SFERA-III

Solar Facilities for the European Research Area

1st Summer School "Thermal energy storage systems, solar fields and new cycles for future CSP plants"
WP1 Capacity building and training activities
Odeillo, France, September 9th-11th 2019

"Power Cycles for CSP/STE Plants"

Eduardo Zarza, CIEMAT-PSA (Spain)

NETWORKING

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO **823802**

SFERA-III

1st Summer School

September, 9th- 10th, 2019

CNRS- PROMES, Odeillo, France

Power Cycles for CSP/STE Plants

Dr. Eduardo Zarza Moya
Plataforma Solar de Almería (PSA)
R+D Unit for Concentrating Solar Thermal Systems
E-mail: eduardo.zarza@psa.es

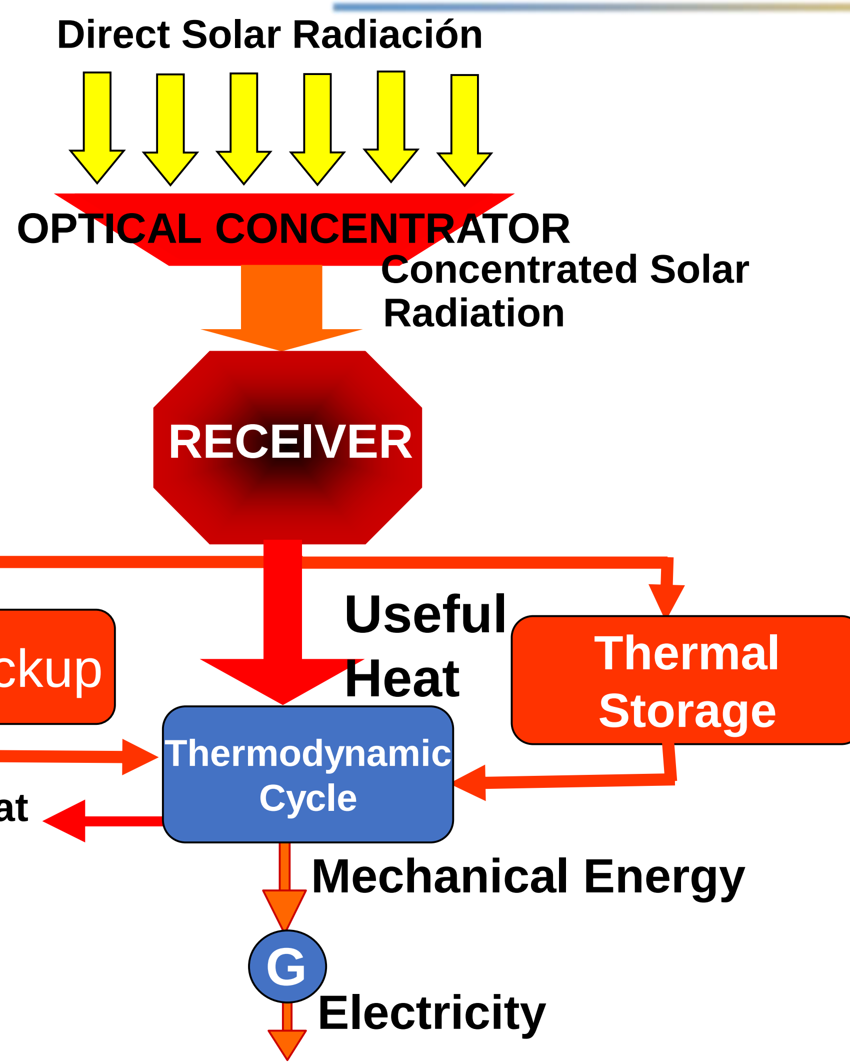
Solar Facilities for the European Research Area
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Power Cycles for STE Plants

Content

- Introduction to Thermodynamic Cycles
- Power Cycles used in STE Plants
  - Rankine Cycle
  - Organic Rankine Cycle
  - Brayton Cycle
  - Combined Cycle
  - Supercritical Cycles
  - Stirling Cycle

Schematic diagram of a Solar Thermal Electricity Plant



(Ref. M. Romero, 2009)

Basic Terms: Thermodynamic Processes

- **Thermodynamic Process**: is any process in which a system changes its thermodynamic properties (e.g., temperature, pressure, mass and volume, mainly). The properties at the beginning of the process are the "*Initial Parameters*" and those at the end of the process are the "*Final Parameters*"

- **Types of Thermodynamic Processes**: depending on the properties changing along the process and the way they change, there are different processes:

+ Adiabatic process: the process takes place without heat or mass transfer

+ Isothermal process: the temperature of the system remains constant, $\Delta T=0$

+ Isochoric process: the volume of the system remains constant, $\Delta V=0$

+ Isobaric process: the system pressure remains constant, $\Delta P=0$

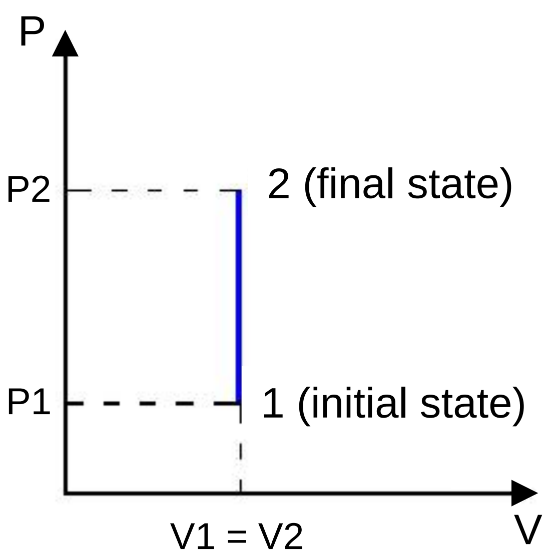
+ Reversible process: the system is continuously in equilibrium with its surrounding all along the process and both the system and its surrounding can be restored to their initial states. It is an ideal process that never occurs in the nature

+ Isentropic process: is a reversible and adiabatic process (it is therefore an ideal process). The entropy remains constant, $\Delta S=0$

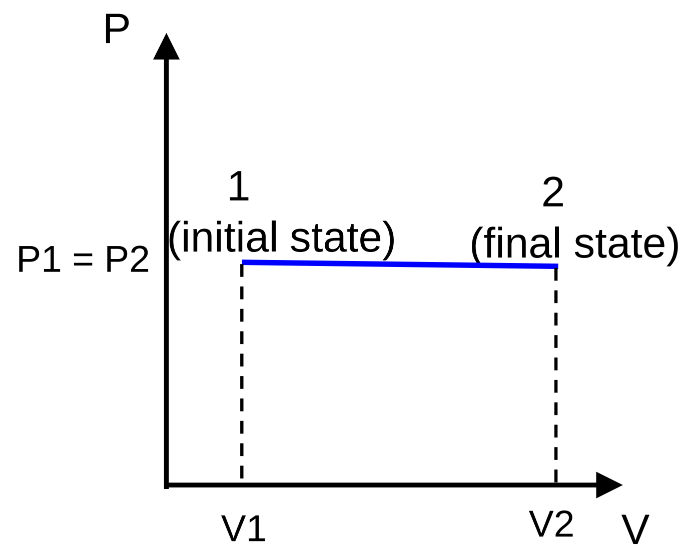
Basic Terms: Thermodynamic Processes

Graphical representation of Thermodynamic Processes (I)

Thermodynamic processes are represented using a Cartesian coordinate system. The parameters assigned to the axis are selected according to the process:



Isochoric process



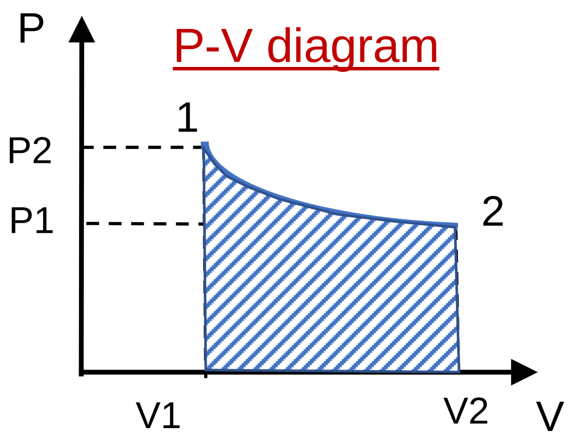
Isobaric process

Basic Terms: Thermodynamic Processes

Graphical representation of Thermodynamic Processes

Thermodynamic processes are represented using a Cartesian coordinate system. The more usual graphical representations are:

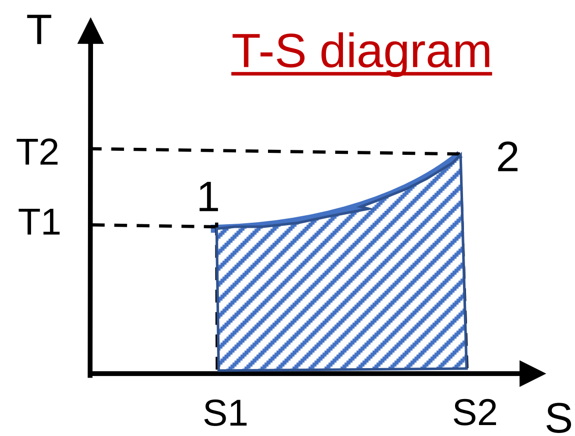
a) Pressure-Volume (P-V)



It is very useful to visualize the amount of work exchanged with the surrounding, *W*:

$$W = \int_1^2 P \cdot dV$$

b) Temperature-Entrophy (T-S)

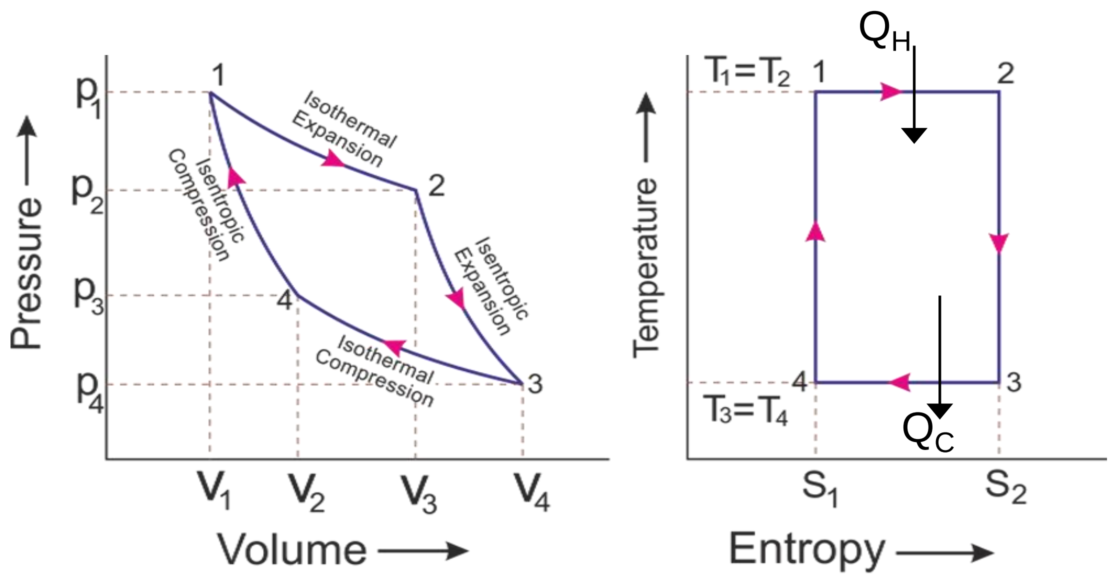


It is very useful to visualize the amount of heat exchanged with the surrounding, *Q*:

$$Q = \int_1^2 T \cdot dS$$

Basic Terms: Thermodynamic Cycle

- A **thermodynamic Cycle** is composed of a series of thermodynamic processes performed in a way that the system is returned to its initial state (i.e., the initial and final parameters are the same). The graphical representation in a Cartesian coordinate system is a closed shape



Graphical representation of a thermodynamic cycle (Carnot cycle)

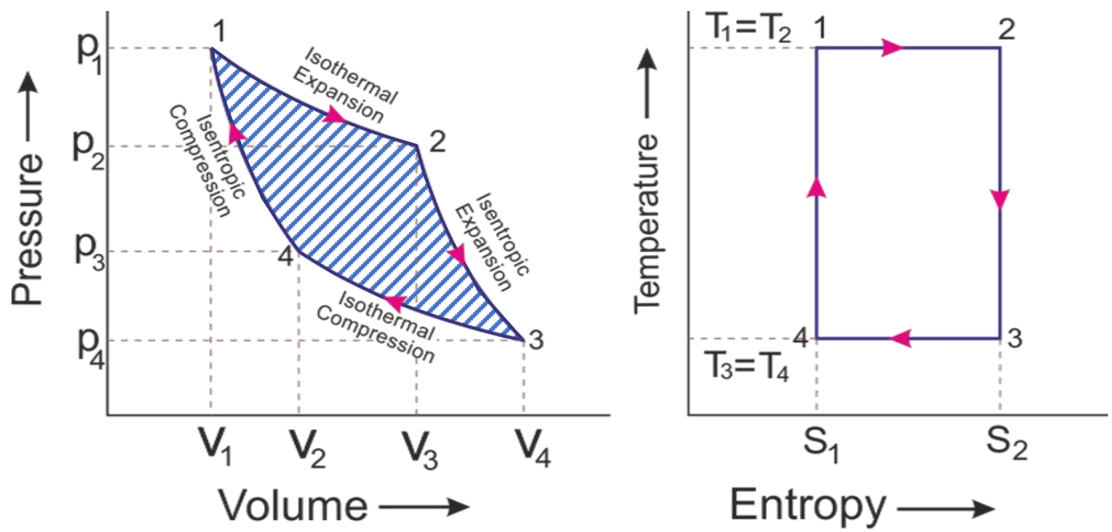
- During a thermodynamic cycle **the system can exchange heat** and/or **mechanical energy (work)** with its surrounding

Basic Principles of Thermodynamic Cycles

Some Basic Principles

- In those cycles used to convert thermal energy into mechanical energy (work) **the amount of work produced is proportional to the area enclosed** by the geometrical shape of the cycle in the P-V diagram.

  Taking the Carnot cycle as a reference, it means that the higher the temperature difference T1-T4, the more mechanical work will be produced.



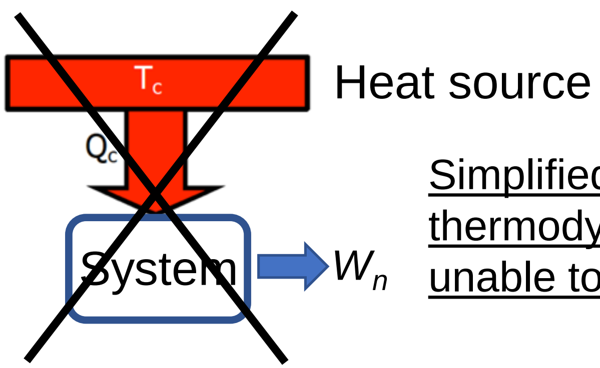
Basic Principles of Thermodynamic Cycles

Some Basic Principles

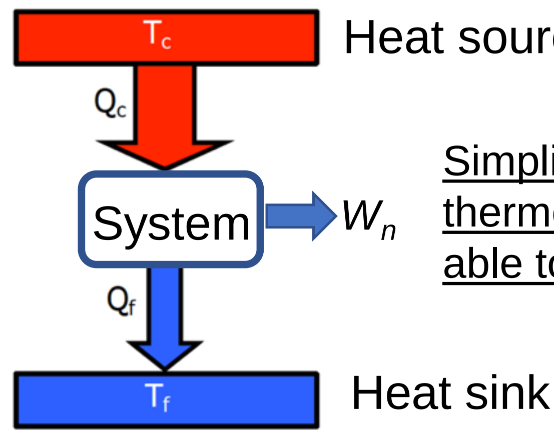
- In those cycles used to convert thermal energy into mechanical energy (work) **the amount of work produced is proportional to the area enclosed** by the geometrical shape of the cycle in the P-V diagram.

  Taking the Carnot cycle as a reference, it means that the higher the temperature difference T1-T4, the more mechanical work will be produced.

- **Kelvin principle:** It is impossible to produce work with a thermodynamic system in contact with only one heat source/sink



Simplified scheme of a thermodynamic cycle unable to produce work



Simplified scheme of a thermodynamic cycle able to produce work

Basic Principles of Thermodynamic Cycles

Some Basic Principles

- In those cycles used to convert thermal energy into mechanical energy (work) **the amount of work produced is proportional to the area enclosed** by the geometrical shape of the cycle in the P-V diagram.

  Taking the Carnot cycle as a reference, it means that the higher the temperature difference T1-T4, the more mechanical work will be produced.

- **Kelvin principle:** It is impossible to produce work with a thermodynamic system in contact with only one heat source/sink

- Due to the **First Law of Thermodynamic** the amount of energy (mechanical energy + thermal energy) delivered by the system to its surrounding is equal to the amount of energy (mechanical + thermal) received from its surrounding

$$\sum Q_i + \sum W_i = 0$$

- **Hierarchy principle:** The fraction of thermal energy that can be transformed into work (mechanical energy) increases with the temperature difference between the hot source and the cold sink (T1-T4 in the Carnot Cycle)

Thermodynamic Power Cycles

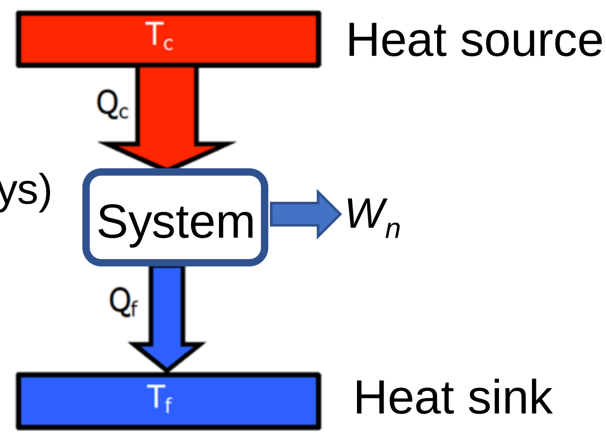
- A Power Cycle is a **thermodynamic cycle aimed at transforming thermal energy into mechanical energy, which is then converted into electricity** with an electricity generator

- According to Kelvin principle, **a heat source and a heat sink are needed**

- **The efficiency, η, of a Power Cycle** is the quotient between the net mechanical energy produced, W_n, and the thermal energy consumed, Q_c

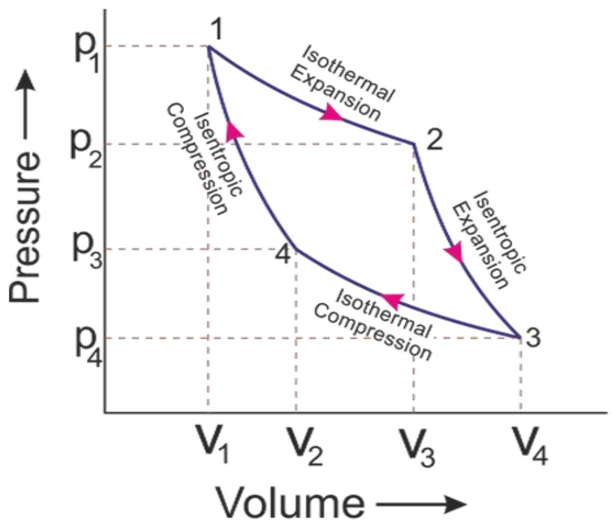
$$\eta = \frac{W_n}{Q_c} = \frac{Q_c - Q_f}{Q_c} = 1 - \frac{Q_f}{Q_c} < 1 \text{ (always)}$$

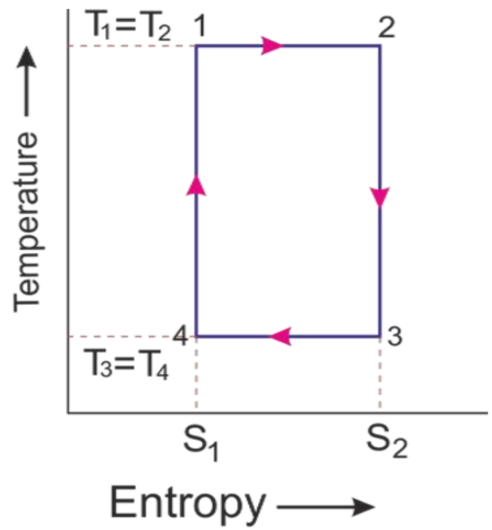
1^{st} Law of Thermodynamic

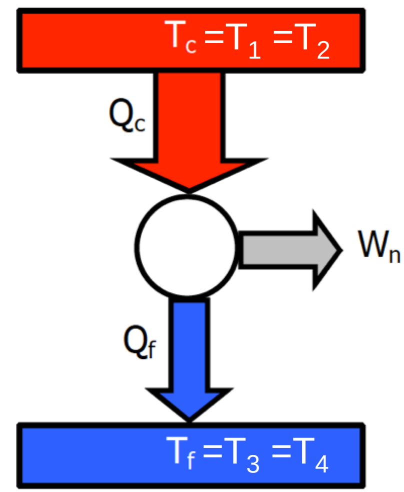


The Ideal Power Cycle: the Carnot Cycle

The Carnot cycle is an ideal thermodynamic cycle composed of **four reversible processes** (1 isothermal expansion + 1 isentropic expansion + 1 isothermal compression and 1 isentropic compression), taking heat from a heat source, delivering heat to a heat sink at lower temperature and producing mechanical work







Since the four processes are reversible, this cycle **is the cycle with the maximum possible efficiency** for a thermodynamic cycle connected to the same heat source and heat sink:

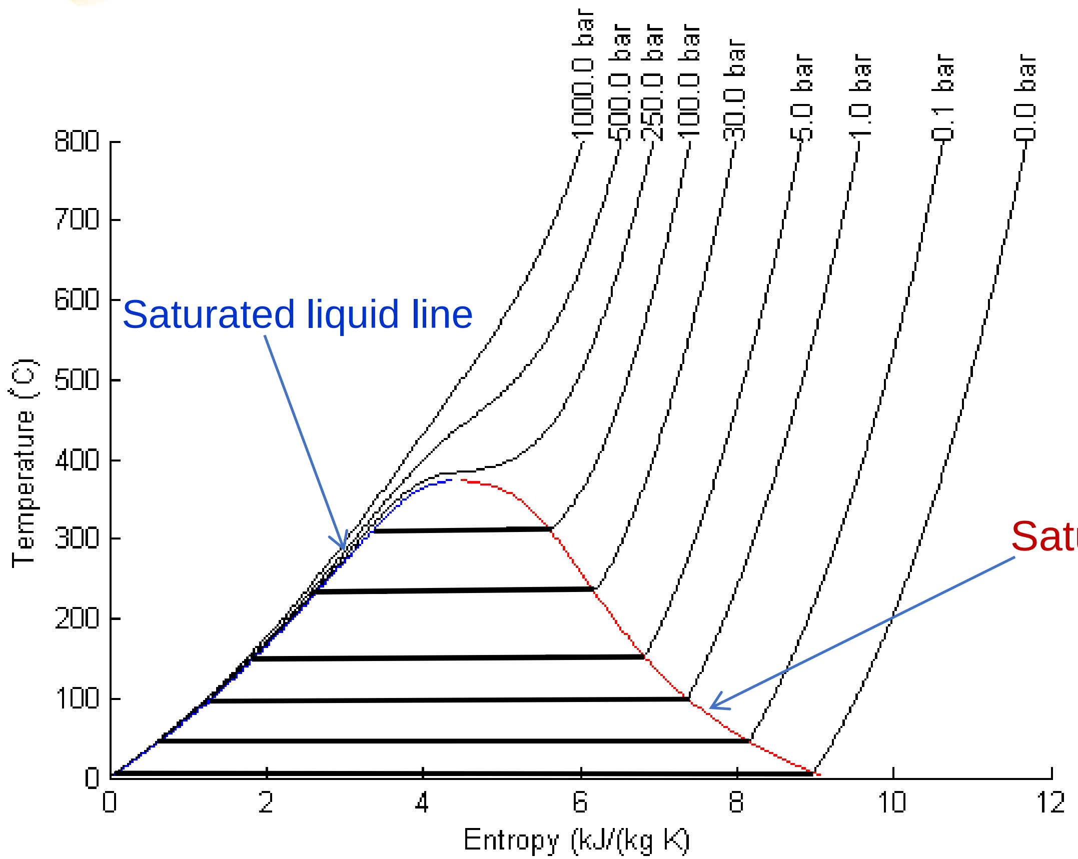
$$\eta_{Carnot} = \eta_{max.} = 1 - \frac{T_f}{T_c} < 1$$

Power Cycles for STE Plants

Content

- Introduction to Thermodynamic Cycles
- Power Cycles used in STE Plants
  - Rankine Cycle
  - Organic Rankine Cycle
  - Brayton Cycle
  - Combined Cycle
  - Supercritical Cycles
  - Stirling Cycle

“Temperature – Entropy” diagram of Water

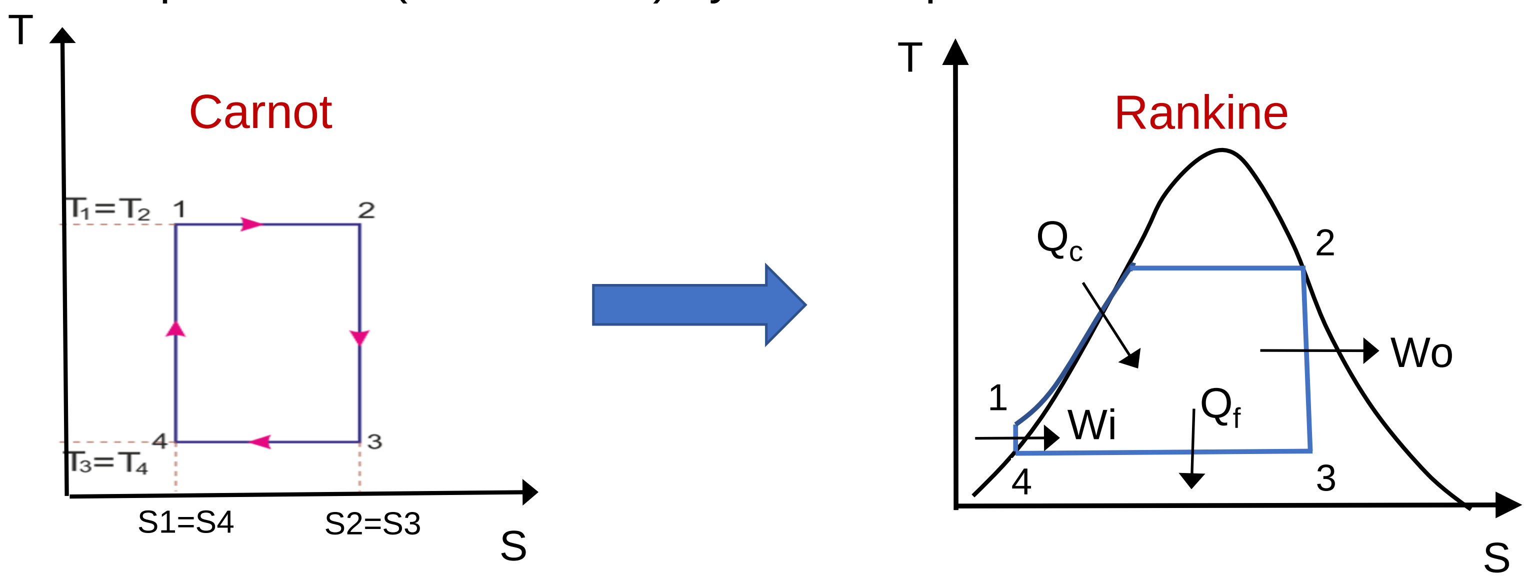


T- S diagram for water

When liquid water is heated at constant pressure, the water increases its temperature until the saturation temperature is reached. At that moment, water starts boiling and passing from liquid to steam phase without increasing its temperature (<u>liquid+steam</u>). When all water is in gas phase it increases its temperature (<u>superheated steam</u>)

Basic Rankine Cycle

The Rankine cycle is an approximation to the ideal Carnot cycle, changing the isothermal processes (1-2 and 3-4) by isobaric processes with water

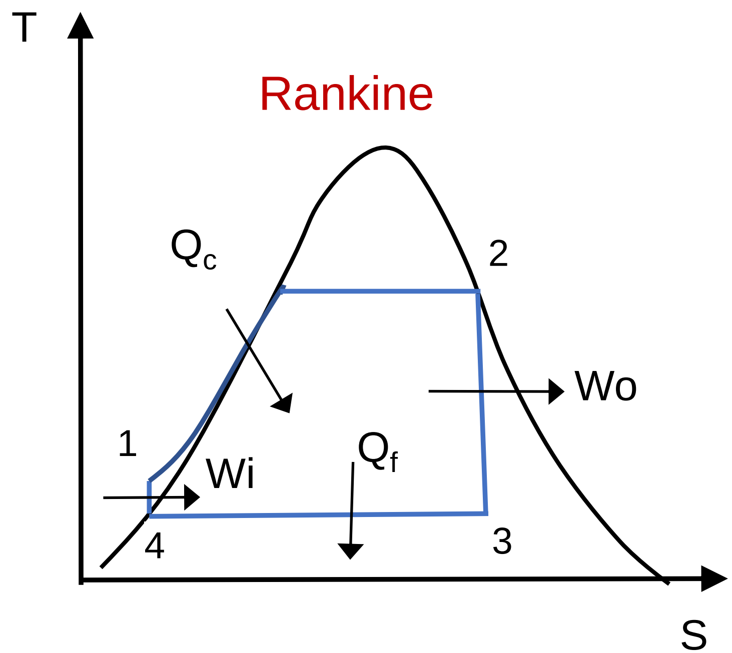


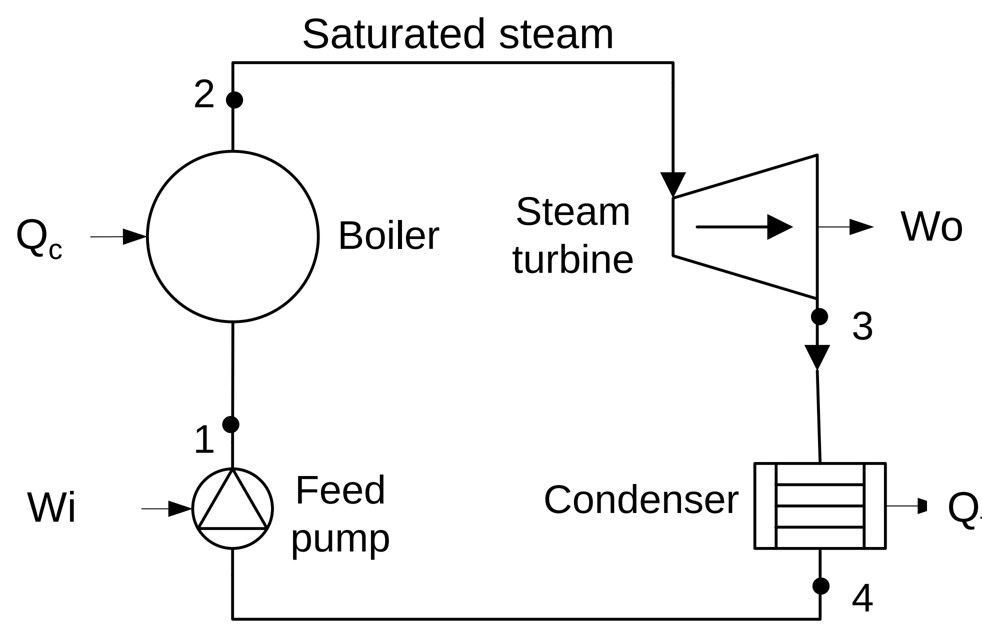
- 1–2: Isobaric evaporation of water (boiler, heat source of the cycle)
- 2–3: Isentropic expansion of the steam (turbine, mechanical work obtained)
- 3–4: Isobaric steam condensation (condenser, heat sink of the cycle)
- 4–1: Isentropic compression of liquid water (boiler feed pump, mechanical work consumed).

Basic Rankine Cycle

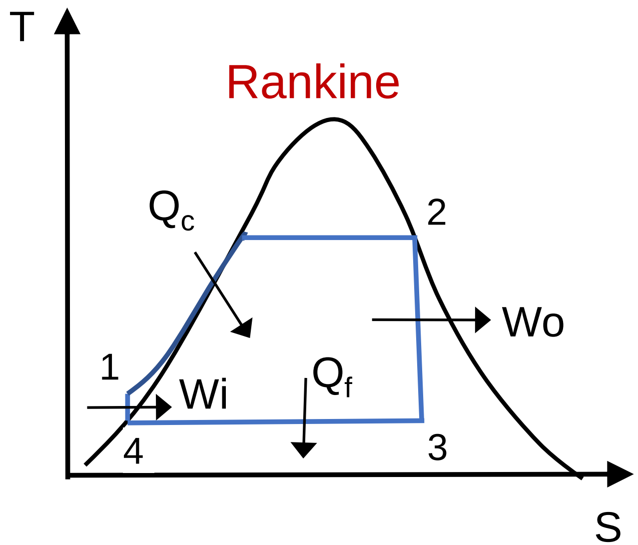
Physical Implementation of a Basic Rankine Cycle

Pressurized liquid water is evaporated in a boiler where thermal energy is given to the cycle (process 1-2). The saturated steam thus produced is expanded in a turbine (process 2-3) and then condensed (process 3-4). Once condensed the liquid water is pressurized and sent to the boiler (process 4-1) to start the cycle again.





Basic Rankine Cycle



Efficiency:

$$\eta = \frac{W_{net}}{\dot{Q}_c} = \frac{\dot{W}_o - \dot{W}_i}{\dot{Q}_c} = \frac{(h_2 - h_3) - (h_1 - h_4)}{h_2 - h_1}$$

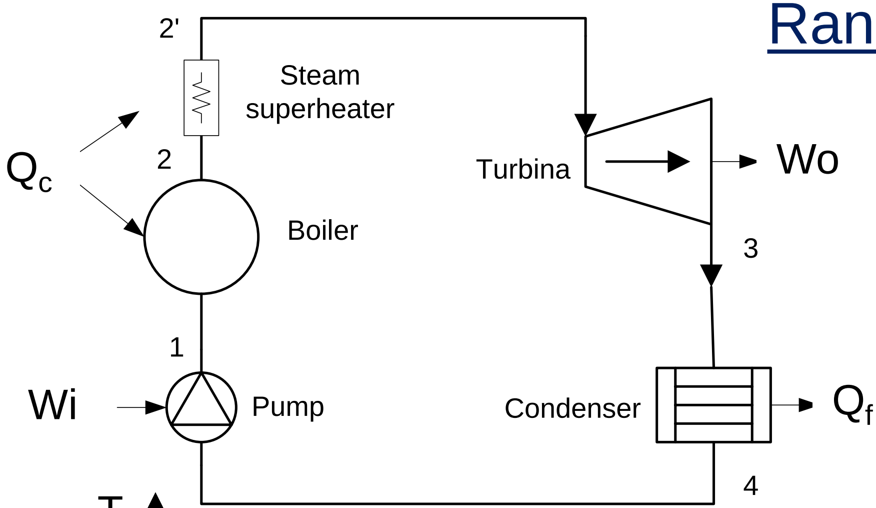
Example:

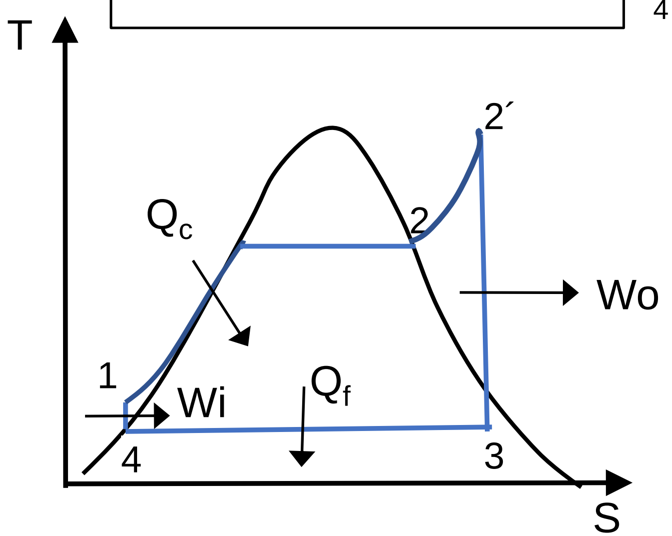
$$\left.\begin{array}{l} P_2 = 100\ \text{bar}, T_2 = 311°\text{C} \\ P_3 = 0.05\ \text{bar} \\ \text{steam fraction}_3 = 0.65 \end{array}\right\} \eta \approx 21\%$$

Main problems of the basic Rankine Cycle:

- Low steam fraction → erosion problems in the blades of the turbine
- Moderate efficiency if the maximum pressure is not very high

Improved Rankine Cycles





Rankine cycle with steam superheating

The temperature of the steam is increased before its expansion in the turbine. It has two benefits: a) the efficiency is increased, and b) less erosion in the blades of the turbine due to a higher steam quality at the turbine exit

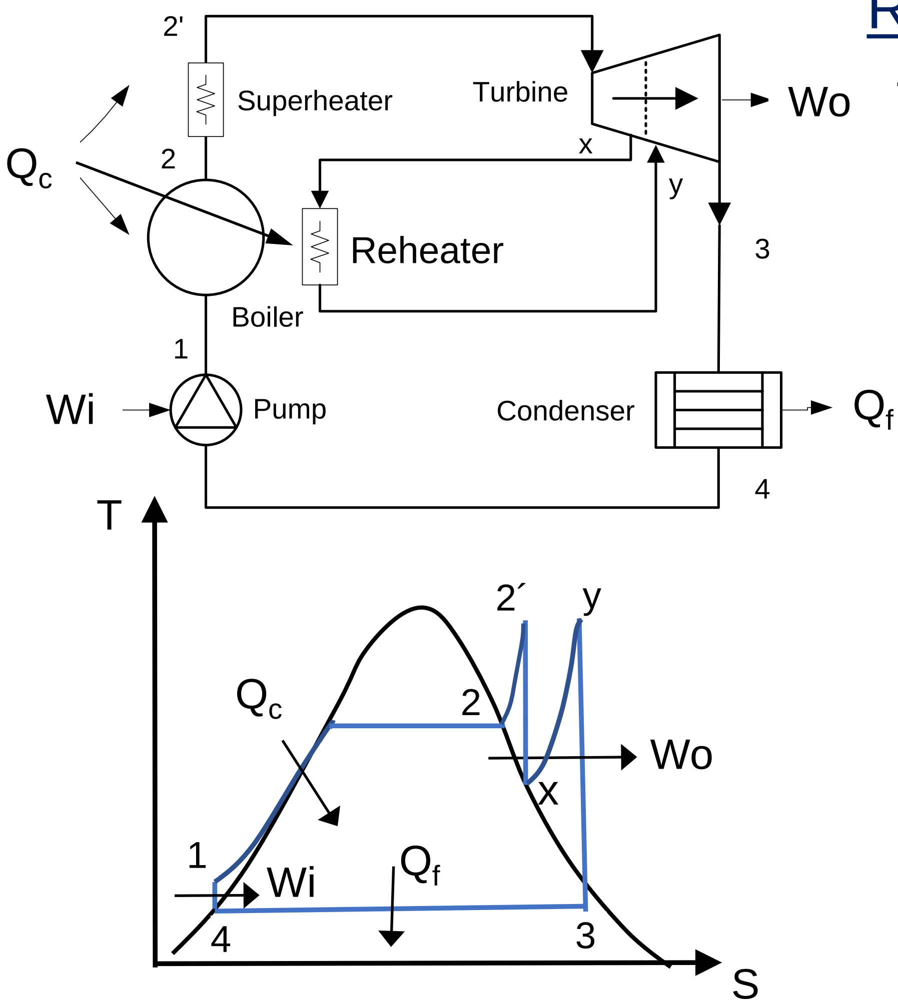
Efficiency:

$$\eta = \frac{W_{net}}{\dot{Q}_c} = \frac{\dot{W}_o - \dot{W}_i}{\dot{Q}_c} = \frac{(h_{2'} - h_3) - (h_1 - h_4)}{h_{2'} - h_1}$$

Example:

$$\left.\begin{array}{l} P_2 = 100\ \text{bar}, T_{2'} = 450°\text{C} \\ P_3 = 0.05\ \text{bar} \\ \text{steam fraction}_3 = 0.85 \end{array}\right\} \eta \approx 34\%$$

Improved Rankine Cycles



Rankine cycle with steam reheating

The steam is reheated before it completes its expansion in the turbine. The benefits are: less erosion inside the turbine and higher η

To increase the efficiency: $T_{2'}-T_x < T_x-T_3$

Efficiency:

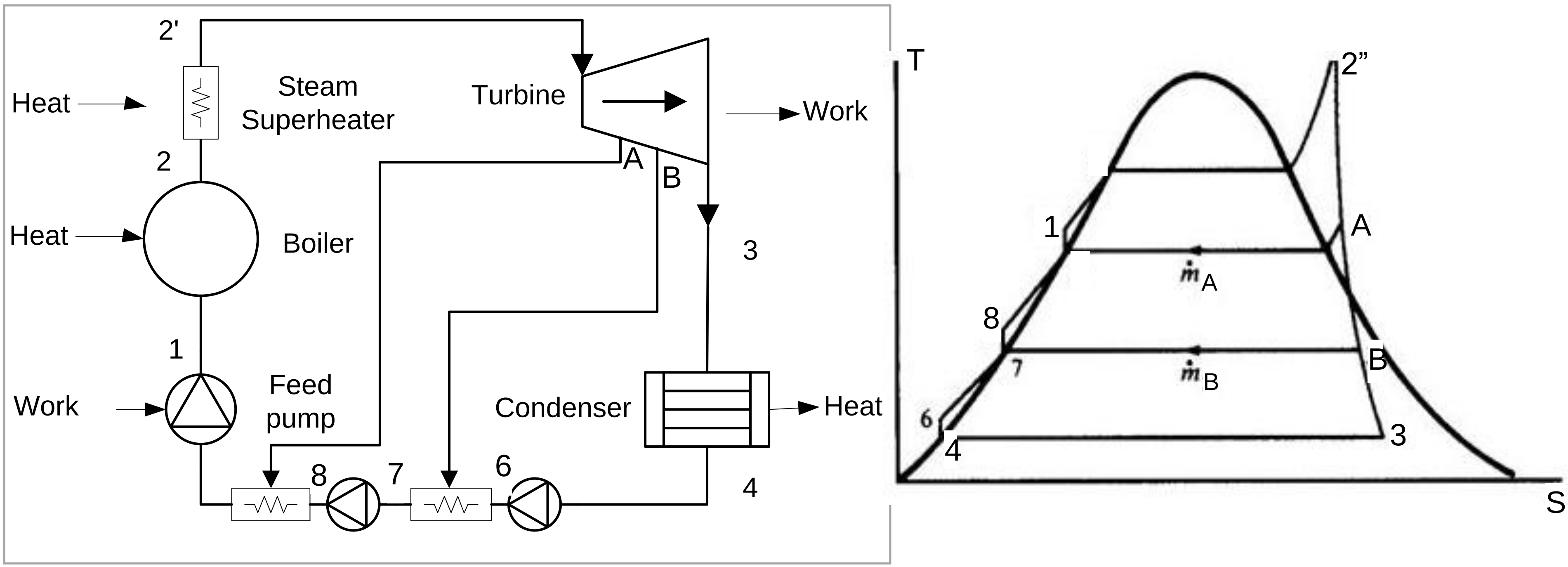
$$\eta = \frac{W_{net}}{\dot{Q}_c} = \frac{\dot{W}_o - \dot{W}_i}{\dot{Q}_c} = \frac{(h_{2'} - h_x) + (h_y - h_3) - (h_1 - h_4)}{(h_{2'} - h_1) + (h_y - h_x)}$$

Example:

$$\left.\begin{array}{l} P_2 = P_{2'} = 100 \text{ bar}, T_{2'} = 450°C \\ P_x = P_y = 10 \text{ bar}, T_y = 250°C \\ P_3 = 0.05 \text{ bar} \\ \text{steam fraction}_x = 1.0 \\ \text{steam fraction}_3 = 0.85 \end{array}\right\} \eta \approx 37\%$$

Improved Rankine Cycles

Regenerative Rankine cycle



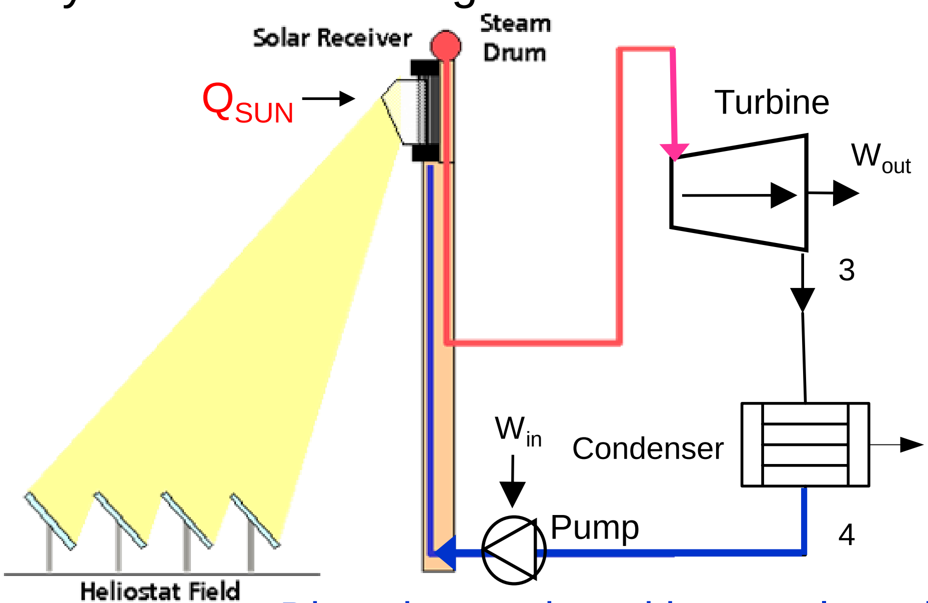
The **cycle efficiency is increased by raising the mean cycle input temperature**. The working fluid in the cycle is heated by steam extractions from the turbine. Although the more steam extractions the higher the efficiency, **there are practical limitations** due to the cost of the regenerators.

Integration of a Rankine Cycle in STE Plants

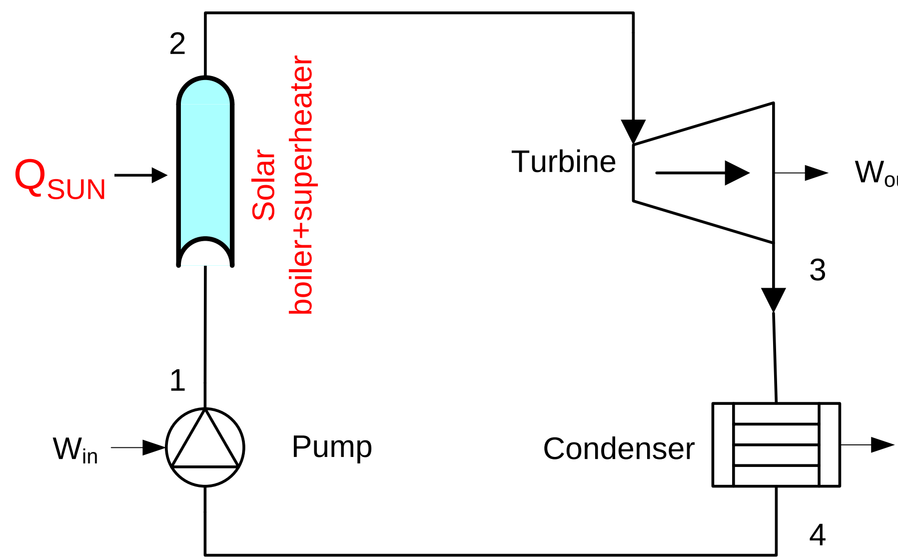
Direct Integration

Liquid water is directly heated and converted into steam by the concentrated solar Radiation in the receiver. This integration is called **Direct steam generation (DSG)**. It can be implemented with either central receivers or parabolic troughs.

The main limitation is the maximum steam temperature/pressure, which are limited by the receiver design and materials due to stress (P<150bar, T<575ºC)



Direct integration with central receiver

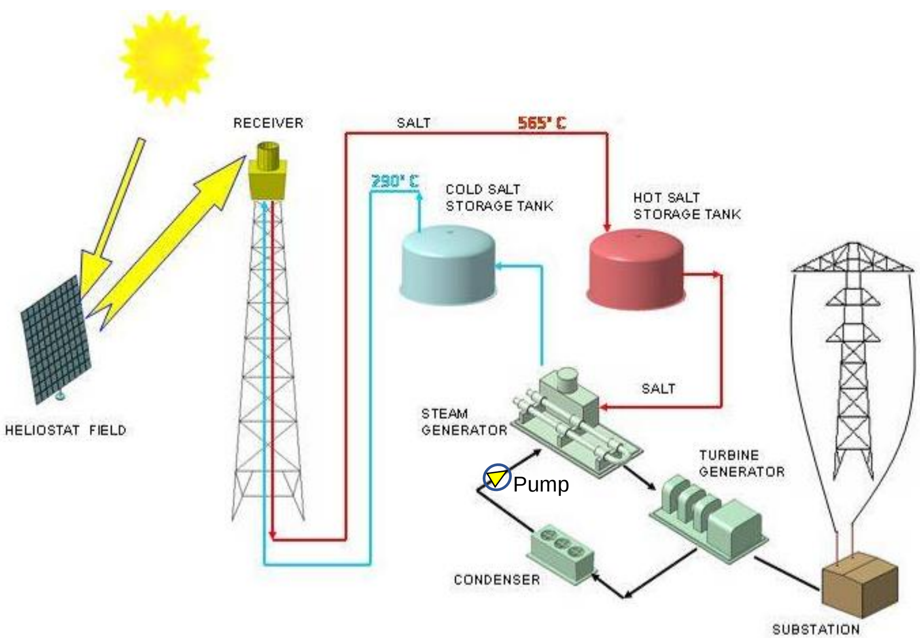


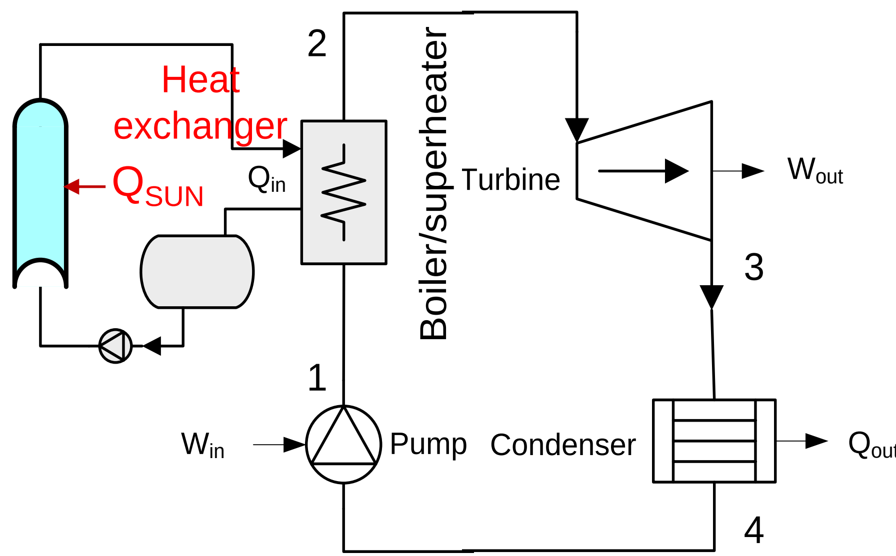
Direct integration with parabolic troughs

Integration of a Rankine Cycle in STE Plants

Indirect Integration

A Heat Transfer Fluid (HTF) is heated by the solar field and the steam is produced in a heat exchanger with the thermal energy delivered by the HTF. This integration can be implemented with either central receivers or parabolic troughs. The main limitation is the maximum HTF temperature: 400°C (Oil), 565°C (Molten salts)

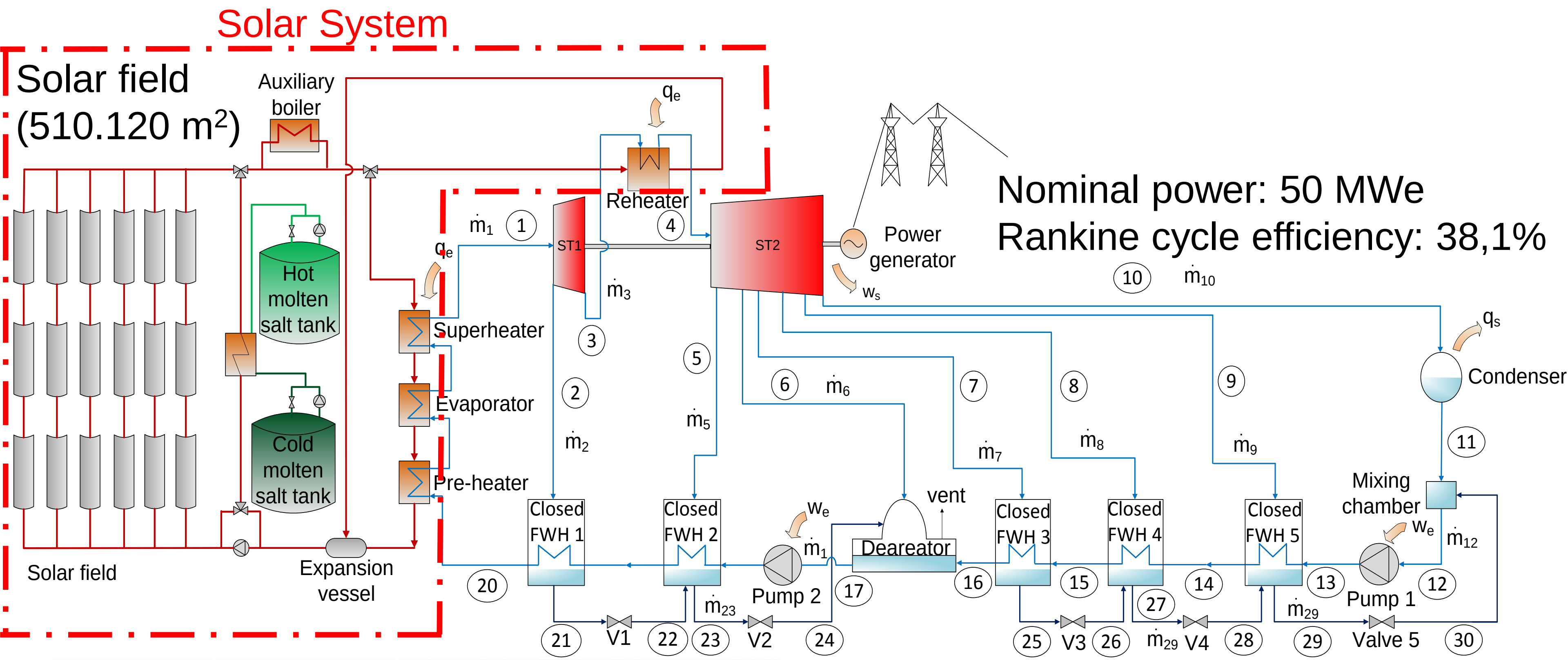




Typical Rankine Cycle used in STE Plants

Simplified scheme of a 50 MWe STE plant

Regenerative (6 steam extractions) Rankine cycle with steam reheating and superheated steam

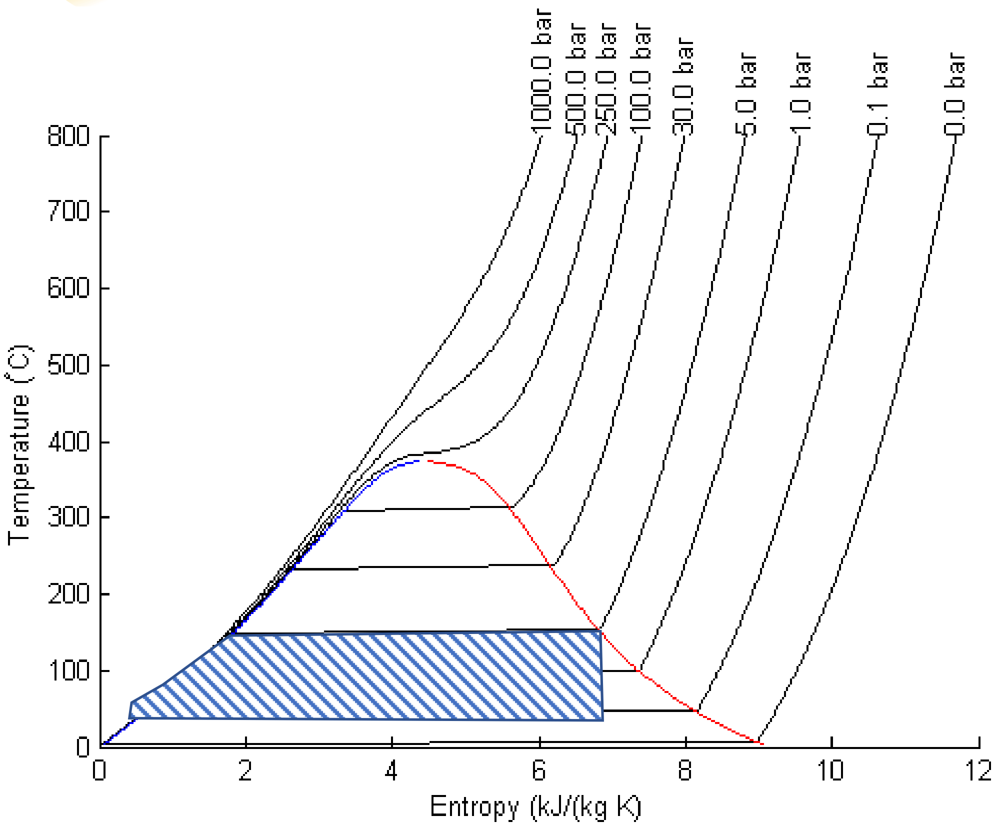


Power Cycles for STE Plants

Content

- Introduction to Thermodynamic Cycles
- Power Cycles used in STE Plants
  - Rankine Cycle
  - Organic Rankine Cycle
  - Brayton Cycle
  - Combined Cycle
  - Supercritical Cycles
  - Stirling Cycle

Organic Rankine Cycle (ORC)



When the temperature of the heat source available is low (T<150ºC) the use of water for a Rankine cycle is not good because of two main problems:

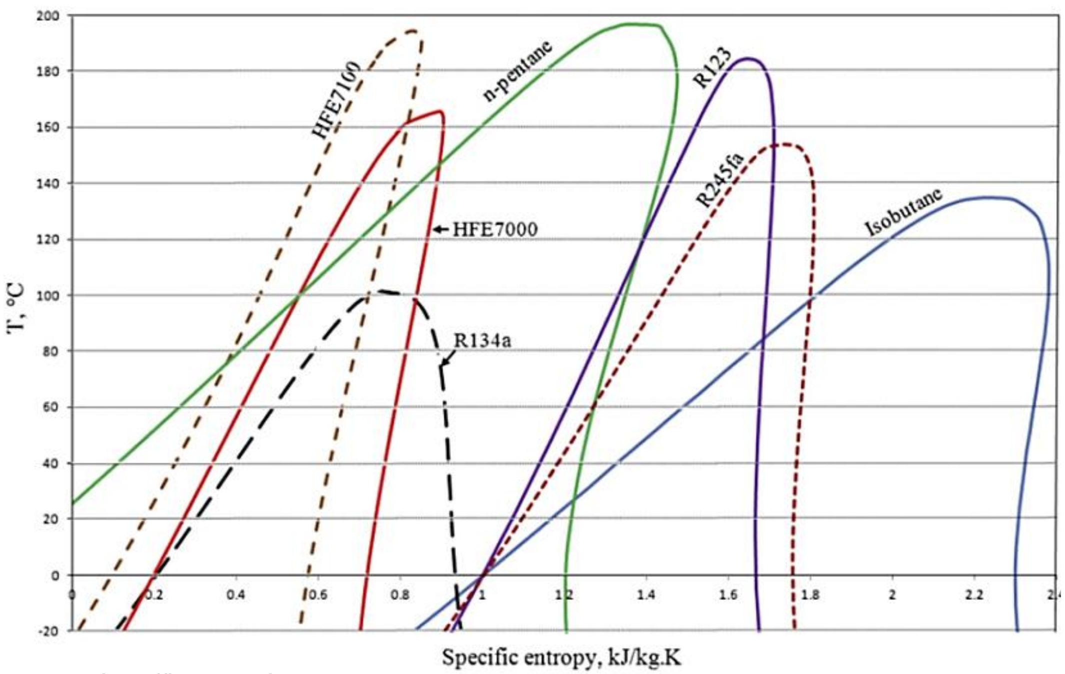
- Superheating or reheating is not feasible → **low cycle efficiency**
- Low steam quality at the end of the expansion→ **dangerous for the turbine**

T- S diagram for water

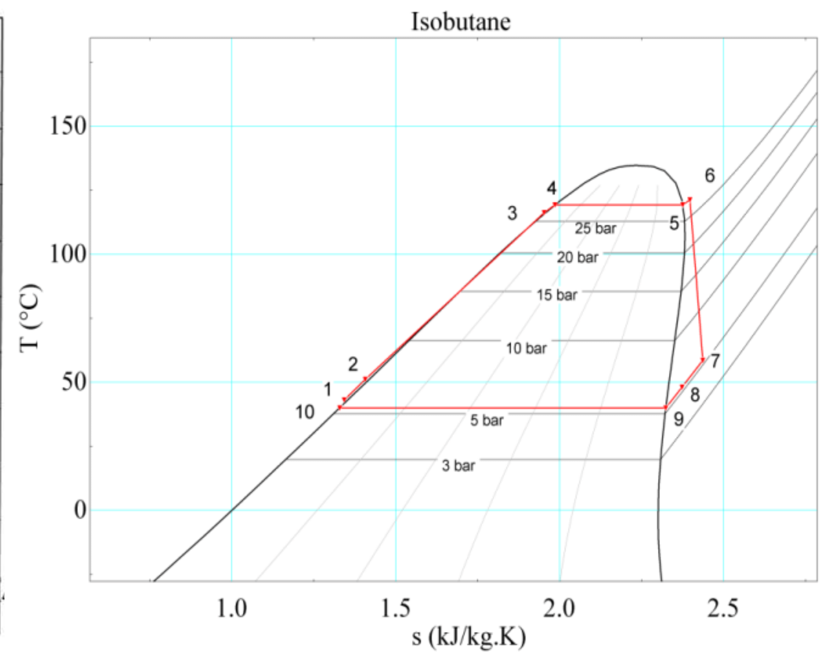
In this case, replacement of water by a hydrocarbon is a good option → **Organic Rankine Cycle (ORC)**

Organic Rankine Cycle (ORC)

The hydrocarbons used in ORCs have a positive slope of their saturated vapor curve



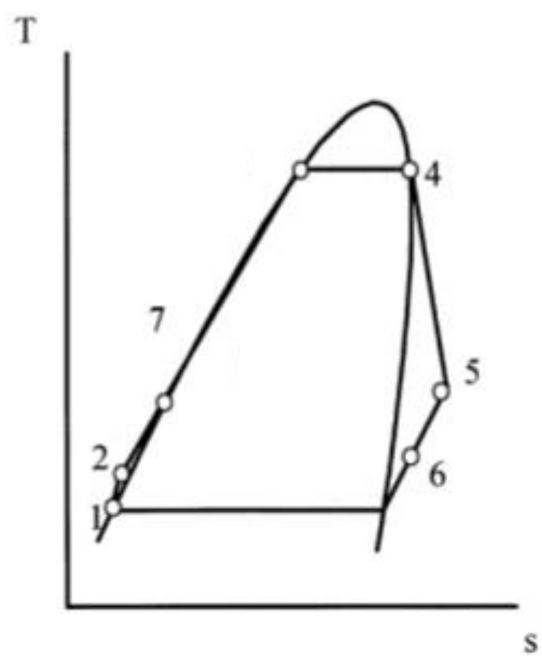
Source: http://heatcatcher.com

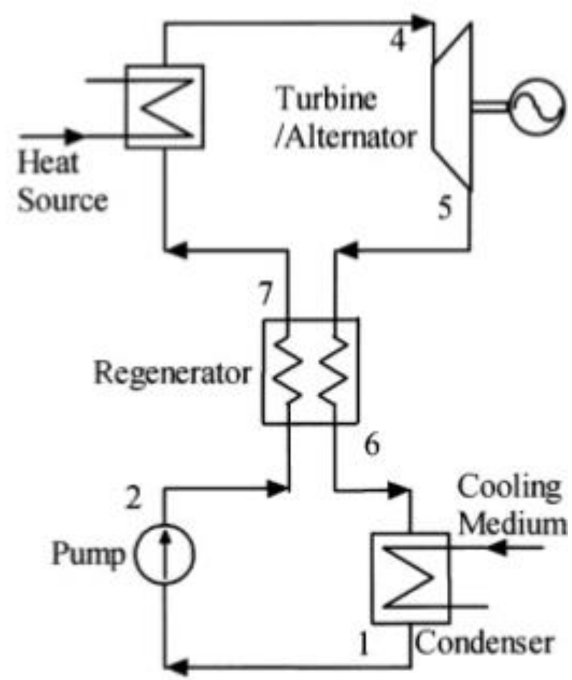


Benefits of the Organic Rankine Cycles

BENEFITS:

- Higher efficiency than a standard Rankine Cycle using water with the same temperature of the heat source (~15% for T=150ºC)
- Simple configuration: pump + evaporator + turbine + regenerator + condenser

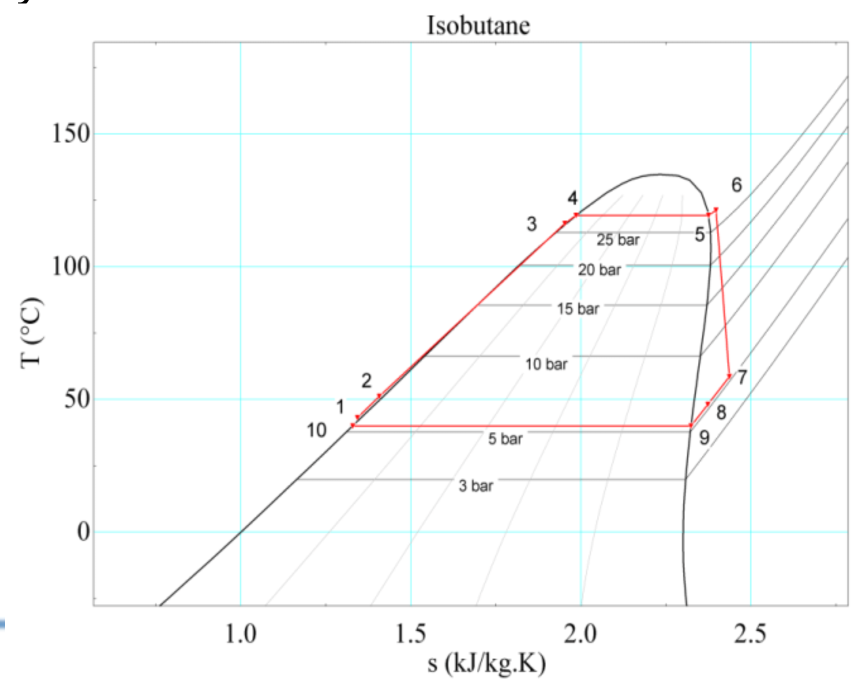




Benefits of the Organic Rankine Cycles

BENEFITS:

- Higher efficiency than a standard Rankine Cycle using water with the same temperature of the heat source (~15% for T=150ºC)
- Simple configuration: pump + evaporator + turbine + regenerator + condenser
- No need for superheating or reheating to achieve a high steam quality, thus achieving a reasonable efficiency without risk for the turbine



Drawbacks of the Organic Rankine Cycles

DRAWBACKS

- Low thermal stability of the hydrocarbons used (low maximum temperatures)
- Compatibility of the fluids with raw materials and lub oil
- Fluid decomposition may produce gases that reduce the heat transfers in the condenser and increase corrosion

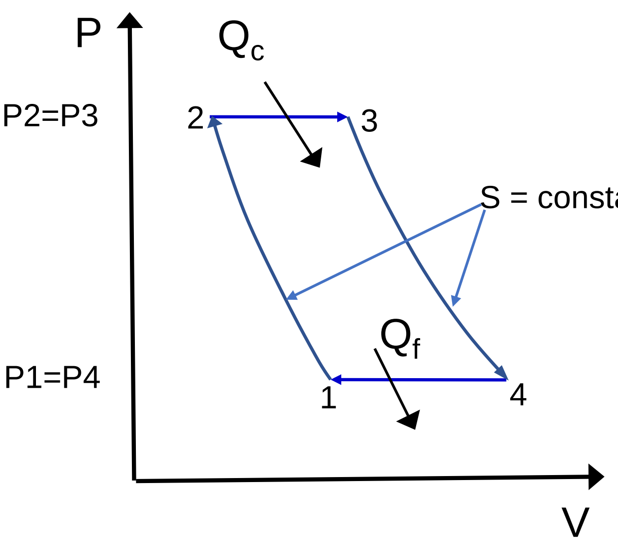
Power Cycles for STE Plants

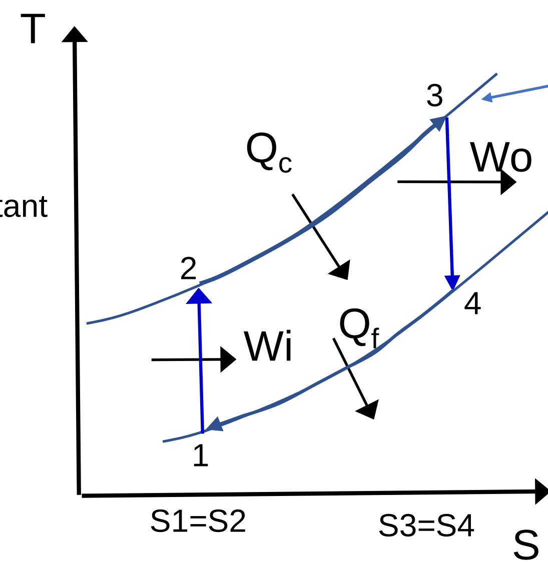
Content

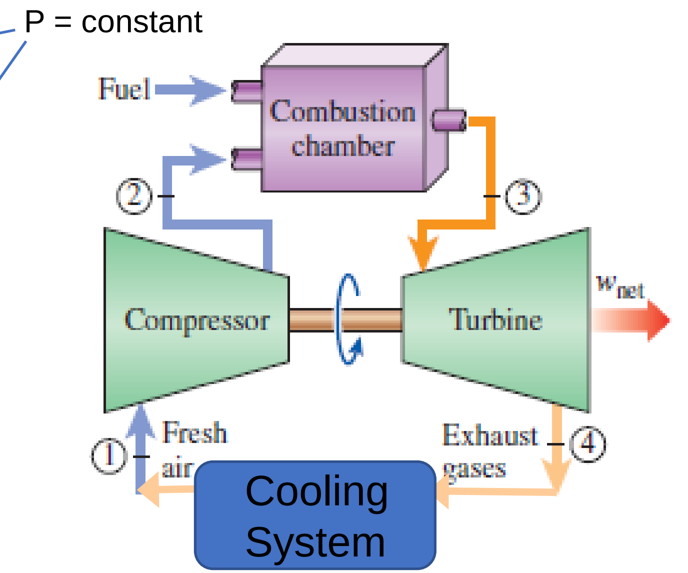
- Introduction to Thermodynamic Cycles
- ☛ Power Cycles used in STE Plants
  - Rankine Cycle
  - Organic Rankine Cycle
  - ☛ Brayton Cycle
  - Combined Cycle
  - Supercritical Cycles
  - Stirling Cycle

The (ideal) Brayton Cycle

- This cycle was designed by the American engineer George Brayton en 1870.
- The working fluid is gas (usually air)



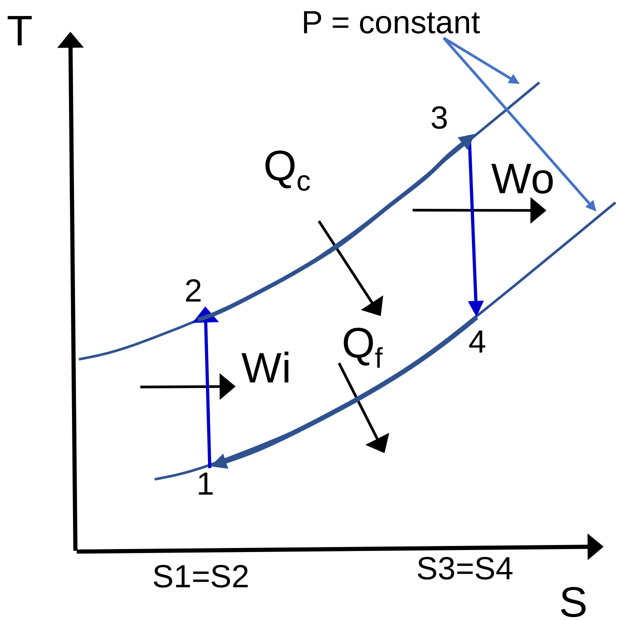


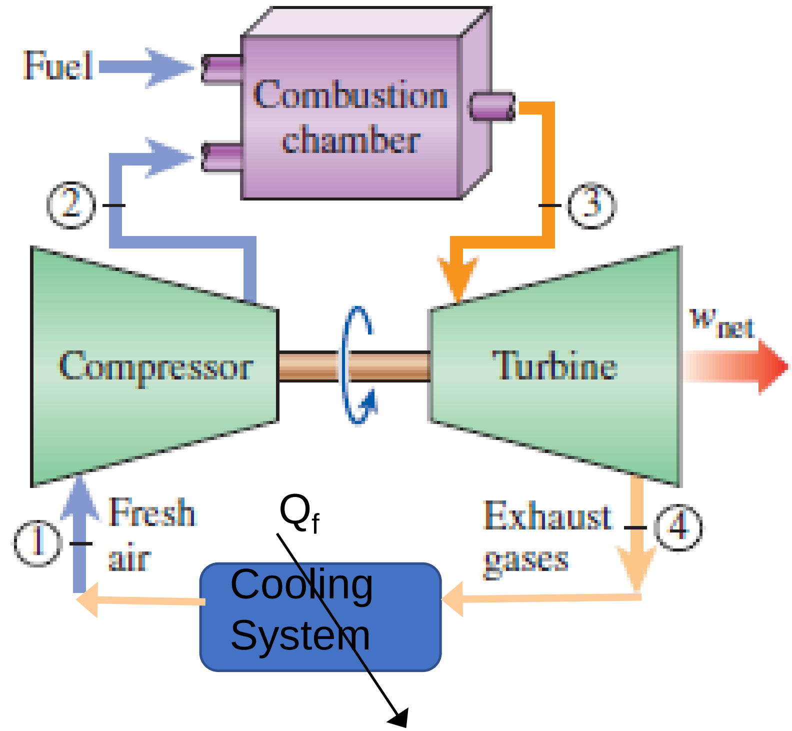


This cycle is composed of four processes:

- 1–2: Isentropic compression (Gas compressor)
- 2–3: Isobaric heating (Combustion chamber)
- 3–4: Isentropic expansion (Gas turbine)
- 4–1: Isobaric heat rejection (gas rejection to the atmosphere)

Parameters of the (ideal) Brayton Cycle





Compression thermal ratio $\lambda = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

$\gamma = C_p / C_v > 1$

Temperature ratio $\tau = \frac{T_3}{T_1}$

Pressure ratio $r_p = P_2/P_1$

Efficiency of the (ideal) Brayton Cycle

The efficiency, η, is calculated **assuming that the working gas behaves as an ideal gas** with **constant heat capacity all through the cycle**:

$C_p = constant$

$\Sigma Q_i + \Sigma W_i = 0$

$$\eta = \frac{W_{net}}{\dot{Q}_c} = \frac{\dot{W}_o - \dot{W}_i}{\dot{Q}_c} = \frac{(h_3 - h_2) - (h_4 - h_1)}{h_3 - h_2} = 1 - \frac{(h_4 - h_1)}{h_3 - h_2} = 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$\eta = 1 - \frac{(T_4 - T_1)}{T_3 - T_2} = 1 - \frac{T_1[\left(\frac{T_4}{T_1}\right) - 1]}{T_2[\left(\frac{T_3}{T_2}\right) - 1]} = 1 - \frac{T_1}{T_2}$$

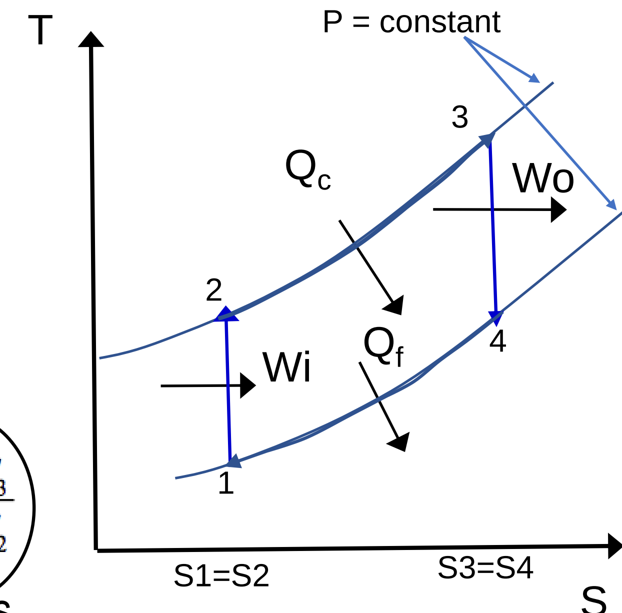
Adiabatic process for ideal gases: $TP^{\frac{1-\gamma}{\gamma}} = Cte$

Process 3-4 $\quad T_4 P_4^{\frac{1-\gamma}{\gamma}} = T_3 P_3^{\frac{1-\gamma}{\gamma}}$

Process 1-2 $\quad T_1 P_1^{\frac{1-\gamma}{\gamma}} = T_2 P_2^{\frac{1-\gamma}{\gamma}}$

$$\rightarrow \frac{T_4}{T_1}\left(\frac{P_4}{P_1}\right)^{\frac{1-\gamma}{\gamma}} = \frac{T_3}{T_2}\left(\frac{P_3}{P_2}\right)^{\frac{1-\gamma}{\gamma}} \rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

2-3 and 4-1 are Isobaric processes



Efficiency of the (ideal) Brayton Cycle

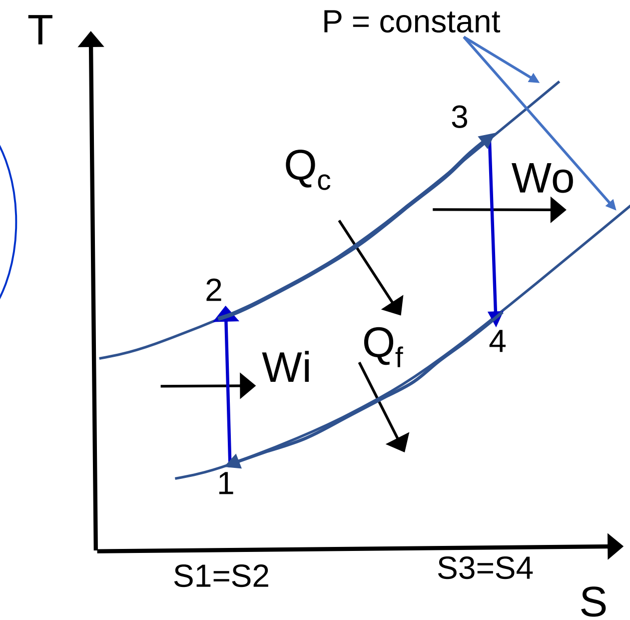
The efficiency, η, can be expressed in different ways:

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}}$$

Since γ is >1, the efficiency of the Brayton cycle increases with the Pressure Ratio

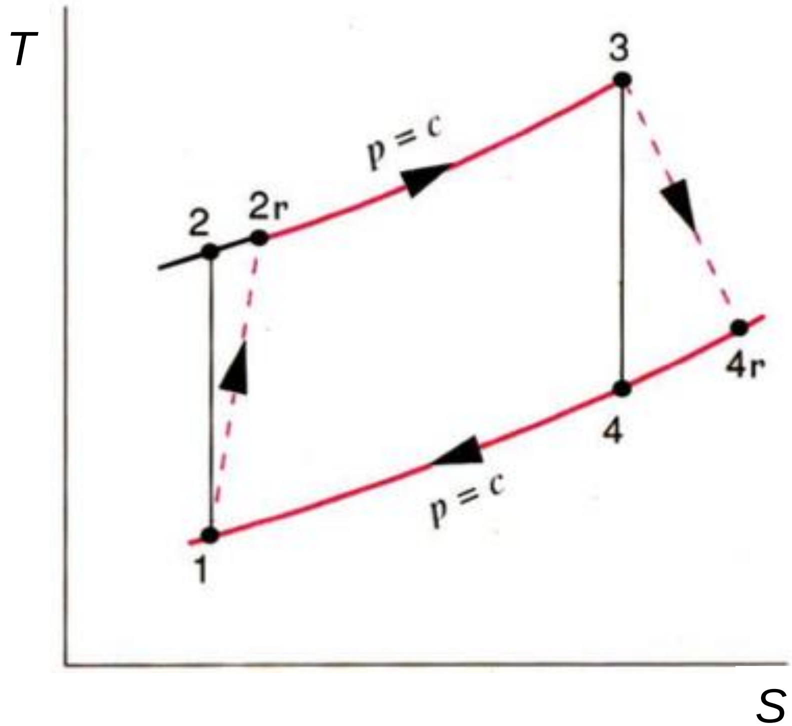
Proceso 1-2 $$T_1 P_1^{\frac{1-\gamma}{\gamma}} = T_2 P_2^{\frac{1-\gamma}{\gamma}} \longrightarrow \frac{T_1}{T_2} = \left(\frac{P_2}{P_1}\right)^{\frac{1-\gamma}{\gamma}} = \frac{1}{\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}} = \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}}$$

$r_p = P_2/P_1$ Pressure Ratio



The real Brayton Cycle (Irreversibilities)

- Due to irreversibilities in the compressor and turbine, neither the compression nor the expansion are isentropic processes
- Usual values of the compressor and turbine efficiencies are 80-90%,



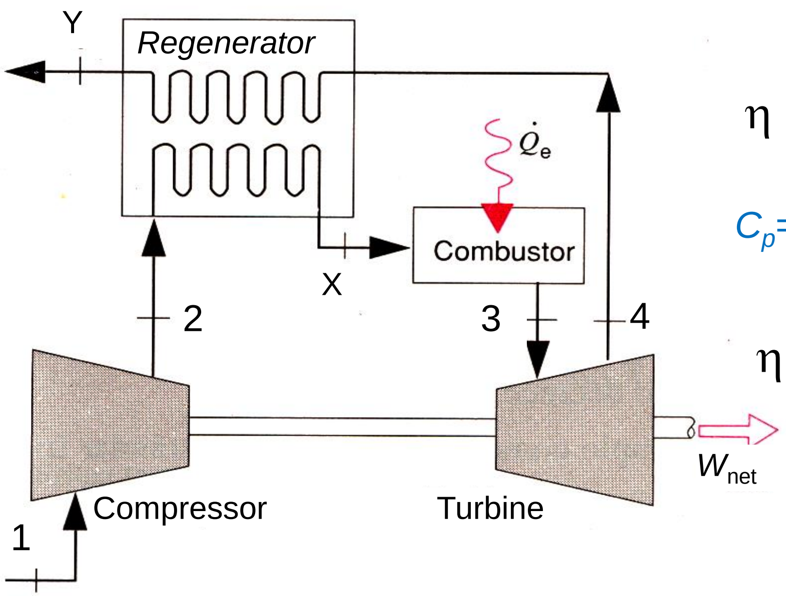
$$\mu_C = \frac{W_{IC}}{W_{RC}} = \frac{h_2 - h_1}{h_{2R} - h_1}$$

$$\mu_T = \frac{W_{RT}}{W_{IT}} = \frac{h_3 - h_{4R}}{h_3 - h_4}$$

Improvements of the basic Brayton Cycle

The Regenerative Brayton Cycle

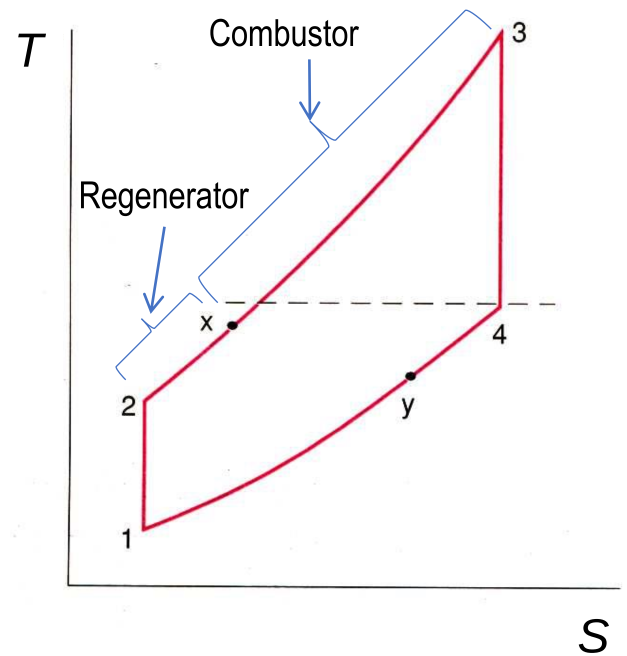
In a Regenerative Brayton Cycle the thermal energy of the air at the outlet of the turbine is used to preheat the compressed air before entering into the combustor, thus reducing the amount of thermal energy consumed by the cycle and increasing its thermal efficiency of the cycle.



$$\eta = 1 - \frac{(h_y - h_1)}{h_3 - h_x}$$

C_p= constant

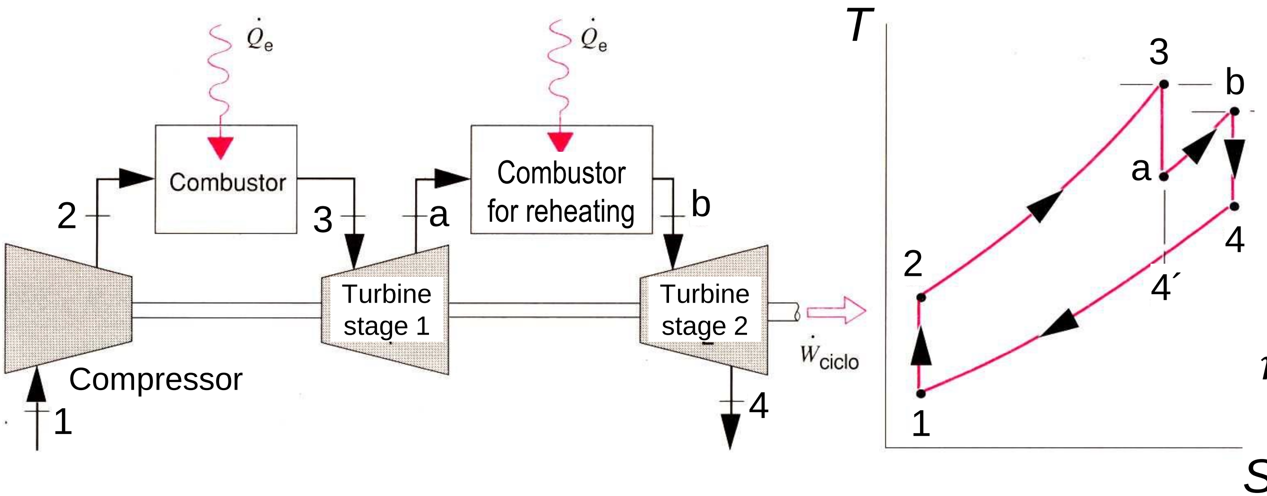
$$\eta = 1 - \frac{(T_y - T_1)}{T_3 - T_x}$$



Improvements of the basic Brayton Cycle

Brayton Cycle with Reheating

- The expansion process has two stages (segments 3-a and b-4), so that the air is reheated at constant pressure (segment a-b) between the first and second expansion (segment a-b)



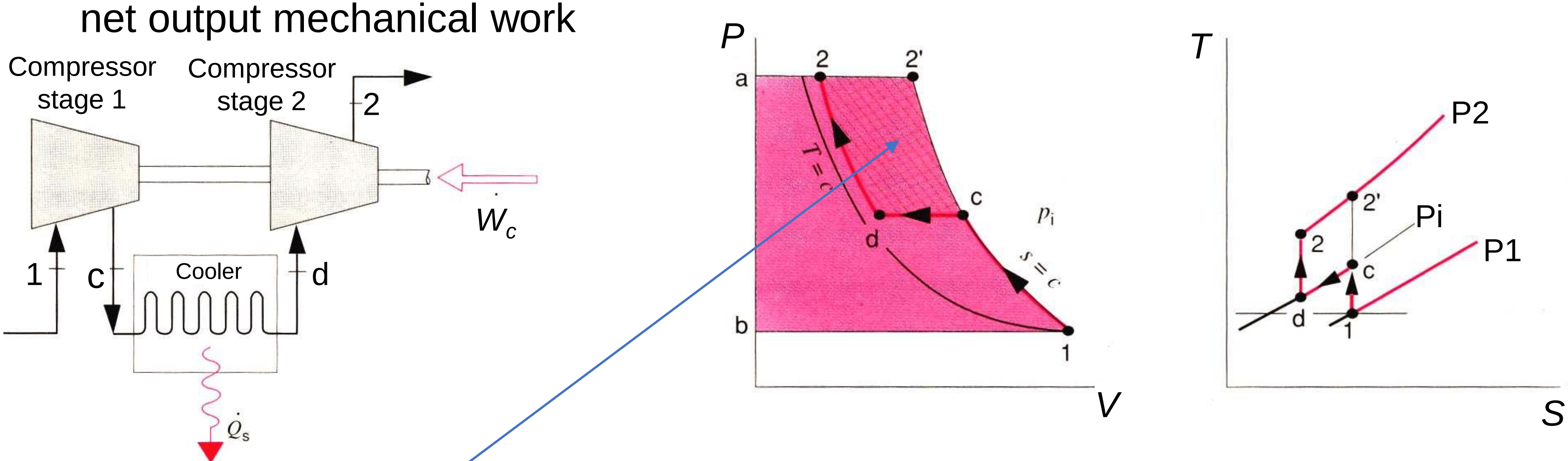
$$\eta = 1 - \frac{h_4 - h_1}{(h_3 - h_2) + (h_b - h_a)}$$

- Although the net mechanical work is higher the thermal energy consumption is higher too → the efficiency is not necessarily higher than that of a basic Brayton cycle. The efficiency will be higher than the basic cycle only if T_b-T_a > T_4-$T_{4'}$

Improvements of the basic Brayton Cycle

Compression with intercooling

- Air compression is performed in two stages (segments 1-c and d-2) with a cooling between the two stages (segment c-d) . **This cooling reduces the mechanical work required for the overall compression**, thus increasing the net output mechanical work

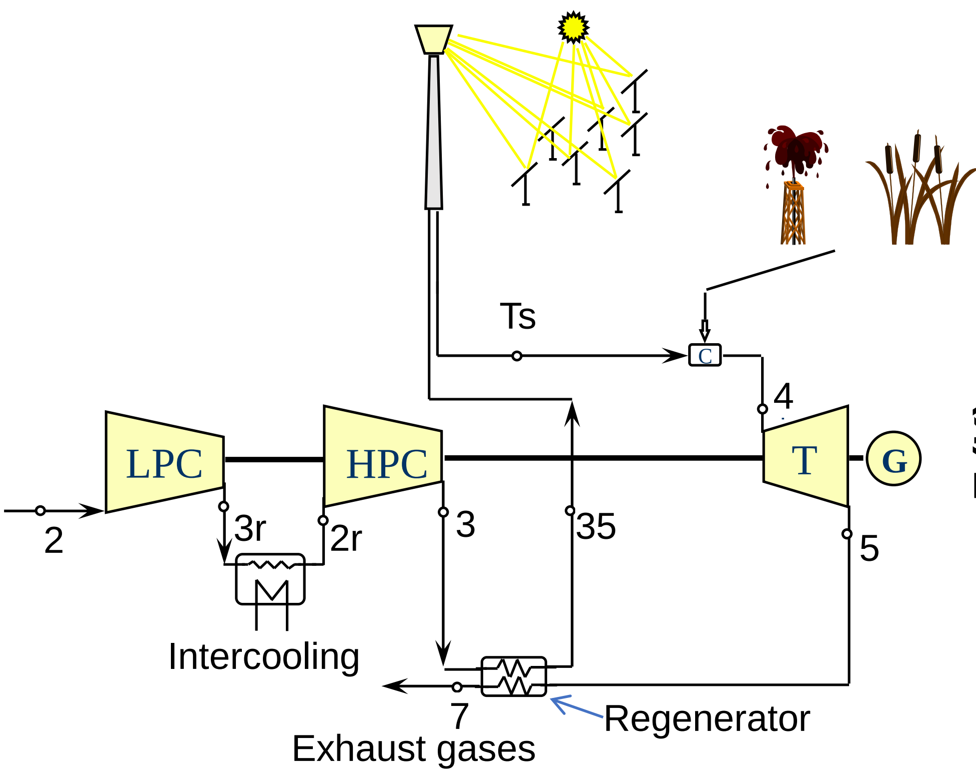


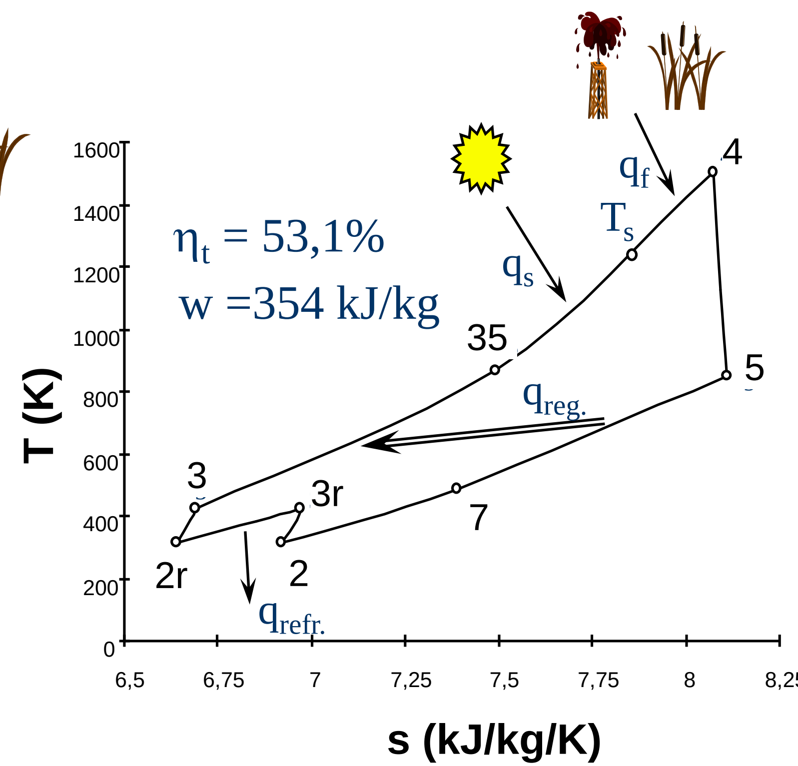
- The marked area in the P-V diagram represents the reduction of mechanical work for the compression process when we have an intermediate cooling (intercooling)
- The mechanical work saving depends on the outlet temperature T_d at the cooler **and** the intermediate pressure P_i

Integration of a Brayton Cycle in STE Plants

Regenerative Brayton Cycle with Intercooling

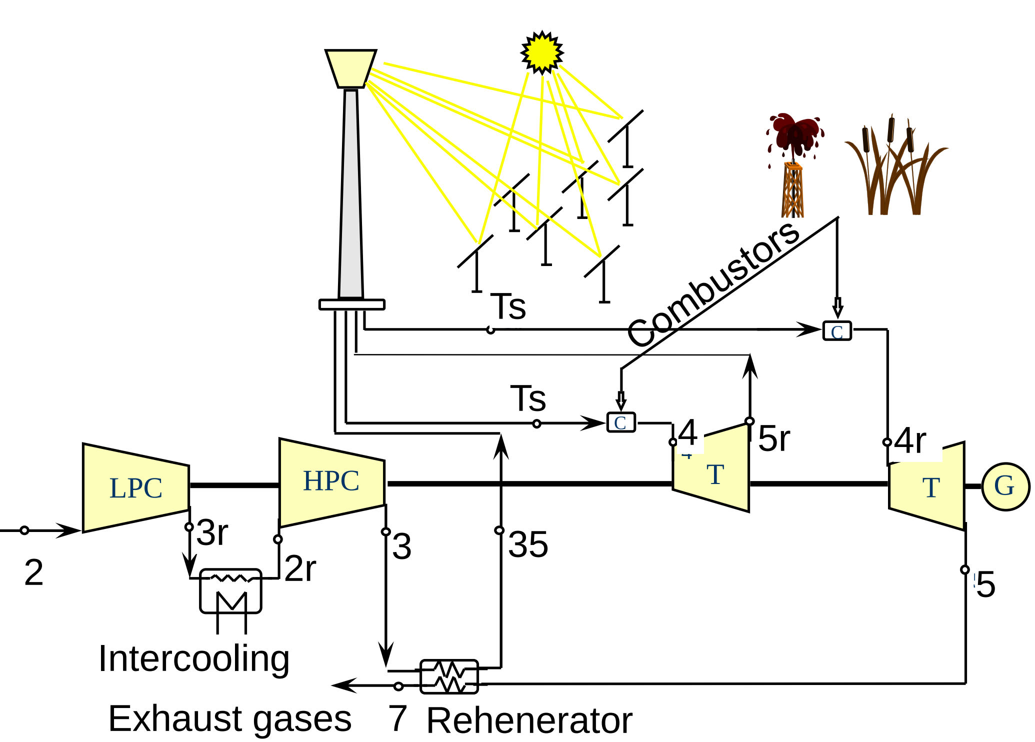
Because of the high temperatures required to achieve a good cycle efficiency, the Brayton cycles are usually integrated in solar tower plants:

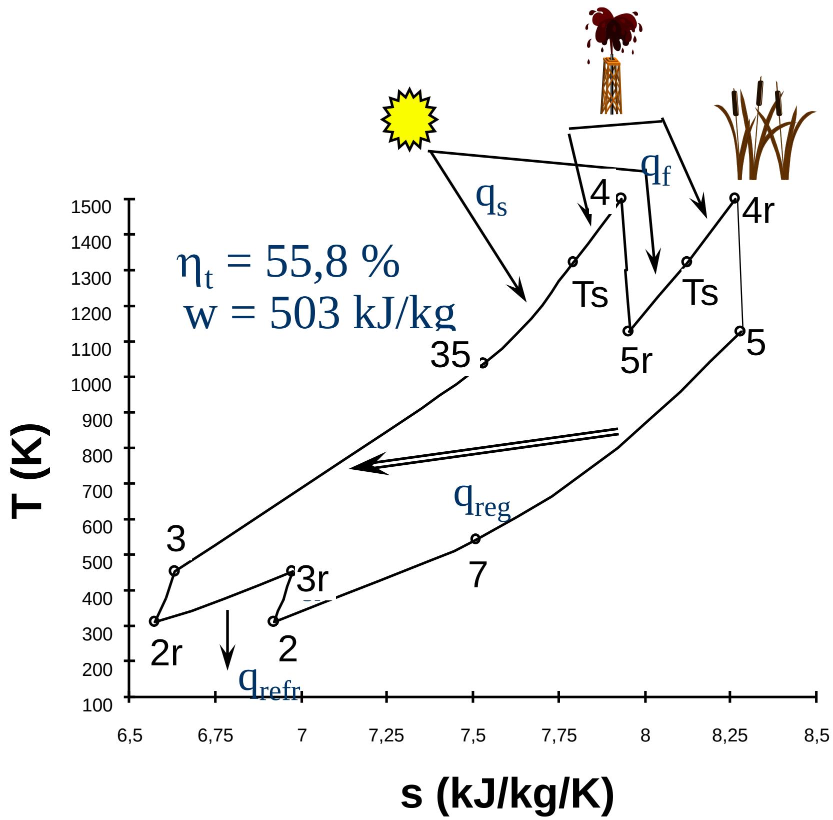




Integration of a Brayton Cycle in STE Plants

Regenerative Brayton Cycle with intercooling and reheating





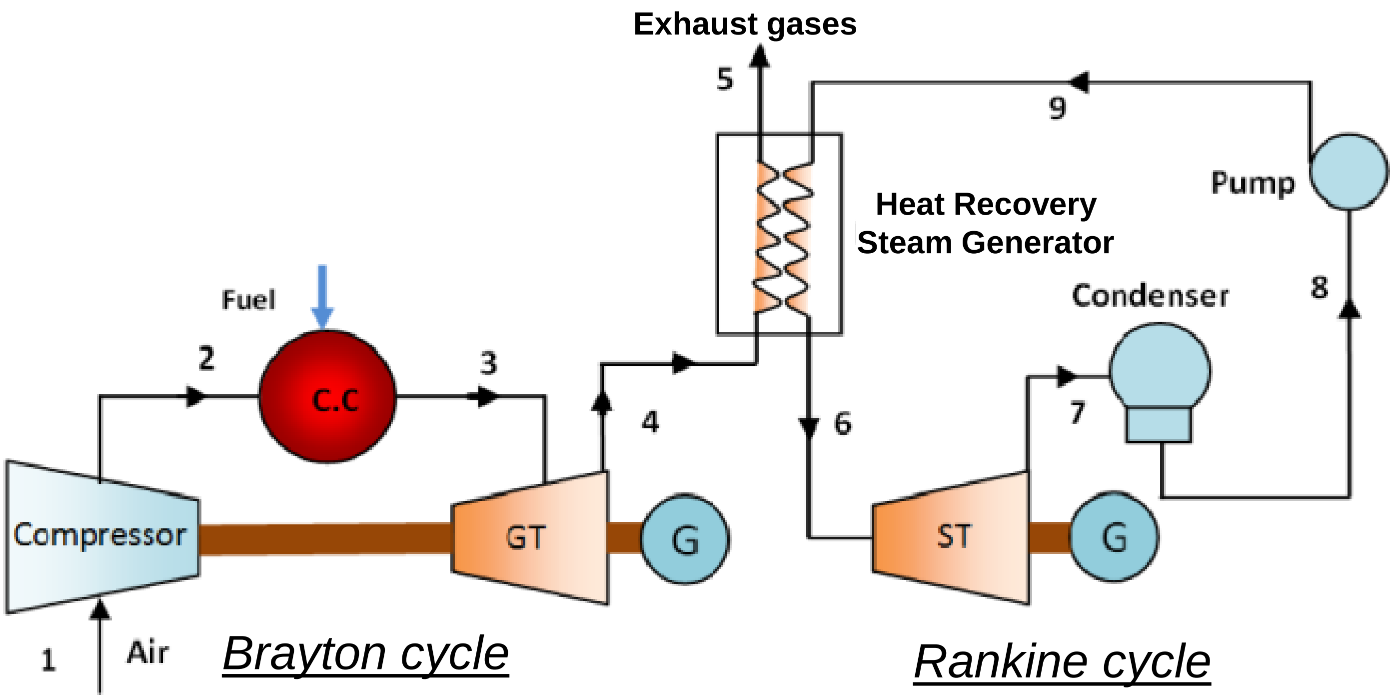
Power Cycles for STE Plants

Content

- Introduction to Thermodynamic Cycles
- ☛ Power Cycles used in STE Plants
  - Rankine Cycle
  - Organic Rankine Cycle
  - Brayton Cycle
  - ☛ Combined Cycle
  - Supercritical Cycles
  - Stirling Cycle

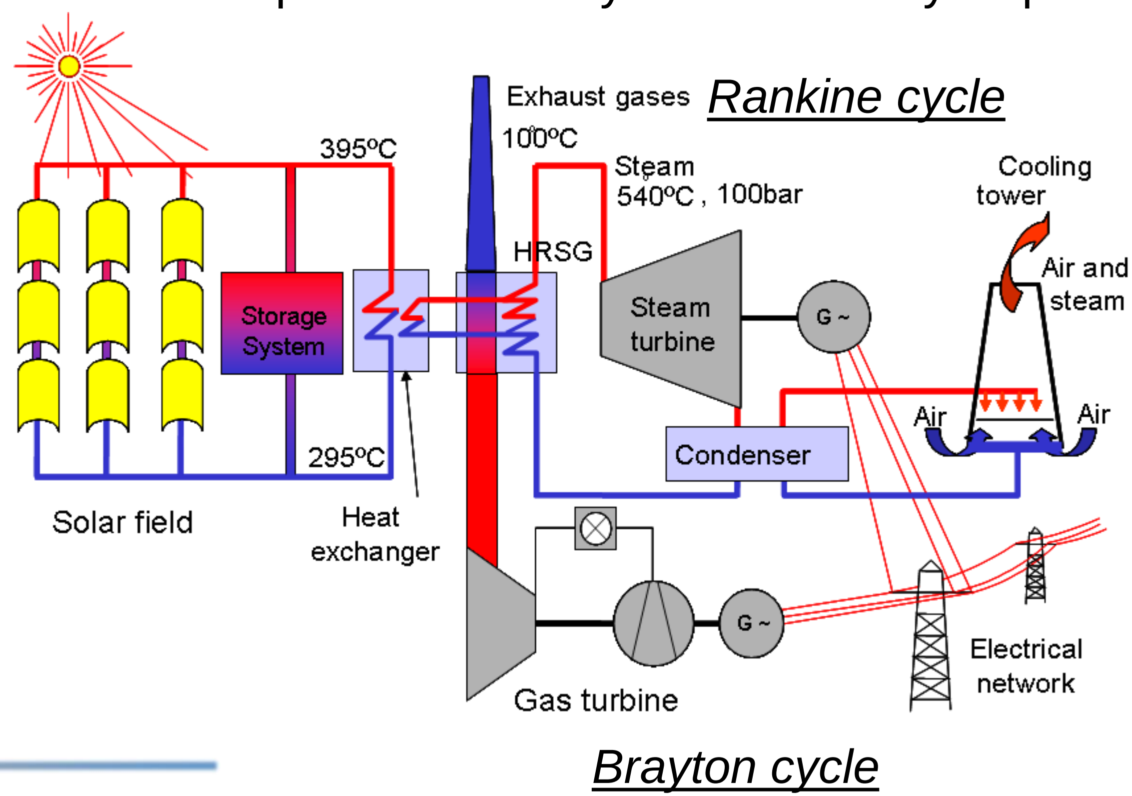
Combined cycle

- A combined cycle is composed of a Brayton cycle coupled to a Rankine cycle in a way that the heat of the gas turbine exhaust gases are used to evaporate the water of a Rankine cycle
- The heat recovery from the exhaust gases increases the overall efficiency up to about 50%, which is higher than the efficiency of any of the basic cycles separately.



Integrated Solar Combined Cycle (ISCC) Plant

- A ISCC plant is composed of a combined cycle with a solar field connected to the Rankine cycle to increase the electricity production of the steam turbine.
- The yearly solar fraction is small (~10%). However, this type of solar plant is an excellent option for countries willing to learn about solar thermal plants without taking a significant risk, because an ISCC plant is basically a combined cycle plant
- There are three ISCC plants in operation at Morocco, Algeria and Egypt



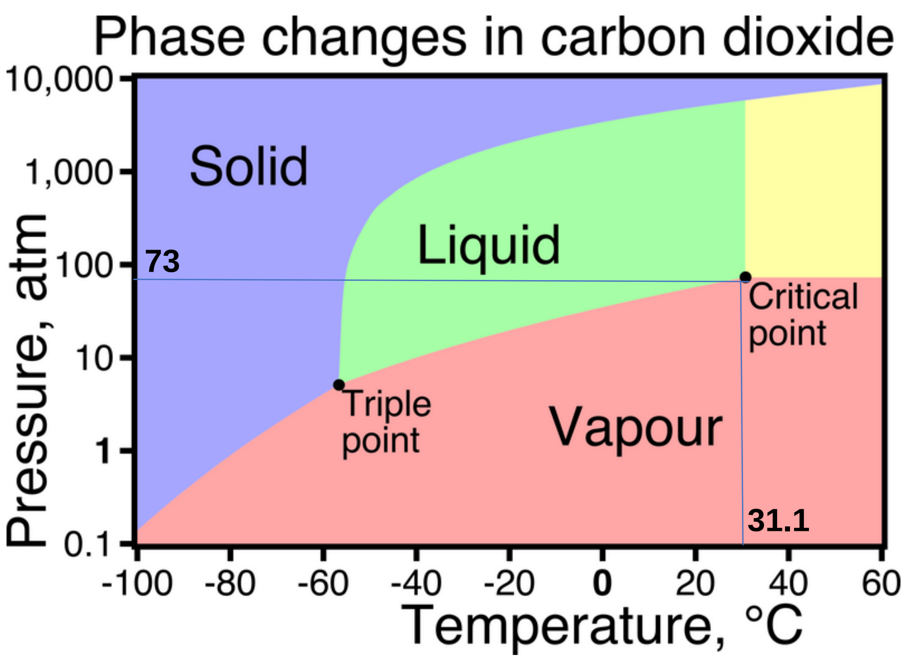
Power Cycles for STE Plants

Content

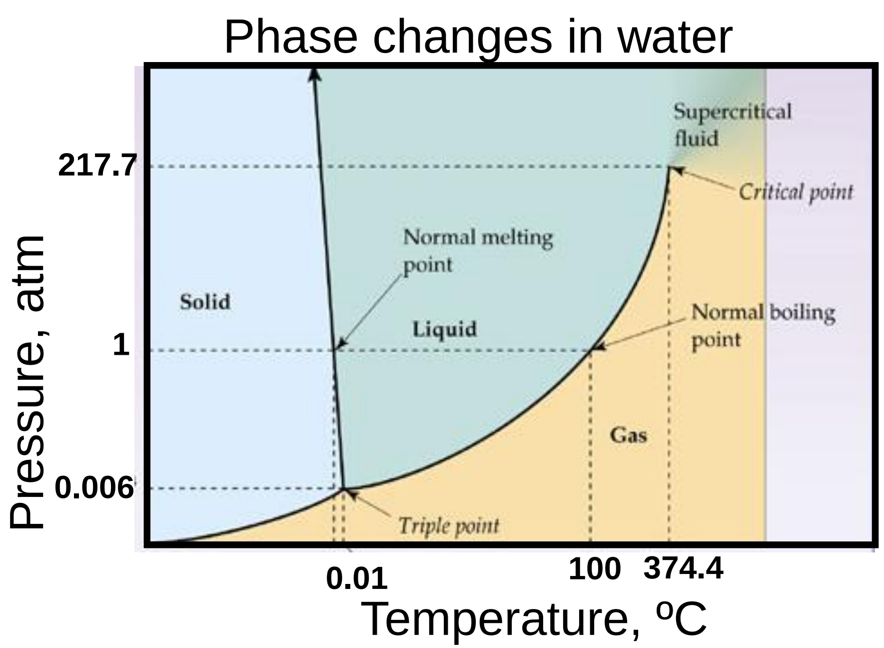
- Introduction to Thermodynamic Cycles
- Power Cycles used in STE Plants
  - Rankine Cycle
  - Organic Rankine Cycle
  - Brayton Cycle
  - Combined Cycle
  - Supercritical Cycles
  - Stirling Cycle

Supercritical Fluids

- When the fluid is at a pressure/temperature higher than those of its "*Critical Point*" is named "***Supercritical Fluid***"
- A *Supercritical Fluid* has both gas-and liquid-like properties. It is gas-like in that it is compressible, and liquid-like in density



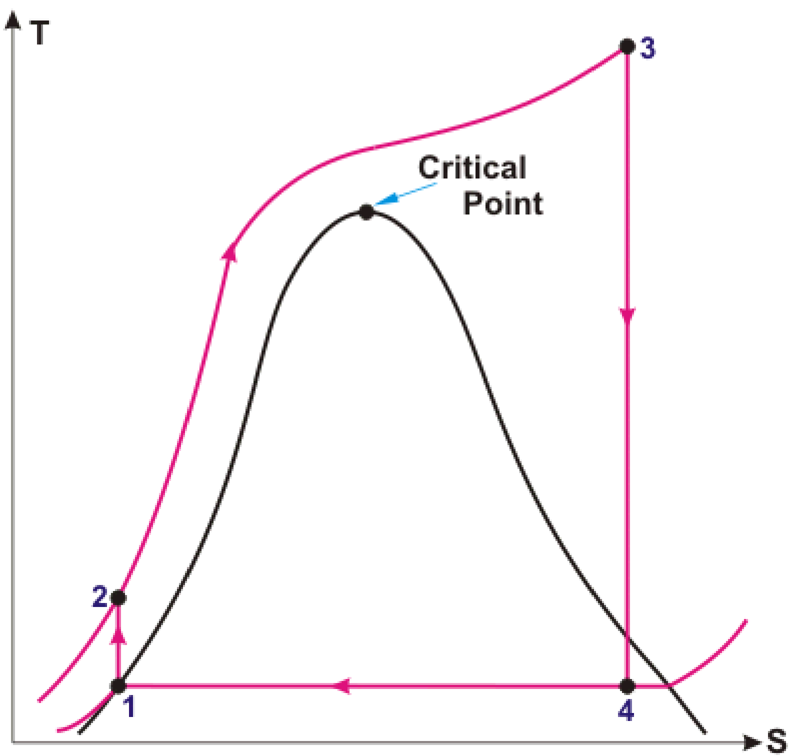
CO_2: P_c = 73 atm, T_c = 31,1°C



H_2O: P_c = 217.7 atm, T_c = 373.4°C

Supercritical Rankine Cycle (SBC)

➢ In a Supercritical Rankine Cycle (SBC) the water is in the boiler at a pressure higher than > 218 bar, so that the water does not change from liquid to steam in the boiler, but expands as it increases its temperature. Typical water pressure/ temperature in commercial SRCs are 300 bar/600ºC



➢ The main benefit of a SBC is a higher efficiency that a superheated Rankine cycle (43% → 46%)

➢ The main drawback is the high pressure that the boiler and the steam turbine must withstand

➢ The water entering the boiler has to be of extremely high levels of purity to avoid deposits on the turbine blades

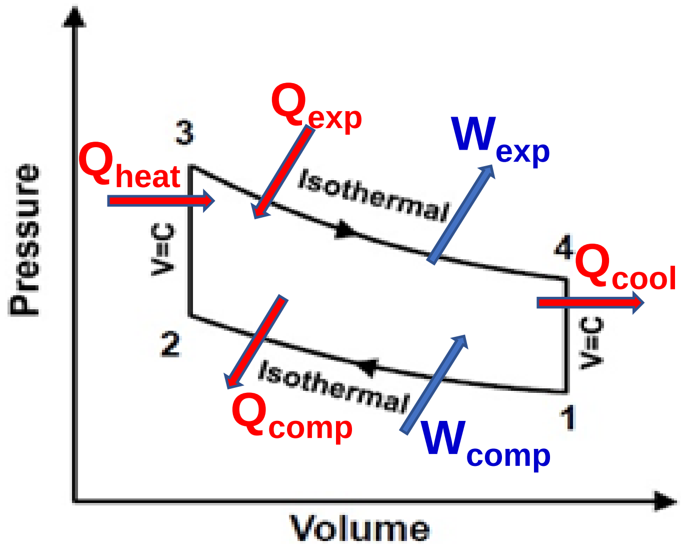
Power Cycles for STE Plants

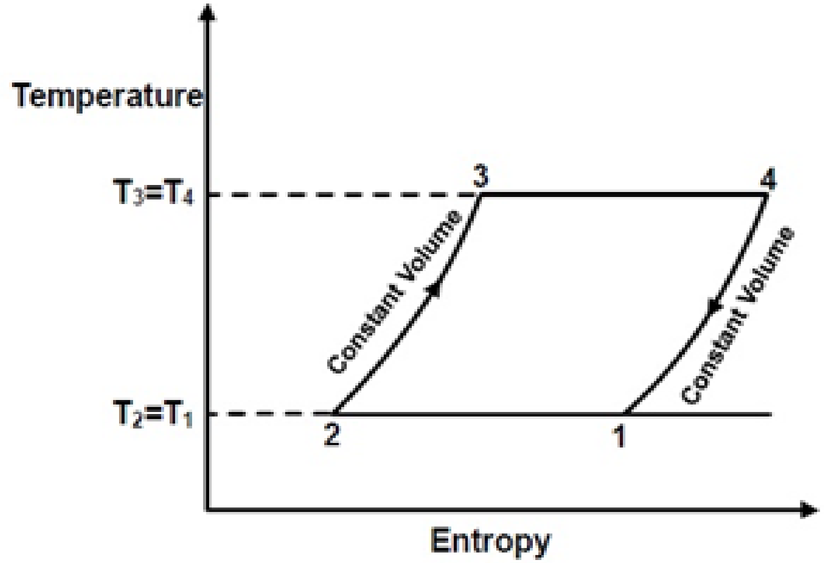
Content

- Introduction to Thermodynamic Cycles
- ☛ Power Cycles used in STE Plants
  - Rankine Cycle
  - Organic Rankine Cycle
  - Brayton Cycle
  - Combined Cycle
  - Supercritical Cycles
  - ☛ Stirling Cycle

The Stirling cycle

- This cycle was patented by Robert Stirling in 1860 and it is composed of four processes (**2 isothermal + 2 isochoric processes**):

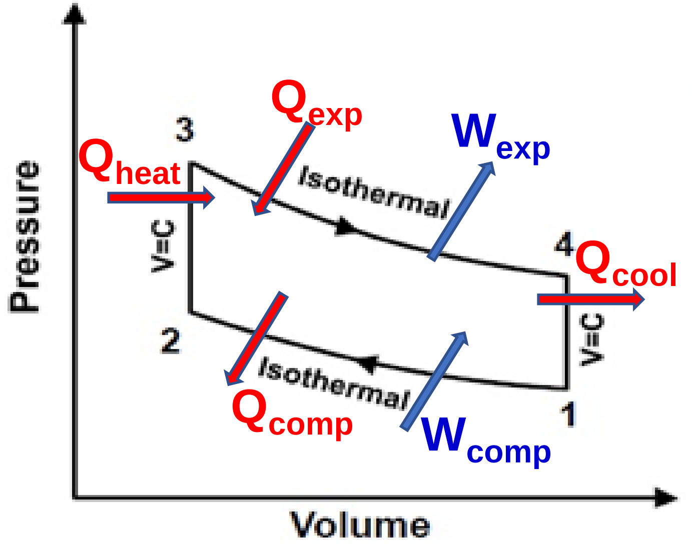


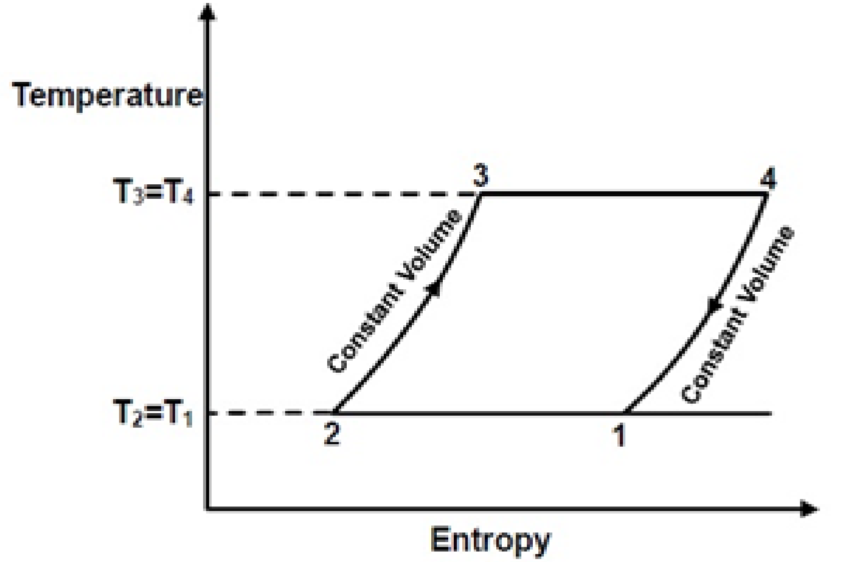


- Process1-2: Isothermal compression extracting heat at constant temperature and adding mechanical work
- Process 2-3: Isochoric compression absorbing heat at constant volume
- Process 3-4: Isothermal expansion adding heat at constant temperature and extracting mechanical work
- Process 4-1: Isochoric expansion extracting heat at constant volume

The Stirling cycle

- This cycle was patented by Robert Stirling in 1860 and it is composed of four processes (**2 isothermal + 2 isochoric processes**):



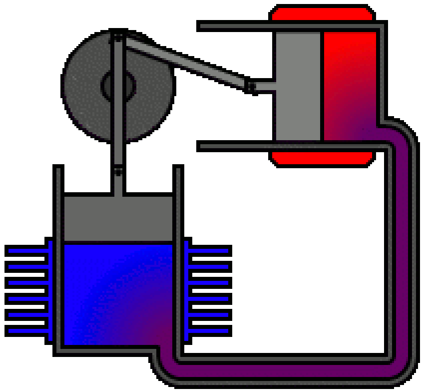


- Since the amount of heat added in 2-3 and extracted in 4-1 are quite similar, an **internal regenerator** is used in Stirling engines to temporarily store Q_{cool}

- Since W_{exp} > W_{comp} there is a net positive mechanical work

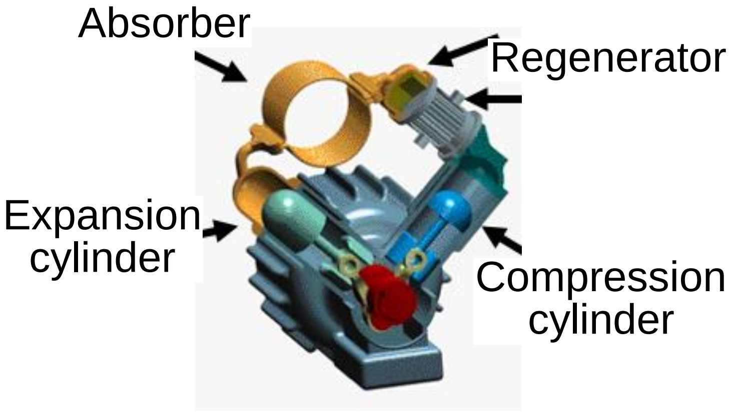
Integration of the Stirling cycle in STE plants

- Stirling cycle is commercially implemented using the so-called ***Stirling engines***, which are **closed-cycle regenerative heat engines with a permanently gaseous working fluid (He or H_2)**.
- Due to the technical features of Stirling engines, they are very suitable to be used with parabolic dish concentrators (600ºC-800ºC / 150-200 bar)



Simple sketch of a Stirling engine

A solar Stirling dish



A solar Stirling engine

- The two main benefits of Stirling engines are their high thermal efficiency (>30%) and the absence of pollutant combustion gases

SFERA-III
1st Summer School
September, 9th- 10th, 2019
CNRS- PROMES, Odeillo, France

Power Cycles for CSP/STE Plants

End of Slide Show

Questions ?

Dr. Eduardo Zarza Moya
Plataforma Solar de Almería (PSA)
R+D Unit for Concentrating Solar Thermal Systems
E-mail: eduardo.zarza@psa.es

Solar Facilities for the European Research Area
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas