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ENGINEERING THERMODYNAMICS

Thermodynamics:

Thermodynamics is an axiomatic science which deals with the relation among heat, work and properties of system which are in equilibrium.

It describes the state and changes in state of physical systems.

Thermodynamics has four axioms: Zeroth, First, Second and Third law.

~~The~~ A substance consists of a large number of particles called molecules.

(*): Classical Thermodynamics:

The macroscopic approach to the study of thermodynamics that doesn't require a knowledge of the behaviour of individual particles is called classical thermodynamics.

(*) Statistical Thermodynamics:

The microscopic approach to the study of thermodynamics that requires a knowledge of the behaviour of individual particles is called statistical thermodynamics.

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(*) Application Areas of Thermodynamics:

- All activitives involving some interaction between energy and matter.
- Generation of body heat and rejection in environment
- Heating and AC system.
- Humidifier - Pressure Cooker, etc.

System, Boundary and Surroundings

(*) **System:** The quantity of matter or a ~~system~~ region in space chosen for study is called system.

(*) **Surrounding:** The region outside the system is called surrounding.

(*) **Boundary:** The real and imaginary surface that separates the system from its surroundings is called boundary.
It can be fixed & or movable.

*) Closed System	*) Open System	*) Isolated system
→ No exchange of mass but exchange of energy	→ Exchange of mass and energy	→ No exchange of mass or energy.
→ Known as control mass	→ Control volume.	
Eg: sealed tanks, piston cylinder devices	Eg: water heater, turbine, compressor.	Eg:

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Thermodynamic Processes

Quantity	General Equation	Isobaric ($\Delta P = 0$)	Isochoric ($\Delta V = 0$)	Isothermal ($\Delta T = 0$)	Adiabatic ($Q = 0$)
Work (W)	$\delta W = P \cdot dV$	$p\Delta V$	0	$nRT\ln(V_2/V_1)$	$C_v(T_1 - T_2)$
Heat capacity (c)	as for real gas	$C_p = \frac{5}{2}nR$	$C_v = \frac{3}{2}nR$	∞	0
Internal Energy (ΔU)	$\Delta U = \frac{3}{2}nRT$	$Q - W$ $Q_p - p\Delta V$	Q $C_v(T_2 - T_1)$	0 $Q = W$	$-W$ $C_v(T_2 - T_1)$
Enthalpy (ΔH)	$H = U + pV$	$C_p(T_2 - T_1)$	$Q_v + V\Delta P$	0	$C_p(T_2 - T_1)$
Entropy (ΔS)	$ds = C_p\frac{dT}{T} - R\frac{dP}{P}$	$C_p\ln\left(\frac{T_2}{T_1}\right)$	$C_v\ln\left(\frac{T_2}{T_1}\right)$	$\frac{Q}{t}$	$C_p\ln\left(\frac{V_2}{V_1}\right) + C_v\ln\left(\frac{P_2}{P_1}\right) = 0$

Homogeneous System:

A homogeneous thermodynamic system is defined as the system whose chemical composition and physical properties are the same in all parts of the system, or change continuously from one point to another.

Eg: column of atmospheric air.

Heterogeneous System:

A heterogeneous thermodynamic system is defined as the system consisting two or more homogeneous bodies. The chemical and physical properties are not same throughout the system and will change abruptly while moving ~~the~~ to different state.

The homogeneous bodies of a heterogeneous system are referred as phases.

Eg: sealed steel tube containing liquid mercury, ~~stat~~ saturated liquid ethyl alcohol, and mixture of vapours of alcohol and mercury. {3 phases}

Properties of a System

Any characteristic of a system is called a property.

Properties of a system are of two types: extensive and intensive properties.

a) Extensive Properties:

The properties that depends on the system size or the amount of matter in the system is called extensive properties.

The properties are:

- mass (m)
- volume (V)
- total energy (E)
- Amount of substance (n)
- Heat capacity (Cp)

(b): Intensive Properties

The properties that doesn't depends on the system size or the amount of matter in the system is called intensive properties.

The properties are:

- temperature (T)
- pressure (P)
- age
- colour
- specific heat capacity.

Mathematically,

$$\text{Intensive properties} = \frac{\text{Extensive properties}}{\text{mass}}$$

State, Equilibrium, Process and Properties State:

(*) State:

The condition of the system at an instant of time as ~~described~~ measured by its properties is called state.

At a given state, all the properties of a system have fixed values.

If value of one property change, the state changes.

Equilibrium:

⊛ ~~Thermodynamics~~

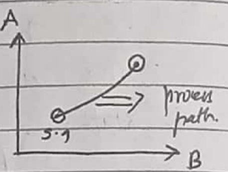
The state of balance is called equilibrium.

A system is said to be in thermodynamic equilibrium if it maintains thermal, mechanical, phase and chemical equilibrium.

- Thermal equilibrium: temperature is same throughout the entire system.
- Mechanical equilibrium: no change of pressure at any point of system in time.
- Phase equilibrium: mass of each phase reaches equilibrium level and stays there.
- Chemical equilibrium: no change of chemical composition with time.

(*): Process

Any change that a system undergoes from one equilibrium state to another state is called process.



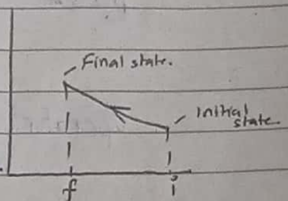
The series of states ~~through~~ ~~whi~~ through which a system passes during a process is called path of the process.

(*): Quasi-Static / Quasi-Equilibrium:

When a process proceeds in the manner that the system remains infinitesimally close to equilibrium at all times, it is called quasi-static or quasi-equilibrium.

It is a sufficiently slow process that allows the system to adjust itself internally so that properties in one part of the system don't change faster than those other parts.

Process path indicates a series of equilibrium states through which system passes during process. It has only significance for quasi-static process.

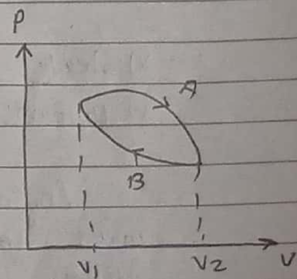


For non-quasi-equilibrium, process is denoted by dashed line between the initial and final states.

Cycle:

A system is said to have undergone a cycle if it returns to its initial state at the end of the process.

Here, initial and final states are identical.



Point Functions:

When two properties locate a point on the graph, those properties are called point functions.

Path Functions

Certain quantities which cannot be located on graph but are given by the area on graph.
The area under the graph to particular process is function of the path of the process. There are called path functions.

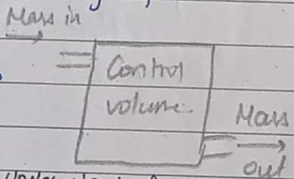
Operator: $\delta \Rightarrow$ inexact differentials $\Rightarrow$ path functions.
$d \Rightarrow$ exact differentials. $\Rightarrow$ point function

Properties are point functions.
Heat and work are path functions.

*) Steady: No change with time.
*) Uniform: No change with location over specific region.

Engineering devices operate long time periods under same conditions, hence called steady-flow devices.

Steady flow process is defined as process during which a fluid flows through a control volume steadily.



Under steady flow, mass and energy contents of C.V are constant.

Pressure:

The normal force exerted ~~on~~ by the fluid per unit area is called pressure.
SI unit = Pascal (Pa) or Newton per meter square (N/m^2)

Temperature:

A thermal state of a body which distinguisheds a hot body from a cold body is called temperature.
The average molecular kinetic energy of the molecules in a system is called temperature.

Thermometers measuring ordinary temperature whereas pyrometers measure higher temperature.

*) Absolute Zero Temperature:
The temperature at which gas occupies no volume is called absolute zero temperatures.

Zeroth Law of Thermodynamics

Zeroth law of thermodynamics states that, " If two bodies are in thermal equilibrium with the third body, ~~all three~~ separately, then they are in thermal equilibrium with each other.

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First law of thermodynamics

It is based on principle of conservation of Energy.

First law of thermodynamics states that, " Energy can neither be created nor be destroyed, but can be converted from one form to another."

Mathematically,

$$Q = \Delta U + W$$

The heat added into the system is equal to the sum of change in internal energy and the workdone by the system.

→ Change in total energy of system = Total energy entering system − Total energy leaving system

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2} m (v_2^2 - v_1^2)$$

$$\Delta PE = mg(z_2 - z_1)$$

For steady flow system,

$$\Delta E_{system} = E_{in} - E_{out}$$
$$= (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out})$$

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Second law of Thermodynamics

Second law of thermodynamics places restriction on the direction of heat transfer and attainable efficiences of heat engine.

This law has two statements:

i) Kelvin- Planck's statement ii) Clausius statement.

i) Kelvin-Planck's statement

Kelvin- Planck's statement states that, " It is impossible to construct a cyclically operating device such that it produces no other effect than the absorption of energy as heat from single reserviour performing equivalent amount of work."

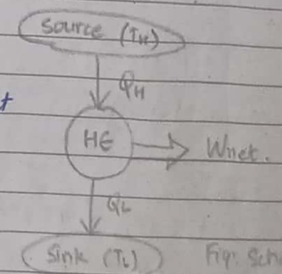

Fig: Schematic diagram of heat engine

ie, no heat engine can have thermal efficiency of 100%.

(ii): Clausius statement

Clausius statement states that, " It is impossible to construct a device that operators in a cycle and has no effect other than the transfer of heat from lower temp. to higher temp of the body.

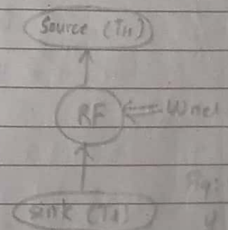

Fig: Schematic diagram of refrigerator.

ie, refrigerator cannot work unless its compressor is driven by an external power source.

Working of Heat Engine

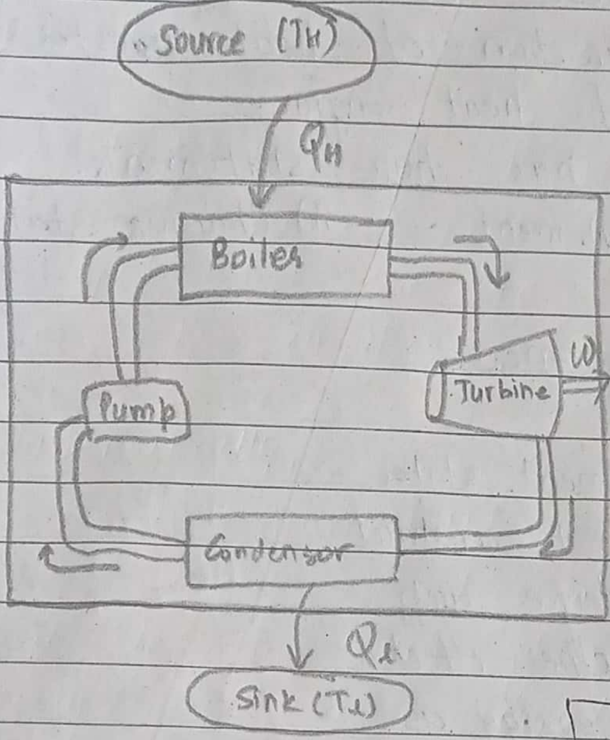

Fig: Working of heat engine.

- The water in the boiler takes Q_H heat from source and converts to vapour.
- The vapour is passed to turbine which is then rotated producing work.
- The hot vapour is sent to condensor where it condenses to water losing 'Q_L' heat to sink.
- The pump pushes the water to the boiler and the process is continued.

Working of Refrigerator!

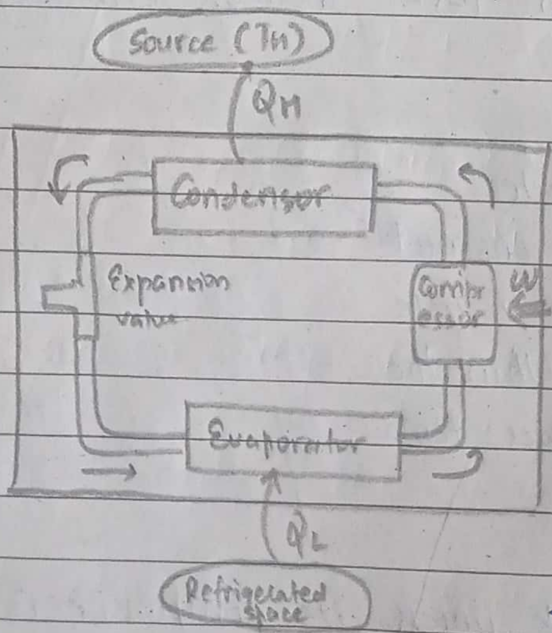

Fig: Working of refrigerator.

- The compressor has some workdone on it and converts refrigerant from low-pressure to high pressure gas.
- The condensor removes heat from the hot refrigrant ~~fror~~ coming from the compressor until it condenses to a liquid state still at high temperature. It releases heat to the source.
- The expansion value ~~minizes to~~ minimizes pressure of gas from condensor ~~from~~ to evaporator.
- Evaporation absorbs heat from sink and the evaporated water is sent to compressor. and process continues.

Entropy:

A thermodynamic quantity representing the unavailability of a system's thermal energy for conversion into mechanical work is called entropy.

It is known as degree of disorder or randomness in system.

Mathematically,

$$\Delta S = \frac{Q}{T}$$

ΔS = change in entropy
Q = heat absorbed
T = absolute temperature

Third law of Thermodynamics:

Third law of thermodynamics states that,
" the entropy of a pure crystalline substance at absolute zero is zero since there is no uncertainty about the state of molecules at that instance. "

Reversible and Irreversible Process

The process that can be reversed without leaving any trace on the surroundings is called reversible process.
For combined process of original and reverse, the net workdone between the system and surrounding is zero.

The processes that are not reversible are called irreversible process caused by various irreversibilities.

Perpetual Motion Machine

Perpetual motion machine is a hypothetical machine that violates the laws of thermodynamics i.e., can ~~be~~ do work infinitely without an external energy source.

(i): PMM 1:

→ Perpetual Motion machine 1 violates first law of thermodynamics.

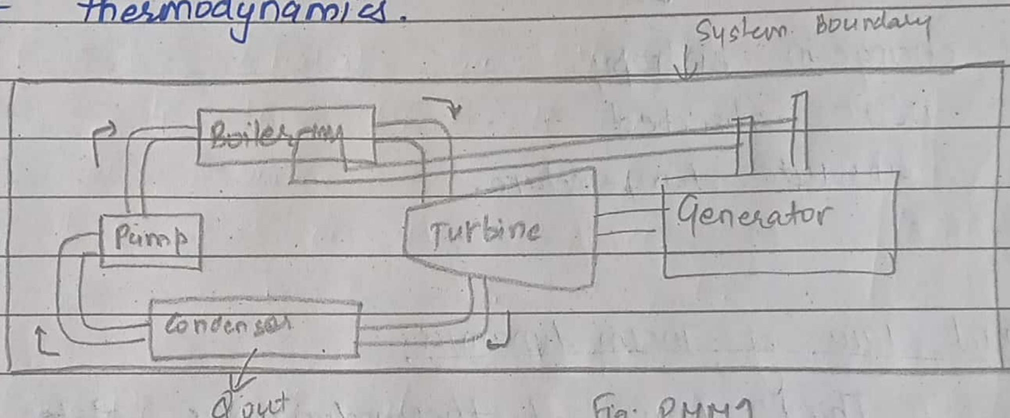

Fig: PMM1

→ Hot air from boiler goes to the turbine that generates electricity for the generator and the hot air is passed to condensor.

- The condensor causes the loss of heat to sink causing water to condense.
- The consensed water is sent to boiler using pump.
- ~~It~~ A resistance wire is connected to generator inside boiler which then ~~ev~~ evaporates the water and passes it to turbine and process continues.

This violates first law because a heat engine must take energy from source but in PMM1 source is absent.

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(ii) PMM2:

Perpetual motion machine 2 violates second law of thermodynamics.

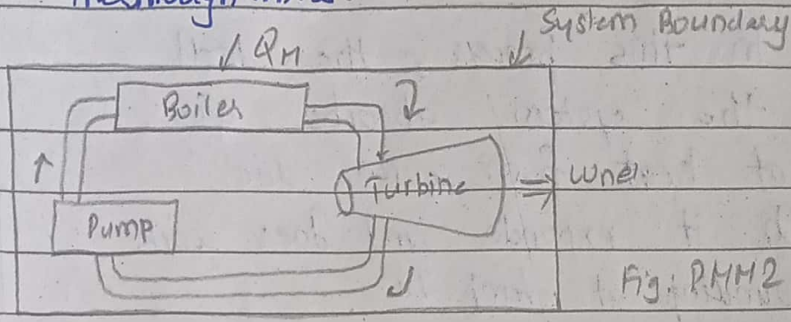


Fig: PMM2

Here, the boiler takes Q_H amount of heat and converts water to vapour. The turbine is rotated by it and the water vapour is pulled by pump and again sent to the boiler.

Here, the heat is not transferred to sink and thus the machine is 100% efficient.

PMM2 violates second law as no machine can be 100% efficient.

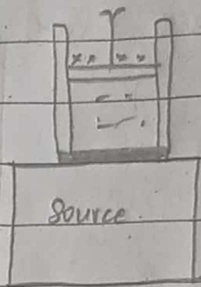
Carnot Cycle:

Carnot cycle is a reversible cycle ie, ideal hypothetical cycle in which all the process constituting the cycle are reversible.

Carnot cycle is the most efficient heat engine based on ~~the~~ assumption of absence of friction and conduction of heat of different engine parts.

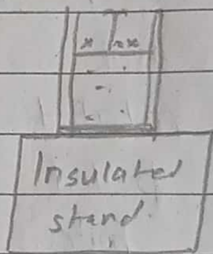
(*) Mechanism:

(1): Reversible Isothermal Gas Expansion



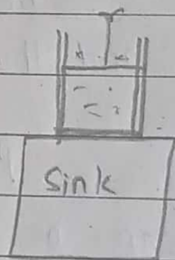
In this process, the ideal gas in the system absorbs Q_{in} amount of heat from source due to which it expands and does work on surrounding. at temp T_H

(2): Reversible Adiabatic Gas Expansion



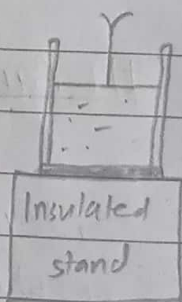
In this process, the system is thermally insulated. the gas expands and does work on surrounding that causes the system to cool. to temp T.

(3): Reversible Isothermal Gas ~~Exp~~ Compression:



In this process, the surrounding does the work to gas and causes it to lose heat Q_{out}, and

(4): Reversible Adiabatic Gas Compression:



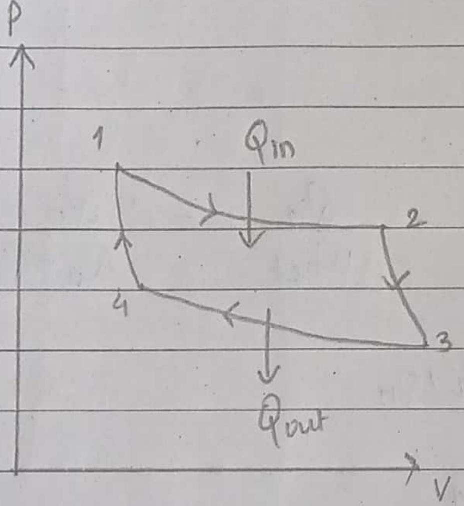
In the process, the system ~~of~~ is thermally insulated. The surrounding continuous to do work on gas and temperature rises ~~to~~ back to T_H.

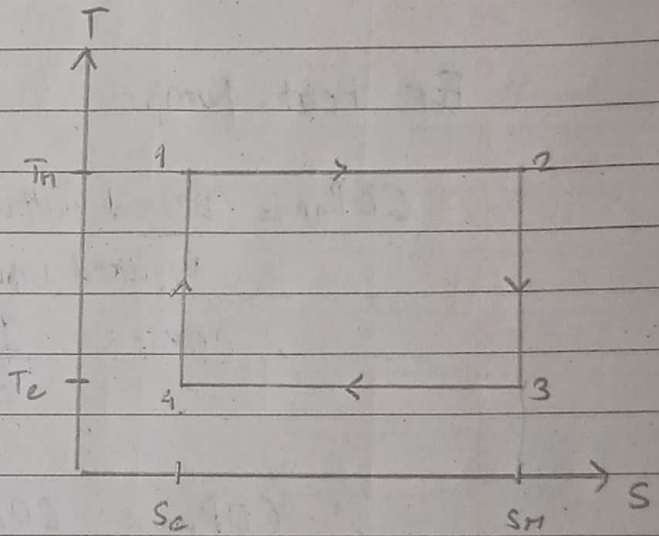
Mathematically,

Thermal efficiency $(\eta) = 1 - \frac{Q_{out}}{Q_{in}}$

$$\frac{Q_{out}}{Q_{in}} = \frac{T_{sink}}{T_{source}}$$

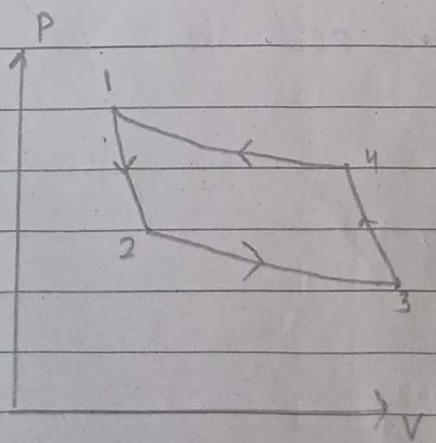
$$\therefore \eta = \left(1 - \frac{T_L}{T_H}\right) \times 100\%$$





1-2 : R Isothermal compression
2-3 : R Adiabatic compression
3-4 : R Isothermal expansion
4-1 : R Adiabatic expansion

For reverse carnot cycle:



1-2 : R Adiabatic expansion
2-3 : R Isothermal expansion
3-4 : R Adiabatic compression
4-1 : R Isothermal compression

Device operating on reverse carnot cycle is called carnot refrigerator or carnot heat pump.

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(*): Coefficient of Performance:

For refrigerator,

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{net}} = \frac{Q_L}{Q_H - Q_L}$$

$$\therefore COP_R = \frac{1}{(Q_H/Q_L - 1)}$$

For heat pump,

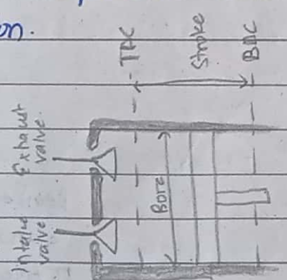
$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{net}} = \frac{Q_H}{Q_H - Q_L}$$

$$\therefore COP_{HP} = \frac{1}{1 - Q_L/Q_H}$$

$$\therefore COP_{HP} = COP_R + 1$$

Reciprocating Engines:

A reciprocating engine is a heat engine that uses one or more reciprocating pistons to convert high temperature and high pressure into a rotating motion.



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(i): Top Dead Centre (TDC)

The position of piston where it forms the smallest volume of the cylinder.

(ii): Bottom Dead Center (BDC)

The position of piston where it forms the largest volume of the cylinder.

(iii): Stroke:

The largest distance piston can travel in one direction.

(iv) Bore:

The diameter of the piston is called bore.

(vi): Clearance volume:

The minimum volume formed in cylinder when piston is at TDC.

(vii) Displacement volume:

The volume displaced by the compression ratio ie, as it moves between TDC and BDC.

(viii) Compression ratio:

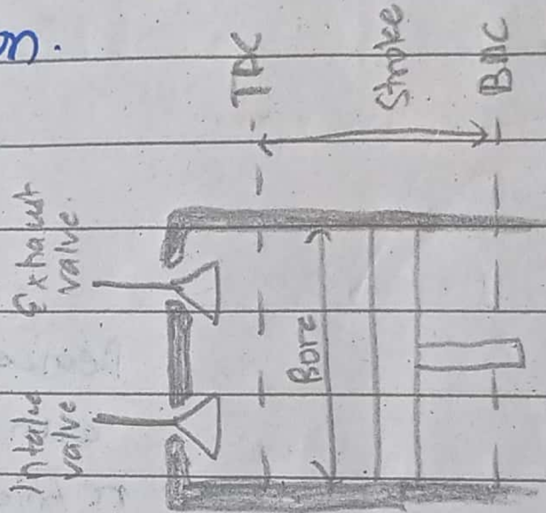
The ratio of ~~making~~ maximum volume to the clearance volume is called compression ratio.

$$\therefore COP_{HP} = \frac{1}{1 - Q_L/Q_H}$$

$$\therefore COP_{HP} = COP_R + 1$$

Reciprocating Engines:

A reciprocating engine is a heat engine that uses one or more reciprocating pistons to convert high temperature and high pressure into a rotating motion.

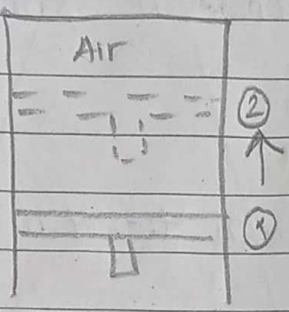


Otto-cycle:

The ideal cycle for spark-ignition engines is called otto-cycle.

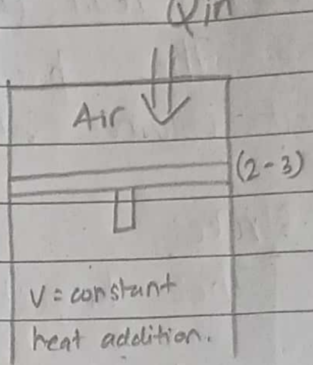
(*): Process:

(1):



R Adiabatic compression

(2)



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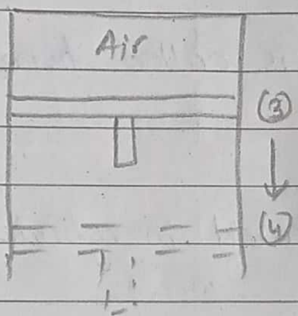

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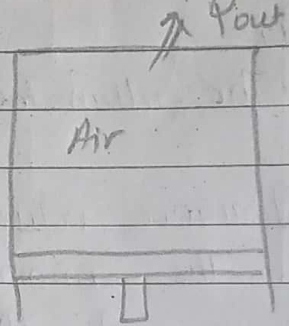
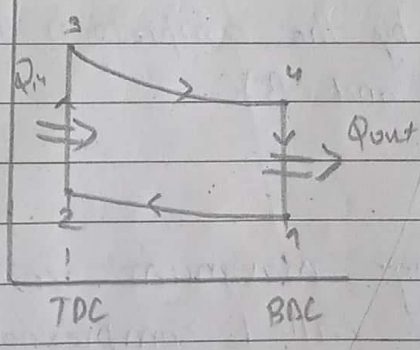
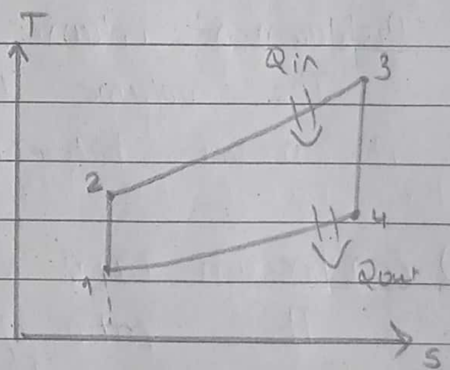


R. Adiabatic expansion





Here,

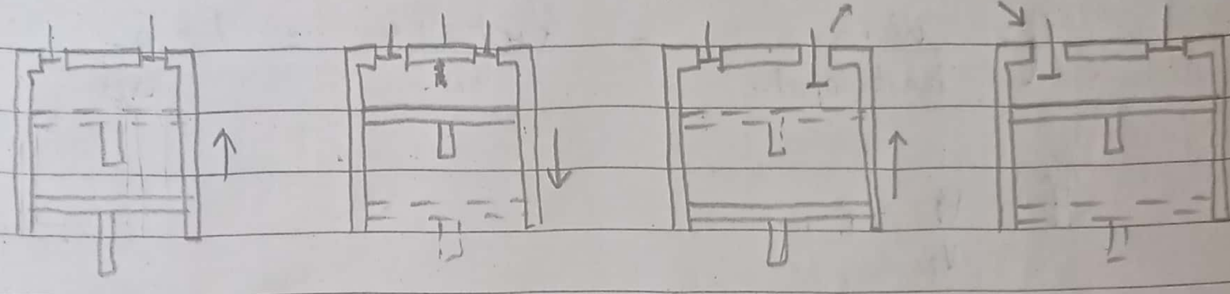
1-2: reversible adiabatic compression.

2-3: heat addition at constant volume

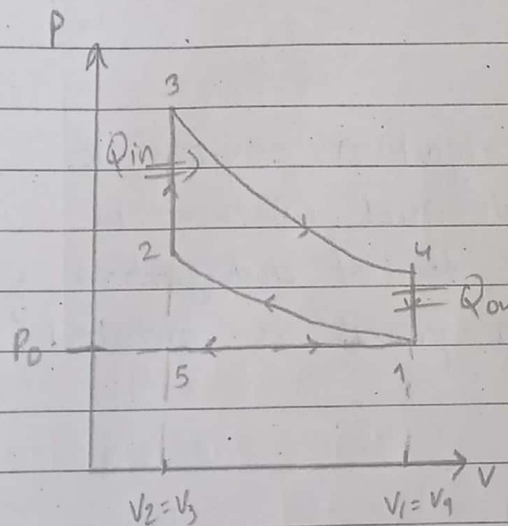
3-4: Reversible adiabatic expansion

4-1: Constant volume heat rejection.

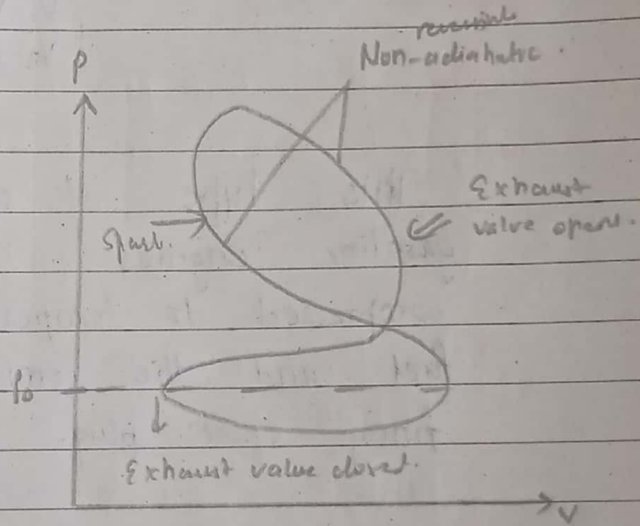
(*): Actual Four Stroke Engine: and working:



Compression stroke. Power stroke Exhaust stroke. Intake stroke.



Ideal otto cycle including intake and exhaust stroke.



Actual otto cycle

Here,

5-1 → Intake stroke

1-2 → Compression stroke, temperature increases

2-3 → spark it, combustion

3-4 → Power stroke, expansion

4-1 → rejection of heat

1-5 → Exhaust stroke.

⊛ Efficiency of otto cycle:

$$\eta = \frac{\text{Work}}{\text{heat input}} = \frac{Q_H + Q_L}{Q_H} = 1 + \frac{Q_L}{Q_H}$$

If $\frac{V_1}{V_2} = r$,

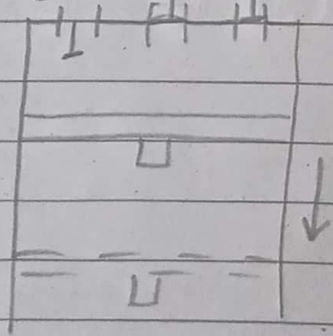
$$\eta = 1 - \frac{1}{\left(\frac{V_1}{V_2}\right)^{\gamma-1}} = 1 - \frac{1}{r^{\gamma-1}}$$

This type of spark-ignition engines i.e, gasoline engines, the air-fuel mixture is compressed to temperature ~~to~~ of autoignition of fuel and the combustion process is initated by firing spark plug.

Diesel Cycle:

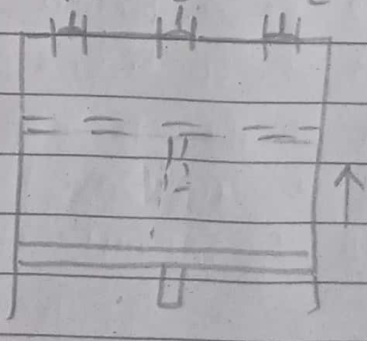
In CI engines, the air is compressed to temperature above ignition temperature of fuel and combustion starts when fuel is injected to hot air.

(1)



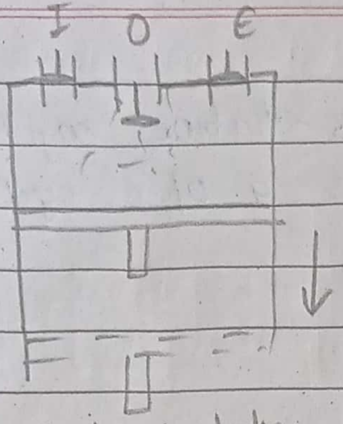
Charging stroke

(2)



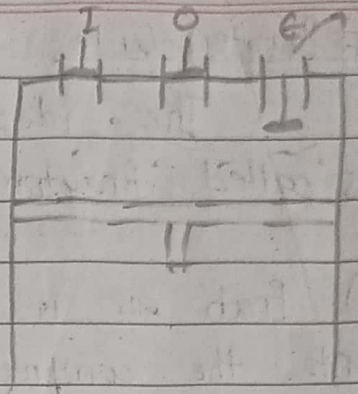
Compression stroke

(3)



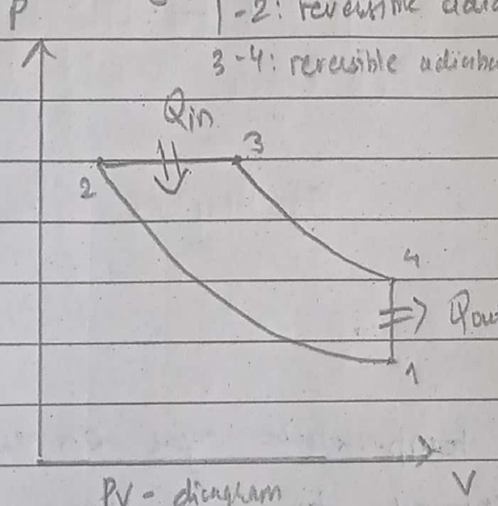
Working stroke

(4)

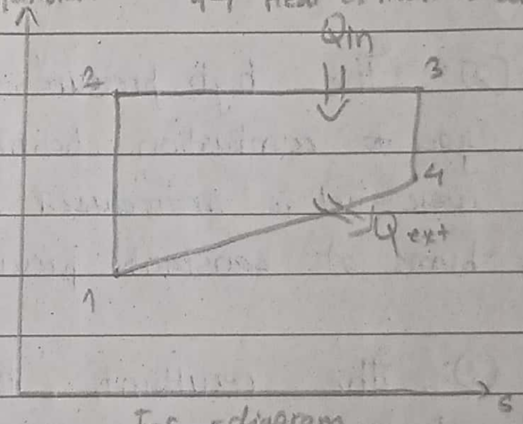


Exhaust stroke

1-2: reversible adiabatic compression
2-3: Heat addition at constant pressure
3-4: reversible adiabatic expansion.
4-1: Heat exhaust at constant volume.



PV - diagram



T-s diagram

Cutoff ratio: (r_c) = ratio of cylinder volume after and before combustion process.

$$r_c = \frac{V_3}{V_2}$$

$$\eta_{diesel} = 1 - \frac{1}{r_c^{\gamma-1}}\left[\frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}\right]$$

Generally thermal efficiency of Diesel cycle is higher but for same compression ratio,

$$\eta_{T,otto} > \eta_{T,diesel}.$$

Brayton-Cycle:

The ideal gas for gas-turbine engines. is called Brayton-cycle. It is a open cycle

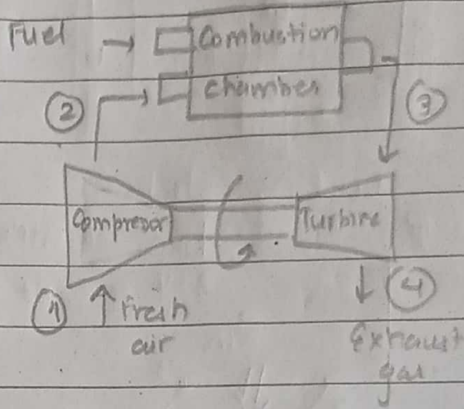


Fig: Brayton's cycle.

(1): Fresh air is drawn into the compressor and its temperature and pressure is raised.

(2): The high pressure air goes to combustion chamber were fuel is introduced and burns at constant pressure.

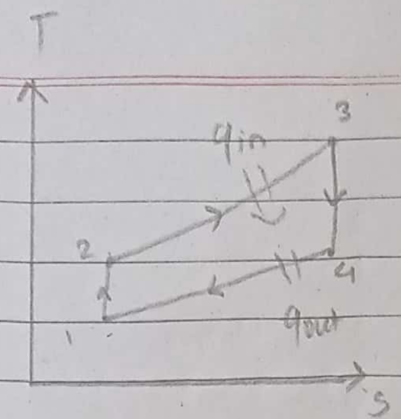
(3): The resultant high temperature gas enters the turbine where they expand to atmospheric pressure producing power.

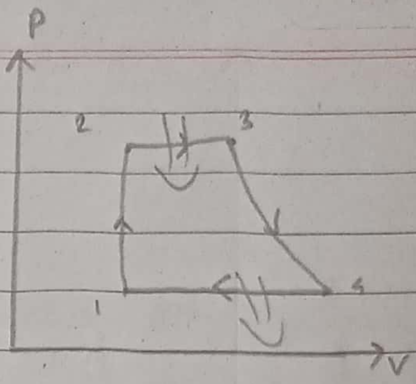
(4) The exhaust gases leaving the turbine are thrown out of the system and not circulated. ie, open system.

$$\text{pressure ratio } (r_p) = \frac{P_2}{P_1}$$

$$\eta_{th\ Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}} \quad \neq \frac{W_{net}}{q_{in}} = \cancel{X} \neq \frac{q_{out}}{q_{in}}$$

Date





Here,

1-2: Adiabatic reversible compression.

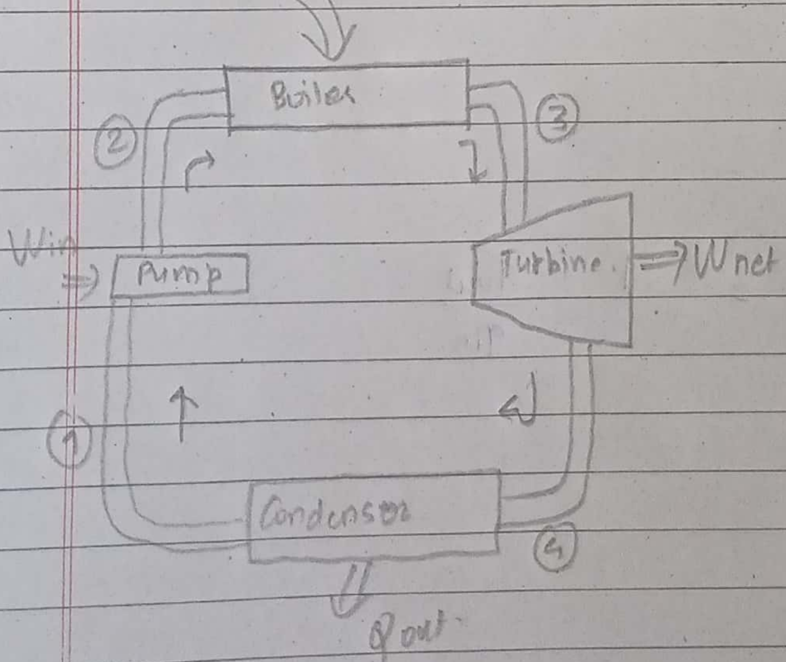
3-4: Adiabatic reversible expansion.

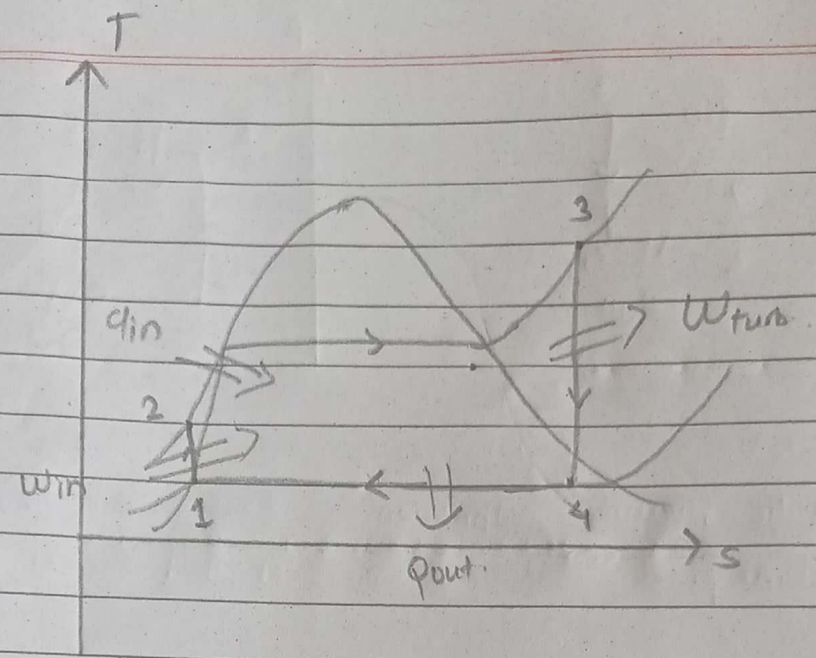
2-3: Constant pressure heat addition.

4-1: Constant pressure heat rejection

Rankine Cycle:

The ideal cycle for vapour power cycles is called Rankine Cycle.





Here,

1-2: Reversible adiabatic compression.
2-3: Constant pressure → heat addition
3-4: Reversible adiabatic expansion
4-1: Constant pressure → heat rejection.

$$\eta_{Rankine} = \frac{W_{net}}{Q_{in}} = 1 - \frac{q_{out}}{q_{in}}.$$