Thermodynamics (80+20)

Data. Compare, Table, Flow Chart

Thermodynamics < therme (heat)
dynamics (motion)

- Science of energy and entropy
- Science of heat and work, their mutual interaction and working substances related to them.
- Science of energy transfer and its effect on physical properties of substances.
- Based on experimental observations which are formulated into thermodynamic laws.
- Applications: @ fields of energy technology, steam and nuclear power plants, IC engines, gas turbines, air conditioning, refrigeneration, gas dynamics, jet propulsions, compressors, chemical power plants.

Scope of Thermodynamics

Civil and Architecture: To design and build the buildings, houses such that max. heat transfer occurs in hot regions & min. heat transfer in cold regions.

Electrical, Electronics, Computer: Use of motor fans so that heat transfer occurs steadily in electrical & electronic devices as a result these devices are not hampered.

Mechanical engineering: heat engines, power plants, . .

Value of Energy to Society: like GDP, energy consumption value is also a factor which determines the quality of life of people, society and country as a whole. Those with high energy consumption values have better quality of life whereas those with lower values are living in a difficult condition

2003 data : Afghanistan : 3.78 GJ/year/capita compare.
Bangladesh : 8.97 , Nepal (14.11) ,
India (23.76) . USA (300) , Kuwait (512) ,
Qatar (537 58) . Iceland (709.06)

Macroscopic & Microscopic view :

From which the behaviour of matter can be studied, there are two viewpoints:

Macroscopic viewpoint	Microscopic viewpoint
i) In this approach, a certain quantity of matter is considered without taking into account the events occurring at the molecular level.	i) In this approach, behavioral pattern of individual molecule is taken into account & macroscopic study is combined with inter-molecular forces and molecular configuration.
ii) ~~Also eta~~ Done in classical thermodynamics	ii) Done in statistical thermodynamics
iii) Simple calculation is required	iii) Complex calculation is required
iv) Engineers use this viewpoint	iv) Physicists use this viewpoint
v) Few coordinate points are required	v) Many coordinate points are required
vi) Single observation represents the whole property.	vi) Many observations are needed to describe the whole property.
vii) Nature of matter independent	vii) Nature of matter dependent
viii) Concept of continuum used	viii) Concept of continuum isn't followed.

Equilibrium: A condition of steady state when no change in any property is observed.

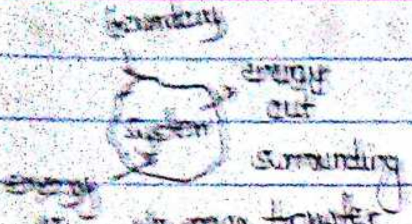
Thermal equilibrium: no temperature change
Chemical equilibrium - no chemical reaction or transfer of matter from one system to other
Mechanical equilibrium: no pressure difference or no unbalanced force within the system itself or also between the system & surrounding.

If the system already in some sort of equilibrium is disturbed, then the system undergoes change in state until equilibrium state is reached.

If the system is in equilibrium regarding all possible changes of state, then the system is said to be in thermodynamic equilibrium. In it, there can be no spontaneous change in any macroscopic property.

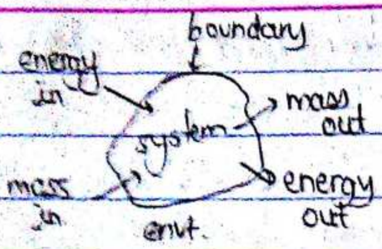
System: A quantity of matter or a region in space upon which effect of macroscopic properties is observed. En
External to system is surrounding or envt.
Both are separated by a real or hypothetical boundary (fixed or moving).

	Mass transfer	Heat transfer	Example
Closed System (Control mass)	No.	Yes	A vessel with water & movable piston on heating acts as closed system
Open System (Control volume)	Yes	Yes	Air compressor
Isolated system	No	No	Thermos

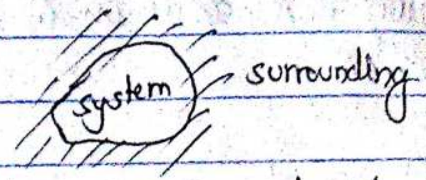


No mass transfer

A Closed system



An Open System



No mass or energy transfer

An Isolated system

Thermodynamic property

Any parameter or variable used to describe or represent a thermodynamic state is called a thermodynamic property.

Acc. to their nature classified into two groups:

Intensive property Thermodynamic property independent of mass

eg: pressure, temperature ; intensive properties cannot be additive

- {denoted by 'e'} - its value remains the same either whole system or part of it is taken

Extensive property thermodynamic property proportional to mass.

eg: volume, surface area, energy

- {denoted by 'E'}
- extensive properties are additive in nature
- it depends on how big a portion of the system is being considered.

eg: If a quantity of matter in a given state is divided into two equal parts, each part will have the same value of intensive properties as the original but half the value of extensive properties.

Extensive properties proportional to mass can be converted into intensive form by dividing its value by mass. Thus, the ratio of an extensive property to the mass is called specific value of that property.

eg. If the total energy of a system is denoted by E, and the mass is m, then specific total energy or total energy per unit mass is given by

$e = E/m$

In general, an intensive property $(e) = \frac{\text{Extensive property } (E)}{\text{mass } (m)}$

Let for a system property ϕ is made of properties ϕ_1, ϕ_2, ϕ_3 ---

for an intensive property, $\phi = \phi_1 = \phi_2 = \phi_3$

for an extensive property, $\phi = \phi_1 + \phi_2 + \phi_3 +$ ---

Thermodynamic State

Each unique condition at which a thermodynamic system can exist is called a thermodynamic state. It is specified with the values of thermodynamic properties.

eg: Consider a system of a cylinder containing gas with a piston system. The initial state being represented by P_1, V_1, T_1 & on moving the piston upwards, the system reaches to another equilibrium eqⁿ state represented by P_2, V_2, T_2.

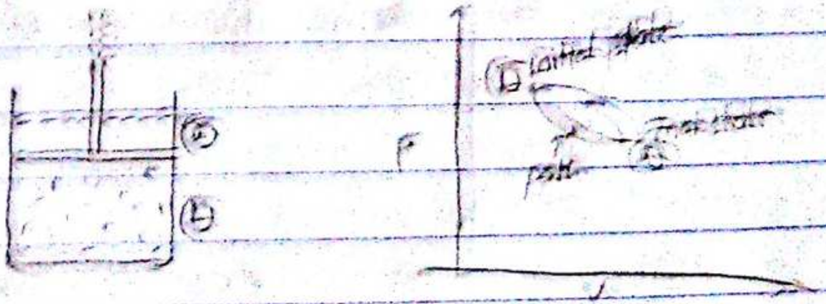


Fig: The P-V diagram of a expansion process showing the system, initial state, final ~~state~~ and process path.

The ~~the~~ change from state 1 to state 2 shows a process.

Thus, the path followed by a system when it undergoes from one equilibrium state to another is called a thermodynamic process.

When a system in a given initial state goes through a number of different changes of state and finally returns to its initial state, then the process undergone is cyclic process. The process ~~f~~ of change in state from 1 to 2 & 2 to 1 is a cyclic process.

Features of thermodynamic properties:

a) A variable is a property, if and only if, it has single value at each equilibrium state.

b) A variable is a property, if and only if, a change in its value between any two prescribed states is independent of path.

Based on dependency upon path followed or not,

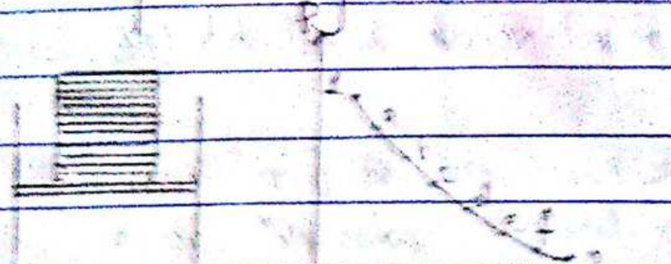
state functions depend on final & initial states of a thermodynamic process or is a function of state only.

path function: depend not only on the end states but also on path followed.
- they are not thermodynamic properties
- eg: work and heat

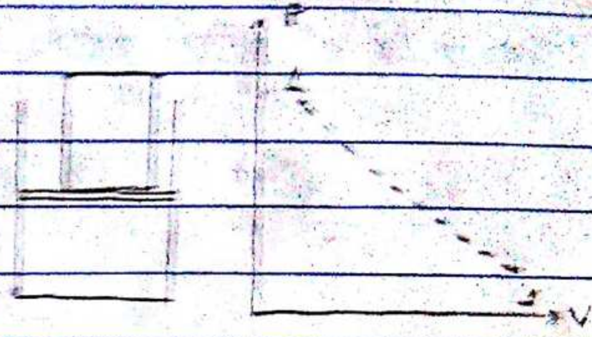
- With reference to the intermediate states, thermodynamic processes can be classified as:

Reversible process: Any process which passes through a series of intermediate states such that each intermediate state can be located on a property diagram is c/a reversible process.
- Represented by a continuous line.
- Also c/a a quasi-equilibrium or quasi-static process → is the one in which the deviation from thermodynamic equilibrium is infinitesimal & all the states the system passes through during a quasi-equilibrium process may be considered in equilibrium states.

Irreversible process : It is any process which passes through a series of intermediate states which can't be defined or located on a property diagram - is represented by a broken line



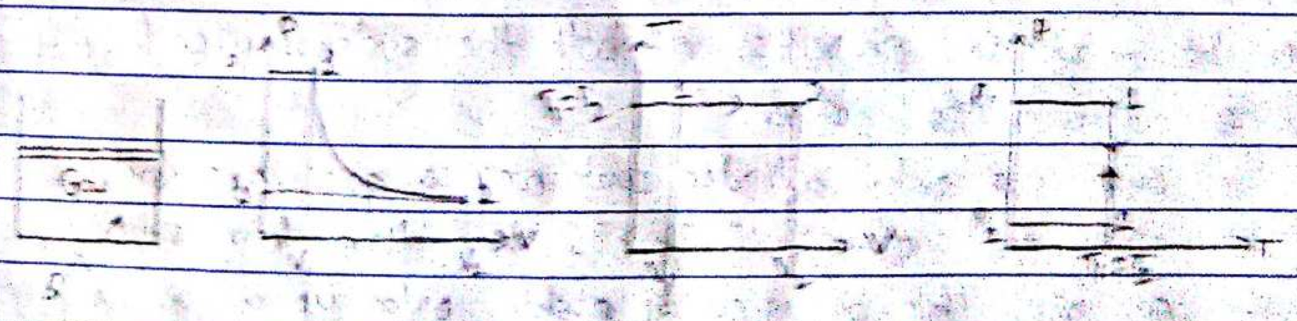
Arrangement for slow transition and reversible process (quasi-equilibrium process) ①



Arrangement for rapid transition and irreversible process. ②

Consider piston cylinder arrangement ① & ② for same size & weight. initial state of P & V is same for both. In ①, when blocks are removed one by one, then the system goes through the states 1-a-b-c-d-e-f --- to final state where all intermediate states are in equilibrium. Initial state can be attained by placing the blocks one by one too.

In ②, when block is removed at once, system reaches to final state instantaneously. This cannot be brought back to initial state & hence is irreversible process.



Constant temperature heating process.

Pressure $P = F/A$ (N/m^2)

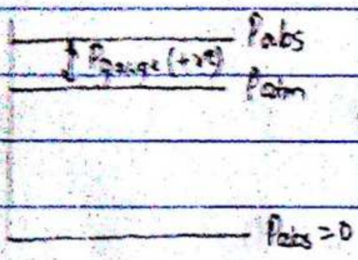
1 bar = 100 kPa = 10^5 Pa

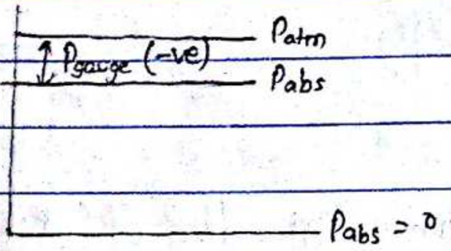
1 atm = 101325 Pa = 1.01325×10^5 Pa = 760 mm Hg

Pressure exerted by the ambient air on any surface is atmospheric pressure.

Pressure of any system measured with reference to atmospheric pressure is gauge pressure

Pressure of a system expressed relative to perfect vaccum is absolute pressure.





-ve gauge pressure also c/a vaccum gauge.

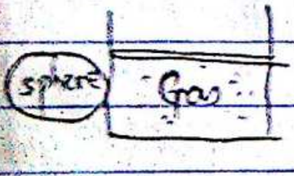
$P_{abs} = P_{atm} + P_{gauge}$ $\qquad$ $P_{abs} = P_{atm} - P_{gauge}$

Temperature

$$\frac{C}{100} = \frac{F-32}{180} = \frac{K-273}{100} \Rightarrow \frac{C}{5} = \frac{F-32}{9} = \frac{K-273}{5}$$

Equality of temperature:

It states that "Two systems are said to be at equal temperatures, if there is no change in any properties of both the systems when they are brought in contact with each other."



Consider a piston cylinder containing a gas in contact with metal sphere. If $T_s > T_g$, heat flows from sphere to gas such that gas expands pushing piston up on gaining heat. After some time, $T_s = T_g$ and piston stops moving. This condition is c/a equality of temperature.

Zeroth law of Thermodynamics

"When two systems are separately in thermal equilibrium with the third system, then those two systems should also be in thermal equilibrium with each other.

Is fundamental & c/a Zeroth law - used in all temperature measurement process.

Energy and Energy Transfer

Work And Heat

1. Differentiate (i) heat & work - (ii) stored energy & transient energy
2. Define total energy of a system, internal energy
3. Similarities & differences between heat transfer and work transfer.
4. Define heat transfer & work transfer. Also mention their sign conventions used in the analysis of thermodynamic problems.
5. Derive an expression for displacement work transfer for a polytropic process.
6. Derive an expression for work transfer for any process on piston cylinder device Reduce it to get the expression for work transfer during a polytropic process.

Classification of Energy

Stored Energy

- Energy which remains within the system boundary as inherent property of system
- eg: Internal energy. Potential energy. Kinetic energy.
- Stored energies have unique value for each equilibrium state
- They are path independent and hence are thermodynamic properties.

Transient Energy

- Energy which can cross the boundary of the system during a thermodynamic process.

- They do not have unique value for each thermodynamic equilibrium state as they depend on both the properties of the system and of the surroundings.
- They are path dependent and hence are not thermodynamic properties
- eg: Heat transfer and Energy Transfer

Stored Energy

Internal energy: Energy due to molecular arrangement & motion of molecules
Denoted by U. Often used as ΔU.
$U = P.E + K.E$; $U \uparrow \leftarrow T \uparrow$

Potential energy: energy due to elevation.
$P.E = mgz$, z = elevation of system

Kinetic energy: energy due to motion
$KE = \frac{1}{2} m v^2$

Total energy (E):
$E = U + P.E + KE$
$e = \frac{E}{m} = u + gz + \frac{v^2}{2}$; e = specific total energy

Energy transfer:
Energy which can be transferred from system to surrounding or vice-versa are heat transfer and work transfer.

Heat transfer:
- Transfer of energy without transfer of mass, because of temperature difference between the system and the surroundings is heat transfer.
- eg: transfer of heat from a metal ball at 100°c to surrounding metal plate at 30°c.

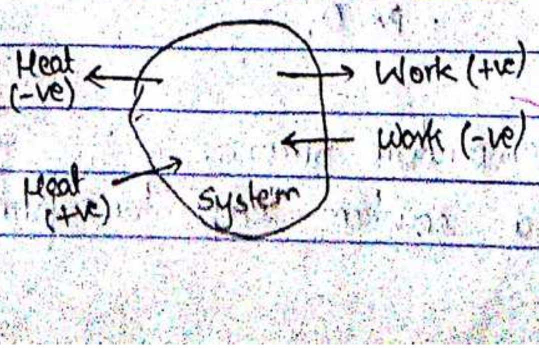
- Occurs only if there is temperature difference.
- Denoted by Q and is expressed in J.
- Heat transfer to system (+ve heat transfer) ; heat lost from system (-ve heat transfer)
- Viewed as a disorganised form of energy. External to system, only partial effect of heat can be ~~Work~~ reduced to raise of weight as a portion of heat is always reduced or lost.

Work transfer

- Transfer of energy without transfer of mass, because of any property difference other than temperature is defined as work transfer
- Is Brought about by property differences like pressure, gravitational potential, electric potential etc
- Denoted by W and is expressed in J.
- Work done by system (+ve work transfer)
  Work done on system (-ve work transfer)
- Viewed as an organised form of energy. External to the system, the work's sole effects could be reduced to raise of weight.

Similarities:

- Both are transient phenomena or energy in transit. System never possess heat or work but when a system undergoes a change of state, either or both crosses the boundary of system
- Both are boundary phenomena as are observed only at boundary when crossing it.
- Both are not thermodynamic properties. As are path dependent and have inexact differentials.



Expression for Displacement - Work Transfer

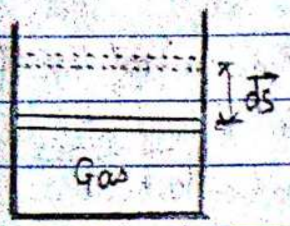


Fig: Displacement Work Transfer

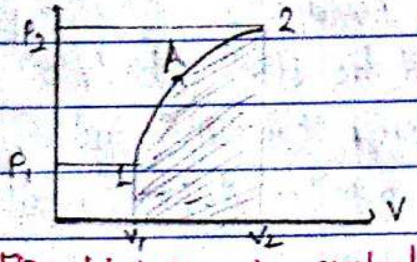


Fig: Work transfer evaluated as Area Under Curve

Consider a piston cylinder device containing a gas. During process 1-2, piston is displaced by $\vec{ds}$ from state 1 to state 2. Applying mechanical defination, work transfer is

$$W = \int_1^2 F\vec{ds}$$, where F is force provided by gas pressure

$$= \int_1^2 PA\vec{ds} \qquad [\because P = F/A]$$

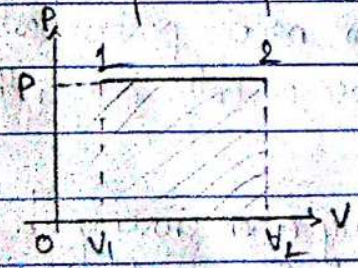
$$= P\int_1^2 A\vec{ds}$$

$$= \int_{V_1}^{V_2} P\cdot dV$$

This shows work done during any process can be found by evaluating area covered by the process on a P-V diagram.

Isobaric Process:

constant pressure process.



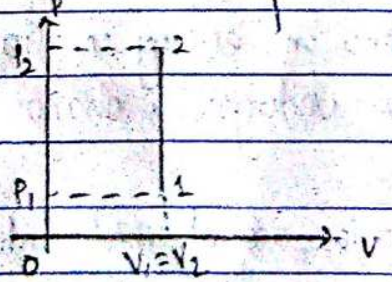
Work: $W = \int_1^2 PdV$

$$= P\int_{V_1}^{V_2} dV$$

$$= P(V_2 - V_1)$$

Isochoric Process

constant volume process



Area under curve in P-V diagram is zero

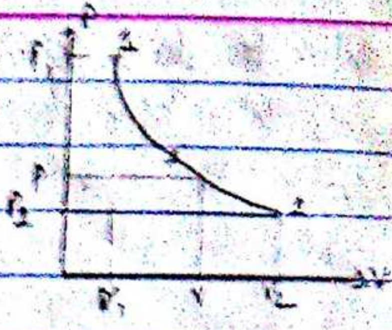
$$\therefore W = \int_1^2 PdV$$

$$= P \times 0.$$

Isothermal Process: Constant temperature process.

For an ideal gas undergoing a constant temperature process.

$P \propto \frac{1}{V}$ or $PV = \text{constant}$ — ①



For a gas undergoing isothermal process from state 1 to 2.

$$PV = P_1V_1 = P_2V_2$$

$$\Rightarrow P = P_1V_1/V$$

For work transfer.

$$W = \int_{V_1}^{V_2} p\,dV = \int_{V_1}^{V_2} \frac{P_1V_1}{V}\,dV = P_1V_1 \ln V \Big|_{V_1}^{V_2} = P_1V_1 \ln\left(\frac{V_2}{V_1}\right)$$

$$= P_1V_1 \ln\left(\frac{P_1}{P_2}\right)$$

Polytropic process:

It is the thermodynamic process which follows the relation $PV^n = \text{constant}$. where index n is called a polytropic index. It is the generalized equation for thermodynamic processes and for different values of n. represents different processes.

Value of n	Equation	Process
0	$P = \text{constant}$	Isobaric
1	$PV = \text{constant}$	Isothermal
γ	$PV^{\gamma} = \text{constant}$	Adiabatic
∞	$V = \text{constant}$	Isochoric.

P-V relationship for initial, final and any intermediate state during a polytropic process is given as

$$PV^n = P_1V_1^n = P_2V_2^n$$

$$\Rightarrow P = \frac{P_1V_1^n}{V^n}$$

Work transfer is given as

$$W = \int_{V_1}^{V_2} p\,dV = \int_{V_1}^{V_2} \frac{P_1V_1^n}{V^n}\,dV = P_1V_1^n \int_{V_1}^{V_2} V^{-n}\,dV$$

$$= P_1V_1^n \cdot \left(\frac{V_2^{-n+1} - V_1^{-n+1}}{1-n} \right)$$

$$= \frac{P_2V_2^n V_2^{1-n} - P_1V_1^n V_1^{1-n}}{1-n}$$

$$= \frac{P_2V_2 - P_1V_1}{1-n} \qquad [\because P_1V_1^n = P_2V_2^n]$$

<u>Note</u>:

Reads pressure of A
relative to B

⑮ A 15kg piston in a cylinder with diameter 0.15m is loaded with a linear spring & the outside Patm of 100 KPa as shown in figure. Spring exerts no force on cylinder piston when it is at the bottom of the cylinder and for the state shown. The pressure is 300 kPa with volume of 0.02m³. The valve is opened to let some air in, causing the piston to rise 5cm. Find the new pressure.

Given.

$m = 15\,kg$; $g = 9.81\,m/s^2$

$d = 0.15m$, $P_{atm} = 100\,kPa$

Initial Condition.

$KA + mg + P_{atm} \times A = P \times A$

~~$k \times \frac{\pi d^2}{4} + 15 \times 9.81 = 300k \times \frac{\pi d^2}{4}$~~

~~or $k = 91679$~~

x = When pressure is 300 kPa with volume of 0.02m³

$mg + F_{spring} + P_{atm} \times A = P \times A$

$15 \times 9.81 + F_{spring} + 100k \times \frac{\pi d^2}{4} = 300k \times \frac{\pi d^2}{4}$

or, $F_{spring} = 200 \times 10^3 \times 0.01767 - 15 \times 9.81$

or, $F_{spring} = 3386.85\,N$

Now, $x = V/A$

$= 0.02/0.01767 = 1.13\,m$

$\therefore$ $F_{spring} = K \times x = 3386.85N$

or, $K = 2997.21\,N/m$

When piston rises to 5cm, then, total $x = 1.18m$

$mg + F_{spring} + P_{atm} \times A = P \times A$

$15 \times 9.81 + k \times 1.18 + 100k \times 0.01767 = P \times 0.01767$

or, $P = 308.481\,KPa$

3. PROPERTIES OF COMMON SUBSTANCES

Pure Substance : A substance that has fixed chemical composition throughout is a pure substance.

Or It is the substance which is
- homogeneous in composition and chemical aggregation
- invariable in chemical aggregation

eg: N_2, CO_2, air, water
, ice + water, water + vapour, ice + water + vapour
gaseous air, liquid air + gaseous air (not pure substance)

④ All mixtures are homogeneous

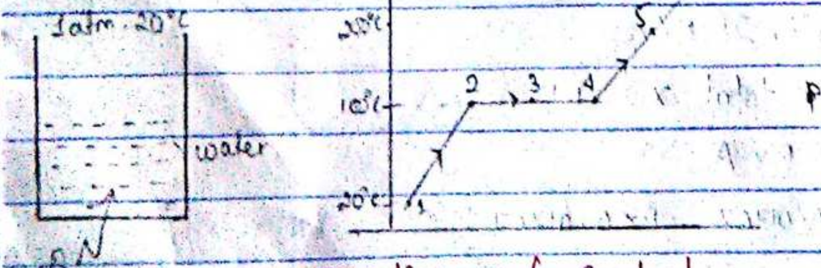
State Postulates : For a pure substance, all thermodynamic properties can be determined if two independent thermodynamic properties are given. This special feature of a pure substance is called state postulate or two-property rule.

It can be stated as

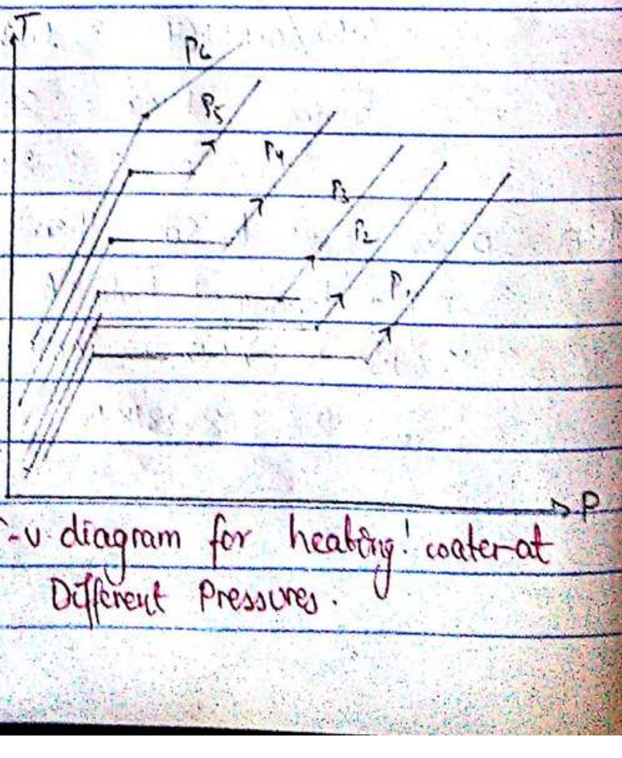
"Two independent thermodynamic properties are sufficient to establish a stable thermodynamic state of a system composed of a pure substance."

eg: temperature (T) of a pure substance for any state can be determined if its pressure (P) and volume V are given, i.e

$$T = T(P, V)$$



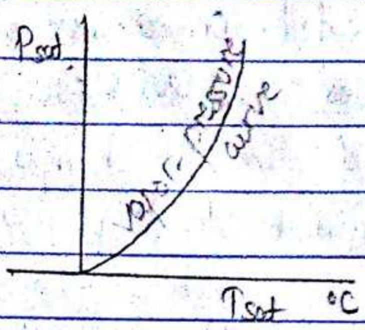
T-V diagram for Constant Pressure Heating of Water



T-v diagram for heating water at Different Pressures.

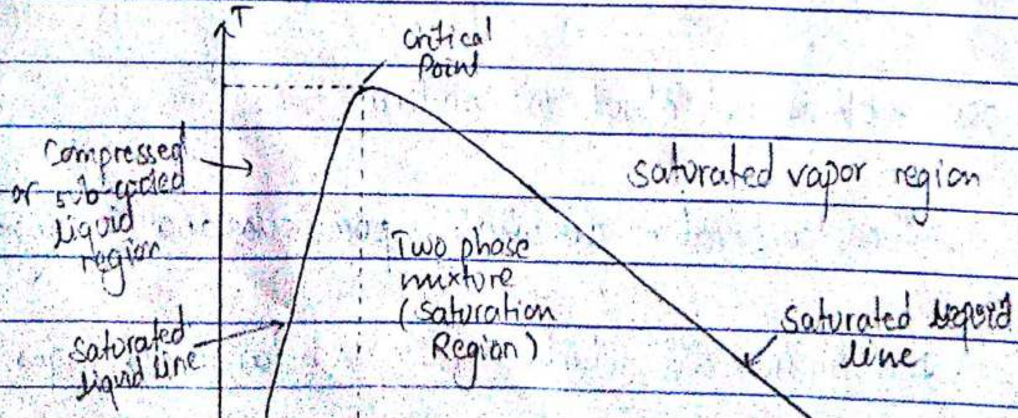
Saturation Pressure of Water at Various Temperatures

T (°C)	Psat (KPa)
−10	0.26
−5	0.40
0	0.61
10	1.23
50	12.35
100	101.4
300	8588



Latent Heat: Amount of energy absorbed or released during a phase change process
↳ fusion : 333.7 kJ/kg at 1 atm pressure
↳ vaporisation : 2256.5 kJ/kg

Elevation	Atm pressure (KPa)	Boiling temp. (°C)
0	101.33	100
1000	89.55	96.5
2000	79.50	93.3
20000	85.53	34.7.



Saturation Curve for Two-phase Mixture on T-v diagram

Critical Point: It is the point at which saturated liquid and saturated vapor phase or states are identical.

Saturated liquid line: line formed by joining all saturated liquid states

Saturated vapor line: line formed by joining all saturated vapour states.

Quality (x): Defined as the ratio of mass of saturated vapor and the total mass of the two phase mixture. Also c/a dryness fraction.

$$x = \frac{m_g}{m} = \frac{m_g}{m_l + m_g}$$

m_g = mass of saturated vapor

m_l = mass of saturated liquid

m = ~~ma~~ total mass of two phase mixture

For saturated liquid state, $x = 0$ as $m_g = 0$

For saturated vapor state, $x = 1$ ~~as~~ m.

For saturated liquid - vapor state, $x = 0$ to 1

It has meaning only when the substance is in a saturated state.

Specific Properties of a Two-Phase Mixture

- Can be expressed in terms of quality
- For specific volume of a two phase mixture,

$V = V_l + V_g$; $m = m_l + m_g$

$V = mv$; $V_l = m_l v_l$, $V_g = m_g v_g$

Now, $mv = m_l v_l + m_g v_g$

or, $v = \frac{m_l}{m} v_l + \frac{m_g}{m} v_g$

or, $v = (1-x) v_l + x v_g$

or, $v = v_l + x v_{lg}$, $v_{lg} = v_g - v_l$ is the change in specific vol. during evaporation

Specific internal energy, $u = u_l + x u_{lg}$

Specific enthalpy, $h = h_l + x h_{lg}$

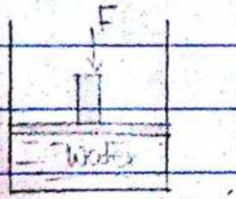
Specific entropy, $s = s_l + x s_{lg}$

Saturation Curve on P-v-diagram

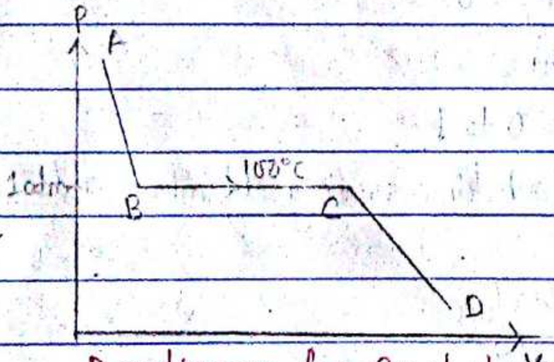
At constant temperature, water is heated and variation in pressure and specific volume was observed.

On reducing external force, (at 100°c const. temp.) pressure decreased and sp. volume increased slightly until pressure reached 1atm. to reach to saturated liquid state B. On providing heat, v increased at 1atm pressure to reach the saturated vapor state C. On further reducing pressure, v increases as shown in CD.

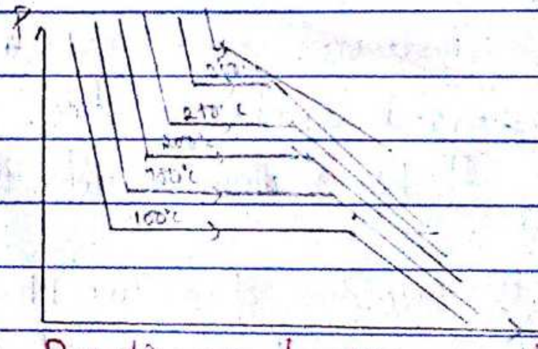
At higher temperatures, evaporation takes place correspondingly at higher pressures such that length BC reduces.



Arrangement for Constant Temp. expansion of Water



P-v diagram for Constant Temp. expansion of water



P-v diagram for expansion of water at different temperatures

Degree of superheat

The difference in temperature of a superheated vapor and the corresponding saturation temperature is c/a degree of superheat.

Note:

All the gases are actually superheated vapor.

- A pure substance can exist in no. of different solid phases
- A transition phase from one solid phase to another is c/a allotropic transformation.
- A pure substance can have a no. of triple points, but only one triple point has solid, liquid & vapor equilibrium.

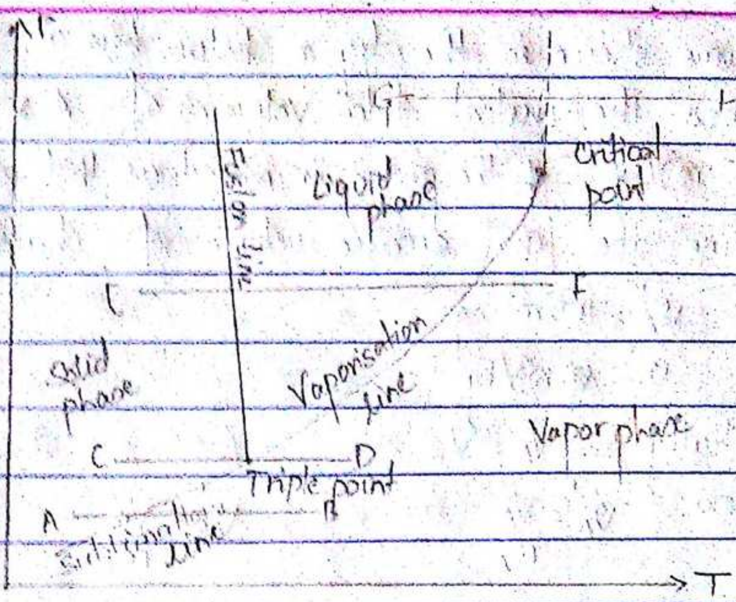
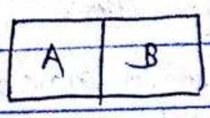


Fig. Pressure-Temperature diagram for water

The device shown in the figure below has a free moving piston between the two chambers. The initial total volumes of A & B are equal with $v_A = 100\ m^3/kg$ & $v_B = 50\ m^3/kg$. If the piston is moved so that x is one-fourth of the entire length, determine the final specific volume of chambers A & B.



Soln

$v_A^1 = 100\ m^3/kg$

$v_B^1 = 50\ m^3/kg$

Initially, $V_A = V_B$

Now, $v_A^1 = \frac{V_A}{m_A}$ $v_B^1 = \frac{V_B}{m_B}$

or, $V_A = 100 m_A\ m^3$ or, $V_B = 50 m_B\ m^3$

Now, ~~Total volume~~ $V_A = V_B$

or, $100\cancel{0} m_A = 5\cancel{0} m_B$

or, $2 m_A = m_B$

Total volume, $V = V_A + V_B = 100 m_A + 50 \times 2 m_A = 200 m_A\ m^3$

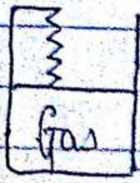
When piston is moved $V_A = \frac{1}{4}V$, then,

ie. $V_A = V/4$

Then, $v_A^2 = \frac{V_A}{m_A} = \frac{200 m_A}{4 \times m_A} = 50\ kg/m^3$

$v_B^2 = \frac{V_B}{m_B} = \frac{3 \times 200 \cancel{m_A}}{4 \times 2 \cancel{m_A}} = \frac{300}{4} = \frac{150}{2} = 75\ kg/m^3$

A piston cylinder arrangement loaded with a linear spring as shown in fig. below has CSA of $0.1\ m^2$, contains gas piston mass of 80 kg. Initially spring touches the piston but exerts no pressure on it. Heat is supplied to the system until volume doubles. Determine final pressure.



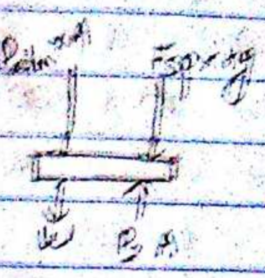
Take $g = 9.81\ m/s^2$

Outside Patm = 100 kPa, k = 50 kN/m

Initial volume of gas = $0.06\ m^3$

Soln $V_1 = 0.06\,m^3$, $CSA = 0.1\,m^2$, $x_1 = V_1/CSA = 0.6\,m$

$P_{atm} = 100\,kPa$, $K = 50\,kN/m$.



Initially spring exerts no pressure,
when volume doubles. $V_2 = 0.12\,m^3$

$x_2 = \frac{0.12}{0.1} = 1.2\,m$

$\therefore \Delta x = 0.6\,m$

NOW, $P_{abs} \times A = mg + K\Delta x + P_{atm} \times A$

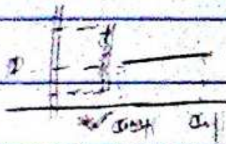
$\Rightarrow P_{abs} \times 0.1 = 80 \times 9.81 + 50k \times 0.6 + 100k \times 0.1$

$\Rightarrow P_{abs} \times 0.1 = 40.785$

$\Rightarrow P_{abs} = 407.85\,kPa$

A gas contained in a piston cylinder device initially at a pressure of 150 kPa & a volume of $0.04\,m^3$. Calculate the work done by the gas when it undergoes the following changes to a final volume of $0.1\,m^3$.

i) at constant pressure ; $W = P\Delta V = 150\,kPa \times (0.1 - 0.04) = 9\,kJ$



ii) constant temp $W = P_1V_1 \ln V_2/V_1$

$= 150k \times 0.04 \ln \frac{0.1}{0.04}$

$= 5.49\,kJ$

iii) $PV^{1.35} = \text{constant}$

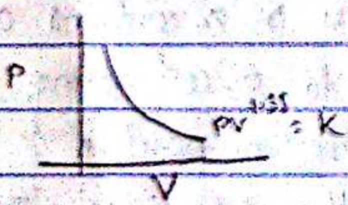
$W = \frac{-P_2V_2 + P_1V_1}{1-n}$

$P_1V_1^{1.35} = P_2V_2^{1.35}$

$\Rightarrow P_2 = 150k \times \left(\frac{0.04}{0.1}\right)^{1.35}$

$= 150k \times 0.29$

$= 43.54\,kPa$



$\therefore W = 4.7\,kJ$

In a quasi-equilibrium process in a closed system, a gas expands from a volume of 0.15 m³ & a pressure of 120 kPa to a volume of 0.25 m³ in such a manner that $p(v + 0.030) = $ const. where v is in m³. Calculate work.

Sol

we have, $p(v + 0.030) = \text{const.}$

$p_1 = 120\,kPa$, $V_1 = 0.15\,m^3$, $V_2 = 0.25\,m^3$. $\qquad p_1 v_1^n = p_2 v_2^n$ ⓝ

So, $p_1(V_1 + 0.030) = p_2(V_2 + 0.030)$

$\Rightarrow 120k(0.15 + 0.030) = p_2(0.25 + 0.030)$

$\Rightarrow p_2 = 120k \times \frac{0.18}{0.28}$

$\Rightarrow p_2 =$

Work done, $W = \int_1^2 P\,dV$

$= \int_{V_1}^{V_2} \frac{P_1(V_1 + 0.03)}{V + 0.03}\,dV$

$= P_1 \int_{V_1}^{V_2} \frac{0.18}{V + 0.03}\,dV$

$= P_1 \times 0.18 \; \ln(V + 0.03)\Big|_{V_1}^{V_2}$

$= P_1 \times 0.18\,[\ln(0.28) - \ln(0.18)]$

$= 9.54\,KJ$

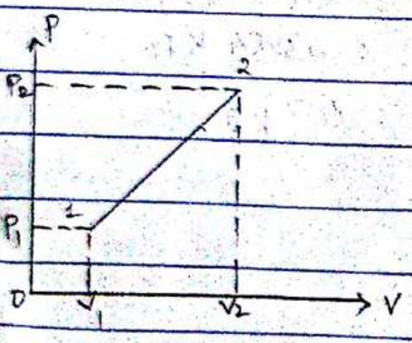
A cylinder with a frictionless piston contains 0.1 m³ of a gas at 200 kPa pressure. The piston is connected to a coil spring which exerts a force proportional to displacement from the equilibrium position. The gas is heated until its volume is doubled at which the pressure is 500 kPa. Determine the workdone by gas.

Sol $V_2 = 2V_1 = 0.2\,m^3$

$W =$ Area under curve 1-2

$= \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$

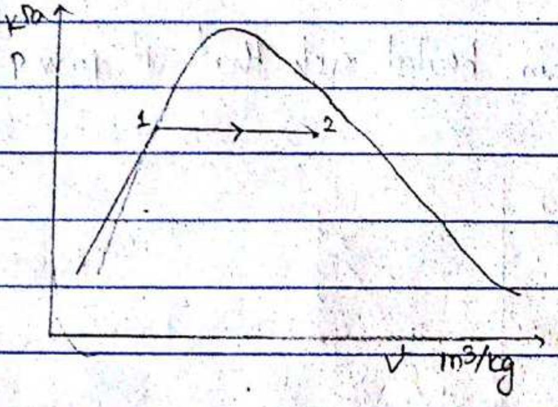
$= 35\,kJ$

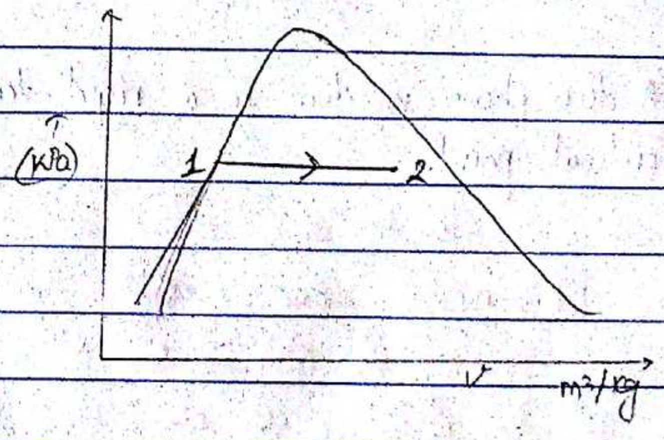


A cylinder with a frictionless piston contains 0.1 m³ of a gas at 200 kPa pressure. The piston is connected to a coil spring, which exerts a force pro

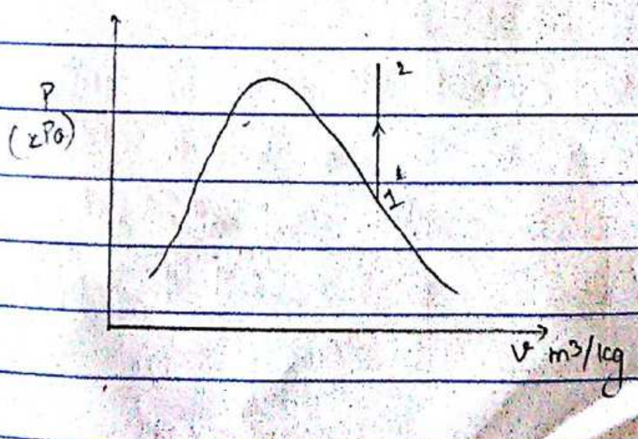
Sketch the following processes on P-V & T-V diagrams. Show both initial and final states property relative to saturation curves:

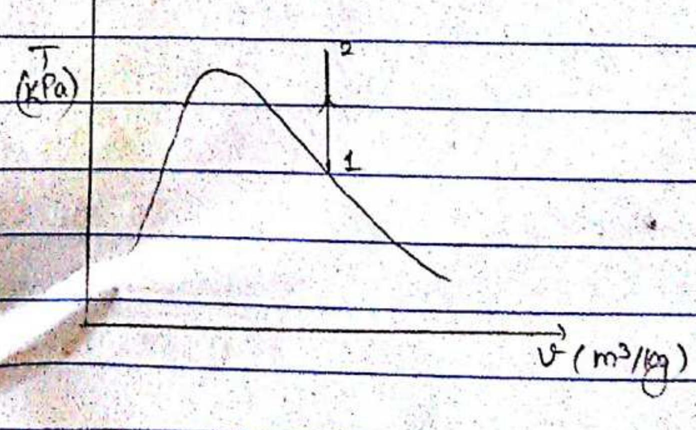
a) A saturated liquid undergoing an isothermal process until it becomes a mixture with a quality of 0.8



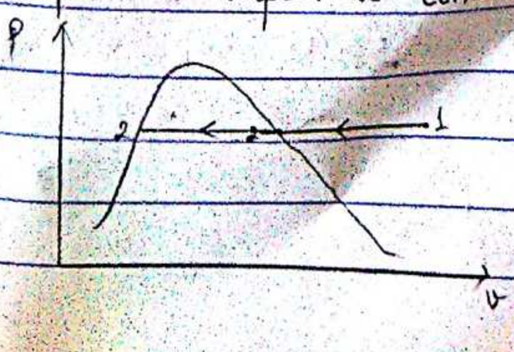


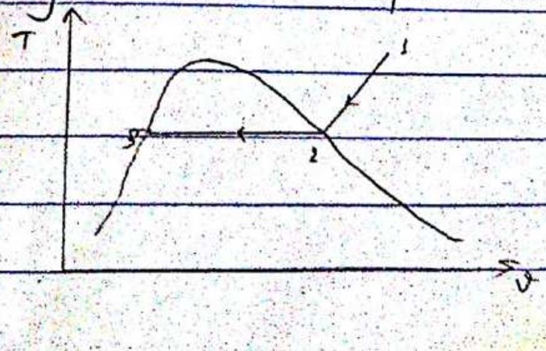
b) A saturated vapour in a rigid tank is heated



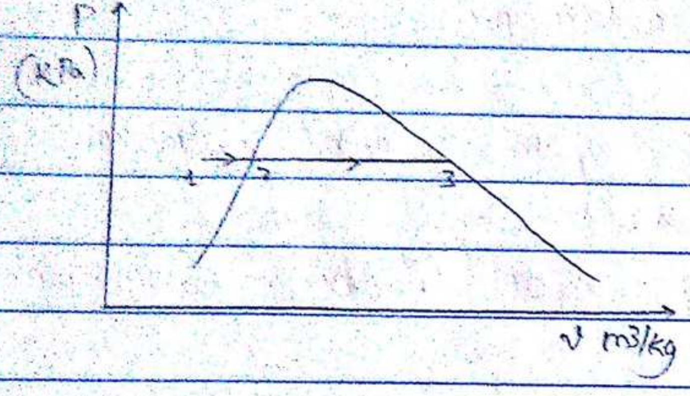


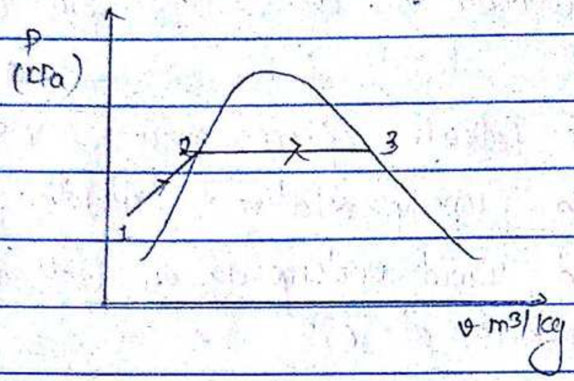
c) A superheated vapour is condensed isobarically to the saturated liquid state



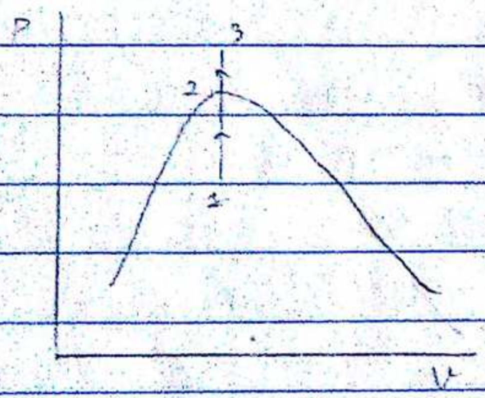


d). A compressed liquid is heated isobarically to the saturated vapour.





e) A two phase mixture in a rigid tank is heated such that it passes through a critical point.



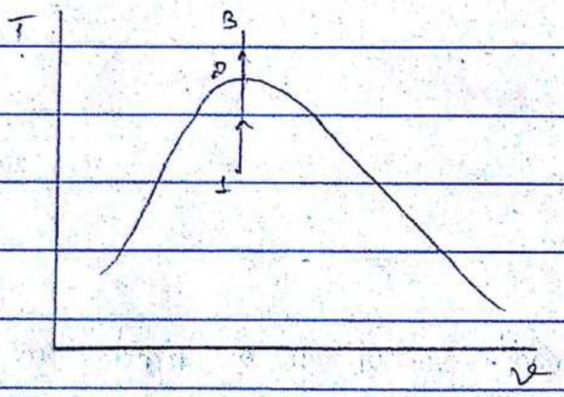


Table :

S.N	Thermal process	Relations	Work done	$dQ = dU + dW$ Heat transfer	Remarks
1.	Isobaric	$\Delta P = 0$ $\frac{V}{T} = K$ (gas only)	$W = PdV$	$dU + P\Delta V$	
2.	Isochoric	$\Delta V = 0$ $\frac{P}{T} = K$	$W = 0$	dU	
3.	Isothermal	$\Delta T = 0$ $PV = K$	$W = P_1V_1 \ln \frac{V_2}{V_1}$ $= RT_1 \ln V_2/V_1$	$dQ = P_1V_1 \ln V_2/V_1$	$dU = 0$.
4	Adiabatic	$PV^{\gamma} = \text{constant}$	$W = \frac{P_1V_1 - P_2V_2}{1-\gamma}$	$dQ = 0$	$dW = -dU$
5.	Polytropic	$PV^n = \text{constant}$	$W = \frac{P_1V_1 - P_2V_2}{1-n}$		

A gas undergoes a thermodynamic cycle consisting of three processes

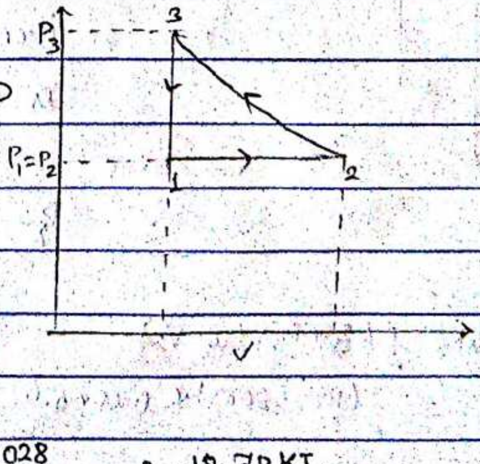
Process 1-2 : constant pressure, $p = 1.4$ bars, $V_1 = 0.028 m^3$, $W_{12} = 10.5 kJ$

Process 2-3 : compression with $PV =$ constant ; $U_3 = U_2$

Process 3-1 : constant volume ; $U_1 - U_3 = -26.4$ KJ

There are no significant changes in K.E & P.E.

Sol



$P = 1.4$ bars $= 1.4 \times 10^5$ Pa

$W_{12} = P(V_2 - V_1)$

or, $10.5 \times 10^3 = 1.4 \times 10^5 (V_2 - 0.028)$

or, $0.075 = V_2 - 0.028$

$\therefore V_2 = 0.103 m^3$

For $W_{23} = P_2V_2 \ln \frac{V_3}{V_2} = 1.4 \times 10^5 \times 0.103 \times \ln \frac{0.028}{0.103} = -18.78$ KJ

$\therefore$ Nett work done = -3.25 kJ

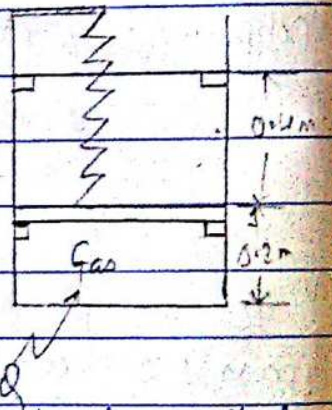
c) Heat transfer of process 1-2 in kJ

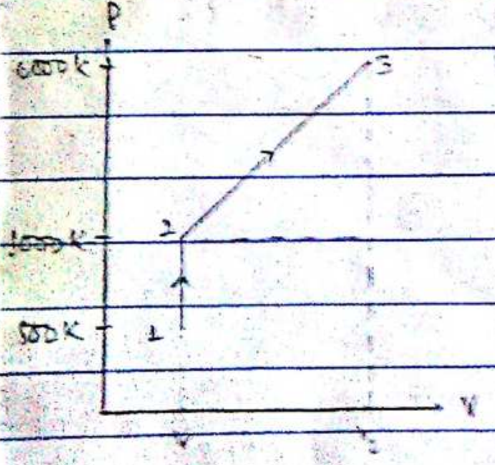
$$dQ = (dU)_{1-2} + W_{1-2}$$
$$= (U_2 - U_1) + 10.5\,kJ$$
$$= (U_3 - U_1) + 10.5\,kJ$$
$$= (25.4 + 10.5)\,kJ$$
$$= 35.9\,kJ$$

Exercise 2 (Energy & Energy Transfer)

Q(14) $K = 12\,kN/m$. CSA $= 0.05\,m^2$

Initial pressure of gas is 500kPa & pressure required to lift the piston is 1000kPa. Heat is supplied to the gas until pressure reaches 6000 kPa. Sketch process on PV diagram determine the total work transfer.





Initial pressure is 500kPa. & to lift piston from initial state 1000kPa pressure is required. So, from ~~for~~ state 1-2, pressure increases at constant volume. Then only, volume increases with increase in pressure till final pressure is 6000kPa as shown in fig.

$P_2 = 1000\,kPa$ $P_3 = 6000\,kPa$ $V_1 = V_2 = 0.05 \times 0.2\,m^3$

$V_3 = 0.05 \times 0.6\,m^3$

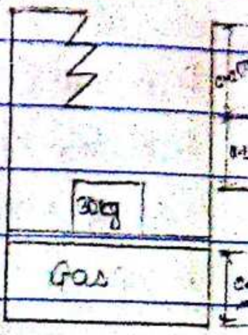
$$\therefore W = \frac{1}{2}(P_2 + P_3)(V_3 - V_2)$$
$$= \frac{1}{2}(1000 + 6000) \times 0.05 \times 0.4$$
$$= 70\,kJ.$$

Q.21. A gas enclosed by a piston shown in fig. starts to expand due to heating. The initial movement of 0.2m is restrained by a fixed mass of 30kg and the final 0.05m is restrained both by the mass and a spring of stiffness 10kN/m. CSA of piston is 0.15m² & Patm = 100kPa.

a) Neglecting mass of spring & piston, sketch P-V diagram of process

b) Calculate work during initial 0.2m movement

c) Calculate total work done

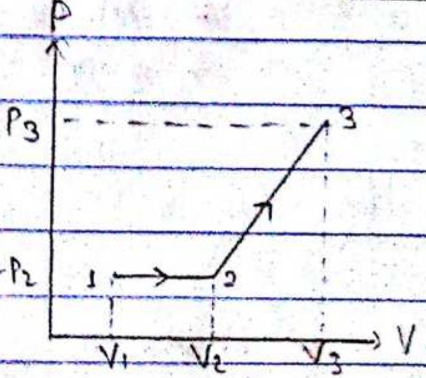


Soln

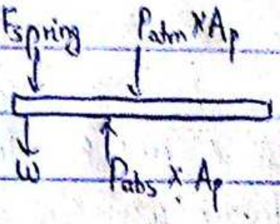
$x_1 = 0.2m$, $m = 30kg$ CSA $= 0.15m^2$

$x_2 = 0.05m$. $k = 10kN/m$, $P_{atm} = 100kPa$

$V_1 = 0.15 \times 0.05 = 0.0075m^3$



a) Free body diagram,



$P_{abs} = \frac{W}{A_p} + \frac{F_{spring}}{A_p} + P_{atm}$

$P_1 = \frac{30 \times 9.81}{0.15} + 100 = 101.962 \, kPa$

During ~~initial~~ final ~~0.2m~~ movement

$P_2 = P_{atm} + \frac{W}{A_p} + \frac{F_{spring}}{A_p}$

$= 101.962 + \frac{10k \times 0.05}{0.15}$

$= \cancel{115.x3} \; 105.29 \, kPa$

b) Work done during 0.2m movement,

$W_{12} = P_2(V_2 - V_1) = P_1(V_2 - V_1)$

$= 101.962 \times 0.15 \times (0.25 - 0.05)$

$= 3.059 \, kJ$

+ Vol. of gas at final state $= V_3 = A_p(0.05 + 0.2 + 0.05)$

$= 0.045m^3$

$W = \frac{1}{2} W_{12} + \frac{1}{2}(101.962 + 105.295) \times (0.045 - 0.0375)$

$= 3.059 + 0.78$

$= 3.84 \, kJ$

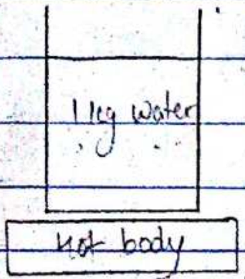
Chapter 4: First law of Thermodynamics

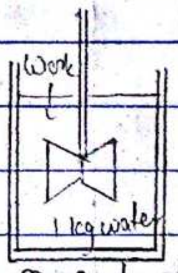
First law of Thermodynamics - ~~cons~~ law of conservation of energy

First law of Thermodynamics for a Control mass Undergoing a Cycle

First law of thermodynamics for a cycle states that:

"During any cycle a system (control mass) undergoes, the cyclic integral of heat is proportional to the cyclic integral of work"





(b) System (B) with work interaction only.

(a) system A with heat interaction only

When the study of rise in temperature of water in A and B due to heat obtained from hot body and work done by paddle respectively was carried out, it was found out that.

$$\frac{\text{Work required to accomplish given effect } (W)}{\text{Heat } \cancel{\text{Work}} \text{ required to accomplish same effect } (Q)} = \text{a constant} = \text{Mechanical Equivalent of Heat } (J)$$

$J = 4.1868$ Nm/cal if W (Nm) & Q (Kcal)

In SI, $J = 1$ Nm/J

Here the process had different initial & final states.

If process is modified: heat obt. or rise in temp of water by stirring of padal is carried out first and then touched with a cold body; the former one being uninsulated heat is lost & temperature drops until it is at the same state before stirring, the combined process of stirring & cooling of water form a cyclic process.

Observation on such cyclic experiments varying the nature of process and nature of system led to a conclusion that: "the algebraic summation of all the work interactions equals to a constant times the algebraic summation of all heat interactions, the constant being J.

Symbolically, $\Sigma_{cycle} W = J \Sigma_{cycle} Q$

$\therefore \oint \delta W = J \oint \delta Q$

For same unit of both W & Q,
first law of thermodynamics for cyclic process becomes

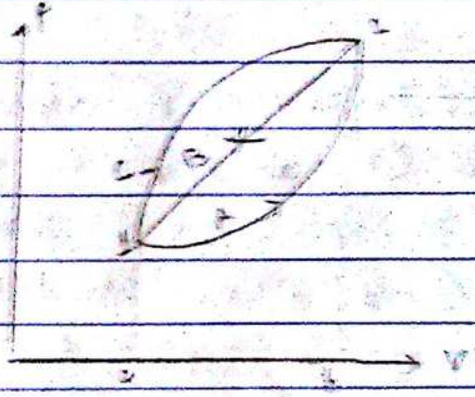
$\oint \delta W = \oint \delta Q$

$\therefore \oint (\delta Q - \delta W) = 0$

During a cyclic process total energy of system is constant so incoming energy should be equal to outgoing energy.

First law of thermodynamics for a process

Let us consider a system that undergoes a cycle first from state 1 to state 2 first from process A & back to 1 by B second by process C & back to 1 by B as shown in P-V diagram.



From the first law of thermodynamics for a cycle,

$\oint \delta W = \oint \delta Q$

Expressing in terms of 2 different process,

$\int_1^2 \delta Q_A + \int_2^1 \delta Q_B = \int_1^2 \delta W_A + \int_2^1 \delta W_B$ —— ① for process AB

$\int_1^2 \delta Q_C + \int_2^1 \delta Q_B = \int_1^2 \delta W_C + \int_2^1 \delta W_B$ —— ②

Subtracting ② from ①

$\int_1^2 \delta Q_A - \int_1^2 \delta Q_C = \int_1^2 \delta W_A - \int_1^2 \delta W_C$

$\therefore \int_1^2 (\delta Q - \delta W)_A = \int_1^2 (\delta Q - \delta W)_C$ —— ③

eqn ③ & diagram shows $(\delta Q - \delta W)$ depends only on initial & final states but not on the path followed so, a property of mass should be assigned to $(\delta Q - \delta W)$ & this property of mass is E.

So, $\delta E = \delta Q - \delta W$

$\therefore \delta Q = \delta E + \delta W$ —— ④

Integrating. $Q_{12} = E_2 - E_1 + W_{12}$

E = Internal energy + Kinetic Energy + Potential Energy

$= U + KE + PE$

$$Q_{12} = U_2 - U_1 + \frac{1}{2}m(\bar{v}_2^2 - \bar{v}_1^2) + mg(z_2 - z_1) + W_{12}$$

It implies that the net change of the energy of control mass is always equal to the net transfer of energy across the boundary as heat & work.

This is statement for conservation of energy.

Thus first law is also k/a law of conservation of energy.

First law as Rate Eqn:

First law as rate eqn expresses either the instantaneous or average rate at which energy crosses the control surface as heat and work & the rate at which the energy of control mass changes.

Consider a time interval δt during which an amount of heat δQ crosses the control surface, amount of work δW is done by control mass, energy changes are ΔU, ΔKE & ΔPE. From 1st law, we can write

$$\delta Q = \cancel{\delta}\,\Delta U + \Delta KE + \Delta PE + \delta W$$

Dividing by δt we have average rate of energy transfer as heat and work and increase of energy of control mass.

$$\frac{\delta Q}{\delta t} = \frac{\Delta U}{\Delta t} + \frac{\Delta KE}{\delta t} + \frac{\Delta PE}{\delta t} + \frac{\delta W}{\delta t}$$

Taking limit $\Delta t \to 0$ for each, we get,

$$Q = \frac{dU}{dt} + \frac{dKE}{dt} + \frac{dPE}{dt} + W$$

$$\therefore Q = \frac{dE}{dt} + W$$

First law of thermodynamics

Energy can neither be ~~de~~ created nor destroyed ; ~~it can~~ or during a process, it can only change forms.

Conservation Principles

i) Principle of conservation of mass for closed system

Mass can't be created or destroyed but may be converted from one chemical form to another. Mass of control mass system never changes

$dm = 0$

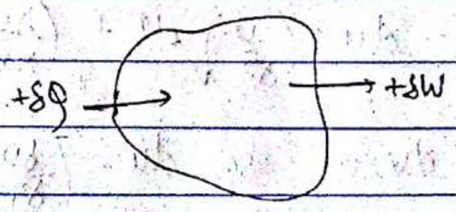
$\Rightarrow m_2 - m_1 = 0$

$\therefore m_2 = m_1$

$\therefore dm/dt = 0$

ii) Principle of Conservation of energy for Closed system

"A change in total energy of a control mass system is equal to the net energy transfer to (or from) the system as heat & work."



Energy balance for closed system

$$dE = \delta Q - \delta W$$

$$dU + d(KE) + d(PE) = \cancel{\delta Q - \delta}\ Q_{12} - W_{12}$$

$$dE/dt = Q - W$$

Constant pressure

For a constant pressure process, displacement work transfer from state 1 to state 2 is given as

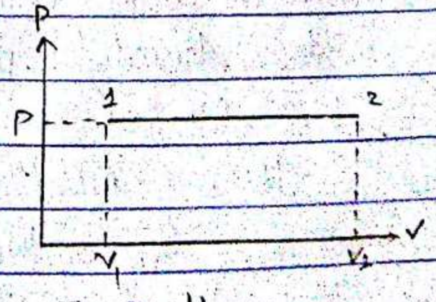


Fig : P-V diagram

$W_{12} = P(V_2 - V_1)$

$Q_{12} = (U_2 - U_1) + (P_2V_2 - P_1V_1)$

$= (U_2 + P_2V_2) - (U_1 + P_1V_1)$

$= (U+PV)_2 - (U+PV)_1$

$\boxed{Q_{12} = H_2 - H_1}$, where

$\boxed{H = U + PV}$ is enthalpy of system at a state.

Specific enthalpy, $h = H/m$

$\Rightarrow h = u + Pv$

Hence, heat transferred to a control mass during a constant pressure process is equal to increase in enthalpy of the system

Enthalpy is defined as the summation of internal energy and product of pressure and volume.

Specific heats of an Ideal Gas (2 bcoz diff at C_p & C_v)

a) at C_v (Constant volume)

We have, sp. heat due to change in internal energy

$u = u(T, v)$

$$du = \left(\frac{\partial u}{\partial T}\right)_v dT + \left(\frac{\partial u}{\partial v}\right)_T dv$$

For C_v, $dv = 0$. so. $du = \left(\frac{\partial u}{\partial T}\right)_v dT$

$\therefore du = C_v dT$

$\therefore du = mC_v dT$

where, $C_v = \left(\frac{\partial u}{\partial T}\right)_v$

at C_p (constant pressure)

We have, sp. heat due to change in enthalpy

$h = h(T, P)$

$$dh = \left(\frac{\partial h}{\partial T}\right)_P dT + \left(\frac{\partial h}{\partial P}\right)_T dP$$

$dP = 0$, so. $dh = \left(\frac{\partial h}{\partial T}\right)_P dT$

$\therefore dh = C_p dT$

$\therefore dh = mC_p dT$

where, $C_p = \left(\frac{\partial h}{\partial T}\right)_P$

Isothermal process for an ideal gas:

For constant temperature process, displacement work transfer is given by

$W_{12} = P_1V_1 \ln\left(\frac{V_2}{V_1}\right)$

Now, $(\Delta U)_{12} = mC_v(T_2 - T_1) = 0$

We have, $Q_{12} = W_{12} = P_1V_1 \ln(V_2/V_1)$

Hence heat transferred to a control mass at const. temp. is equal to work done by the system

Polytropic process for an Ideal Gas

During polytropic process.

$$W_{12} = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{mR(T_2-T_1)}{1-n}$$

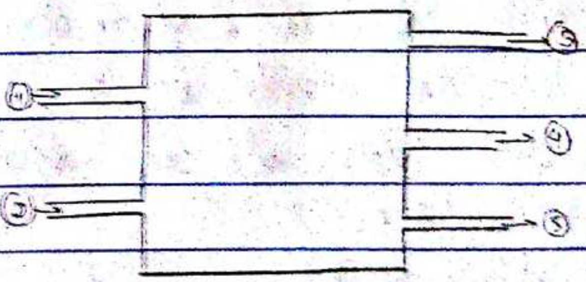
$$(\Delta U)_{12} = mC_v(T_2-T_1)$$

Sub Now,
$$Q_{12} = W_{12} + (\Delta U)_{12}$$
$$= \frac{mR(T_2-T_1)}{1-n} + mC_v(T_2-T_1)$$
$$= m(T_2-T_1)\left(\frac{R}{1-n} + C_v\right)$$

$$\therefore \quad Q_{12} = mC_n(T_2-T_1) \quad , \text{ where, } C_n = C_v + \frac{R}{1-n}$$

First law of Thermodynamics for a Control Volume

Conservation of Mass for control volume.



Any control volume system can interact with its surrounding by mass transfer as well as energy transfer.

Mass of control volume may change or not under certain specific condition.

The change in mass within control volume is equal to mass entering through each inlets minus mass leaving through each outlets.

i.e.
$$\frac{dm_{cv}}{dt} = \dot{m}_{in} - \dot{m}_{out}$$
$$= \sum_{in}\dot{m} - \sum_{out}\dot{m}$$

as shown in fig.,
$$\frac{dm_{cv}}{dt} = (\dot{m}_1 + \dot{m}_2) - (\dot{m}_3 + \dot{m}_4 + \dot{m}_5)$$

Expression for Mass flow rate

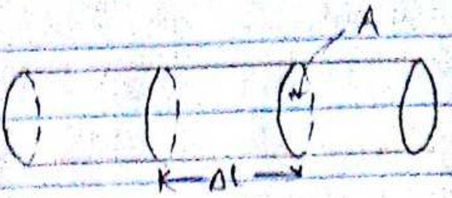


Fig: Mass flow at a port

Consider fluid flowing through port as in fig, which sweeps vol V at time Δt, then total mass of fluid ~~flowing~~ passing through section ΔL is given by

$$m = \int \rho V_{swept} = \rho A \cdot \Delta L$$

mass flow rate is given by

$$\dot m = \rho A \cdot \frac{\Delta L}{\Delta t} = \rho A \bar{V}$$

$$\therefore \dot m = \frac{A\bar{V}}{v} \quad \left(\frac{\text{Area} \times \text{velocity}}{\text{specific vol.}}\right)$$

In terms of section properties,

$$\frac{dm_{cv}}{dt} = \sum_{in}\left(\frac{A\bar{V}}{v}\right) - \sum_{out}\left(\frac{A\bar{V}}{v}\right)$$

Conservation of Energy for a Control Volume

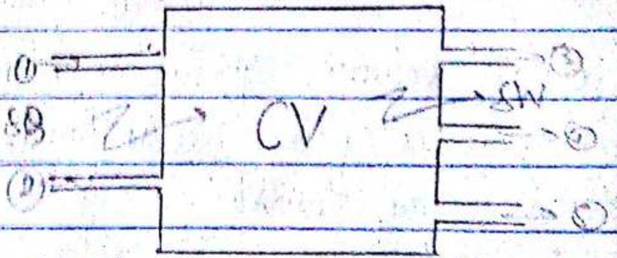


Fig. Interaction betn Control Volume & Surroundings

Since mass transfer also affects the total energy of a control volume along with heat and work transfer. So, conservation of energy for a control volume can be stated as:

" The change in total energy of a control volume is equal to net energy transported by the fluid into the control volume plus heat transferred to the control volume minus work done by control volume."

Mathematically,

$$\frac{dE_{cv}}{dt} = \dot E_{net} + \dot Q - \dot W \quad \text{---} ①$$

$$\because \dot E_{net} = \dot E_{in} - \dot E_{out}; \quad \frac{dE_{cv}}{dt} = \dot E_{in} - \dot E_{out} + \dot Q - \dot W$$

where, $\dot E_{in} = \sum_{in}\{\dot m(u + \frac{V^2}{2} + gz)\}$; $\dot E_{out} = \sum_{out}\{\dot m(u + \frac{V^2}{2} + gz)\}$

Heat transfer always occurs due to temp. difference betn system & surrounding
ie $\dot{Q} = \dot{Q}_{cv}$

However, total work transfer includes various works like flow work, shaft work, expansion/compression work.
ie. $\dot{W} = \dot{W}_{flow} + \dot{W}_{shaft} + \dot{W}_{general}$

W_{flow} is as energy required to get flowing fluid into control volume or work done by fluid coming out of control volume. So, W_{inlet} (-ve), W_{out} (+ve)
for inlet of CSA A with fluid covering ΔL at Δt,

$$W_{flow} = F \cdot \Delta L = PA \cdot \Delta L = PV_{swept}$$

$$\therefore \dot{W}_{flow} = \dot{m} \times \omega_{flow} = \dot{m}Pv$$

$$\dot{W} = -\sum_{in}(\dot{m}Pv) + \sum_{out}(\dot{m}Pv) + \dot{W}_{cv}, \quad \text{where } \dot{W}_{cv} = \dot{W}_{shaft} + \dot{W}_{general}$$

in eqn ①,

$$\frac{dE_{cv}}{dt} = \sum_{in}\left\{\dot{m}\left(u + \frac{\bar{v}^2}{2} + gz\right)\right\} \mp \sum_{out}\left\{\dot{m}\left(u + \frac{\bar{v}^2}{2} + gz\right)\right\} + \dot{Q}_{cv} + \sum_{in}(\dot{m}Pv) - \sum_{out}(\dot{m}Pv) - \dot{W}_{cv}$$

$$= \sum_{in}\left\{\dot{m}\left(h + \frac{\bar{v}^2}{2} + gz\right)\right\} - \sum_{out}\left\{\dot{m}\left(h + \frac{\bar{v}^2}{2} + gz\right)\right\} + \dot{Q}_{cv} - \dot{W}_{cv} \quad \text{—— ②}$$

eqn ② is general eqn of energy conservation for a control volume
Here, expression $\left\{\dot{m}\left(h + \frac{\bar{v}^2}{2} + gz\right)\right\}$ represents energy carried by the fluid & is c/a flow energy.

Control Volume Analysis

- any control volume can be analysed either with reference to space or time

with reference to space
- properties of system at a particular instant of time doesnot vary with space – uniform system ; if varies with space – non-uniform system

- With reference to time:

if properties of system do not vary with time : steady state system
- varies with time: unsteady state system

Steady State Analysis

- For steady state operation of a control volume, total mass & total energy shouldn't change with time. eg: turbine, compressor, nozzle etc.

i.e. $\frac{dm_{cv}}{dt} = 0$

$\Rightarrow \dot{m}_{in} - \dot{m}_{out} = 0$

$\therefore \dot{m}_{in} = \dot{m}_{out}$

& $\frac{dE_{cv}}{dt} = 0$

$\Rightarrow \sum_{in} \{\dot{m}(h + \frac{\bar{V}^2}{2} + gz)\} - \sum_{out} \{\dot{m}(h + \frac{\bar{V}^2}{2} + gz)\} + \dot{Q}_{cv} - \dot{W}_{cv} = 0$

- Substituting $\dot{m}_{in} = \dot{m}_1$, $\dot{m}_{out} = \dot{m}_2$, $\dot{m}_1 = \dot{m}_2 = \dot{m}$

$\dot{Q}_{cv} - \dot{W}_{cv} = \dot{m}[(h_2 - h_1) + \frac{1}{2}(\bar{V}_2^2 - \bar{V}_1^2) + g(z_2 - z_1)]$

Unsteady state analysis:

During the unsteady state analysis of a control volume, the properties change with time i.e. total mass and total energy of the system is function of time.

i.e. $\frac{dm_{cv}}{dt} \neq 0$ - $m_{cv} = f(t)$

& $\frac{dE_{cv}}{dt} \neq 0$ - $E_{cv} = f_2(t)$

For any process 1-2 between state 1 (instant t_1) and state 2 (instant t_2), mass conservation equation reduces to

$\int_{t_1}^{t_2} \left(\frac{dm_{cv}}{dt}\right) dt = \int_{t_1}^{t_2} \dot{m}_{in}\, dt - \int_{t_1}^{t_2} \dot{m}_{out}\, dt$

$\therefore m_2 - m_1 = m_{in} - m_{out}$ ......①

For energy conservation,

$\int_{t_1}^{t_2} \left(\frac{dE_{cv}}{dt}\right) dt = \int_{t_1}^{t_2} \sum_{in} \{\dot{m}(h + \frac{\bar{V}^2}{2} + gz)\} dt - \int_{t_1}^{t_2} \sum_{out} \{\dot{m}(h + \frac{\bar{V}^2}{2} + gz)\} dt + \int_{t_1}^{t_2} \dot{Q}_{cv} dt - \int_{t_1}^{t_2} \dot{W}_{cv} dt$

$\therefore (E_{cv})_2 - (E_{cv})_1 = m_{in}(h_{in} + \frac{\bar{V}_{in}^2}{2} + gz_{in}) - m_{out}(h_{out} + \frac{\bar{V}_{out}^2}{2} + gz_{out}) + Q_{12} - W_{12}$

Control Volume Applications

Steady state work applications:

- devices operating at steady state condition either produce or consume works.
eg: turbine, compressor, pump, fan etc.

-

Turbine:

- device which produces power by consuming energy carried by a fluid.

So, general eqn is

$\dot{Q}_{cv} - \dot{W}_{cv} = \dot{m}[(h_2 - h_1) + \frac{1}{2}(\bar{V}_2^2 - \bar{V}_1^2) + g(z_2 - z_1)]$ —— ①

if the turbine surface is insulated & heat transfer is negligible, it is called an adiabatic turbine. eqn reduces to

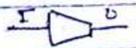
$\dot{W}_{cv} = \dot{m}[(h_1 - h_2) + \frac{1}{2}(\bar{V}_1^2 - \bar{V}_2^2) + g(z_1 - z_2)]$

Compressor - increases pressure energy of the gaseous substance
pump - increases pressure or potential energy of the liquid substance
fan - increases kinetic energy of the fluid
All these instruments have energy eqn given by ①

Steady state flow applications:

Devices which operate under steady state conditions & do not produce or consume

work are c/a steady state flow applications
eg: nozzle, diffuser, heat exchanger, evaporator, condenser, throttling valve

nozzle: device with ↓ CSA, & used to increase fluid velocity 

diffuser: device with ↑ CSA & used to decrease fluid velocity 

No work done

$\dot{Q}_{cv} = \dot{m}[(h_2-h_1) + \frac{1}{2}(\bar{V}_2^2-\bar{V}_1^2) + g(z_2-z_1)]$

In these devices, change in P.E is usually negligible in comparison to change in KE or change in enthalpy

If they are operating at adiabatic condition

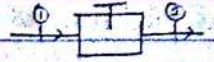
$(h_2-h_1) + \frac{1}{2}(\bar{V}_2^2-\bar{V}_1^2) = 0$

$\therefore\ h_1 + \frac{\bar{V}_1^2}{2} = h_2 + \frac{1}{2}\bar{V}_2^2$

In case of heat exchanger, on studying the effect of heat exchange on the properties of hot or cold fluid, change in PE & KE are negligible in comparison to the change in enthalpy. So,
energy equation becomes
[illegible] (hot fluid)
[illegible] (cold fluid)

In case of evaporator and condenser energy eqn becomes
[illegible] ... ②

Throttling valve reduces pressure of the fluid without performing work and heat transfer. Change in PE & KE, energy eqn is given as

$h_2 - h_1 = 0$ 

$\therefore\ h_2 = h_1$ = constant enthalpy.

Unsteady state flow Applications:
devices turbine, pump, compressor etc. operate at steady state at their normal operation, however operate at unsteady state during the start up and shut down period.

$m_2 - m_1 = m_{in}$ .... ①

$(E_{cv})_2 - (E_{cv})_1 = m_{in}(h_{in} + \frac{1}{2}\bar{V}_{in}^2 + gz_{in}) + Q_{12} - W_{12}$ ....

In case of piston cylinder device, changes in PE & KE are negligible in comparison to change in internal energy
the energy eqn becomes

$m_2u_2 - m_1u_1 = m_{in}(h_{in} + \frac{1}{2}\bar{V}_{in}^2 + gz_{in}) + Q_{12} - W_{12}$

Unsteady state flow application:
eg discharging gas cylinder

$m_2u_2 - m_1u_1 = -m_{out}(h_{out} + \frac{1}{2}\bar{V}_{out}^2 + gz_{out}) + Q_{12}$

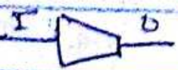
Other statements of 1st law:
a) 1st law of Thermodynamics for an isolated system:
for isolated system $\delta Q = \delta W = 0$
So, 1st law $dE = \delta Q - \delta W$ becomes
$dE = 0$
i.e. $E_2 = E_1$ (total energy of isolated system becomes constant)

b) First law of Thermodynamics for a control mass Undergoing an Adiabatic Process

On insulating boundary of control mass, no heat transfer occurs.
$\delta Q = 0$, energy equation reduces to
$$dE = -\delta W$$

c) Perpetual Motion Machine of 1st kind (PMM-I) is not possible
not possible becoz of friction.

work are c/a steady state flow applications.
eg: nozzle, diffuser, heat exchanger, evaporator, condenser, throttling valve

nozzle: device with ↓ CSA, & used to increase fluid velocity


diffuse: device with ↑ CSA & used to decrease fluid velocity


No work done

$$\dot{Q}_{cv} = \dot{m}[(h_2-h_1) + \frac{1}{2}(\bar{V}_2^2-\bar{V}_1^2) + g(z_2-z_1)]$$

In these devices, change in P.E. is usually negligible in comparison to change in KE or change in enthalpy.
If they are operating at adiabatic conditions,

$$(h_2-h_1) + \frac{1}{2}(\bar{V}_2^2-\bar{V}_1^2) = 0$$

$$\therefore \quad h_1 + \frac{\bar{V}_1^2}{2} = h_2 + \frac{1}{2}\bar{V}_2^2$$

In case of heat exchanger, on studying the effect of heat exchange on the properties of hot or cold fluid, change in P.E. & K.E. are negligible in comparison to the change in enthalpy. so,
energy equation becomes:

$$\dot{Q} = \dot{m}_h(h_{2h}-h_{1h}) \quad \text{(hot fluid)}$$

$$\dot{m}_h h_{1h} + \dot{m}_c h_{1c} = \dot{m}_h h_{2h} + \dot{m}_c h_{2c} \quad \text{(cold fluid)}$$

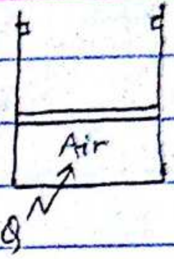
In case of evaporator and condenser, energy eqⁿ becomes

$$\dot{Q} = \dot{m}(h_2-h_1) \; \ldots\ldots ①$$

Throttling valve reduces pressure of the fluid without performing work. Heat transfer, change in P.E. & K.E., energy eqⁿ is given as

MCL EX:2

P.12 Given: $m = 0.1\,kg$ of air, $R = 287\,J/kgK$
initially pressure 4 MPa & temp. 200°C
heat (+Q) added till pressure 8MPa, temp 800°C



Soln $P_1 = 4\,MPa$. $T_1 = (200+273)K$
heat is added. so, at constant pressure. vol. of air increases till it reaches upper stop. Then at const. vol., pressure increases to final state.

$P_2 = P_1 = 4\,MPa$, $P_3 = 8\,MPa$, $T_3 = 800\,°C = (800+273)K$

2 to 3 state

$\frac{P_2}{T_2} = \frac{P_3}{T_3}$

$\therefore T_2 = \frac{4M \times 1073}{8M}$ $= 536.5K$

$P_1V_1 = mRT_1$

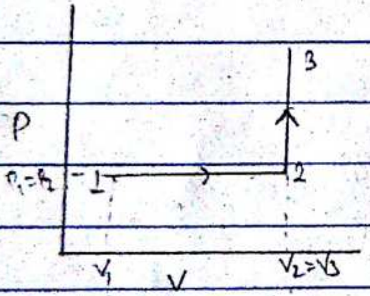
$\therefore V_1 = \frac{0.1 \times 287 \times 473}{4 \times 10^6}$

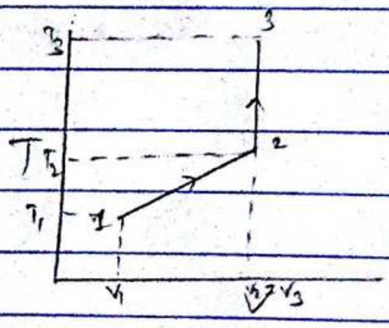
$\therefore V_1 = 3.39 \times 10^{-3}\,m^3$

$P_2V_2 = mRT_2$

$\therefore V_2 = \frac{0.1 \times 287 \times 536.5}{4 \times 10^6}$

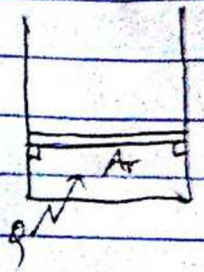
$V_2 = 3.85 \times 10^{-3}\,m^3$



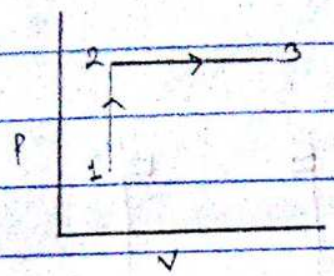


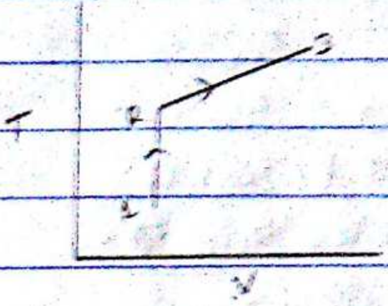
$\therefore {}_1W_2 = P(V_2 - V_1)$
$= 4 \times 10^6 (3.85 \times 10^{-3} - 3.39 \times 10^{-3})$
$= 4 \times 10^6 \times 4.6 \times 10^{-4}$
$= 1.84\,KJ$

Q13. Given: $m = 1\,kg$, $R = 208\,J/kgK$
initially pressure 500 kPa, temperature 90°c
final temp 600°C, pressure of 1 MPa req. to lift piston from the stops
Now, On giving heat Q, 1st pressure ↑es at const vol.



Then at const pressure, vol. increases





$P_1 = 500\,kPa$. $T_1 = 343K$, $V_1 = V_2 = 0.143 m^3$, $P_2 = 1000\,kPa$ $T_3 = 600°C = 873\,K$

$P_1V_1 = mRT_1$ $P_1/T_1 = P_2/T_2$ $\frac{V_2}{T_2} = V_3/T_3$

$\therefore V_1 = \frac{1 \times 208 \times 343}{500 \times 10^3}$ $\therefore T_2 = 686K$ $\therefore V_3 = 0.182 m^3$

$= 0.143 m^3$

$\therefore W = 1000 \times 10^3 (0.182 - 0.143)$

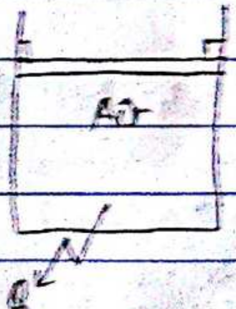
$= 39\,kJ$

⑭. $m = 0.5kg$, $R = 287\,J/kgK$

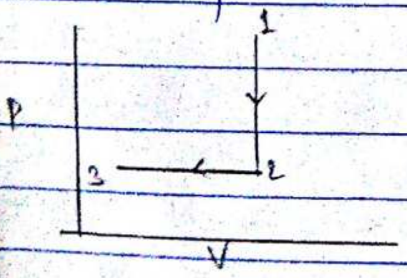
Initially. Pressure 1 MPa, temp 500°C

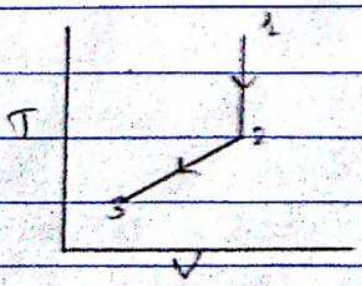
system cooled till temp 50°C.

pressure of 0.5MPa req. to support piston



Sol^n On cooling, 1st pressure dec at const vol. then at const. pressure, vol. decreases.





$P_1 = 1000\,kPa$, $T_1 = 500°C$, $T_3 = 50°C$, $P_2 = P_3 = 0.5MPa$

$P_1V_1 = mRT_1$ $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ $\frac{V_2}{T_2} = \frac{V_3}{T_3}$

$\therefore V_1 = \frac{0.5 \times 287 \times 773}{1000 \times 10^3} = 0.11 m^3$ $\therefore T_2 = \frac{0.5}{1} \times 773 = 386.5K$ $\therefore V_3 = 0.092 m^3$

Second law of thermodynamics

Entropy Relations:

As entropy is a thermodynamic property, it can be used with any other property to completely describe state of ~~sty~~ system. Apply state postulate, internal energy of system is determined if entropy & volume are given as:

$$U = U(S, V)$$

$$dU = \left(\frac{\partial U}{\partial S}\right)_V dS + \left(\frac{\partial U}{\partial V}\right)_S dV \quad \text{— ①}$$

These 2 partial derivatives are ratios of two extensive properties, hence are intensive parameters.

$$T = \left(\frac{\partial U}{\partial S}\right)_V \quad \& \quad p = -\left(\frac{\partial U}{\partial V}\right)_S \quad \text{— ②}$$

From ① & ②, $dU = T\,dS - P\,dV$ — Gibbs equation

Rearranging Gibbs eqn

$$dS = \frac{dU}{T} + \frac{P}{T}dV \quad \text{— ③}$$

Entropy in terms of enthalpy is given by:

$$H = U + PV$$

$$dH = dU + PdV + VdP$$

$$\therefore \; dH = TdS + VdP$$

$$\therefore \; dS = \frac{dH}{T} - \frac{V}{T}dP \quad \text{— ④}$$

For ideal gas,

$$PV = mRT$$

$$\therefore \; \frac{P}{T} = \frac{mR}{V} \quad \text{— ⑤}$$

Change in internal energy of ideal gas is given by

$dU = m C_v dT$ — ②

Substituting ① & ② in $ds = \frac{dU}{T} + \frac{P}{T} dV$

$$\therefore \quad ds = m c_v \frac{dT}{T} + \frac{mR}{V} dV$$

Integrating from state 1 to state 2,

$$\boxed{S_2 - S_1 = mC_v \ln\left(\frac{T_2}{T_1}\right) + mR \ln\left(\frac{V_2}{V_1}\right)}$$

Similarly, $\frac{V}{T} = \frac{mR}{P}$ — ①

Change in enthalpy of ideal gas is given by

$dH = m c_p dT$ — ②

We know, $ds = \frac{dH}{T} + \frac{V}{T} dP$ — ③

From ①, ② & ③,

$$ds = m c_p \frac{dT}{T} + mR \frac{dP}{P} \quad — ④$$

To find entropy change from state 1 to state 2, we integrate eqn ④ from state ① to state ②.

$$\boxed{S_2 - S_1 = mC_p \ln\left(\frac{T_2}{T_1}\right) + mR \ln\left(\frac{P_2}{P_1}\right)}$$

Entropy Relation for an Incompressible substance

Vol. of solid & liquid substances do not change significantly with pressure or temperature. hence, are assumed as incompressible substance

entropy relation :

$$ds = \frac{dU}{T} + \frac{P}{T} dV$$

$dV = 0, \quad ds = \frac{dU}{T} = \frac{mc\,dT}{T}$

$$\boxed{S_2 - S_1 = mc \ln\left(\frac{T_2}{T_1}\right)}$$

Limitations of First law

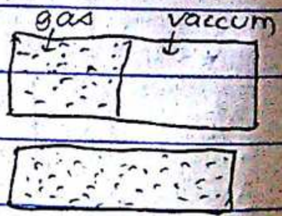
First law of thermodynamics explains
- Thermodynamic processes with reference to mass and energy conservation
- deals with quantitative aspect of energy &
- gives only condition that any process is possible provided that energy conservation occurs

However some ~~p~~ natoral process are possible even when no energy conservation occurs.

- Second law of thermodynamics deals with quality or nature of energy & defines the direction of the process in which system can proceed

① 1st law: for cyclic process, heat transfer = work transfer
but real devices, even operating on cycle, cannot convert heat completely to work
hence 2nd law explains why real engine cannot operate without heat loss.

② 1st law is satisfied when a system proceeds from state 1 to state 2 & vice-versa, as energy remains constant. However, system can never proceed in reverse direction.



③ Work transfer occurs due to relative displacement betn system & surrounding
Thus, ~~as~~ during process, friction occurs, work gets converted into heat.
But, heat conversion to work is not possible.

2nd law: defines the directions of the processes with reference to system property c/a entropy

- System itself tends to undergo process from low entropy to high entropy. However, reverse is not possible.

▲ Work itself gets converted to ~~cool~~ heat, & reverse direction is not possible.

~~System~~ Second law of Thermodynamics for an Isolated System:

Isolated system can proceed in the , direction in which its randomness or uncertainity i.e. entropy increases.

" Entropy of an isolated system always increases or may remain constant." (in an ideal process)

Mathematically,

$$(ds)_{isolated} \geq 0$$

$$\therefore S_{final} - S_{initial} \geq 0$$

$$\therefore S_{final} \geq S_{initial}$$

Difference in entropies of initial & ~~both~~ final state during any process is c/a entropy production or entropy generation. Denoted by δS_{gen}.

$$(ds - \delta S_{gen})_{isolated} = 0, \quad \text{where} \quad (\delta S_{gen})_{isolated} \geq 0$$

equations given can also be expressed in terms rate as

$$(ds/dt)_{isolated} \geq 0$$

$$\& \quad (ds/dt)_{isolated} - \dot{S}_{gen} = 0$$

Reversible and Irreversible process

In terms of entropy,

for any real process, $S_2 \geq S_1$

if $S_2 = S_1$, reversible process,

$S_2 > S_1$, irreversible process

Cause of irreversibility:

- mechanical and thermal irreversibility

- internal and external irreversibility

Control Mass formulation of Second law of Thermodynamics:

- Control Mass interacts with surrounding by work transfer & heat transfer
- So, control mass formulation of 2nd law gives "expression for the change in entropy of the control mass because of heat & work transfer."

Consider an isolated system consisting of a control mass interacting with heat transfer and work transfer ~~mechanisms~~ reservoirs.

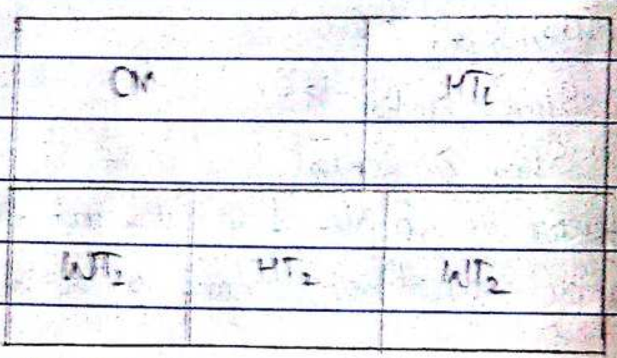


Fig: Isolated system consisting of Control Mass, ~~Heat transfer~~ and Work transfer reservoirs

Contribution of Heat Transfer on Entropy

To study effect of heat transfer on entropy, consider system having infinite heat capacity such that its temperature is unaffected by heat transfer. Such reservoir interacting only with heat transfer is reversible heat transfer & specified by its temp. (T_i)

Since no work transfer, so,

$$\delta W = PdV = 0 \Rightarrow$$ [illegible]

in $ds = \frac{dU}{T} + \frac{P dV}{T}$.

$$ds = \frac{dU}{T} \quad \text{— ①}$$

Applying first law, $\delta Q = dU + PdV = dU$ — ②

from ① & ②, $ds = \frac{\delta Q}{T}$ — ③

eqn ③ shows that entropy of a system increases if heat is supplied to it and decreases if it loses heat.

Contribution of Work Transfer on Entropy:

To study this effect, consider a system having infinite work capacity such that the pressure is unaffected by work transfer. Such reservoir is reversible work transfer reservoir & is specified by its pressure (P_i).

Applying 1st law of thermodynamics.

$$\delta Q\,(=0) = dU + PdV$$

$$\therefore\ -dU = PdV$$

In eqn

$$ds = \frac{dU}{T} + \frac{PdV}{T}$$

$$ds = -\frac{PdV}{T} + \frac{PdV}{T} = 0$$

Thus, work transfer doesnot have any contribution on the entropy of the system.

Applying 2nd law, $(ds)_{isolated} \geq 0$

Total change in entropy of isolated system is given by sum of change in entropy of control mass, of the reversible heat transfer and work transfer reservoirs. i.e.

$$(ds)_{CM} + \sum (ds)_{HT} + \sum \overset{\to 0}{(ds)_{WT}} \geq 0$$

$$dS_{CM} + \sum dS_{HT} \geq 0$$

$$\therefore\ dS_{CM} + \sum \left(\frac{\delta Q_i}{T_i}\right)_{HT} \geq 0$$

If $(\delta Q_i)_{HT}$ is heat supplied to the reservoir at temperature T_i, it is supplied by the control mass.

$$\therefore\ (\delta Q_i)_{HT} = -(\delta Q_i)_{CM}$$

So,

$$\delta S_{cm} - \sum \left(\frac{\delta Q_i}{T_i}\right)_{CM} \geq 0$$

or,

$$\delta S_{cM} \geq \sum \left(\frac{\delta Q_i}{T_i}\right)_{cM} \quad \text{—} \ ①$$

From eqn ①, we can state 2nd law of thermodynamics for control mass as
" The change in entropy of a control mass is greater than or equal to sum of heat transfers divided by the corresponding boundary absolute temperatures."

$$(dS)_{CM} - \sum \left(\frac{\delta Q_i}{T_i}\right)_{CM} - (dS)_{gen} = 0$$

where, $(dS)_{gen} = (dS)_{CM} - \sum \left(\frac{\delta Q_i}{T_i}\right)_{CM}$

In terms of rate,

$$(dS/dt)_{CM} \geq \sum \left(\frac{\dot{Q}_i}{T_i}\right)_{CM}$$

$$\therefore \left(ds/dt\right)_{CM} - \sum \left(\frac{\dot{Q}_i}{T_i}\right)_{CM} - \dot{S}_{gen} = 0$$

For a single reservoir undergoing reversible,

$$ds = \frac{\delta Q}{T}$$

$$\therefore \delta Q = T\,ds \quad \text{—— ②}$$

eqn ② shows area under T-S diagram gives the magnitude of heat transfer.

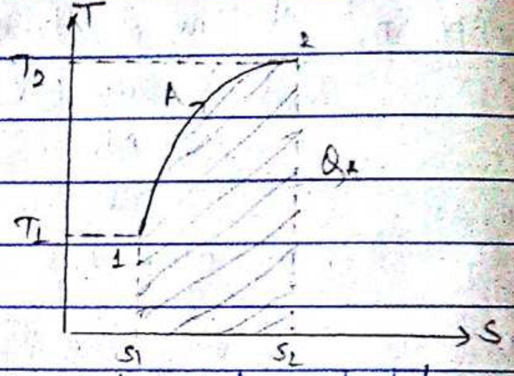


Fig: Heat transfer evaluated as area under curve on T-S diagram

Control Volume Formulation of Second law of Thermodynamics

Control vol. formulation of 2nd law gives expression for change of entropy of a control vol. due to mass and energy transfer.

2nd law ~~of~~ for control vol. is stated as :

" Change in entropy of control vol. minus net entropy change of working substance due to mass transfer is greater than or equal to the sum of heat transfers divided by the corresponding boundary absolute temperatures."

i.e.

$$(ds/dt)_{cv} - \dot{S}_{net} \geq \sum \left(\frac{\dot{Q}_i}{T_i}\right)_{cv}$$

Substituting, $\dot{S}_{net} = \dot{S}_{in} - \dot{S}_{out}$

$$(ds/dt)_{cv} - \dot{S}_{in} + \dot{S}_{out} \geq \sum \left(\frac{\dot{Q}_i}{T_i}\right)_{cv}$$

or

$$\left(\frac{ds}{dt}\right)_{cv} - \dot{S}_{in} + \dot{S}_{out} - \sum \left(\frac{\dot{Q}_i}{T_i}\right) - \dot{S}_{gen} = 0$$

where, $\dot{S}_{gen} = \left(\frac{ds}{dt}\right)_{cv} - \dot{S}_{in} + \dot{S}_{out} - \sum \left(\frac{\dot{Q}_i}{T_i}\right)$

Isentropic Process :

During reversible process change in entropy is given by

$$ds = \frac{dQ}{T}$$

If that reversible process is adiabatic too. then

$ds = 0$

$\Rightarrow S_2 = S_1 \Rightarrow$ entropy of the system remains constant

Isentropic Relations for an ideal gas

For ideal gas, entropy relations is given by

$$S_2 - S_1 = mC_v \ln\left(\frac{T_2}{T_1}\right) + mR\ln\left(\frac{V_2}{V_1}\right)$$

$$S_2 - S_1 = mC_p \ln\left(\frac{T_2}{T_1}\right) + mR\ln\left(\frac{P_2}{P_1}\right)$$

For isentropic process, $S_2 - S_1 = 0$

① $mC_v \ln(T_2/T_1) + mR\ln(V_2/V_1) = 0$

$\therefore mC_v \ln(T_2/T_1) = -mR\ln(V_2/V_1)$

$\therefore C_v \ln(T_2/T_1) = -R\ln(V_2/V_1)$

$\therefore \ln(T_2/T_1)^{C_v} = \ln(V_2/V_1)^{-R}$

$\therefore \left(\frac{T_2}{T_1}\right)^{C_v} = \left(\frac{V_2}{V_1}\right)^{-R} = \left(\frac{V_1}{V_2}\right)^{R}$

$\therefore \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\frac{R}{C_v}} = \left(\frac{V_1}{V_2}\right)^{\frac{C_p - C_v}{C_v}}$

or $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1}$

② $mC_p \ln\left(\frac{T_2}{T_1}\right) + mR\ln(P_2/P_1) = 0$

$\therefore mC_p \ln(T_2/T_1) = -mR\ln(P_2/P_1)$

$\therefore C_p \ln(T_2/T_1) = -R\ln(P_2/P_1)$

$\therefore \ln(T_2/T_1)^{C_p} = \ln(P_2/P_1)^{-R}$

$\therefore \left(\frac{T_2}{T_1}\right)^{C_p} = \left(\frac{P_2}{P_1}\right)^{-R} = \left(\frac{P_1}{P_2}\right)^{R}$

$\therefore \frac{T_2}{T_1} = \left(\frac{P_1}{P_2}\right)^{\frac{R}{C_p}} = \left(\frac{P_1}{P_2}\right)^{\frac{C_p - C_v}{C_p}}$

$\therefore \frac{T_2}{T_1} = \left(\frac{P_1}{P_2}\right)^{1-\frac{1}{\gamma}} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$

Isentropic Relation for an Incompressible Substance

For incompressible substance, $ds = \frac{du}{T}$ — ①

For isentropic process, $ds = 0 = \frac{du}{T}$

$\Rightarrow du = 0$

In terms of enthalpy, $h = u + pv$

$\therefore dh = du + Pdv + vdP$

Substituting $du = 0$ & $dv = 0$ for incompressible, substance going isentropic process

$dh = vdP$ —— ⑧

Integrating eqn ⑧ for any process 1-2 betn state 1 to state 2, we get.

$h_2 - h_1 = v(P_2 - P_1)$

Isentropic efficiency of steady flow devices

isentropic process is an ideal process where not any losses (ie. frictional loss, heat loss etc.) occur as compared to real process

so. isentropic efficiency helps to compare performance of the real device with the idealised device (isentropic device)

Isentropic efficiency of turbine.

KE of fluid $\xrightarrow{\text{turbine}}$ output work, which is always less than the isentropic work output bcoz of losses.

so. isentropic efficiency, $\eta_{iT} = \frac{W_{real}}{W_{isen}}$

Isentropic efficiency of pump/compression

pump/compression $\longrightarrow$ works on fluid $\rightarrow$ to get desired output effect

$\eta_{iP} / \eta_{iC} = \frac{W_{isen}}{W_{real}}$

Isentropic efficiency of a nozzle

increase KE of fluid while going out from outlet.

$\eta_{iN} = \frac{(\bar{V}_{real})^2/2}{(\bar{V}_{isen})^2/2} = \frac{\bar{V}_{real}}{\bar{V}_{isen}}$ ∴ for same inlet state & exit pressure

Carnot Cycle ; Heat Engine . Heat pump , Refrigenerator

Carnot Cycle :

- Ideal cycle devised by Carnot
- has efficiency equal to that of a reversible cycle (theoritical efficiency)
- though has highest efficiency but is not practically possible
- used as reference standard for the comparison of different practical cycles

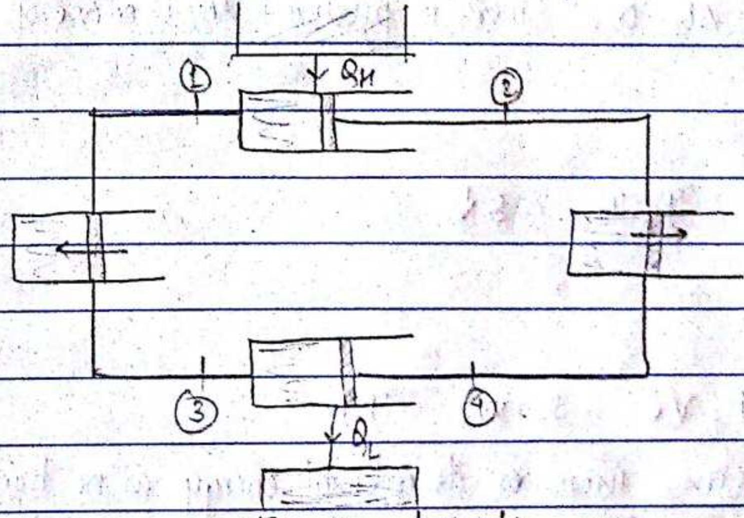


Fig. Carnot cycle

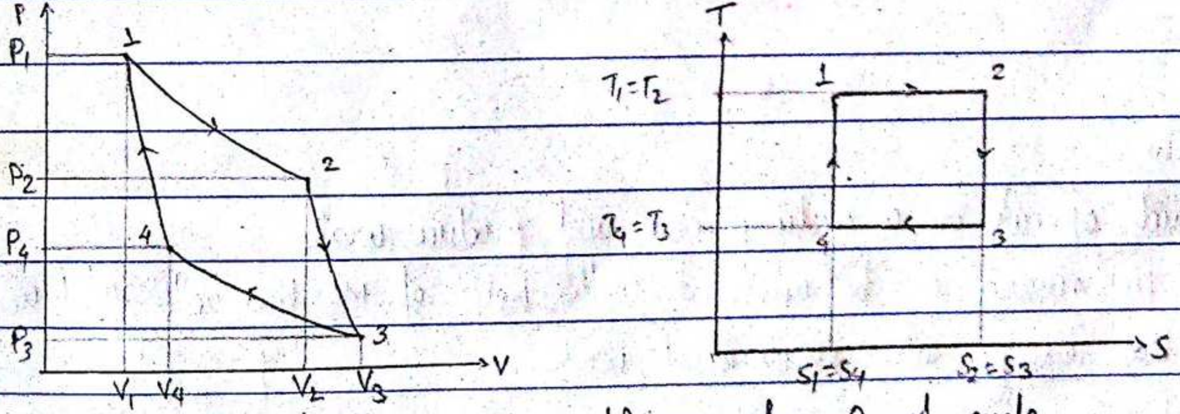


Fig : P-v & T-s diagrams for Carnot cycle

Process 1-2 : Isothermal heat addition (expansion)

Process 2-3 : Isentropic expansion

Process 3-4 : Isothermal heat rejection (compression)

Process 4-1 : Isentropic compression

Process 1-2 :

Q added to working subs s.t. isothermal expansion occurs
T const, $P\downarrow$, $V\uparrow$, $S\uparrow$

Process 2-3 :

isentropic expansion occurs s.t. $P\downarrow$, $V\uparrow$ $S_2 = S_3$, $T\downarrow$
both adiabatic & reversible, so, $\Delta Q = 0$, work is produced in expense of internal energy

Process 3-4 :

Q lost to sink s.t. $P\uparrow$, $V\downarrow$, $T_3 = T_4$, $S\downarrow$

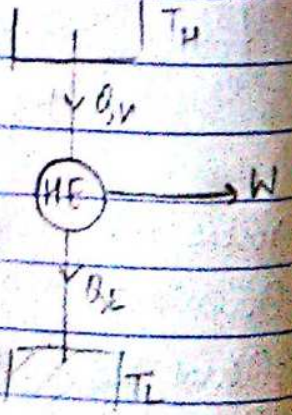
Process 4-1 :

isentropic compression s.t. $P\uparrow$, $V\downarrow$, $S_4 = S_1$, $T\uparrow$
work is supplied to the system increases its internal energy as no heat loss

Heat Engine

: device which operate on a cyclic process and produce work
: ~~p~~ their performance can be analysed with help of 1st law and 2nd law.
: convert heat energy into mechanical work

: takes Q_H heat from high temp. source (T_H) and converts it into work whereas rejects some heat, Q_L to low temp. sink (T_L)



Performance is measured by ~~heat~~ its efficiency, defined as ratio of output work to heat supplied i.e. $\eta = \frac{W}{Q_H}$ —— ①

Applying 1st law of Thermodynamics for a cyclic process.

$$\oint \delta Q = \oint \delta W$$

$\therefore Q_H - Q_L = W$ —— ②

From ① & ②, $\eta = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$ —— ③

Now, applying 2nd law for cyclic process

$$\oint dS_{cm} \geq \oint \Sigma \left(\frac{\delta Q_i}{T_i}\right)_{cm}$$

Since entropy is prop. of system & for cyclic process, change in entropy is zero

i.e. $0 \geq \oint \Sigma \left(\frac{\delta Q_i}{T_i}\right)_{cm}$

$\Rightarrow 0 \geq \frac{Q_H}{T_H} - \frac{Q_L}{T_L}$

For a reversible heat engine,

$\frac{Q_H}{T_H} - \frac{Q_L}{T_L} = 0 \Rightarrow \frac{Q_H}{T_H} = \frac{Q_L}{T_L}$

$\therefore \frac{Q_L}{Q_H} = \frac{T_L}{T_H}$ —— ④

From ③ & ④, $\eta_{carnot} = 1 - \frac{T_L}{T_H}$

For an irreversible heat engine, Q_L ↑ due to losses, so, η ↓

& $\eta_{irre} < 1 - \frac{T_L}{T_H}$

In General, $\eta \leq 1 - \frac{T_L}{T_H}$

Heat Pump:

- device operating on a cyclic process which takes heat from low temp sink (T_L) & delivers to high temp source (T_H)

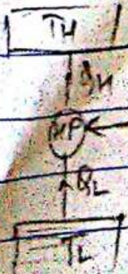


Fig: Schematic Representation of heat pump with help of external work

- helps to maintain temp of desired space higher than that of surroundings

~~its~~ Performance measured in terms of coefficient of performance (COP)

$$COP = \frac{\text{Desired Effect}}{\text{Net Work input}}$$

- in heat pump, desired effect → amt. of heat supplied to desired space (Q_H)

$$(COP)_{HP} = \frac{Q_H}{W} \quad — ①$$

Applying 1st law, $\oint \delta Q = \oint \delta W$

$$\therefore -Q_H + Q_L = -W \quad \text{(cor by ext. work)}$$

$$\therefore W = Q_H - Q_L \quad — ②$$

From ① & ②, $(COP)_{HP} = \dfrac{Q_H}{Q_H - Q_L} = \dfrac{1}{1 - Q_L/Q_H}$

Applying 2nd law, $\oint dS_{cm} (=0) \geq \oint \sum \left(\dfrac{\delta Q_i}{T_i}\right)_{cM}$

$$\therefore 0 \geqslant -\frac{Q_H}{T_H} + \frac{Q_L}{T_H}$$

for reversible heat pump, $\dfrac{Q_H}{T_H} = \dfrac{Q_L}{T_L} \Rightarrow \dfrac{Q_L}{Q_H} = \dfrac{T_L}{T_H}$

$$(COP)_{rev} = \frac{1}{1 - T_L/T_H} = \frac{T_H}{T_H - T_L}$$

For irreversible heat pump, COP ↓.

$$(COP)_{irre, HP} < \frac{1}{1 - T_L/T_H}$$

In General, $(COP) \leq \dfrac{T_H}{T_H - T_L}$

Refrigenerator

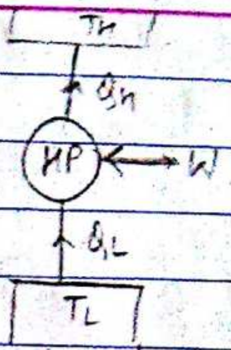


Fig: Schematic Representation of Refrigenerator

- device operating on a cyclic process which takes heat from low temp. reservoir (T_L)-/desired space) & delivers to high temp. (T_H) surrounding
- maintains temp of desired space lower than that of surrounding.

- its performance measured by COP

i.e. $(COP)_R = \frac{Q_L}{W}$

Wrt heat pump, $COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$

In terms of temp. ratio, $(COP)_R = \frac{1}{T_H/T_L - 1} = \frac{T_L}{T_H - T_L}$

$\therefore (COP)_{irre.\,R} < \frac{T_L}{T_H - T_L}$.

General. $(COP)_R \leq \frac{T_L}{T_H - T_L}$

$(COP)_{HP} - (COP)_R = 1$

Clausius inequality:

$\oint \left(\frac{\delta Q}{T}\right) \leq 0$: Clausius inequality

$\oint \left(\frac{\delta Q}{T}\right) < 0$, irreversible cycle

$\oint \left(\frac{\delta Q}{T}\right) = 0$, reversible cycle

$\oint \left(\frac{\delta Q}{T}\right) > 0$, impossible cycle

THERMODYNAMIC CYCLES

· devices which are used for continuous energy conversion operate on cyclic processes

Classification

1) Acc to Power (Work)

Power cycle : produces power or delivers work to surr. on executing cycle

eg: Brayton cycle, Otto cycle, Diesel cycle, Rankine cycle

Refrigeneration cycle : power is supplied to it to execute cycle

eg Vapor compression refrigeneration cycle

2) Acc to Working Substance

Gas cycle : working subs. is in gaseous state throughout the cycle

eg: Brayton cycle, Otto cycle, Diesel Cycle

Vapor cycle : working subs. can undergo phase change (from liquid to vapor & vice versa) throughout the cycle

eg Rankine cycle

3) Acc to Combustion location (only applicable for power cycle)

IC cycle : eg Otto cycle, Diesel cycle

EC cycle eg: Brayton cycle Rankine cycle

	Ideal cycle	Gas cycles			Vapor cycle
Processes/Cycle	Carnot	Otto	Diesel	Brayton	Rankine
Compression	Isentropic	Isentropic	Isentropic	Isentropic	Isentropic
Heat addition	Isothermal	Isochoric	Isobaric	Isobaric	Isobaric
Expansion	Isentropic	Isentropic	Isentropic	Isentropic	Isentropic
Heat rejection	Isothermal	Isochoric	Isochoric	Isobaric	Isobaric

Air Standard IC Cycles

- are idealised models for the operation of petrol & diesel engines

Operation of Four Stroke Engines

$\text{Piston} \xrightarrow[\text{rod}]{\text{connecting}} \text{crank} \xrightarrow[\text{power transmission unit}]{\text{flywheel}} \text{wheel}$

On moving ~~piston~~ betn TDC & BDC, crank rotates in a circular slot thereby driving the wheel of vehicle

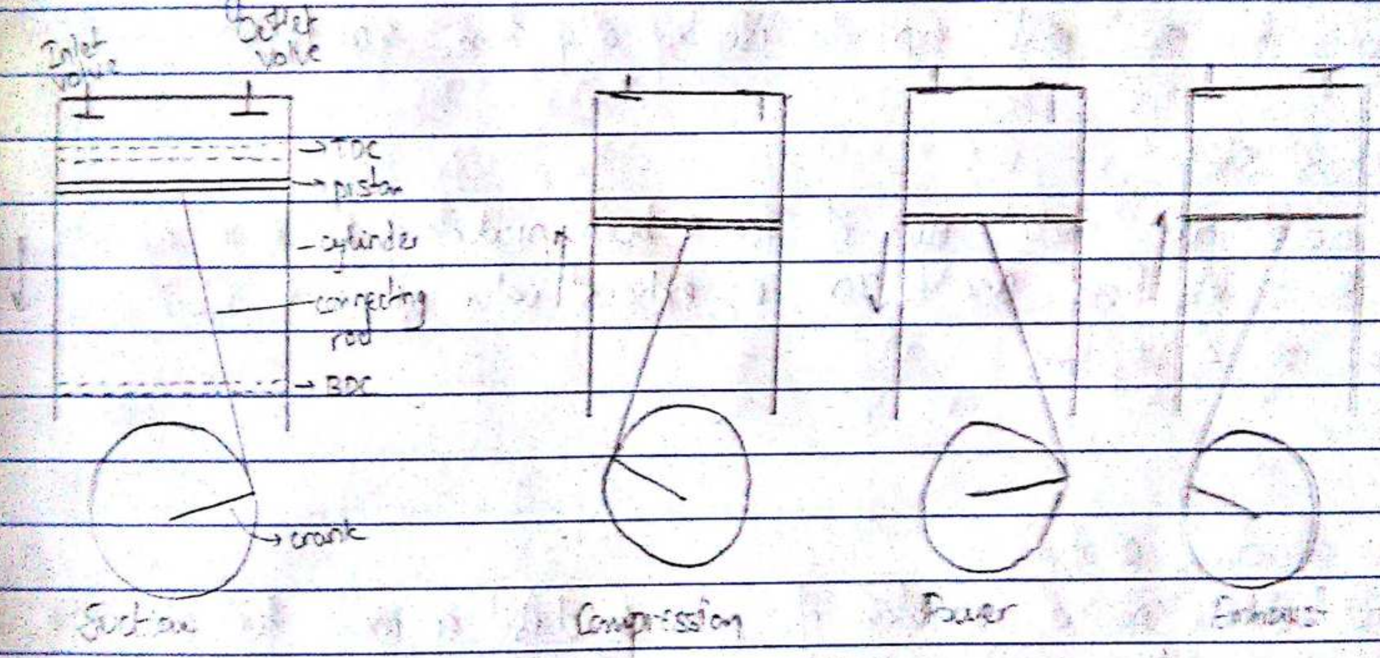


Fig: operation of 4 Stroke Engine

For Petrol engine fuel is ignited by spark produced by spark plug (spark ignition engine)
Diesel engine self-burning of fuel due to high temp. of air (compression ignition engine)

Suction Stroke : piston travels ~~of~~ fm TDC to BDC, inlet valve opens
petrol engine : mix. of air & petrol enters
diesel engine : air only enters

Compression Stroke : piston travels from BDC to TDC, inlet valve is closed fuel inside cylinder is compressed isentropically due to which temp & pressure inside increases

Power (expansion) stroke :

petrol engine : spark plug produces electric spark & fuel is burned
diesel engine : fuel is injected by injector & diesel gets self-burned as the temp. of air is greater than the self-ignition temp. of diesel

Due to burning, piston expands isentropically from TDC to BDC

Exhaust stroke :

At end of power stroke, mix. of fuel & burnt products of fuel is in cylinder piston travels from BDC to TDC e, exhaust valve opens & burnt products flow out of system

Air standard analysis :

Since during normal operation of petrol & diesel engines, fuel-air ratio is very small (0.08 – 0.25), therefore properties of fuel-air mixture before combustion is nearly same to that of air.

So, simplified analysis is done by considering only air as working substance
Thus, the idealized analysis of the cycle considering only air as working substance is da air standard analysis.
efficiency from such analysis – air standard efficiency

Assumptions :

1) the cycle consists of fixed mass of air
2) expansion & compression process are isentropic

3) combustion process is replaced by an eqvt. heat addition process from an external source

4) exhaust process is replaced by an eqvt heat rejection process ~~from~~ to an external sink

5) Properties of air (c_p, c_v, R) remain constant

Air Standard Otto Cycle

- Is an idealised model for the operation of petrol engines
- has 2 isentropic & 2 isochoric process

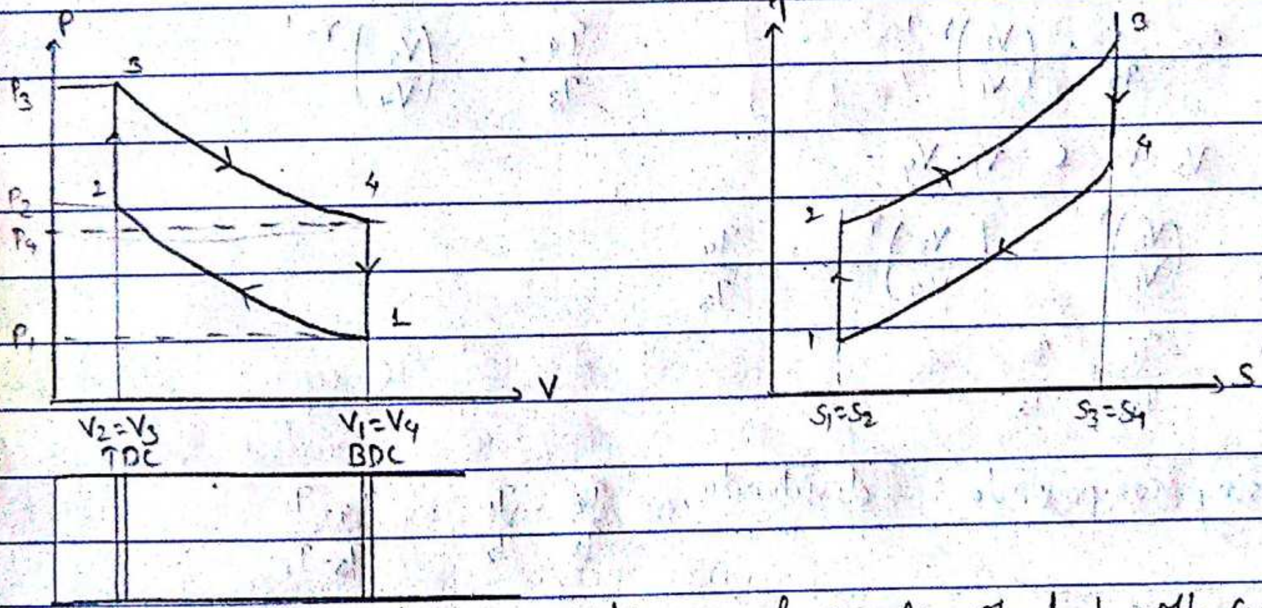


Fig: P-V & T-S diagrams for an Air Standard Otto Cycle

Process 1-2 : Isentropic Compression
Process 2-3 : Isochoric heat addition
Process 3-4 : Isentropic Expansion
Process 4-1 : Isochoric heat rejection

Efficiency of an Air Standard Otto cycle

efficiency of an IC cycle is given by

$\eta = 1 - \frac{q_L}{q_H}$, q_L : heat rejected per kg of air per cycle
q_H : heat added per kg of air per cycle

Now, $q_L = c_v(T_4 - T_1)$: process 4-1
$q_H = c_v(T_3 - T_2)$: process 2-3

$$\therefore \eta = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)}$$

$$= 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

Process 1-2, $P_1V_1^{\gamma} = P_2V_2^{\gamma}$
$\therefore T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1}$
$\therefore \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$

Process 3-4
$T_3V_3^{\gamma-1} = T_4V_4^{\gamma-1}$
$\therefore \frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1}$

Also, $V_2 = V_3$ & $V_1 = V_4$

$$\therefore \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \frac{T_4}{T_3}$$

$$\Rightarrow \frac{T_1}{T_2} = \frac{T_4}{T_3}$$

By using componendo & dividendo, $\frac{T_4}{T_3} = \frac{T_1}{T_2} = \frac{T_4 - T_1}{T_3 - T_1}$

$$\boxed{\therefore \eta = 1 - \frac{T_4}{T_3} = 1 - \frac{T_1}{T_2}}$$

$\therefore \eta = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma-1} = 1 - \left(\frac{1}{r}\right)^{\gamma-1}$, where $r = \frac{V_1}{V_2}$ = compression ratio

$\boxed{\eta = 1 - \frac{1}{r^{\gamma-1}}}$; $r\,(8-12)$

For compression ratio, $r = \frac{V_1}{V_2} = \frac{V_c + V_s}{V_c} = 1 + \frac{V_s}{V_c} = 1 + \frac{\pi D_p^2 \cdot L_s}{4 \cdot V_c}$

Air standard Diesel Cycle

- Is idealised model for diesel engine
- Cosists of 2 isentropic process, 1 isobaric & 1 isochoric process.

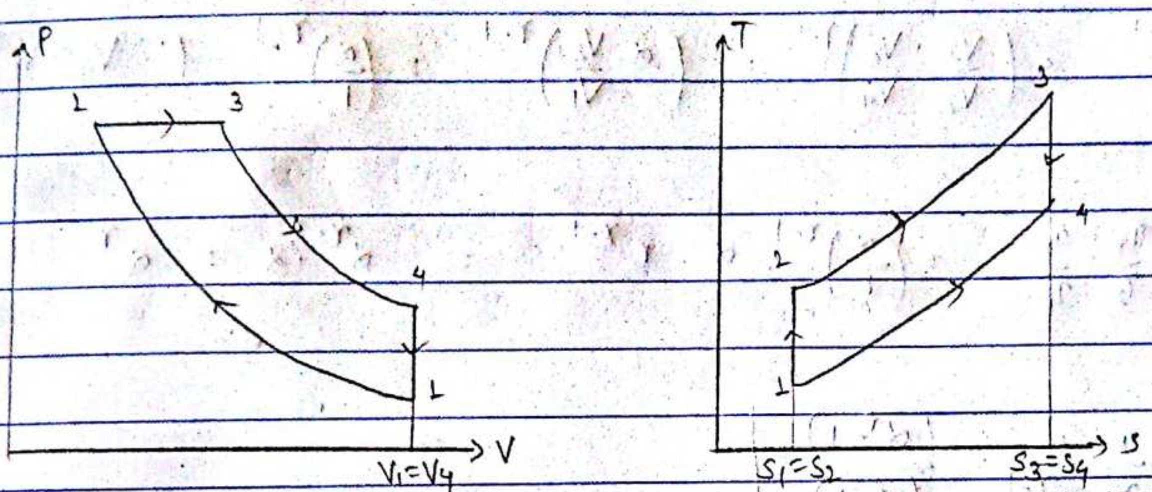


Fig : P-V & T-s diagram for Air standard Diesel cycle

Process 1-2 : Isentropic Compression
Process 2-3 : Isobaric heat addition
Process 3-4 : Isentropic expansion
Process 4-1 : Isochoric heat rejection

Efficiency of an air standard Diesel Cycle

$$\eta = 1 - \frac{q_L}{q_H} \quad \begin{matrix} \rightarrow \text{Process } 4\text{-}1 \\ \rightarrow \text{Process } 2\text{-}3 \end{matrix}$$

$q_L = c_v(T_4 - T_1)$

$q_H = c_p(T_3 - T_2)$

$$\therefore \eta = 1 - \frac{c_v(T_4 - T_1)}{c_p(T_3 - T_2)}$$

$$\text{or } \eta = 1 - \frac{1}{\gamma}\frac{T_1}{T_2}\left(\frac{T_4/T_1 - 1}{T_3/T_2 - 1}\right)$$

Process 1-2 , process 3-4.

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = r^{\gamma-1}$$

Process 2-3

$$\frac{V_2}{T_2} = \frac{V_3}{T_3} \Rightarrow \frac{T_3}{T_2} = \frac{V_3}{V_2} = \alpha \text{ (cut off ratio)}$$

Process 3-4

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{V_3}{V_2}\cdot\frac{V_2}{V_4}\right)^{\gamma-1} = \left(\alpha\cdot\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{\alpha}{r}\right)^{\gamma-1} \quad (\because V_4 = V_1)$$

$$\therefore \frac{T_4}{T_1} = \frac{T_4}{T_3}\cdot\frac{T_3}{T_2}\cdot\frac{T_2}{T_1} = \left(\frac{\alpha}{\cancel{r}}\right)^{\gamma-1}\cdot\alpha\cdot\cancel{r^{\gamma-1}} = \alpha^{\gamma-1}\cdot\alpha = \alpha^{\gamma}$$

$$\boxed{\therefore \eta = 1 - \frac{1}{\gamma}\,\frac{1}{r^{\gamma-1}}\cdot\frac{(\alpha^{\gamma}-1)}{(\alpha-1)}}$$

Mean effective pressure :

- parameter used for the comparison of different IC cycles
- is defined as magnitude of pressure required to produce the same output work as that produced by actual pressure varying cycle.

$$W = P_{MGP}\,(V_{stroke}) = P_{MEP}(V_1 - V_2)$$

$$\therefore P_{MEP} = \frac{W}{V_1 - V_2} = \frac{w}{v_1 - v_2}$$