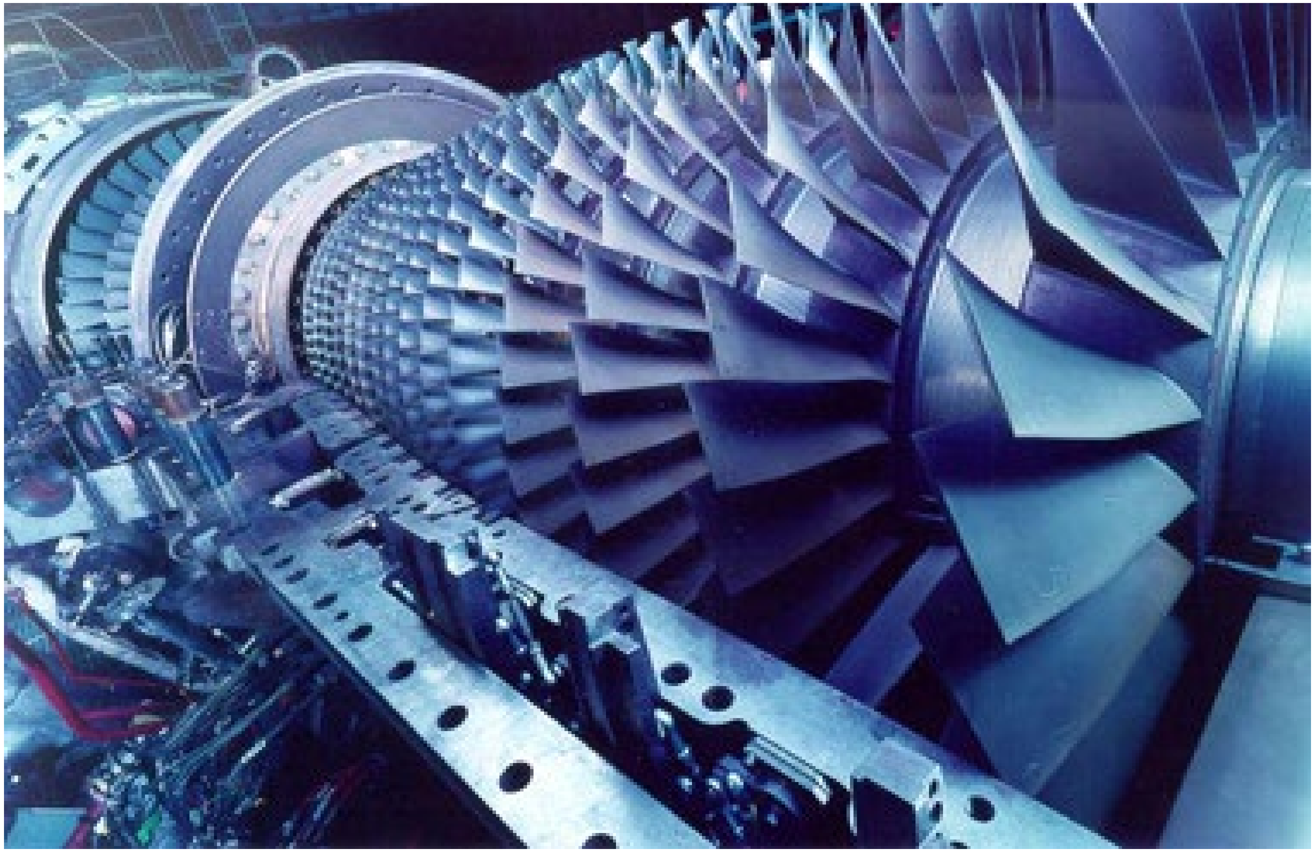
Class 10: Gas power cycles, simple Brayton cycle

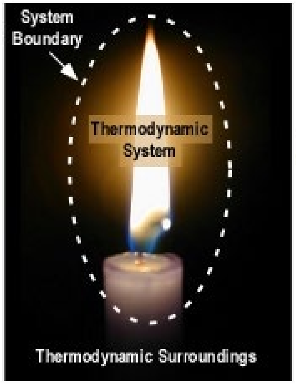


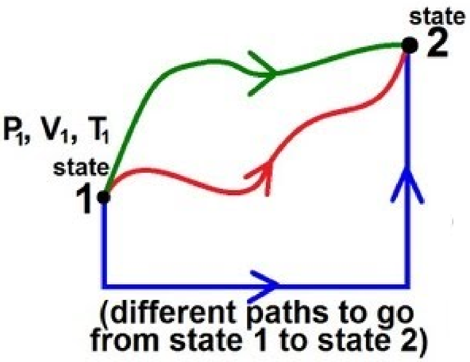
Gas turbine (Beavers Technologies Ltd.)

Roadmap Engineering Thermodynamics

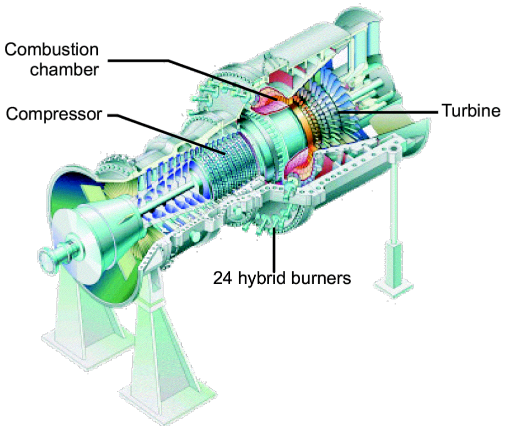
- Using thermodynamics for practical applications requires knowledge of:

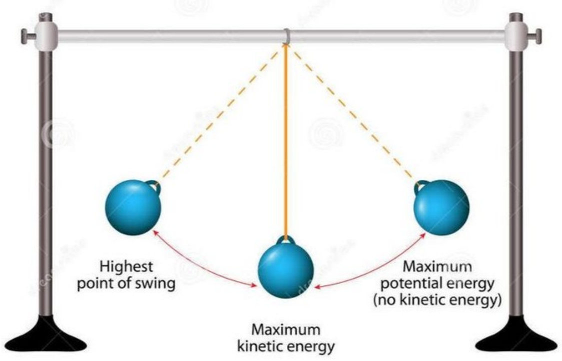
Concepts and definitions (Class 1) → Various forms of energy (Class 2)

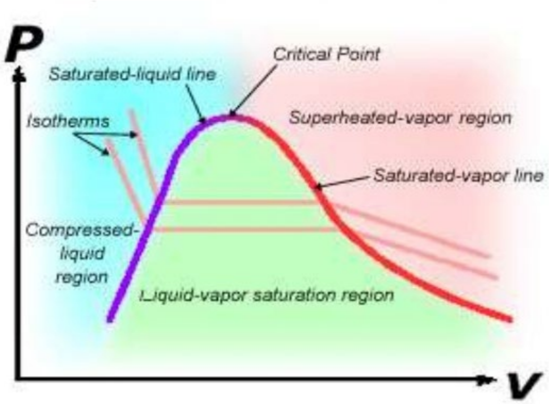




Power cycles (Class 6 – 11) ← Laws of Thermo (Class 4 and 5) ← Properties of Substances (Class 3, 9)

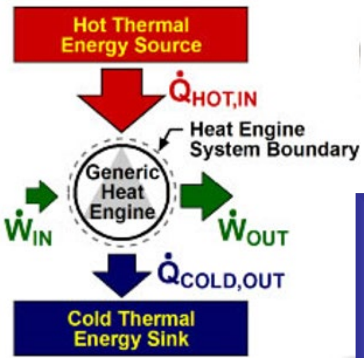




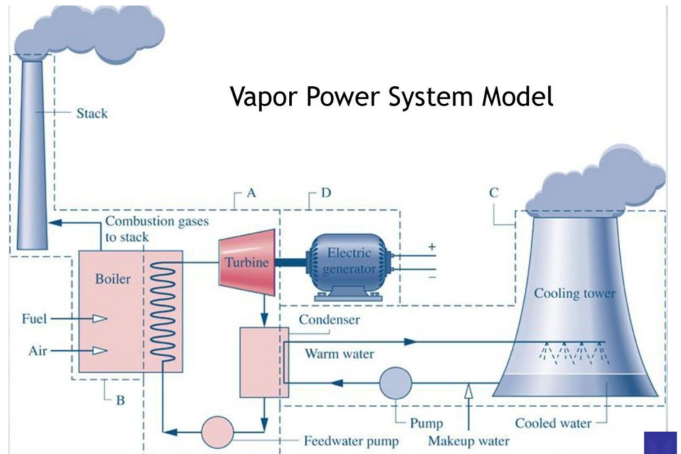


Roadmap Engineering Thermodynamics

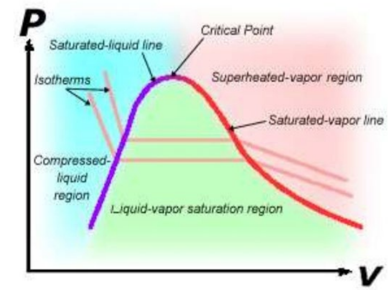
Thermodynamic cycles (Class 6)

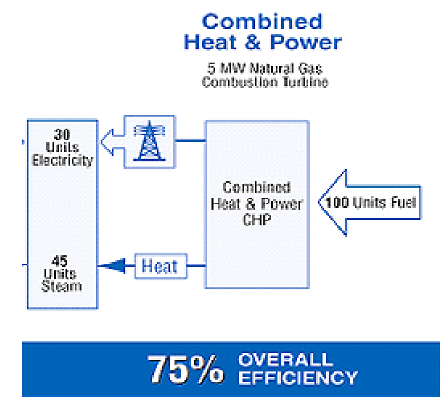


Vapor power cycles – Rankine cycle (Class 7, 8)

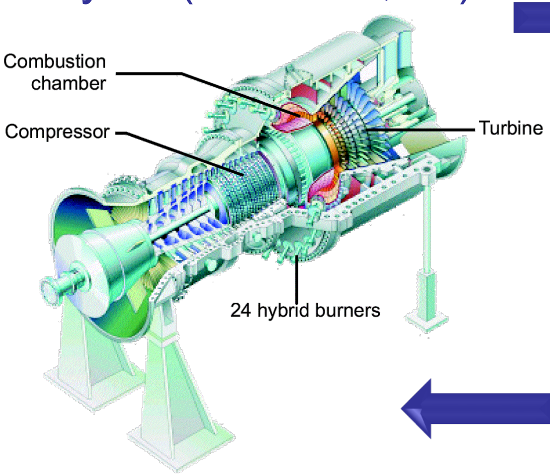


Properties of water (Class 3)



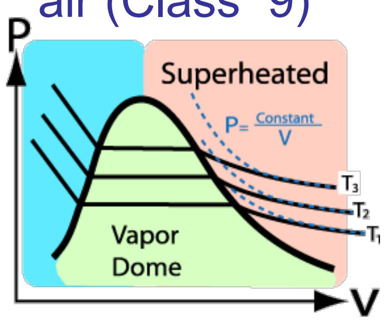


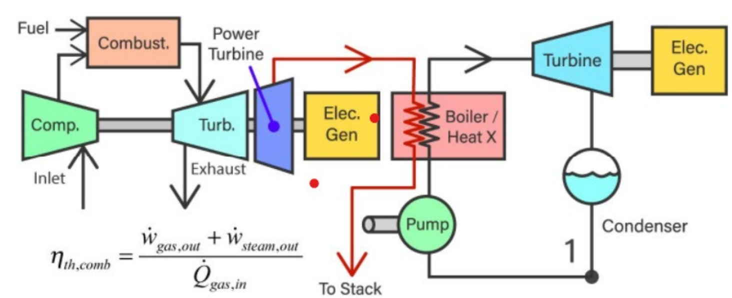
Gas power cycles – Brayton cycle (Class 10, 11)



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

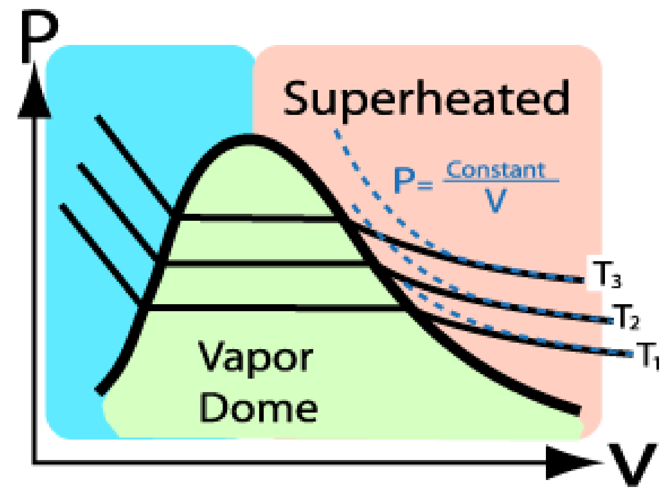
Properties of air (Class 9)





Recapitulate class 9

- Ideal gas equation of state: $\mathrm{P}v = RT$
- Tables for ideal gas
- Mollier diagram for air



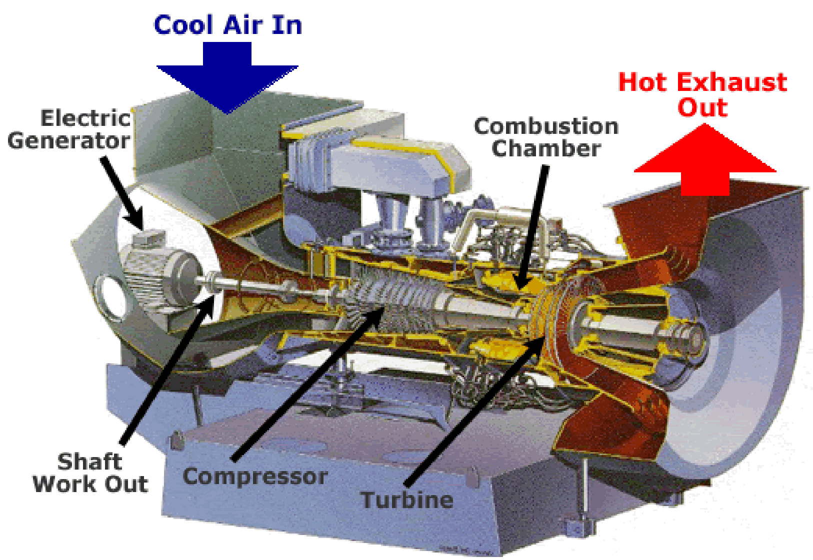
- Specific heat
  - Constant pressure specific heat, c_p
  - Constant temperature specific heat, c_v
- Relation between them: $c_p - c_V = R$

- Internal energy and enthalpy of ideal gases depends on temperature only, u and h for ideal gas: $du = c_V dT$ and $dh = c_p dT$
- Entropy ideal gas: $s_2 - s_1 = c_V \ln\frac{T_2}{T_1} + R\ln\frac{v_2}{v_1}$ & $s_2 - s_1 = c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}$
- Isentropic processes for ideal gas:

$$Pv^k = \text{constant} \;\&\; Tv^{k-1} = \text{constant} \;\&\; \frac{P^{\frac{k-1}{k}}}{T} = \text{constant}$$

Content Class 10

- **Gas power cycles – Brayton cycle, simple**
- **Gas power cycles,** cycles using gas as working fluid through the whole cycle to produce power
  - Air-standard cycle
  - Open and closed Brayton cycle
  - Ideal and real Brayton cycle
    - Power in- and output
    - Thermal efficiency
  - Comparison to the Rankine cycle
  - Design parameters
  - Mollier diagram for air

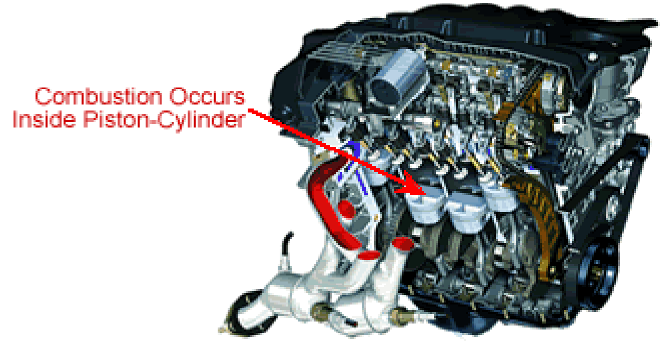


A basic gas turbine engine

- **Learning goal:** recognize a simple 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

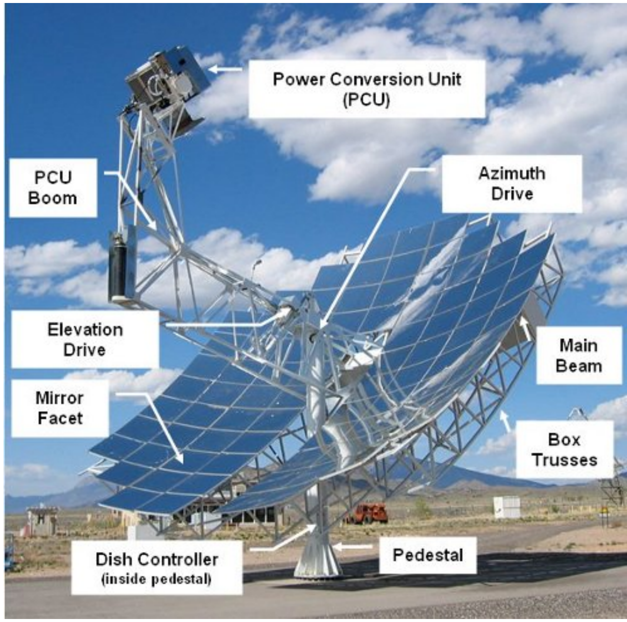
Open and Closed Gas Power Cycles

- **Gas power cycles** use gas as working fluid throughout the whole cycle
- **Open cycle**
  - Working fluid exchanged with environment (intake & exhaust)
  - Internal Combustion (IC)
  - Working fluid: Air + Fuel → Air + Combustion Products
  - Examples: Otto, Diesel, Brayton (Gas Turbine) cycles



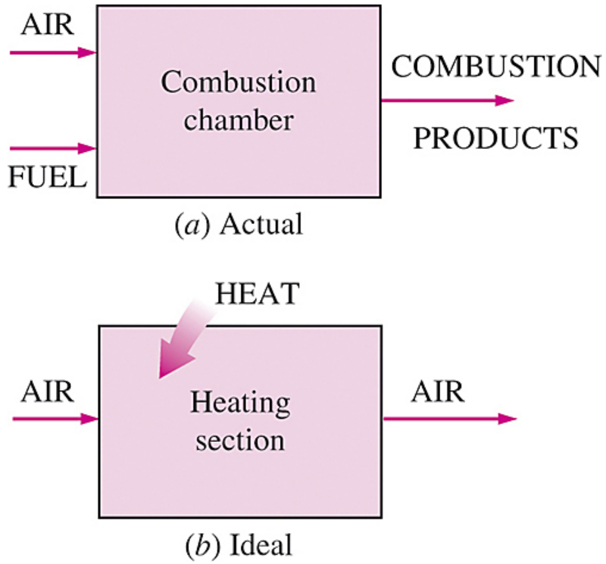
- **Closed cycle**
  - Working fluid completely sealed (not exchanged with environment)
  - External "Combustion" (EC), nuclear & geothermal, solar energy possible
  - Helium common working fluid
  - Example: Stirling

Solar Stirling engine



The Air Standard Cycle

- The **air-standard cycle** approximates the actual, real gas cycle with some simplifications
  - Good for comparing trends
  - Not good for detailed analyses



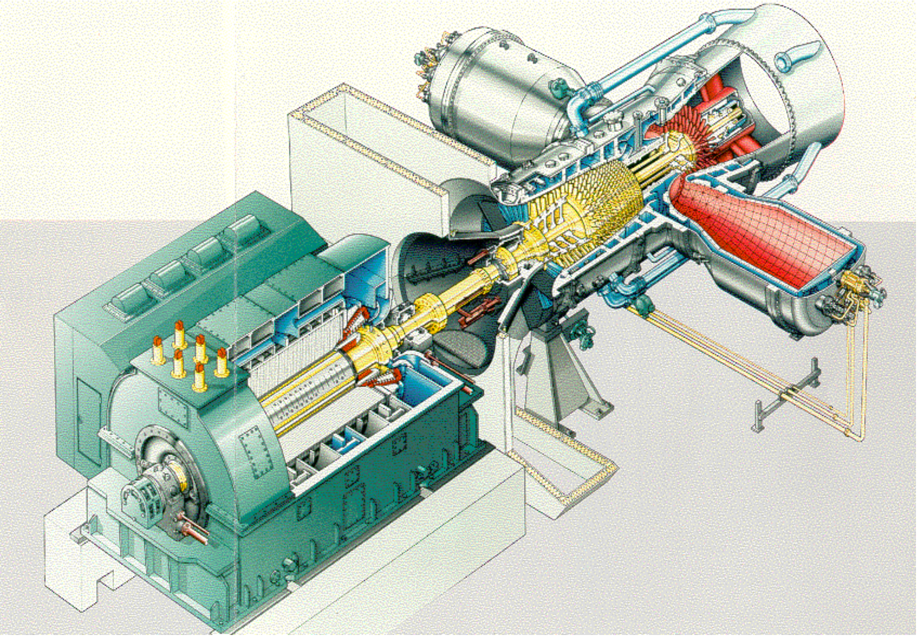
- **Air-standard assumptions**
  1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas (fuel and combustion products are neglected)
  2. All the processes that make up the cycle are internally reversible
  3. The combustion process is replaced by a heat-addition process from an external source
  4. The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state
- **Cold-air-standard assumptions:** the working fluid is considered to be air with constant specific heats at room temperature (25°C)

The Brayton Cycle

- The **Brayton cycle** refers to the cycle associated with gas turbine - compressor engines
- They are used in
  - Aircraft
  - Ships
  - Stationary power generation

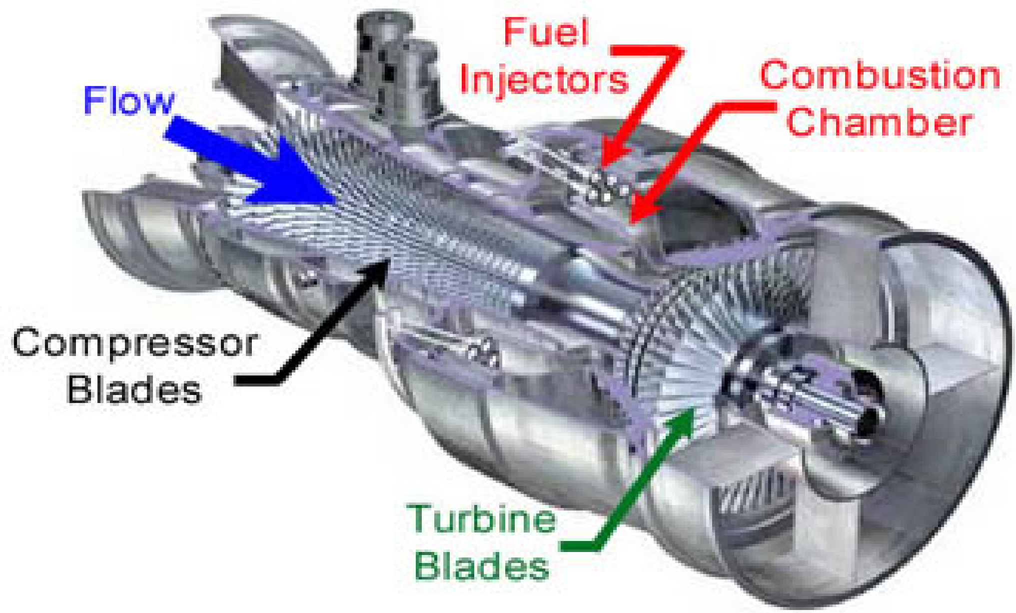
Siemens V94.3 200 MW Gas turbine cycle for electricity production (the green device connected to the axis is the generator)

Pratt & Whitney



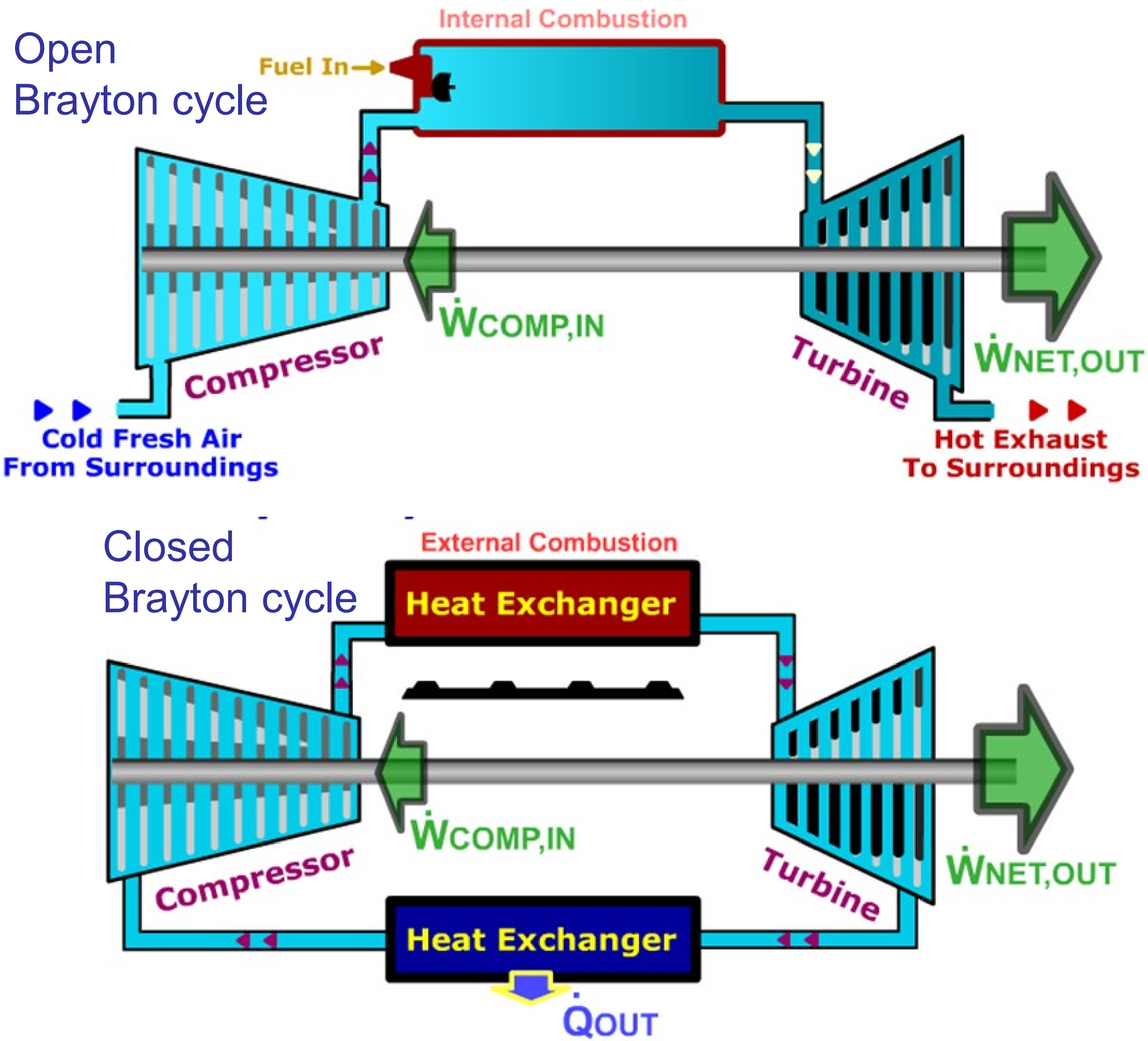
The Brayton Cycle

- The cycle is originally developed by **George Bailey Brayton** (1830-1892) for use in piston engines
  - 2 constant pressure and 2 constant entropy processes (ideal)
- **Open** versus **closed** Brayton cycle
  - Commercial gas turbines are open cycles
  - Some research gas turbines are closed cycles



- Why can a gas turbine cycle working with air not be a closed cycle?

Open versus closed Brayton Cycle



- Almost all gas turbine cycles commercially used are open cycles
- Why can a gas turbine cycle working with air not be a closed cycle?
- The use air with internal combustion, this consumes the oxygen in the air, after a few rounds there is not enough oxygen left for the combustion process

Gas Turbine Rotor

V94.2, 157 MW, rotor

V64.3A, 67 MW, rotor / annulaire combustor

Principle of the Ideal Brayton Cycle

Principle of the ideal closed Brayton cycle (reversible)

- **1 → 2: Isentropic compression (w_{in})**

Air enters the compressor and is compressed to a higher pressure, the compressor is assumed to be adiabatic and ideal (reversible, isentropic) work is taken from the turbine

- **2 → 3: Isobaric heat addition (q_{in})**

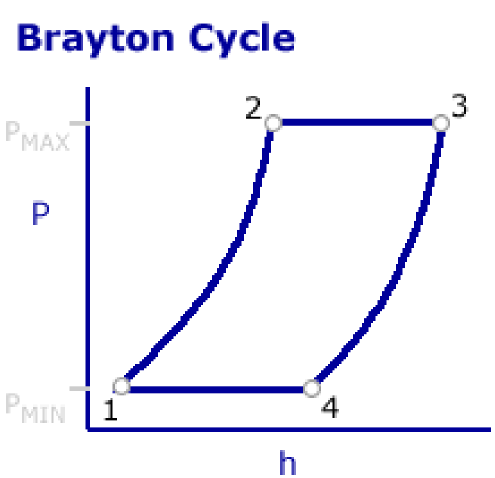
At high pressure, combustion occurs in the combustion chamber, heat is added at constant (high) pressure

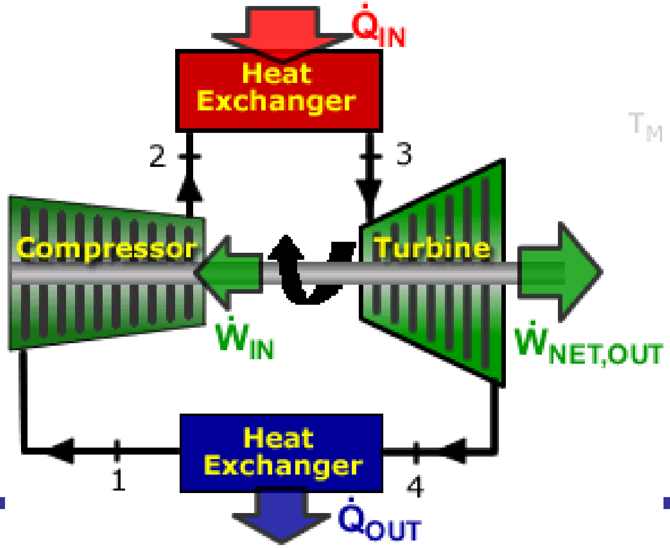
- **3 → 4: Isentropic expansion (w_{out})**

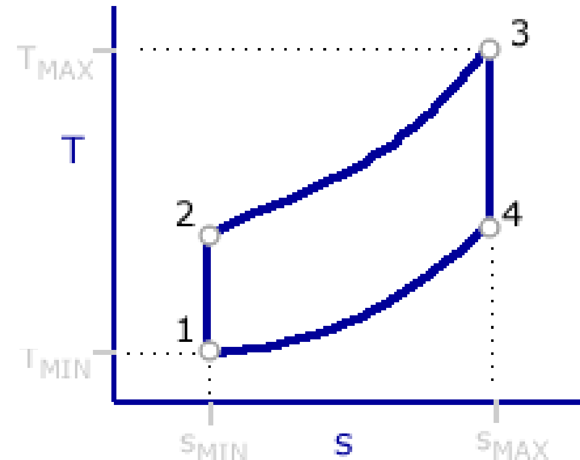
The hot gasses are expanded in the turbine producing work, the turbine is assumed to be adiabatic and ideal (reversible, isentropic)

- **4 → 1: Isobaric heat rejection (q_{out})**

Heat rejection at constant low pressure, in a closed cycle a heat exchanger is use to cool the gases till the inlet temperature, **in an open cycle the gases are feed into the air**



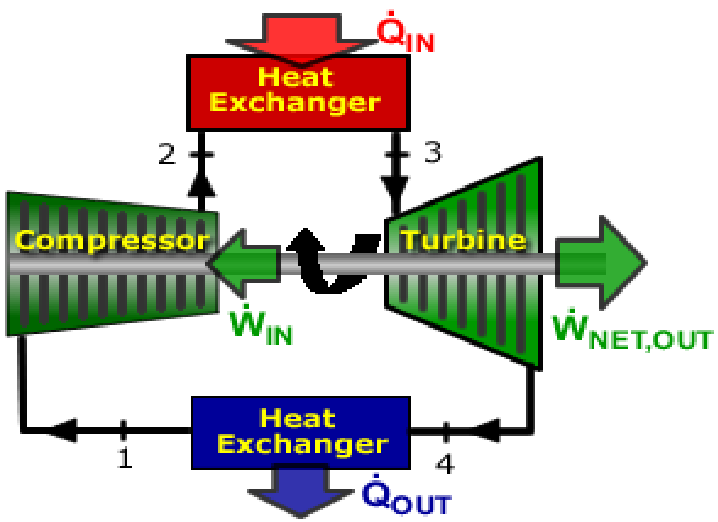


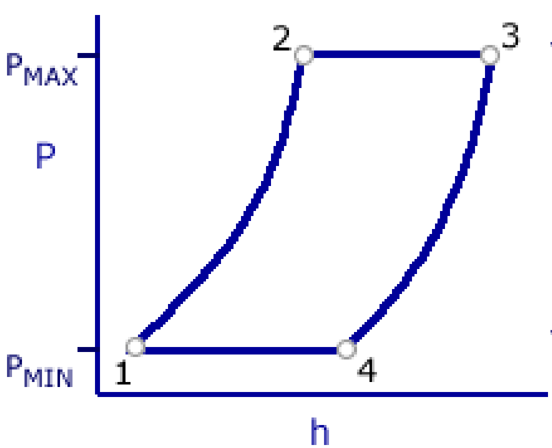


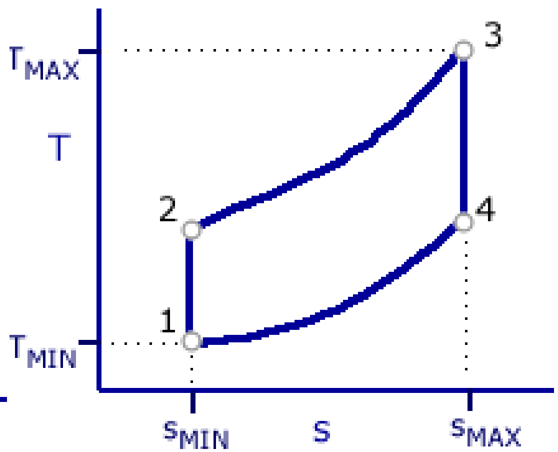
Ideal Brayton Cycle Analysis

- **Closed ideal Brayton cycle** (Reversible → $s_{GEN} = 0$)

Process	Component	q	w	Const.
1 → 2 Isentropic compression	Compressor	0	w_{IN}	s
2 → 3 Isobaric heating	Heat Exchanger	q_{IN}	0	P
3 → 4 Isentropic expansion	Turbine	0	w_{OUT}	s
4 → 1 Isobaric cooling	Heat Exchanger	q_{OUT}	0	P



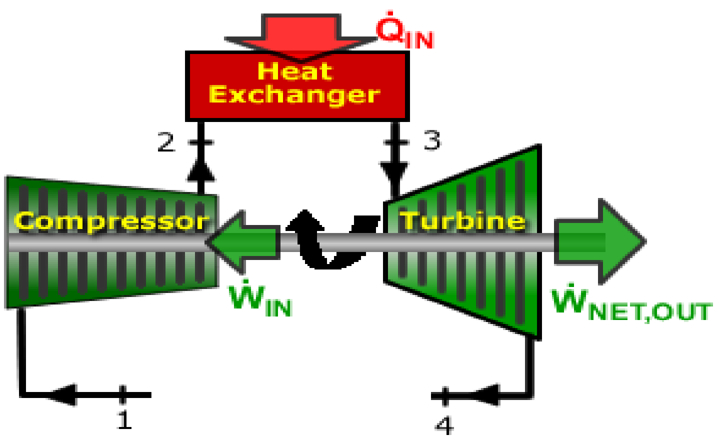


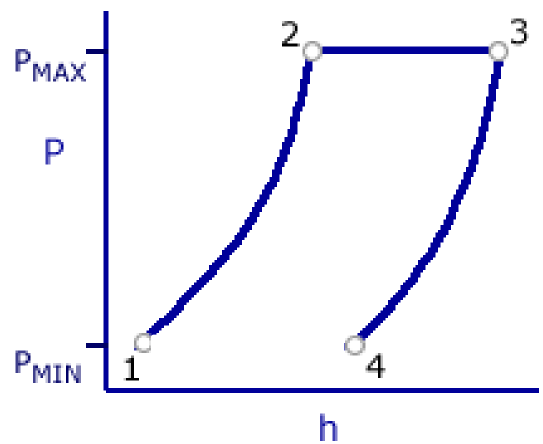


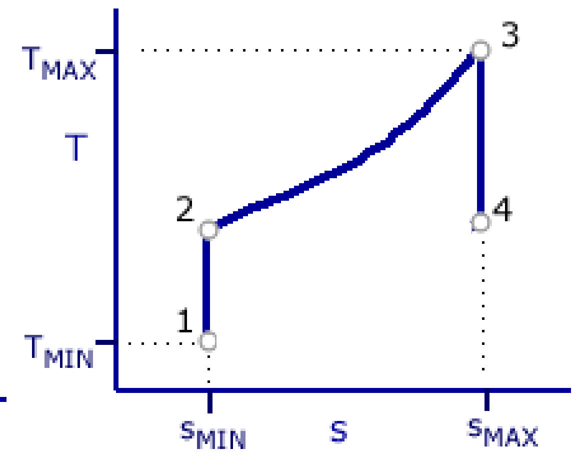
Ideal Brayton Cycle Analysis

- **Open ideal Brayton cycle** (Reversible → $s_{GEN} = 0$)

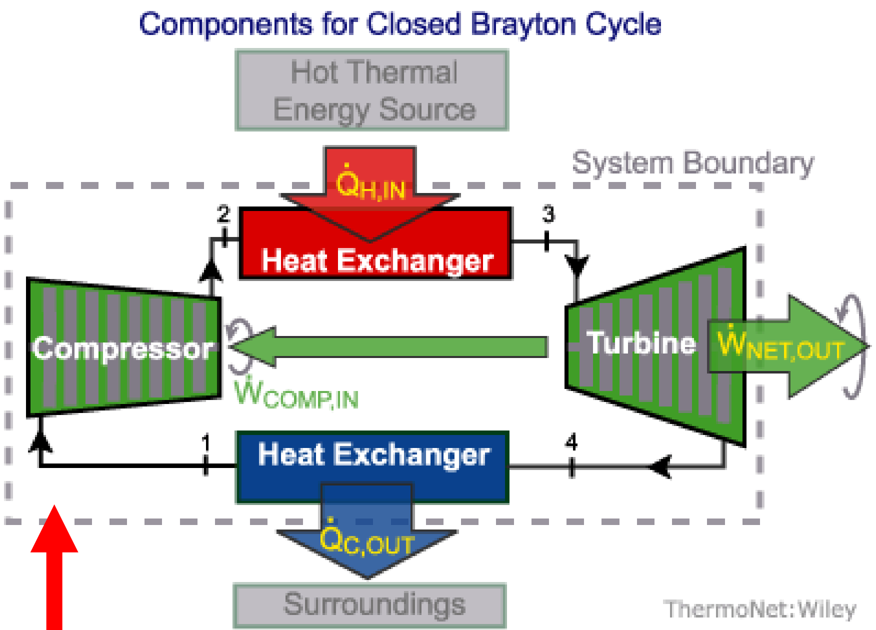
Process	Component	q	w	Const.
1 → 2 Isentropic compression	Compressor	0	w_{IN}	s
2 → 3 Isobaric heating	Combustion chamber	q_{IN}	0	P
3 → 4 Isentropic expansion	Turbine	0	w_{OUT}	s
4 → 1 Isobaric cooling	Exhaust hot combustion gasses & intake fresh cold air	q_{OUT}	0	P

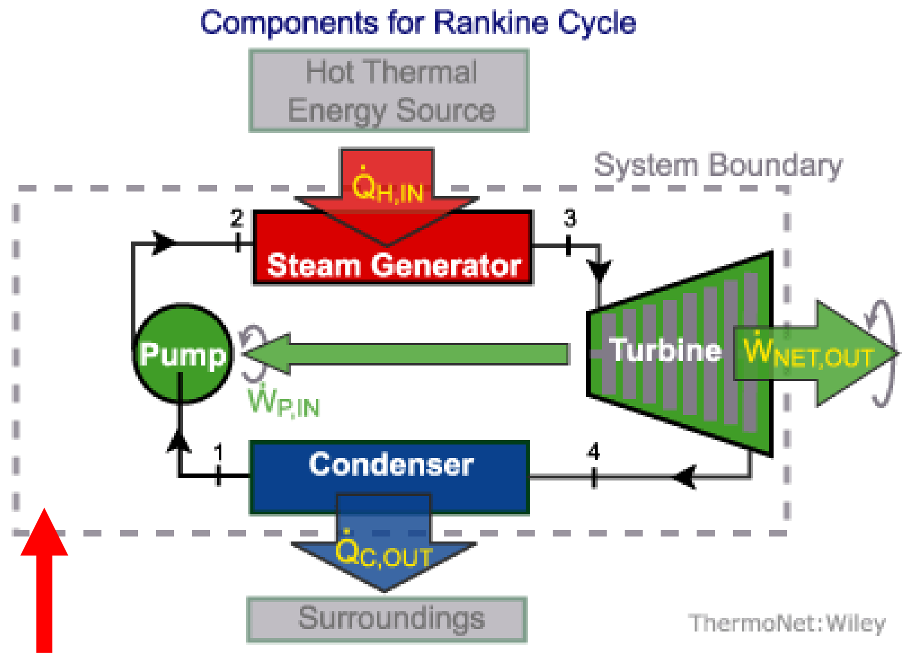






Comparison of Brayton to Rankine Cycle

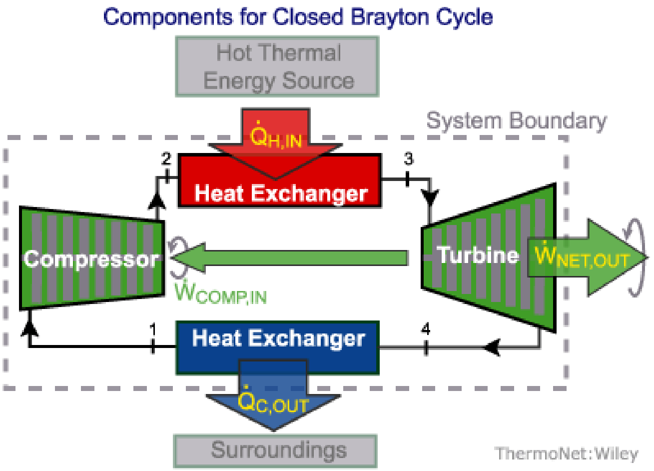


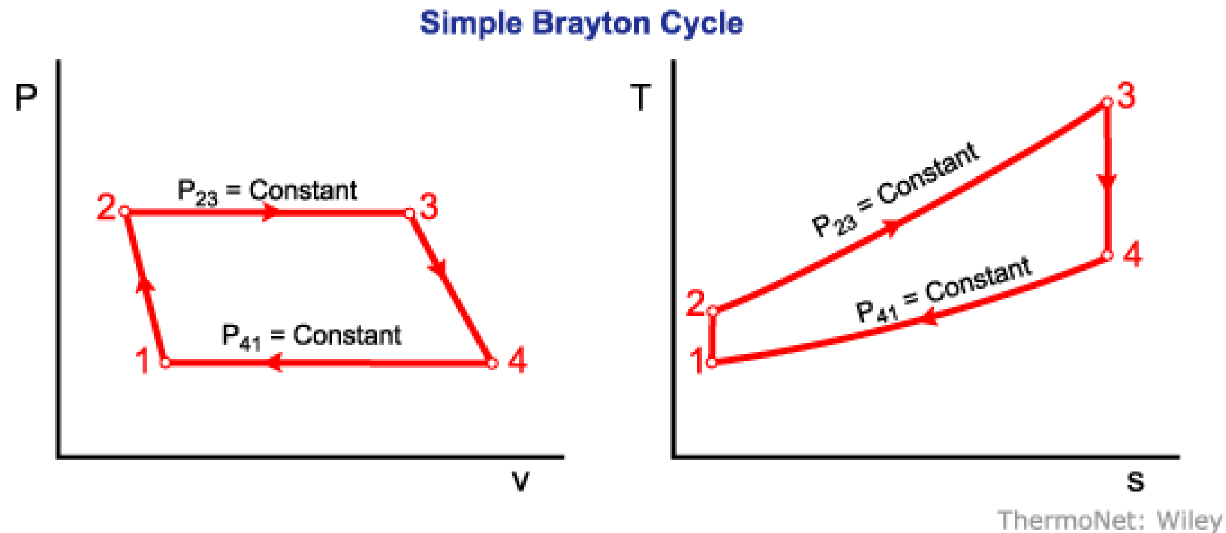


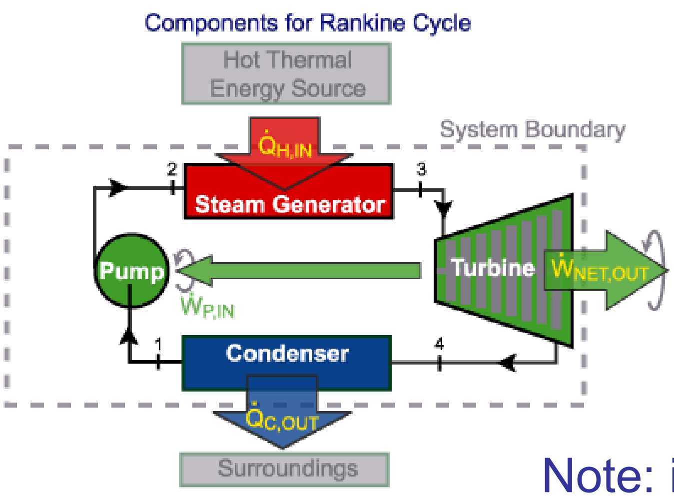
- Brayton cycle
  - Air everywhere
  - Compressor instead of pump
- Rankine cycle
  - Liquid at the pump
  - Vapor (gas) at the turbine
  - Phase change in steam generator and condenser

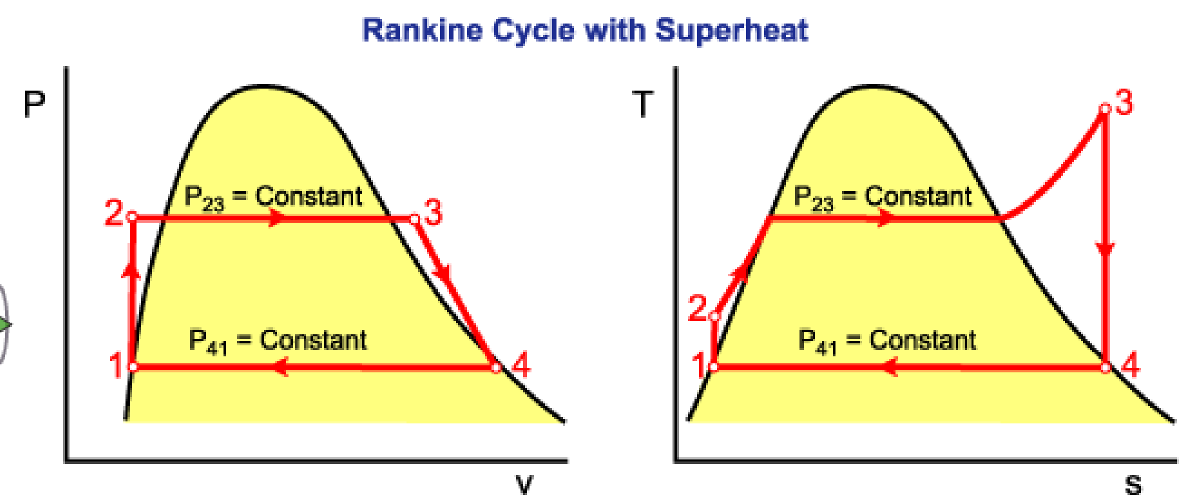
- Compare the Rankine cycle to the Brayton cycle
  - The pump for liquid changed by a compressor for air
  - Condenser for phase transition changed by a heat exchanger for air

Comparison of Brayton to Rankine Cycle









Note: in the Brayton cycle (gas turbine) no saturation region as the working fluid is in the gas phase during the whole cycle

Comparison of Brayton to Rankine Cycle

Process	States	Constant Property	Phase: Brayton	Phase: Simple Rankine
Pressure Increase	1→2	s	Ideal Gas	Liquid
Heat Transfer to Working Fluid	2→3	P	Ideal Gas	Liq.-Vapor
Expansion	3→4	s	Ideal Gas	Liq.-Vapor
Heat Transfer from Working Fluid	4→1	P	Ideal Gas	Liq.-Vapor
Property Source			Air Tables Air Diagram Ideal Gas Law	Steam Tables Steam Diagram No analytical relations

Comparison of Rankine to Brayton Cycle

- The **back work ratio** is the ratio of the compressor input work to the turbine output work → $\text{back work ratio} = \frac{w_{in-comp-or-pump}}{w_{out-turbine}}$,
  - **Modern Rankine cycle:** $\text{back work ratio} = \frac{w_{in-pump}}{w_{out-turbine}} \sim 0.01$
  - **Modern Brayton cycle:** $\text{back work ratio} = \frac{w_{in-comp}}{w_{out-turbine}} 0.50$

- **Why is this ratio so different?**
  - The input work is the work required to compress the working fluid
  - This work is proportional to the volume change → **δw = Pdv**
    → volume change liquid << volume change gas → $w_{in,liquid} << w_{in,gas}$

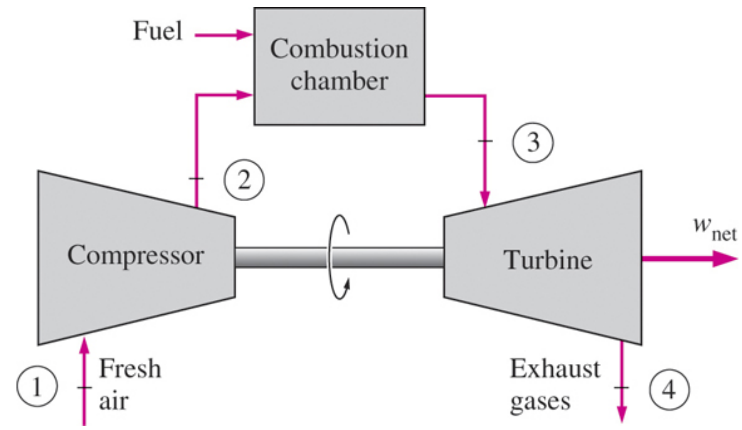
- Therefore, a Rankine cycle can operate with an inefficient pump and turbine: 1712 Thomas Newcomen's steam engine used in coal mines
- But for a Brayton cycle to work an efficient compressor and turbine is needed: 1939 First flight of turbojet engine using Hans von Ohain design

Ideal Brayton Cycle Analysis

- Modeling of the **ideal Brayton cycle** (note: ideal i.e., assumed to be reversible $\rightarrow s_{GEN} = 0$)
- Model each component as an open system at SSSF like in the Rankine cycle
- Use standard air cycle assumptions
  - Neglect fuel and assume the working fluid to be pure air behaving as an ideal gas
  - Combustion is replaced by a heat transfer process in which heat is added
- Mass flow rate through each component in the cycle is constant
- Cycle can be analyzed analytical (use of formulas), graphical (Mollier diagram) or by using tables

Work and Power Output Brayton Cycle

- The work of the Brayton cycle is produced by the turbine (3-4)
- However, the compressor consumes work (1-2)
- The work used by the compressor is taken from the produced work by the turbine

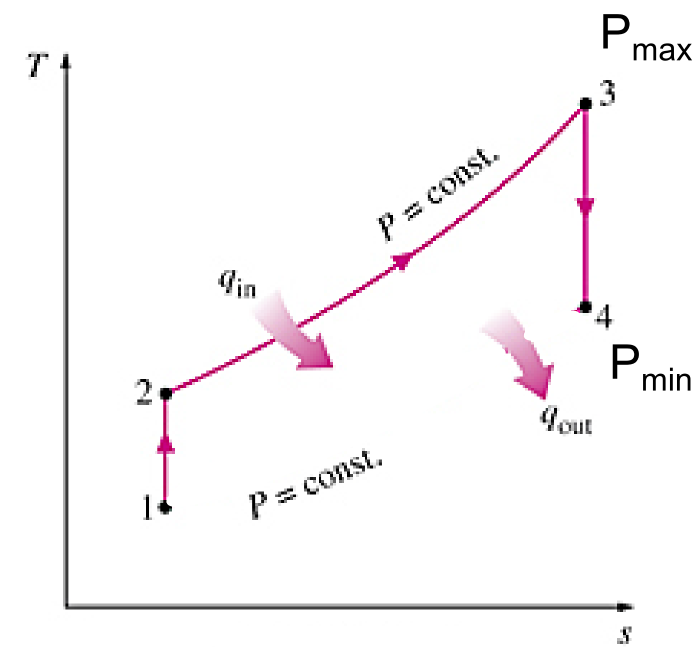


- **The work produced by the turbine:**

$$w_{turbine} = w_{out} = w_{3\text{-}4} = h_3 - h_4 \quad (kJ/kg)$$

- **The work consumed by the compressor**:

$$w_{compr} = w_{in} = w_{1\text{-}2} = h_2 - h_1 \quad (kJ/kg)$$



Work and Power Output Brayton Cycle

- **The work produced by the turbine:**

  $w_{turbine} = w_{out} = w_{3\text{-}4} = h_3 - h_4 \quad (kJ/kg)$

- **The work consumed by the compressor**:

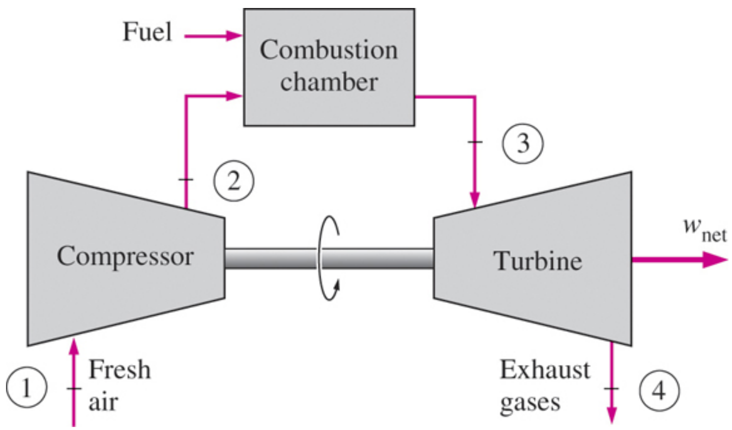
  $w_{compr} = w_{in} = w_{1\text{-}2} = h_2 - h_1 \quad (kJ/kg)$

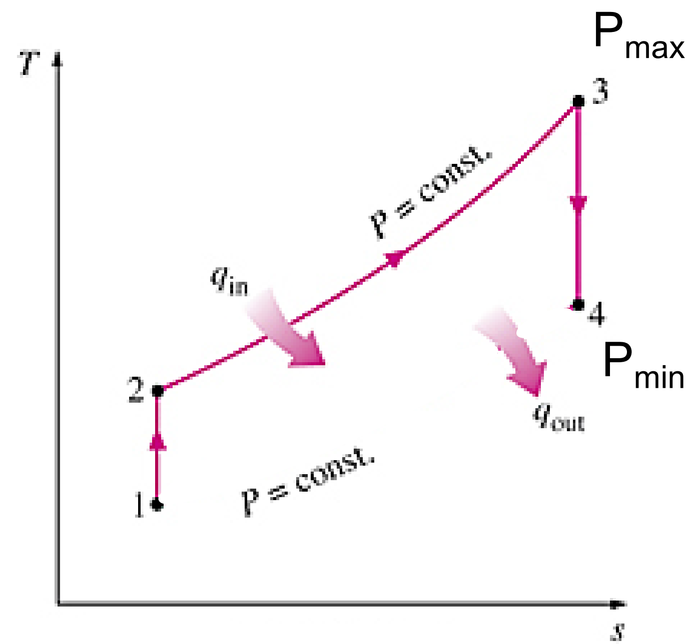
- The **net work output** of the gas turbine per kg fluid is:

  $w_{net} = w_{out} - w_{in} = w_{turbine} - w_{compressor}$
  $= (h_3 - h_4) - (h_2 - h_1) \quad (kJ/kg)$

- The **total net power** is:

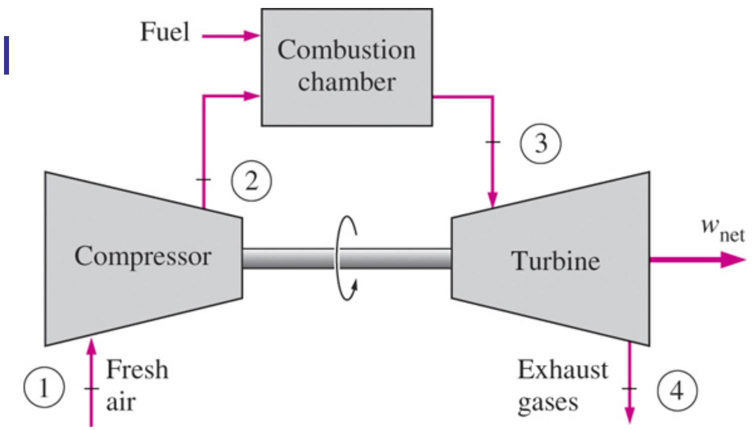
  $\dot{W}_{net} = \dot{m} w_{net} = \dot{m}[(h_3 - h_4) - (h_2 - h_1)]$
  (kg/s*kJ/kg = kJ/s = kW)





Heat and Power Input Brayton Cycle

- Heat is added to the Brayton cycle in the combustion chamber by combustion of fuel (2-3)
- Heat is rejected to the environment (4-1)

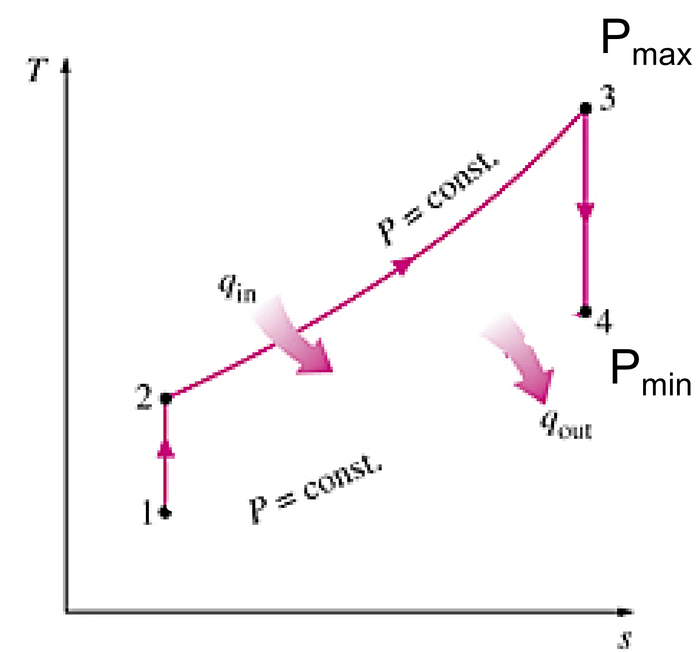


- **The heat input to the cycle:**

  $q_{combustion} = q_{in} = q_{2\text{-}3} = h_3 - h_2 \quad (kJ/kg)$

- **The heat rejected by the cycle:**

  $q_{out} = q_{4\text{-}1} = h_4 - h_1 \quad (kJ/kg)$



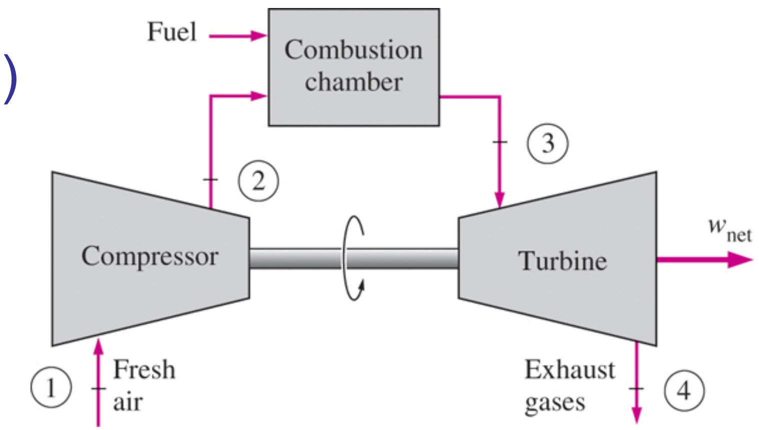
Heat and Power Input Brayton Cycle

- **The heat added to the cycle:**

  $$q_{combustion} = q_{in} = q_{2\text{-}3} = h_3 - h_2 \quad (\text{kJ/kg})$$

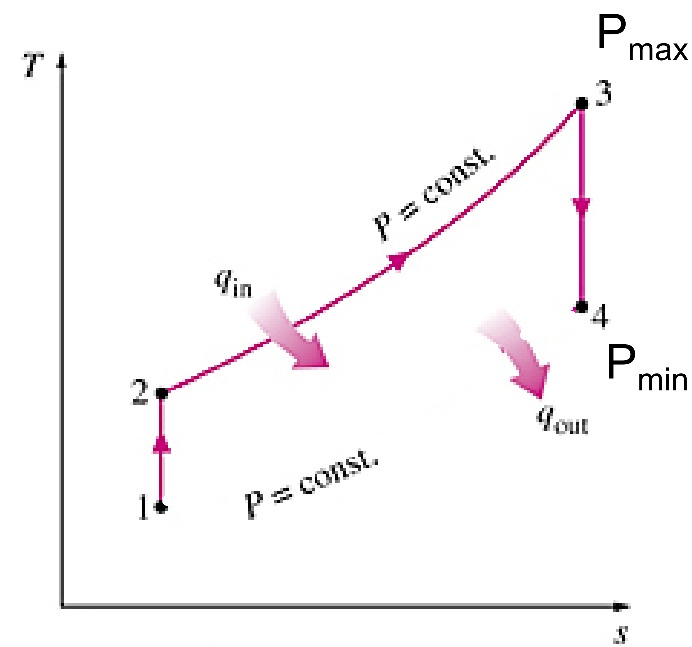
- **The heat rejected by the cycle:**

  $$q_{out} = q_{4\text{-}1} = h_4 - h_1 \quad (\text{kJ/kg})$$



- The **power input** is:

  $$\dot{Q}_{in} = \dot{m}q_{in} = \dot{m}(h_3 - h_2) \quad (\text{kJ/s = kW})$$



- Values of h can be looked up in the tables or in a graph (Mollier diagram) or can be calculated for ideal cycles (analytical)

Brayton Cycle Efficiency

- The **net work output** of the gas turbine per kg fluid is:
  - $w_{net} = w_{out} - w_{in} = w_{turbine} - w_{compressor} = (h_3 - h_4) - (h_2 - h_1)$ (kJ/kg)

- The **heat added** to the cycle:
  - $q_{combustion} = q_{in} = q_{2\text{-}3} = h_3 - h_2$ (kJ/kg)

- **Efficiency Brayton** cycle:

$$\eta_{Brayton} = \frac{\text{Wanted}}{\text{Payed for}} = \frac{\dot{w}_{net}}{\dot{q}_{in}} = \frac{\dot{m} w_{net}}{\dot{m} q_{in}}$$

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

Brayton Cycle Efficiency

- **Efficiency Brayton** cycle:

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

- For a Brayton cycle with **ideal air standard assumptions** (ias) the efficiency can be rewritten as

$$\eta_{Brayton,ias} = \frac{C_p(T_3 - T_4) - C_p(T_2 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1}{T_2}\frac{(T_4/T_1 - 1)}{(T_3/T_2 - 1)} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

- In the evaluation relations derived for an ideal gas (class 9) are used
  - $dh = c_p dT$ and $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$

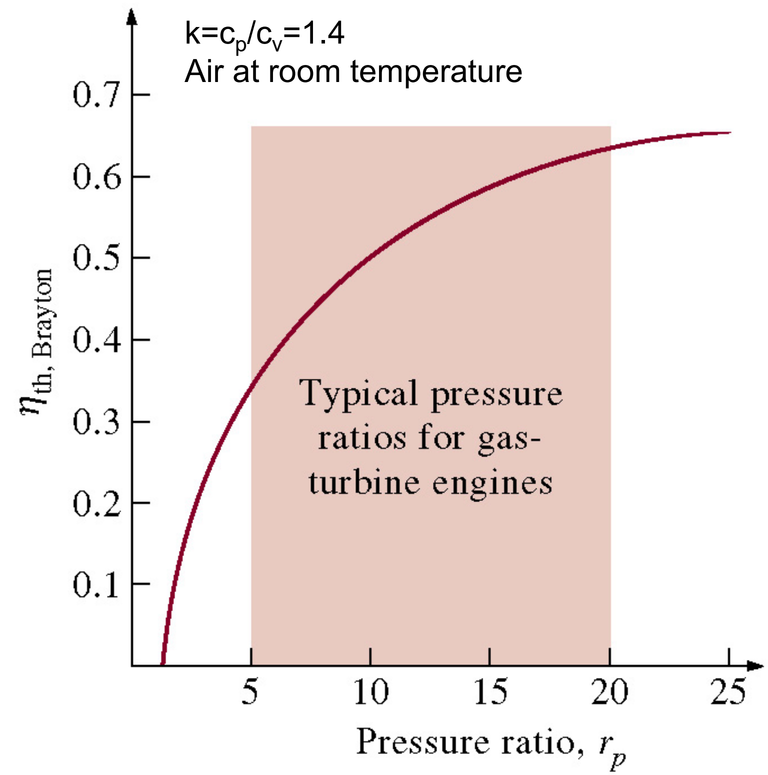
- Note that his relation is only valid under the assumption that C_p does not depend on the temperature and when the compressor and turbine are ideal
- However, it can be used to determine the effect of different parameters on the efficiency

Brayton Cycle Efficiency

- **Efficiency Brayton, ideal air standard cycle:**

$$\eta_{Brayton,ias} = \frac{w_{net}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

- The formula shows that the efficiency only depends on the pressure ratio across the compressor and k
- For fixed T_{Max} (turbine inlet temperature)
  - Efficiency increases with r_P
  - $w_{net} = w_{turb.out} - w_{compr.in}$ decreases with r_P
  - Compromise between efficiency and work output
- T_{MAX} limited by materials (material sciences !)



BREAK

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

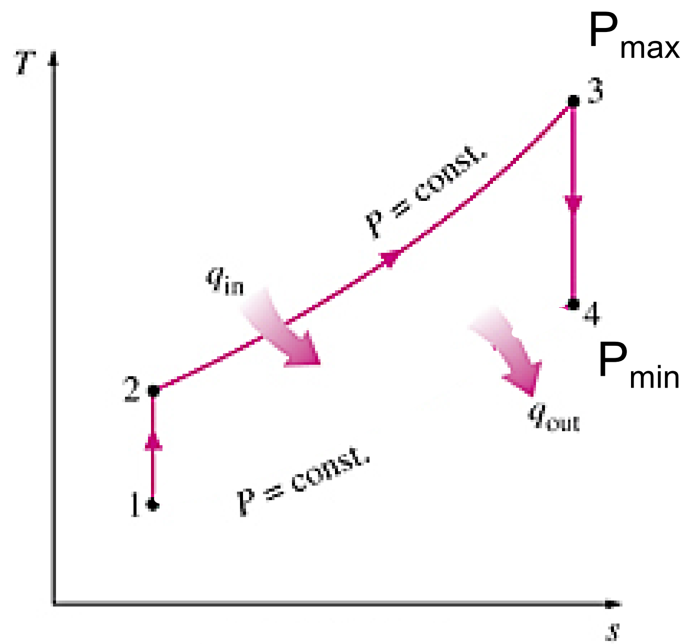
Design parameters Brayton Cycle

- **How can the efficiency of the basic Brayton cycle be increased?**

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

- **Remember**
  - The net work output is the area enclosed by the cycle 1 – 2 – 3 – 4
  - The net heat input is the area below the curve 2 – 3

- **This area can be enlarged by**
  - Increasing the turbine inlet temperature
  - Increasing the pressure ratio
  - Changing the type of working medium

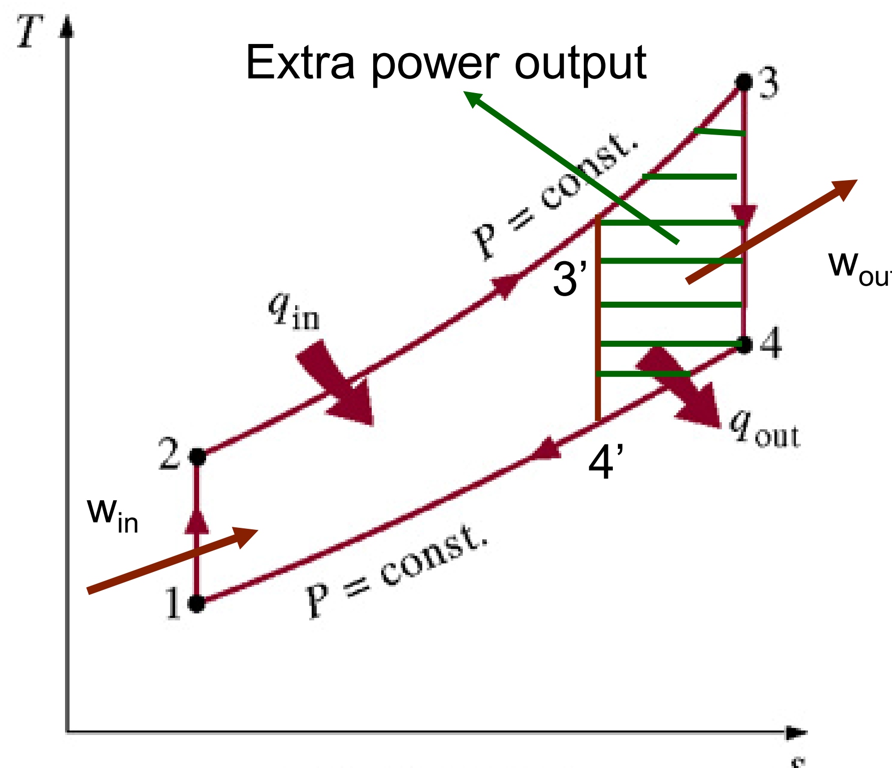


Design parameters Brayton Cycle

- **The effect of increasing the turbine inlet temperature on the ideal Brayton cycle**

- Increasing the turbine inlet temperature increases the area enclosed by the cycle 1-2-3-4 and W_{net} increases
- But the area below the curve 2-3, the heat input also increases
- However, the efficiency increases as the average temperature at which heat is added to the cycle increases

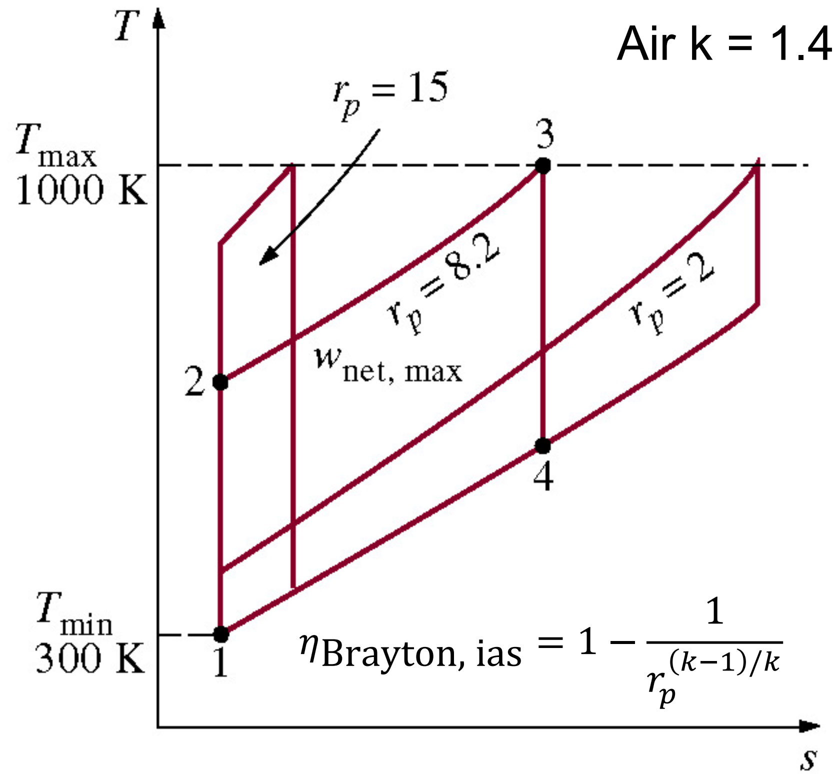
- T_{max} is restricted by the materials, but sometimes blades are actively cooled to reach higher temperatures
- Nowadays temperatures vary between 1000-1600 K



(a) T-s diagram

Design parameters Brayton Cycle

- **The effect of changing the compression ratio on the ideal Brayton cycle** → optimal pressure ratio at a given T_{max} and T_{min}
- The efficiency increases with higher compression ratio
- However, the maximum compression ratio is restricted by the maximum temperature in the cycle



- For fixed values of T_{min} and T_{max} the net work of the Brayton cycle first increases with pressure ratio, then reaches a maximum at

$r_p = \left(\frac{T_{max}}{T_{min}}^{k/2(k-1)}\right)$ and finally decreases

- In most common designs, the pressure ratio of gas turbines ranges from about 11 to 16

Design parameters Brayton Cycle

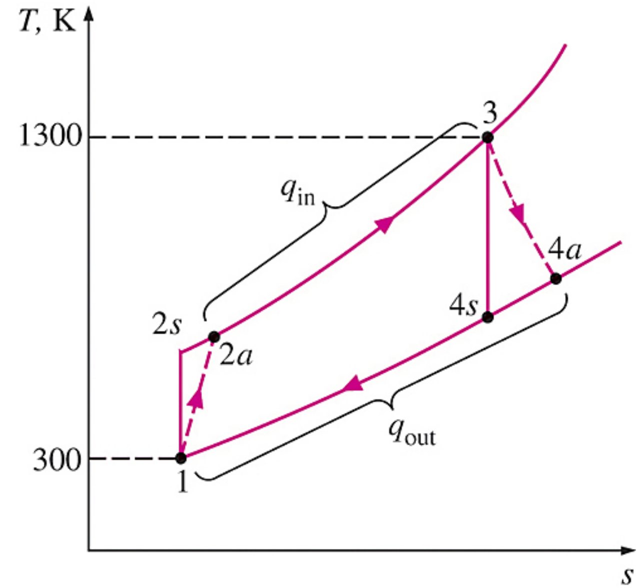
- **The effect of changing the working fluid on the ideal Brayton cycle**
- The efficiency depends on k, the ratio of the specific heats of the working fluid, $k = {}^{c_p}/_{c_v}$: $\eta_{Brayton,ias} = 1 - \frac{1}{r_p^{(k-1)/k}}$
- The formula shows that the efficiency increases with increasing value of k
- At room temperature (300 K)
  - Air, nitrogen, oxygen: k = 1.4
  - Helium, argon, neon: k = 1.66
- Note: gasses like He, Ar and Ne are only possible in closed systems and no internal combustion can be applied

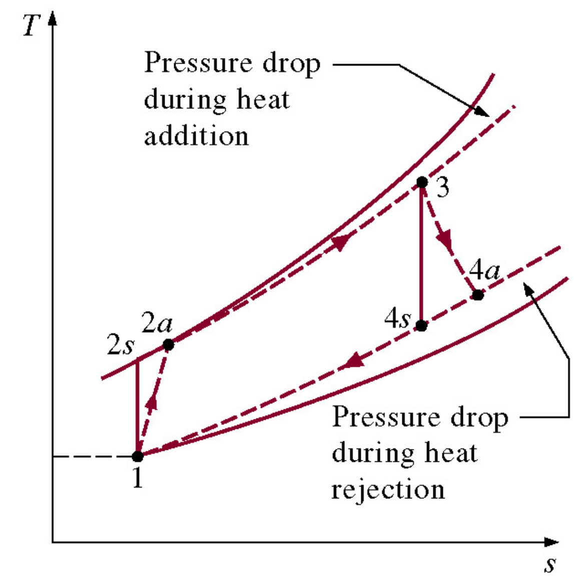
Effect of Component Efficiencies

- Thus far the modeling assumed a reversible (ideal) Brayton cycle
- However, there is a major departure from the ideal cycle due to irreversibilities in the compressor and turbine

- In process 1-2 and 3-4 the entropy increases
- Take the isentropic efficiency of the compressor and the turbine into account

- In a real gas turbine also, pressure drop occurs in the heat addition and rejection processes, however this can be neglected in the analysis





Effect of Component Efficiencies

- **Model non-ideal cycle using isentropic efficiencies (class 5)**

- For the **turbine:**

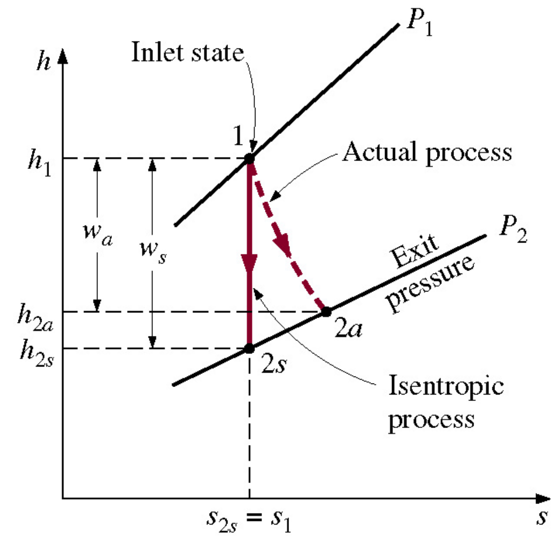
$$\eta_{S,Turbine} = \frac{h_{IN}-h_{OUT,A}}{h_{IN}-h_{OUT,S}} = \left(\frac{T_{IN}-T_{OUT,A}}{T_{IN}-T_{OUT,S}}\right)_{IAS}$$

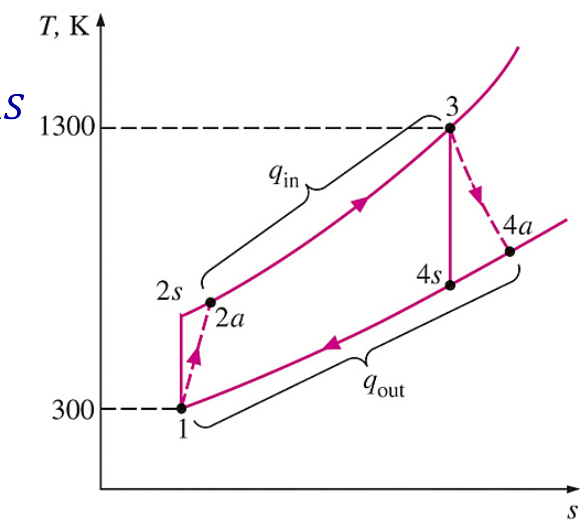
$dh = c_p dT$ and c_p is constant

- For the **compressor:**

$$\eta_{S,Compressor} = \frac{h_{OUT,S}-h_{IN}}{h_{OUT,A}-h_{IN}} = \left(\frac{T_{OUT,S}-T_{IN}}{T_{OUT,A}-T_{IN}}\right)_{IAS}$$

- The entropy must increase
- To calculate the thermal efficiency the actual h values must be used

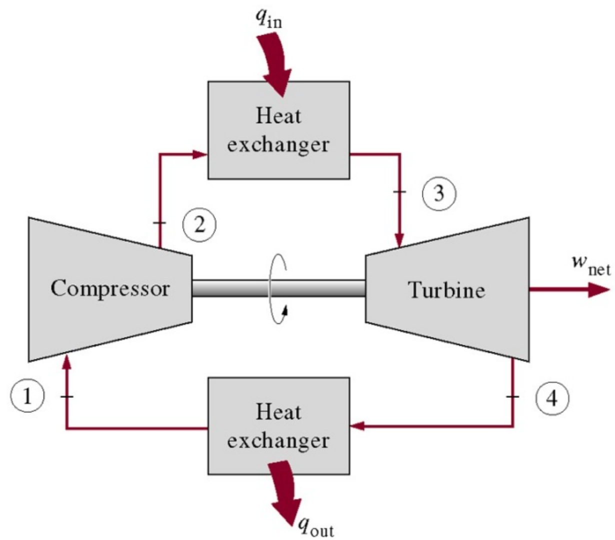


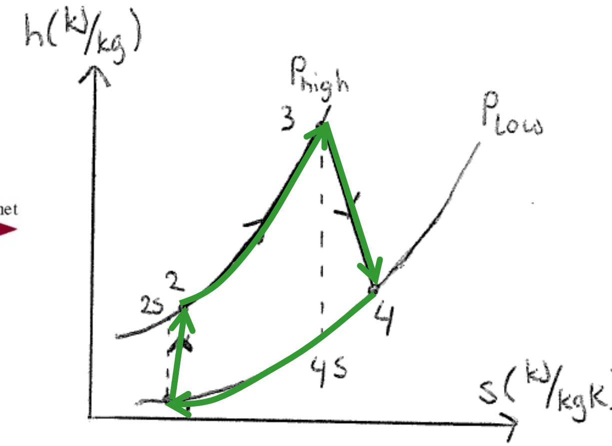


Closed versus Open Brayton Cycle

- **The difference between the open and closed Brayton cycle is the presence of the heat exchanger to reject heat**

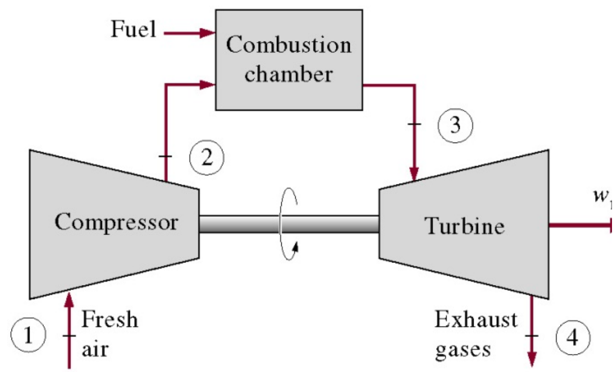
- In the open cycle the air passed through the turbine is blown in the surroundings and fresh air for the compressor is taken from the surroundings

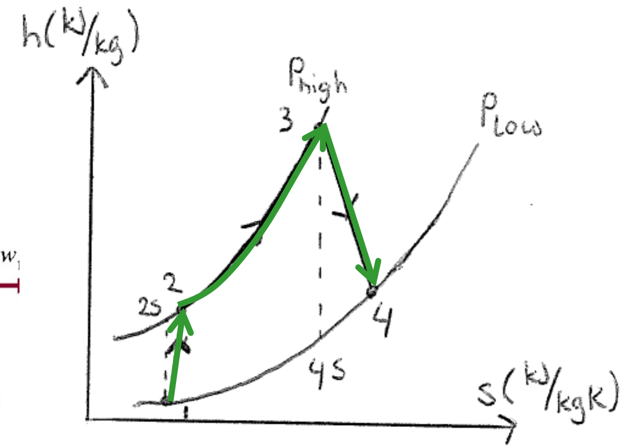




- In the diagram for the open cycle the line 1 to 4 is NOT connected

- Most real gas turbines are open cycles

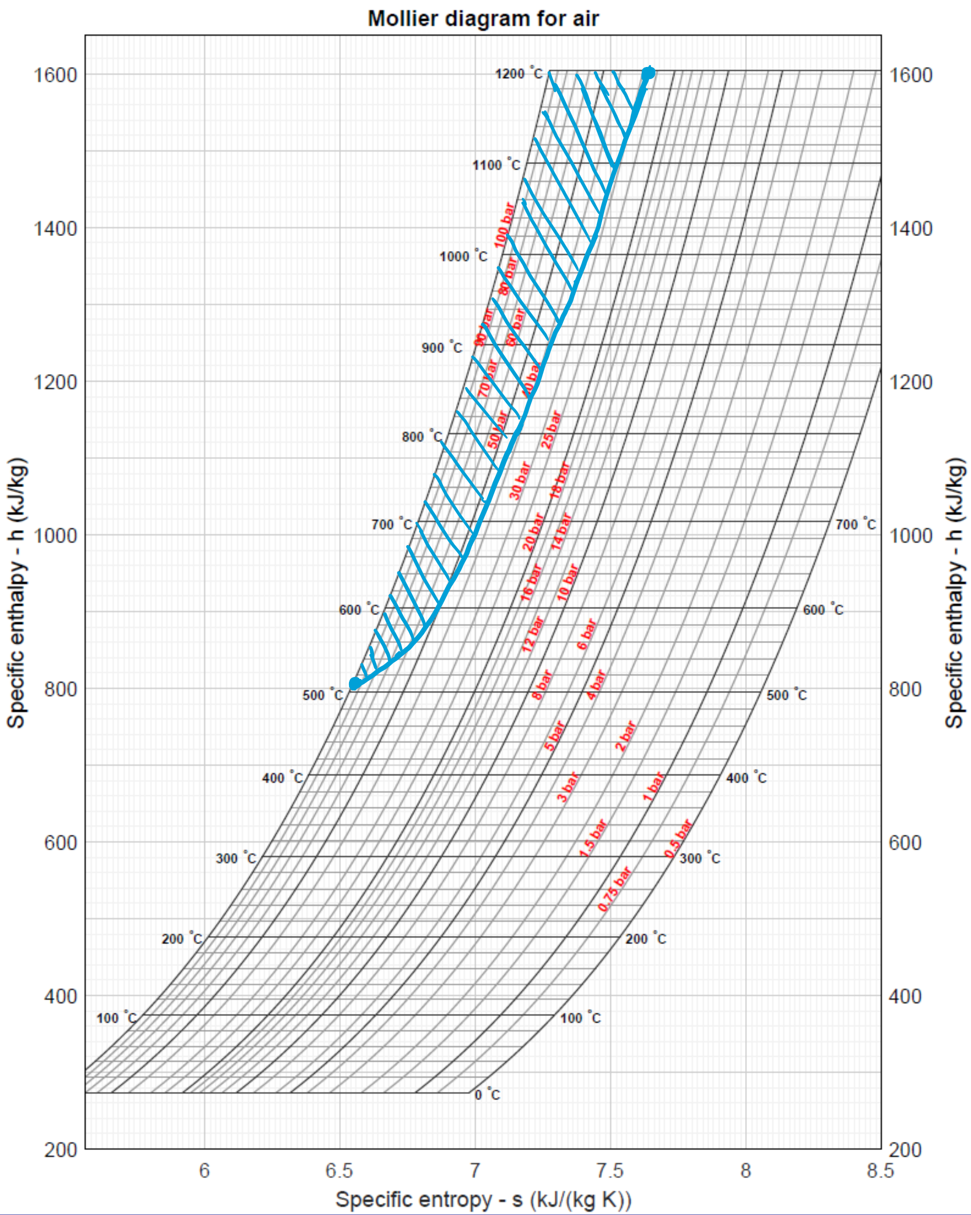




Mollier Diagram Air for Brayton Cycle

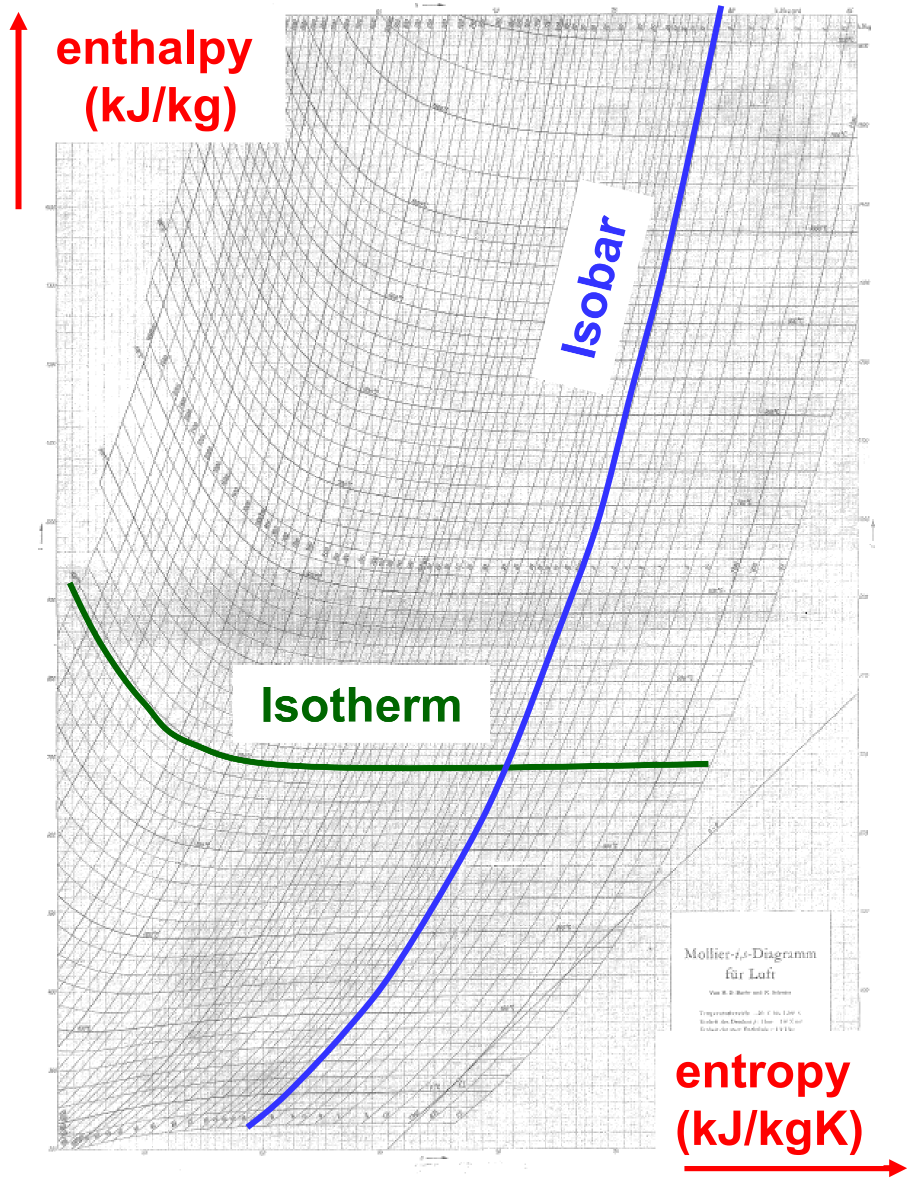
- Enthalpy values for air can also be found using the Mollier diagram
- Diagram is less exact, but gives a good overview of the process

- This diagram is made using Matlab
- In the program some assumptions are made, the most important one is that air is assumed to be an ideal gas, however the dependence of the specific heats on temperature is taken into account
- So, the diagram is valid for air assumed to be an ideal gas
- If the air cannot be assumed ideal (high P and high T indicated in bleu) the values slightly deviate
- We will use this diagram to analyse the gas power cycles (next class)



Mollier diagram air

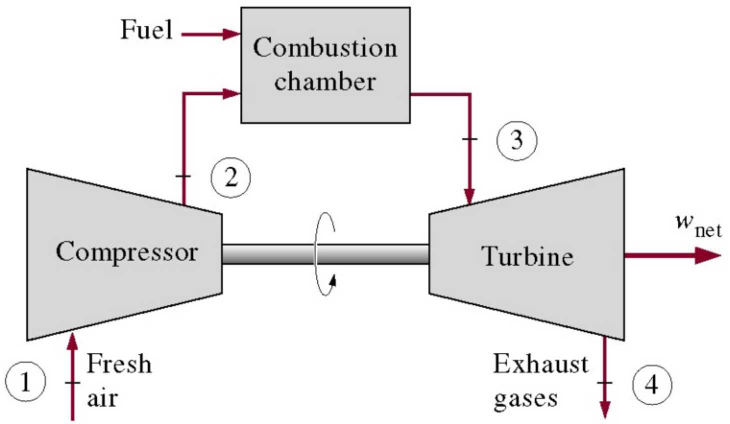
- Scanned version of a Mollier diagram for real air
  - Enthalpy (kJ/kg) on the y-axis, horizontal line → dh = 0
  - Entropy (kJ/kgK) on the x-axis, vertical line → ds = 0
  - Isobars (in **Bar** !!)
  - Isotherms (in degree Celsius)
- The main difference with the one in which the air is assumed to be an ideal gas (previous page) is that the isotherms bend upwards in the high T and high P region where the air cannot be approximated as an ideal gas anymore
- This diagram is mostly used in the answers for the assignments

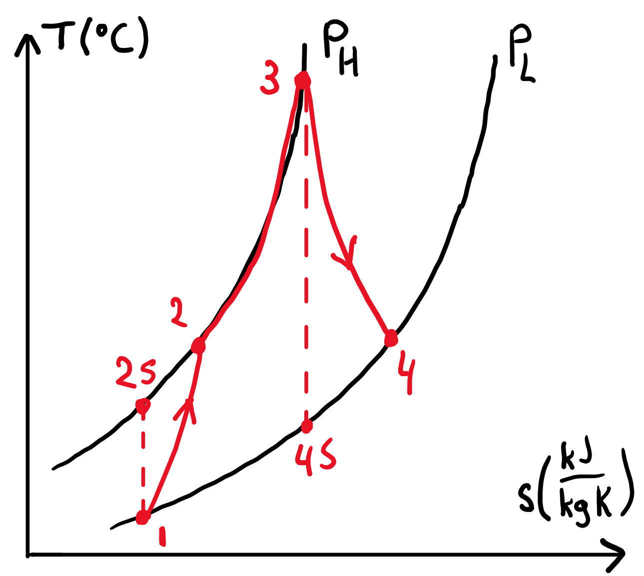


Systematic Analysis of Problems

- Large problems for cycles should be analyzed systematically
- Tables, diagrams or formulas can be used

1. Make a schematic diagram of the setup
2. Number the characteristic points connecting the different devices
3. Sketch the Ts – diagram
4. Collect the two known properties per point in a table (e.g., P, T, s, isentropic efficiency, ……), if known give mass flow or power output
5. Determine the **enthalpy per point** and add it also to the table
6. Now all interesting data, like power in- and output and efficiency can be determined

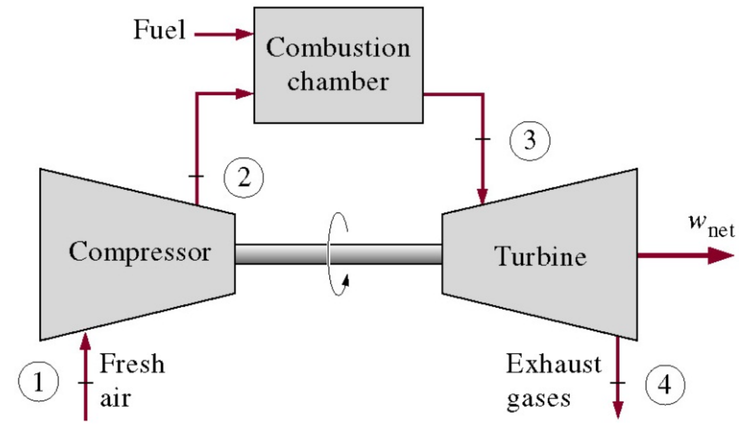


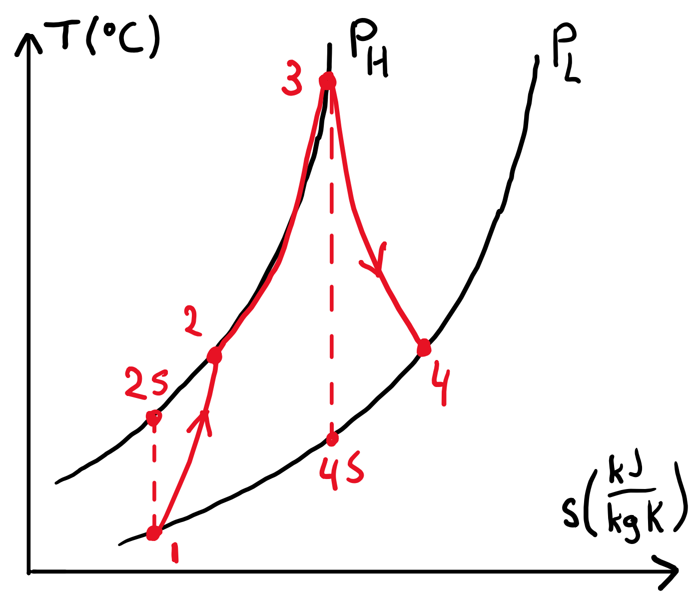


Note on Ts - diagram

- Put parameters along the axis (T and s)
- Add the units along the axis (°C and kJ/kgK)
- Draw the isobars and put the value or indicate P_{high} / P_{low} / P_{medium}
- Indicate the points with the right number
- Put arrows in the direction of the processes
- Use - - - - for isentropic processes
- Use —— for real processes
- Add values along the axis if you know them

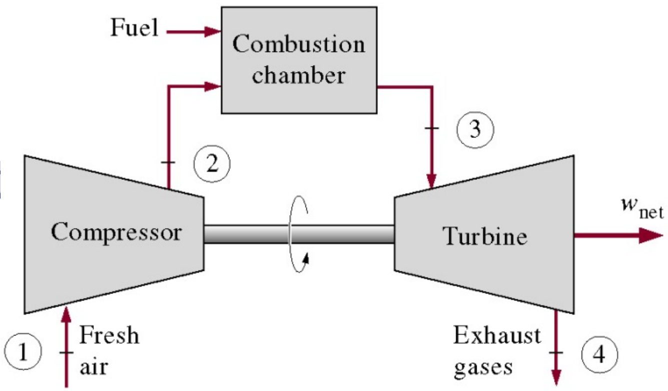
- Do not make them too small
- For air, no vapor dome (I do not want to see that on the exam)





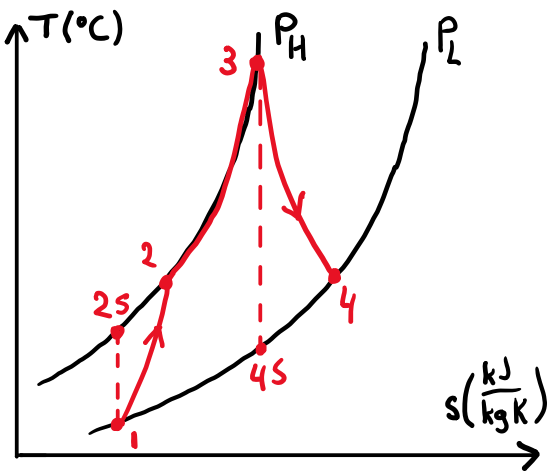
Example Simple Brayton Cycle

- A gas turbine installation undergoes a Brayton cycle
- The inlet conditions are 1 bar and 15°C, the temperature after combustion is 900°C, the pressure ratio is 8, the isentropic efficiencies of the turbine and the compressor are 80% and the mass flow rate is 15 kg/s
- Determine the power output and the efficiency
- Solution start with:
- Scheme, diagram, two characteristics per point



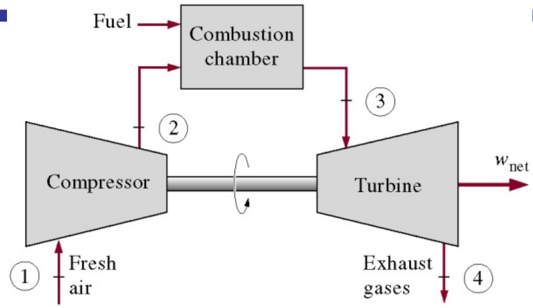
	First	Second
1	P_1=1 bar	T_1=15°C
2s	P_{2s} = $8P_1$	s_{2s} = s_1
2	P_2 = $8P_1$	η=0.8
3	P_2 = P_3	T_3=900°C
4s	P_{4s} = P_1	s_{4s} = s_3
4	P_4 = P_1	η=0.8

Mass flow = 15 kg/s

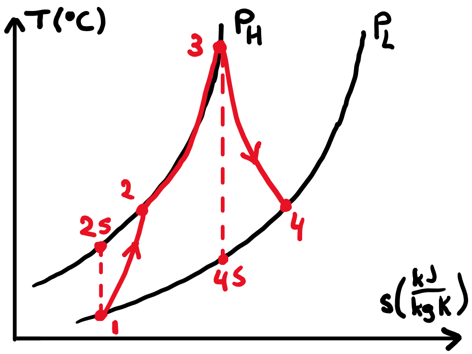


With these basics we can start to find the h values using the Mollier diagram

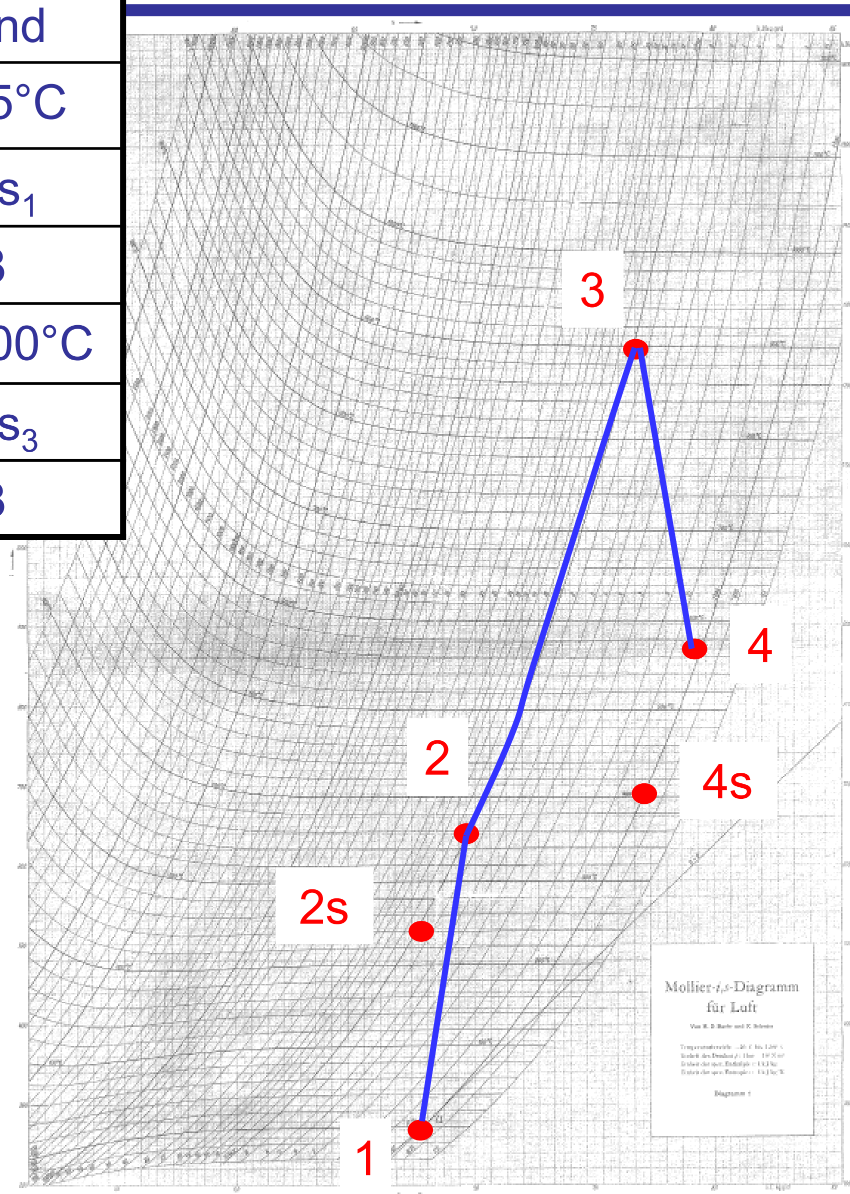
Example Simple Brayton Cycle



	First	Second
1	P_1=1 bar	T_1=15°C
2s	$P_{2s} = 8P_1$	$s_{2s} = s_1$
2	$P_2 = 8P_1$	η=0.8
3	$P_2 = P_3$	T_3=900°C
4s	$P_{4s} = P_1$	$s_{4s} = s_3$
4	$P_4 = P_1$	η=0.8



Mass flow = 15 kg/s

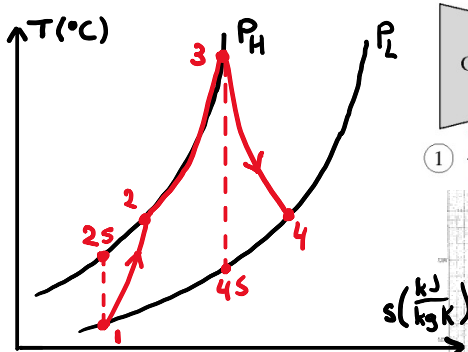


- Point 1: h_1 diagram P_1=1 bar, T_1=15°C
- Point 2s: h_{2s} diagram P_2=8 bar, $s_1 = s_{2s}$
- Point 2: h_2 from $\eta_{S,COMP} = \frac{h_{2S}-h_1}{h_2-h_1}$
- Point 3: h_3 diagram P_3=8 bar, T_3=900°C
- Point 4s: h_{4s} diagram P_4=8 bar, $s_3 = s_{4s}$
- Point 4: h_4 from $\eta_{S,TURB} = \frac{h_3-h_4}{h_3-h_{4S}}$

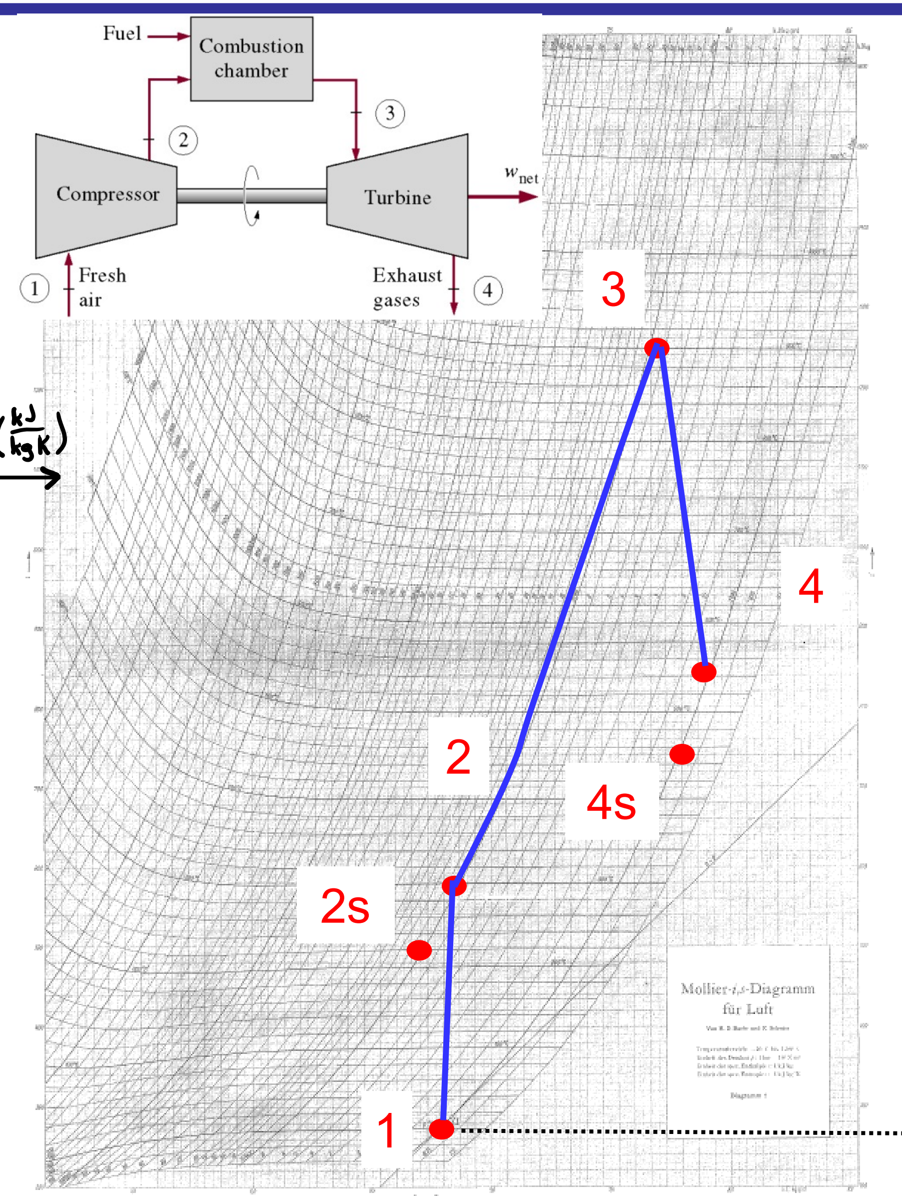
Example Simple Brayton Cycle

- **Find the h value of every point**

	P (bar)	T (°C)	h (kJ/kg)
1	1	15	290
2s	8	220	490
2	8	300	540
3	8	900	1250
4s	1	450	710
4	1	540	818



Mass flow = 15 kg/s



- $w_{in} = h_2 - h_1 = 250$ kJ/kg
- $q_{in} = h_3 - h_2 = 710$ kJ/kg
- $w_{out} = h_3 - h_4 = 432$ kJ/kg
- $w_{net} = w_{out} - w_{in} = 182$ kJ/kg
- $\dot{W}_{net} = \dot{m}(w_{out} - w_{in}) = 15 \cdot 182 = 2730$ kW
- $\dot{Q}_{in} = \dot{m} q_{in} = 15 \cdot 710 = 10650$ kW
- $\eta_{Brayton} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{w_{net}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)} = 0.26 \rightarrow 26\%$

Example Simple Brayton Cycle

- Other characteristics to evaluate the cycle
- **Second law efficiency:** $\eta_{Second\ law,HE} = \frac{\eta_{HE}}{\eta_{CARNOT}}$

(second law efficiency, not for the exam, important for the project)

with $\eta_{\text{Brayton}} = \frac{(h_3-h_4)-(h_2-h_1)}{(h_3-h_2)} = 0.26$

and $\eta_{CARNOT} = 1 - \frac{T_{MIN}}{T_{MAX}} = 1 - \frac{20+273}{900+273} = 0.75$

this gives → $\eta_{Second\ law,HE} = \frac{\eta_{HE}}{\eta_{CARNOT}} = \frac{0.26}{0.75} = 0.35 \rightarrow 35\%$

- **Check the first law** (conservation of energy)
- $e_{in} = e_{out} \rightarrow q_{in} + w_{in} = q_{out} + w_{out} \rightarrow (h_3 - h_2) + (h_2 - h_1) = (h_4 - h_1) + (h_3 - h_4)$

  → 710 +250 = 528 +432! 960 = 960 → right, energy conserved

- **Check the second law** (generation of entropy) $\sum_{i=1}^{n} \frac{q_{net,i}}{T_i} \leq 0$

$$\sum_{i=1}^{n} \frac{q_{net,i}}{T_i} = \underbrace{\frac{q_{in}}{T_{in}} - \frac{q_{out}}{T_{out}}}_{ds_{in}-ds_{out}} = \frac{710}{873} - \frac{528}{550} = 0.81 - 0.96 = -0.15 \leq 0 \rightarrow \text{Right !}$$

- Note: take the mean T_{in} and T_{out} (in Kelvin of course) !

Gas Turbine at UT (TE)

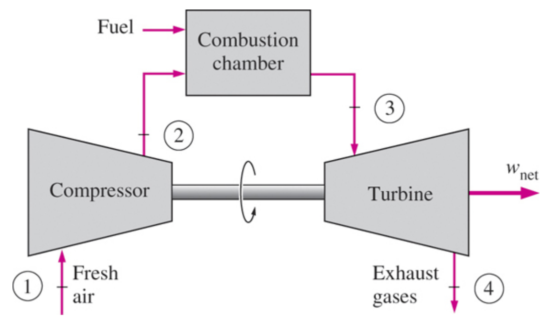
- Electricity for the apparatus in these tanks is delivered by a gas turbine
- A turbine of this type is used in our lab for research by Artur Pozarlik

Places where the tanks were used

Recapitulate class 10

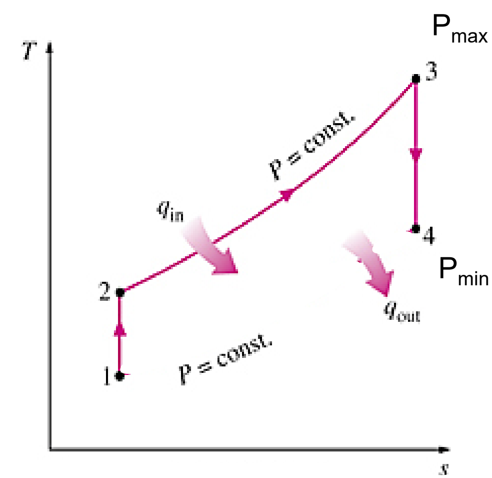
- **Gas power cycles (Brayton cycles):** cycles using gas as working fluid throughout the whole cycle
  - Air-standard cycle, open and closed, ideal and real Brayton cycle
    - Heat and power in- and output simple Brayton

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



    - Thermal efficiency simple Brayton cycle

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

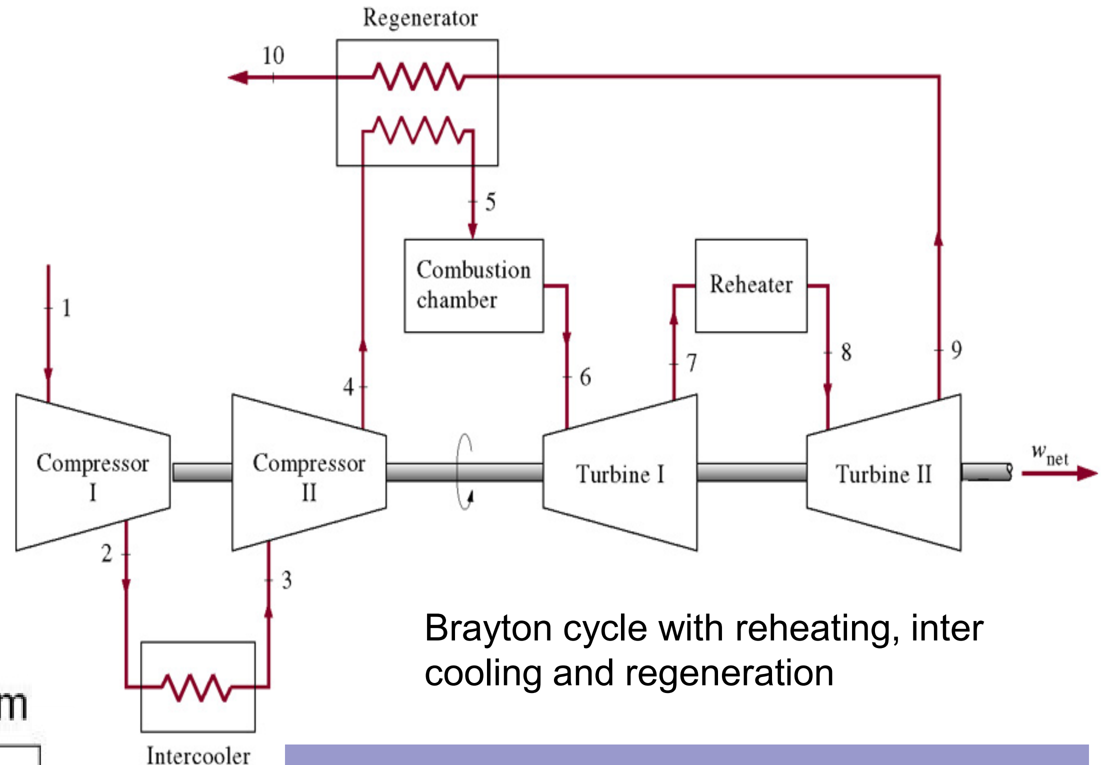


Simple open ideal Brayton cycle

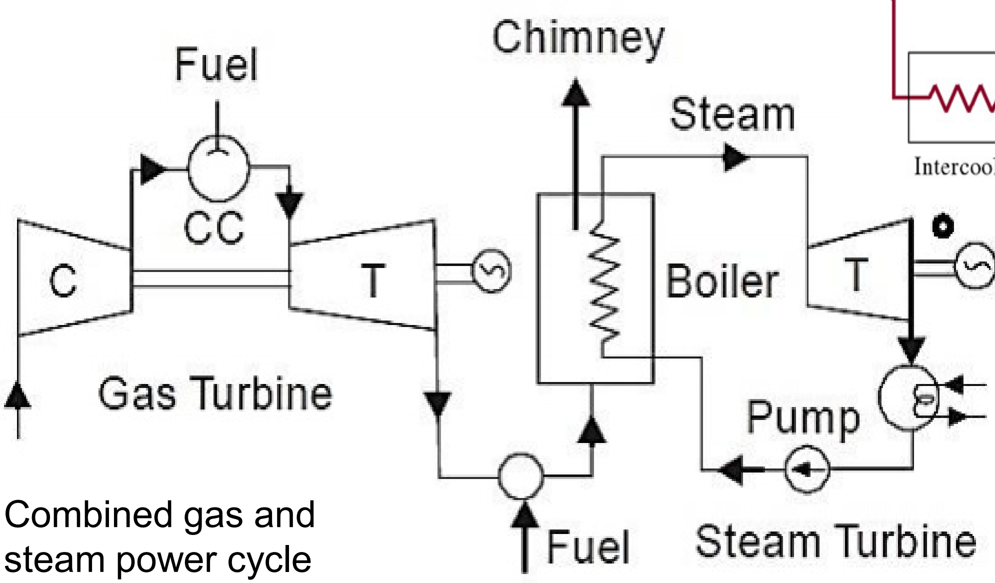
  - Design parameters
    - Turbine inlet temperature
    - Pressure ratio
    - Working medium
  - Mollier diagram for air

Next Class 11: Gas Power Cycles - Advanced

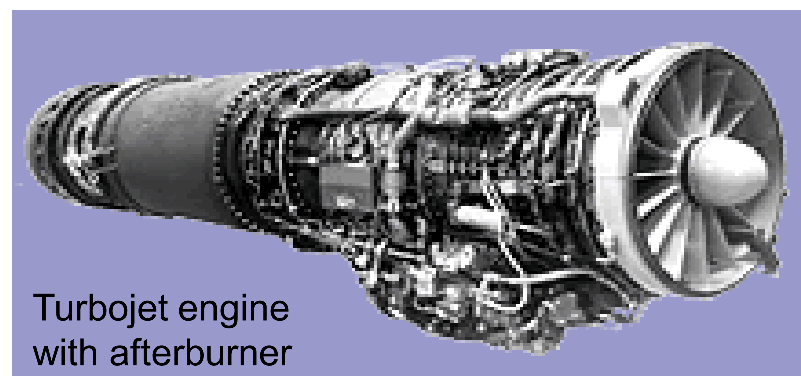
- Extra devices improve the efficiency of a Brayton cycle
  - Reheating
  - Inter cooling
  - Regeneration
- Aircraft gas turbines
- Combined cycles



Brayton cycle with reheating, inter cooling and regeneration



Combined gas and steam power cycle



Turbojet engine with afterburner

Keep in mind: Important Formulas

- Specific volume v = V/m [m^3/kg] and density ρ = 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 $\eta_{thermal} = \dfrac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \dfrac{\dot{W}_{net}}{\dot{Q}_{in}}$
- Mixture fraction $x = \dfrac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
- 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 $ds \geq \dfrac{\delta q_{net}}{T_{res}}$ (= 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 $\eta_{INPUT,S} = \dfrac{w_{IN,S}}{w_{IN,A}}$, $\eta_{OUTPUT,S} = \dfrac{w_{OUT,A}}{w_{OUT,S}}$
- Isentropic processes ideal gas Pv^k =constant, Tv^{k-1}=constant, $P^{(k-1)/k}/T$ = constant
- Thermal efficiency power cycles $\eta_{he} = \dfrac{w_{out} - w_{in}}{q_{in}} = 1 - \dfrac{q_{out}}{q_{in}}$ Carnot efficiency $\eta_{carnot} = 1 - \dfrac{T_{cold}}{T_{hot}}$

- Phase diagrams