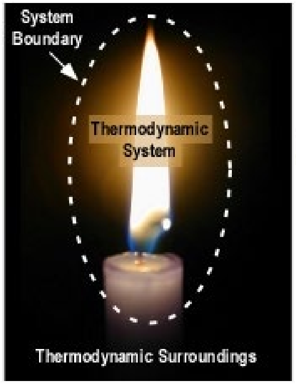
Class 11: Gas power cycles, advanced Brayton cycle and aircrafts

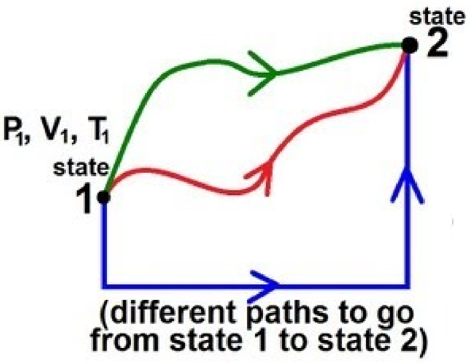
Turbojet-powered Raptor fighter aircraft

Roadmap Engineering Thermodynamics

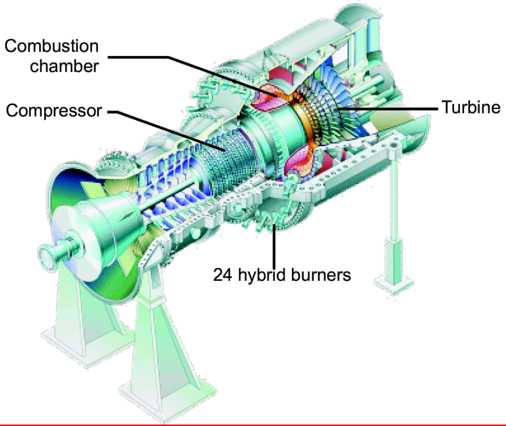
- Using thermodynamics for practical applications requires knowledge of:

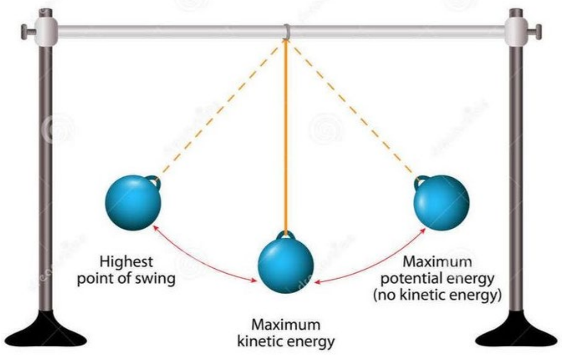
Concepts and definitions (Class 1) → Various forms of energy (Class 2)

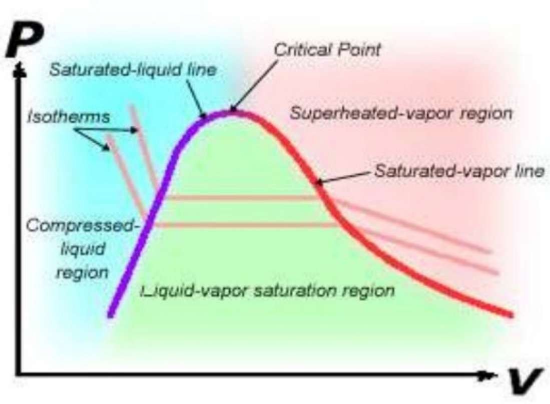




Power cycles (Class 6 – 11) ← Laws of Thermo (Class 4 and 5) ← Properties of Substances (Class 3, 9)

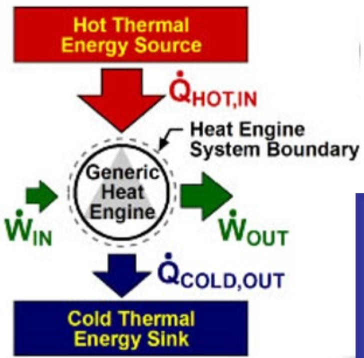




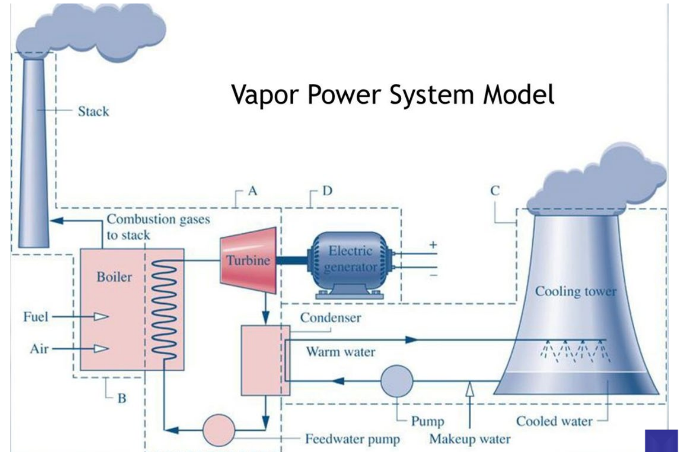


Roadmap Engineering Thermodynamics

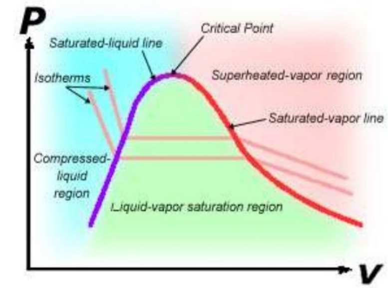
Thermodynamic cycles (Class 6)

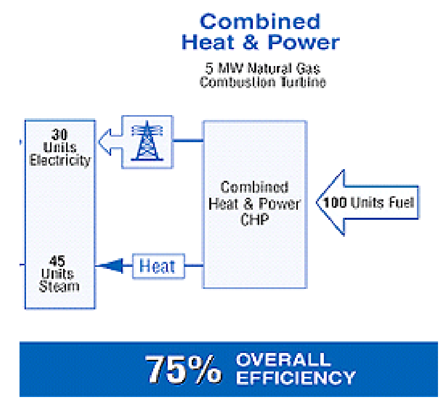


Vapor power cycles – Rankine cycle (Class 7, 8)

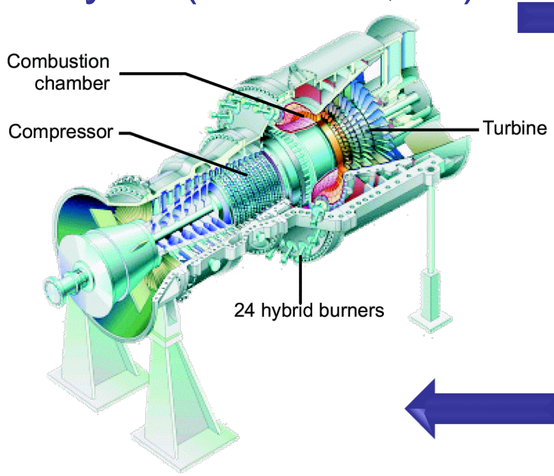


Properties of water (Class 3)

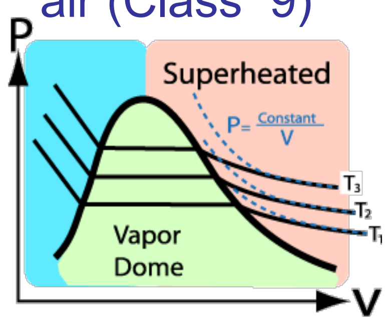




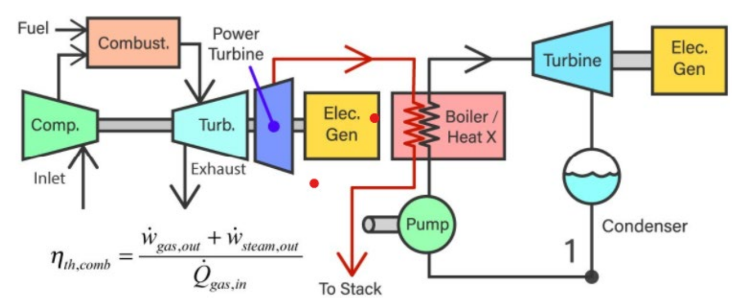
Gas power cycles – Brayton cycle (Class 10, 11)



Properties of air (Class 9)



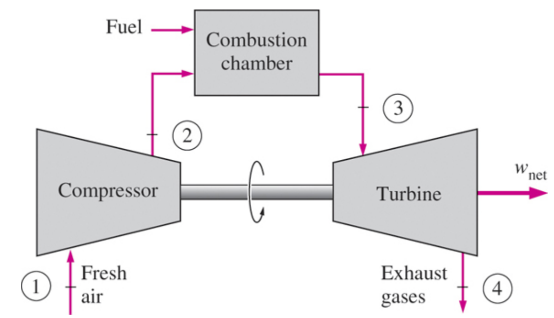
Combined cycles Combined heat & power (Class 8, 11)



Recapitulate class 10

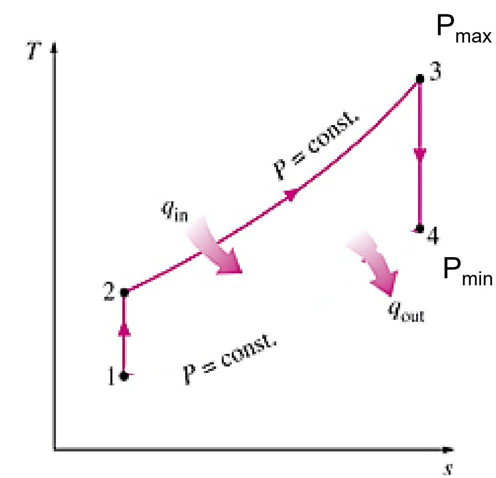
- **Gas power cycles (Brayton cycles):** cycles using gas as working fluid throughout the whole cycle
  - Air-standard cycle, open and closed, ideal and real Brayton cycle
    - Heat and power in- and output simple Brayton

$$w_{compessor,in} = h_{out} - h_{in} = h_2 - h_1$$
$$q_{in,combustion} = h_{out} - h_{in} = h_3 - h_2$$
$$w_{out,turbine} = h_{in} - h_{iut} = h_3 - h_4$$
$$q_{out,to\ environment} = h_{in} - h_{out} = h_4 - h_1$$
$$w_{net} = w_{out,turbine} - w_{comp,in} = (h_3 - h_4) - (h_2 - h_1)$$



    - Thermal efficiency simple Brayton cycle

$$\eta_{Brayton} = \frac{w_{turbine,out} - w_{compr,in}}{q_{in,combustion}} = \frac{w_{net}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$



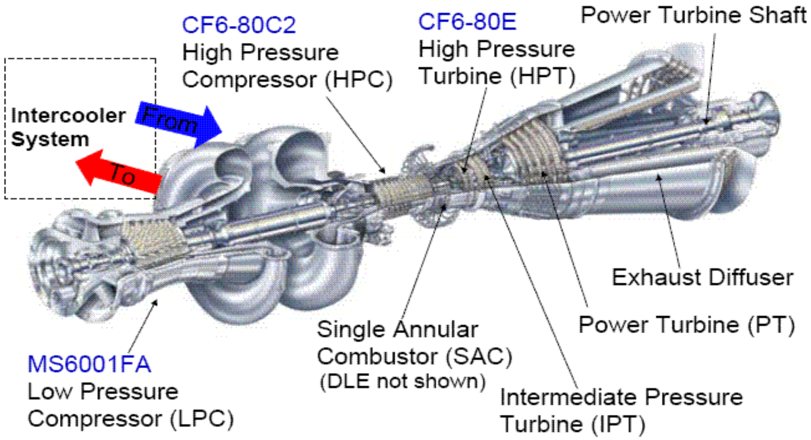
Simple open ideal Brayton cycle

- Design parameters
  - Turbine inlet temperature
  - Pressure ratio
  - Working medium
- Mollier diagram for air

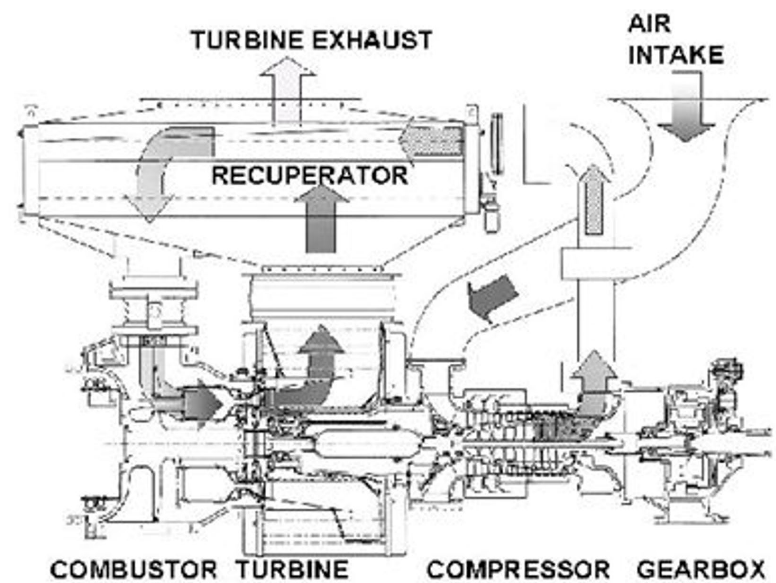
Content Class 11

- **Gas power cycles – Brayton cycles, advanced**
- Adding extra devices → improves efficiency or power output
  - Extra heater & Intercooling & Regeneration
- Aircraft gas turbines
- Combined cycles

Intercooled gas turbine



Recuperated gas turbine



- **Learning goal:** recognize a **complicated** thermodynamic system to produce work, explain the configuration, analyse the thermodynamic aspects from the viewpoint of the first law of thermodynamics, interpret and evaluate the results and suggest improvements

Increasing the Brayton Cycle Performance

- In the previous class the simple Brayton cycle was explained and analysed
- It was discussed that the net power output or efficiency can be increased by
  1. Increasing the turbine output
  2. Decreasing the compressor input
  3. Decreasing the heat input
- The Brayton cycle can be further improved by adding extra devices, like in the Rankine cycle, for the Brayton cycle we can apply
  1. Reheating (comparable to reheating in the Rankine)
  2. Intercooling
  3. Regeneration (also called recuperation, comparable to feed water heating in the Rankine cycle)

Increasing the Brayton Cycle Performance

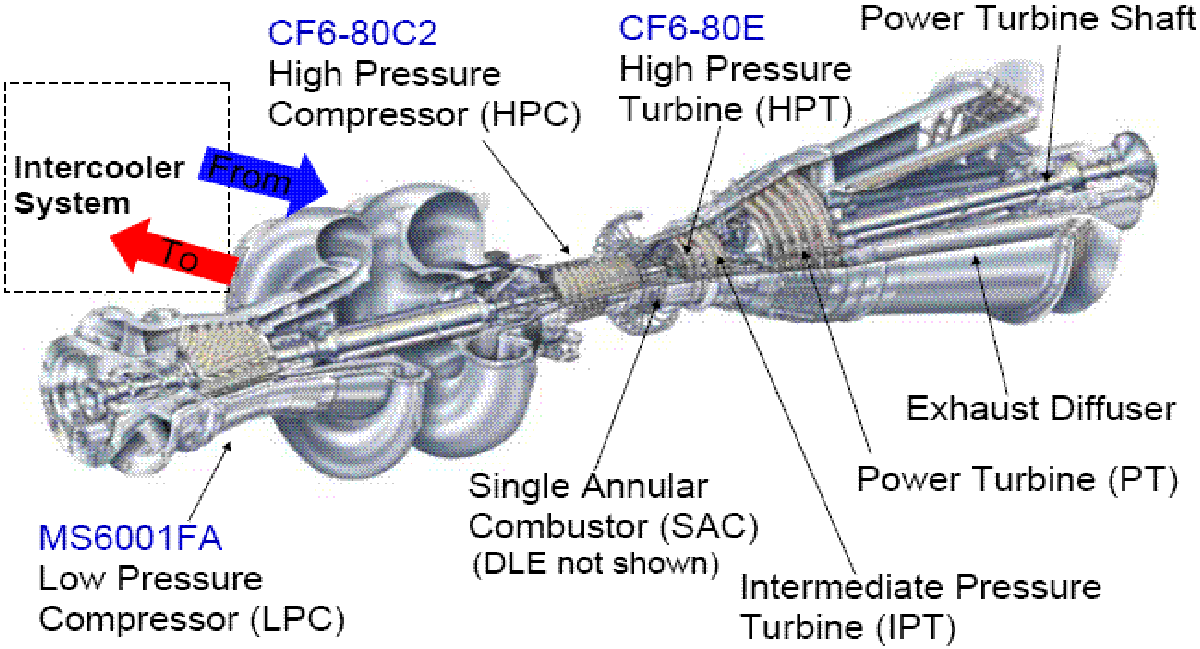
- For the (improved) design of the Brayton cycle designers are not only concerned with increasing the efficiency but also with increasing the net power output
  - Higher efficiency means a lower fuel / energy consumption
  - However, for some applications a minimum amount of power is needed, and efficiency can be considered less important
- The improved cycle can be more efficient and / or produce more power

Airplane cruising: Long time, high efficiency is important but lower power output required

Airplane take off: High power output required, but short time and high efficiency is less important

Brayton Cycle: Intercooling

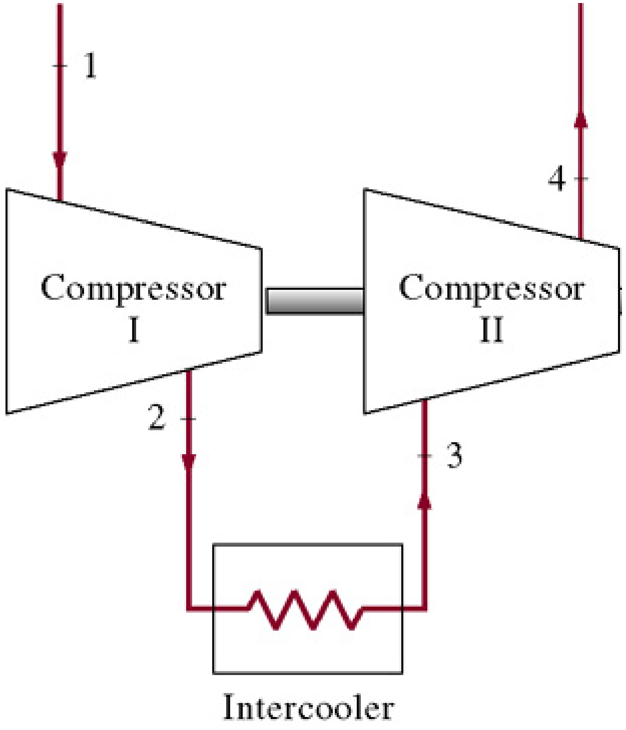
- An **isothermal** compressor requires less power than an **isentropic** (adiabatic & reversible) compressor as $\delta w_{comp} = dh = c_p dT$
- The work input is 0 if dT=0 ,so if T=constant as in an isothermal process
- However, an isothermal compressor is not practical (you should cool the fluid during compression)
- An adiabatic compressor is more practical



Brayton Cycle: Intercooling

- An isothermal compressor can be approximated by using inter cooling
  - Multiple adiabatic compressor stages are placed after each other
  - The working fluid is cooled in between the stages

- Intercooling
  - Increases the power output per unit mass flow as the power input decreases
  - Extra heat is rejected in the intercooler
  - Decreases the cycle efficiency without regeneration as the heat input increases (compression also heats the air so if the gas is cooled during compression it will have a lower temperature after compression and more energy is needed to end up with the same inlet turbine temperature as without compression



Compressor Intercooling in h-s Diagram

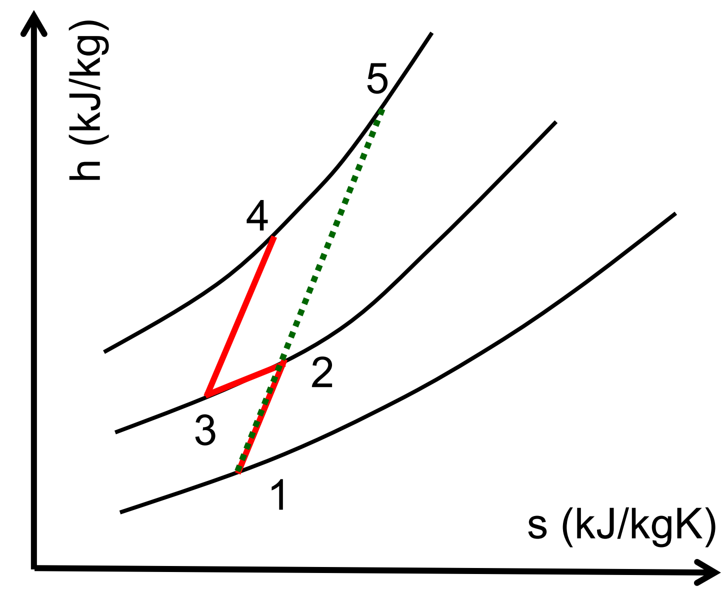
- The work input for the compressor without inter cooling is:

  $$w_{compressor} = h_5 - h_1$$

- With inter cooling the work input is less

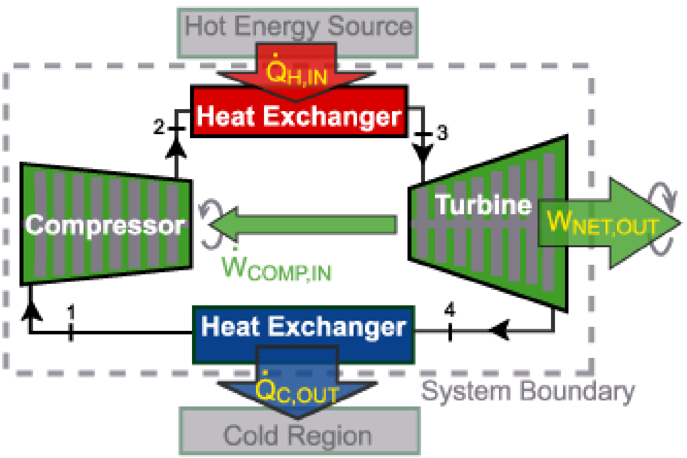
  $$w_{compressor\text{-}intercooling} = (h_2 - h_1) + (h_4 - h_3)$$

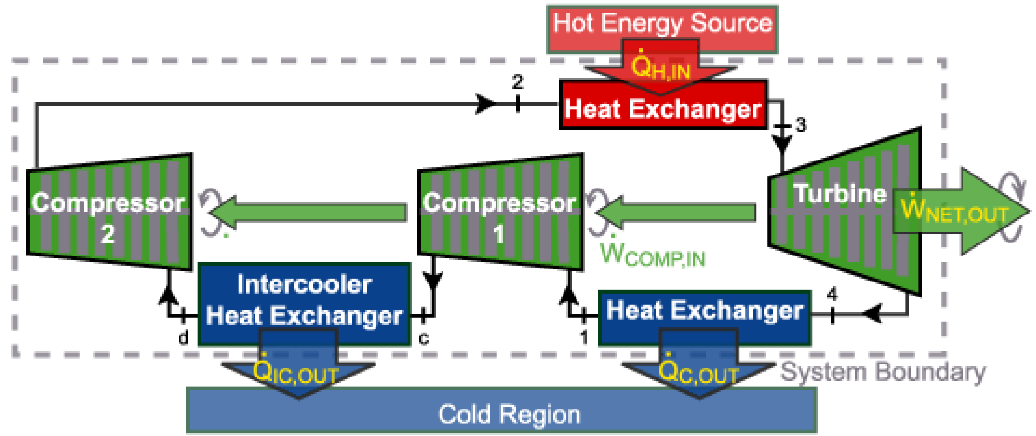
- Conclusion → the net work will increase



- However, there is big drawback, extra heat is needed as the gas leaves the compressor at a lower temperature: $q_{extra\text{-}heat} = h_5 - h_4$
- Extra disadvantageous is that this heat must be added at low temperature (remember, Carnot efficiency, it is better to add heat at high temperature)
- Inter cooling → compressor work reduced
  → thermal efficiency decreased (without regeneration)
- Inter cooling is applied as extra power output is required

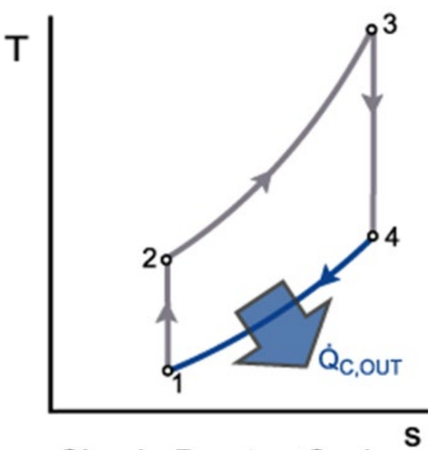
Brayton Cycle: Intercooling



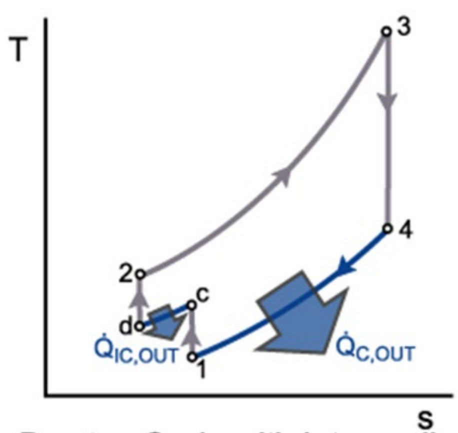


Brayton Cycle with Intercooling

Simple Brayton Cycle



Simple Brayton Cycle



Brayton Cycle with Intercooling

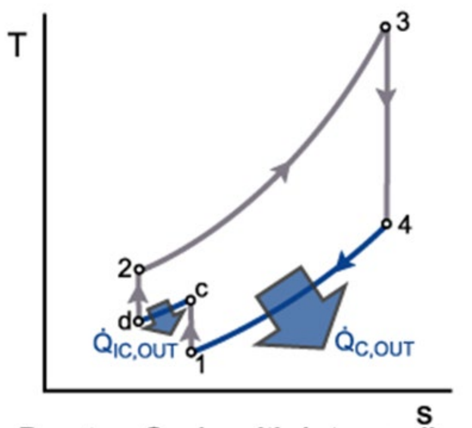
- To calculate the total work input the work input of all compressor stage should be added
- Work input (kJ/kg):

$$w_{in} = w_{compr1} + w_{compr2} = (h_c - h_1) + (h_2 - h_d)$$

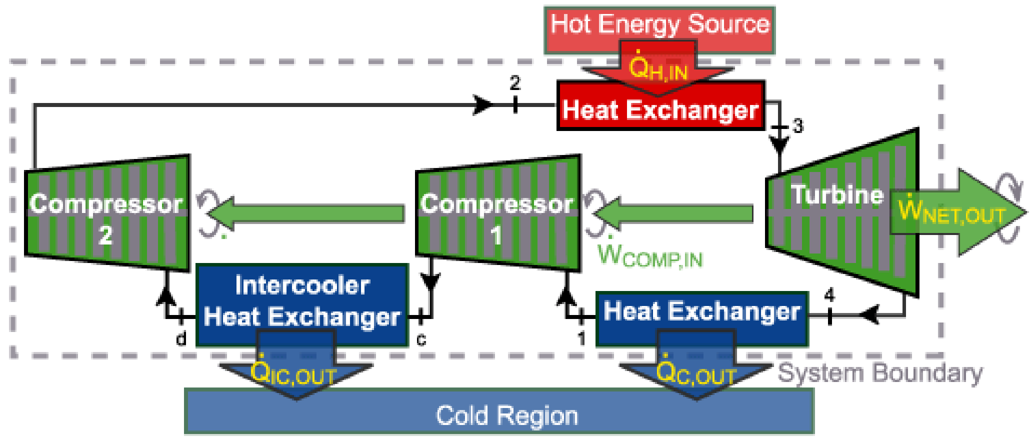
- Intercooling results also in extra contributions to the heat output
- Heat output (kJ/kg):

$$q_{out} = q_{c,out} + q_{ic,out} = (h_4 - h_1) + (h_c - h_d)$$

Brayton Cycle: Intercooling



Brayton Cycle with Intercooling



Brayton Cycle with Intercooling

- Work input (kJ/kg):

  $w_{in} = w_{compr1} + w_{compr2} =$
  $(h_c - h_1) + (h_2 - h_d)$

- Heat output (kJ/kg):

  $q_{out} = q_{c,out} + q_{ic,out} =$
  $(h_4 - h_1) + (h_c - h_d)$

- Efficiency Brayton cycle with inter cooling

$$\eta_{th-Brayton-intercooling} = \frac{w_{net}}{q_{in}}$$

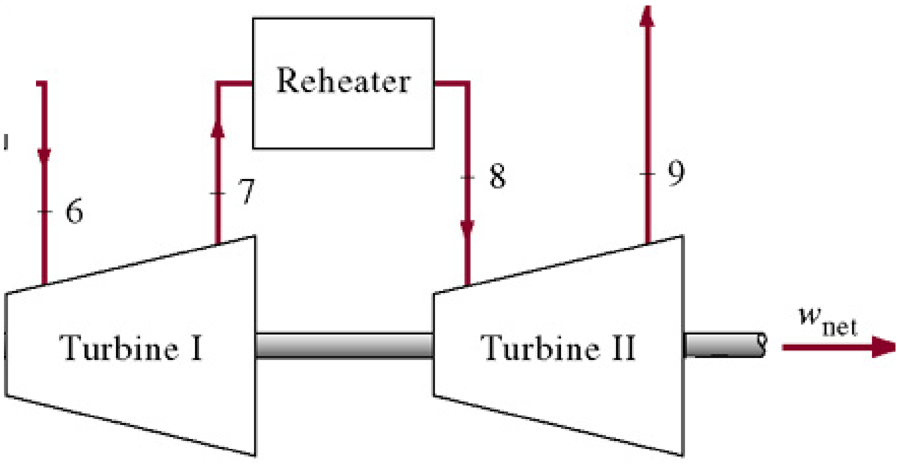
$$= \frac{w_{turb} - (w_{comp1} + w_{comp2})}{q_{heat}}$$

$$= \frac{(h_3 - h_4) - [(h_c - h_1) + (h_2 - h_d)]}{(h_3 - h_2)}$$

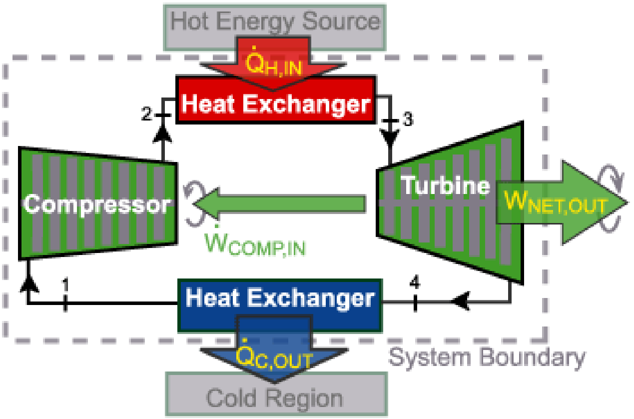
Brayton Cycle with Reheating

- An **isothermal** turbine produces more power than an **isentropic** (adiabatic & reversible) turbine
- However, an isothermal turbine is not practical (you should heat the fluid during the expansion)
- An adiabatic turbine is more practical
- An isothermal turbine can be approximated by using reheating
  - Multiple adiabatic turbine stages are placed after each other
  - The working fluid is reheated in between the stages

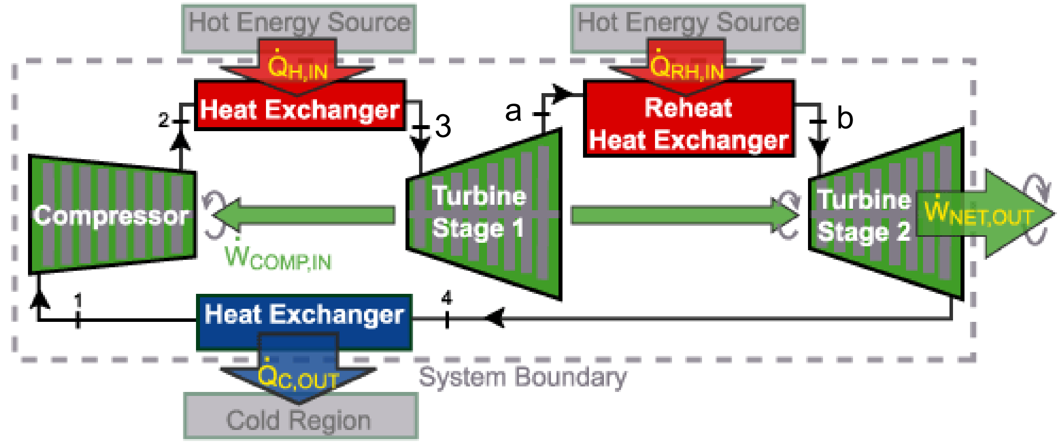
- Reheating
  - Increases the power output per unit mass flow
  - Increases the energy rejected at the turbine outlet
  - Decreases cycle efficiency without regeneration as extra heat is needed in the reheater



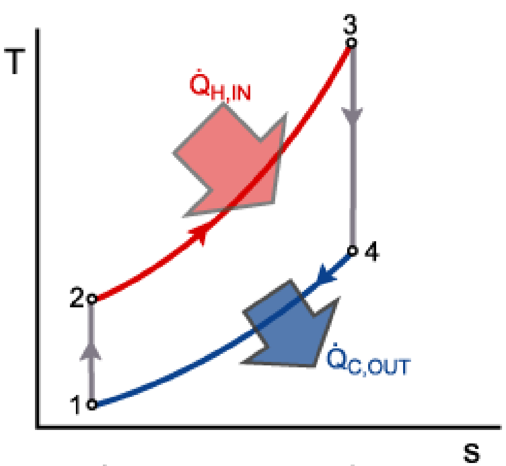
Brayton Cycle with Reheating



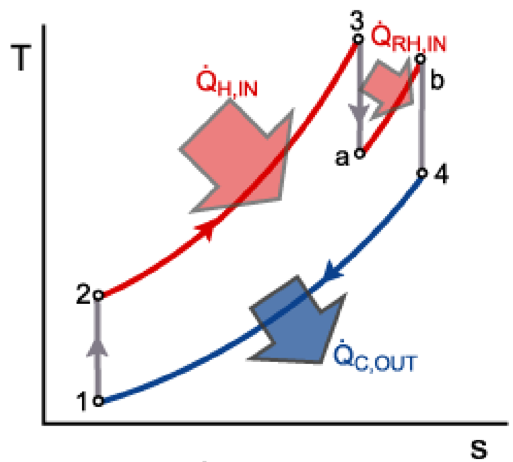
Simple Brayton Cycle



Brayton Cycle with Reheat



Simple Brayton Cycle



Brayton Cycle with Reheat

- Net output (kJ/kg):

  $w_{net} = w_{out} - w_{in} =$

  $w_{turb1} + w_{turb2} - w_{compr} =$

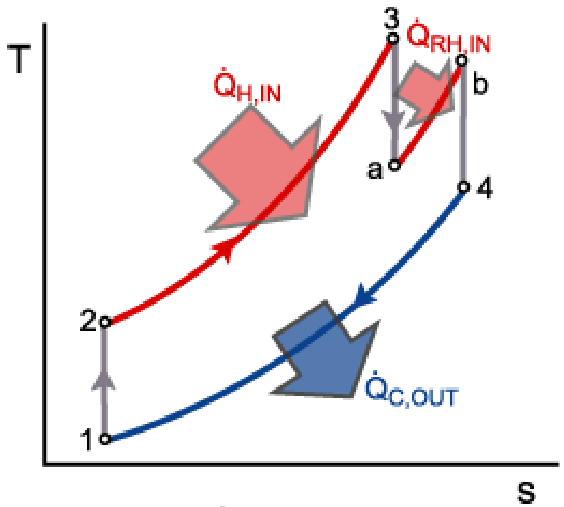
  $(h_3 - h_a) + (h_b - h_4) - (h_2 - h_1)$

- Heat input (kJ/kg):

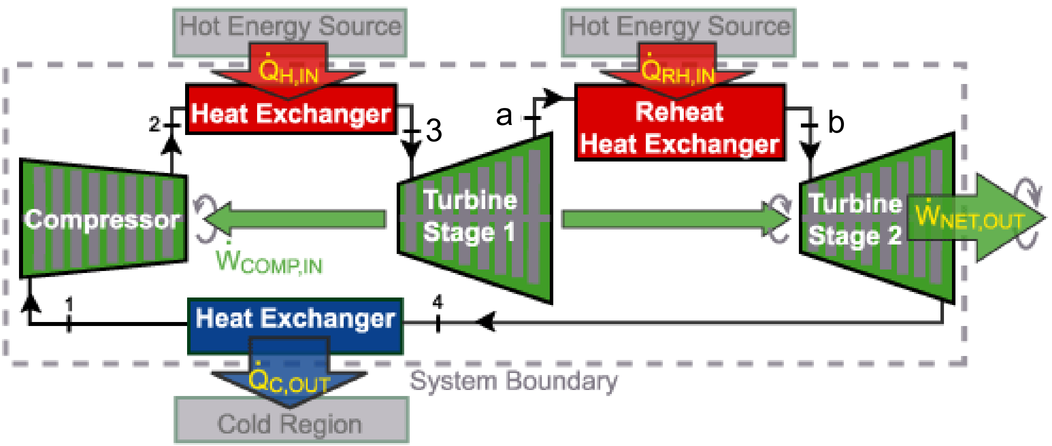
  $q_{in} = q_{heat} + q_{reheat} =$

  $(h_3 - h_2) + (h_b - h_a)$

Brayton Cycle with Reheating



Brayton Cycle with Reheat



Brayton Cycle with Reheat

- Net output (kJ/kg):

  $w_{net} = w_{out} - w_{in} =$

  $w_{turb1} + w_{turb2} - w_{compr} =$

  $(h_3-h_a) + (h_b-h_4) - (h_2-h_1)$

- Heat input (kJ/kg):

  $q_{in} = q_{heat} + q_{reheat} =$

  $(h_3-h_2) + (h_b-h_a)$

- Efficiency Brayton cycle with reheat

$$\eta_{th-Brayton-reheating} = \frac{w_{net}}{q_{in}}$$

$$= \frac{(w_{turb1} + w_{turb2}) - w_{comp}}{q_{heat} + q_{reheat}}$$

$$= \frac{(h_3 - h_a) + (h_b - h_4) - (h_2 - h_1)}{(h_3 - h_2) + (h_b - h_a)}$$

Brayton Cycle with Reheating / Intercooling

- **Reheating increases the net output of Brayton cycle** as the work output of the turbine increases
- **Inter cooling increases the net output of the Brayton cycle** as the work input of the compressor decreases

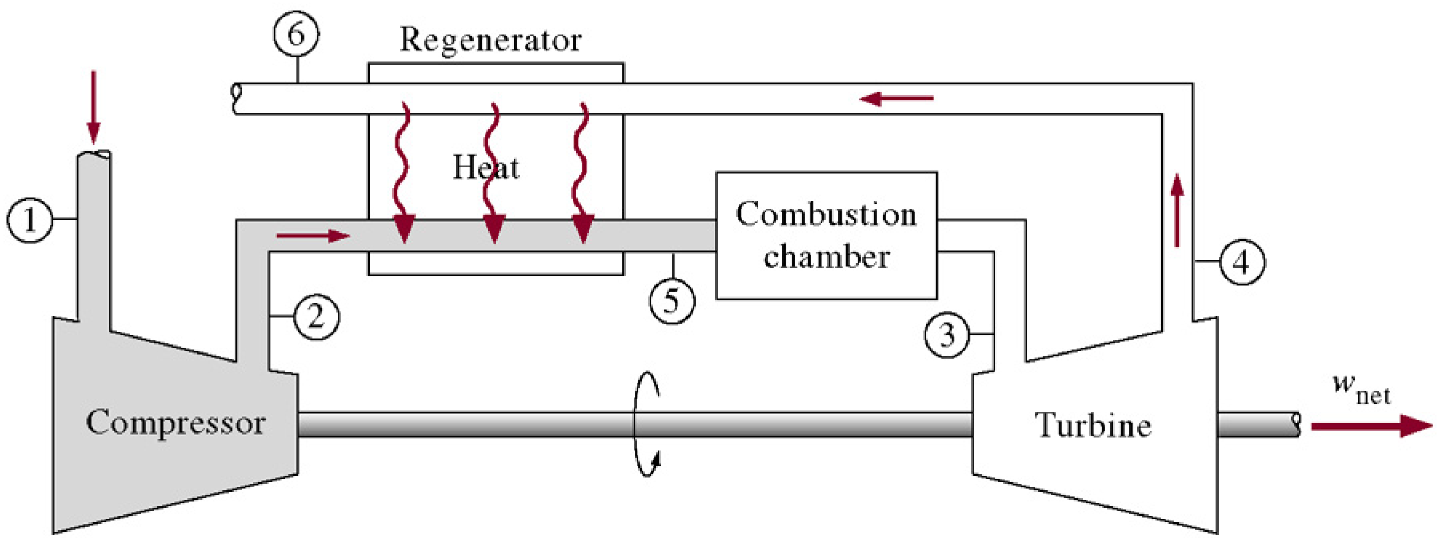
- However, **both modifications decrease the thermal efficiency** of the Brayton cycle
  - For intercooling more heat input is required to reach the same inlet temperature as without inter cooling
  - For reheating extra heat is necessary to reach the high temperature for the second turbine

- **Regeneration or recuperation** can increase the thermal efficiency of the Brayton cycle with inter cooling and / or reheating by decreasing the heat input

Brayton Cycle Regeneration

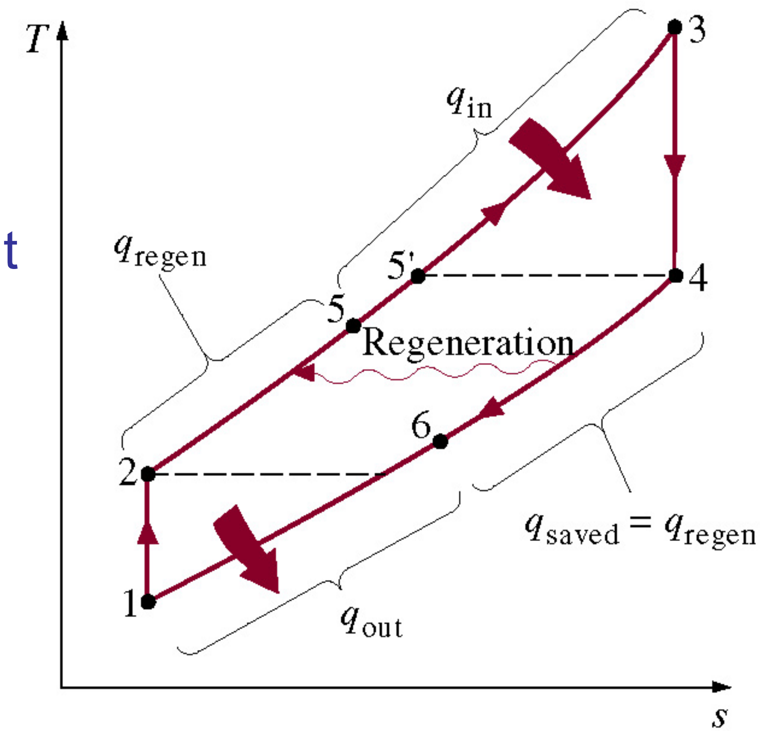
- Part of the heat input, q_{IN} is ‘lost’ to the surroundings as q_{OUT} with the exhaust gases, due to 2nd law limitations
- The Brayton cycle rejects relative hot exhaust gases

- **Regeneration** (or recuperation)
  - The heat still present in the exhaust gasses leaving the turbine is used to pre heat the high-pressure air leaving the compressor in a counter flow heat exchanger which is known as a regenerator or recuperator



Brayton Cycle Regeneration

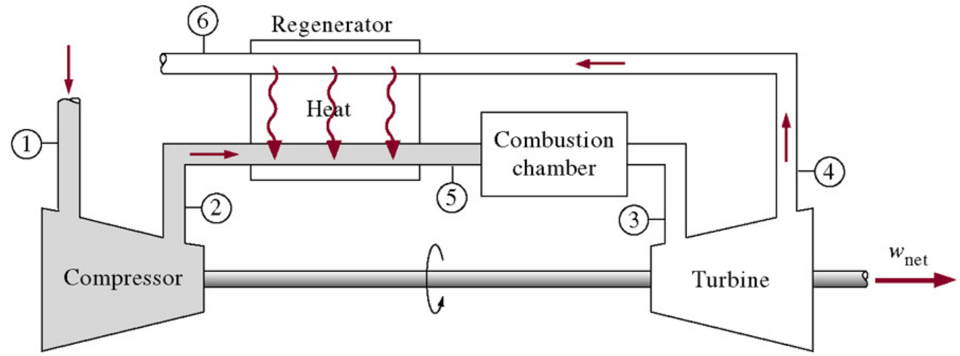
- With regeneration the energy of the relative hot turbine exhaust gases is used to pre heat the gas before combustion and therefore the heat input decreases
- The power output remains the same and therefore the thermal efficiency increases



- Regeneration is only possible if the turbine outlet temperature is higher than the compressor outlet temperature
  - Reheating: turbine outlet temperature (T_4) ↑
  - Intercooling: compressor outlet temperature (T_2) ↓
- So, reheating as well as inter cooling are advantageous for regeneration

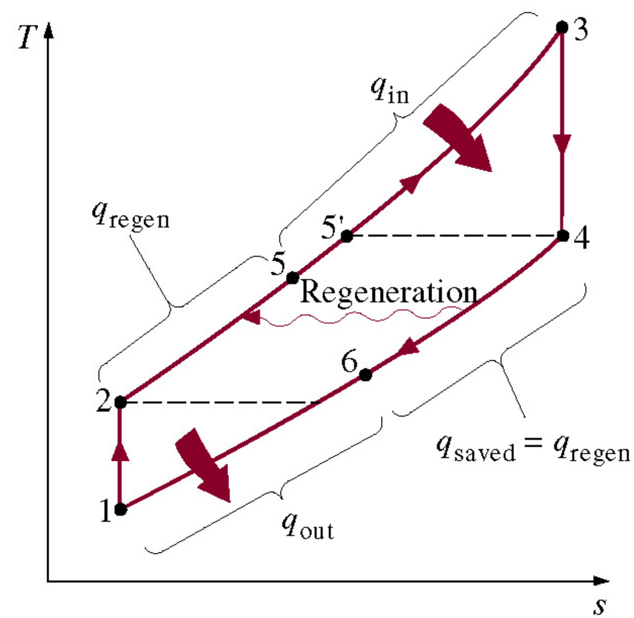
Brayton Cycle Regeneration

- Regeneration → only possible if $T_{turbine\ outlet} > T_{compressor\ outlet}$
- T_4 → highest temperature within the regenerator



- High-pressure air (T_5) → can never be pre heated to a temperature above T_4
- Limiting (ideal) case → the air will exit the regenerator at the temperature of the exhaust gasses ($T_{5'} = T_4$)
- Actual case → air will exit the re-generator at a lower temperature T_5

$$q_{reg\text{-}actual} = h_5 - h_2$$
$$q_{reg\text{-}max} = h_{5'} - h_2 = h_4 - h_2$$



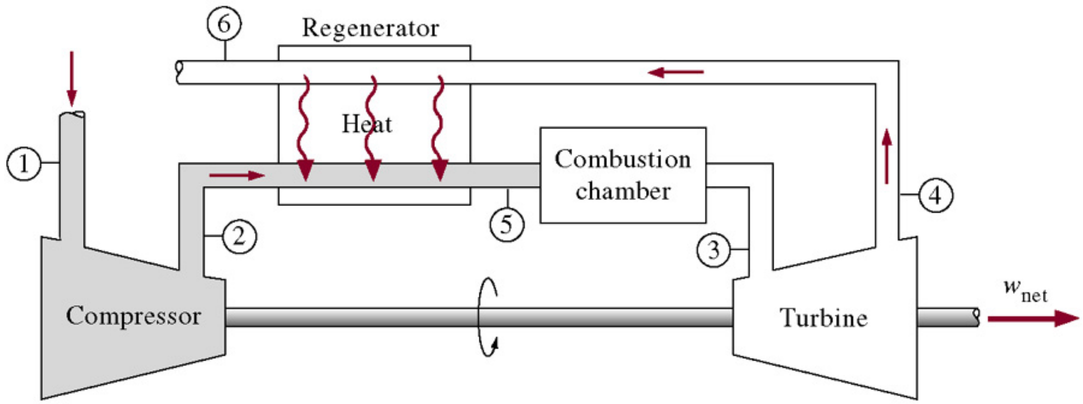
Brayton Cycle Regeneration

- Actual heat transferred:

  $$q_{reg\text{-}actual} = h_5 - h_2$$

- Maximum heat transferred:

  $$q_{reg\text{-}max} = h_{5'} - h_2 = h_4 - h_2$$

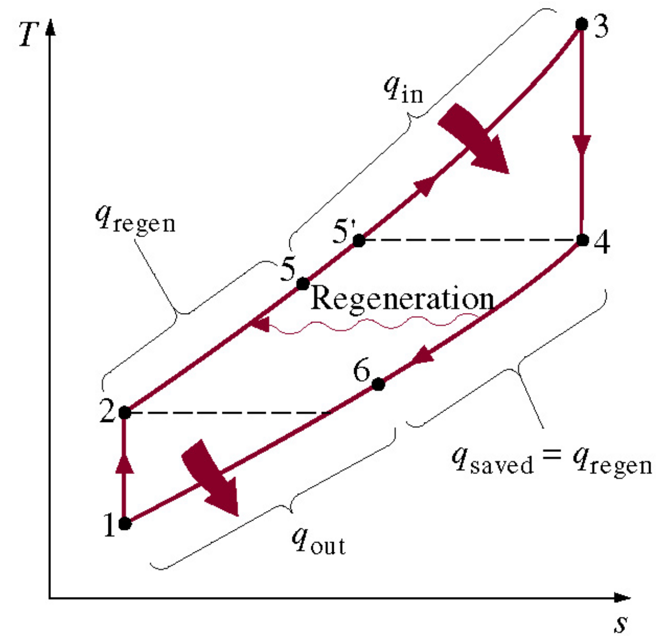


- Effectiveness regenerator (ε): the extend to which a regenerator approaches an ideal regenerator

$$\varepsilon = \frac{q_{reg-actual}}{q_{reg-max}} = \frac{h_5 - h_2}{h_4 - h_2}$$

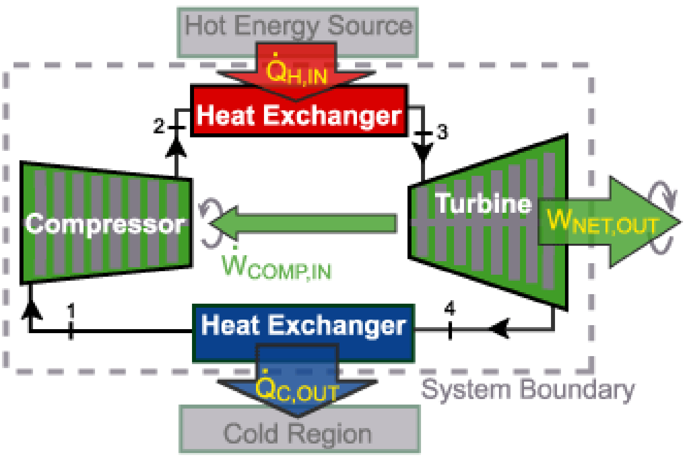
- Under cold-air-standard assumptions this reduces to:

$$\varepsilon \cong \frac{T_5 - T_2}{T_4 - T_2}$$

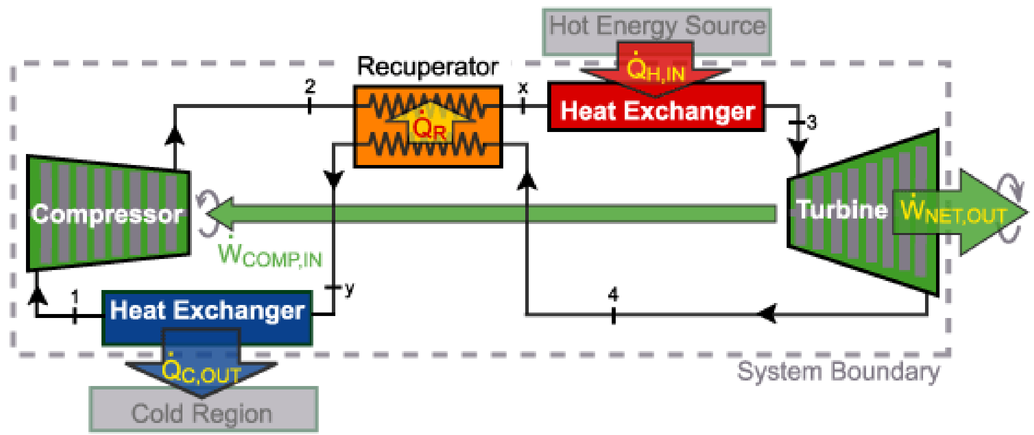


Note: $q_{saved} = q_{regen} \rightarrow h_4 - h_6 = h_5 - h_2$

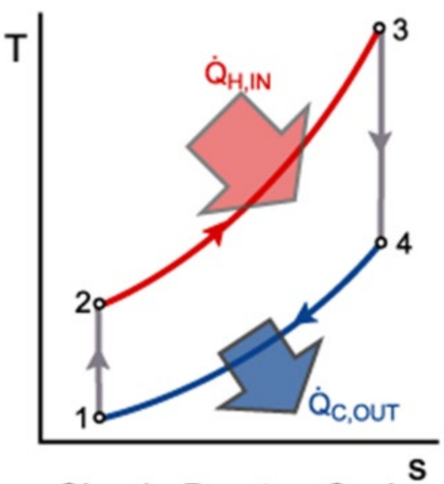
Brayton Cycle Regeneration



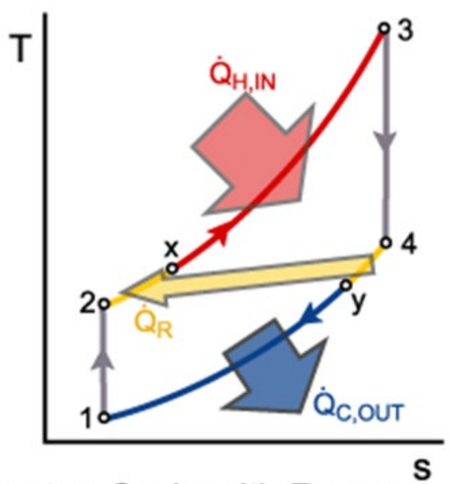
Simple Brayton Cycle



Brayton Cycle with Regeneration



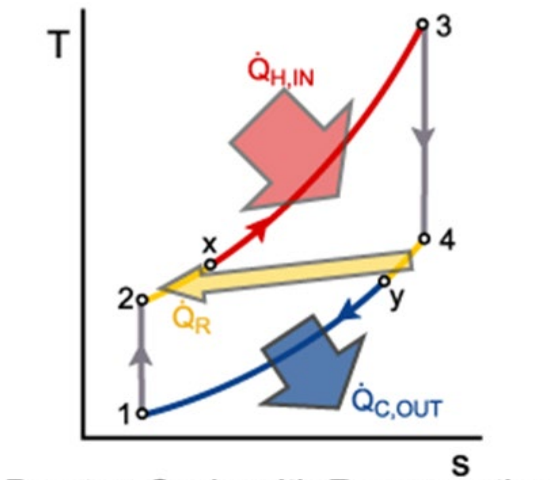
Simple Brayton Cycle



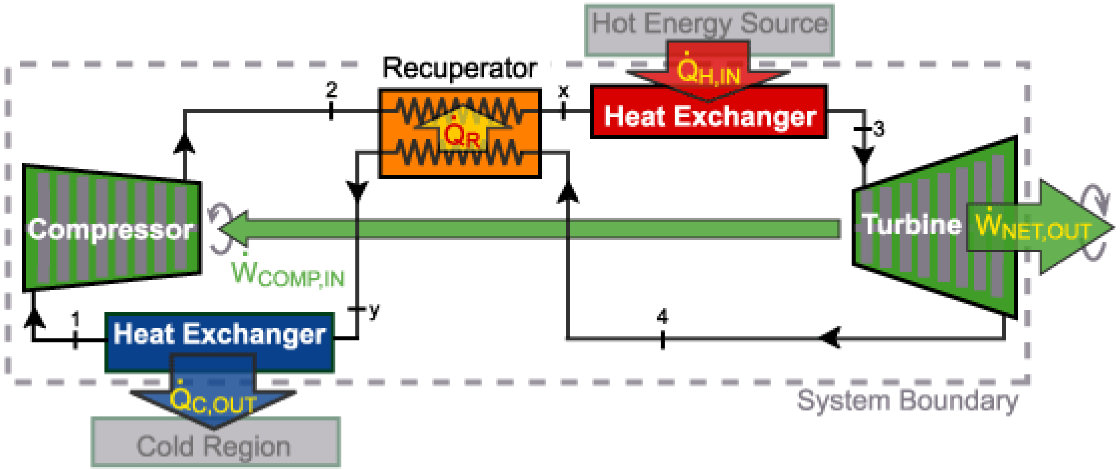
Brayton Cycle with Regeneration

- Heat input (kJ/kg):
  $q_{in} = (h_3 - h_x)$
- Heat output (kJ/kg):
  $q_{out} = (h_y - h_1)$
- Heat regenerated (kJ/kg):
  $q_{reg} = (h_4 - h_y) = (h_x - h_2)$

Brayton Cycle Regeneration



Brayton Cycle with Regeneration



Brayton Cycle with Regeneration

- Heat input (kJ/kg):

  $q_{in} = (h_3 - h_x)$
- Heat output (kJ/kg)

  $q_{out} = (h_y - h_1)$
- Heat regenerated (kJ/kg)

  $q_{reg} = (h_4 - h_y) = (h_x - h_2)$

- Efficiency Brayton cycle with regeneration

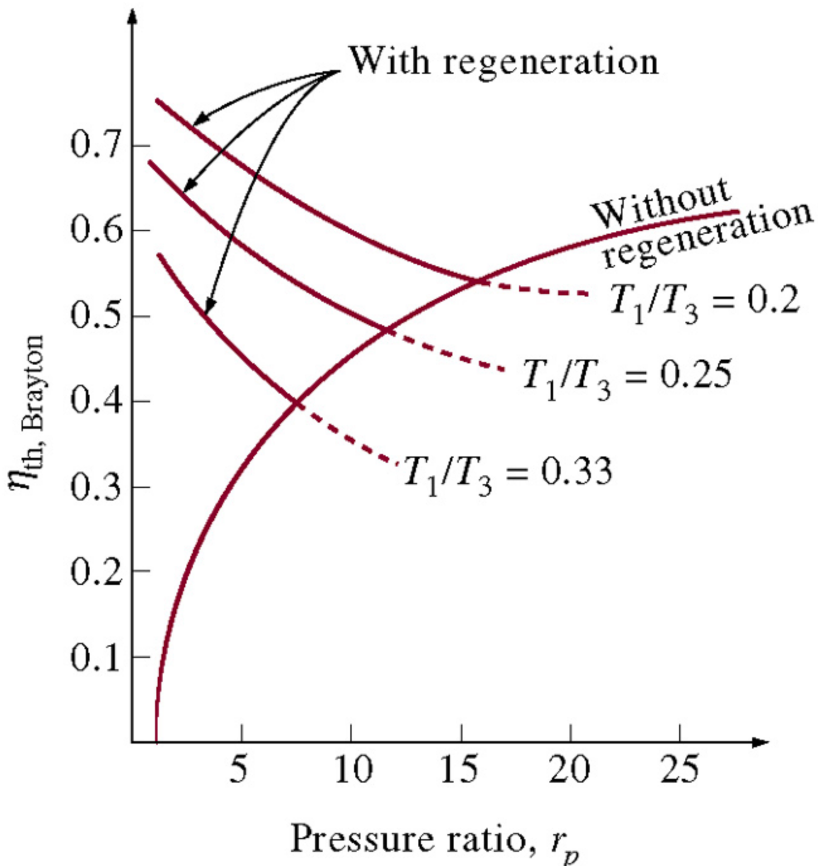
$$\eta_{th-Brayton-regeneration} = \frac{w_{net}}{q_{in}} = \frac{w_{turb} - w_{comp}}{q_{heat}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_x)}$$

Pressure Ratio and Recuperation

- Thermal efficiency, ideal air standard Brayton cycle with regeneration:

$$\eta_{th-Brayton-reg-ias} = 1 - \left(\frac{T_1}{T_3}\right) r_p^{(k-1)/k}$$

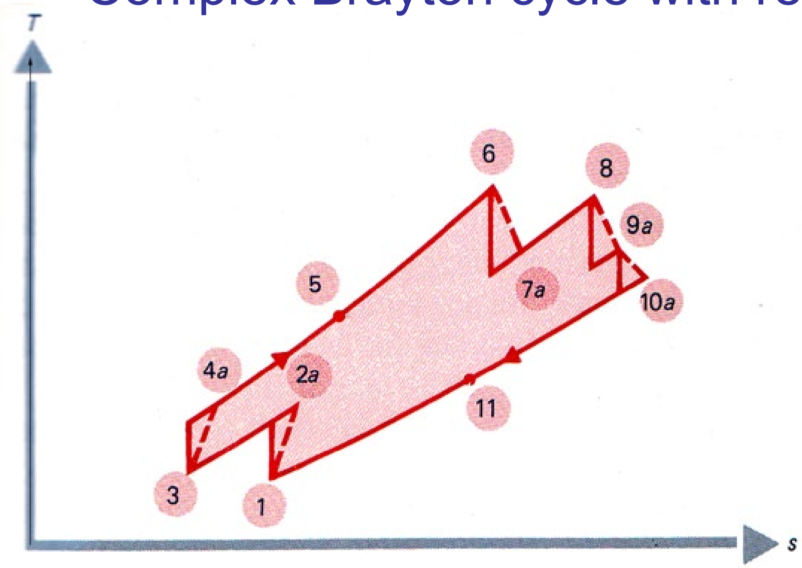
- For an ideal air standard cycle, the thermal efficiency depends on:
  - the pressure ratio (r_p)
  - the ratio of T_{min} (T_1) and T_{max} (T_3)
- Regeneration is most effective at:
  - lower pressure ratios
  - low minimum to maximum temperatures

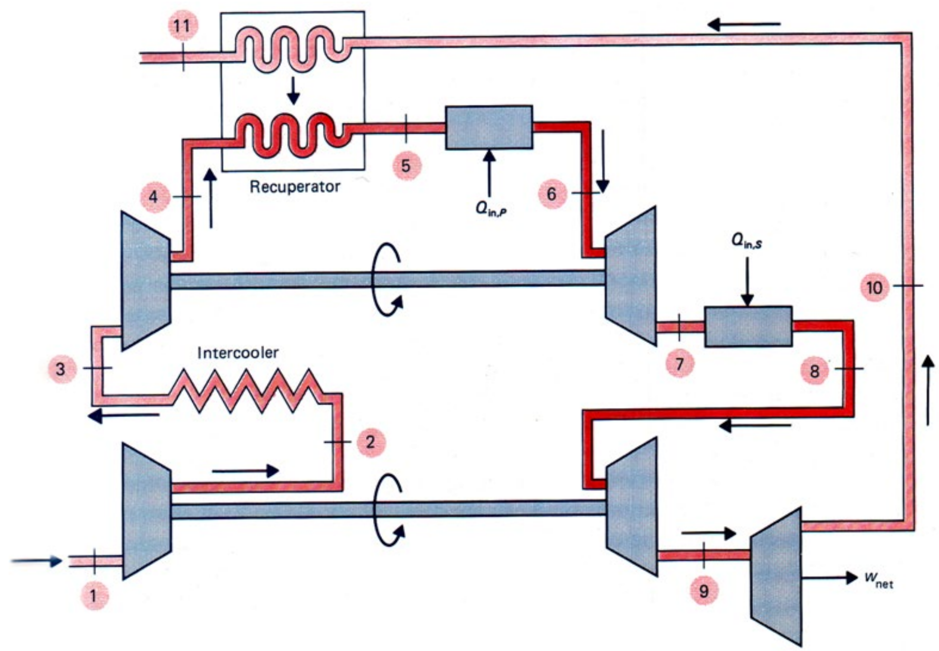


- Regeneration is attractive as heat is added at a higher average temperature which increases the efficiency

Increasing Brayton Cycle Performance

- All the different improvements can be applied at once
- Complex Brayton cycle with reheat, inter cooling and regeneration





- Thermal efficiency: $\eta_{th-Brayton} = \frac{w_{net}}{q_{in}}$

$$= \frac{(w_{turb1} + w_{turb2} + w_{turb3}) - (w_{comp1} + w_{comp2})}{q_{heat} + q_{reheat}}$$

$$= \frac{[(h_6 - h_7) + (h_8 - h_9) + (h_9 - h_{10})] - [(h_2 - h_1) + (h_4 - h_3)]}{(h_6 - h_5) + (h_8 - h_7)}$$

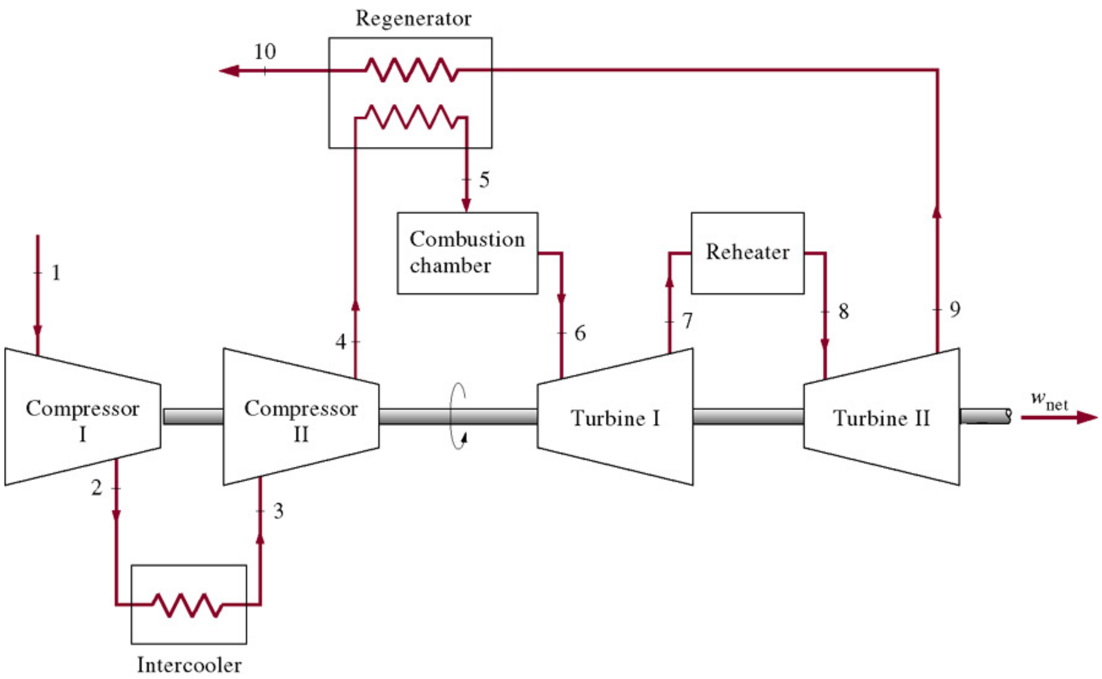
- In this case

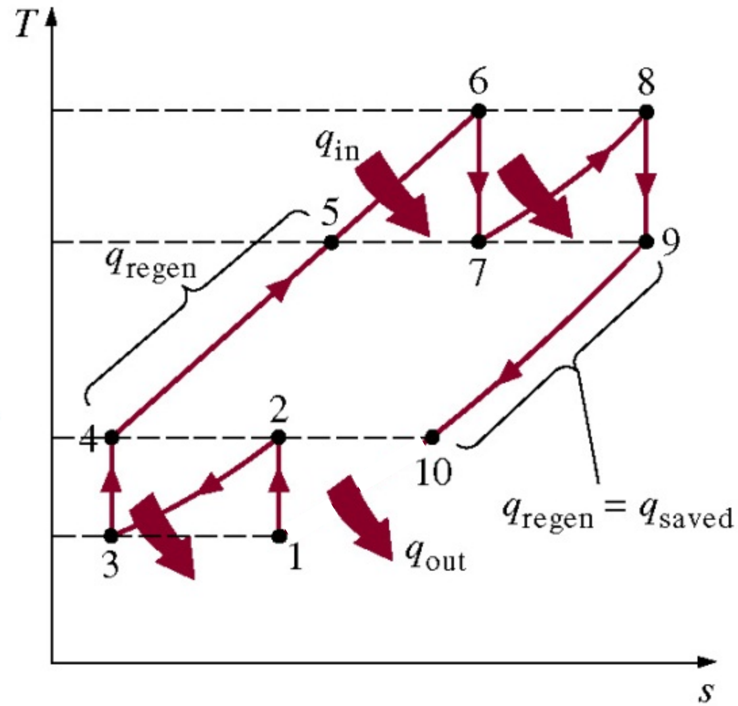
$w_{compr1} = w_{turb2}$

$w_{compr2} = w_{turb1}$

$w_{net} = h_9 - h_{10}$

Inter Cooling, Reheating, Recuperation

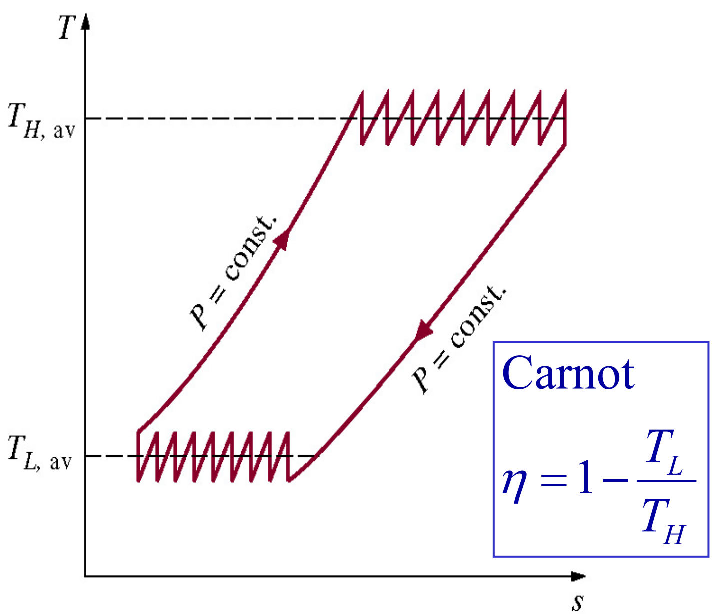


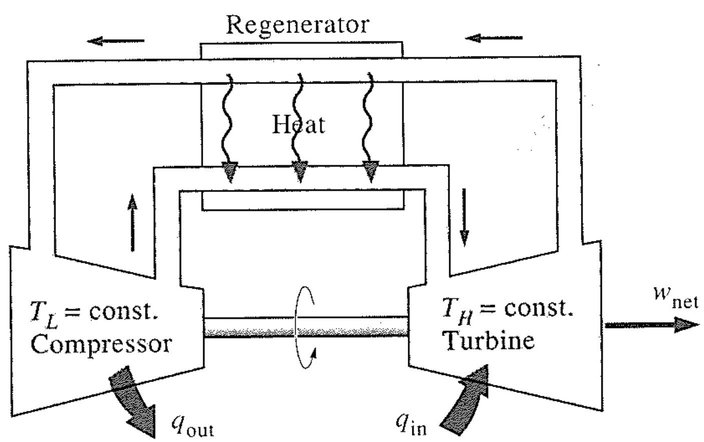


- For minimizing work input to compressor and maximizing work output from turbine: $\frac{P_2}{P_1} = \frac{P_4}{P_3}$ and $\frac{P_6}{P_7} = \frac{P_8}{P_9}$
- In principle infinite reheaters and intercoolers can be used to improve the efficiency, however the extra costs of those devices should be justified by the increased efficiency

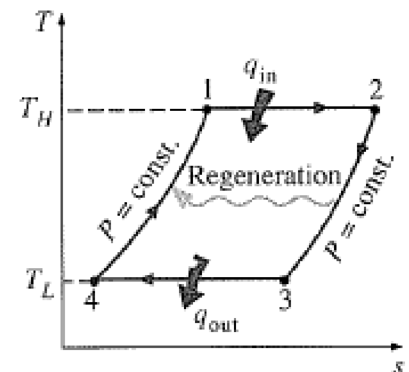
The Ericsson Cycle

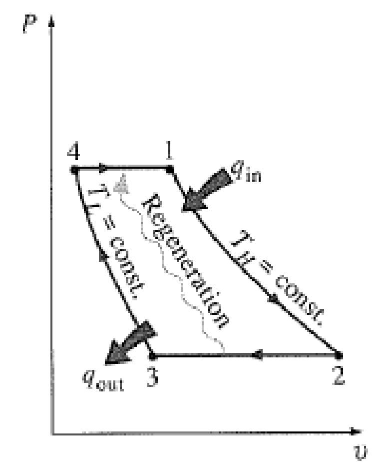
- If the number of compression and expansion stages is increased, the ideal gas turbine cycle with reheating, inter cooling and regeneration will approach the Ericsson cycle
- Ericsson cycle → Ideal cycle, thermal efficiency approaches the theoretical limit: $\eta_{Carnot} = 1 - \frac{T_L}{T_H}$
- However, the use of more than 2 or 3 stages cannot be justified economically





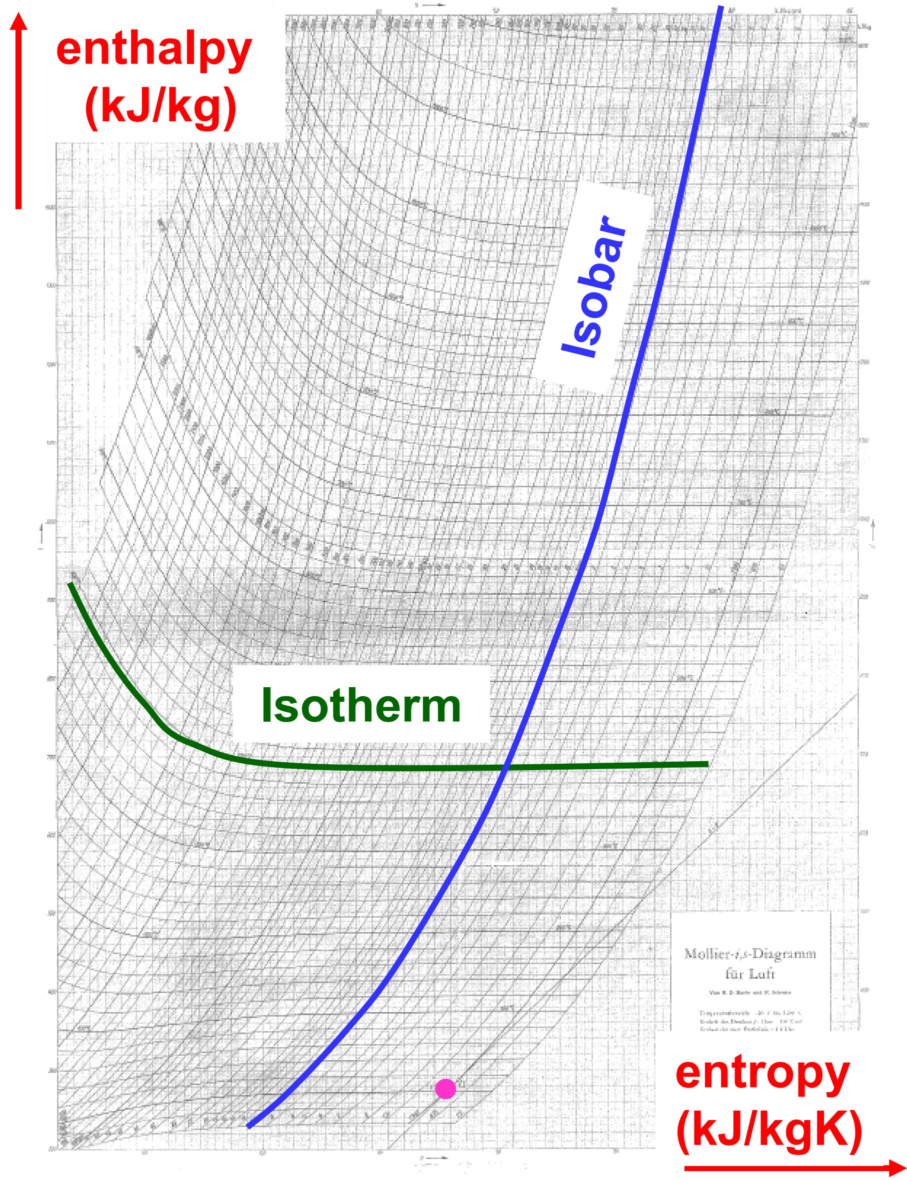
Ericsson cycle, all heat is recuperated





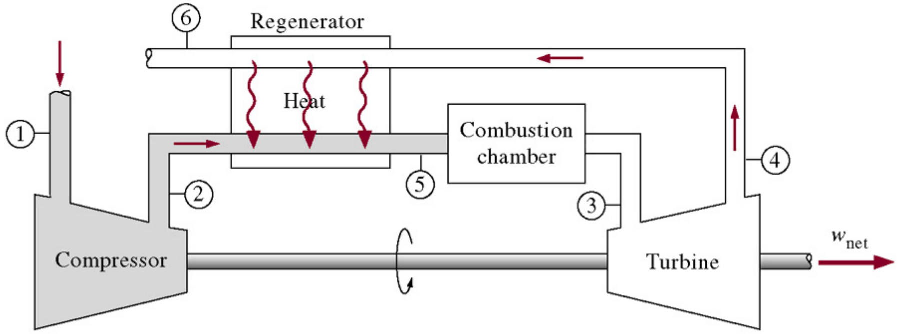
Example Gas Turbine with regeneration

- Consider a Brayton cycle with regeneration
- The pressure ratio is 8
- The air inlet temperature is 300K
- The temperature before the turbine inlet is 1300K
- The isentropic efficiency of the compressor is 80%
- The isentropic efficiency of the turbine 85%
- The effectiveness of the regenerator is 0.8
- Determine the thermal efficiency, the regenerated heat and the net work output using the Mollier diagram



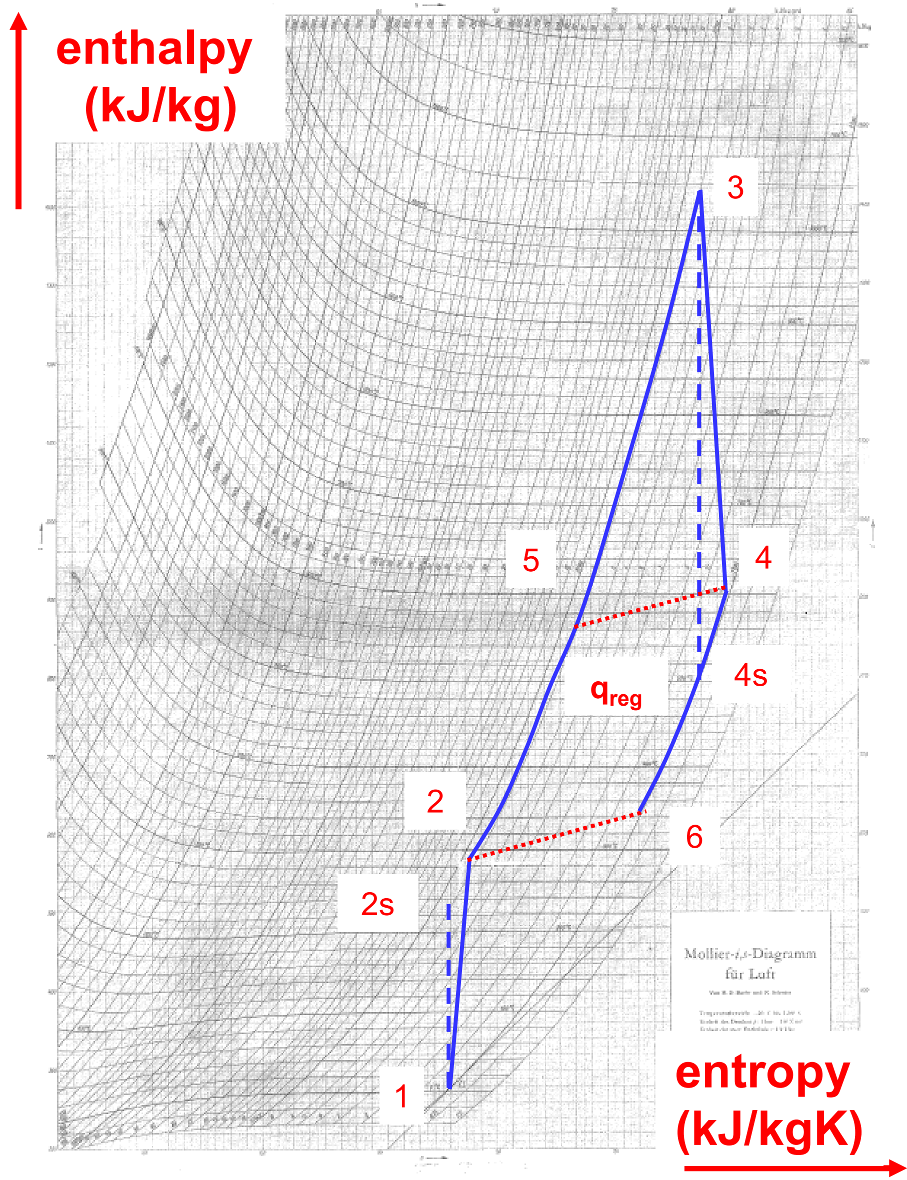
Example Gas Turbine with regeneration

- Solution, give first scheme, h-s diagram and two characteristics per point



	1st	2nd
1	1 bar	300 K
2s	8 bar	$s_1 = s_{2s}$
2	8 bar	$\eta_c = 0.8$
3	8 bar	1300 K
4s	1 bar	$s_3 = s_{4s}$
4	1 bar	$\eta_t = 0.85$
5	8 bar	$\varepsilon = 0.8$
6	1 bar	$h_4 - h_6 = h_5 - h_2$

- After this first analyses find all the h values from the diagram or from the known formulas for isentropic efficiencies or effectiveness and so on



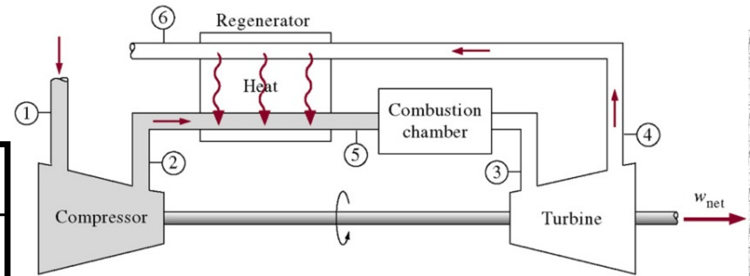
Example Gas Turbine with regeneration

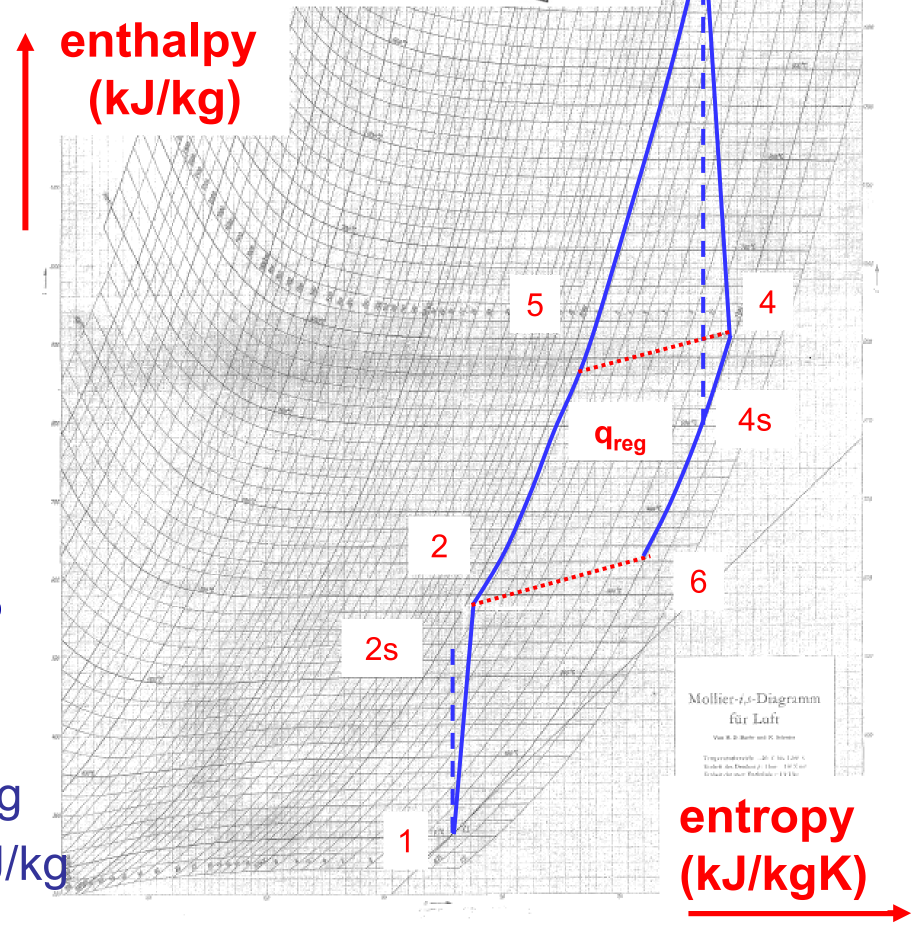
- After this find all the h values from the diagram or from the known formulas

	h(kJ/kg)	
1	300	Read from diagram
2s	545	Read from diagram
2	605	$h_2 = h_1 + 1/\eta_c(h_{2s} - h_1)$
3	1395	Read from diagram
4s	790	Read from diagram
4	880	$h_4 = h_3 - \eta_t(h_3 - h_{4s})$
5	825	$h_5 = h_2 + \varepsilon(h_4 - h_2)$
6	660	$h_6 = h_4 - (h_5 - h_2)$

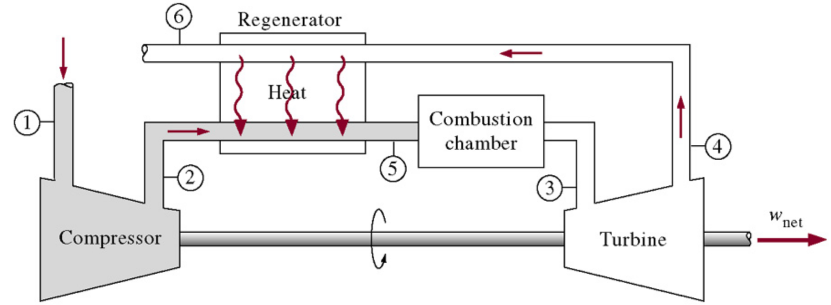
$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{turb} - w_{comp}}{q_{heat}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_5)} = 37\%$$

- With regeneration the efficiency is 37%
- Regenerated heat: $q_{reg} = h_5 - h_2 = 220$ kJ/kg
- Net work: $w_{net} = (h_3 - h_4) - (h_2 - h_1) = 210$ kJ/kg





Example Gas Turbine with regeneration



- Comparison of different efficiencies
- The Carnot efficiency is 77%

$$\eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}} = 1 - \frac{300}{1300} \Rightarrow 77\%$$

- **With** regeneration the efficiency is 37%

$$\eta_{th-reg} = \frac{w_{net}}{q_{in}} = \frac{w_{turb} - w_{comp}}{q_{heat}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_5)} \Rightarrow 37\%$$

- **Without** regeneration the efficiency is 27%

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{turb} - w_{comp}}{q_{heat}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)} \Rightarrow 27\%$$

- The second law efficiency in the case **with** regeneration is 48%

$$\eta_{2nd-law-reg} = \frac{\eta_{th-reg}}{\eta_{Carnot}} = \frac{0.37}{0.77} \Rightarrow 48\% \text{ and}$$

- The second law efficiency in the case **without** regeneration is 35%

$$\eta_{2nd-law-reg} = \frac{\eta_{th}}{\eta_{Carnot}} = \frac{0.27}{0.77} \Rightarrow 35\%$$

- In the ideal case, with an 100% efficient regenerator and 100% isentropic efficiencies of compressor and turbine, h_5=h_4, it would have been 70%

$$\eta_{th-reg-ideal} = \frac{w_{net}}{q_{in}} = \frac{w_{turb} - w_{comp}}{q_{heat}} = \frac{(h_3 - h_{4s}) - (h_{2s} - h_1)}{(h_3 - h_4)} \Rightarrow 70\%$$

	h(kJ/kg)
1	300
2s	545
2	605
3	1395
4s	790
4	880
5	825
6	660

second law efficiency not for the exam

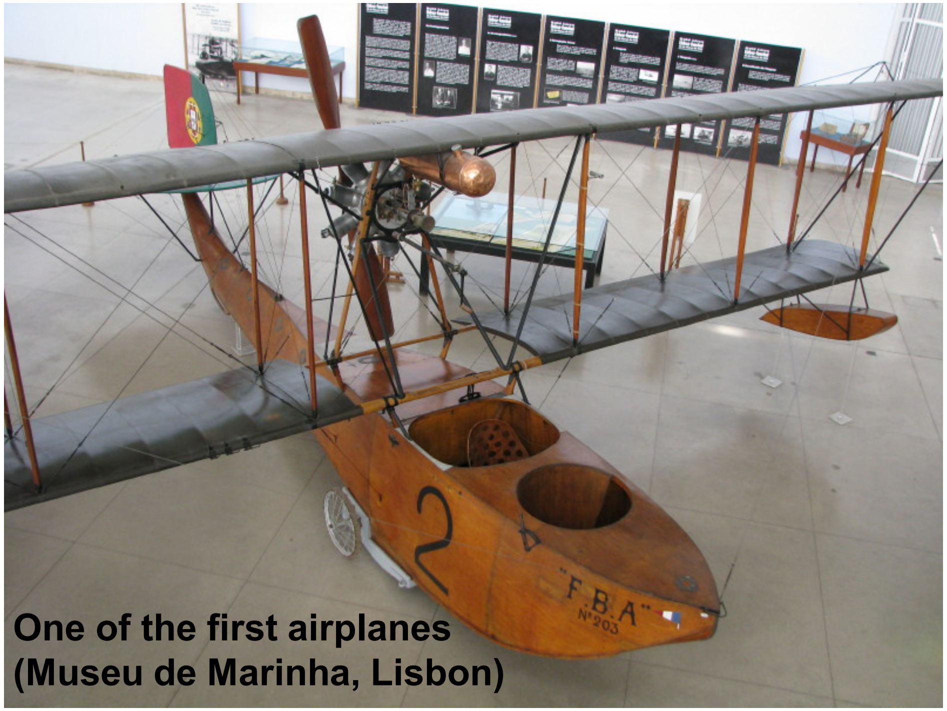
BREAK

https://www.cafepress.com/+thermodynamics+mugs

Aircraft Gas Turbine Engines

- The first airplanes were powered using piston cylinder engines
- Around 1940 the jet engine, powered by a gas turbine, was invented
- From 1944 on the first military jet engines were used
- The first jet engine for passenger transport flew in January 1951

Modern airplane

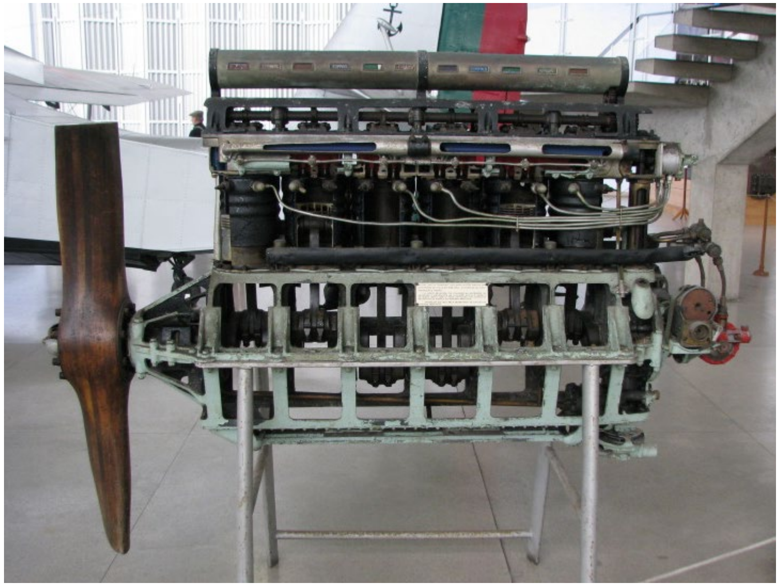


One of the first airplanes (Museu de Marinha, Lisbon)

Aircraft Gas Turbine Engines

- The first airplanes were powered using piston cylinder engines like in an automobile
- The crank was connected to a propeller instead of to the wheels

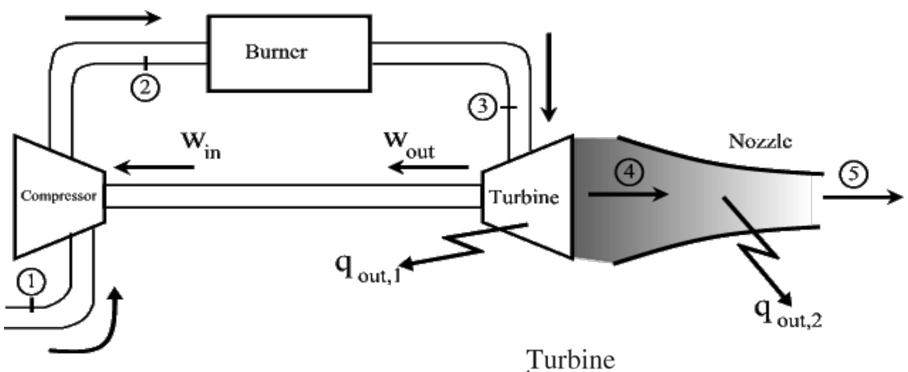
(Pictures made in Museu de Marinha, Lisbon)



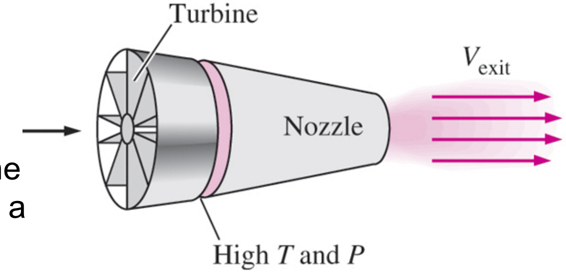
Aircraft Gas Turbine Engines

- The Brayton cycle is also used in engines that power aircraft
- Aircraft gas turbines operate on an open cycle called a **jet-propulsion cycle**
- In a **pure turbojet gas turbine,** a nozzle is added after the turbine
- The cycle differs from the Brayton cycle in that the gases are not expanded to ambient pressure, but to a pressure such that they produce just enough power to drive the compressor

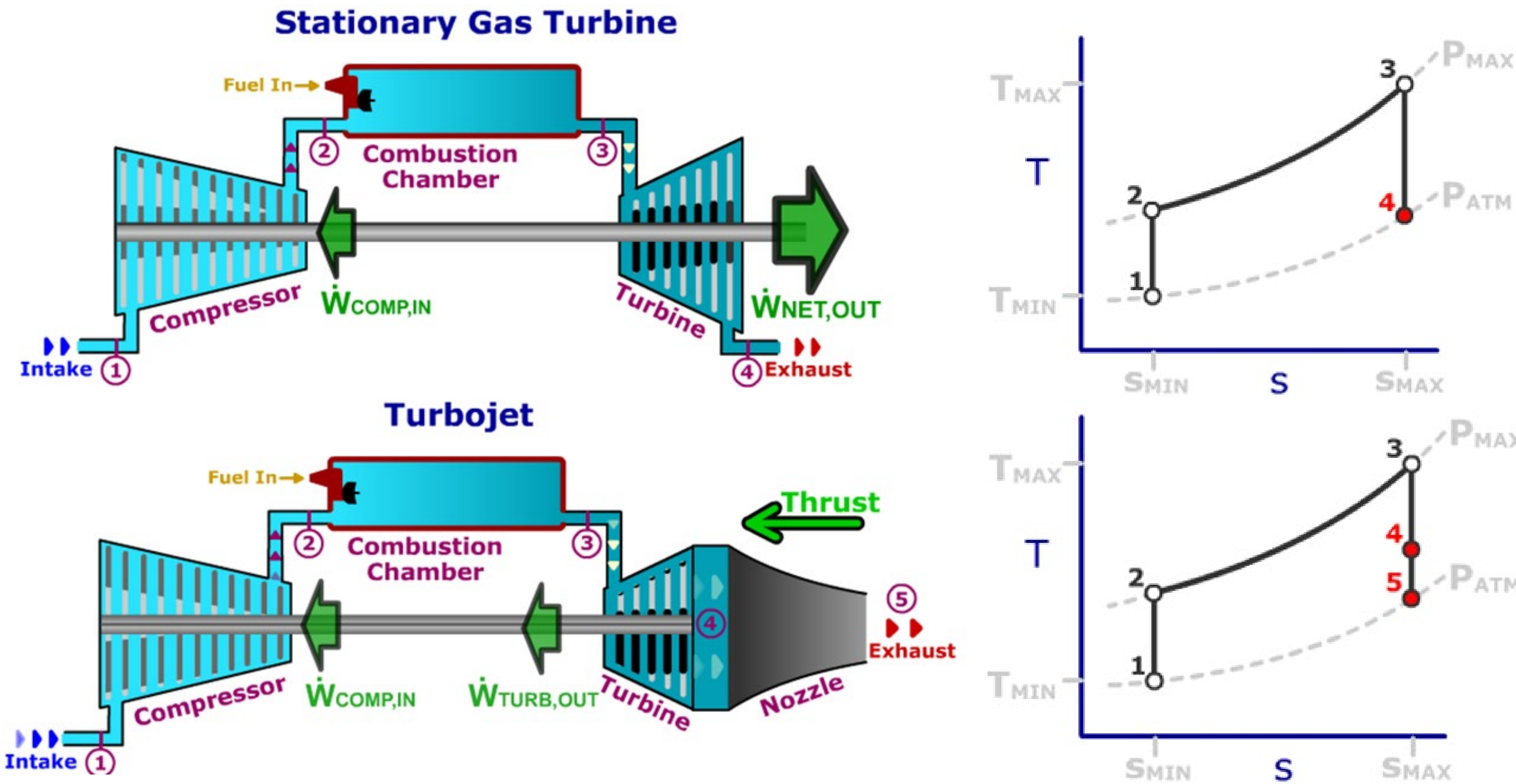
- **The net work output is zero !**
- The gases that exit the turbine at a relative high pressure are accelerated in a nozzle to provide thrust (F = ma) to propel the aircraft
- Afterburner → Inject fuel after turbine & combust → extra thrust



In jet engines, the high-temperature and high-pressure gases leaving the turbine are accelerated in a nozzle to provide thrust.



Stationary gas turbine - Turbojet

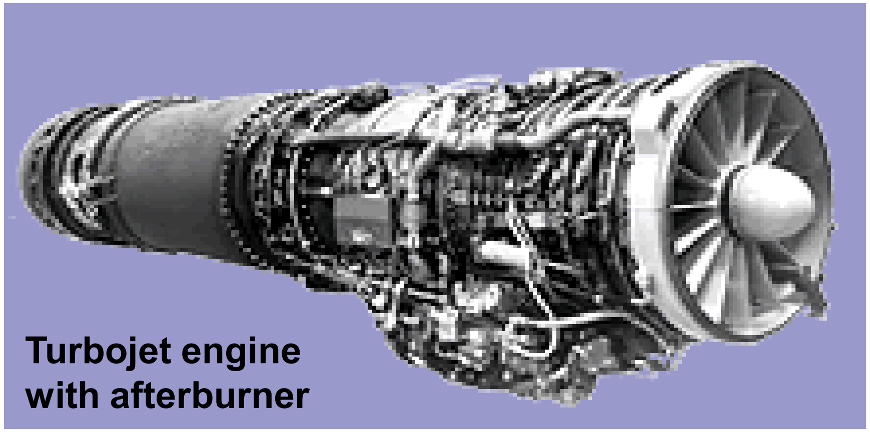


- Compare the stationary Brayton cycle with the turbojet, the turbojet does not produce net work output, only work is produced to drive the compressor the (3 – 4), the energy left is converted into thrust (4 – 5)

Turbojet Engine

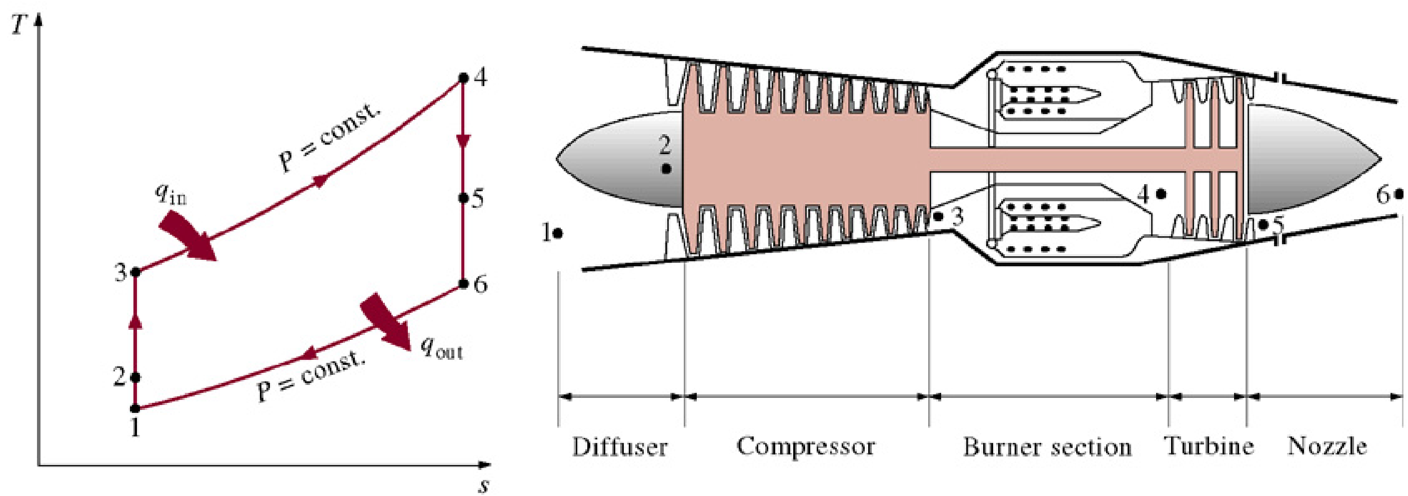
- **Turbojet engines** are used to power high speed aircraft.
  - enthalpy of the combustion gasses is converted into shaft work by turbines to drive the engine's compressor
  - The rest of the enthalpy is converted into kinetic energy in a nozzle, which accelerates the gas resulting in thrust

- In a **turbojet engine with an after-burner**:
  - The hot gasses that are leaving the turbine are injected with more fuel and re-combusted, increasing the gasses' enthalpy before it enters the nozzle and therefore producing more thrust in the nozzle



Turbojet Engine Principle

- **Ideal jet-propulsion cycle**
- The pressure of the intake air rises slightly as it is decelerated in the diffuser (1-2) this does not require work
- Air is compressed in the compressor (2-3) requiring work
- The air is mixed with fuel in the combustion chamber and burned at a constant high pressure (3-4), heat is added to the air
- The high temperature, high pressure gases are partly expanded in a turbine (4-5), producing work to drive the compressor
- The gases finally expand in a nozzle to the ambient air pressure (5-6) and leave the aircraft at high velocity producing thrust



Turbojet Engine Analyses

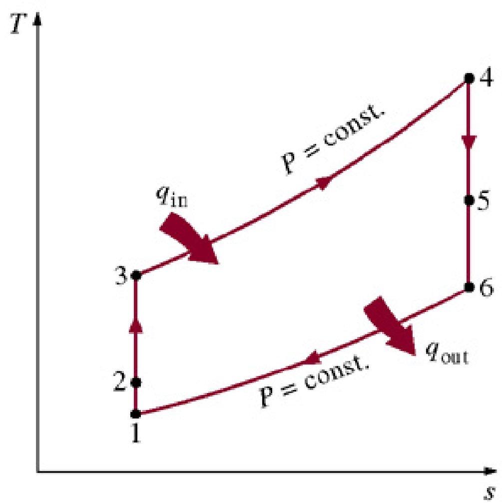
- Like all other cycles the ideal jet propulsion cycle is analyzed as a series of processes occurring in open devices
- The diffuser has no heat and power input, it can be assumed that $v_2 = 0$ and v_1 is $v_{aircraft}$, conversion of energy gives:

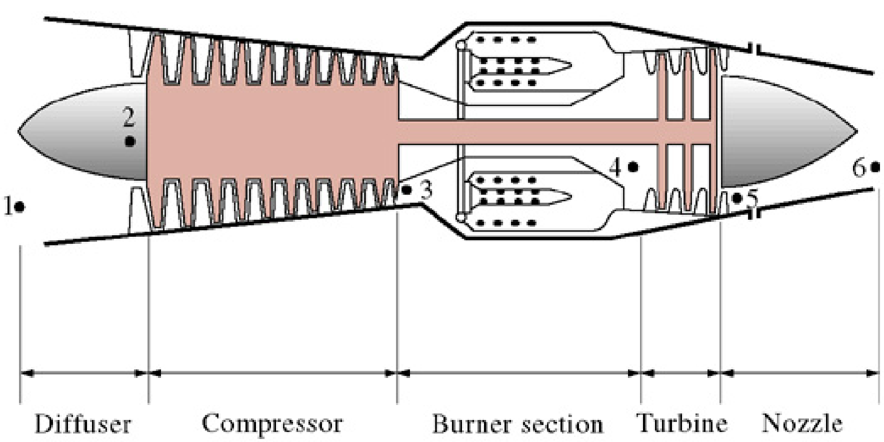
$$\left(h_2 + \frac{1}{2}{v_2}^2\right) - \left(h_1 + \frac{1}{2}{v_1}^2\right) = 0 \text{ and } dh = c_p dT \Rightarrow h_2 = h_1 + \frac{v_1^2}{2} \Rightarrow T_2 = T_1 + \frac{v_1^2}{2c_p}$$

- Work produced by the turbine is used to drive the compressor:

$$w_{comp} = w_{turb} \rightarrow h_3 - h_2 = h_4 - h_5$$

- The heat added to the air is: $q_{in} = h_4 - h_3$





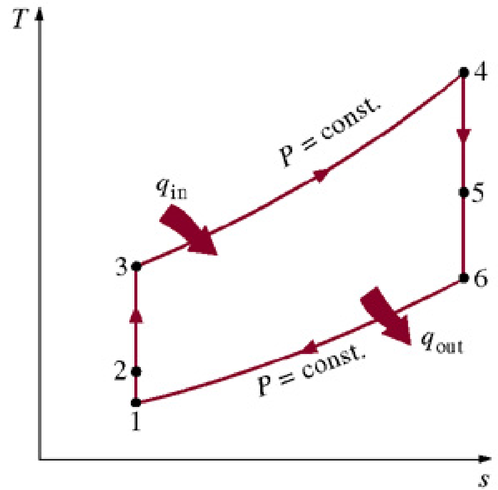
Turbojet Engine Analyses

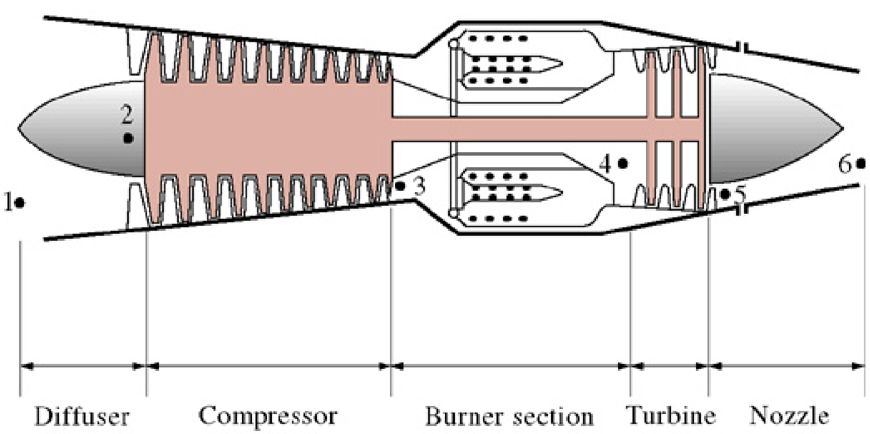
- The enthalpy difference over the nozzle (no work, no heat) is converted to speed under the assumption that $v_5 = 0$ and the specific heat is constant

$$\left(h_5 + \frac{1}{2}v_5{}^2\right) - \left(h_6 + \frac{1}{2}v_6{}^2\right) = 0 \quad \text{and} \quad dh = c_p dT \quad \Rightarrow \quad v_6 = \sqrt{2(h_5 - h_6)} = \sqrt{2c_p(T_5 - T_6)}$$

- The **thrust** developed in a turbojet engine is the unbalanced force that is caused by the difference in the momentum of the low velocity air entering the engine and the high velocity exhaust gases leaving the engine

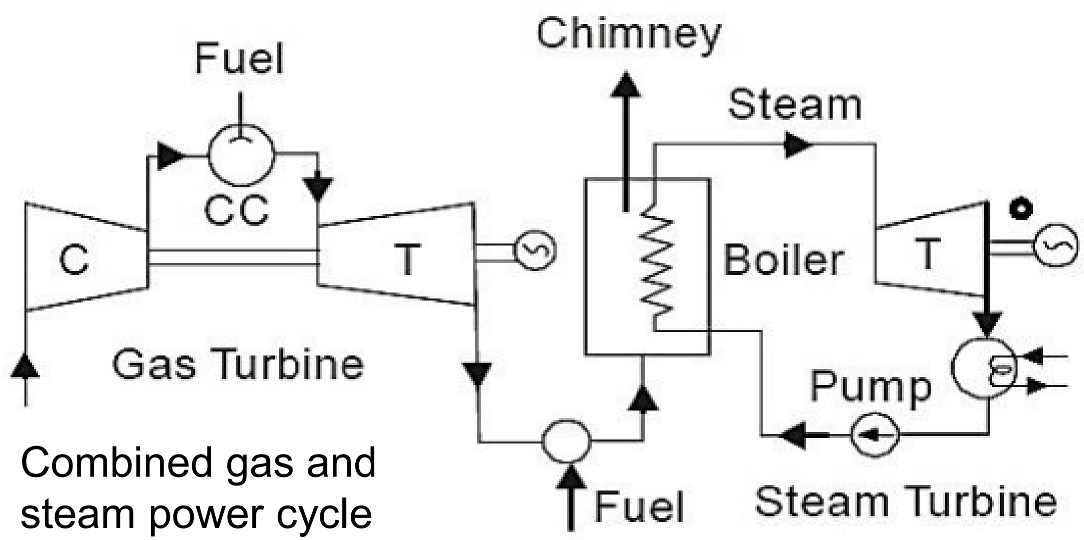
- Newton's law gives $F = \dot{m}(v_{exhaust} - v_{inlet}) = \dot{m}(v_6 - v_1)\ [N]$





Combined Cycles

- The continued quest for more power and higher thermal efficiencies has resulted in rather innovative modifications of conventional power plants
- A modification can be a first power cycle topping a second power cycle
- In such a **combined cycle** the rejected heat, q_{OUT} of the first cycle is used as input, q_{IN} for a second cycle
- **Combined gas-vapor cycle:** The combined cycle of greatest interest is the gas-turbine (Brayton) cycle topping a steam-turbine (Rankine) cycle, which has a higher thermal efficiency than either of the cycles executed individually



Combined gas and steam power cycle

Combined Gas – Vapor power Cycles

- A combined cycle consisting of a gas power cycle (Brayton) topping a vapor power cycle (Rankine) will have a higher thermal efficiency than either of the cycles executed individually

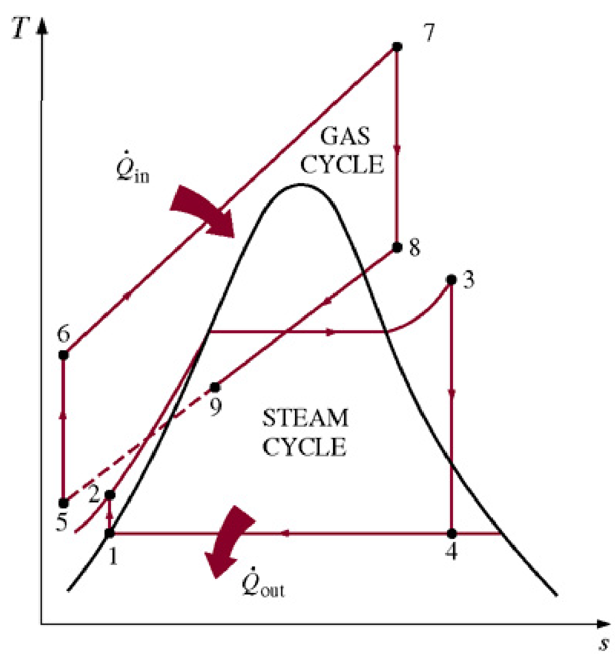
- Gas turbine cycles operate at considerably higher temperatures than steam cycles, T_{max} at the turbine inlet:
  - Modern steam power plants: 620°C
  - Modern gas turbine power plant: 1150°C
  - Modern turbo jet engine: over 1500°C

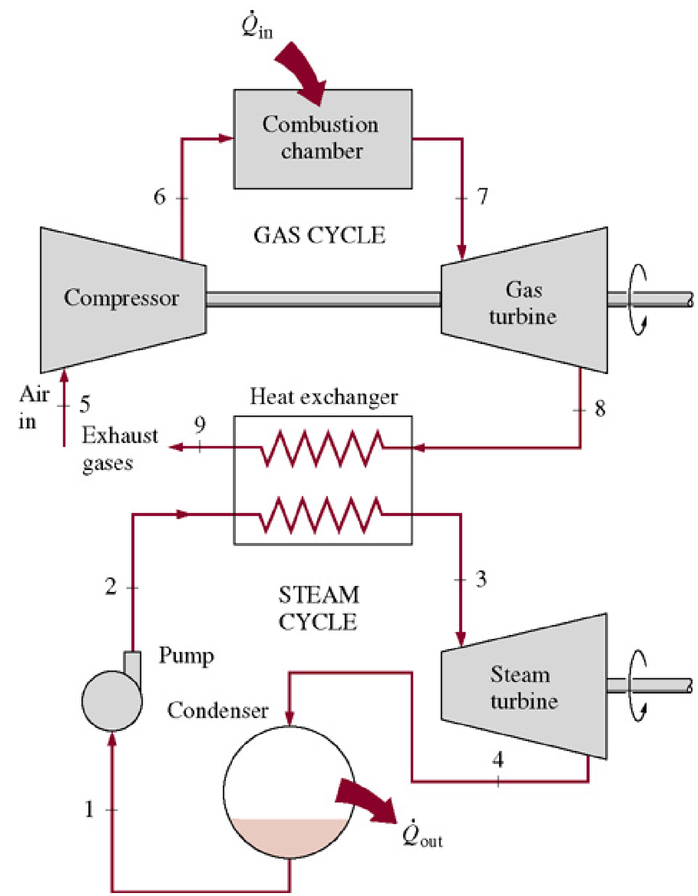
- Because of the higher average temperature at which heat is supplied gas-turbine cycles have a greater potential for higher efficiencies, however the exhaust gas leaves the gas turbine at relative very high temperatures which reduces the efficiency a lot

- In a **combined gas – vapor power cycle** the relative hot exhaust gases of the Brayton cycle are used to heat the fluid in the Rankine cycle

Combined Gas – Vapor power Cycles

- In a combined gas – vapor power cycle the energy from the exhaust of the gas turbine is recovered by transferring it to the steam in a heat exchanger that serves as a boiler
- Generally, more than one gas turbine is needed to supply sufficient heat to the steam
- The steam cycle may involve regeneration as well as reheating
- The energy for reheating can be supplied by burning some additional fuel in the oxygen-rich exhaust gases

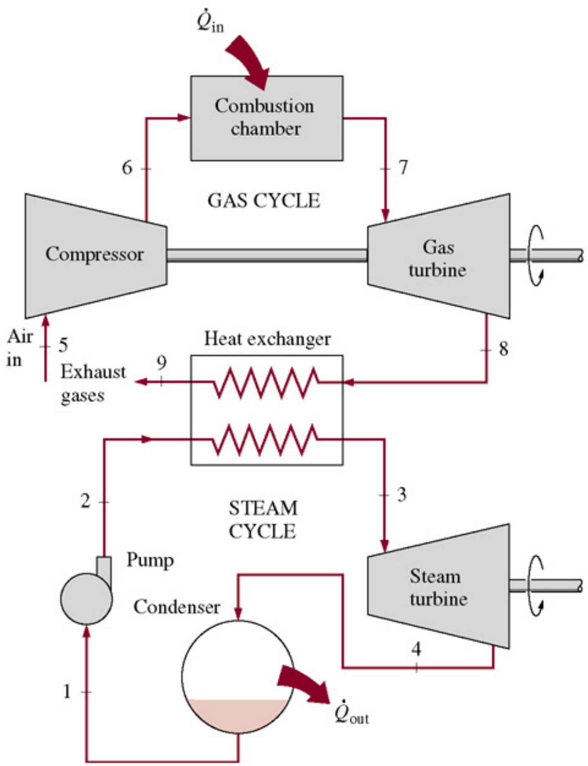


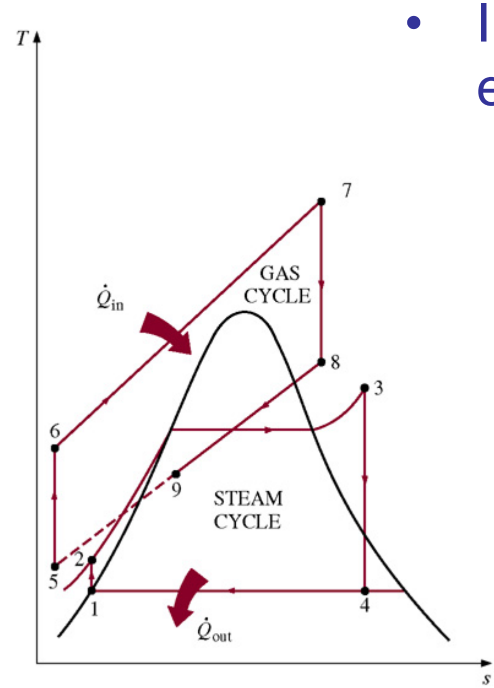


Combined Gas – Vapor power Cycles

- The cycles are connected by the heat exchanger, this gives a relation to connect both cycles in the analysis
- It relates the mass flow of the Rankine and the Brayton cycle
- The heat from the exhaust gases is transferred to the steam

$$\dot{Q}_{out\ \_\ gas} = \dot{Q}_{in\ \_\ steam} \rightarrow \dot{m}_{gas}(h_8 - h_9) = \dot{m}_{steam}(h_3 - h_2)$$





- In the heat exchanger the entropy increases (second law)

$$Q_{out-gas} = Q_{in-steam}$$

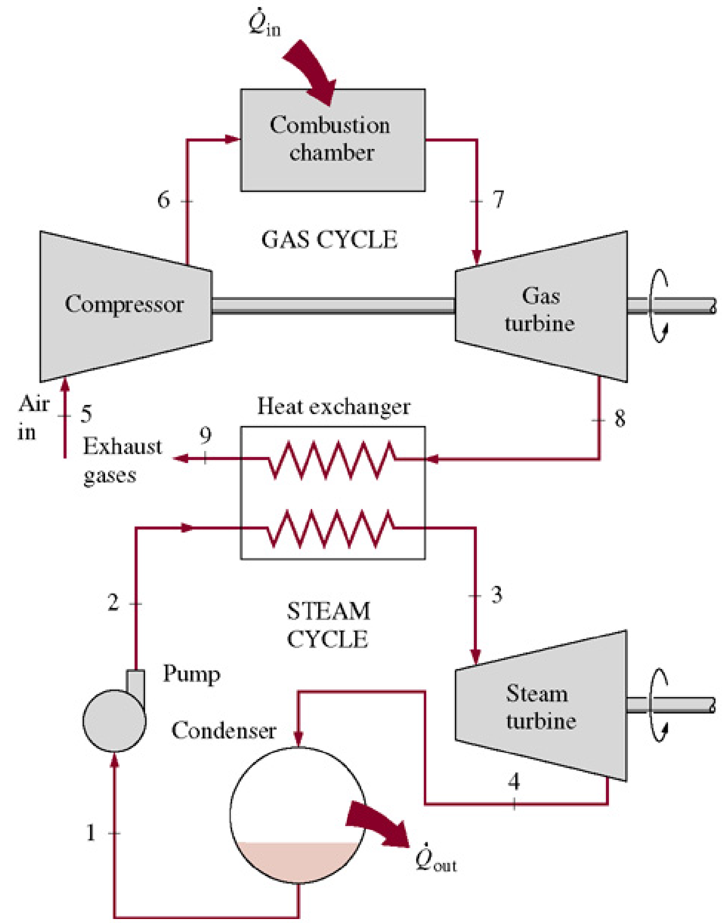
$$T_{out-gas}\Delta s_{out-gas} = T_{in-steam}\Delta s_{in-steam}$$

$$\Delta s_{in-steam} = \frac{T_{out-gas}}{T_{in-steam}}\Delta s_{out-gas}$$

$$\frac{T_{out-gas}}{T_{in-steam}} > 1 \rightarrow \Delta s_{in-steam} > \Delta s_{out-gas}$$

Combined Gas – Vapor power Cycles

- Combined cycle: Brayton cycle and Rankine cycle
- Thermal efficiency, add all outputs (note only one input)



$$\eta_{combined-cycle} = \frac{\dot{W}_{netto}}{\dot{Q}_{in}} =$$

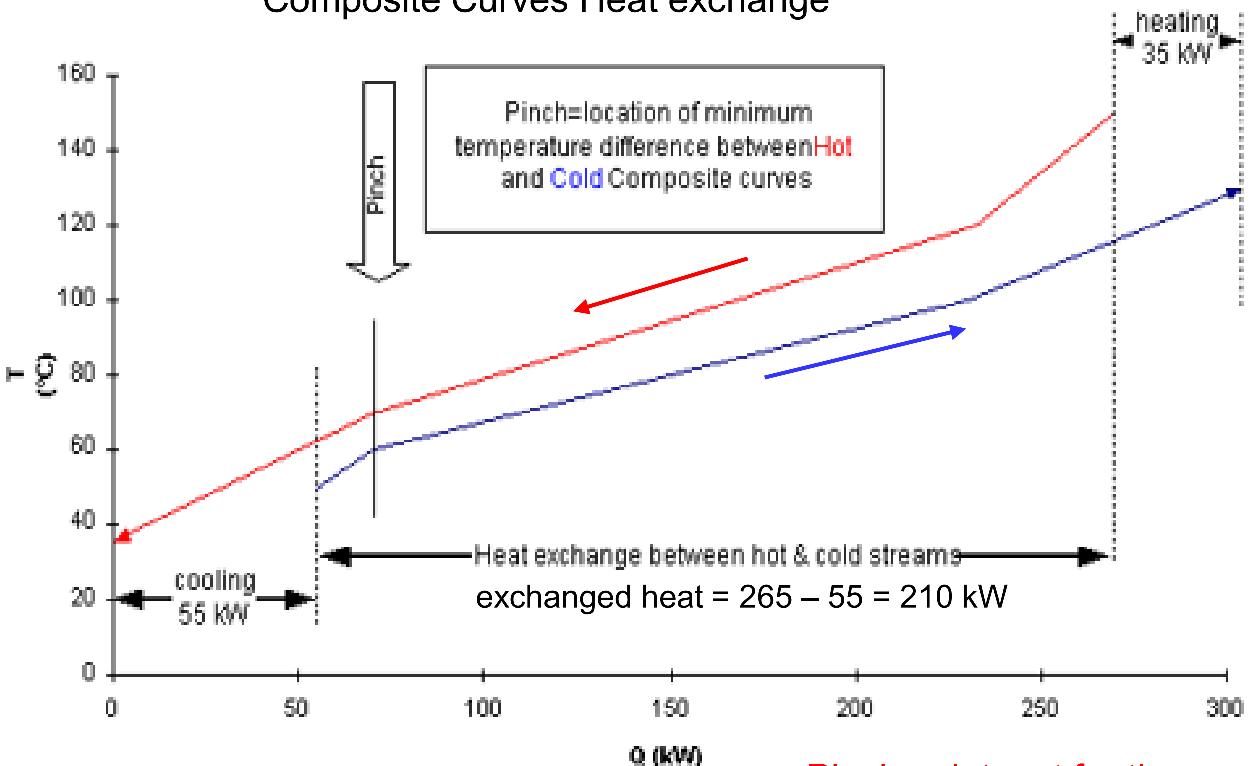
$$\frac{\dot{w}_{out-gas} - \dot{w}_{in-gas}}{\dot{q}_{in-gas}} + \frac{\dot{w}_{out-steam} - \dot{w}_{out-steam}}{\dot{q}_{in-gas}} =$$

$$\frac{\dot{w}_{out-turb-gas} - \dot{w}_{in-comp} + \dot{w}_{out-turb-gas} - \dot{w}_{in-pump}}{\dot{q}_{in-gas}}$$

Pinch point analysis

- In combined cycles heat is exchanged in the heat exchanger, in the heat exchanger the temperature of the bottom cycle must always be lower than the temperature of the upper cycle
- In the figure the temperature of the hot and the cold flow is given as function of the exchanged heat (Tq-diagram) between 2 flows with *different inclination*
- The location with smallest temp difference is called the **pinch point**
- If the hot and the cold line touch each other heat exchange cannot occur any more

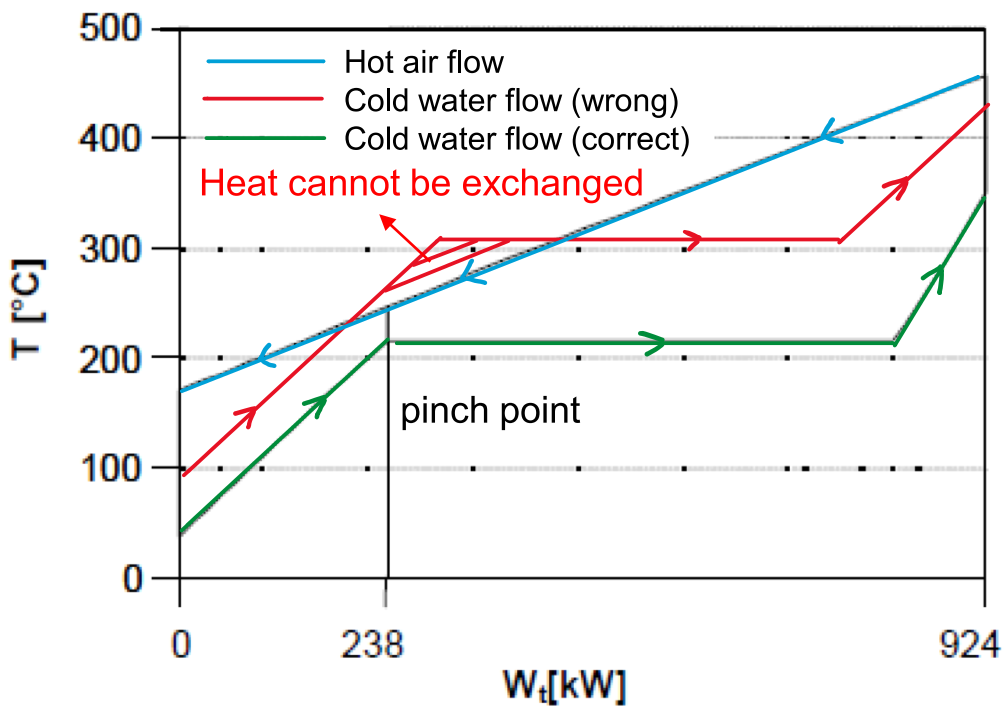
Composite Curves Heat exchange



Pinch point: not for the exam

Pinch point analysis

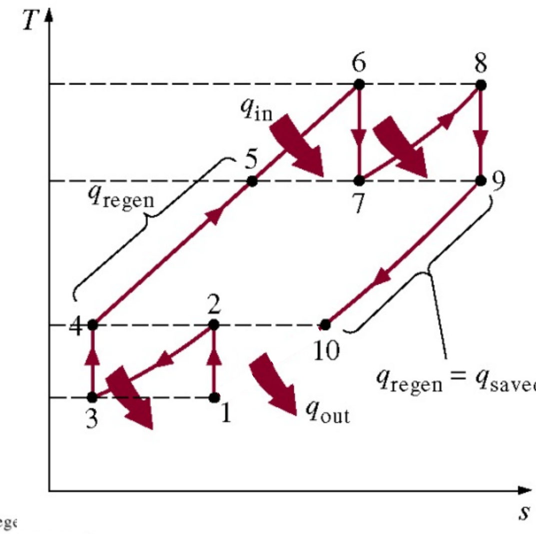
- The pinch point should specially be considered in gas – vapor combined power cycles, in the heat exchanger the colder water should always have a lower temperature than the hotter air
- The water undergoes a phase change and part of the cold water curve is horizontal, therefore the begin and end temperature of the water can be lower that the end and begin temperature of the gas but still in the middle of the heat exchanger there can be a problem
- This is shown in the figure, for the red line the begin and end temperature are below the air temperature but somewhere in the middle of the heat exchanger they cross each other, and heat cannot be exchanged any more as the water temperature gets hotter
- The green line doesn't show this problem



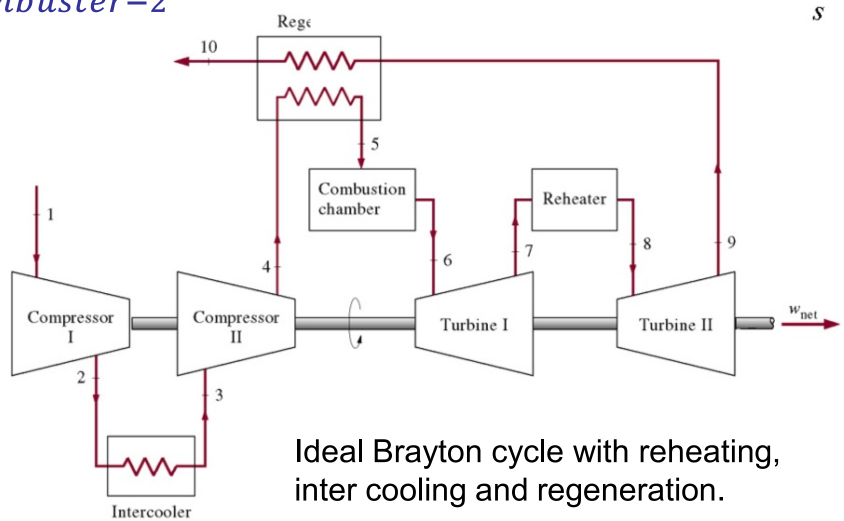
Recapitulate Class 11

- Improve the efficiency of the Brayton cycle by adding extra devices
  - Extra combustion chamber → reheating the air during expansion
  - Inter cooler → cooling the air during compression
  - Regenerator / recuperator → relative hot turbine exhaust gases pre heat air before combustion
- Effectiveness regenerator (ε): $\varepsilon = \frac{q_{reg-actual}}{q_{reg-max}} = \frac{h_5 - h_4}{h_9 - h_4}$
- Thermal efficiency:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{out-HPT} + \dot{W}_{out-LPT} - \dot{W}_{in-c1} - \dot{W}_{in-c2}}{\dot{Q}_{in-combuster-1} + \dot{Q}_{in-combuster-2}}$$



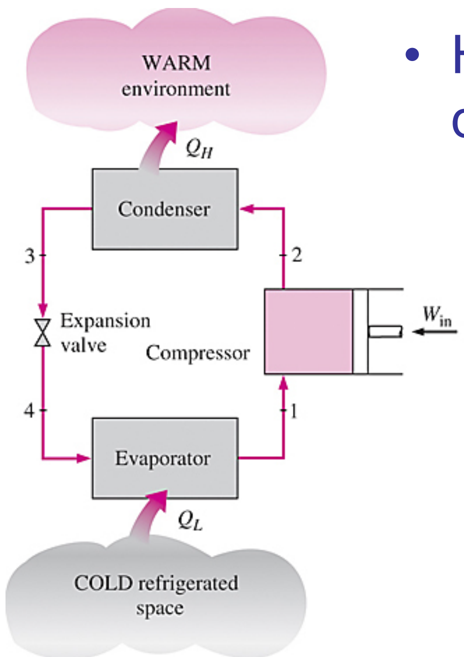
- Aircraft gas turbine engines, just enough work is produced to power the compressor and the rest of the energy of the gases that exit the turbine at a relative high pressure are accelerated in a nozzle to provide thrust (F = ma)
- Combined gas – vapor power cycles

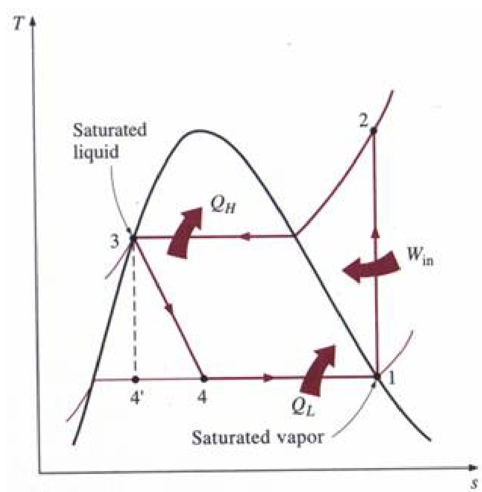


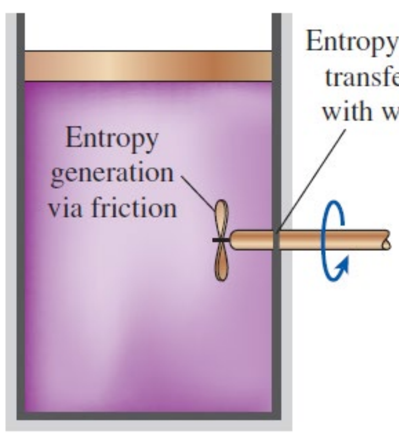
Ideal Brayton cycle with reheating, inter cooling and regeneration.

Next Module: Engineering Thermodynamics 2

- Engineering thermodynamics 2 (1.5 ec) in module 3 is a follow up of engineering thermodynamics 1 (3 ec)
  - Class 12: Refrigerating / heat pump cycles
  - Class 13: Internal combustion engines
  - Class 14: More about entropy, calculation of entropy generation
  - Class 15, 16 & 17: Mathematical background Thermodynamics
    - How are tables and diagrams composed?
    - How can unknow properties that can not be measured be determined from a set of limited available data?







Entropy may be generated within the system as work is dissipa-ted into a less useful form of energy

Keep in mind: Important Formulas

- Specific volume $v = V/m$ [m^3/kg] and density $\rho = 1/v = m/V$ [kg/m^3]
- Volume work $\delta w = Pdv$
- Enthalpy $h = u + Pv$, (u internal energy, P pressure, v volume)
- Thermal efficiency $\eta_{thermal} = \frac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$
- Mixture fraction $x = \frac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
- Ideal gas law $Pv = RT$, $c_p - c_V = R$
- For an ideal gas $du = c_V dT$ and $dh = c_p dT$
- Conservation of mass $m_{in} = m_{out}$, mass flow rate $\dot{m} = \rho v A$
- Conservation of energy, first law of thermodynamics
  - Closed system $du = \delta w - \delta q \rightarrow \Delta u = w - q$
  - Open system $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$
- S increases, second law $ds_{total} = ds_{system} + ds_{surroundings} = \delta s_{gen} \geq 0$
- Inequality of Clausius $ds \geq \frac{\delta q_{net}}{T_{res}}$ (= for reversible process)
- Reversible heat transfer $\delta q_{net,rev} = Tds$, irreversible $\delta q_{net,irrev} < Tds$
- Gibbs equations $Tds = du + Pdv$ and $Tds = dh - vdP$
- Isentropic efficiencies $\eta_{INPUT,S} = \frac{w_{IN,S}}{w_{IN,A}}$, $\eta_{OUTPUT,S} = \frac{w_{OUT,A}}{w_{OUT,S}}$
- Isentropic processes ideal gas Pv^k = constant, Tv^{k-1} = constant, $P^{(k-1)/k}/T$ = constant
- Thermal efficiency power cycles $\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$ Carnot efficiency $\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}$

- Phase diagrams