5. SECOND LAW OF THERMODYNAMICS

THERMAL ENERGY RESERVOIRS:

HEAT SOURCE: It's a thermal energy reservoir which supplies heat at constant temperature. E.g. Hot Gas in IC engine, Fission in nuclear reactors, Hot gases in boiler furnace.	**HEAT SINK:** It's a thermal energy reservoir which absorbs heat at constant temperature. E.g. Atmosphere, River Water, Ocean.

STATEMENT OF SECOND LAW:

KELVIN-PLANK'S STATEMENT: It's impossible to construct a device which is operating on a cycle and producing work continuously and exchanging heat with single reservoir.	**CLAUSIUS STATEMENT:** It's impossible to construct a device which operates on a cycle and transferring heat from low temperature body to high temperature body without any external work input.

PERPETUAL MOTION MACHINE OF SECOND KIND (PMM-II): It's impossible to have 100% efficiency of engine. And It violates the second law of thermodynamics.

HEAT ENGINE:

It works on cycle and takes heat from higher energy medium and converts in to work and transfers remaining heat to lower energy medium. E.g. IC Engine, Steam Power Plant, Gas Turbine Power Plant.

FIRST LAW OF THERMODYNAMICS TO HEAT ENGINE: It's valid for reversible and irreversible process.

For Cycle, $Q_{net} = W_{net} \Rightarrow W_{net} = Q_1 - Q_2$ $\eta = \frac{O/P}{I/P} = \frac{W_{net}}{Q_1} = 1 - \frac{Q_2}{Q_1}$	Q_1= Heat Supplied to Engine, Q_2= Heat Rejected from Engine, W_{net}= Work Done by Engine,	see table below

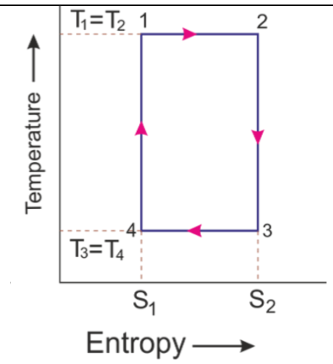
$\boldsymbol{T_1}$	
$\boldsymbol{HE_1}$	$\rightarrow \boldsymbol{W_1}$
$\boldsymbol{T_2}$	

CARNOT CYCLE:

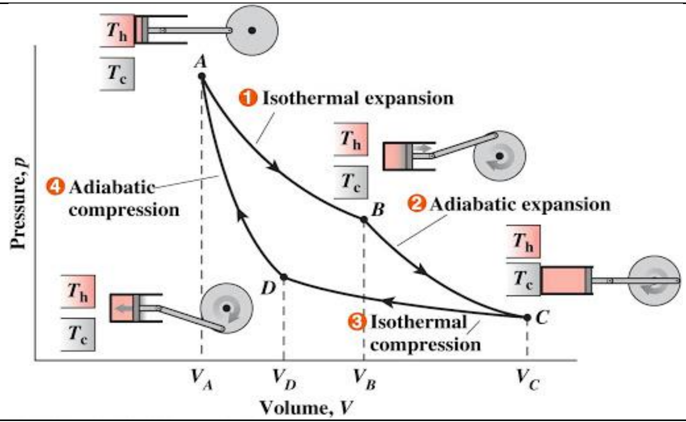
1. It's reversible cycle.
2. It's work producing cycle (Clockwise Dir.)

Processes:

1-2: Rev. Isothermal Heat Supply Expansion
2-3: Rev. Adiabatic Expansion
3-4: Rev. Isothermal Heat Rejection Compression
4-1: Rev. Adiabatic Compression.



(b) T-S diagram



Here,

$T_1 = T_2 = T_H$	$T_3 = T_4 = T_L$
$Q_1 = Q_S$	$Q_2 = Q_R$

Process 1-2: $Q_1 = P_1V_1 \ln (V_2/V_1) = mRT_H \ln (V_2/V_1)$
Process 3-4: $Q_2 = P_3V_3 \ln (V_3/V_4) = mRT_L \ln (V_3/V_4)$

From process 2-3 & 4-1:

$$\frac{T_H}{T_L} = \left(\frac{V_3}{V_2}\right)^{\gamma-1} = \left(\frac{V_4}{V_1}\right)^{\gamma-1}$$

$$\eta = \frac{W_{net}}{Q_1} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1} (Vaild\ for\ Rev.\ only)$$

IMPORTANT POINTS:

- Two Rev. isothermal and Two Rev. adiabatic process.
- Ideal Cycle for H.E. and gives η_{max}.
- Not Practical cycle since Rev. isothermal and Rev. Adiabatic are difficult to achieve in practice.
- η_{Carnot} depends only on temperature Limits.
- η_{Carnot} doesn't depend on working fluid (E.g. gas or Vapour or etc…)

- For exam problems,

$W_{net} \uparrow \Leftrightarrow \eta \uparrow$	$Q_1 \downarrow \Leftrightarrow \eta \uparrow$
$W_{max} \Leftrightarrow \eta_{max} = \eta_{Carnot}$	$Q_{1\,min} \Leftrightarrow \eta_{max} = \eta_{Carnot}$

- For Cyclic Rev. Process, $Q_1/T_1 = Q_2/T_2$
- Carnot cycle is used to compare practical H.E. Efficiency.

Only Temp. Given or Rev. H.E. or Carnot Cycle	Simple H.E. or T1, T2 & Q1, Q2 given or Irreversible or Practical H.E.
$\eta = 1 - (T_2/T_1)$	$\eta = 1 - (Q_2/Q_1)$

TWO REVERSIBLE HEAT ENGINES IN SERIES:

Efficiencies are same: $\eta_1 = \eta_2$ $\Rightarrow \boldsymbol{T_2 = \sqrt{T_1 T_3}}$ $[\because \eta\ equation]$	**Work Outputs are Same,** $W_1 = W_2$ $Q_1 - Q_2 = Q_1 - Q_2$ $\boldsymbol{T_2 = {T_1 + T_3}/_2}$ $[\because Q_1/T_1 = Q_2/T_2 = Q_3/T_3 = c]$	**Overall Efficiency in terms of Temp.,** $\eta_{Overall} = 1 - (T_3/T_1)$ $\boldsymbol{\eta_{Overall} = \eta_1 + \eta_2 - \eta_1\eta_2}$ $[\because \eta\ equation]$	$\boldsymbol{T_1}$	 $\boldsymbol{HE_1}$	$\boldsymbol{\rightarrow W_1}$ $\boldsymbol{T_2}$	 $\boldsymbol{HE_2}$	$\boldsymbol{\rightarrow W_2}$ $\boldsymbol{T_3}$	

REFRIGERATOR:

It works on cycle and absorbs heat from lower energy medium and rejects heat to higher energy medium by consuming work. E.g. Domestic Refrigerator, Air Conditioner, Water Cooler, Ice Plant.

$$\boldsymbol{Coefficient\ of\ Performance, COP = \frac{Desired\ Effect}{Energy\ Input}}$$

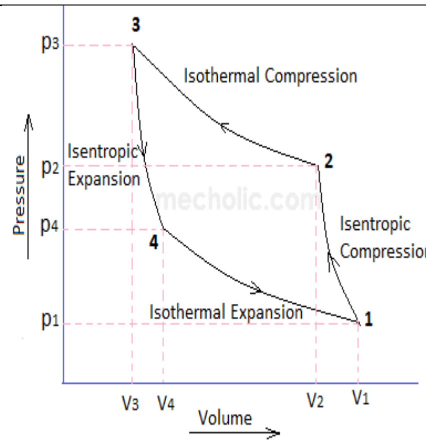
For Cycle, $Q_{net} = W_{net} \Rightarrow W_{net} = Q_1 - Q_2$ $COP_R = \dfrac{Cooling\ Effect}{Energy\ Input} = \dfrac{Q_2}{W_{net}} = \dfrac{Q_2}{Q_1 - Q_2}$ It's Valid for Rev.& Irreversible Cycle. If Refrigerator Door is Open in room, Room temperature increase.	Q_1= Heat Rejected to Refrigerator, Q_2= Heat Absorbed by Refrigerator, W_{net}= Work Supplied to Refrigerator,

REVERSIBLE CARNOT CYCLE:

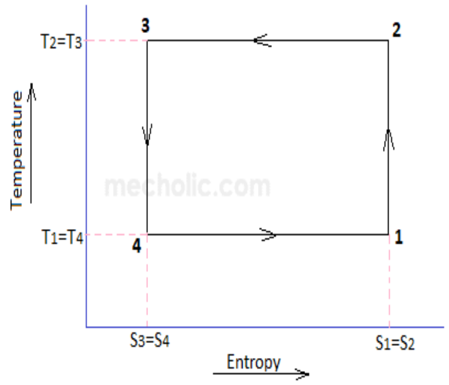
1. It's reversible cycle.
2. It is work consuming cycle (Anti-Clockwise Dir.)
3. It gives maximum COP_R.

Processes:

1-2: Rev. Adiabatic Compression (Compressor Work)
2-3: Rev. Isothermal Heat Rejection. (Heat Exchanger)
3-4: Rev. Adiabatic Expansion. (Throttling)
4-1: Rev. Isothermal Heat absorption. (Refrigerating effect).



Fig(1) p-v diagram



Fig(2) T-s diagram

Here,

$T_1 = T_4 = T_L$	$T_2 = T_3 = T_H$
$Q_1 = Q_R$	$Q_2 = Q_A$

Process 2-3: $Q_1 = P_2V_2\ ln\ (V_3/V_2) = mRT_H ln\ (V_2/V_3)$
Process 4-1: $Q_2 = P_3V_3\ ln\ (V_1/V_4) = mRT_L ln\ (V_4/V_1)$

From process 1-2 & 3-4:

$$\frac{T_H}{T_L} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$\therefore COP_R = \frac{Q_2}{Q_1 - Q_2} = \frac{T_L}{T_H - T_L} (Vaild\ for\ Rev.\ only)$$

IMPORTANT POINTS:

- Two Rev. isothermal and Two Rev. adiabatic process.
- Ideal Cycle for Refrigerator and gives $COP_{R\ max}$.
- Not Practical cycle since Rev. isothermal and Rev. Adiabatic are difficult to achieve in practice.
- COP_R depends only on temperature Limits.
- COP_R doesn't depend on working fluid (E.g. gas or Vapour or etc…)
- For exam problems,

$Q_2 \uparrow \Leftrightarrow COP \uparrow$	$W_{net} \downarrow \Leftrightarrow COP \uparrow$
$Q_{2\ max} \Leftrightarrow$ $COP_{max} = COP_{Rev.\ R}$	$W_{net\ min} \Leftrightarrow$ $COP_{max} = COP_{Rev.\ R}$

TWO REVERSIBLE REFRIGERATORS ENGINES IN SERIES:

COPs are same: $COP_1 = COP_2$ $\Rightarrow \boldsymbol{T_2 = \sqrt{T_1 T_3}}$ $[\because COP\ equation]$	**Work Inputs are Same,** $W_1 = W_2$ $Q_1 - Q_2 = Q_2 - Q_3$ $\boldsymbol{T_2 = {T_1 + T_3}/_2}$ $[\because Q_1/T_1 = Q_2/T_2 = Q_3/T_3 = c]$	**Overall COP,** $COP_{Overall} = T_3/(T_1 - T_3)$ $COP_{Overall} = \dfrac{COP_1 COP_2}{1 + COP_1 + COP_2}$ $[\because COP\ equation]$		$\boldsymbol{T_1}$ $\boldsymbol{W_1 \rightarrow}$	$\boldsymbol{REF_1}$ | $\boldsymbol{T_2}$ $\boldsymbol{W_2 \rightarrow}$	$\boldsymbol{REF_2}$ | $\boldsymbol{T_3}$

HEAT PUMP (HEAT TRANSFORMER): It's same as refrigerator only concern medium is higher temperature whereas in refrigerator concern medium is lower temperature medium.

For Cycle, $Q_{net} = W_{net} \Rightarrow W_{net} = Q_1 - Q_2$ $$COP_{HP} = \frac{Heating\ Effect}{Energy\ Input} = \frac{Q_1}{W_{net}} = \frac{Q_1}{Q_1 - Q_2}$$ It's Valid for Rev.& Irreversible Cycle. • Derivations are same as refregerator only COP equation changes.	Q_1= Heat Rejected to Cabin, Q_2= Heat Absorbed by Atmosphere, W_{net}= Work Supplied to Heat Pump,	T_1 / $W_1 \rightarrow$ HP_1 / T_2
	$\therefore COP_{HP} = \frac{Q_1}{Q_1 - Q_2} = \frac{T_H}{T_H - T_L} = \frac{T_1}{T_1 - T_2}$ It's Valid for Reversible Cycle only.	

IMPORTANT POINTS:

- Two Rev. isothermal and Two Rev. adiabatic process.
- Ideal Cycle for Refrigerator and gives $COP_{HP\ max}$.
- Not Practical cycle since Rev. isothermal and Rev. Adiabatic are difficult to achieve in practice.
- COP_{HP} depends only on temperature Limits.
- COP_{HP} doesn't depend on working fluid (E.g. gas or Vapour or etc…)
- For exam problems,

$Q_1 \uparrow \Leftrightarrow COP \uparrow$	$W_{net} \downarrow \Leftrightarrow COP \uparrow$
$Q_{1\ max} \Leftrightarrow$ $COP_{max} = COP_{Rev.\ HP}$	$W_{net\ min} \Leftrightarrow$ $COP_{max} = COP_{Rev.\ HP}$

RELATION BETWEEN REFRIGERATOR & HEAT PUMP:

From COP_{HP}, COP_R & Energy Balance,	$COP_{HP} = COP_R + 1$

RELATION BETWEEN HEAT ENGINE & HEAT PUMP:

From COP_{HP}, η_{HE} Equations,	$\eta_{HE} = 1/COP_{HP}$
$\boldsymbol{Always, \eta < 1}$	$\boldsymbol{Always, COP \geq 1}$

ELECTRICAL HEATING COIL OR ELECTRIC RESISTANCE HEATER:

$$COP_{Coil} = \frac{Heating\ Effect}{Energy\ Input} = \frac{Q_1}{W_{net}} = \frac{W_{Ele.}}{W_{Ele.}} = 1 (\because Q_1 = W_{net} = W_{Ele.})$$

HEAT PUMP	ELECTRIC HEATER
It's better than electric heater because energy consumption is less ($W_{net} = Q_1 - Q_2$)	Energy consumption is high ($Q_1 = W_{Ele.}$)in comparison so it's not better to use.

SPECIAL CASE OF REFRIGERATOR:

REFRIGERATED SPACE WITH VENTILATION: Room is opened to atmosphere. Hence, it's constant Pressure process.	$Q_2 = mC_P dT$
REFRIGERATED SPACE WITH PERFECTLY SEALED & INSULATED: Room is Insulated & Closed System (Room with no opening). Hence, it's constant Volume process.	$Q_2 = mC_V dT$

CALCULATION OF POWER BILL FOR REFRIGERATION MACHINE:

$Power\ Bill\ =\ \dot{W}(Consumption\ in\ KWh) * Cost_{Ele}(Unit\ price\ in\ Rs/KWh)$	$1\ KWh = 1\ Unit = 3600\ KJ$

COMBINED HEAT ENGINE & REFRIGERATORS:

$W_{HE} = Q_1 - Q_2$ $W_R = Q_4 - Q_3$	$W_{HE} = W_R = W$	$COP_R = \frac{Q_3}{W} = \frac{Q_3}{Q_4 - Q_3}$	$\eta = \frac{W}{Q_1} = 1 - \frac{Q_2}{Q_1}$
$Net\ Work\ Output\ of\ Combined\ System, W_{Net} = W_{HE} - W_R$			

T_1	Q_1	T_4	Q_4
HE_1	$\rightarrow W \rightarrow$	REF_1	
T_2	Q_2	T_3	Q_3

COMBINED HEAT ENGINE & HEAT PUMP:

$W_{HE} = Q_1 - Q_2$ $W_{HP} = Q_4 - Q_3$	$W_{HE} = W_{HP} = W$	$COP_{HP} = \frac{Q_4}{W} = \frac{Q_4}{Q_4 - Q_3}$	$\eta = \frac{W}{Q_1} = 1 - \frac{Q_2}{Q_1}$
$Net\ Work\ Output\ of\ Combined\ System, W_{Net} = W_{HE} - W_R$			

T_1	Q_1	T_4	Q_4
HE_1	$\rightarrow W \rightarrow$	REF_1	
T_2	Q_2	T_3	Q_3

CLAUSIUS INEQUALITY: It's Valid for H.E., Refrigerator & H.P.	$\oint dS \leq 0, Where\ dS = \frac{Q}{T}$	Q = Heat Transfer (in J), T = Absolute Temp. (in K),
If $\oint dS = 0$, Reversible Cycle. $E.g.\ \ Q_1/T_1 = Q_2/T_2$	If $\oint dS < 0$, Irreversible Cycle. $E.g.\ \eta_{irr} < \eta_{Carnot}$	If $\oint dS > 0$, Impossible Cycle.

HEAT ENGINES WITH MULTIPLE RESERVOIRS: $\eta_{HE} = 1 - (\sum Q_{iS}/\sum Q_{iR})$

PERPETUAL MOTION MACHINE OF THIRD KIND (PMM-III): The continual motion of a movable device in absence of friction.