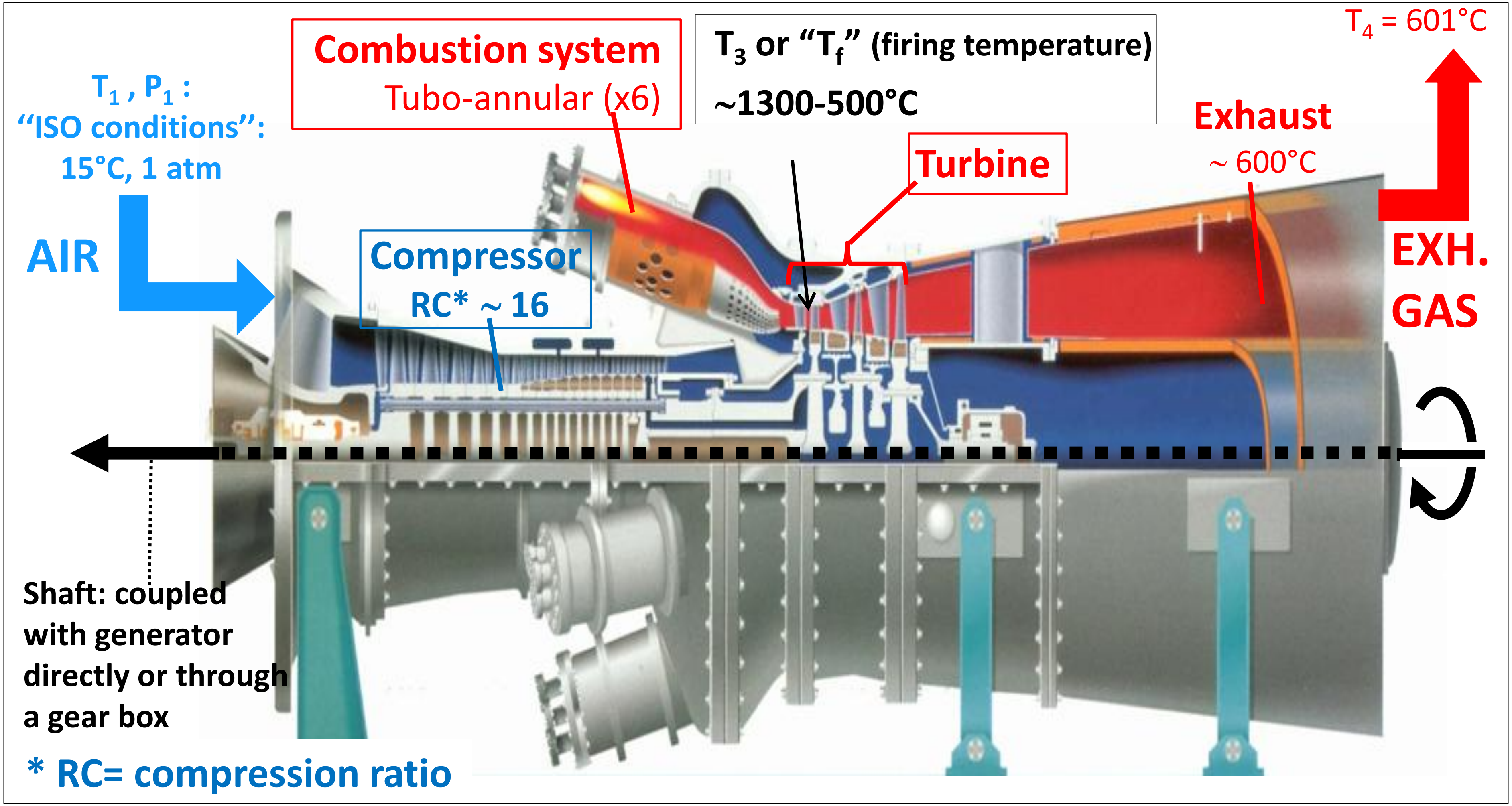
A modern, "medium power" gas turbine (80 MWe)

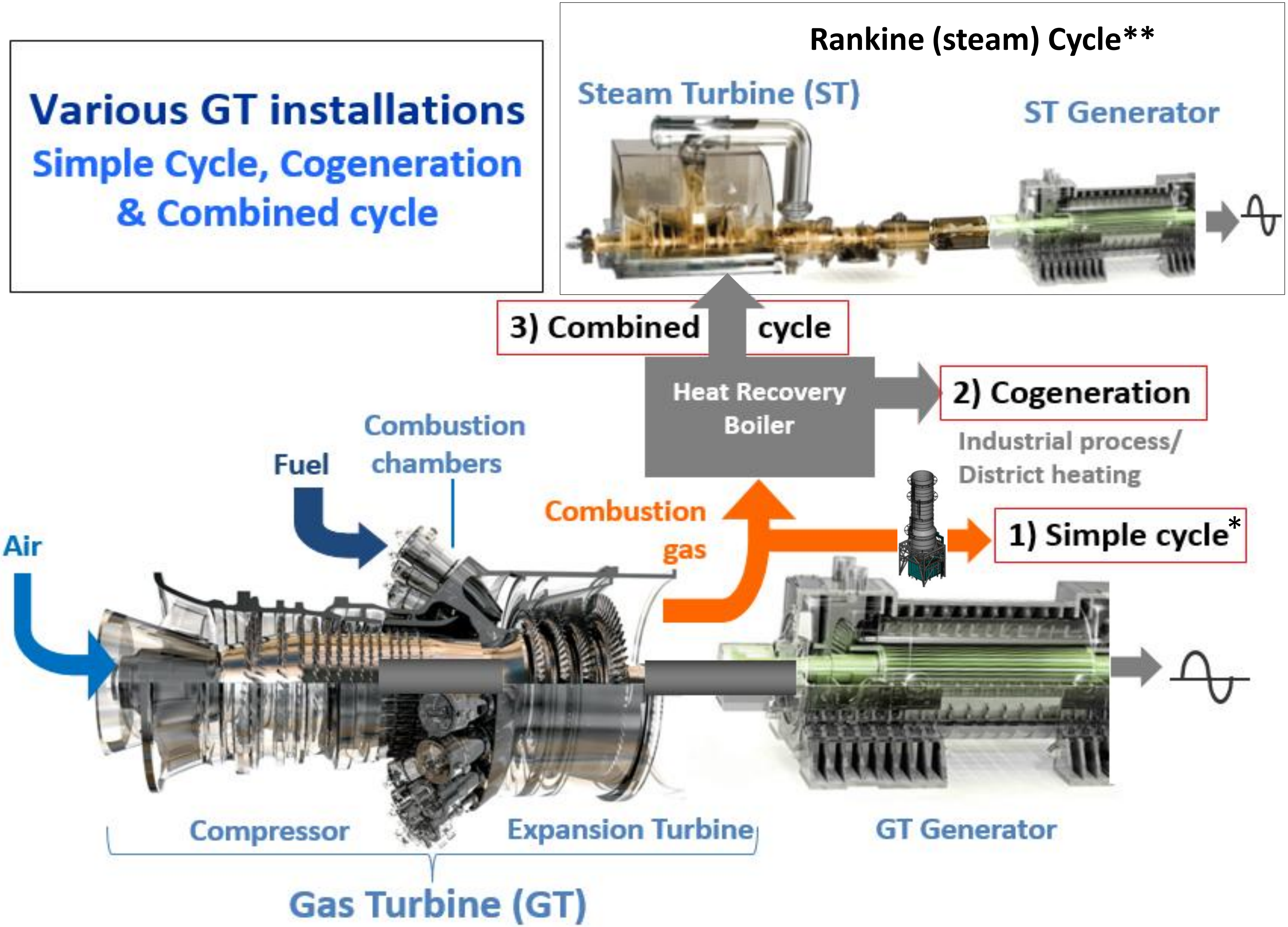


❑ **By increasing T_f (T_3) and RC (compression ratio: RC = P_2/P_1), cycle efficiency gets increased.**

Note: In modern GTs, T_3 exceeds 1500°C, which is higher than the melting point of the hottest parts material (melting point of nickel: 1455°) ⇒ **powerful cooling is indispensable**

Various GT installations

Simple Cycle, Cogeneration & Combined cycle



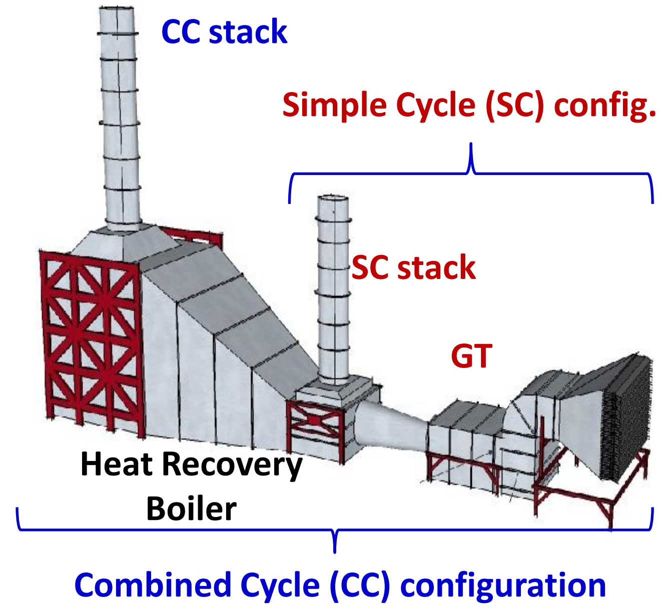
*** or "Topping cycle"** **** or "Bottoming cycle",** single shaft config. also possible: single generator

Examples of stationary GTs in onshore power units

A 126 MWe class GT

1x40 MWe Simple cycle GT in Guadeloupe (EDF)

2x100 MWe Combined Cycle GTs (Sri Lanka)



Technology Traits specific to gas turbines

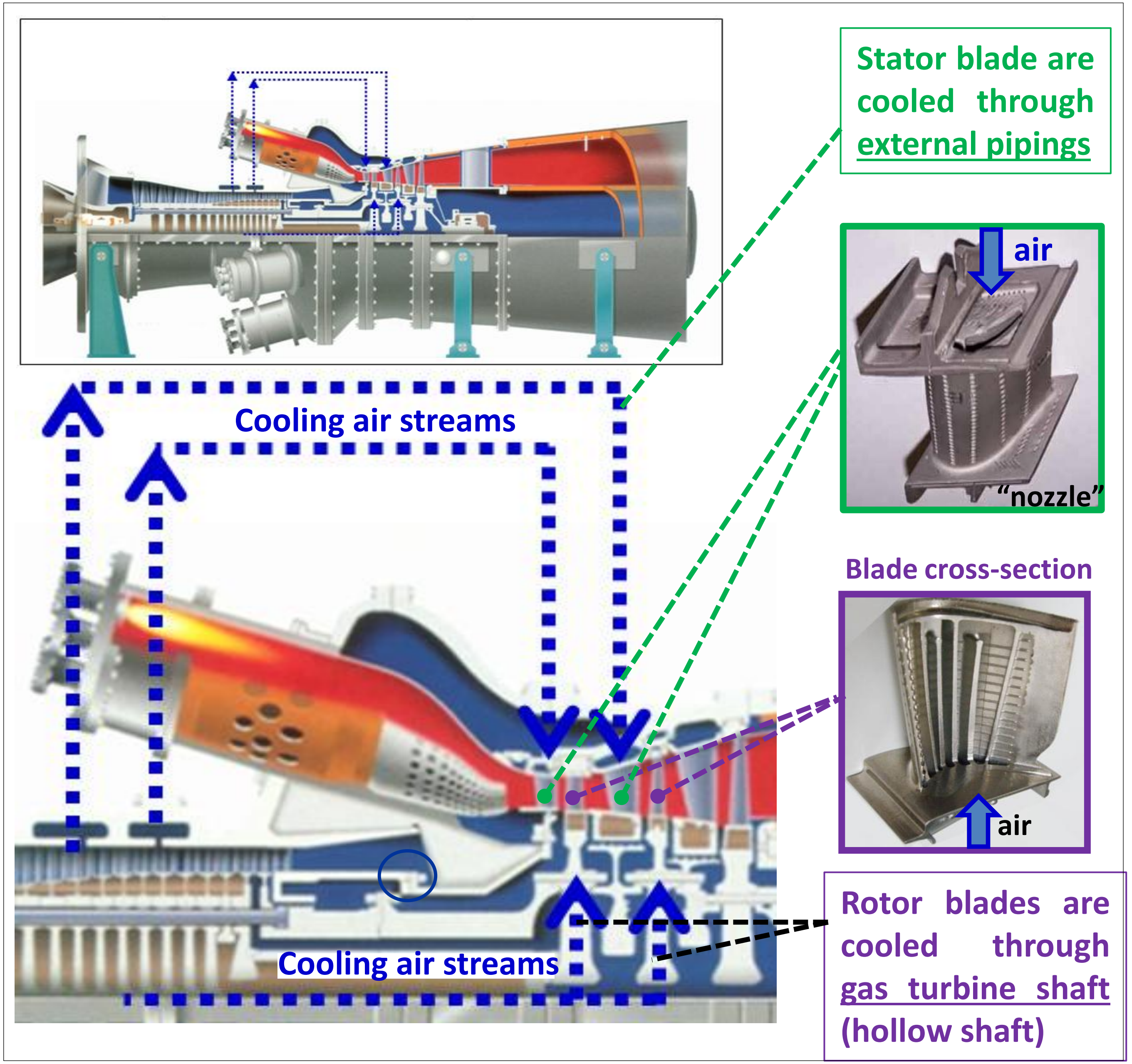
1) Turbine Blade cooling in stationary gas turbines

T3 in most modern GTs: 1500°C

Melting temp. of nickel: 1420°C

The metallic materials of the hottest turbine parts (rotor blades and stator blades or "nozzles") must be protected against melting and overheating. Therefore the 1st and 2nd turbine stages (and in most modern GTs, the 3rd stage) are cooled internally.

This cooling is performed by using air streams that are extracted from the last stages of the compressor.



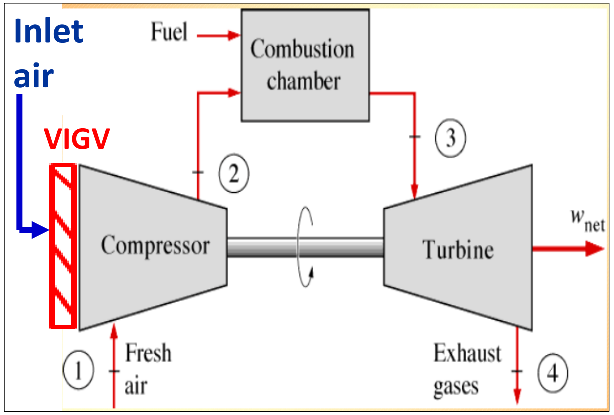
Technology Traits specific to gas turbines

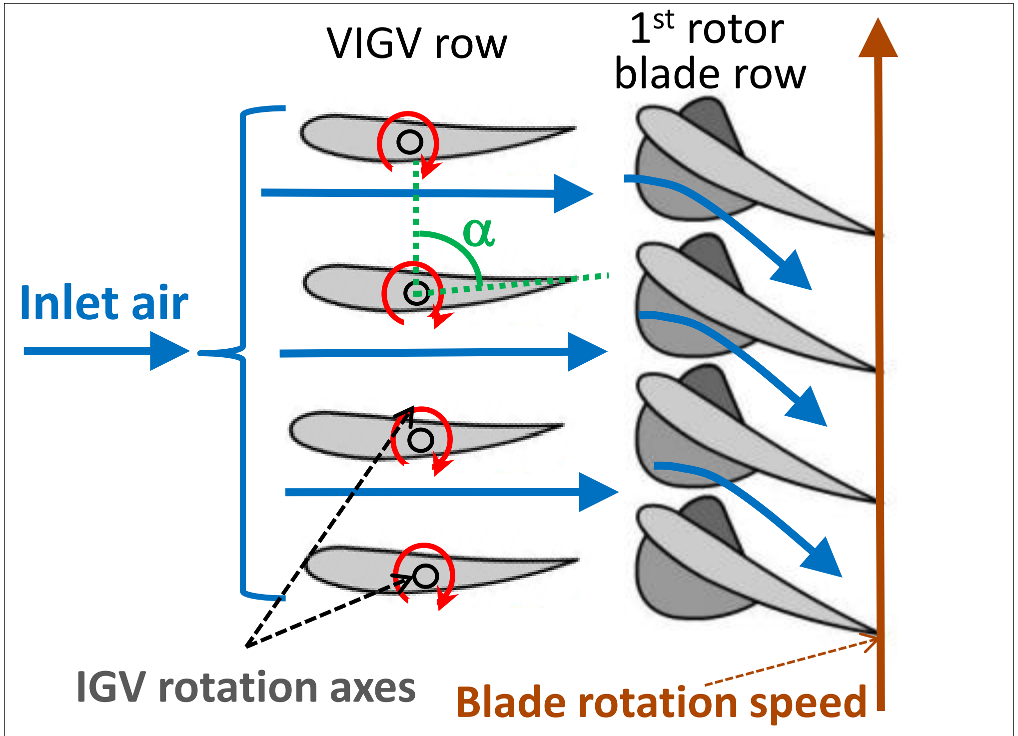
2) "Variable Inlet Guide Vanes" (VIGVs) to control inlet air flow

When the load of the gas turbine is decreased, the fuel flow gets reduced. One must decrease the inlet air flow in order to:

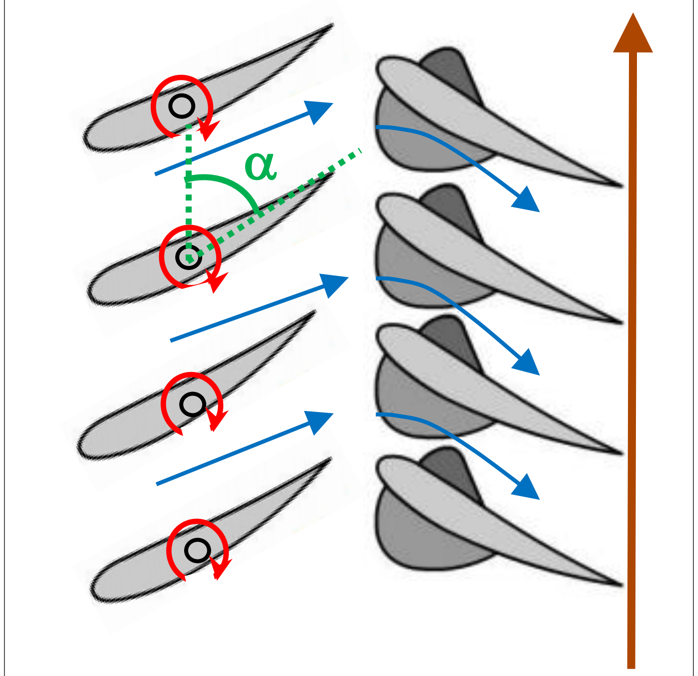
- avoid flame instabilities (if too fuel/air ratio becomes too low)
- keep the exhaust gas temperature high enough to preserve the performances when operating in combined cycle.

This is performed by the IGVs (Variable Inlet Guide Vanes): VIGs are statoric (non rotating) vanes the angle ("α") of which can be adjusted.





Open VIGVs: Full air flow



Closed VIGVs: Reduced air flow

Energy performances of simple cycle gas turbines

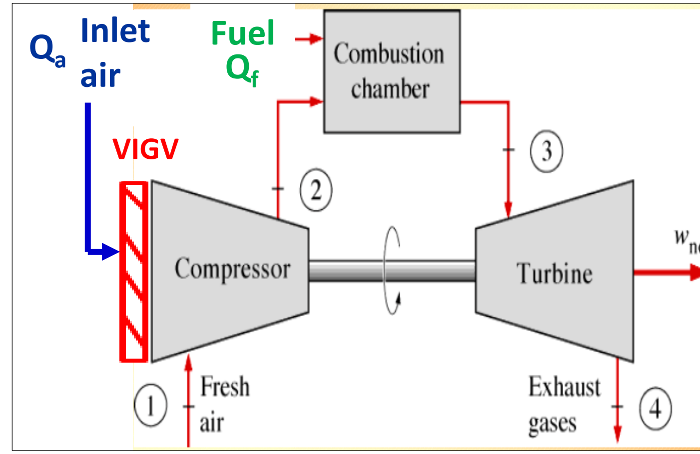
The master thermodynamic equations (1st principle)

1) Compression & Expansion Equations

$$T_2 = T_1\, RC^{R/(\eta_c C_{pa})}$$

$$T_4 = T_3\, RC^{-R\eta_t/C_{pg}}$$

RC: compression ratio*
η_c: compressor **polytropic** efficiency
η_t: turbine **polytropic** efficiency*
Cp_a & Cp_g: averaged Cp's of air & comb. gas



2) Defining a reduced power parameter: w_{GT}

$$w_{GT} = \frac{W_{GT}}{Q_a^\circ\, C_{pa}\, T_1^\circ}$$

(dimensionless number)

3) Power Output & Efficiency

$$w_{GT} = (1+\varepsilon_g+\varepsilon_{cp})\left(1 - RC^{-R\eta_t/C_{pg}}\right)\left(\frac{T_3}{T_1}\right) - \left(RC^{R/(\eta_c C_{pa})} - 1\right)$$

$$\eta_{GT} = \frac{(1-\varepsilon_f)\,(1-RC^{-R\eta_t/C_{pg}}).(T_3/T_1) - (1-\varepsilon_g-\varepsilon_{cp}-\varepsilon_f)\,(RC^{R/(\eta_c C_{pa})}-1)}{T_3/T_1 - RC^{R/(\eta_c C_{pa})}}$$

Approximation: the parameters ε_f and ε_g are considered constant

$Q_f << Q_a$: $Q_f = (1+\varepsilon)\, Q_a$

ε_g *represents the (small) contribution of fuel to the combustion gas flow*

Composition of combustion gas close to that of air

$Cp_g = Cp_a(1 + \varepsilon_g)$

ε_{cp} *represents the (small) contribution of fuel to the Cp of combustion gas*

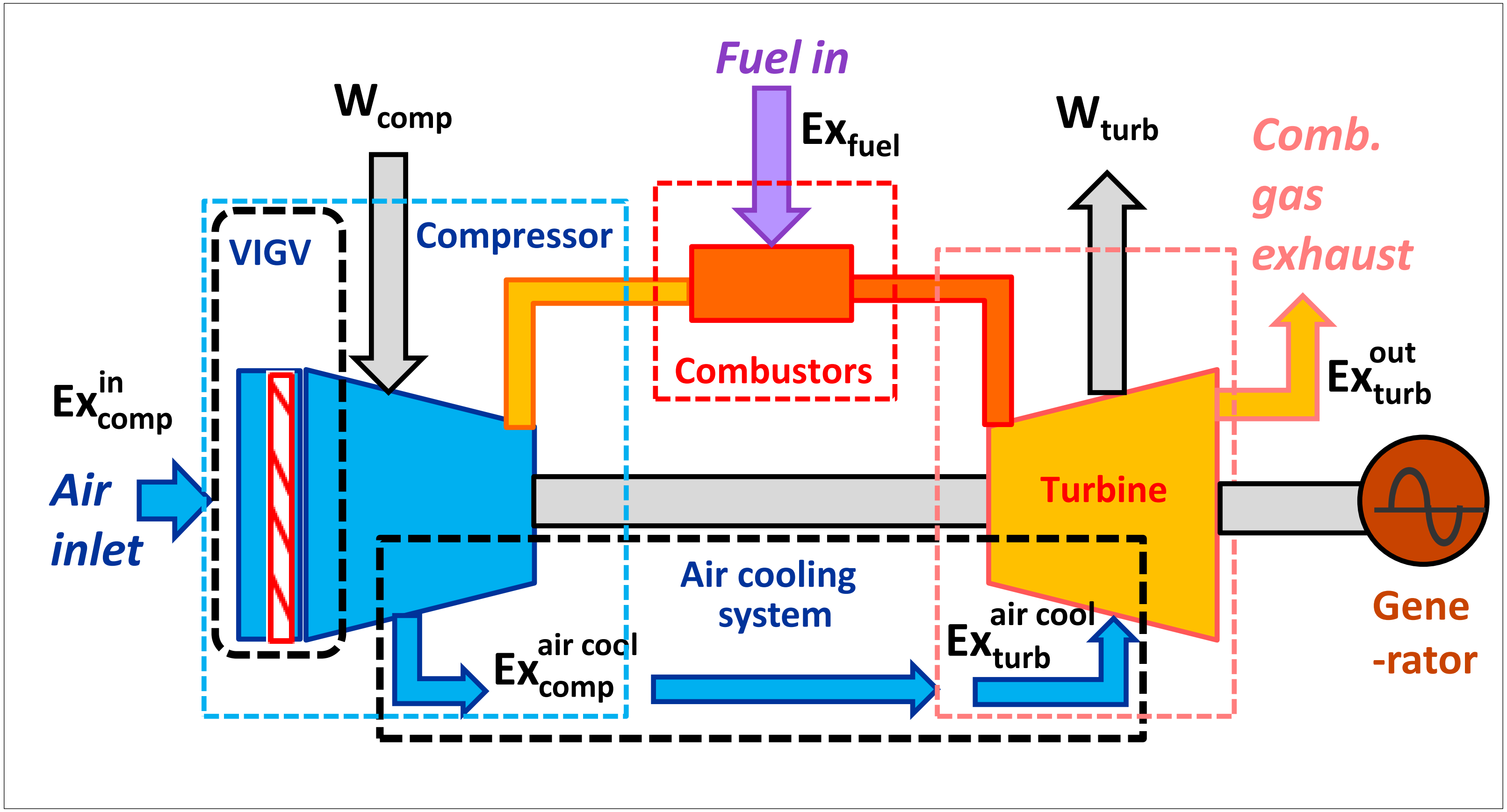
* **Note**: Equivalent equations can be established using <u>isentropic</u> efficiency data

Ref: *Performances of Gas Turbines in O&G Applications: Simple Thermodynamic Methods Help Predict Major Trends*, T. Schuhler, M. Riche, D. Orhon, A. Zoughaïb, A. Busco, M. Moliere, ASME Turbo Expo 2018, June 2018, Paper GT2018-75046

Simplified Exergetic Analysis of simple cycle gas turbines:
The sub-systems considered

Three main sub-systems considered:

- **Compressor sub-system:** includes the Variable Inlet Guide Vanes (VIGV**)**
- **Combustion sub-system:** includes cooling air extraction
- **Expansion turbine:** includes cooling air inflow



The evaluation of the exergy losses tied with turbine air cooling need have at least some **estimates of the cooling air flow rates…**

Simplified Exergetic Analysis of simple cycle gas turbines

Main sub-systems considered : *Compressor – Combustors - Turbine*

For each sub-system "j": $Ex_j^{in} = Ex_j^{out} + W_{mech} + Ex_j^{destr}$ $\qquad Ex_j^{destr} = T_o\, S_j^{created}$

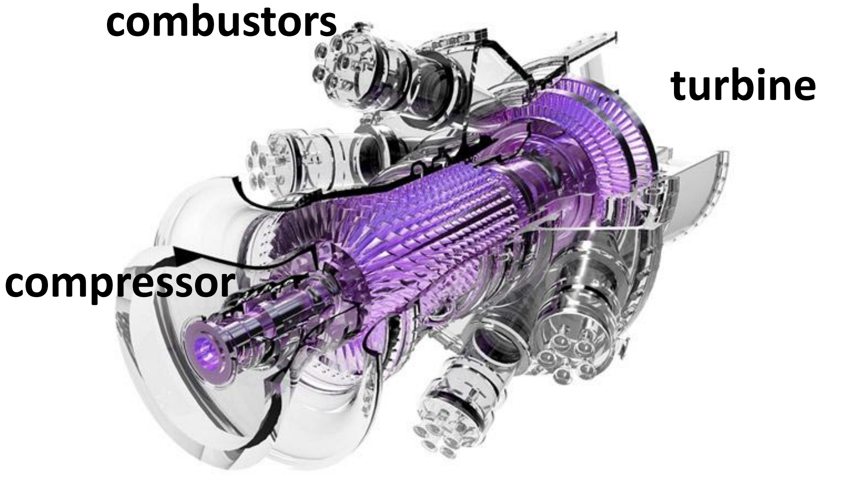
Compressor

Exergy Efficiency:

$$\eta_{x,comp} = \frac{Ex_{comp}^{prod}}{Ex^{supplied}} = \frac{Ex_{comp}^{out} + Ex_{comp}^{air\ cooling} - Ex_{comp}^{in}}{W_{comp}}$$

Exergy Destruction:

$$Ex_{comp}^{destr} = Ex_{comp}^{in} + W_{comp} - Ex_{comp}^{out} - Ex_{comp}^{air\ cooling}$$



Combustors

Exergy Efficiency:

$$\eta_{x,comb} = \frac{Ex_{comb}^{prod}}{Ex_{comb}^{supplied}} = \frac{E_{x,comb}^{out}}{Ex_{comb}^{in} + Ex_{fuel}\ (\approx HHV)}$$

Exergy Destruction:

$$Ex_{comb}^{destr} = Ex_{comb}^{in} + Ex_{fuel} - Ex_{comb}^{out}$$

Turbine

Exergy Efficiency:

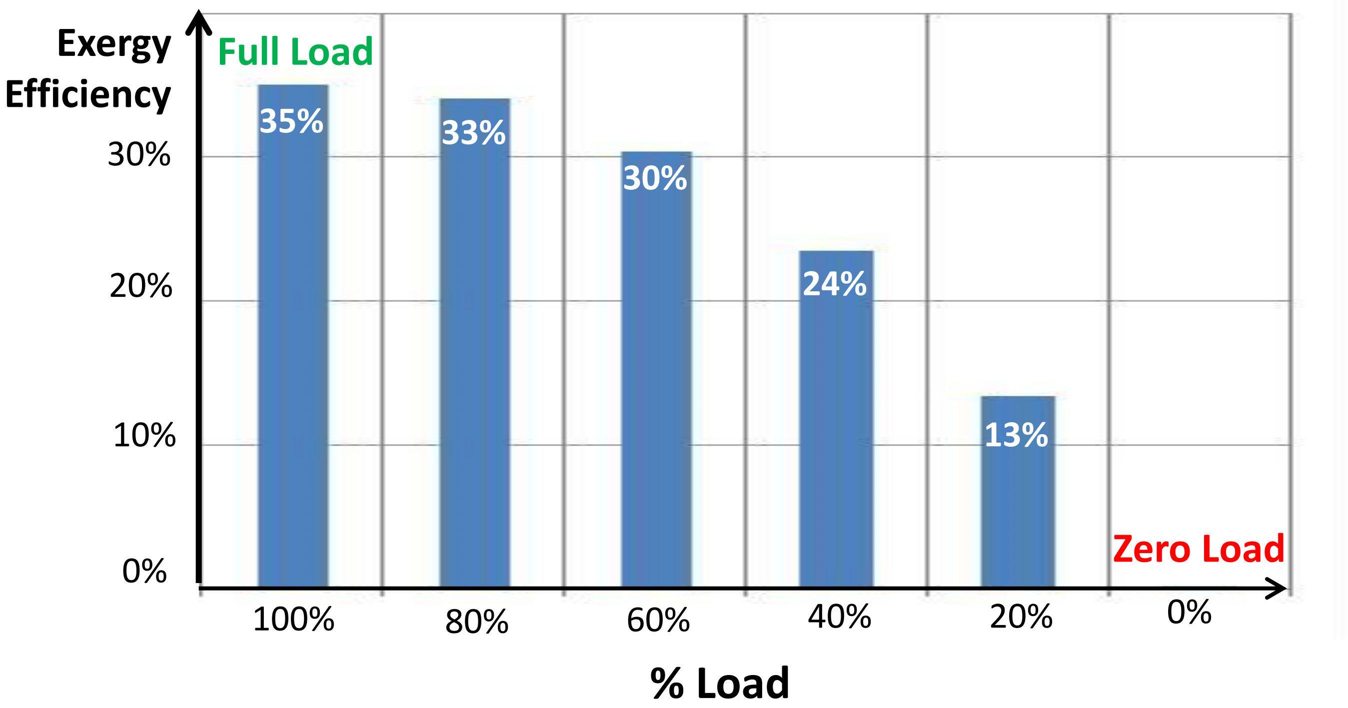
$$\eta_{x,turb} = \frac{Ex_{turb}^{prod}}{Ex_{turb}^{supplied}} = \frac{W_{turb}}{Ex_{turb}^{in} + Ex_{turb}^{air\ cooling} - Ex_{turb}^{out}}$$

Exergy Destruction:

$$Ex_{turb}^{destr} = Ex_{turb}^{in} + Ex_{comp}^{air\ cooling} - Ex_{turb}^{out} - W_{turb}$$

Note: all terms Ex_j , W_j are defined as powers (time derivative of energies)

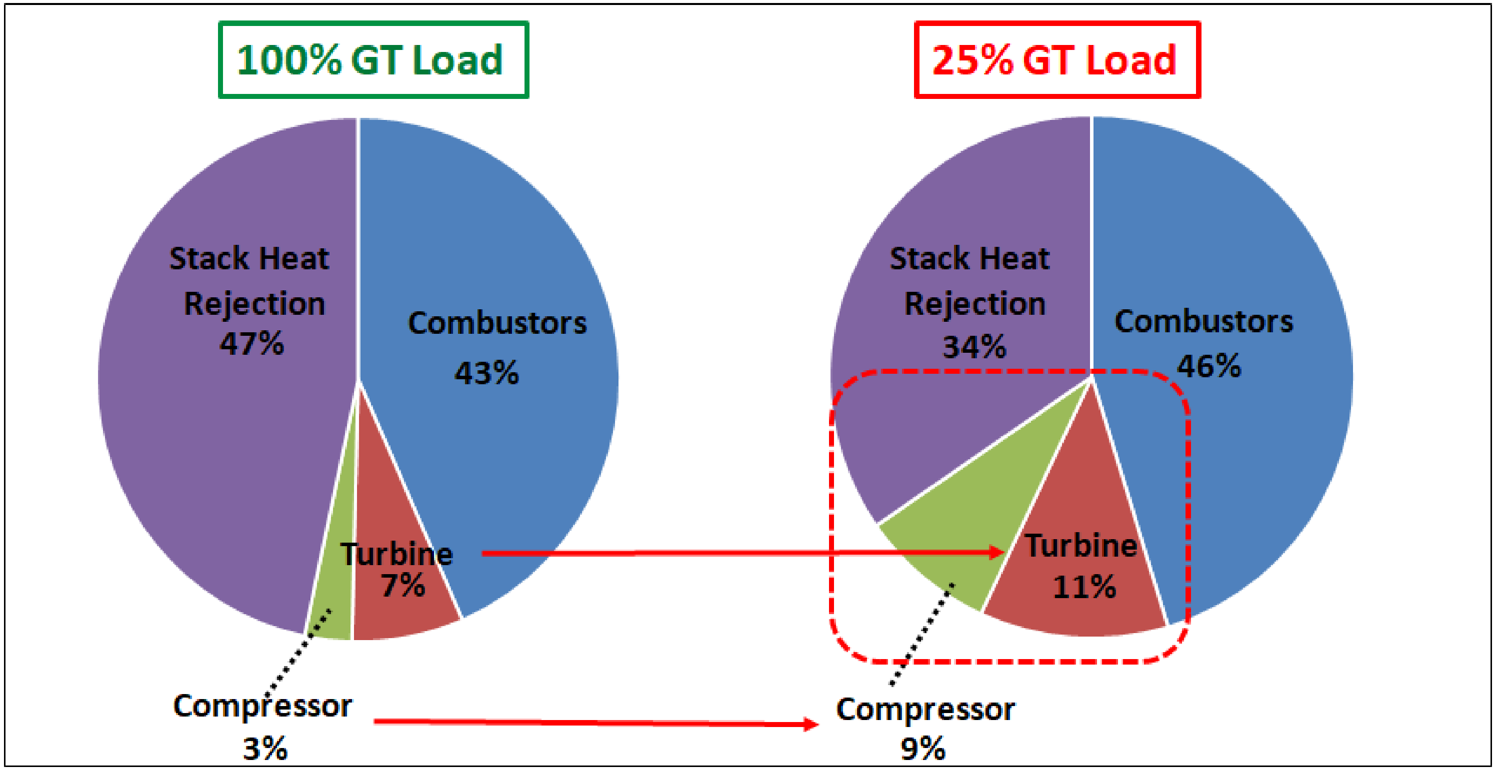
Exergy Efficiency versus Load



When the gas turbine load decreases, an increasing fraction of exergy gets destroyed.

The zero load point is also called “*Full speed No Load*” because the GT rotates at its full speed but does not produce any power (the generator being still not connected to the electrical grid).

Break-Down of Exergy destruction by GT component



Irreversibility in combustion and stack losses (no heat recovered) are the main “exergy destroyers”

However, when the gas turbine load drops from 100% to 25% load:

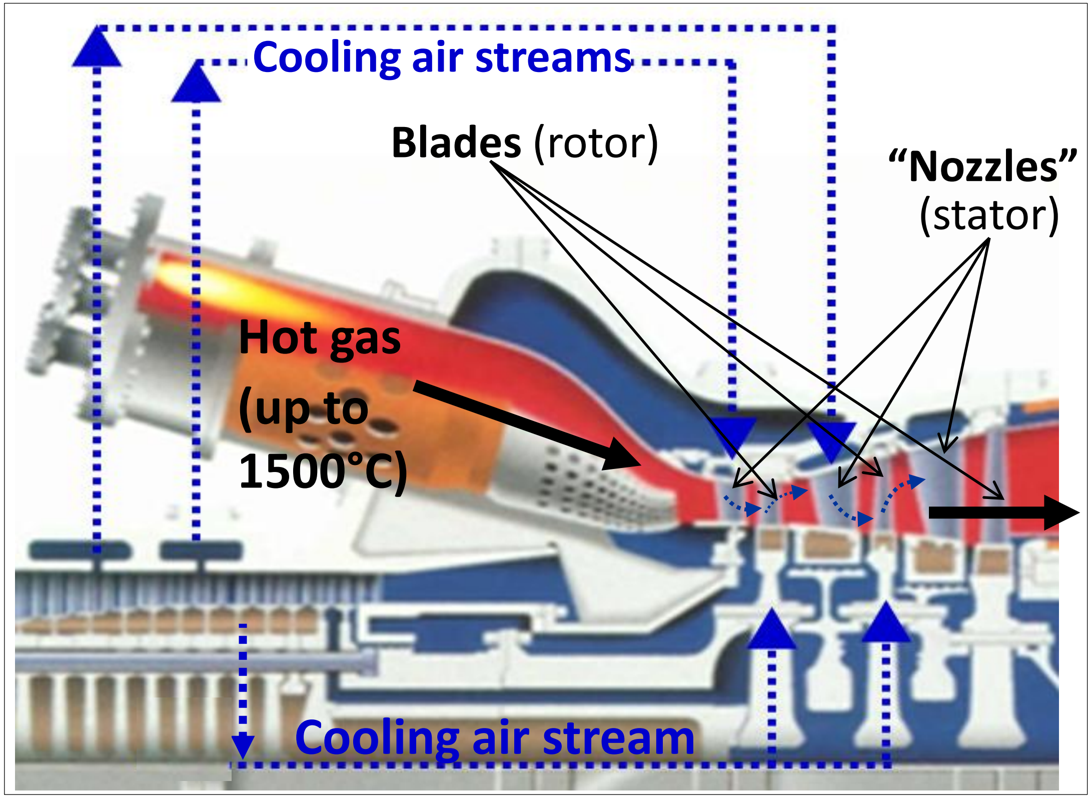
- The contribution of turbine increases by more than 50% ?
- **The contribution of compressor in exergy destruction gets multiplied by** 3

Questions:

- Why ?
- Are there “light solutions” to fill these gaps ?

Brief discussion

1) Effect of air cooling on turbine efficiency



The air cooling of turbine blades creates efficiency losses because:

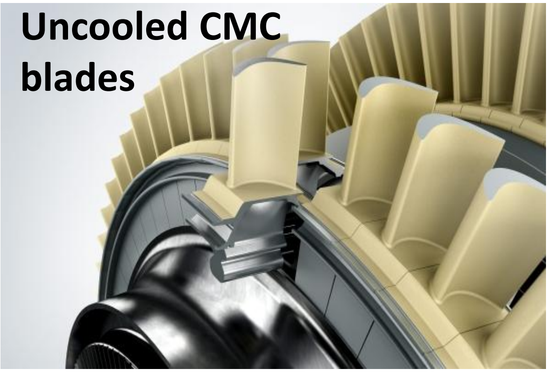
- the mechanical "work" of the cooling air stream is poor during the expansion step.

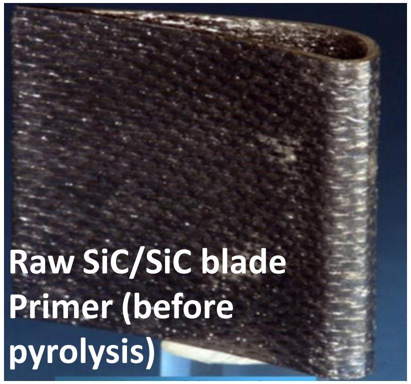
- These cold streams mix with very hot combustion gases.

Note: Besides internal air cooling, hot turbine parts are covered with "thermal barrier coatings" (**TBC**) that are ceramic insulators decreasing metal temperature

Next generation materials shaould be uncooled "CMC" (ceramic matrix composites).
They will offset the performance penalty associated with turbine air cooling.

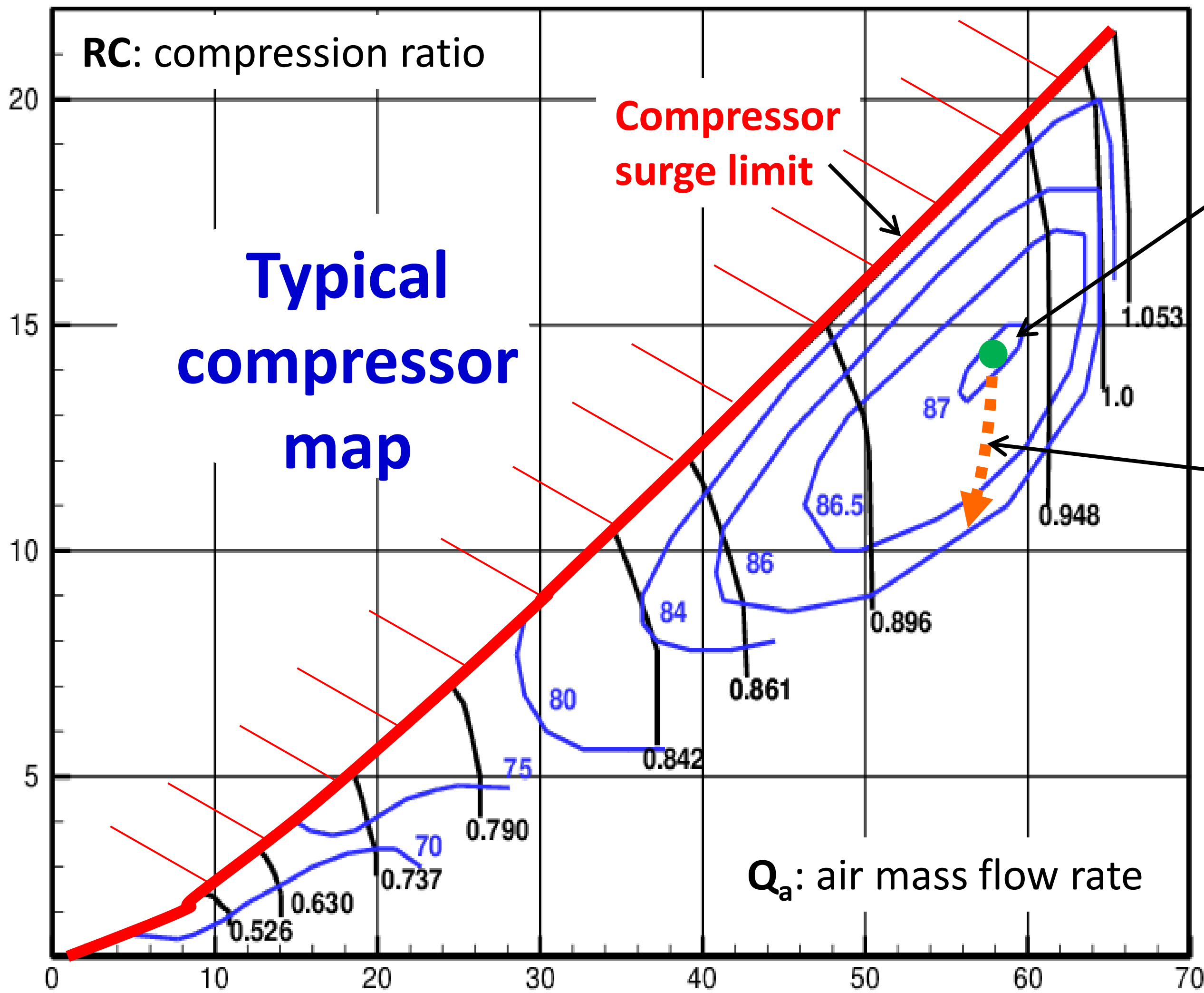
Difficulty: Ceramics are very brittle !!





Brief discussion

2) Effect of GT load on compressor efficiency

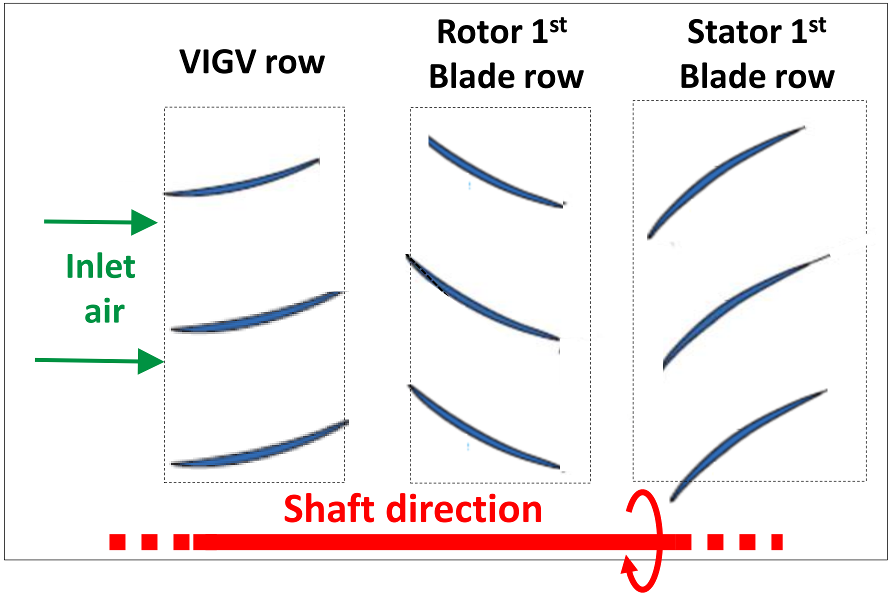


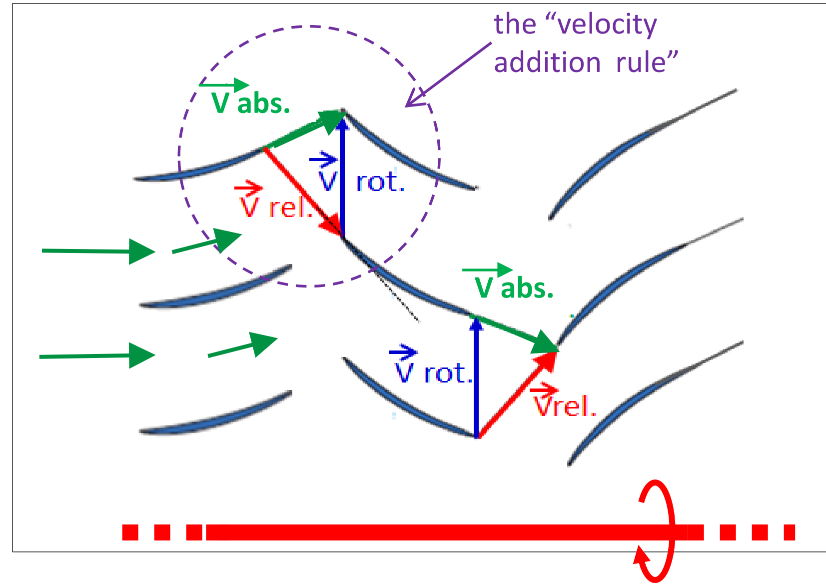
Compressor design is optimized for maximum efficiency @ base load.

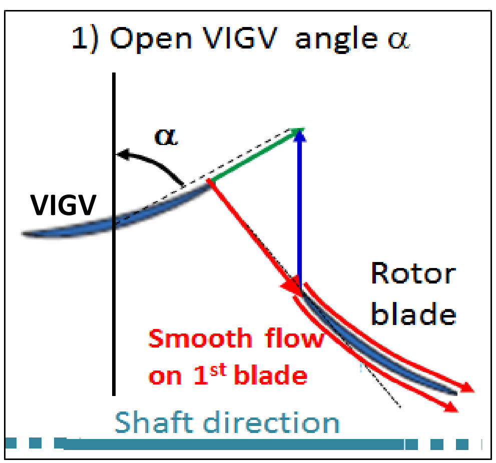
When GT load decreases (at constant VIGV angle), the comb. Gas flow decreases: so does the compression ratio RC decreases and the compressor efficiency decreases as well.

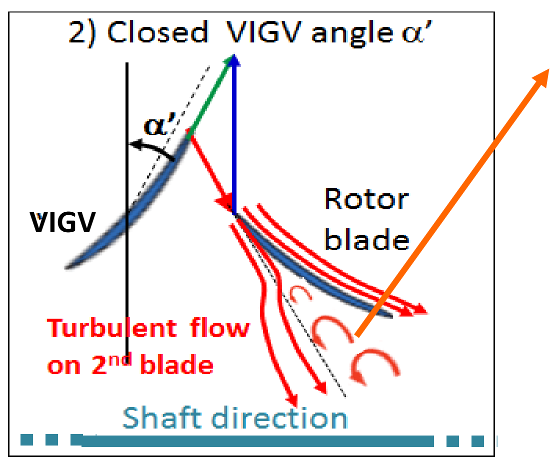
Note: the air flow (Q_a) does not change much because the compressor behaves much like a “volumetric pump”.

Brief discussion: 3) Effect of closing the VIGVs on compressor aerodynamics









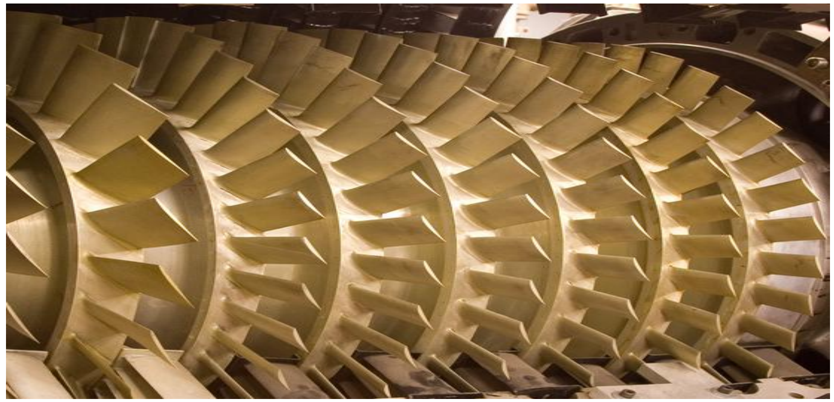
Closing the IGVs causes the separation of the boundary layer and turbulences on the 1st stage blade row of the compressor.
By a domino effect, the 2, 3, 4 and 5th stages are also impacted.

Such degradation of compressor aerodynamics causes a decrease by several points of the polytropic efficiency of the compressor.

This explains the important drop of the exergy efficiency at low loads.

Can compressor designs offset this part load performance gap ?

- First generation of axial gas turbine compressors featured “1D” design.
- Latest generation ones feature now “3D” designs to optimize aerodynamics.



Typical 1st generation design

Typical 3D design

Solving the low IGV angle penalty issue exceeds the capabilities of flexible compressor designs.

Conclusions & Prospects

An original, promising strategy to reduce the performance penalty of simple cycle gas turbines at low load may consist in:

- Maintaining the VIGV fully open
- **Heating the air at compressor inlet as a way to reduce its flow.**

This study is being conducted in the context of the Oil&Gas power units, through an ongoing collaboration (PhD thesis) between TOTAL, MINES ParisTech, with UTBM as consultant.

More generally, outside this very specific O&G problematic, the improvement of gas turbine performances is a matter of evolutionary compromises between ***thermodynamic***, ***aerodynamic***, ***materials*** & ***emissions*** considerations.

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