

Course ME1100 (Module 4)

(Thermodynamics)

Course Grading and Exam Timing:

- Assignments: 40%
- Quizzes: 60%
 - 4 Quizzes and best 3 will be considered
- Quiz 4: 28th june

Entropy

Part 1

Recap of 2nd Law of Thermodynamics

- 2nd Law of Thermodynamics is only for a Cycle.
- Both the Kelvin Plank (KP) and the Clausius (CL) statements are for a device that operates in a cycle.
- And in entropy, we often deal with processes rather than cycles.

So, generally here we are interested in processes.

Recap of 2nd Law of Thermodynamics

- Efficiency of a heat engine

$$\eta_{\text{rev HE}} = 1 - \frac{Q_{\text{L,rev}}}{Q_{\text{H,rev}}} = 1 - \frac{T_L}{T_H} \quad \because \frac{Q_{\text{L,rev}}}{Q_{\text{H,rev}}} = \frac{T_L}{T_H}$$

$$\Rightarrow \frac{Q_{\text{L,rev}}}{Q_{\text{H,rev}}} = \frac{T_L}{T_H} \text{ (This is only for reversible process.)}$$

$$\text{Efficiency} = \eta_{\text{rev HE}} = \frac{1}{COP_{\text{rev HP}}}$$

Recap of 2nd Law of Thermodynamics

- COP of a Refrigerator $COP_{\text{Ref}} = \frac{Q_L}{W_{\text{net, in}}}$

- COP of a Heat Pump $COP_{\text{HP}} = \frac{Q_H}{W_{\text{net, in}}}$

- COP of Reversible Heat Pump

$$COP_{\text{rev HP}} = COP_{\text{max HE}} = \frac{Q_{\text{H, rev}}}{W_{\text{net in, rev}}} = \frac{Q_{\text{H, rev}}}{Q_{\text{H, rev}} - Q_{\text{L, rev}}} = \frac{T_H}{T_H - T_L}$$

- COP of Reversible Refrigerator

$$COP_{\text{rev Ref}} = COP_{\text{max Ref}} = \frac{Q_{\text{L, rev}}}{W_{\text{net in, rev}}} = \frac{Q_{\text{L, rev}}}{Q_{\text{H, rev}} - Q_{\text{L, rev}}} = \frac{T_L}{T_H - T_L}$$

Recap of 2nd Law of Thermodynamics

- For a reversible process

$$\frac{Q_{\text{rev } H}}{Q_{\text{rev } L}} = \frac{T_H}{T_L}$$

$$\frac{Q_{\text{rev } H}}{T_H} - \frac{Q_{\text{rev } L}}{T_L} = 0$$

$$\frac{Q_{\text{rev } H}}{T_H} + \left(\frac{-Q_{\text{rev } L}}{T_L} \right) = 0$$

$$\sum_{\text{cycle}} \left(\frac{Q}{T} \right)_{\text{rev}} = 0$$

$$\oint \left(\frac{\delta Q}{T} \right)_{\text{rev}} = 0$$

Entropy

- Entropy is an extensive property (A state function)
- Unit: kJ/K
- Change in Entropy = $S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T} \right)_{rev}$
- Entropy leads to make a qualitative analysis of processes based on the 2nd Law of Thermodynamics.
- For reversible adiabatic process-

$$\text{Entropy} = \int \left(\frac{\delta q}{T} \right)_{rev} = \Delta S = 0$$

Entropy Change for Carnot Cycle

- It is a reversible cycle.

And net change in Entropy for any reversible cycle is Zero.

So, change in Entropy = $\oint \left(\frac{\delta Q}{T} \right)_{rev} = 0$

The absolute value of Entropy

- Basis to determine the Absolute Value of Entropy-
“The Entropy of a Perfect Crystal is Zero at Absolute Zero Temperature”

Clausius inequality

- Statements-

1. For reversible cycle,

change in entropy = $\oint \left(\frac{\delta Q}{T} \right)_{rev} = 0$

2. For irreversible cycle,

change in entropy = $\oint \left(\frac{\delta Q}{T} \right) < 0$

So, Overall $\oint \frac{\delta Q}{T} \leq 0$

Entropy changes in reversible and irreversible processes between two states

For two states 1 to 2, We know-

$$W_{irr} < W_{rev}$$

$$\Delta U_{irr} = \Delta U_{rev}$$

By first law-

$$\Rightarrow Q_{irr} < Q_{rev}$$

Hence, $\Delta S_{irr} > \Delta Q/T$ and $\Delta S_{rev} = \Delta Q/T$

ISENTROPIC Process

- In a reversible adiabatic process the heat transfer is zero and the change in entropy is also zero.

So, this process called an **ISENTROPIC Process**.

- And the flow through nozzles, compressors and turbines is often taken to be reversible and adiabatic.

Entropy Changes during processes

- For any process-

$$\Delta S_{\text{system}} = \Delta S_{\text{due to heat transfer}} + \Delta S_{\text{production}}$$

Where $\Delta S_{\text{production}}$ = Entropy generated due to dissipative effects i.e. irreversibilities.

Entropy calculations for various processes and substances

- For reversible process-

$$TdS = \delta Q_{rev},$$

And by first law-

$$\delta Q_{rev} = dU + pdV,$$

$$\Rightarrow \mathbf{TdS = dU + pdV}$$

- And we know $H = U + pV$,

$$dH = dU + pdV + Vdp,$$

By substituting the value of dU –

$$\Rightarrow \mathbf{TdS = dH - Vdp}$$

And these relations can be use for both reversible and irreversible process.

Entropy Change for an ideal gas with constant specific heats undergoing a process

By using $TdS = dU + pdV$ -

We know $dU = C_v dT$ and $PV = RT$

$$\Delta S = m \left[C_v \ln \left(\frac{T_2}{T_1} \right) + R \ln \left(\frac{V_2}{V_1} \right) \right]$$

By using $TdS = dH - Vdp$ -

We know $dH = C_p dT$ and $PV = RT$

$$\Delta S = m \left[C_p \ln \left(\frac{T_2}{T_1} \right) - R \ln \left(\frac{p_2}{p_1} \right) \right]$$

Entropy Changes in Solids and Liquids

- In solids and liquids volume changes are negligible.

And $C_p = C_v = C$

If change in Temp. is $T_2 - T_1$, then

$$\text{Entropy change} = \Delta S = m \cdot C \cdot \ln\left(\frac{T_2}{T_1}\right)$$

Entropy changes in Steam

- $S = S_f + x \cdot S_{fg}$

And

- $S_{\text{compressed liquid } T, p} = S_{\text{saturated liquid, } T}$

Qualitative Test for Irreversibility

- *For an irreversible process $\Delta S > \int_1^2 \frac{\delta Q}{T}$*
- *For an irreversible process $\int \frac{\delta Q}{T}$ does not equal Change in Entropy*
- *For an irreversible process Entropy Change is greater than $\int \frac{\delta Q}{T}$*

=> Hence Entropy change for an irreversible process is higher than the change in a reversible process for the same dQ and T.

Entropy Generation

- Only for an irreversible process

Entropy change

$$dS = \frac{\delta Q}{T} + \delta S_{gen} \text{ Where } S_{gen} \geq 0$$

Where ΔS_{gen} is the entropy generated due to irreversibilities in the system.

And $\delta Q_{irr} = T dS - T \delta S_{gen}$

$$\delta W_{irr} = \bar{P} dV - T \delta S_{gen}$$

Principle of Increase of Entropy

- Let us consider a system and its surroundings.

$$dS_{\text{sys}} \geq \frac{\delta Q}{T}$$

And

$$dS_{\text{surr}} = \frac{-\delta Q}{T_0}$$

$$\Rightarrow \text{Hence } dS_{\text{net}} = dS_{\text{sys}} + dS_{\text{surr}}$$

$$dS_{\text{net}} \geq \delta Q \left(\frac{1}{T} - \frac{1}{T_0} \right)$$

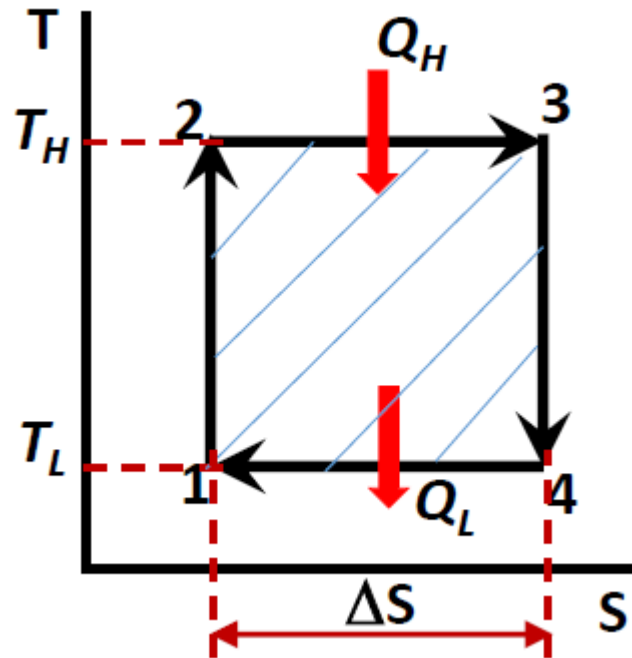
$$\text{So, } dS_{\text{sys}} + dS_{\text{surr}} \geq 0$$

Thermodynamic Cycles

Part 2

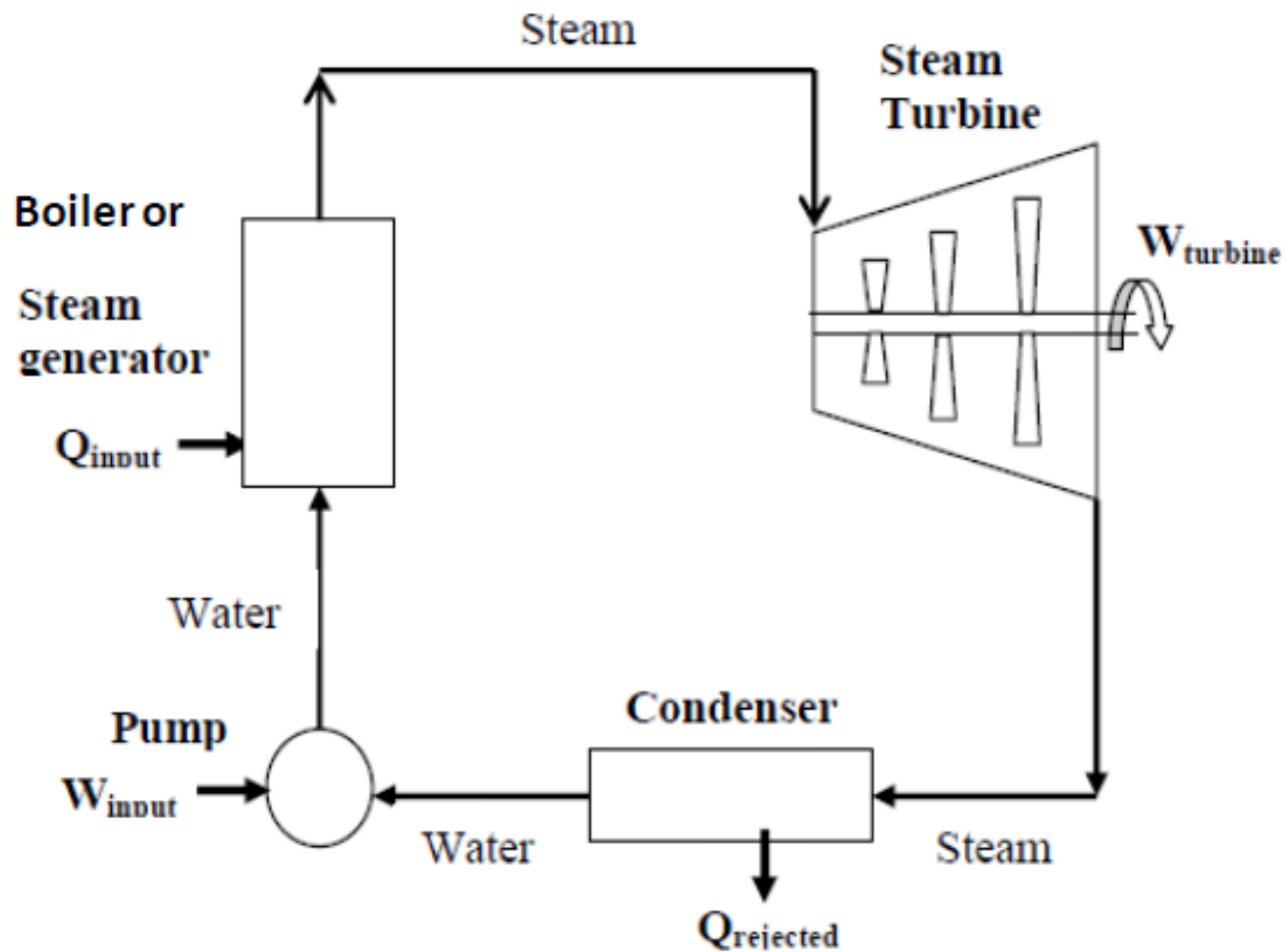
T-S Diagram of Carnot Cycle

- 1-2: Reversible Adiabatic Compression
- 2-3: Reversible Isothermal (Heat Addition at constant temperature)
- 3-4: Reversible Adiabatic Expansion
- 4-1: Reversible Isothermal (Heat Rejection at constant temperature)



Shaded area in T-S gives net heat transfer

The steam cycle: Arrangement



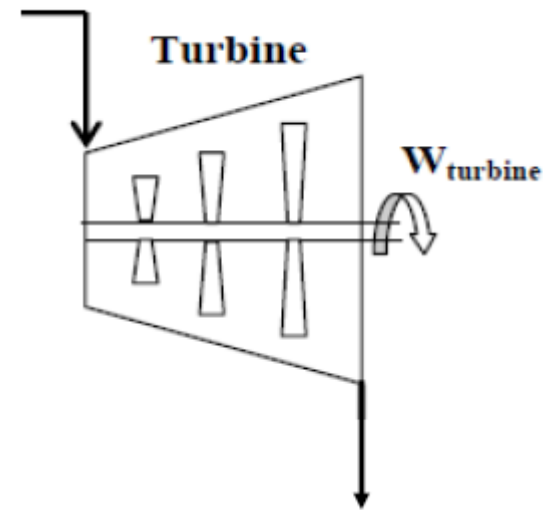
Steam/Gas Turbine

- Adiabatic condition
- d(P.E.) and d(K.E.) are negligible.
- By Steady Flow Energy Equation-

$$\cancel{Q'} - W'_{ext} = \dot{m} \left(h_e + \cancel{\frac{V^2}{2}} + \cancel{gz_e} \right) - \dot{m} \left(h_i + \cancel{\frac{V^2}{2}} + \cancel{gz_i} \right)$$

Power produced by the turbine-

$$W'_{ext} = \dot{m}(h_i - h_e)$$



Heat Exchanger

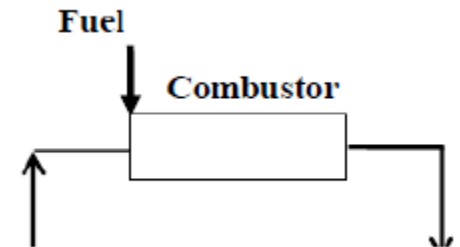
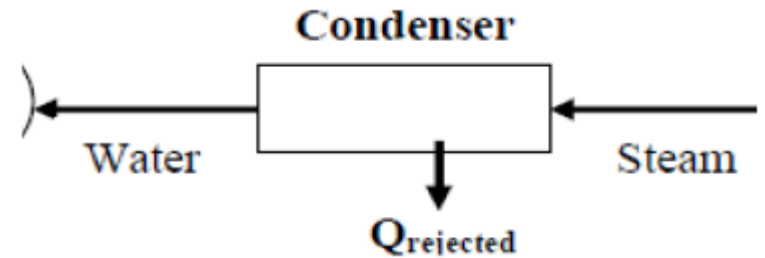
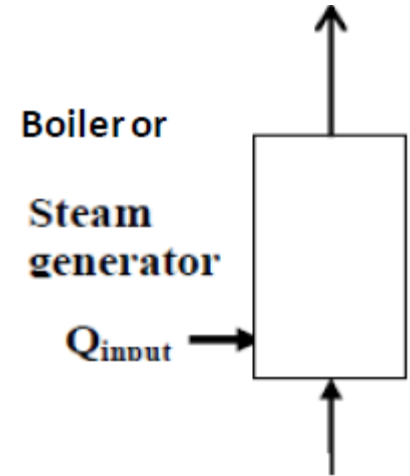
- d(P.E.) and d(K.E.) are negligible.

Steady Flow Energy Equation

$$\cancel{Q'} - \cancel{W'_{ext}} = \dot{m} \left(h_e + \cancel{\frac{V_e^2}{2}} + \cancel{gz_e} \right) - \dot{m} \left(h_i + \cancel{\frac{V_i^2}{2}} + \cancel{gz_i} \right)$$

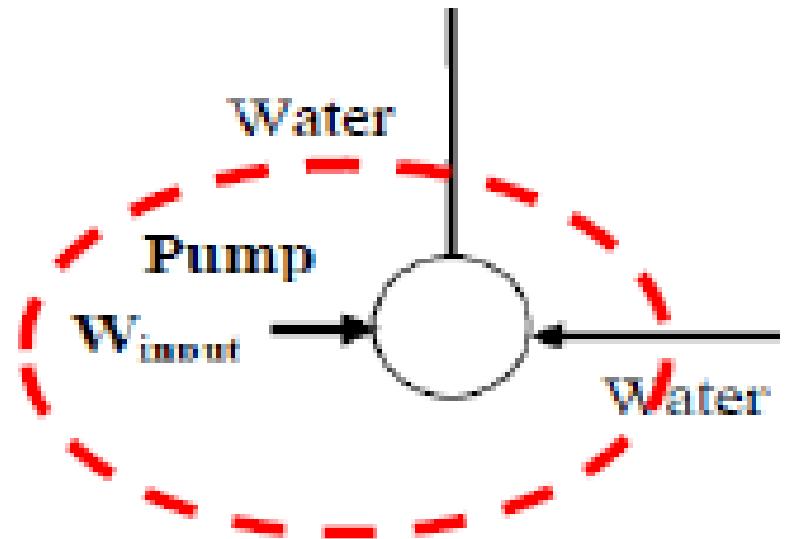
Rate of heat transfer:

$$Q' = \dot{m}(h_e - h_i)$$



Water pump

- Adiabatic condition
- $d(\text{P.E.})$ and $d(\text{K.E.})$ are negligible.
- Change in specific volume is negligible.
- Change in temperature is negligible



Water pump

By Steady Flow Energy Equation-

$$\cancel{Q'} - W'_{ext} = \dot{m} \left(h_e + \cancel{\frac{V_e^2}{2}} + \cancel{gz_e} \right) - \dot{m} \left(h_i + \cancel{\frac{V_i^2}{2}} + \cancel{gz_i} \right)$$

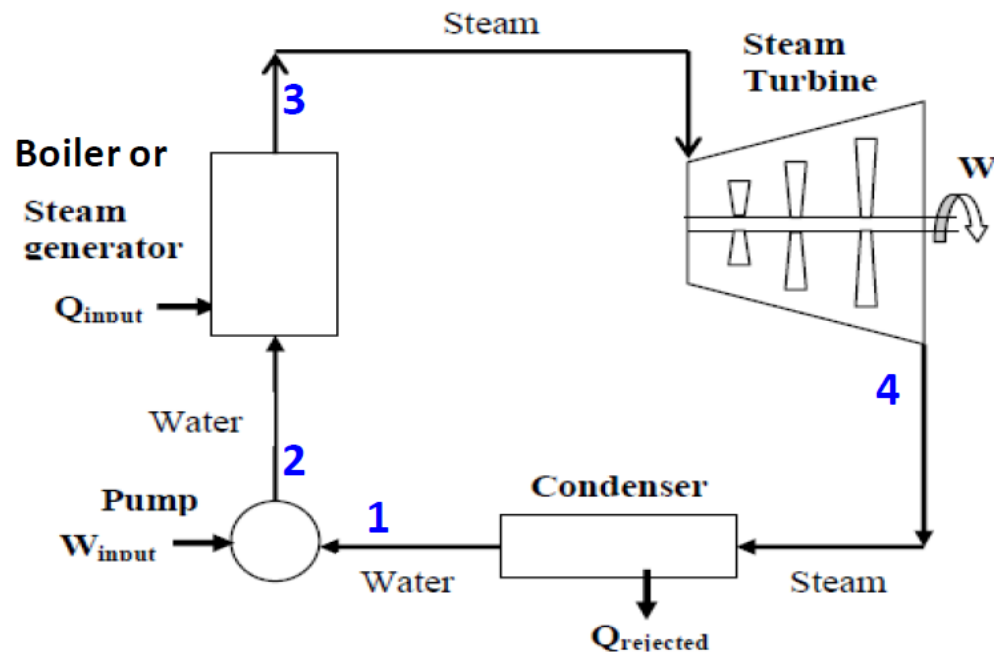
Power required by the pump:

$$W'_p = -W'_{ext} = \dot{m} (h_e - h_i)$$

$$\Rightarrow W'_p = \dot{m} (v_f)_{T_f} (p_e - p_i)$$

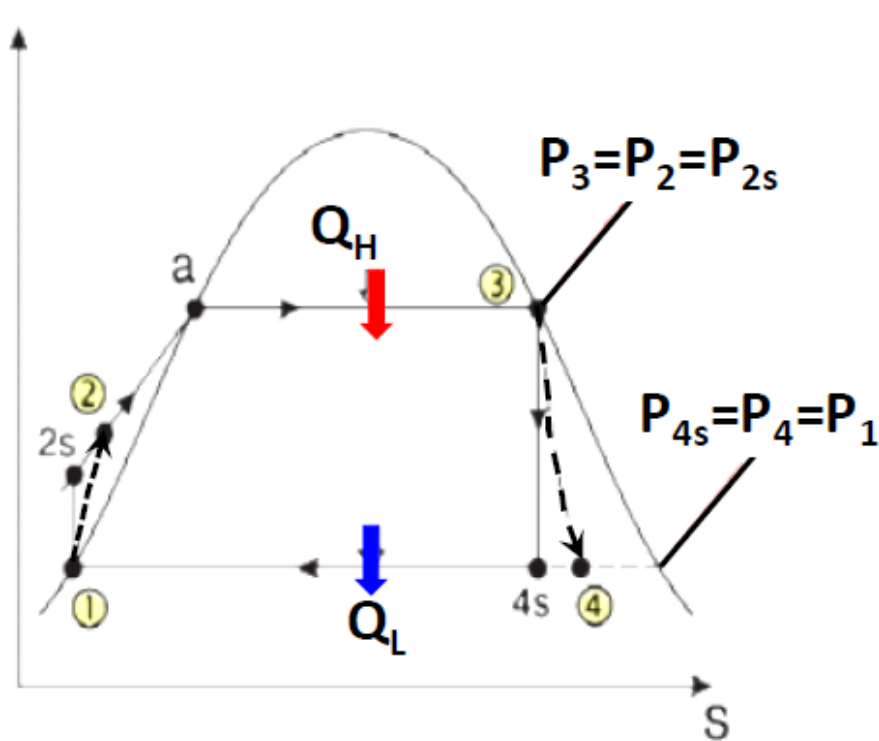
Processes involved in the Steam Cycle

- 1-2: Isentropic Compression
- 2-3: Reversible heat addition (*transfer to the device*) at constant temperature
- 3-4: Isentropic expansion
- 4-1: Reversible heat rejection at constant temperature



Ideal Rankine Cycle: 1-2s-3-4s-1

Heat addition in boiler	$Q'_H = \dot{m}(h_3 - h_{2s})$
Heat removal in condenser	$Q'_L = \dot{m}(h_{4s} - h_1)$
Work done by turbine	$W'_T = \dot{m}(h_3 - h_{4s})$
Work input to the pump	$W'_P = \dot{m}(h_{2s} - h_1)$
Net work output from the cycle	$W'_{net} = W'_T - W'_P$
Efficiency of Rankine cycle	$\eta = \frac{W'_{net}}{Q'_H}$



Actual Rankine Cycle: 1-2-3-4-1

Heat addition in boiler $Q'_H = \dot{m}(h_3 - h_2)$

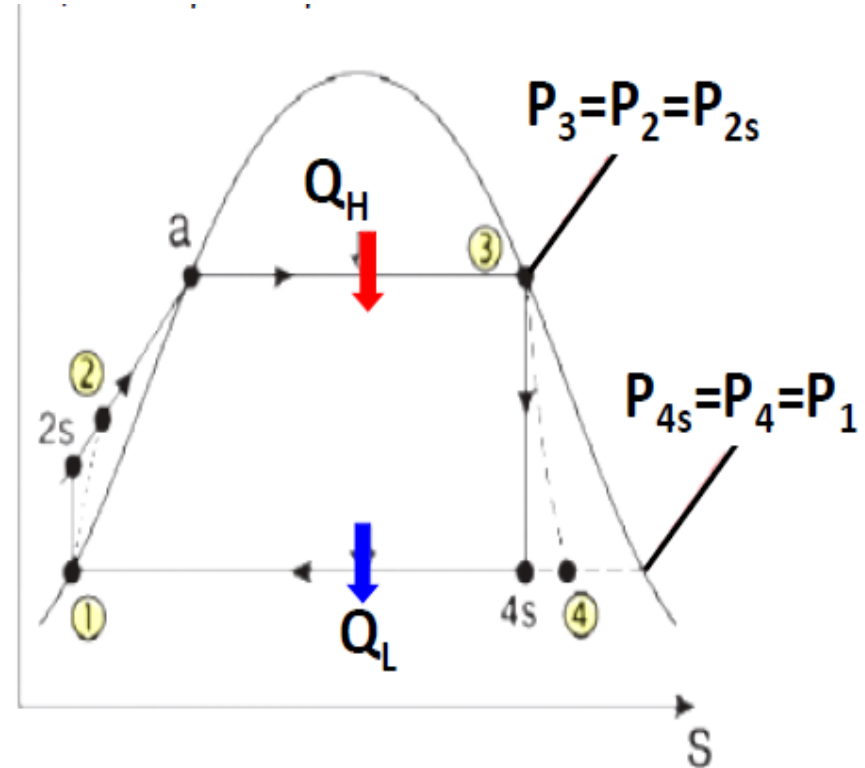
Heat removal in condenser $Q'_L = \dot{m}(h_4 - h_1)$

Work done by turbine $W'_T = \dot{m}(h_3 - h_4)$

Work input to the pump $W'_P = \dot{m}(h_2 - h_1)$

Net work output from the cycle $W'_{net} = W'_T - W'_P$

Efficiency of Rankine cycle $\eta = \frac{W'_{net}}{Q'_H}$



Actual Rankine Cycle: 1-2-3-4-1

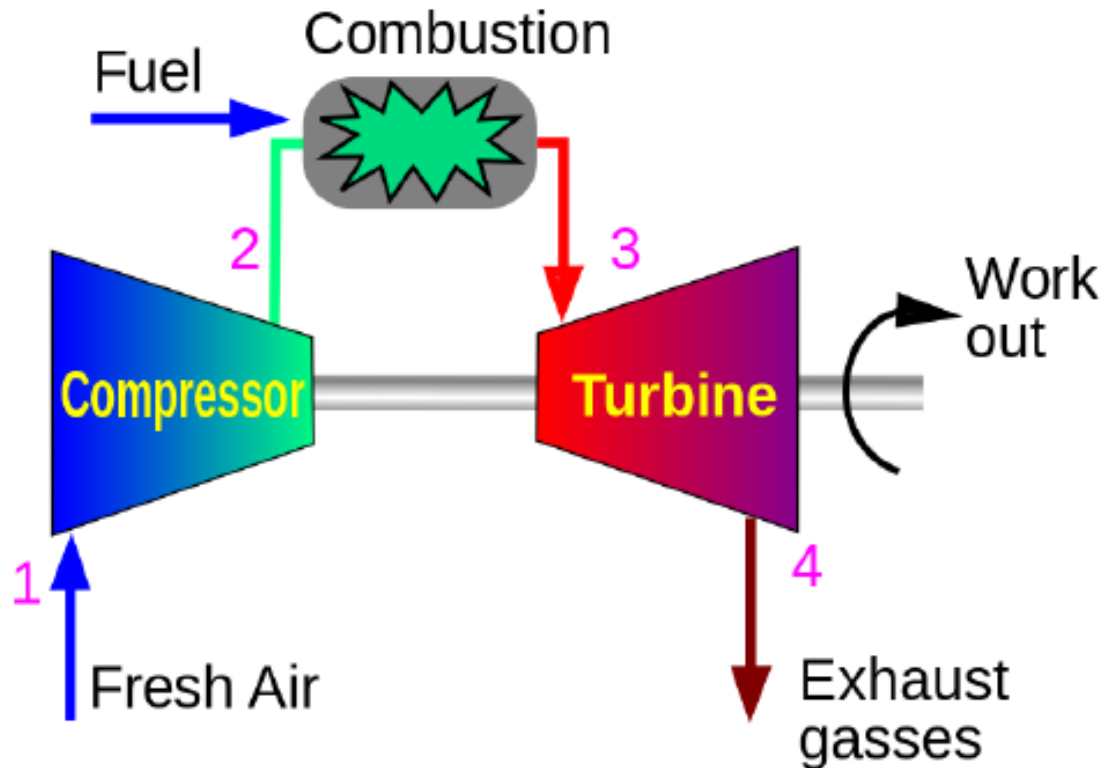
- Isentropic efficiency of pump

$$\eta_P = \frac{(h_{2s} - h_1)}{(h_2 - h_1)}$$

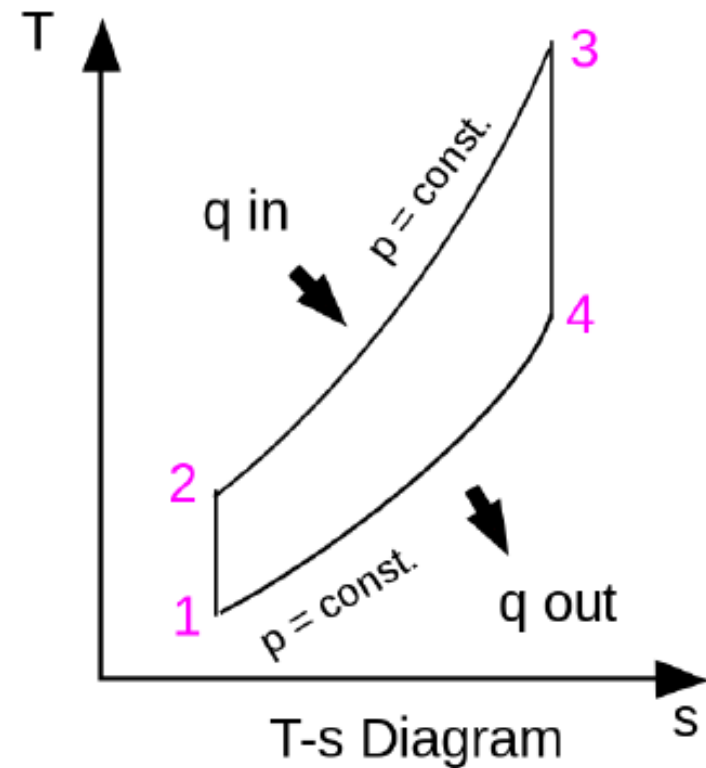
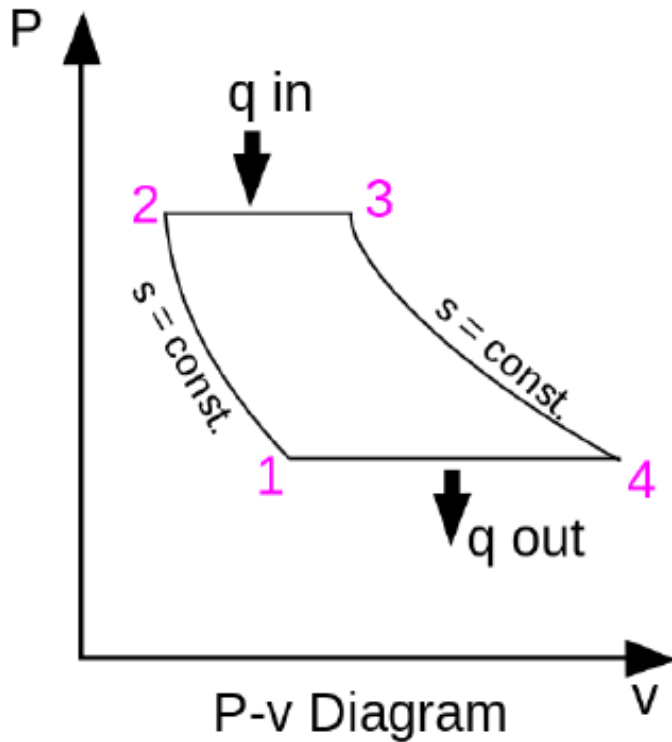
- Isentropic efficiency of turbine

$$\eta_T = \frac{(h_3 - h_4)}{(h_3 - h_{4s})}$$

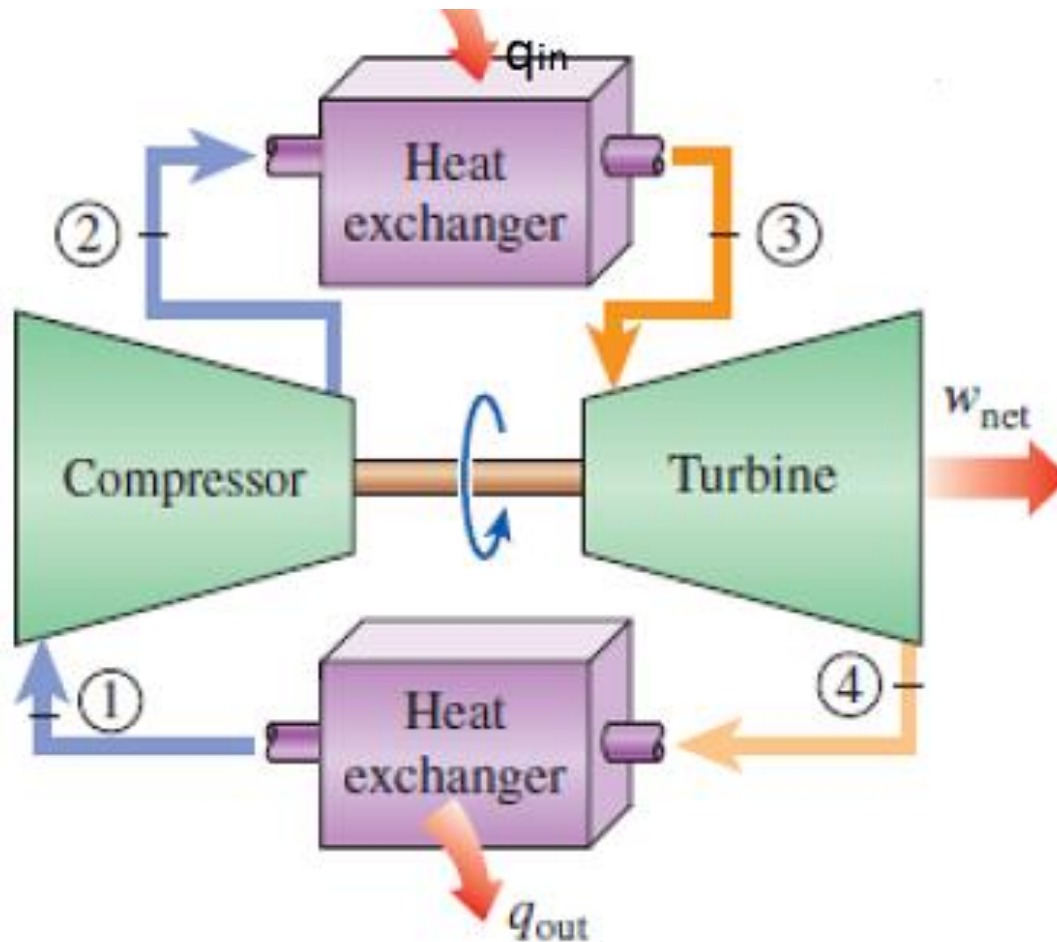
Open Cycle Gas Turbine: Arrangement



Open Cycle Gas Turbine

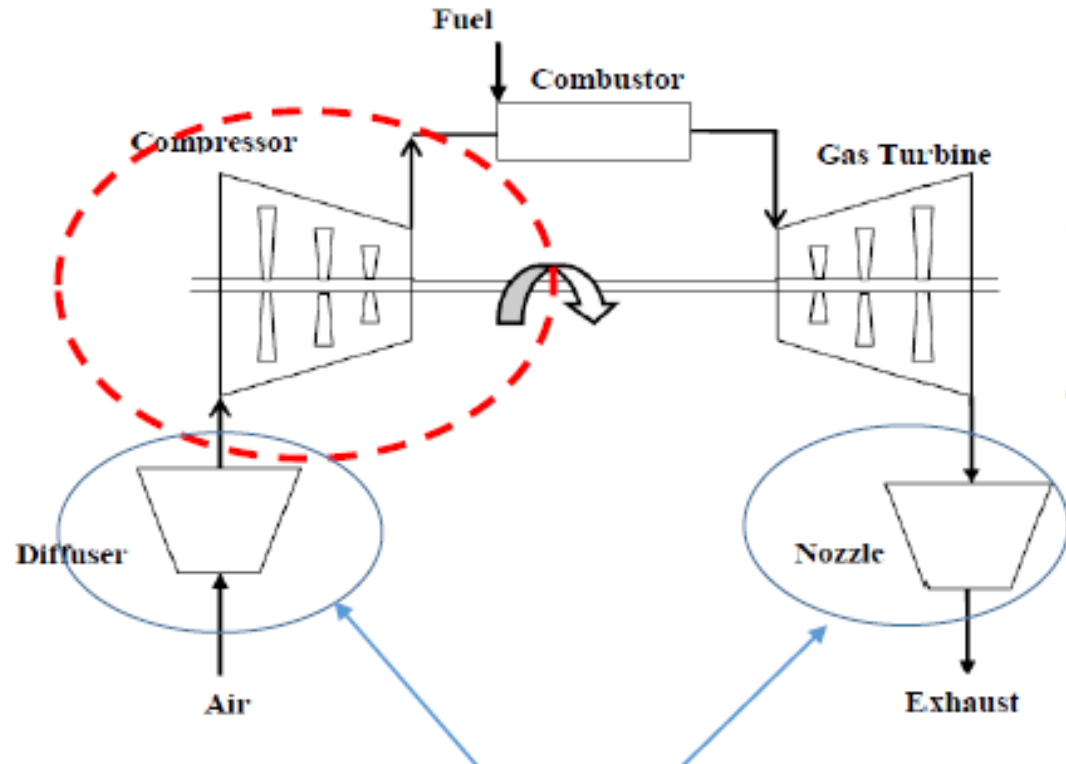


Closed Cycle Gas Turbine Engine: Arrangement



Compressor

- adiabatic condition
- $d(P.E.)$ and $d(K.E.)$ are negligible.



May or may not be present
Present only in Aircraft gas turbines
Not needed in land gas turbines

Compressor

By Steady Flow Energy Equation-

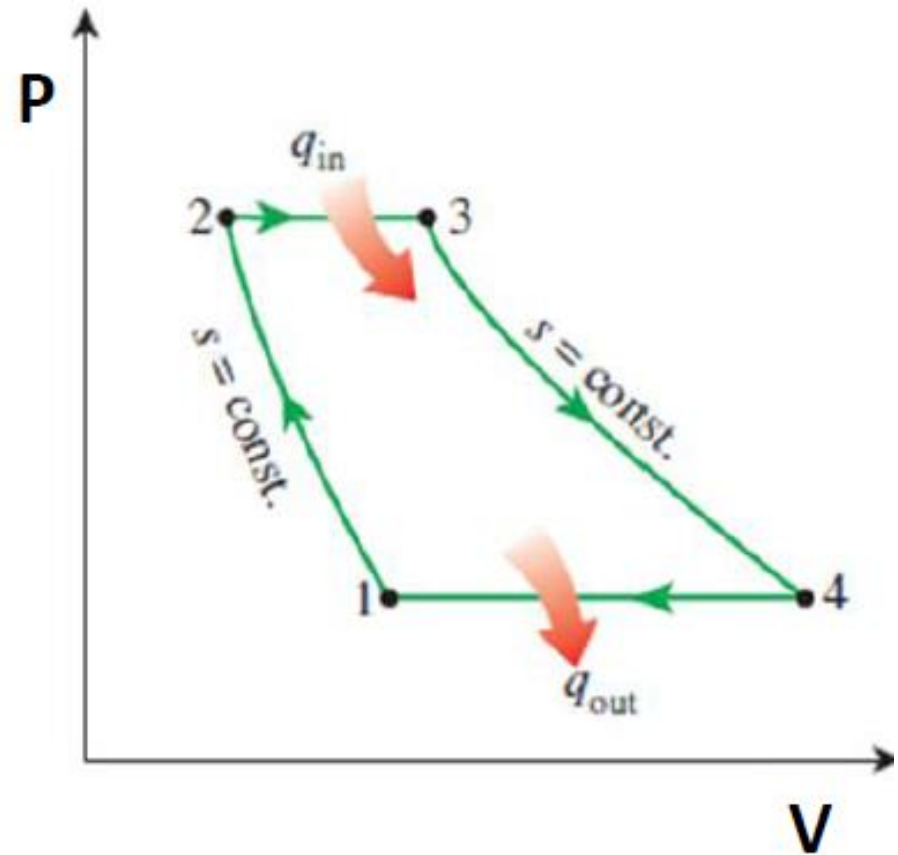
$$\cancel{Q'} - W'_{ext} = \dot{m} \left(h_e + \cancel{\frac{V_e^2}{2}} + \cancel{gz_e} \right) - \dot{m} \left(h_i + \cancel{\frac{V_i^2}{2}} + \cancel{gz_i} \right)$$

Power needed by the compressor:

$$W'_c = -W'_{ext} = \dot{m} (h_e - h_i)$$

Brayton Cycle

- 1-2: Isentropic Compression
- 2-3: Reversible constant pressure heat addition in heater
- 3-4: Isentropic expansion in turbine
- 4-1: Reversible constant pressure heat rejection in cooler



Brayton Cycle

Heat addition in the heater

$$Q'_H = \dot{m}(h_3 - h_2)$$

Heat rejection in the cooler

$$Q'_L = \dot{m}(h_4 - h_1)$$

Work done by the turbine

$$W'_T = \dot{m}(h_3 - h_4)$$

Work input to the compressor

$$W'_C = \dot{m}(h_2 - h_1)$$

Net work output from the cycle

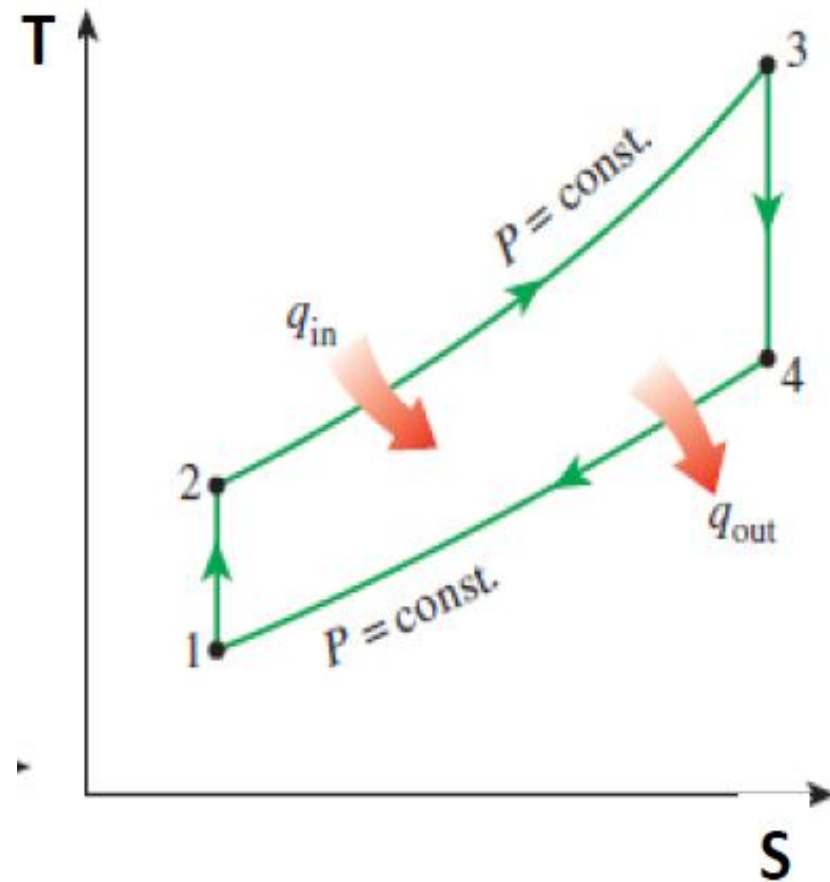
$$W'_{net} = W'_T - W'_C$$

Efficiency of the Brayton cycle

$$\eta = \frac{W'_{net}}{Q'_H}$$

$$\frac{P_2}{P_1} = \left(\frac{T_{2s}}{T_1} \right)^{\gamma/\gamma-1}; \frac{P_3}{P_4} = \left(\frac{T_3}{T_{4s}} \right)^{\gamma/\gamma-1}$$

$$\Delta h = C_p \Delta T$$



Brayton Cycle

Isentropic efficiency of turbine

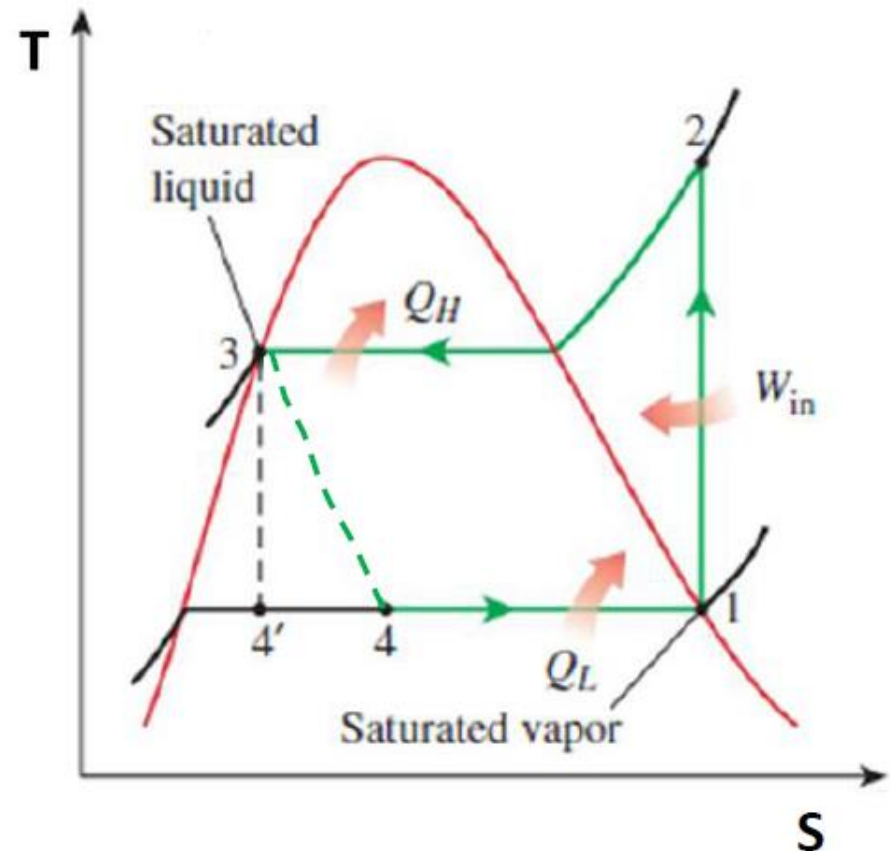
$$\eta_T = \frac{(h_3 - h_4)}{(h_3 - h_{4s})}$$

- Isentropic efficiency of compressor

$$\eta_c = \frac{(h_{2s} - h_1)}{(h_2 - h_1)}$$

Vapour Compression Refrigeration Cycle(Ideal Cycle)

- 1-2: Isentropic Compression
- 2-3: Reversible constant pressure heat rejection in condenser
- 3-4: Isenthalpic
- Irreversible expansion in valve
- 4-1: Reversible constant pressure heat addition in evaporator



Vapour Compression Refrigeration Cycle(Actual Cycle)

- Heat addition in evaporator

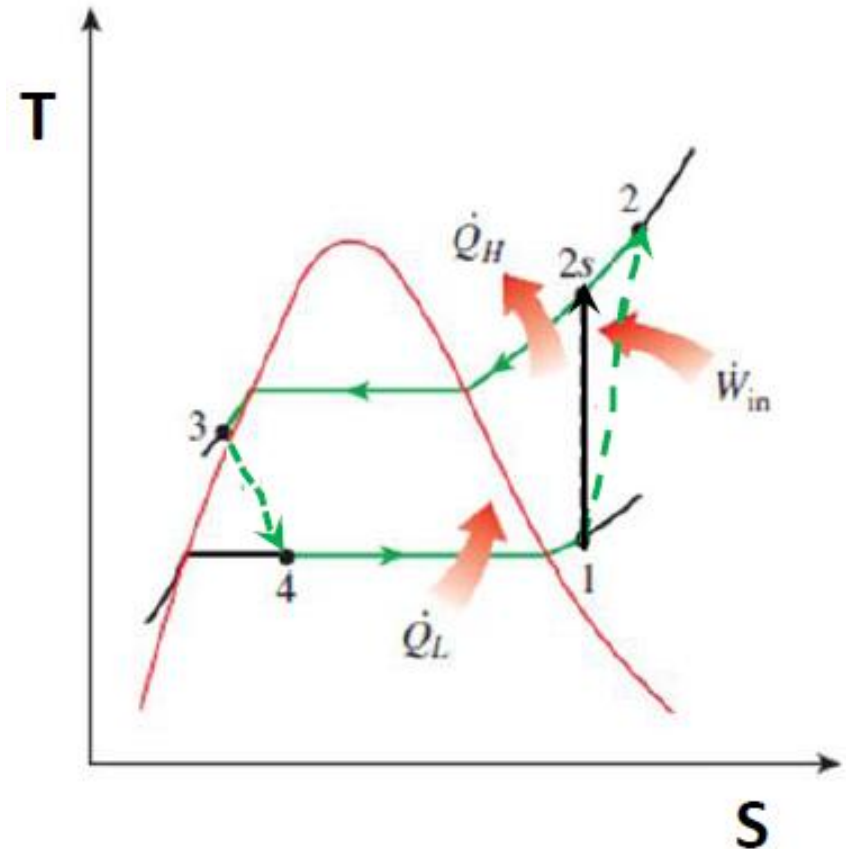
$$Q'_L = \dot{m}(h_1 - h_4)$$

- **Work input to the compressor**

$$W'_c = \dot{m}(h_2 - h_1)$$

- Isentropic efficiency of compressor

$$\eta_c = \frac{(h_{2s} - h_1)}{(h_2 - h_1)}$$



- **Coefficient of performance**

$$COP = \frac{Q'_L}{W'_c}$$

Thank You