Sustainable Power Generation MJ2405

Miro Petrov

Gas Turbine Cycles

– major types and variations

Thermodynamic properties of air and hot gases
– the ”perfect gas” approximation

Thermal balance & basic calculations on
gas turbine performance

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Reading material on gas cycles

Many books can be used!

Any chapter on gas cycles or on gas turbines and compressors could serve just fine for the purpose of this course.

The main suggested sources:

Advanced Energy Systems (Khartchenko&Kharchenko), *CRC Press 2014* – (chapter 4): sections 4.1 to 4.4.

Energy Conversion – *free e-book by courtesy of the University of Tulsa*, Kenneth C. Weston, 2000 – (chapter 5)
http://www.personal.utulsa.edu/~kenneth-weston/

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På Svenska:

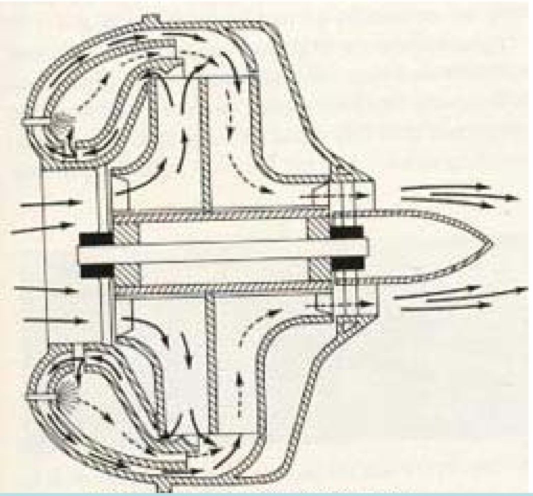
Energiteknik -Del 2; Henrik Alvarez, *Studentlitteratur 2006* – delar av kapitel 7 & kapitel 11.

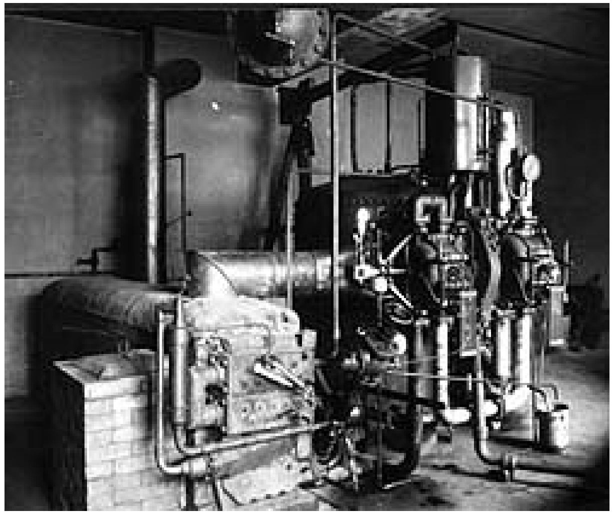
Tillämpad termodynamik; Ingvar Ekroth, Eric Granryd; *Studentlitteratur 2006* – delar av kapitel 6

History of gas turbines

The air-gas cycle was known since long ago, but in the past it was difficult to manufacture rotodynamic compressors and expanders with high isentropic efficiency and able to operate at high temperature, so they would be able to deliver a positive power output…

Aegidius Elling in 1903, in Norway, managed to demonstrate a gas turbine with radial compressor and expander, which for the first time could produce net power output :



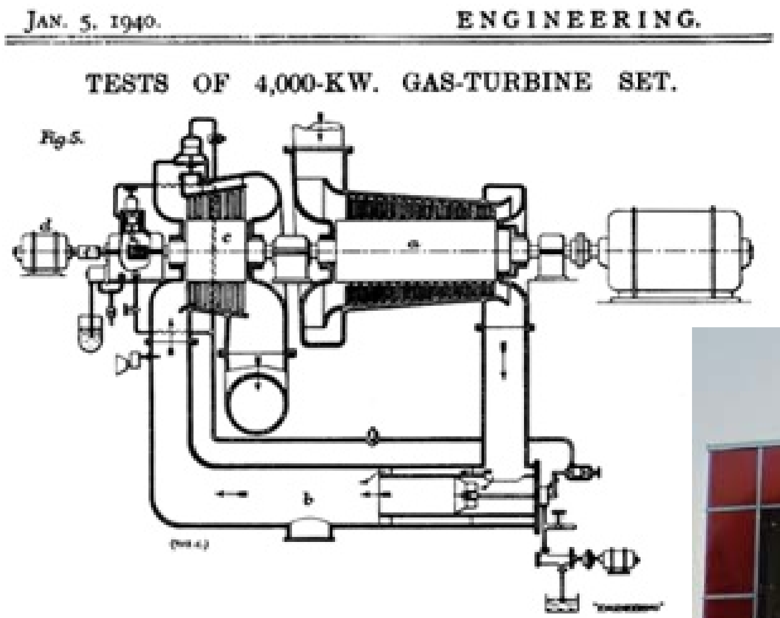


Frank Whittle's patent drawing… and Hans von Ohain's first jet engine in 1939

However, the materials and production techniques needed further development, so jet engines entered the commercial market only after 1950.

First reliable gas turbine power generator

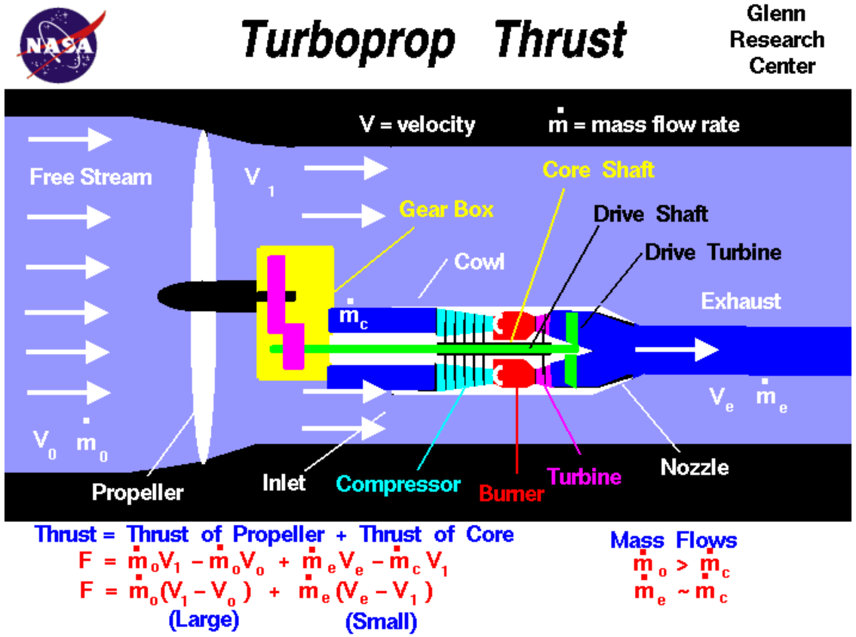
Charles Brown & Walter Boveri, **1939**, designed the first electricity-generating gas turbine in Switzerland. It had for the first time axial compressor and expander placed in reverse, with a single combustion chamber outside the machine casing.



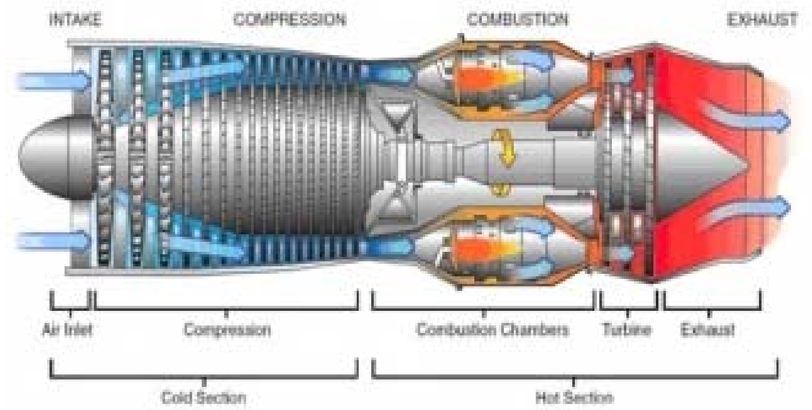
THE WORLD'S FIRST INDUSTRIAL GAS TURBINE SET – GT NEUCHÂTEL

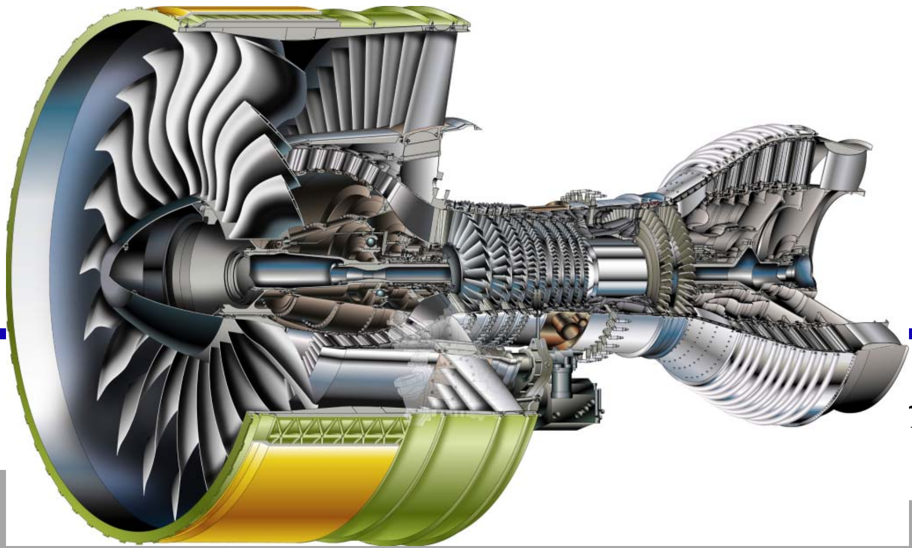
A Historic Mechanical Engineering Landmark

The advent of jet engines



It was the rush towards developing jet engines for military aircraft that later resulted also in modern gas turbines for civil applications – aeroengines (turboprops, turbofans, turbojets), industrial machine drives, marine propulsion, and power production!





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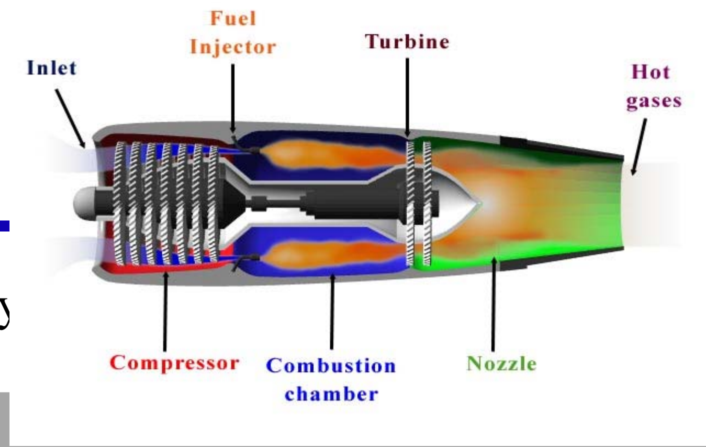
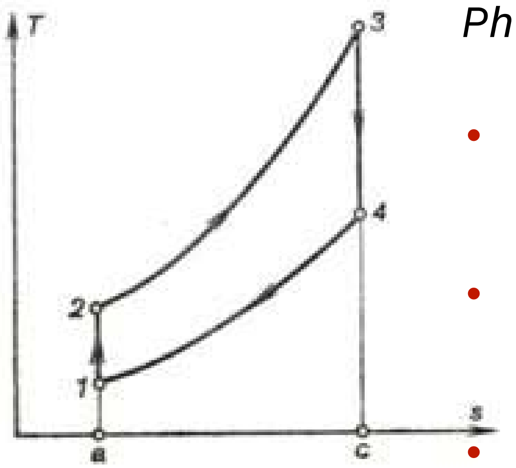


The classical gas turbine cycle
(a.k.a. Joule or Brayton cycle)

Operates with gaseous fluids (any gas) in continuous circulation, represented by two isobaric and two adiabatic processes. Heat addition and heat rejection occur at presumably constant pressures.
Phase change should not happen anywhere. Needs 4 main components:



- A **compressor** – the fluid is compressed in gaseous form. The compression process requires lots of power and raises the temperature of the fluid.
- A **heat addition stage** – either a heat exchanger (if externally heated) or some sort of internal combustion chamber (if using clean fuels).
- An **expander** – expanding the hot gas and delivering the power output.
- A **cooling stage** – sinking the remaining heat of the expanded fluid to the surroundings and returning the cooled fluid to the compressor.

The externally-heated gas turbine (closed cycle)

- Can operate with air, or with exotic gases for better heat exchange, such as helium, hydrogen, carbon dioxide, etc...
- Heat is supplied externally (can use solid fuels in external combustion), while cooling should be provided in the end (after expansion) to complete the circuit and to dump the waste heat to the environment.

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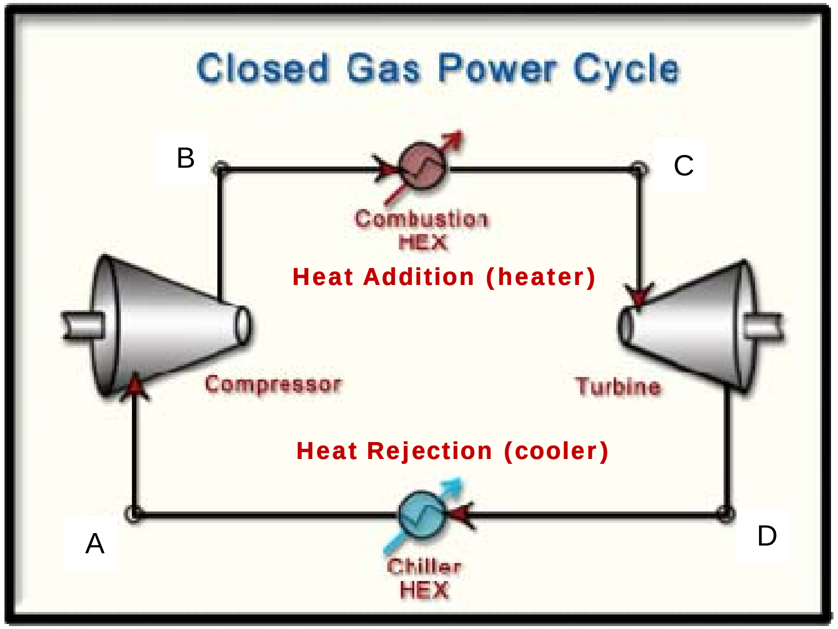

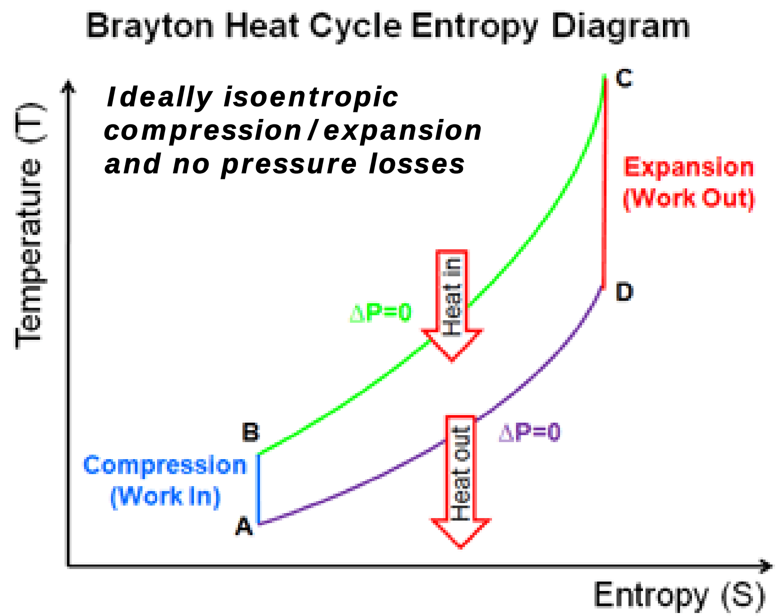

Ideal processes:
isoentropic & isobaric

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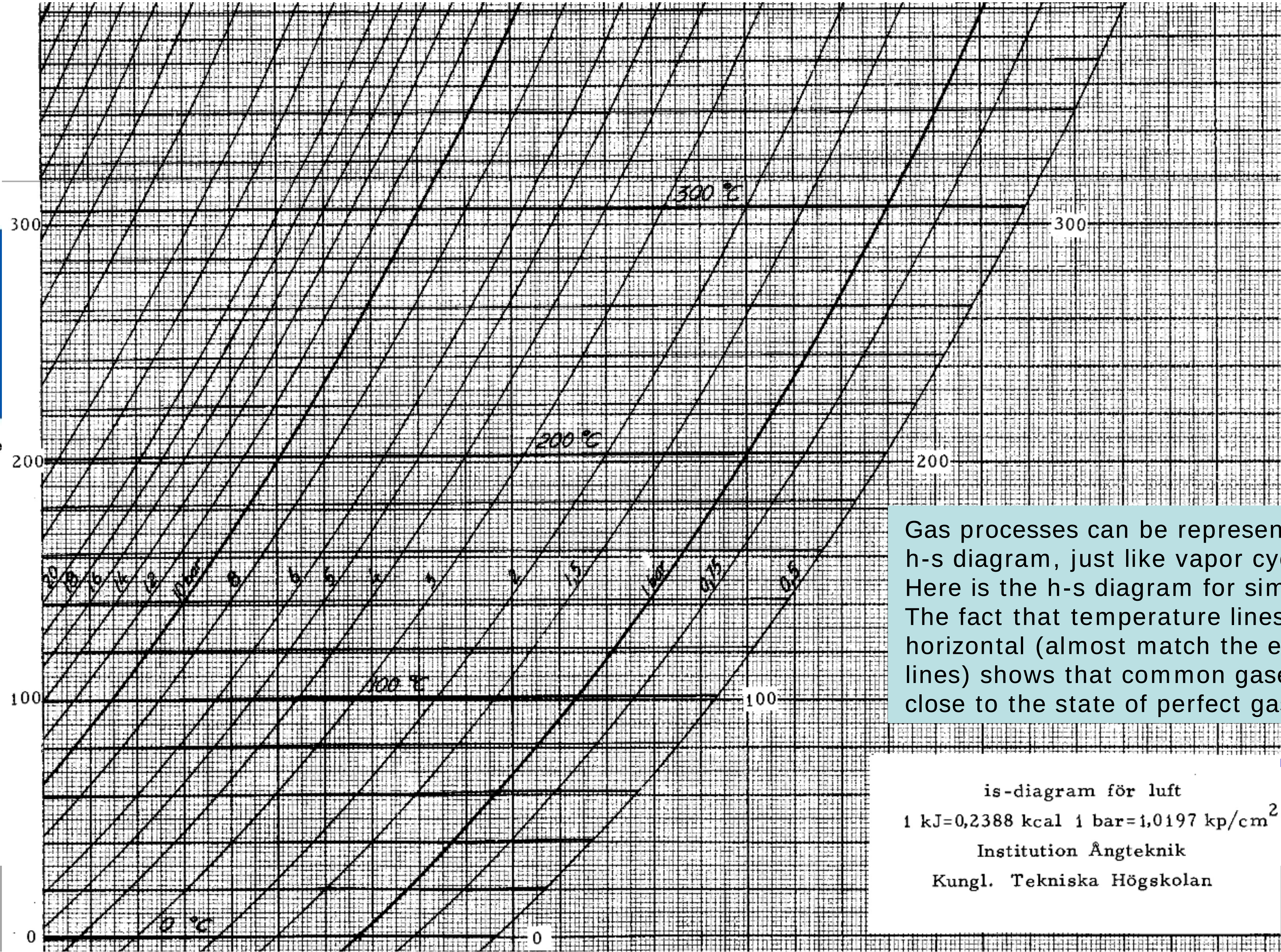

Gas processes can be represented on a h-s diagram, just like vapor cycles. Here is the h-s diagram for simplified air. The fact that temperature lines are almost horizontal (almost match the enthalpy lines) shows that common gases are very close to the state of perfect gas.

Upper section of the same diagram (for the high T & pressure range) shows that for very high pressures the T-lines start to curve a bit, which is a deviation from the perfect gas properties.

Working fluid as a perfect gas

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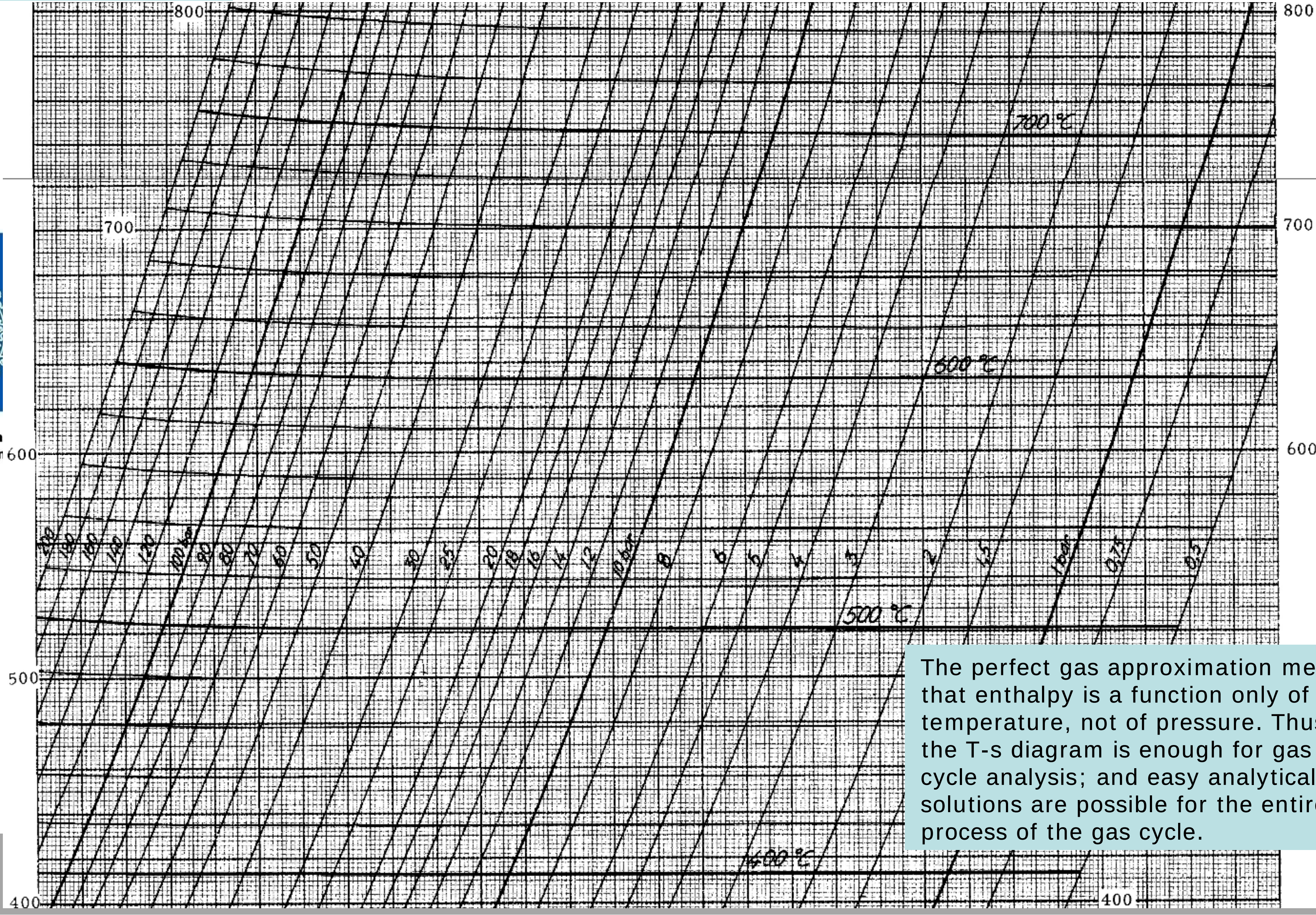

The perfect gas approximation means that enthalpy is a function only of temperature, not of pressure. Thus, the T-s diagram is enough for gas cycle analysis; and easy analytical solutions are possible for the entire process of the gas cycle.

Quasi-Carnot cycle can be approximated at high pressure & temperature ratio

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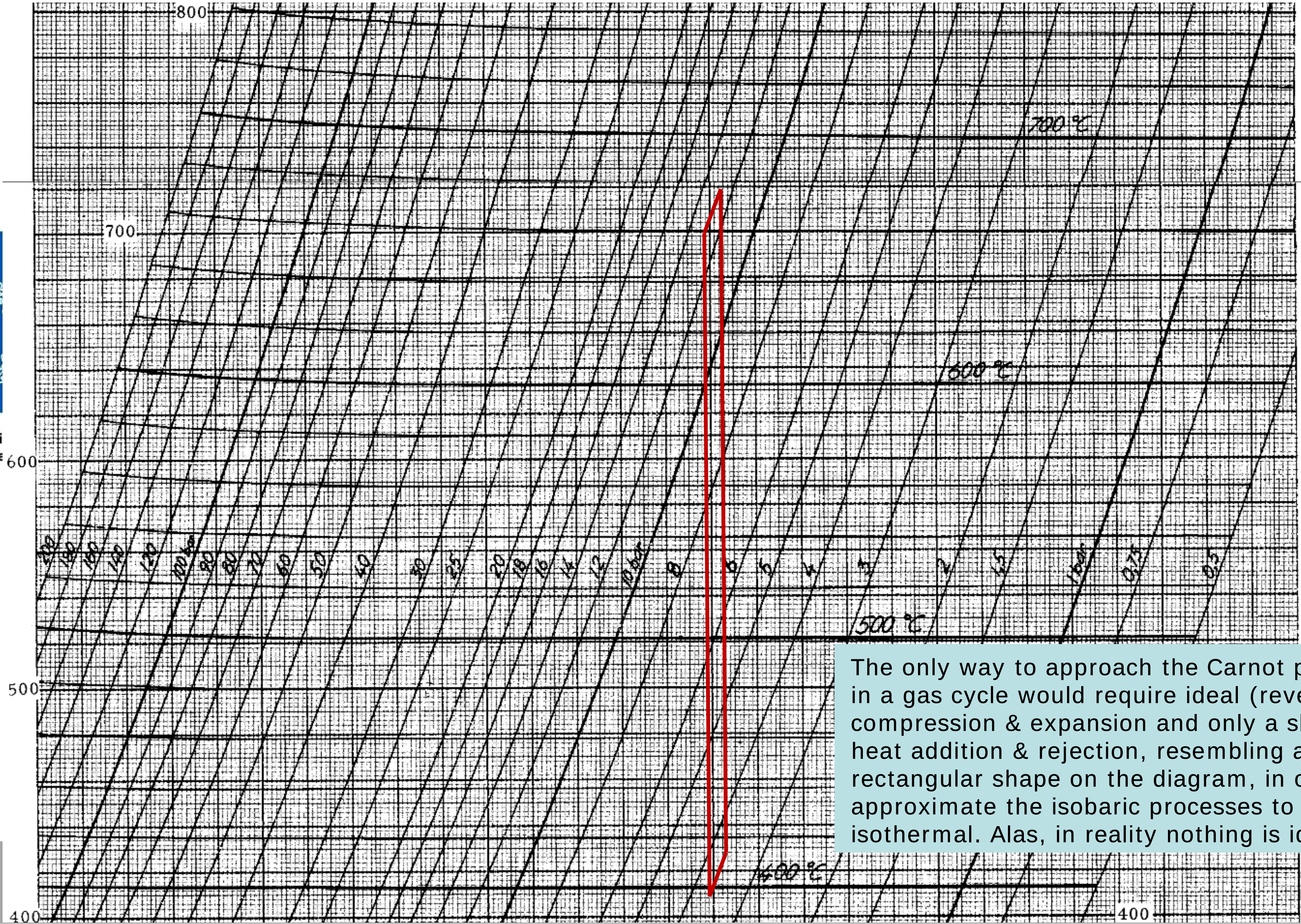

The only way to approach the Carnot potential in a gas cycle would require ideal (reversible) compression & expansion and only a slight heat addition & rejection, resembling a slim rectangular shape on the diagram, in order to approximate the isobaric processes to nearly isothermal. Alas, in reality nothing is ideal.

Real processes and losses

- High isentropic efficiency is crucial for both compression and expansion, but is difficult to achieve, especially difficult for the compressor.
- Pressure losses occur in heating and cooling stages. Should be minimized!
- The unisentropic & unisobaric processes place a limit on the optimum pressure ratio for the practical gas cycle. *However, despite the losses, the gas cycle can be a **very productive** one - as seen in the p-v diagram!*

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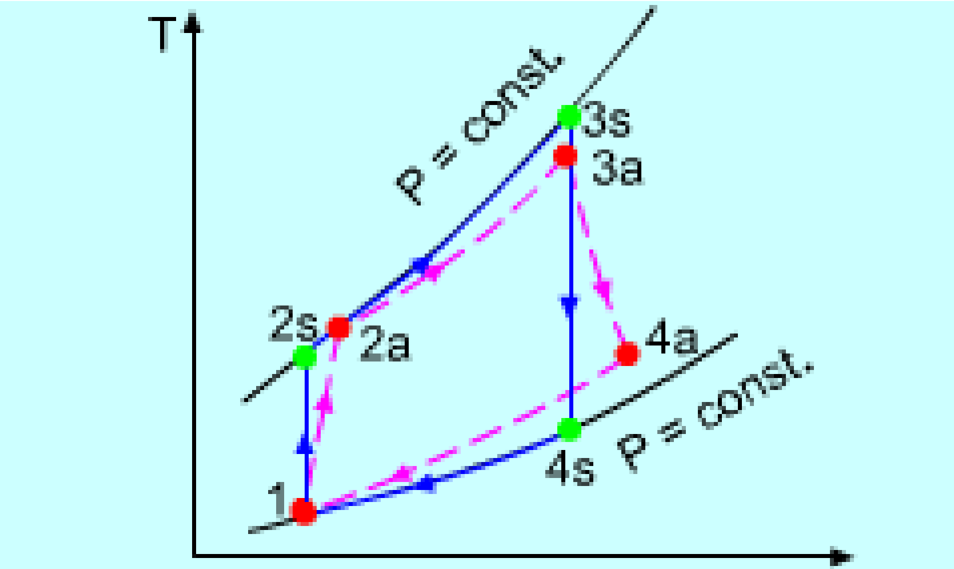
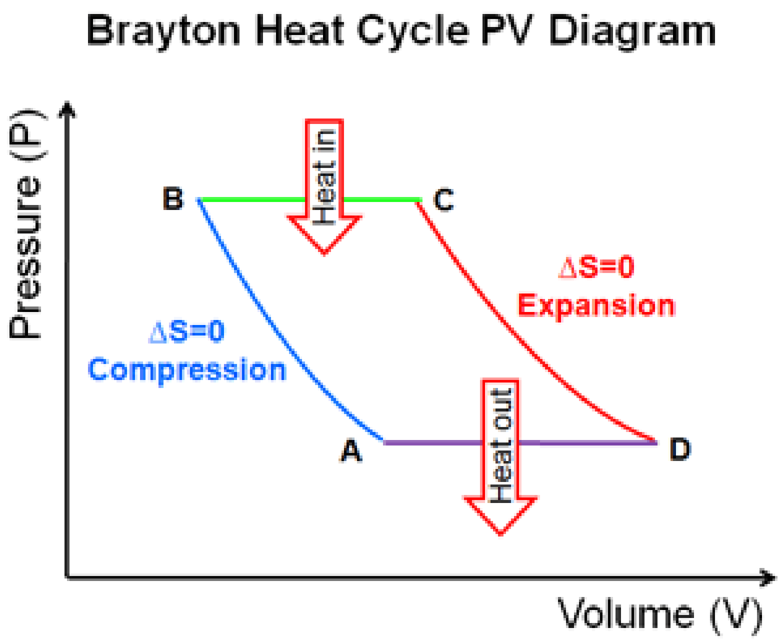


1-2s-3s-4s-1: Ideal Brayton Cycle
1-2a-3a-4a-1: Actual Gas_turbine Cycle



The simple gas turbine cycle (open cycle)

No cooler! Aspirated with ambient air. Includes an air compressor + internal combustion chamber + hot gas expander. Needs good fuel (liquid or gas fuel). Exhausts the expanded gases directly into the atmosphere, thus being ”open”. Pressure losses occur only in the combustion chamber.

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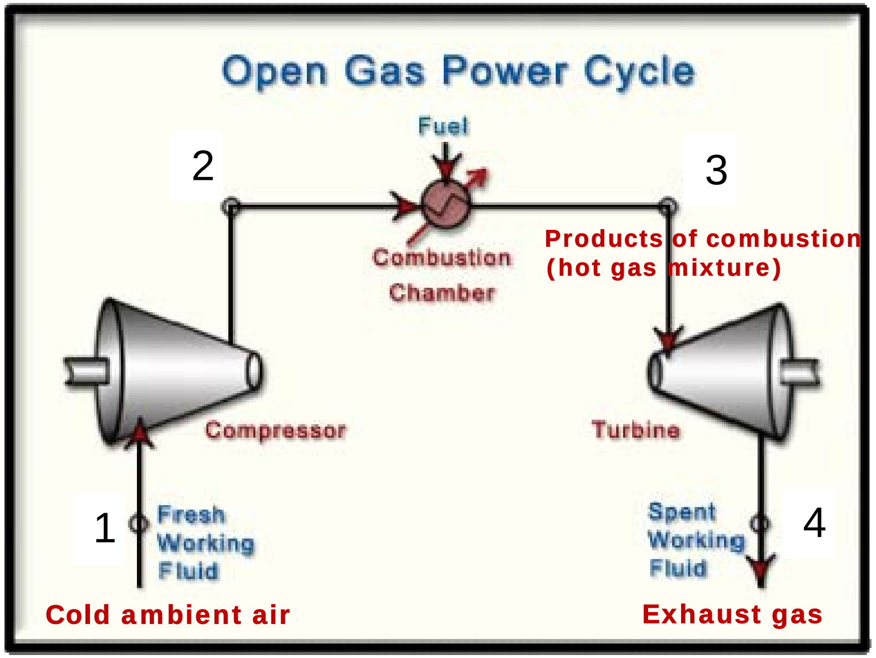

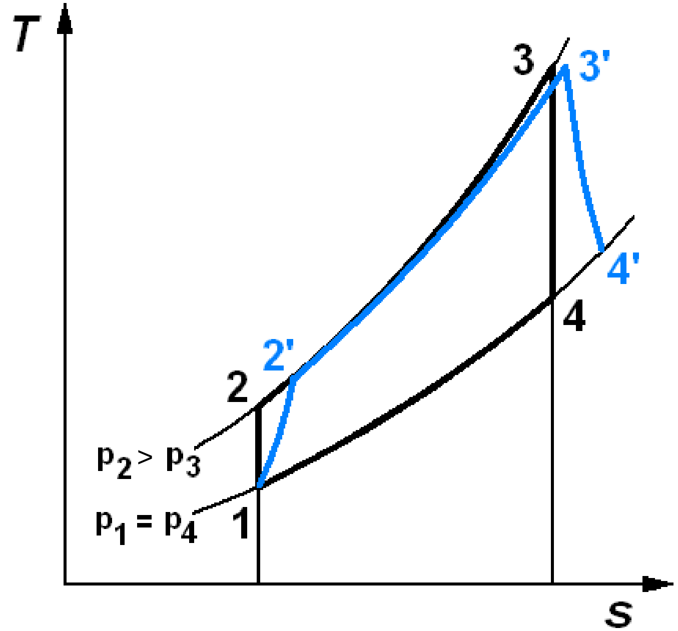

Possible improvements (1): Intercooling

The intercooling process decreases the power consumed by the compressor, but adds pressure losses and complexity.

Also, more heat needs to be provided by the combustion chamber.

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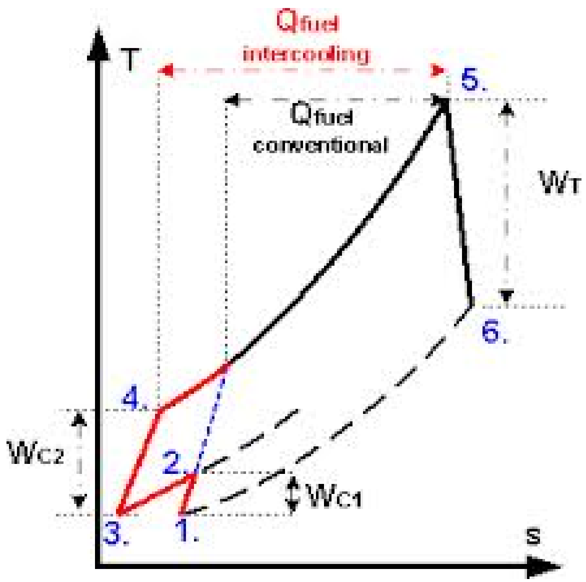
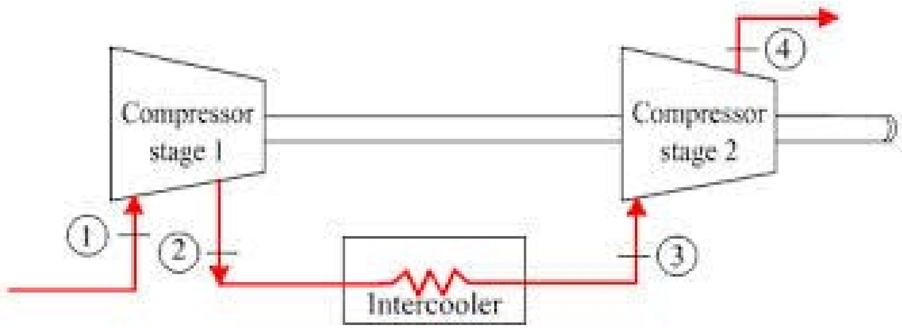
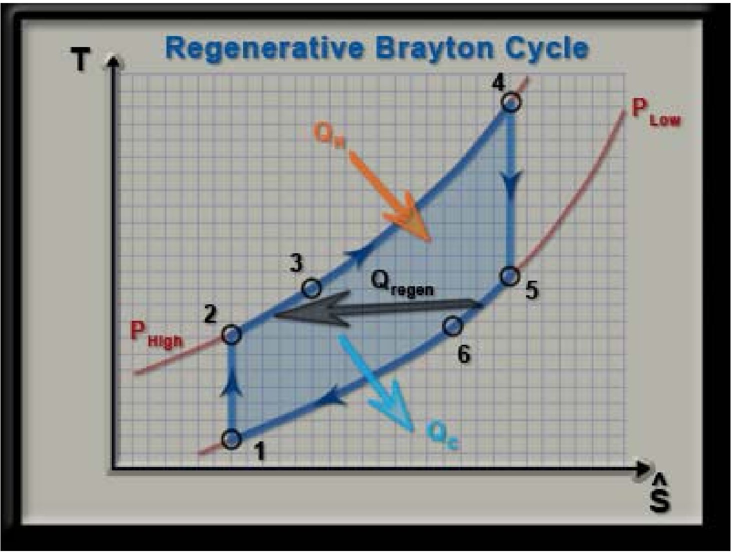
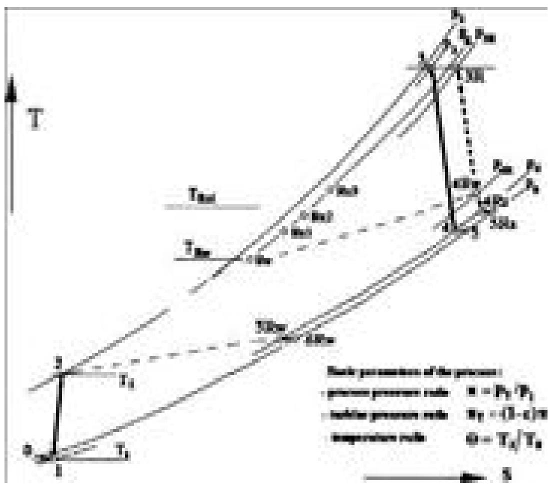


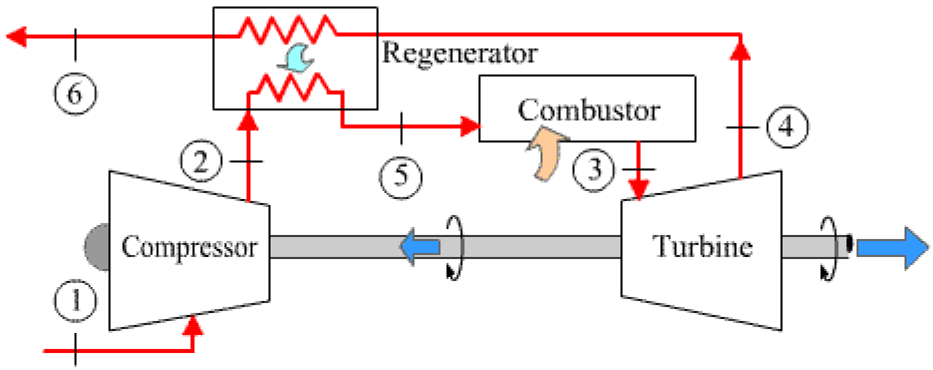


Possible improvements (2): Regeneration / Recuperation

Intercooling combined with recuperation (regeneration of heat inside the cycle) can deliver much higher efficiencies. However, the regenerator is a bulky component that adds enormously to the pressure losses and costs.

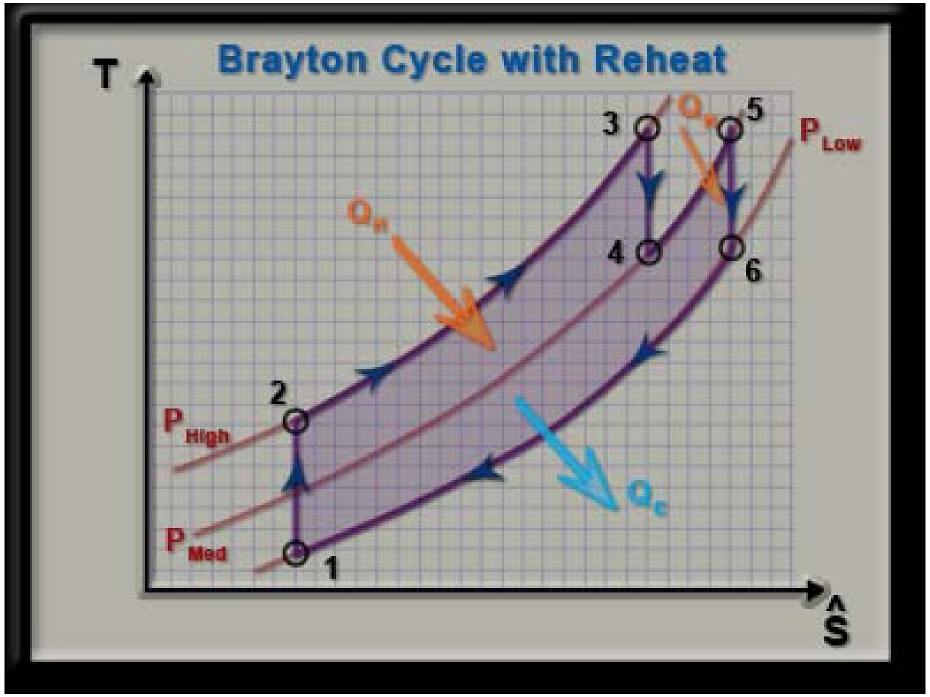


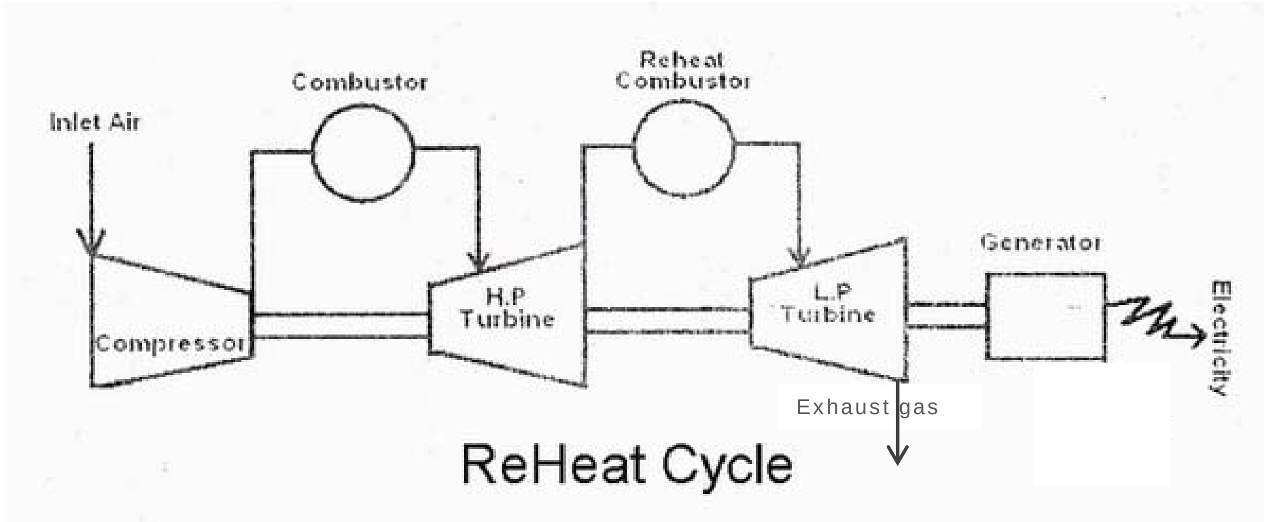




Possible improvements (3): Reheat

Reheat in an open gas cycle would require a second combustion chamber situated between the first and the second expander section





The ultimately complex gas turbine

Uniting intercooling, reheat, and regeneration together should result in the best gas turbine cycle, but… it is very complicated and less productive in reality!
(Lower power output per unit mass and per unit volume of the machine)

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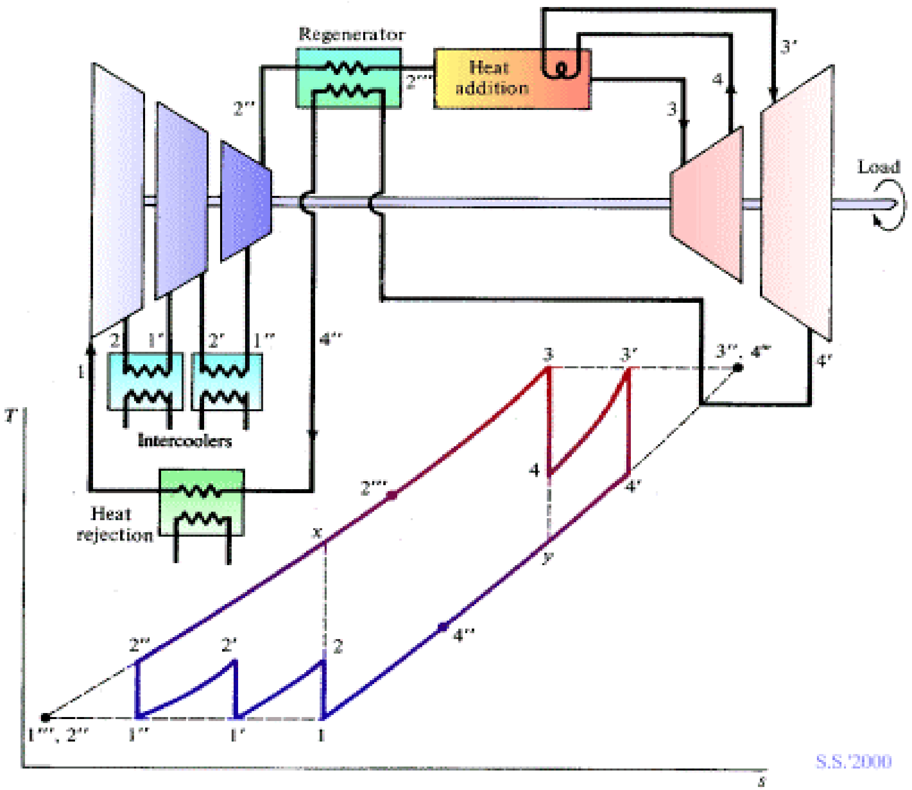
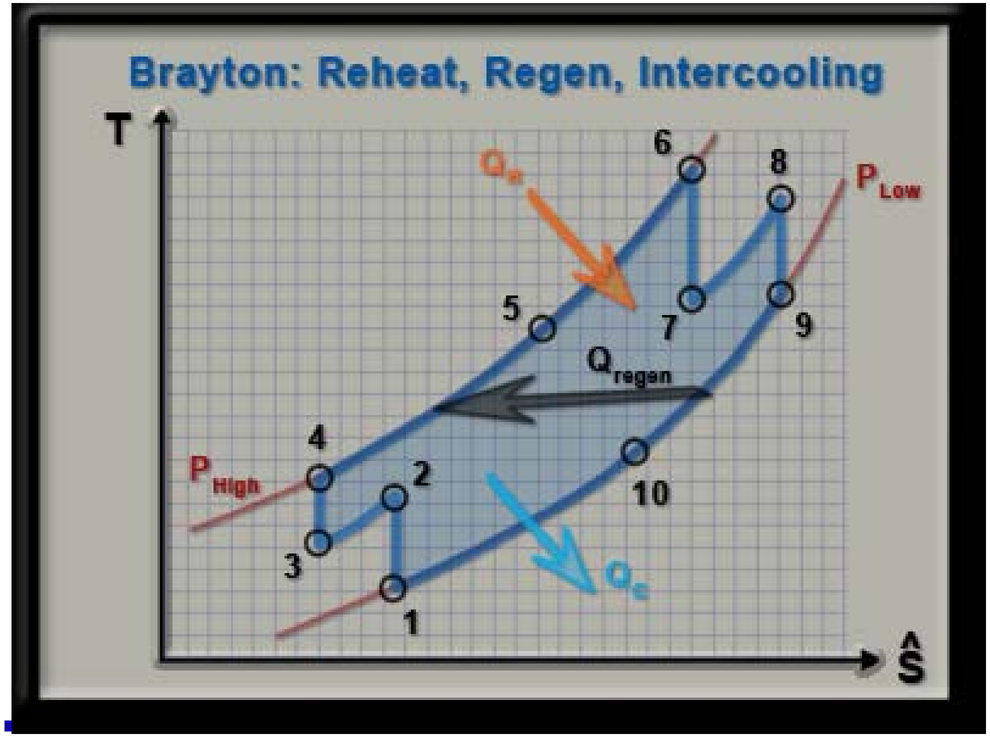
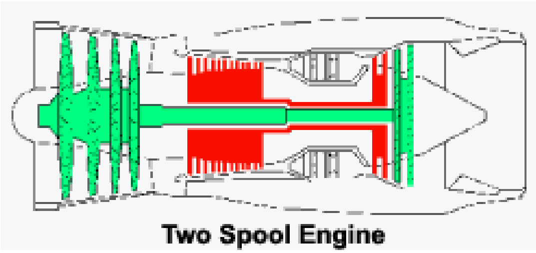


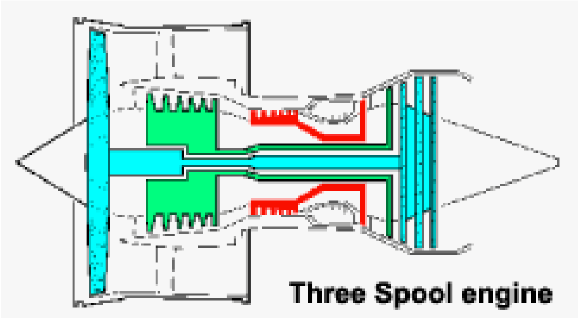


Peculiar gas turbine configurations

- **Two-spool and three-spool arrangements**

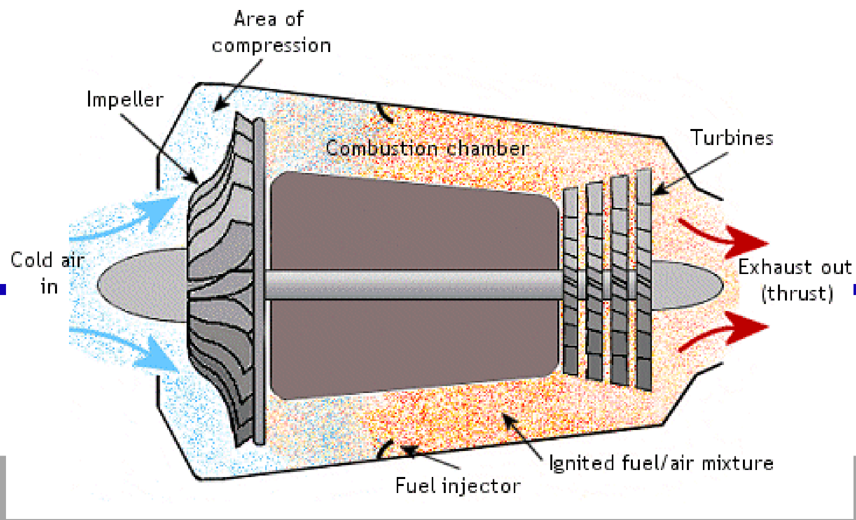
Coaxial shafts connecting separate compressor/expander stages running at different speeds. These machines are able to deliver high efficiencies, better flexibility and quicker response. Commonly used in aircraft engines or in aeroderivative mechanical-drive turbines.





- **The gas generator (basically a jet engine)**

The gas generator is a turbine shaft where ***the expander delivers just enough power to drive the compressor****, thus producing a net output in the form of hot pressurized gas. The available hot gas can be further expanded to produce thrust (jet force) or to run a free power turbine on a separate shaft.*



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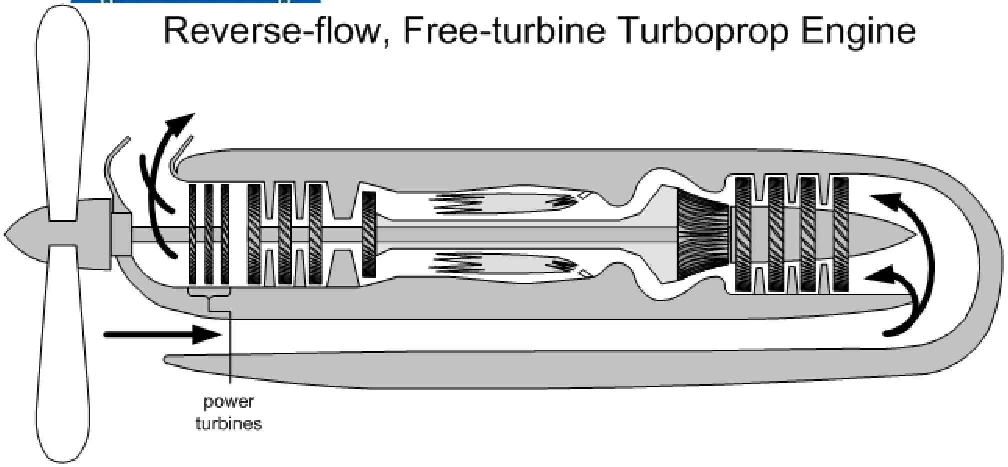
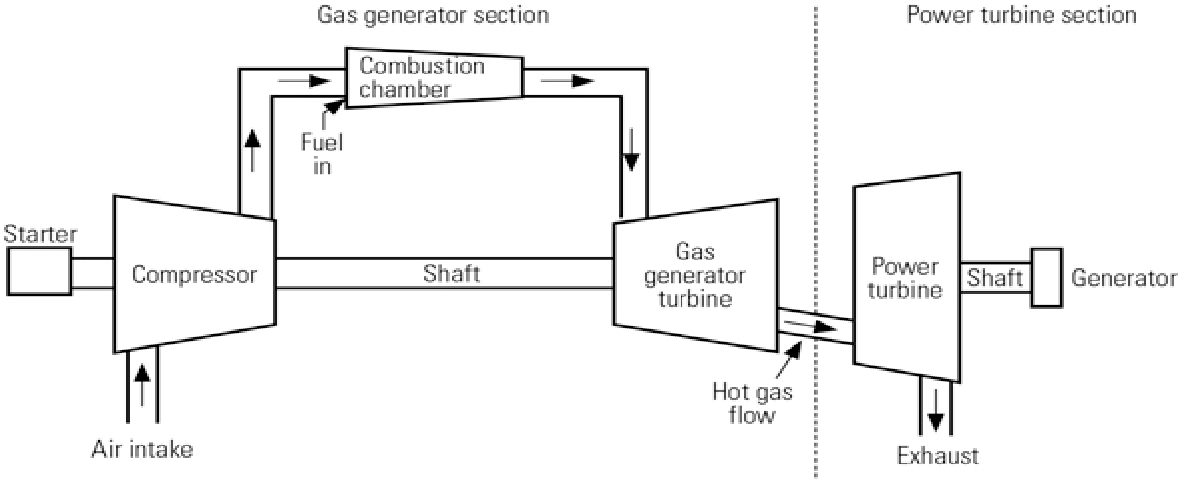
Free power turbine

- **The free power turbine arrangement**

Exactly a gas generator (see the previous slide) with a detached (free) mechanical-drive expander, where the free turbine drives only the payload on a separate shaft, usually ***at a speed optimized for the load****.*

Typical applications: Propeller drives (turboprop or helicopter engines); Marine propulsion; Pump- or compressor-drives for the oil and gas industry; Power production where the el.generator is placed far from the gas generator unit.





Small-scale and micro applications

Microturbines are being used today in various applications. The compressor and expander are usually of radial configuration on a single shaft:

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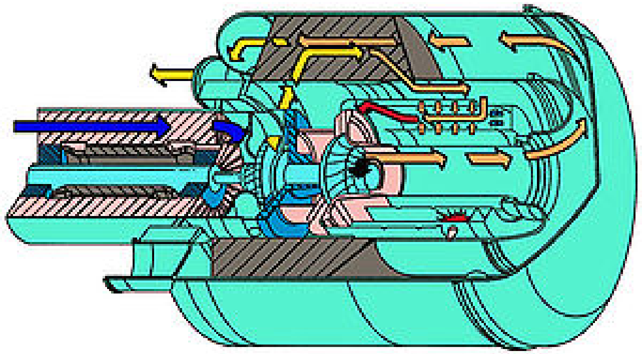
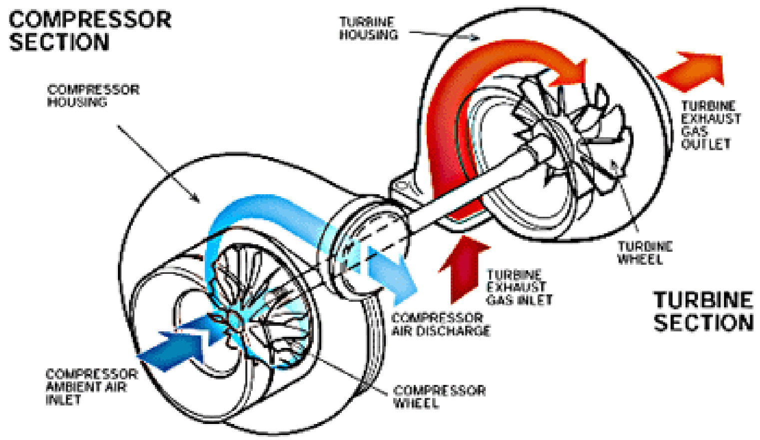
- **Small-scale CHP units**
  – most notably: the Capstone turbine



- **Turbochargers**
  - for the force-aspirated internal combustion engine



- **Tools driven by compressed air**
  - precision tools powered by a micro-size air-turbine

Gas turbine calculations

- The work of compression and expansion is calculated as: $P = \dot{m} * \Delta h$

The heat addition to (or rejection from) the cycle is calculated as: $\dot{Q}_{in} = \dot{m} * \Delta h$

The necessary work input for compression can't be neglected and should be properly taken into account. The compressor usually consumes 50% (or even more) of the gross expander output in the simple gas cycle.

The net power output from the gas cycle is the difference between the expander output and the power consumption of the compressor, including mechanical losses and generator losses:

$$P_{out} = (P_{expander} * \eta_m - P_{compressor}) * \eta_{gen}$$

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Gas turbines behave in a similar way as steam turbines when operated att partial loading (off-design) conditions. Efficiency typically drops quickly at deep part-load. Also the combustion process often is difficult to maintain at sharply varying loads.

Otherwise, gas turbines are very compact, have low thermal inertia and are able to quickly respond to changes in load.

Compression & Expansion calculation

- The compressor increases the pressure of the fluid, and with it also the temperature:

$$T_2 = T_1 \pi^{(k-1)k}$$

where $\pi = \frac{p_2}{p_1}$ and $k = \frac{c_p}{c_v}$

The fluid cools down during expansion:

$$T_4 = T_3 / \pi^{(k-1)k}$$

Practically, the compressor is more difficult to design and has more losses (lower isentropic efficiency) than the expander. Improving the compression process is a major goal for all applications – from aeroengines to stationary gas turbines for power generation.

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Perfect-gas approximation can be used!

Enthalpy for various gases (mostly air and hot products of combustion) can be tabulated or diagrams can be used, just like for steam.

However, hot gas can be assumed a perfect gas, thus: $h = c_p * T$
So that all gas processes can be calculated through their temperature and specific heat!

We are always interested in the **change of enthalpy**, thus: $\Delta h = c_p * \Delta T$
Moreover, various reference levels can be used as we always look for the difference in enthalpy values, corresponding to a difference in temperatures across the process!

However, the **specific heat at constant pressure (c_p) is also a function of the temperature** and should be integrated if precise calculation is needed!

As an approximation, **the arithmetic average of c_p can be used** within the relevant temperature interval:

$$h_1 - h_2 = \frac{c_{p,1} + c_{p,2}}{2} * (T_1 - T_2) \quad , \quad \text{where} \quad c_p = f(T)$$

See the applicable formulae in the gas turbine section of the help file !...

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