# THERODYNAMICS

# (R17A0368)

## COURSE FILE

## II B. Tech I Semester

## (2018-2019)

**Prepared By**

**Mr. I RAMAKRISHNUDU** Assoc. Prof

## Department of Aeronautical Engineering

## MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

## (Autonomous Institution – UGC, Govt. of India)

Affiliated to JNTU, Hyderabad, Approved by AICTE - Accredited by NBA & NAAC – ‘A’ Grade - ISO 9001:2015 Certified)
Maisammaguda, Dhulapally (Post Via. Kompally), Secunderabad – 500100, Telangana State, India.

# MRCET VISION

- To become a model institution in the fields of Engineering, Technology and Management.
- To have a perfect synchronization of the ideologies of MRCET with challenging demands of International Pioneering Organizations.

# MRCET MISSION

To establish a pedestal for the integral innovation, team spirit, originality and competence in the students, expose them to face the global challenges and become pioneers of Indian vision of modern society.

# MRCET QUALITY POLICY.

- To pursue continual improvement of teaching learning process of Undergraduate and Post Graduate programs in Engineering & Management vigorously.
- To provide state of art infrastructure and expertise to impart the quality education.

# PROGRAM OUTCOMES
## (PO's)

**Engineering Graduates will be able to:**

1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design / development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
8. **Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
9. **Individual and team work**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multi disciplinary environments.
12. **Life- long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

# DEPARTMENT OF AERONAUTICAL ENGINEERING

## VISION

Department of Aeronautical Engineering aims to be indispensable source in Aeronautical Engineering which has a zeal to provide the value driven platform for the students to acquire knowledge and empower themselves to shoulder higher responsibility in building a strong nation.

## MISSION

The primary mission of the department is to promote engineering education and research. To strive consistently to provide quality education, keeping in pace with time and technology. Department passions to integrate the intellectual, spiritual, ethical and social development of the students for shaping them into dynamic engineers.

## QUALITY POLICY STATEMENT

Impart up-to-date knowledge to the students in Aeronautical area to make them quality engineers. Make the students experience the applications on quality equipment and tools. Provide systems, resources and training opportunities to achieve continuous improvement. Maintain global standards in education, training and services.

# PROGRAM EDUCATIONAL OBJECTIVES – Aeronautical Engineering

1. **PEO1 (PROFESSIONALISM & CITIZENSHIP):** To create and sustain a community of learning in which students acquire knowledge and learn to apply it professionally with due consideration for ethical, ecological and economic issues.
2. **PEO2 (TECHNICAL ACCOMPLISHMENTS):** To provide knowledge based services to satisfy the needs of society and the industry by providing hands on experience in various technologies in core field.
3. **PEO3 (INVENTION, INNOVATION AND CREATIVITY):** To make the students to design, experiment, analyze, and interpret in the core field with the help of other multi disciplinary concepts wherever applicable.
4. **PEO4 (PROFESSIONAL DEVELOPMENT):** To educate the students to disseminate research findings with good soft skills and become a successful entrepreneur.
5. **PEO5 (HUMAN RESOURCE DEVELOPMENT):** To graduate the students in building national capabilities in technology, education and research

# PROGRAM SPECIFIC OUTCOMES – Aeronautical Engineering

1. To mould students to become a professional with all necessary skills, personality and sound knowledge in basic and advance technological areas.
2. To promote understanding of concepts and develop ability in design manufacture and maintenance of aircraft, aerospace vehicles and associated equipment and develop application capability of the concepts sciences to engineering design and processes.
3. Understanding the current scenario in the field of aeronautics and acquire ability to apply knowledge of engineering, science and mathematics to design and conduct experiments in the field of Aeronautical Engineering.
4. To develop leadership skills in our students necessary to shape the social, intellectual, business and technical worlds.

# MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

**II Year B. Tech, ANE-I Sem**

| L | T/P/D | C |
|---|---|---|
| 5 | 1/-/- | 4 |

## (R17A0364) THERMODYNAMICS

**Objectives:**

- Learn about concepts and laws used in thermodynamics.
- Students acquire knowledge of various cycles.
- Students gain information about the working principle of different engines.

**UNIT - I**

**Introduction: Basic Concepts:** System, Control Volume, Surrounding, Boundaries, Universe, Types of Systems, Macroscopic and Microscopic view points, Concepts of Continuum, Thermodynamic Equilibrium, State, Property, Process, Exact & Inexact Differentials, Cycle - Reversibility - Quasi - static Process, Irreversible Process, Causes of Irreversibility - Energy in State and in Transition, Types, Displacement & Other forms of Work, Heat, Point and Path functions, Zeroth Law of Thermodynamics - Concept of Temperature - Principles of Thermometry - Reference Points - Const. Volume gas Thermometer - Scales of Temperature, Ideal Gas Scale - Joule's Experiments - First law of Thermodynamics – applied to a process and system, Corollaries , Steady Flow Energy Equation.

**UNIT - II**

Limitations of the First Law - Thermal Reservoir, Heat Engine, Heat pump, Parameters of performance, Second Law of Thermodynamics, Kelvin-Planck and Clausius Statements and their Equivalence / Corollaries, PMM of Second kind, Carnot's principle, Carnot cycle and its specialties, Thermodynamic scale of Temperature, Clausius Inequality, Entropy, Principle of Entropy Increase - Energy Equation, Availability and Irreversibility - Thermodynamic Potentials, Gibbs and Helmholtz Functions, Maxwell Relations - Elementary Treatment of the Third Law of Thermodynamics.

**UNIT - III**

Perfect Gas Laws - Equation of State, specific and Universal Gas constants - various Non-flow processes, properties, end states, Heat and Work Transfer, changes in Internal Energy - Throttling and Free Expansion Processes - Flow processes. Perfect Gas Model, derivations - Vader Waals Equation of State - Compressibility charts - variable specific Heats - Gas Tables - Phase Transformations - Triple point at critical state properties during change of phase, Dryness Fraction - Clausius - Clapeyron Equation Property tables. Mollier charts - Various Thermodynamic processes and energy Transfer - Steam Calorimetry.

**UNIT - IV**

Mixtures of perfect Gases - Mole Fraction, Mass friction Gravimetric and volumetric Analysis - Dalton's law of partial pressure, Avogadro's Laws of additive volumes - Mole fraction, Volume fraction and partial pressure, Equivalent Gas const. and Molecular Internal Energy. Enthalpy, specific heats. Heats and Entropy of Mixture of perfect Gases and Vapour, Atmospheric air - Psychrometric Properties and Psychrometric chart.

**UNIT - V**

**Thermodynamic Cycles:** Power cycles: Otto, Diesel, Dual Combustion cycles, Sterling Cycle, Atkinson Cycle, Lenoir Cycle - Description and representation on P-V and T-S diagram, Thermal Efficiency, Mean

Effective Pressures on Air standard basis - comparison of Cycles. Application of Brayton cycles in aviation.
**Refrigeration Cycles:** Bell-Coleman cycle - Vapour compression cycle performance Evaluation.

**Text Books:**

1. Engineering Thermodynamics / PK Nag / TMH, 5th Edition
2. Engineering Thermodynamics / E Rathakrishnan / PHI / Second Edition / 2013

**Reference Books:**

1. Engineering Thermodynamics / DP Mishra / Cengage Learning / Second impression 2012
2. Thermodynamics - An Engineering Approach - Yunus Cengel & Boles / TMH
3. Thermodynamics - J.P. Holman / McGrawHill
4. Engineering thermodynamics - Jones & Dugan
5. Engineering Thermodynamics / P. Chattopadhyay / Oxford higher Education / Revised First Edition
6. Thermodynamics & Heat Engines - Yadav - Central Book Dept. Allahabad

**Outcomes:**

- Basic concepts can be applied by the students
- Students can correlate cycles applicable for engines.
- Students should be able to analyze the relationship between various processes and working mechanisms of the engines.

Unit - I - Extended.

## Zeroth Law of Thermodynamics

The property which distinguishes thermodynamics from other sciences is temperatuse

### Zeroth law of Thermodynamics: (2.1.1)

When a body A is in thermal equilibrium with a body B. and also seporately with a body C, then B and C will be ~~an~~ in thermal equilibrium with each other. It is the basis of temperature measurement.

### Concept of quality of Temperature: (2.1.2)

Temperature is the sense of hotness or coldness of an object when touched it when touched it when hot body and cold body are brought into contact the hot body becomes cooler and cold body becomes warmer.

∴ Two bodies have equality of temperature if, when they are in thermal communication, no change in any observable property occurs.

## Principles of Thermometry (2.1.3)

Thermometry is defined as the art or device of measuring temperature with scientific precision.

In order to obtain a quantitative measure of temp, a reference body is used and a certain physical characteristic of this body which changes with temp is selected. The change in the selected characteristic may be taken as an indication of change in temperature. The selected characteristic is called thermometric property, and the reference body which is used in the determination of temp is called thermometer.

A very common thermometer consists of a small amount of mercury in an evacuated capillary tube.

* A physical characteristic of an arbitrarily chosen body which changes with change in temp is called thermometric property $(x)$ and the reference body is called thermometer.

## Reference Points: (2·1·4)

The temperature of a system is a property that determines whether (or) not a system in a thermal equilibrium with other systems.

If $X$ is the thermometric property, let us arbitrarily choose for the temperature common to the thermometer and to all systems in the thermal equilibrium with it the following linear function of $X$.

Thermometers and Thermometric Properties

| | T. Property | Symbol |
|---|---|---|
| * Constant volume gas thermometer | Pressure | → $P$ |
| * Constant pressure gas thermometer | Volume | → $V$ |
| * Electrical resistance thermometer | Resistance | → $R$ |
| * Thermocouple | Thermal Emf | → $\mathcal{E}$ |
| * Mercury-in-glass thermometer | Length | → $L$ |

$\theta(X) = a(X)$, where $a$ is an arbitrary constant.

if $X_1$ corresponds to $\theta(X_1)$, then $X_2$ will correspond to

$$\frac{\theta(X_1)}{X_1} \cdot X_2 \qquad \theta(X_2) = \frac{\theta(X_1)}{X_1} \cdot X_2$$

Two temp on the linear $X$ scale are to each other as the ratio of the corresponding $X$'s.

16/7

Since 1954 only one fixed point has been in use viz. the triple point of water, the state at which ice, liquid water and water vapour coexist in equilibrium. The temperature at which this state exists is arbitrarily assigned the value of 273·16 degrees kelvin, (or) 273·16K.

Designating the triple point of water by $\theta_t$, and with $X_t$, being the value of the thermometric property when the body, whose temperature $\theta$ is to be measured, is placed in contact with water at its triple point.

$$\theta_t = a X_t$$

$$a = \frac{\theta_t}{X_t} = \frac{273 \cdot 16}{X_t}$$

$$\theta = aX = \frac{273 \cdot 16}{X_t} \cdot X$$

$$\theta = 273 \cdot 16 \frac{X}{X_t}$$

The temperature of the triple point of water, which is an easily reproducible state, is now the standard fixed point of thermometry.

Smallest variation is observed among different gas thermometers. That is why a gas is choosen as the standard thermometric system.

## Constant volume gas thermometer: (2·2)

Let us suppose that the bulb of a constant volume gas thermometer contains an amount of gas such that when the bulb is surrounded by water at its triple point, the pressure $P_t$ is 1000 mmHg. Keeping the volume V constant, let the following procedure be conducted

(a) Surround the bulb with steam condensing at 1 atm, determine the gas pressure P and calculate

$$\theta = 273.16 \frac{P}{1000}$$

(b) Remove some gas from the bulb so that when it surrounded by water at its triple point, the pressure $P_t$ is 500 mmHg. Determine the new value of P and then $\theta$ for steam condensing at 1 atm

$$\theta = 273.16 \frac{P}{500}$$

(c) Continue reducing the amount of gas in the bulb so that $P_t$ and have smaller and smaller values.

(d) Plot $\theta$ vs $P_t$ and extrapolate the curve to the axis where $P_t = 0$

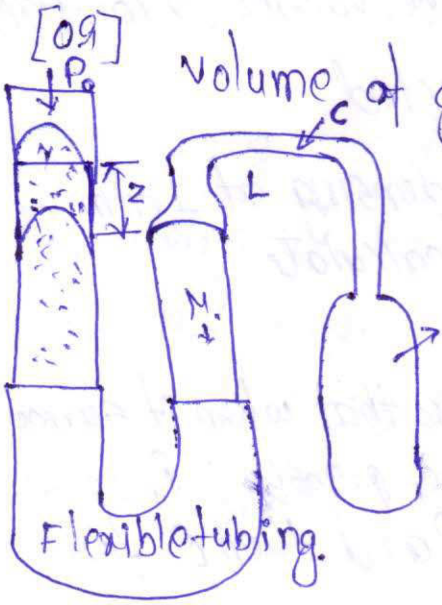
Read from graph $\lim\limits_{P_t \to 0} \theta$

The readings of a constant volume gas thermometer depend upon the nature of gas, all gases indicate the same temp as $P_t$ is lowered and made to approach zero.

The corresponding value of $\theta$ may be calculated from θ Vs P may be plotted. It is found from the experiments that all gases indicate the same value of θ as p approaches zero.

$$\boxed{T = 273.16 \lim \frac{P}{P_t} \qquad P_t \to 0}$$

[OR]

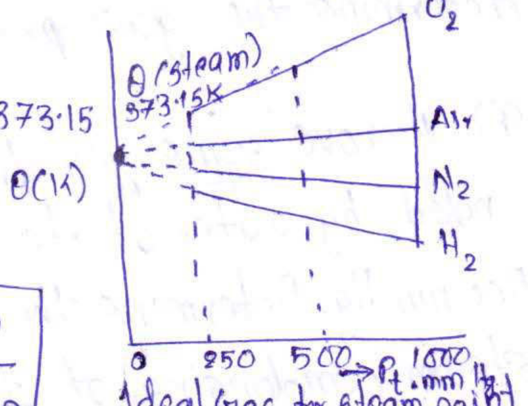


volume of gas is constant = $\lim_{P \to 0} \frac{P}{P_{tp}}$

$$\therefore \frac{T}{T_{tp}} = \frac{P}{P_{tp}}$$

$$T = T_{tp} \cdot \frac{P}{P_{tp}}$$

$$\boxed{T = 273.16 \frac{P}{P_{tp}}}$$



Ideal Gas for steam point

Unknown temperature can be found from above relation by using constant volume gas thermometer.

Scales of Temperature: (2·2·1)

Fahrenheit Scale has 180 units b/w these reference points.

Celsius scale has 100 units.

Zero points on scales are arbitrary

- → The absolute Fahrenheit scale is called Rankine scale
- → The absolute celsius scale is termed as Kelvin scale.
- → The zero points on both absolute scales shows same physical state

$$\left(\frac{T_2}{T_1}\right)_{Rankine} = \left(\frac{T_2}{T_1}\right)_{kelvin}$$

Relations between scales of Temp

$$\frac{°c}{100} = \frac{°F - 32}{180}$$

$$°R = °F + 459.67$$

$$K = °C + 273.16$$

$$°R = 9/5\ K.$$

Ideal Gas (2·2·2)

From experimental observations that the $p-v-T$ behaviour of gases at low pressure is closely given by the following relation

$$P\bar{v} = \bar{R}T$$

$\bar{R}$ is universal gas constant 8.3143 J/mol K and $\bar{v}$ is the molar specific volume, $m^3/gmol$. Div by molecular weight $\mu$,

$$Pv = RT$$

$v \rightarrow$ Specific volume in $m^3/kg$ $\rightarrow$ $R$ is characteristic gas constant

Substituting $R = \bar{R}/\mu$ J/kg.K we get in terms of gas the total volume of V of a gas

$$PV = n\bar{R}T$$

$$PV = mRT$$

n is the number of moles and m is the mass of the gas.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

The above equation is called ideal gas equation of state. At very low pressure or density, all gases and vapours approach ideal gas behaviour.

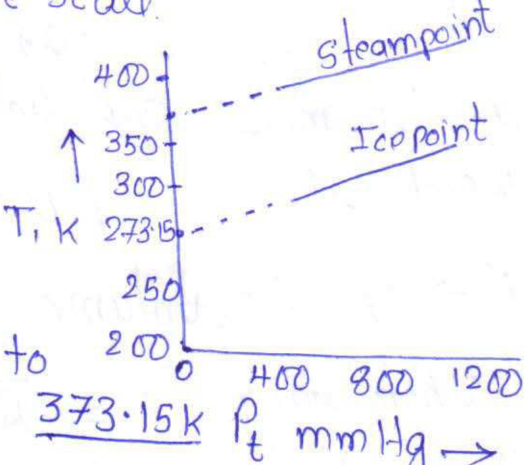
The temp can be measured (or) compared.

## Ideal Gas Scale: (2·3)

where $\theta$ is replaced by T to denote this particular temperature scale, the ideal gas temperature scale.

If $P_s$ & $P_t$ are the measured pressures at the steam point and the Triple point respectively, one gets the value of steam point temp $T_s$

$T_s = 273.16 \lim_{P_t \to 0} P_s/P_t$ which is equal to 373·15 K



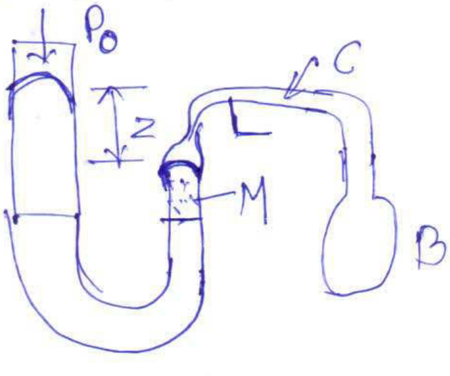
Temperature $T_i$ at the ice point

$T_i = 273.16 \lim_{P_t \to 0} \frac{P_i}{P_t}$ which is equal to 273·15 K

# nst Vol Gas Thermometers (2·3·1)

(23) D: 04

① A small amount of gas is enclosed in Bulb B which is in equilibrium via the capillary tube C with one limb of the mercury manometer M. The other limb of the mercury manometer is open to the atmosphere and can be moved vertically to adjust the mercury levels so that the mercury touches lip L of the capillary. The pressure in the bulb is used as the thermometric property



$$P = P_0 + \rho_m Z g.$$

$P_0 \rightarrow$ Atm pressure

$\rho_m \rightarrow$ density of mercury

The diff in mercury level Z is recorded and the pressure P of the gas in the bulb estimated.

The gas in the bulb expands on being heated. pushing the mercury downward. The flexible limb of the manometer is then adjusted so that the mercury again touches the lip 'L'.

Since volume is const from ideal gas equation

$\Delta T = \frac{V}{R} \Delta P$ Temp increases is proportional to the pressure increase.

---

In constant pressure gas thermometer, mercy level to be adj to keep Z constant and volume of gas V, which would vary with temp. becomes thermometric property.

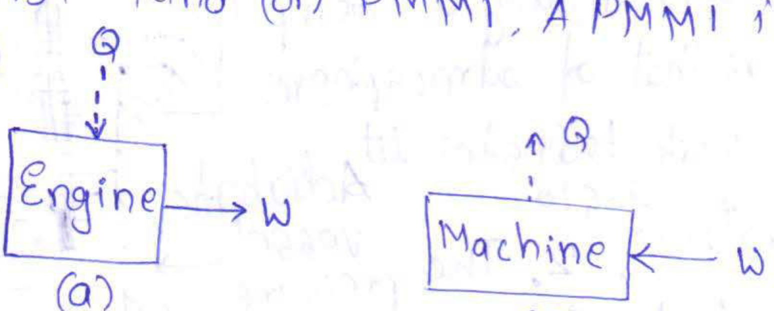
$\Delta T = \frac{P}{R} \Delta V$ Temp increases is proportional to the observed in volume increase

PMM I

## Perpetual Motion Machine of the First kind: (2.4)

The first law states that, energy is neither created nor destroyed, but only gets transformed from one form to another.

There can be no machine which would continuosly supply mechanical work without some other form of energy disappearing simultaneously. Such a fictious machine is called a perpetual motion machine of the first kind (or) PMM1. A PMM1 is thus impossible (a)



(a) (b)

Fig (6). A PMM1 The converse of PMM1

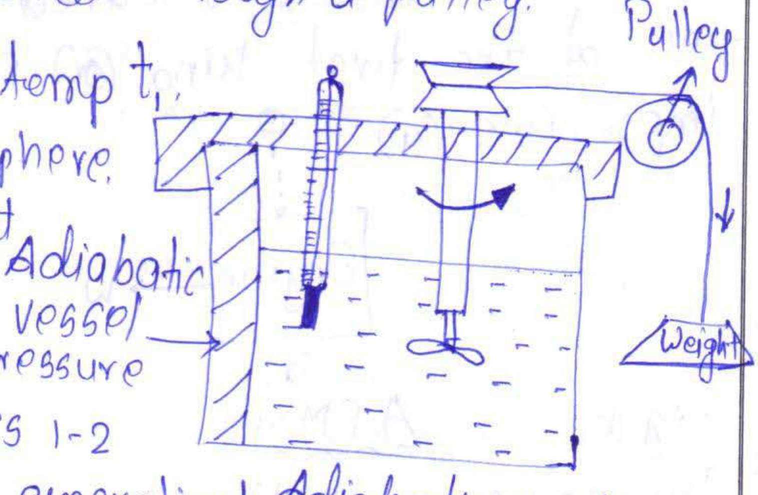
The converse of the above statement is also true i.e. there can be no machine which would continuosly consume work without some other form of energy appearing simultaneously.

## Joule's Experiment: (2·4·1)

First law for a closed system undergoing a cycle.
The transfer of heat and the performance of work may both cause the same effect in a system. Heat and work are different forms of the same entity, called energy, which is conserved. Energy which enters a system as heat may leave the system as work, energy which enters the system as work may leave as heat.

Let us consider a closed system which consists of a known mass of water contained in an adiabatic vessel having a thermometer and a paddle wheel. Let a certain amount of work $W_{1-2}$ be done upon the system by the paddle wheel. The quantity of work can be measured by the fall of weight which drives the paddle wheel through a pulley.

The system was intially at temp $t_1$, the same as that of atmosphere and after work transfer let the temperature rise to $t_2$. The pressure is always 1 atm. The process 1-2 undergone by the system generalized **Adiabatic work.** thermodynamic co-ordinates x, y.

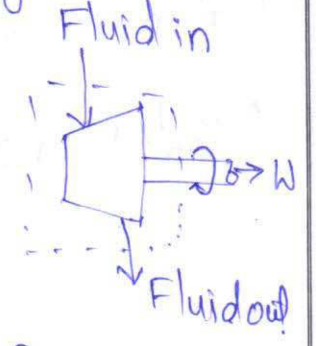


# Applications of steady flow Energy Equation: (2·7·5)

## Turbine:

A turbine is a device in which heat energy is converted into mechanical work.

In a turbine Q=0 Since it is insulated.



Apply steady flow energy equation

$$m\left(\frac{V_1^2}{2}+gz_1+h_1\right)+Q = m\left(\frac{V_2^2}{2}+gz_2+h_2\right)+W$$

Neglect K·E & P·E

$$m(0+0+h_1)+0 = m(0+0+h_2)+W$$

$$\therefore mh_1 = mh_2+W$$

$$W = m(h_1-h_2) = H_1-H_2.$$

## Compressor:

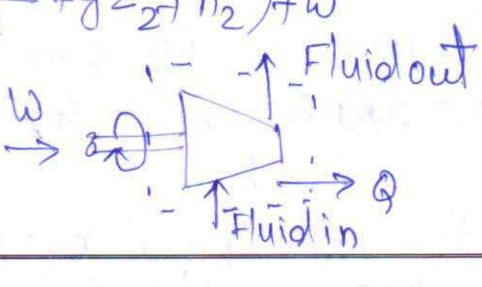
A compressor is a device in which work is done on the system

Apply steady flow energy equation

$$m\left(\frac{V_1^2}{2}+gz_1+h_1\right)+Q = m\left(\frac{V_2^2}{2}+gz_2+h_2\right)+W$$

Neg P·E & K·E.

$$W = Q+m(h_2-h_1).$$

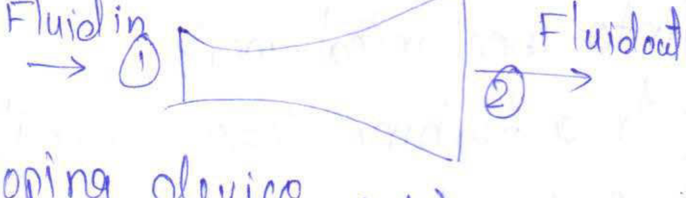


## Nozzle

A nozzle is a device which increases K.E of fluid

Q=0

Datum is same



Nozzle is not a work developing device ∴ W=0.

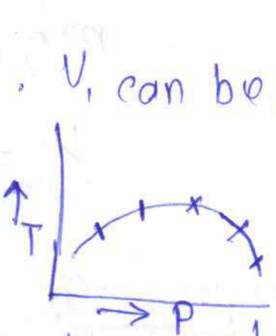
$$\therefore h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

$$\frac{V_2^2}{2} = (h_1 - h_2) + \frac{V_1^2}{2}$$

$$V_2 = \sqrt{2(h_1 - h_2) + V_1^2}$$

When $V_1$ is small compared to $V_2$. $V_1$ can be neg

$$\therefore V_2 = \sqrt{2(h_1 - h_2)}.$$



## Throttling Process:

It happens when a fluid flows through a restricted passage like porous, plug and there is apreciable decrease in pressure.

Q=0, Fluid expands without doing any work W=0

changes in PE are very small neglected

No appreciable K.E in increase K.E=0.

$$h_1 = h_2$$

$$\boxed{\mu = \left(\frac{\partial T}{\partial p}\right)_h}$$

In this enthalpy at entrance is equal to exit

The slope of const enthalpy line is called Joule thomson coefficient

Let the insulation now be removed. The system and the surroundings interact by heat transfer till the system returns to the original temperature $t_1$, attaining the condition of thermal equilibrium with the atmosphere. The amount of heat transfer $Q_{2-1}$ from the system during this process 2-1.

The system thus executes a cycle, which consists of definite amount of work input $W_{1-2}$ to the system followed by the transfer of an amount of heat $Q_{2-1}$ from the system. It has been found that this $W_{1-2}$ is always proportional to the heat $Q_{2-1}$, and the constant of proportionality is called the Joule's equivalent of heat.

If the cycle involves many more heat and work quantites, the same result will be found.

$$(\Sigma W)_{cycle} = J\,(\Sigma Q)_{cycle} \quad J \rightarrow \text{Joule's equivalent.}$$

$$\oint dW = J \oint dQ \qquad (J = 1\,Nm/J)$$

$\oint$ denotes the cyclic integral for the closed path.

## First Law of Thermodynamics: (2.6)

when a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to network done by the system on its surroundings $\oint dQ = \oint dW$ $\oint$ represents the sum for a complete cycle.

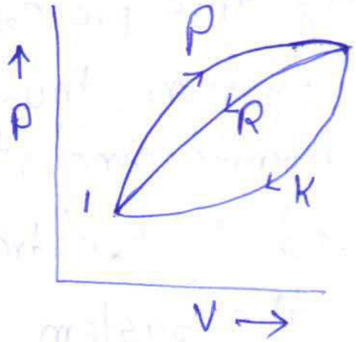
15 (29)

## Corollaries of first law of Thermodynamics: (2·6·1)

*** Heat is a path function: (Newly added)**

Suppose a system changes from state 1 to state 2 by following the path 1-P-2 and restored to state 1 by the path 2-R-1. Then system is said to be undergone a cyclic

∴ For path 1-P-2-R-1 apply 1st law



$$\oint_{1P2R1} dQ = \oint_{1P2R1} dW$$

$$\int_{1P2} dQ + \int_{2R1} dQ = \int_{1P2} dW + \int_{2R1} dW \quad — ①$$

Suppose the system returns from state 2 to state 1 by path 2-K-1. By applying 1st law 1-P-2-K-1.

$$\oint_{1P2K1} dQ = \oint_{1P2K1} dW$$

$$\int_{1P2} dQ + \int_{2K1} dQ = \int_{1P2} dW + \int_{2K1} dW \quad — ②$$

Substracting ① - ②

$$\int_{2R1} dQ - \int_{2K1} dQ = \int_{2R1} dW - \int_{2K1} dW \quad — ③$$

∴ Work depends on path

$$\int_{2R1} dW - \int_{2K1} dW \neq 0 \quad — ④$$

Non - Flow Energy Equation

$$\therefore \int_{2R1} dQ - \int_{2K1} dQ \neq 0 \quad — ⑤$$

$$\therefore \int_{2R1} dQ \neq \int_{2K1} dQ \quad — ⑥$$ Heat is not a property of system

∴ Heat is a path function.

## Energy is a property of System: (2·6·2)

The changes in energy between two states of a system when undergone a process (or) cycle can be evaluated by above mentioned equation ③

$$\int_{2R1} (dQ - dW) = \int_{2K1} (dQ - dW)$$

This equation shows that irrespective of a process $\int (dQ - dW)$ is same.

$\therefore \int (dQ - dW)$ does not depends on path followed by the system but depends on first and final states of system

$\therefore dQ - dW$ is exact differential

So it is a property of system

This property is energy of system $(E)$

$$\therefore dQ - dW = dE$$

$\therefore$ whenever a system changes its state, energy crosses the boundary of system in the format of heat and work and change in energy of system is equal to total energy that crosses the boundary.

## Energy of an Isolated system is constant:

An isolated system is the system in which neither mass nor energy crosses the boundary of system

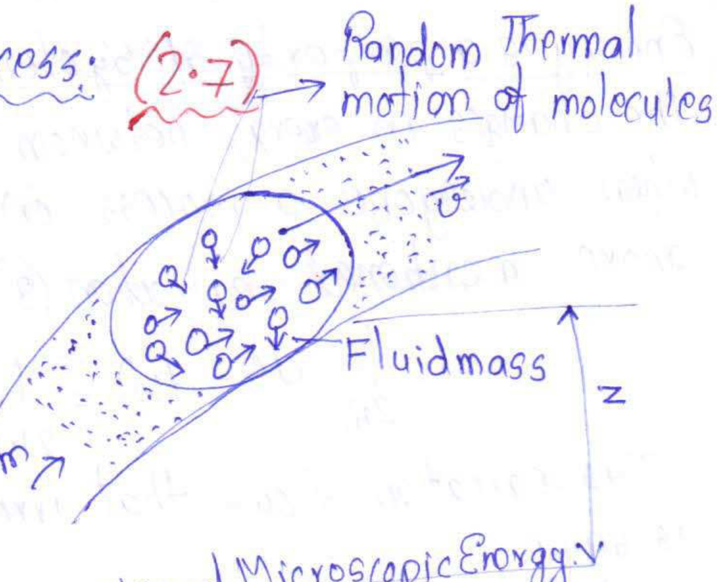
$dQ = 0$, $dW = 0$.

$\therefore dE = dQ - dW \quad dE = 0 \Rightarrow E = \text{constant}$

$\therefore$ Energy of Isolated system is constant.

## First Law Applied to a process: (2·7)

$$\boxed{dQ - dW = dE}$$



Energy may be macroscopic energy (or) microscopic energy.

Macroscopic and Microscopic Energy

Macroscopic energy is energy in molecular and atomic structure of a system (or) molecular internal energy (or) internal energy (U)

$$E_{micro} = E_{Rotational} + E_{Translational} + E_{Nuclear} + E_{electron} + \dots = U$$

$$E_{micro} = U$$

Macroscopic energy includes kinetic energy and potential energy of a system $E = E_{macro} + E_{micro}$

$$= E_{KE} + E_{PE} + U$$

when motion and gravitational energies is Zero $E_{KE} = 0, E_{PE} = 0$

$$E = U$$

$$\therefore dQ - dW = dU \Rightarrow dQ = dW + dU$$

$$\boxed{Q_{1-2} = W_{1-2} + dU}$$

For a process $Q_{1-2} = W_{1-2} + dU$

Internal energy. whenever a system undergoes a process, energy crosses boundary of system in the form of heat and work and change is I.E.

## Enthalpy (2·7·1)

The enthalpy of a substance, H is defined as

$H = U + pv$

U → Internal energy

P → Pressure

v → volume

enthalpy has units of J.

Specific enthalpy $h = \frac{H}{m}$

units: J/kg

Specific enthalpy is intensive property

It is also given as $h = u + pv$

u → Specific I·E

v → specific volume.

## $I^{st}$ Law Applied to a flow system: (2·7·2)

The process in which there is a continuous flow of material through out the equipment are called as flow process.

## Steady flow process (2·7·2·1)

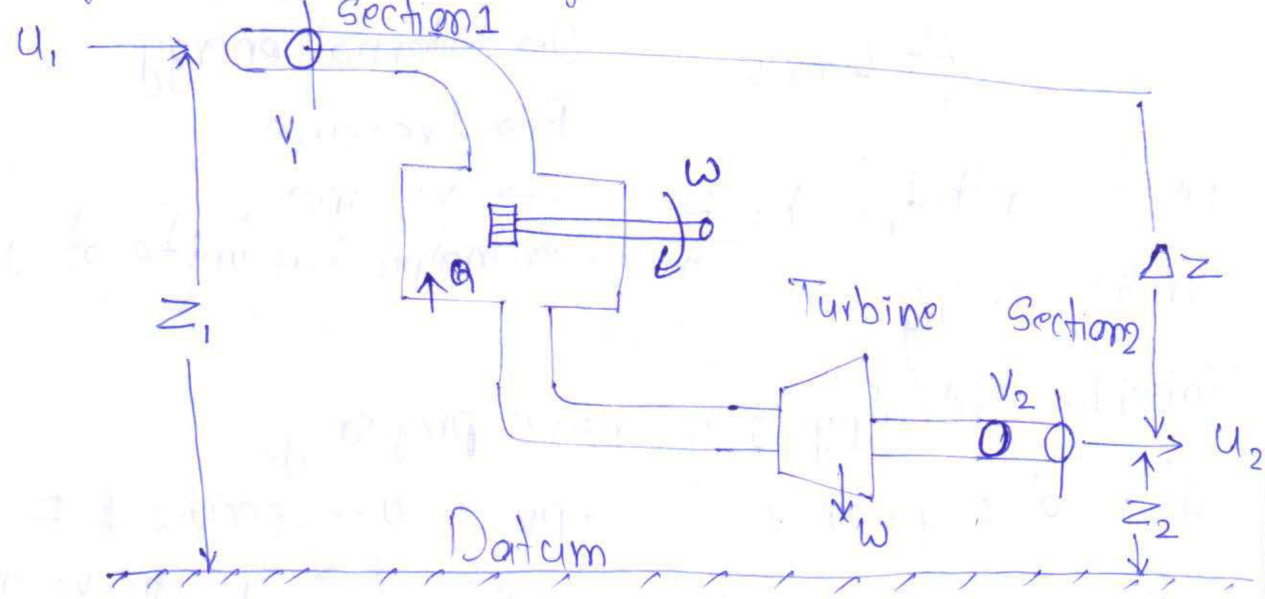
The rate of flow of mass and energy across the control surface are constant. At the steady state of a system any thermodynamic property will have a fixed value at a particular location, and will not alter with time. Steady state means that the state is steady (or) invariant with time

## Unsteady flow process: (2.7.3)

A flow process is variant with time.

## Mass Balance in steady flow process:

In which a fluid flows through the equipment from a single entrance to single exit.



Assuming continuity of mass

Mass flow rate at entrance = Mass flow rate at exit

$$\therefore \quad m_1 = m_2$$

Or
$$\frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2}$$

$A_1, A_2$ → Area of c.s at Entry/Exit, $m^2$
$m_1 = m_2 = m$ Mass flow rate at E & Ex kg/sec
$v_1$ & $v_2$ → Specific volume, $m^3/kg$
$V_1$ & $V_2$ → velocity, m/s

$Z_1$ & $Z_2$ → Datum line
$u_1$ & $u_2$ → sp. internal energy
$h_1$ & $h_2$ → sp. enthalpy
$P_1$ & $P_2$ → Abs pressure
Q → Heat input to system
W → Workout from system.

## Steady Flow Energy Equation: (2·7·4)

The energy may change in all three forms, kinetic, potential internal energies in the steady flows process.

kinetic energy change of fluid flow between sections 1 and 2. from above fig.

$$\Delta E_k = \frac{1}{2} m V_2^2 - \frac{1}{2} m V_1^2 = \frac{1}{2} m (V_2^2 - V_1^2) = \frac{1}{2} m \Delta V2$$

Potential Energy change of fluid between sect ① & ②

$$\Delta E_p = mg Z_2 - mg Z_1 = mg (Z_2 - Z_1) = mg \Delta Z.$$

∴ From first law of thermodynamics for a process

$$Q_{1-2} = W_{1-2} + \Delta E$$

$$Q_{1-2} - W_{1-2} = \Delta E$$

$$= \Delta E_k + \Delta E_p + \Delta U$$

$$= \frac{1}{2} m \Delta V2 + mg \Delta Z + \Delta U$$

Here work output includes shaft work $W_s$, Work done by force exerted on its upstream face is pushing cylinder into apparatus, and work done by system on surroundings as fluid cylinder emerges from apparatus

$$E = P.E + K.E + I.E + \text{Flow work} + \text{Heat Supplied.}$$

Thus $W = W_S + P_2 v_2 - P_1 v_1$

$$\therefore Q_{1-2} - W_{1-2} = \frac{1}{2} m \Delta V^2 + mg\Delta Z + \Delta U$$

$$Q_{1-2} - (W_{S_{1-2}} + P_2 v_2 - P_1 v_1) = \frac{1}{2} m \Delta V^2 + mg\Delta Z + \Delta U$$

$$Q - W + P_1 v_1 - P_2 v_2 = \frac{1}{2} m (V_2^2 - V_1^2) + mg(Z_2 - Z_1) + U_2 - U_1 \quad \boxed{\because mu = U}$$

$$m\left(\frac{V_1^2}{2} + gZ_1 + U_1 + P_1 v_1\right) + Q = m\left(\frac{V_2^2}{2} + gZ_2 + U_2 + P_2 v_2\right) + W$$

$$h = u + pv$$

$$\therefore m\left(\frac{V_1^2}{2} + gZ_1 + h_1\right) + Q = m\left(\frac{V_2^2}{2} + gZ_2 + h_2\right) + W$$

Above Equation is known as steady flow energy equation.

This equation can also be written as

$$\frac{V_1^2}{2} + gZ_1 + h_1 + \frac{\delta Q}{dm} = \frac{V_2^2}{2} + gZ_2 + h_2 + \frac{\delta W}{dm}.$$

$$m\left(gZ_1 + \frac{V_1^2}{2} + h_1\right) + Q = m\left(gZ_2 + \frac{V_2^2}{2} + h_2\right) + W$$

## Newly added

## steady flow process Examples

### Nozzle and Diffuser:

It is a device which increases the velocity (or) K.E of a fluid at the expense of its pressure drop.

$$E_1 = E_2$$

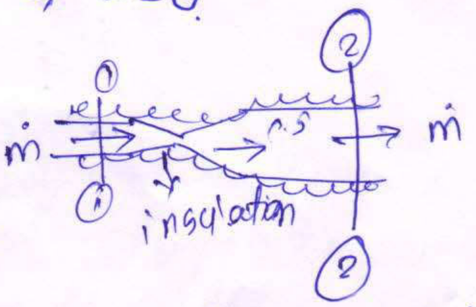
$$h_1 + \frac{v_1^2}{2} + z_1 g + \frac{dQ}{dm} = h_2 + \frac{v_2^2}{2} + z_2 g + \frac{dw_x}{dm}$$

Pressure drop → Result in Enthalpy drop and rise in velocity.

P.E = 0, $z_1 = z_2$, $Q = 0$, $\omega = 0$.

$$h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2}$$

$$\omega = \frac{A_1 v_1}{\vartheta_1} = \frac{A_2 V_2}{\vartheta_2}$$



$$\frac{v_2^2 - v_1^2}{2} = h_1 - h_2 \qquad h_1 = h_2 + \frac{v_2^2}{2}$$

$$\frac{v_2^2}{2} = h_1 - h_2 \qquad V_2 = \sqrt{2(h_1 - h_2)} \text{ m/s.}$$

$v_1$ is neglected compared to $v_2$

### Throttling Device:

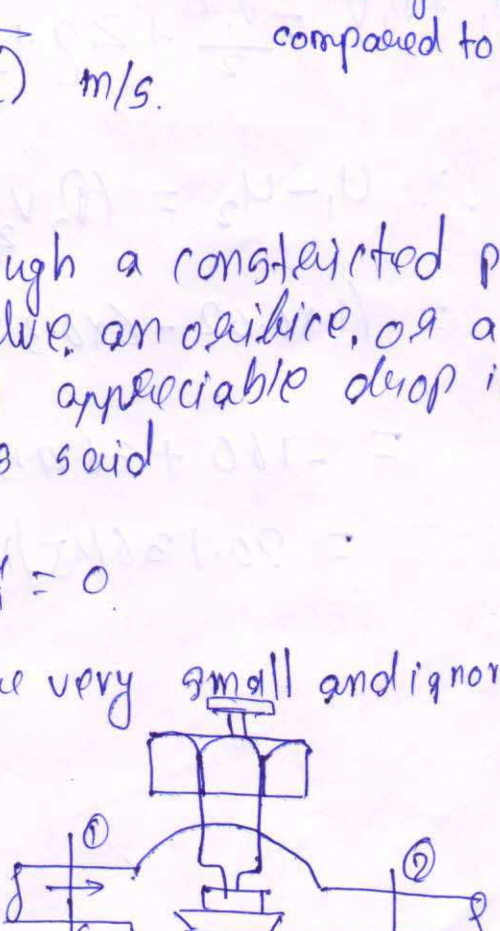
when a fluid flows through a constricted passage, like a partially opened valve, an orifice, or a porous plug, there is an appreciable drop in pressure, and the flow is said

$$\frac{dq}{dm} = 0, \quad \frac{dw_x}{dm} = 0$$

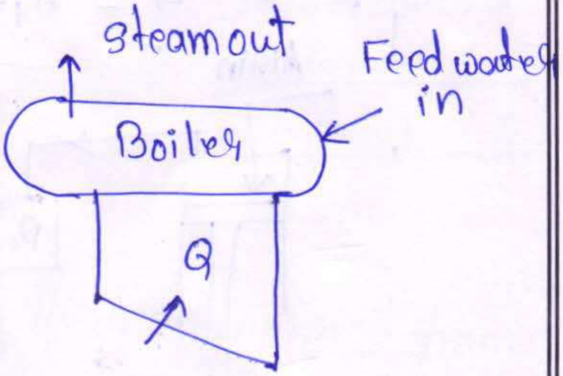
and the changes in P.E are very small and ignored

$$h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2}$$

$$h_1 = h_2$$



## Boiler:



Here P.E & K.E are negligible

$W = 0$

$z_1 = z_2$

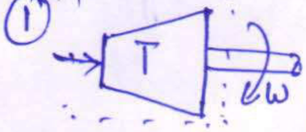
SFEE becomes $mh_1 + Q = mh_2$

$$Q = mh_2 - mh_1$$

$$Q = H_2 - H_1$$

i.e Total heat transferred = change in (total) enthalpy.

## Turbine:



It is a prime mover. It contains a rotating wheels with vanes or blades along their periphery. Steam issuing out of the nozzle impinges on the blades of wheels and cause high rotational speeds. Turbine delivers work. If an electrical generator is coupled to it electrical power is produced.

Here P.E & K.E can be neglected

$Q=0$ as turbine is insulated against any heat transfer. By SFEE $m(h_1) = m(h_2) + W$

$$W = m(h_1 - h_2)$$

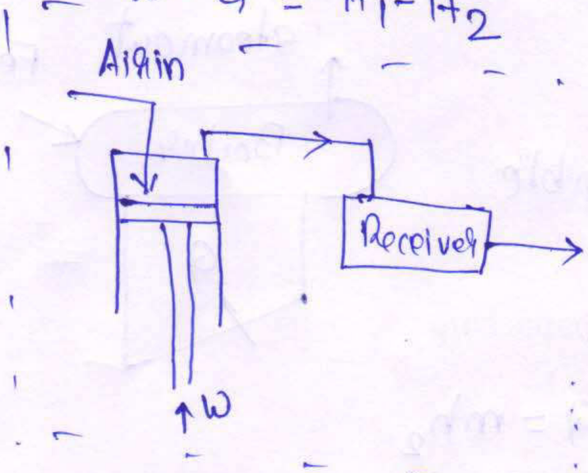
$$W = H_1 - H_2.$$

Work done = change in enthalpy.

## Reciprorating Compressor:

$$Q + H_1 = W + H_2$$

$$W - Q = H_1 - H_2$$



Work being negative in compressor work is done on the system.

## ②Limitations of first law:

According to first law of thermodynamics heat and work are mutually convertible (or) Energy is neither created nor destroyed but only changes from one form to other form.

* It does not explain the direction of flow
* The reverse of this never occurs
* Thermodynamic process is a irreversible process.

* Joule's experiments states that when the energy is supplied as work to a system, it is completely converted in to heat and reverse of it is not possible.

## 2.1 Thermal Reservoir

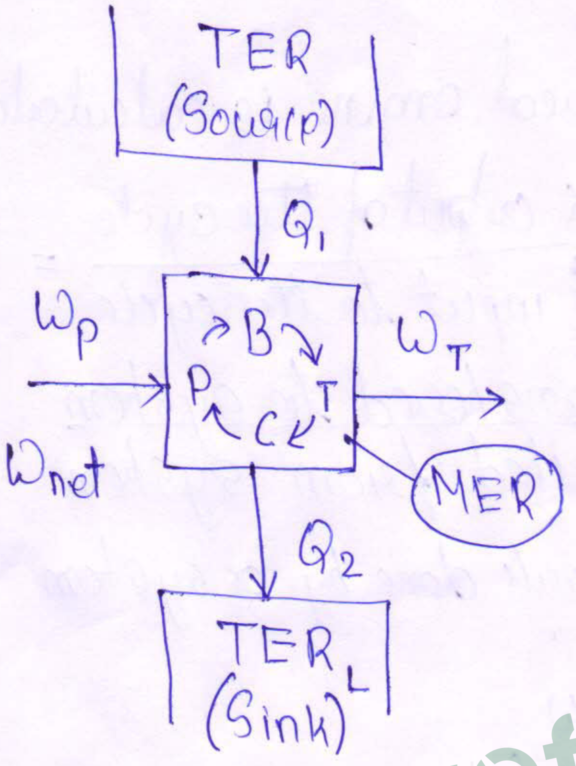
A thermal energy reservoir (TER) is defined as a large body of infinite heat capacity which is capable of absorbing (or) rejecting an unlimited quantity of heat without any appreciable changes in its thermodynamic co-ordinates.

The thermal energy reservoir $TER_H$ from which heat $Q_1$ is transferred to the system operating in a heat engine cycle is called "Source". The thermal energy reservoir $TER_L$ to which heat $Q_2$ is rejected from the system during a cycle is the sink.

Source is a constant temperature furnace where fuel is continuously burnt.
Sink is a river (or) sea.

A mechanical energy reservoir (MER) is a cyclic heat engine exchanging heat with a source and a sink and delivering $W_{net}$ in a cycle to an MER

## 2.1.1 Thermal Reservoir.



Cyclic heat engine with source & sink.

## 2.1.2 Heat engine:

Heat engine is a contrivance to convert heat energy into mechanical work. where as heat pump takes in work and delivers heat continuously.

A heat engine cycle is a thermodynamic cycle inwhich there is net heat transfer to the system and net work from the system. The system which executes a heat engine cycle is called a heat engine.

performance of heat engine is calculated by thermal η.

$$\eta = \frac{\text{Net work output of the cycle}}{\text{Total heat input to the cycle}} = W_{net}/Q_1$$

$$Q_1 = \frac{\text{Heat transfered to system}}{\text{Heat rejected from system}}$$

$W_{net}$ = Net work done by a system

From first law

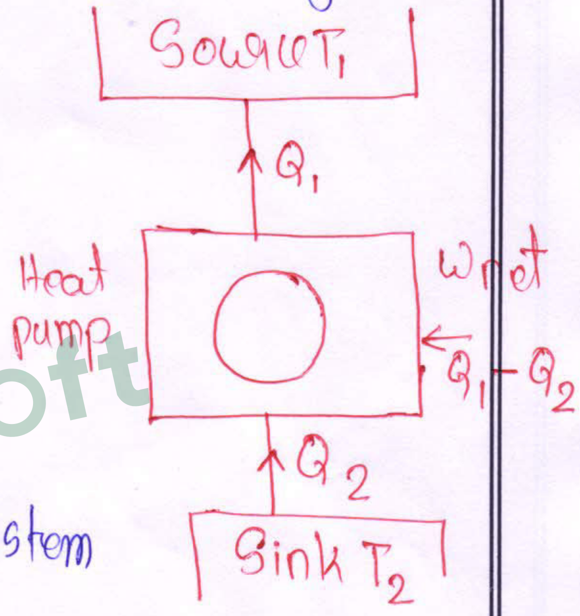
$$\oint dQ = \oint dW$$

$$Q_1 - Q_2 = W_{net}$$

$$\eta_{th} = \frac{Q_1 - Q_2}{Q_1} = 1 - Q_2/Q_1$$

## 2.1.2 Heat pump:

A heat pump is defined as thermodynamic system operating in a cycle which removes heat from a low temp body i.e "Sink" and delivers it to a higher temperature body (i.e). Source by taking external in the form of work input.



Performance of a heat pump is calculated by the C.O.P.

$Q_1$ = heat rejected from system

$Q_2$ = heat supplied to system

$W_{net}$ = Network required by system

I - Law

$$\oint dQ = \oint dw$$

$$Q_1 - Q_2 = W_{net}$$

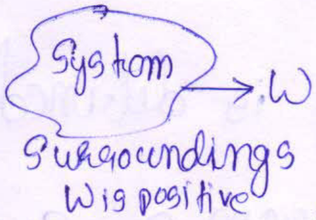
$$(COP)_{Heat\,pump} = \frac{\text{Heating effect (or) Desired effect}}{\text{Work input}}$$

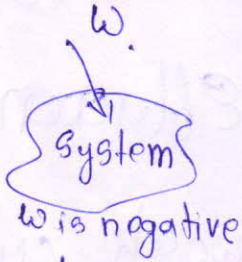
$$Q_1 - Q_2 = W_{net}$$

$$\frac{Q_1}{W_{net}} = \frac{Q_1}{Q_1 - Q_2}$$

## 2.2 Parameters of performance:

- * Work
- * Heat
- * Internal energy
- * Efficiency.





### 2.2.1: Work.

Work is one of the basic modes of energy transfer. In mechanics, the action of a force on a moving body is identified as work. A force is a means of transmitting an effect from one body to another.

The work is done by a force as it acts upon moving in the direction of the force.

The unit of work is N·m or Joule [1 Nm = 1 Joule]

### 2.2.2: Heat

Heat is defined as the form of energy that is transferred across a boundary by virtue of a temperature difference.

The unit of heat is Joule in S.I units

The rate of heat transfer (or) work transfer KW (or) W.

## 2.2.3 Internal Energy:

Energy in storage, called internal energy, is a point or state function and hence a property of a system.

The microscopic energy mode refers to the energy stored in the molecular and atomic structure of the system, which is called molecular internal energy or simply internal energy. (U)

## 2.2.4 Efficiency:

Efficiency ($\eta$) is defined as the ratio of work output from a system to heat input into the system.

$$\eta_{th} = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

For a heat pump instead of $\eta_{th}$ a term called coefficient of performance C.O.P is used.

## 2:3 Second law of Thermodynamics:

Second law is stated in different ways

(a) Kelvin-Max planck's statement:

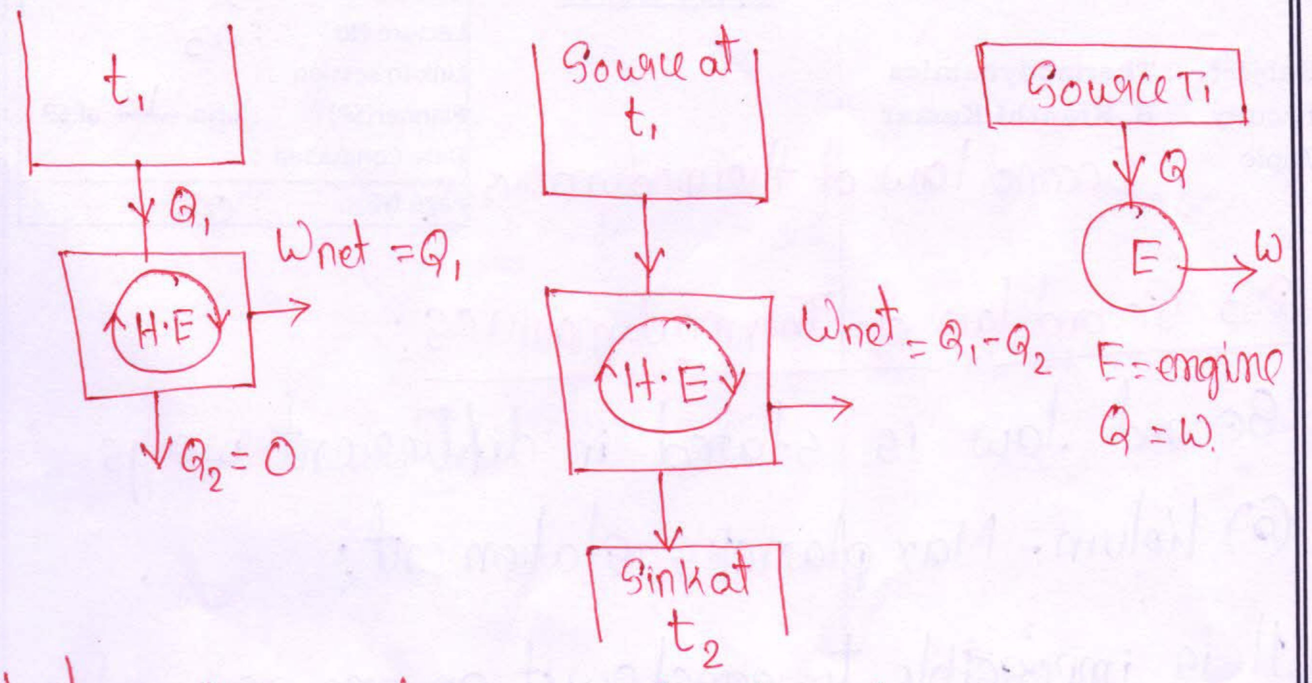
It is impossible to construct an engine working on a cyclic process. whose sole purpose is to convert all the heat supplied to it into equivalent amount of work. If $Q = 0$ (i.e $W_{net} = Q_1$, $\eta = 1.00$) the heat engine will produce net work in a complete cycle by exchanging heat with only one reservoir thus voilating the kelvin-maxplanck statement.

## 2.3.1 PMM2

Such a heat engine is called a perpetual motion machine of the second kind.

* Only a fraction of heat supplied by a high temp source is converted in to useful work.

* No heat engine is 100% law.

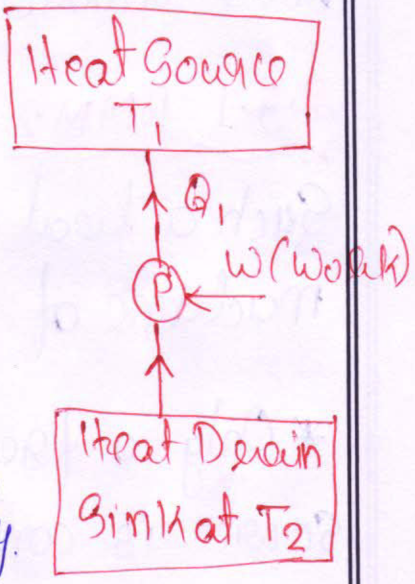


Heat engine producing ~~net~~ network in a cycle by exchanging heat at two different temp.

## 2.3.2 Clausius statement

It is impossible for the heat to flow from a body at a lower temperature to a body at higher temp without the aid of external agency.

This statement concerns heat pump instead of heat engine. Heat engine is a contrivance to convert heat energy into mechanical work. whereas a heat pump takes in work and delivers heat continuously.



$Q_1$ → Heat transferred from pump to source

$Q_2$ → Heat received from ~~pump~~ by pump from sink, W → Work supp to pump

$Q_1 \to Q_2 + W$  Note: $T_2 < T_1$

## 2.4 : Equivalance/corollaries:

* No engine, working on a cyclic process is more efficient than (Carnot's) reversible engine when working between the same two limits of temp.

* All reversible engines have the same efficiency. when working between the same two reservoirs of heat.

* whenever a system executes a complete cyclic process the $\oint dQ/T$ round the cycle is less than zero.

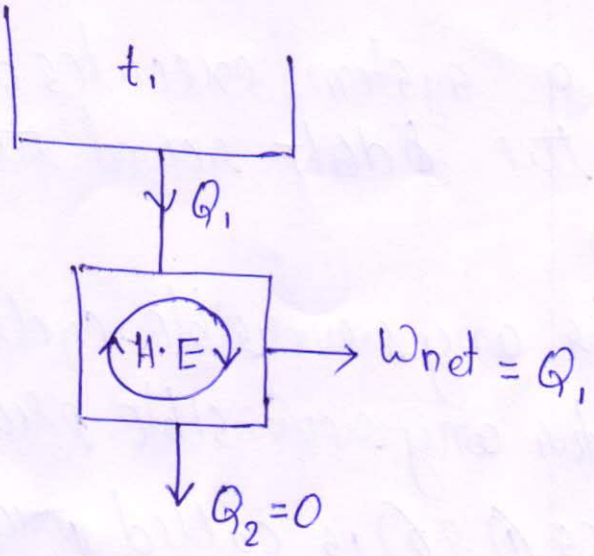
* $\oint dQ/T=0$ for any reversible cyclic process and consequently for any reversible process b/w reference states ① & ② is called property of the system. property is called entropy.

## 2.4.1 PMM of second kind (2.4.1)

According to kelvin-planck statement of the second law states: It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

If $Q_2 = 0$ (ie $W_{net} = Q_1$, $\eta = 1.00$). the heat engine will produce net work in a complete cycle by exchanging heat with only one reservoir, thus voilating the kelvin-planck statement.

Such a heat engine is called a perpetual motion machine of the second kind. abbreviated to PMM2, . A PMM2 is impossible.



A PMM2

## 2.5: Carnot's principle:

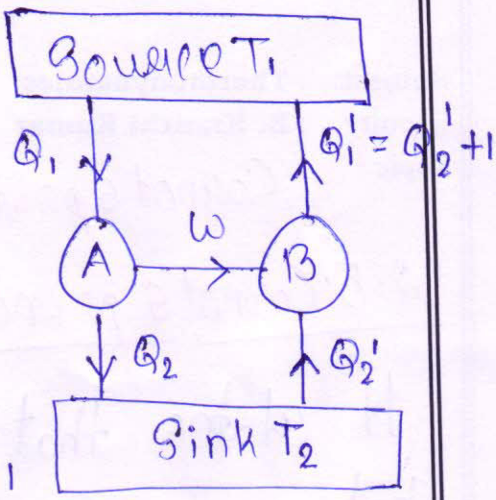
It states that of all heat engines operating between a given constant temp source and a given constant temp. sink, none has a higher efficiency than a reversible engine.

(Or)

"No engine working on a cyclic process, is more efficient than Carnot's engine when between the same limits of temperature"

Let us assume that engine A working on any cyclic process is more efficient than carnot engine B (working on a reversible cycle) Both of them operate B/w the same limits of temp $T_1$ & $T_2$.

Let A & B be coupled to each other such that work done by A = work done on B.



$$Q_1 - Q_2 = Q_1' - Q_2' = W$$

$$\eta_A = Q_1 - Q_2 / Q_1$$

$$\eta_B = Q_1' - Q_2' / Q_1'$$

$$\eta_A > \eta_B = \frac{Q_1 - Q_2}{Q_1} > \frac{Q_1' - Q_2'}{Q_1'}$$

$$\frac{W}{Q_1} > \frac{W}{Q_1'}$$

i.e $\frac{1}{Q_1} > \frac{1}{Q_1'}$

$$Q_1 < Q_1'$$

i.e $\boxed{\begin{matrix} Q_1' > Q_1 \\ Q_2' > Q_2 \end{matrix}}$

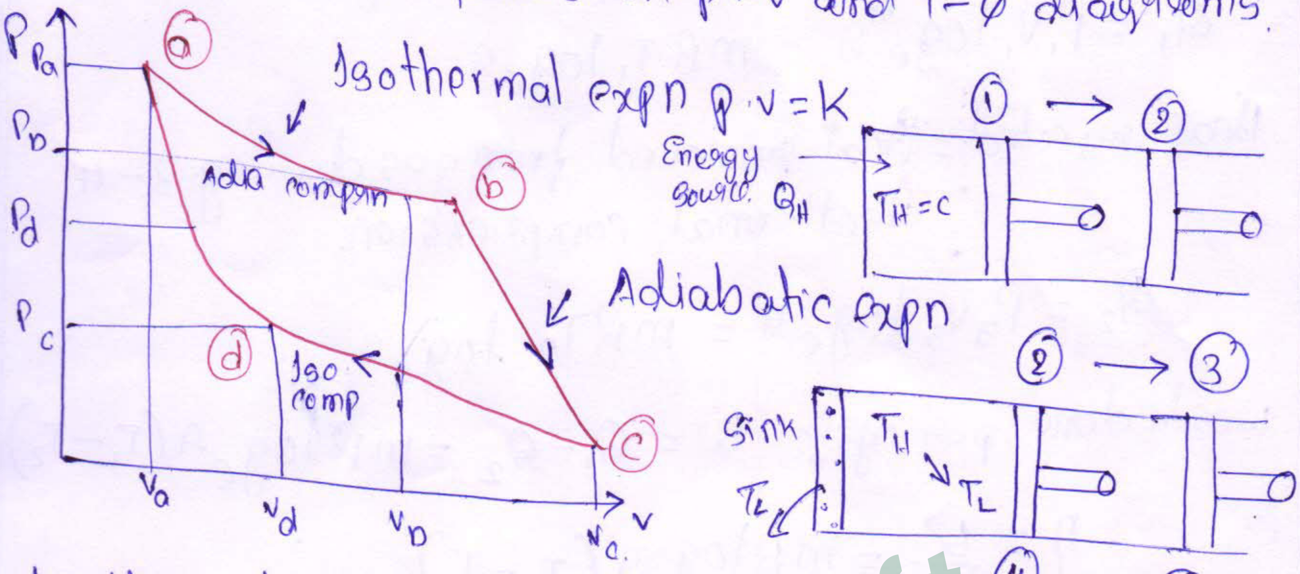
$$Q_1' = Q_2' + W.$$

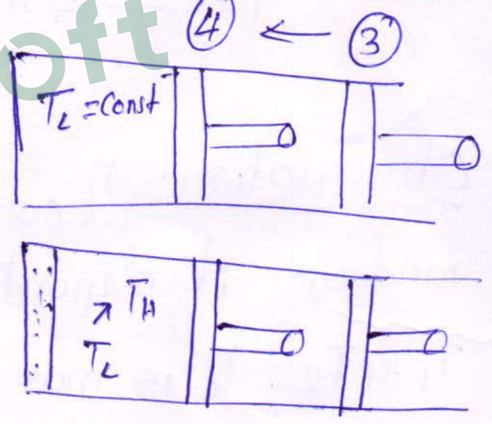
Heat rejected by B > Heat received by A. This means that the source at higher temperature $T_1$ is receiving heat from sink at lower temp $T_2$ which is vailation of 2nd law.

Hence $\eta_A \not> \eta_B$ and $\eta_A < \eta_B$.

## 2.5.1 Carnot cycle:

This cycle was devised by Sadi Carnot in 1824. It is represented as follows on p-v and T-ø diagrams.





Isothermal expansion 1 - 2

$T_H$ = Const

Untill the piston moves ②

Reversible Adiabatic expansion Ins

② - ③

Temp drops $T_H \rightarrow T_L$

assume friction is less process reversible

③ - ④

Reversible Isothermal expansion

$T_L$ = const

heat is transfered to sink temp never exceeds dT

④ - ①

Adiabatic compression $T_L$ - $T_H$.

## 2·5·2 Carnot Cycle and its specialities:

Let $r = \frac{V_2}{V_1} = V_3/V_4$

Ratio of expansion = ratio of compression

Heat supplied = Heat given to working fluid (perfect gas) during 1-2 Isothermal exp.

$$Q_1 = P_1V_1 \log_e r = mRT_1 \log_e r$$

Heat rejected = Heat removed from gas during 3-4 isothermal compression.

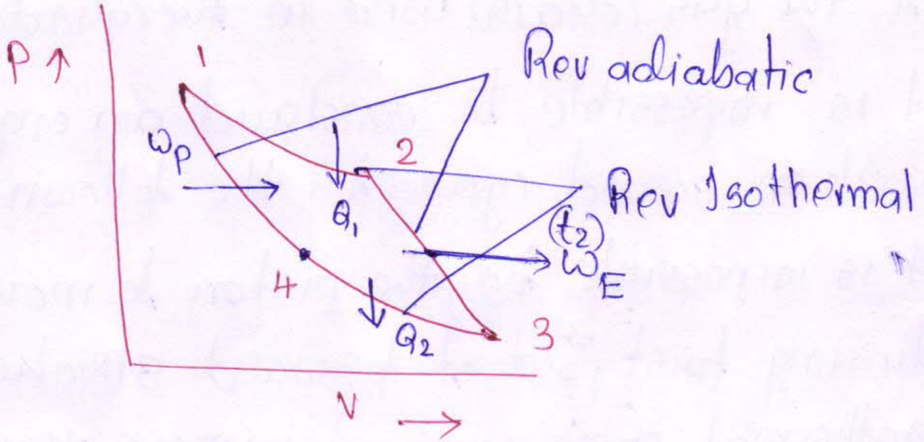
$$Q_2 = P_3V_3 \log_e r = mRT_2 \log_e r$$

work done per cycle $W = Q_1 - Q_2 = mR\log_e r(T_1 - T_2)$

$$\eta = \frac{W}{Q_1} = \frac{mR\log_e r(T_1 - T_2)}{mRT_1 \log_e r} = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

Observation: $\eta_{carnot}$ does not depend on working medium it depends on limiting values of temp $T_1$ & $T_2$. $\eta$ is max when $T_2 = 0$ → This means absence of heat and sink and hence is impossible according to 2nd law.

# EXTENSION OF CARNOT CYCLE



Max possible $\eta$ is obtained if $T_1$ is highest and $T_2$ is lowest. It is a reversible cycle.

To prove that the cyclic integral $\oint \frac{dQ}{T} = 0$ for a carnot's reversible cycle.

Assume $m = 1\,kg$.

For process ①-② $\oint \frac{dQ}{T} = R \log_e r$ Isothermal expan

For process ②-③ $\oint \frac{dQ}{T} = 0$ .... Adiabatic expan

For Isocomp ③-④ $\oint \frac{dQ}{T} = -R \log_e r$

For adia comp ④-① $\oint \frac{dQ}{T} = 0$

For the entire cycle $\oint dQ/T = R \log_e r + 0 - R \log_e r + 0 = 0$

$\therefore \oint dQ/T = 0.$

## 2.5.2 → Extension of Carnot Cycle Specialities:

* Efficiency of carnot cycle depends on the absolute temp limits only and is independent of the properties of the gas (or air) used in the cylinder.

It is impossible to construct an engine which will work on carnot cycle for the following reasons.

It is impossible for the piston to move very slowly during first part of forward stroke (i.e during isothermal expansion) and to move very fast during next part of the forward stroke (i.e Adi Exp). This variation of the piston's speed is not practicable.

P-V diagram of Carnot's cycle is very narrow compared with the length of the stroke. Hence work realised is very small for the piston's displacement, most of which is absorbed by the friction.

Reversible Carnot Cycle (a. b, c, b a) is applied to heat pumps and refrigerators.

For a heat pump instead of $\eta_{th}$ a term called C.O.P

$$(C.O.P) \text{ of pump} = Q_1/W = Q_1/Q_1 - Q_2$$

In case of refrigerators since it draws out heat $Q_2$ from the food stuffs with the help of work W

$$C.O.P = Q_2/W = Q_2/Q_1 - Q_2.$$

# THERMODYNAMIC SCALE OF TEMP.

The efficiency of any heat engine cycle receiving heat $Q_1$ and rejecting heat $Q_2$ is given by $\eta = \frac{W_{net}}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$

For a reversible cycle (Carnot cycle), the $\eta$ will depend solely upon the temperature $t_1$ and $t_2$ at which heat is transferred or

$$\eta_{rev} = f(t_1, t_2)$$

f signifies some function of the temp

$$1 - \frac{Q_2}{Q_1} = f(t_1, t_2)$$

In terms of new function F $= Q_1/Q_2 = F(t_1, t_2)$

If some functional relationship is assigned between $t_1$, $t_2$ and $Q_1/Q_2$, the equation becomes the definition of a temperature scale.

## Entropy principle

Entropy is defined by $\frac{dQ}{T}$ and designated by S or $\phi$.

For any infinitesmall process undergone by a system $ds \geq dQ/T$

For an isolated system which doesnot undergo any energy interaction with the surroundings $dQ=0$

$\therefore$ For isolated system $ds_{iso} \geq 0$

For Reversible process $dS_{iso}=0$ $S=\text{const}$

For Irreversible process $ds_{iso}>0$.

Entropy of an isolated system can never decrease. It always increases and remains constant only when the process is reversible.

# CLASIUS IN EQUIALTY

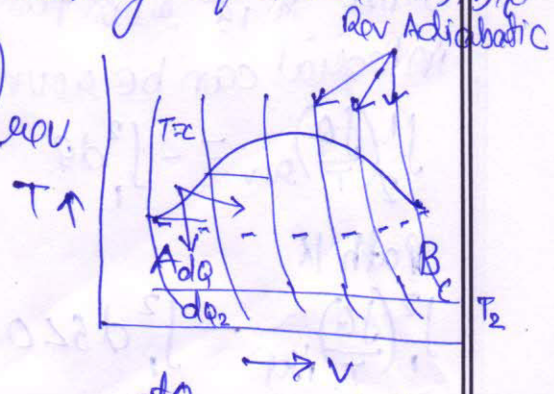
Let us consider a cycle ABCD. Let AB be a general process, either reversible or irreversible while the other process in the cycle are reversible. Let the cycle be divided into a number of elementary cycles. For one of those elementary cycles

$$\eta = 1 - dQ_2/dQ$$

where $dQ$ is the heat supplied at $T$ and $dQ_2$ the heat rejected at $T_2$.

Now, the efficiency of a general cycle will be equal to or less than the efficiency of a reversible cycle.

$$1 - dQ_2/dQ \leq \left(1 - \frac{dQ_2}{dQ}\right)_{rev}$$



$$\frac{dQ_2}{dQ} \geq \left(\frac{dQ_2}{dQ}\right)_{rev} \Rightarrow \left(\frac{dQ}{dQ_2}\right)_{rev} = T/T_2$$

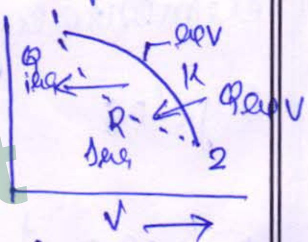
$$\frac{dQ}{dQ_2} \leq \frac{T}{T_2} \Rightarrow$$ For reversible process $$ds = \frac{dQ_{rev}}{T} = \frac{dQ_2}{T_2}$$ $$AB \rightarrow \frac{dQ}{T} \leq ds, \oint \frac{dQ}{T} \leq \oint ds$$

since entropy is a property and the cyclic integral of any property is zero $\oint \frac{dQ}{T} \leq 0.$

## 2.7.1 Principle of entropy increase:

* The entropy of an isolated system increases in all real process and is conserved in reversible process. This statement is known as principle of increase of entropy.

Consider an irreversible process 1-2 along path 'R'. Let the cycle be completed by a reversible process 2-1 along path 'K'. So that process 1-R-2 and 2-K-1 together form as irreversible process cycle $\oint \frac{dQ}{T} < 0$ for irreversible process.



From clausius statement

$$\int_1^2 \left(\frac{\delta Q}{T}\right)_{irr} + \int_2^1 \left(\frac{\delta Q}{T}\right)_{rev} > 0$$

Path R　　　　path K.

$$\int_2^1 \left(\frac{\delta Q}{T}\right)_{rev} = \int_2^1 ds$$

Since K is rev the limits of integral can be reversed

$$\int_2^1 \left(\frac{\delta Q}{T}\right)_{rev} = -\int_1^2 ds$$

Path K

$$\int_1^2 \left(\frac{\delta Q}{T}\right)_{irr} - \int_1^2 ds < 0$$

Path R

$$\int_1^2 ds > \int_1^2 \left(\frac{\delta Q}{T}\right)_{irrev}$$

Path K　　　　path R

$$ds > \left(\frac{\delta Q}{T}\right)_{irr}$$

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

$$\Delta S = S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

$\delta Q$ is heat interaction

T is temp environment

$$\delta Q = 0$$

$$\Delta S \geq 0$$

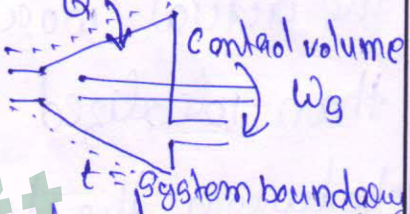
Entropy is zero for a reversible adiabatic process greater than zero for irreversible.

## 2.7.2 Energy equation:

Applying second law of thermodynamics to flow process we get energy equation.

Consider a turbine through which matter continuously flows in and out as the control volume.

$\dot{m}_1$, $\dot{m}_2$ = mass flow rate of fluid at the inlet and out of device.



$s_1$ & $s_2$ = Specific entropy of fluid

$\dot{Q}$ = rate of energy transferred as heat across the control surface.

$\dot{W}_S$ = rate of shaft work delivered by device.

$s(t)$ = specific entropy of fluid in control volume at time t

$s(t+dt) = (t+dt)$

$m(t+dt)$ = mass of fluid in control volume at time $(t+dt)$

$S(t)$ = Entropy of fluid in control volume at time t

$s(t+dt) = (t+dt)$

$\dot{S}_G$ = Rate of entropy generation.

$T$ = Temp of control surface.

### 2·7·3 Availability and Irreversibility.

The availability of a given system is defined as a the maximum useful work (total work minus pdv work) that is obtainable in a process in which the system comes to equilibrium with its surroundings.

Availability is a composite property depending on state of both system and surroundings.

Irreversibility

The actual work done by a system is always less than idealized reversible work and the differences between the two is called the irreversibility of process. Types of irreversibility are.

### 2·7·3 (a) Internal irreversibility

Caused by the dissipative effects like friction, electrical resistance within the system.

### 2·7·3 (b) External irreversibility.

Caused by the system boundary like heat interaction with surroundings due to a finite temp gradient.

## 2.7.4 Thermodynamic potentials.

The conversion of independent variables (ie. intensive) and extensive parameters as the dependent ones. The fundamental relation can be transformed through Legendre transformations such that intensive parameters play the role of independent variables

It is possibly for only some extensive parameters for replacing them by their corresponding intensive parameters through Legendre transforms of the fundamental relation in the energy representation are called as thermodynamic potentials and are known as massieu functions.

Ex: Gibbs free energy. Helmholtz free energy.

## 2·7·5 Gibbs and Helmholtz Functions:

The Gibbs function $G = H - TS$

$$H = U + PV$$

H → Enthalpy   T is temp   S → entropy

$$G = U + Pv - TS$$

For two equilibrium states at same pressure p and temperature T

$$(G_1 - G_2)_{p,T} = (U_1 - U_2)_{p,T} + p(V_1 - V_2)_{p,T} - T(S_1 - S_2)_{p,T}$$

### Helmholtz Function

A property known as Helmholtz function F.

$$F = U - TS$$

U → Internal energy
T → Temp
S → Entropy

For two equilibrium states 1 and 2 at the same temp T is

$$(F_1 - F_2)_T = (U_1 - U_2) - T(S_1 - S_2)_T$$

## 2.8 Maxwell Relations

From first law of thermodynamics

$\delta Q = dU + \delta W \quad \therefore \delta Q = Tds, \; \delta W = pdv$

$Tds = dU + P.dv \quad \therefore du = Tds - P.dv$ — ①

Enthalpy is given by $h = U + PV$

$\therefore dh = d(U+PV) = du + d(v) = du + pdv + vdp$

from ① $dh = Tds + vdp$ — ②

Gibbs function is given by

$g = h - TS$

$dg = d(h - TS) = dh - (d(TS))$

$= dh - Tds - S.dT$

from ① $dh = T.ds + v.dP$

$dh - Tds = v.dP$

$\therefore dg = v.dp - S.dT$ — ③

Helmholtz function is

$f = u - TS$

$df = d(u - TS)$

$= du - d(TS)$

$= du - Tds - SdT$

from ① $du - Tds = -pdv$

$df = -pdv - SdT$

$\therefore$ Since internal energy, enthalpy, Gibbs function, Helmholtz are properties then du, dh, dg, df. are exact diff.

$(\partial T/\partial v)_S = -(\partial P/\partial S)_v$

$(\partial T/\partial P)_S = (\partial v/\partial S)_P$

$(\partial v/\partial T)_P = -(\partial S/\partial P)_T$

$(\partial P/\partial T)_v = (\partial S/\partial v)_T$

are used to determine relationship b/w the properties P, v, T & S for any equilibrium state.

### 2.8.1 Elementary Treatment of the third law of thermodynamics.

On the basis of observation by Nernst and others planck stated third law of thermodynamics in 1912.

* The entropy of all perfect crystalline solids is zero at absolute zero of temp.

* A perfect crystal is one which is in the thermodynamic equilibrium.

Third law of thermodynamics can be stated as

"The entropy of any pure substance in thermodynamic equilibrium approaches zero as the absolute temp approaches zero".

# Perfect Gas Laws

## 3.1 (Avagadro's Law)

A mole of a substance has a mass numerically equal to the molecular weight of the substance.

One g mol of oxygen has a mass of 32g

1 kg mol of oxygen has a mass of 32 kg.

Avagadro's law states that the volume of a g mol of all gases at the pressure of 760mm of Hg. and temperature of 0°C is the same and is equal to the 22.4 lit.

∴ 1g mol of a gas has a volume of $22.4 \times 10^{-3} m^3$ and 1kg mol of a gas has a volume of $22.4 m^3$ at normal temp and pressure.

KSR

For certain gas.

if m is its mass in kg, $\mu$ is molecular weight, then number of kg moles of the gas n would be given by

$$n = \frac{m\,kg}{\frac{\mu\,kg}{kg\,mol}}$$

$$= \frac{m}{\mu}\ kg\ moles$$

$$\bar{v} = \frac{V}{n}\ m^3/kg.mol$$

V is the total volume of gas in $m^3$.

## 3.1.1(a) Boyle's Law:

"Volume of a given mass of a gas varies inversely with absolute pressure if the temp of the gas is held constant"

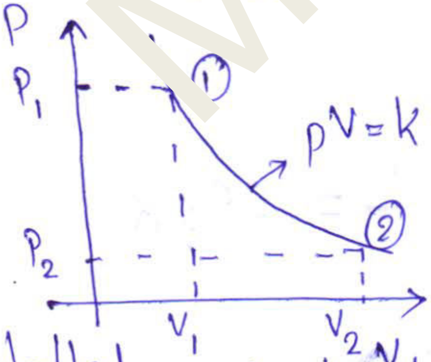
Mathematically $V \propto 1/p$ .... T being constant

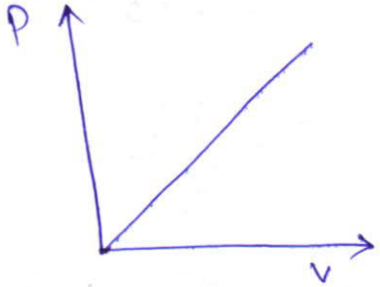
i.e $pV = K$ ...... $K$ = a constant

The graph of the law is an equilateral (rectangular) hyperbola. If two states ① & ② are considered, we find

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}$$

$$\Rightarrow P_1V_1 = P_2V_2 \text{ or } pV = K$$





If p is plotted against 1/v the result will be a straight line as it passes through the origin.

A gas whose original pressure and volume were 400 KN/m² and 0.15 m³ is expanded untill its new pressure is 75 KN/m², while its temp remains constant. what is its new volume?

Sol: $pV = K$ (Boyles-Law)

$$P_1 V_1 = P_2 V_2$$

$$V_2 = \frac{V_1 \cdot P_1}{P_2}$$

$$= \frac{0.15 \times 400}{75}$$

$$= 0.8\,m^3.$$

A quantity of gas whose original volume and temperature are 0.2 m³ and 303°C respectively, is cooled at constant pressure until its volume becomes 0.1 m³ what is the final temp of gas? (Charles-law).

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \qquad V_1 = 0.2\,m^3 \quad V_2 = 0.1\,m^3$$

$$T_1 = 303 + 273 = 576^\circ K$$

$$T_2 = \frac{T_1 \times V_2}{V_1} = \frac{576 \times 0.1}{0.2} = 288^\circ K$$

$$t = 288 - 273 = 15\,C.$$

## Class Notes

Unit No: 03
Lecture No: 31
Link to Session
Planner (SP):S.No.31.of SP
Date Conducted:
Page No: 03

**Subject :** THERMODYNAMICS
**Faculty :** B.Kranthi kumar
**Topic:**

### 3.1.2 Charle's law:

"Volume of a given mass of a gas varies directly with its absolute temp when the pressure is kept constant".

Mathematically, $V \propto T$ ∴ p being const.

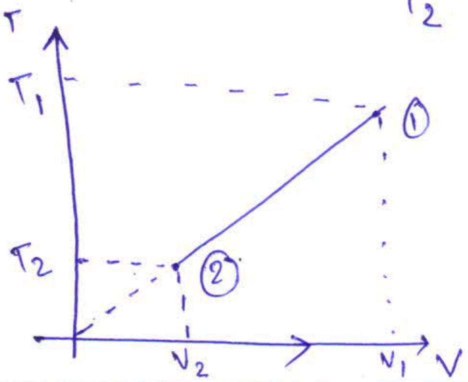
i.e, $V/T = K$ ∴ K is a constant & $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

T $V_s$ V graph at constant p is shown.

$$V_1 T_2 = V_2 T_1 \quad \text{or} \quad \frac{V_1}{V_2} = \frac{T_1}{T_2}$$

(OR)

$$\frac{P_1}{P_2} = \frac{T_1}{T_2} \quad \text{or} \quad P_1 T_2 = P_2 T_1$$



## 3.1.3 Joule's law:

"The internal energy of a perfect gas is a function of temp only and is independent of changes in pressure and volume'

m = mass

c = sp. heat

$$\Delta U \propto \Delta T = m c \Delta T$$

## Regnault's Law: 3.1.4

It states that "the two specific heats namely sp. heat at constant pressure and sp. heat at const. volume of a gas do not change with the change in temp.

# Equation of State

The functional relationship among the properties, pressure, P, molar specific volume V and temperature T is known as equation of state which may be expressed in the form $f(P,V,T)=0$

If any two of these properties of a gas are known, then third can be evaluated from the equation of state.

The ratio of pressure P of a gas at any temperature to pressure $P_t$ of the same gas at the triple point as both P and $P_t$ approach zero, approaches a value independent of the nature of the gas.

## Specific & Universal Gas Constant.

The ideal gas temp T of the system as whose temp the gas exerts pressure P was defined as

$$T = 273.16 \lim_{P_t \to 0} \frac{P}{P_t} \quad \text{const. volume}$$

$$T = 273.16 \lim_{P \to 0} \frac{V}{V_t} \quad \text{const. Pressure}$$

The relation between pv and p of a gas may be expressed by means of a power series of the form

$$PV = A(1 + B'P + C'P^2 + \dots)$$

where A, B', C', etc depend on temp and nature of the gas.

A fundamental property of gases is that $\lim_{P \to 0} (PV)$ is independent of the nature of the gas and depends on T.

where product pv is plotted against P for four different gases in the bulb ($N_2$, Air, $H_2$ & $O_2$)

at the boiling point of sulphur, at steam point and triple point of water.

In each case, it is seen as $p \to 0$ PV approaches the same value for all gases at the same temp $\lim\limits_{P\to 0} pv = A$.

∴ The constant A is a function of temp only and independent of the nature of the gas.

$$\lim \frac{P}{P_t} (\text{Const } V) = \lim \frac{PV}{P_t V} = \frac{\lim PV}{\lim (PV)_t} = \frac{A}{A_t}$$

$$\lim \frac{V}{V_t} (\text{Const} \cdot P) = \lim \frac{PV}{PV_t} = \frac{\lim PV}{\lim (PV)_t} = \frac{A}{A_t}$$

The ideal gas temp T

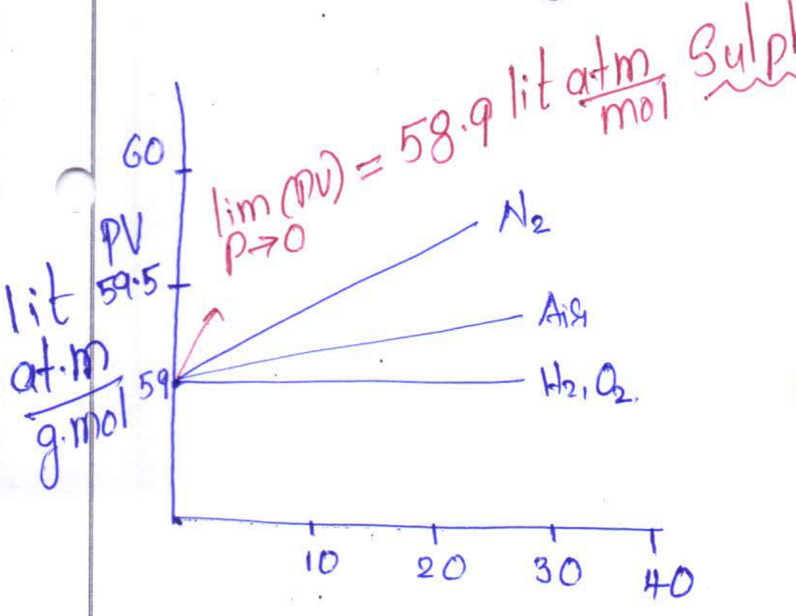
$$T = 273.16 \frac{\lim (PV)}{\lim (PV)_t}$$

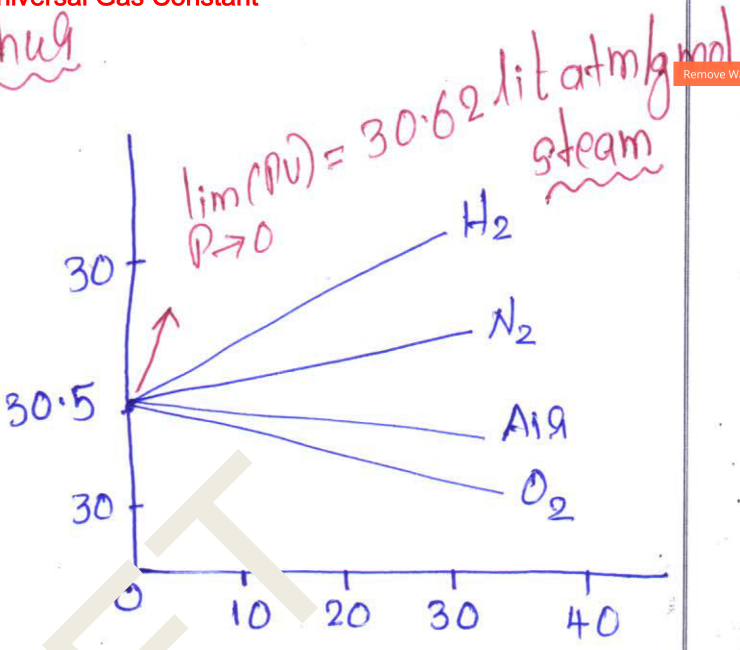
$$\lim (PV) = \left[\frac{\lim (PV)_t}{273.16}\right] T$$

The term within bracket is called the universal gas constant and is denoted by $\bar{R}$

$$\bar{R} = \frac{\lim (PV)_t}{273.16}.$$

# Universal Gas Constant





For any gas $\lim_{P\to0}(P\bar{v})_T$ is independent of the nature of the gas and depends only on T.

The value obtained for $\lim_{P\to0}(P\bar{v})_t$ is $22.4 \frac{\text{lit-atm}}{\text{g mol}}$

$$\bar{R} = \frac{22.4}{273.16} = 0.083 \frac{\text{lit-atm}}{\text{g molK}}$$

The equation of state of a gas is thus

$\lim_{P\to0} P\bar{v} = \bar{R}T$ v is the molar volume.

## Various Non Flow Process

## Non flow process:

The process occuring in closed system which permits only energy transfer only are known as non-flow process.

The heating and expansion of a gas can be done in several ways. But the following are some different non-flow process (reversible / irreversible) in heating and expansion of a perfect gas can be done.

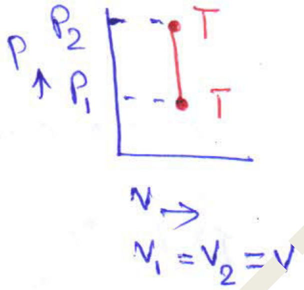
① Reversible Non-flow processes
- ⓐ Isochoric process
- ⓑ Isobaric process
- ⓒ Isothermal process
- ⓓ Adiabatic process
- ⓔ polytropic process

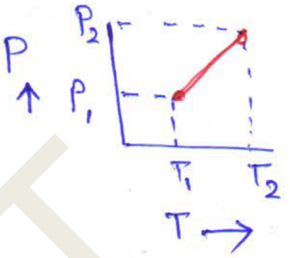
② Irreversible Non-flow processes
- ⓐ Free expansion process.

when a gas is heated and expanded there are changes in properties of gas.

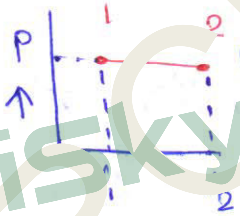
These changes may be in internal energy, enthalpy, entropy etc.

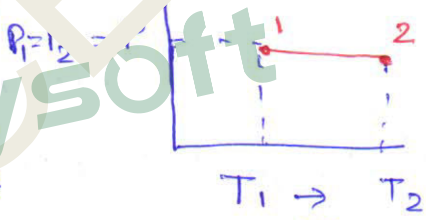
### 3.3.1 Isochoric Process:



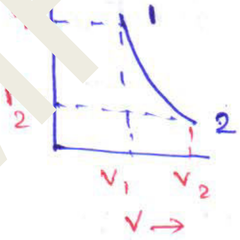


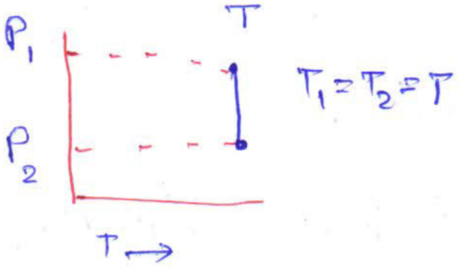
### 3.3.2 Isobaric Process



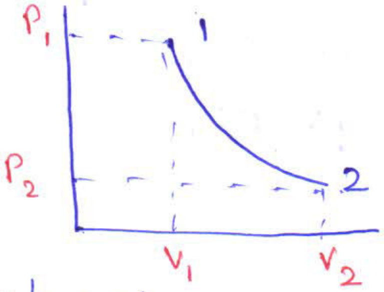


### 3.3.3 Isothermal Process:

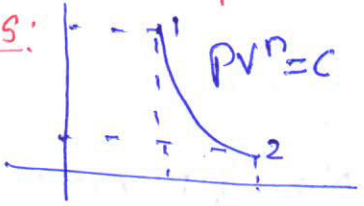


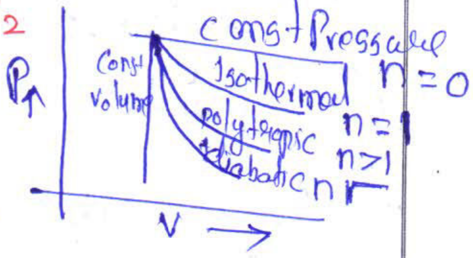


### 3.3.4 Adiabatic Process



### 3.3.5 Polytropic process:





End States , change in Enthalpy

$$dH = d(U+PV)$$

$$dH = dU + d(PV)$$

$$= mC_v(T_2 - T_1) + (P_2V_2 - P_1V_1)$$

$$= mC_v(T_2 - T_1) + mR(T_2 - T_1)$$

$$= m(C_v + R)(T_2 - T_1)$$

$$dU = mC_v(T_2 - T_1)$$

$$= mC_p(T_2 - T_1)$$

Is same for all expansion processes

The change in internal energy and change in enthalpy have same expression for all processes.

## 3.4.1 Change in entropy:

The general expression for change in entropy of a perfect gas is obtained

$P_1V_1T_1$ = Intial state of gas

$P_2V_2T_2$ = Final state of gas

$$dT = T_2 - T_1$$

$$dv = V_2 - V_1$$

work done by gas $W_{1-2} = Pdv$

change in internal energy of gas $= Q_{1-2} = dU + (W_{1-2})$

$$Q_{1-2} = m C_v dT + Pdv$$

Expression interms of volume and absolute temp

$$\therefore S_2 - S_1 = m\left[C_v \ln \frac{T_2}{T_1} + (C_p - C_v) \ln \frac{V_2}{V_1}\right]$$

Expression interms of pressure and absolute temp of gas

$$\therefore S_2 - S_1 = m\left[C_p \ln \frac{T_2}{T_1} + (C_p - C_v) \ln \frac{P_1}{P_2}\right]$$

Expression interms of pressure and volume of gas

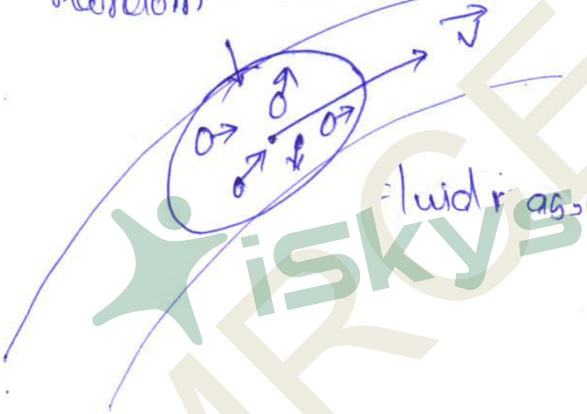
$$\therefore S_2 - S_1 = m\left[C_v \ln \frac{P_2}{P_1} + C_p \ln \frac{V_2}{V_1}\right].$$

$dU = mC_v (T_2 - T_1)$ for all expansion process.

Macroscopic energy & Microscopic

$$E = E_{trans} + E_{rot} + E_{vib} + E_{chem} + E_{electro} + E_{nuclear}$$

Random thermal motion of molecules.



$$E = E_K + E_p + \underbrace{U}_{micro.}$$

$E_K$ → Kinetic

$E_p$ → potential

$U$ → Internal energy.

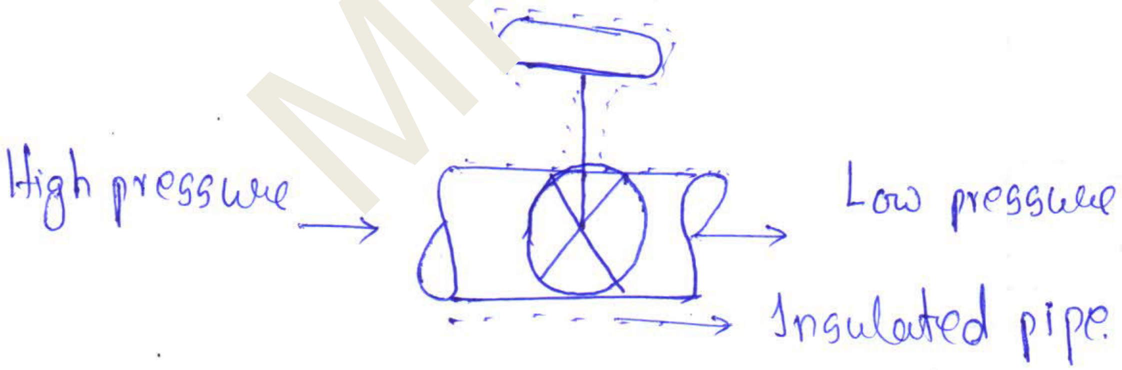
# Throtting and free Expansions Process

when a fluid expands through a small opening (Capture). Such as narrow (or) through a slightly opened valve, the fluid is said to be throttled. In this process the fluid from high pressure to low pressure. $\Delta Q = 0$, $\Delta W = 0$ $\Delta U = 0$.

Total heat of fluid remains constant

This is also called Isenthalpic process as the enthalpy remains constant during the process

$\Delta H = 0$, $H_1 = H_2$.



## 5.1 Free expansion process:

Free expansion process is that during which, no heat is supplied nor rejected and no external work is done.

Hence total heat of the system remains constant. This process occurs, when a fluid is allowed to expand suddenly into vacuum chamber through an orifice of large dimensions.

$\Delta Q = 0,$

$\Delta W = 0,$

$\Delta V = 0$ for a free expansion process.

I$^{st}$ law

$U_2 = U_1$

$T_2 = T_1,$

$H_2 = H_1.$

## Flow Processes

The process occurring in control volume (or) open system in which transfer of mass is permitted through boundary are called flow processes.

The gases which obey the gas law $PV=RT$ are called perfect gases but in actual practice there is no perfect gas.

A real gas does not obey the gas laws $PV=RT$ over the entire range of temp and pressure except when pressure approaches zero at relatively high temp.

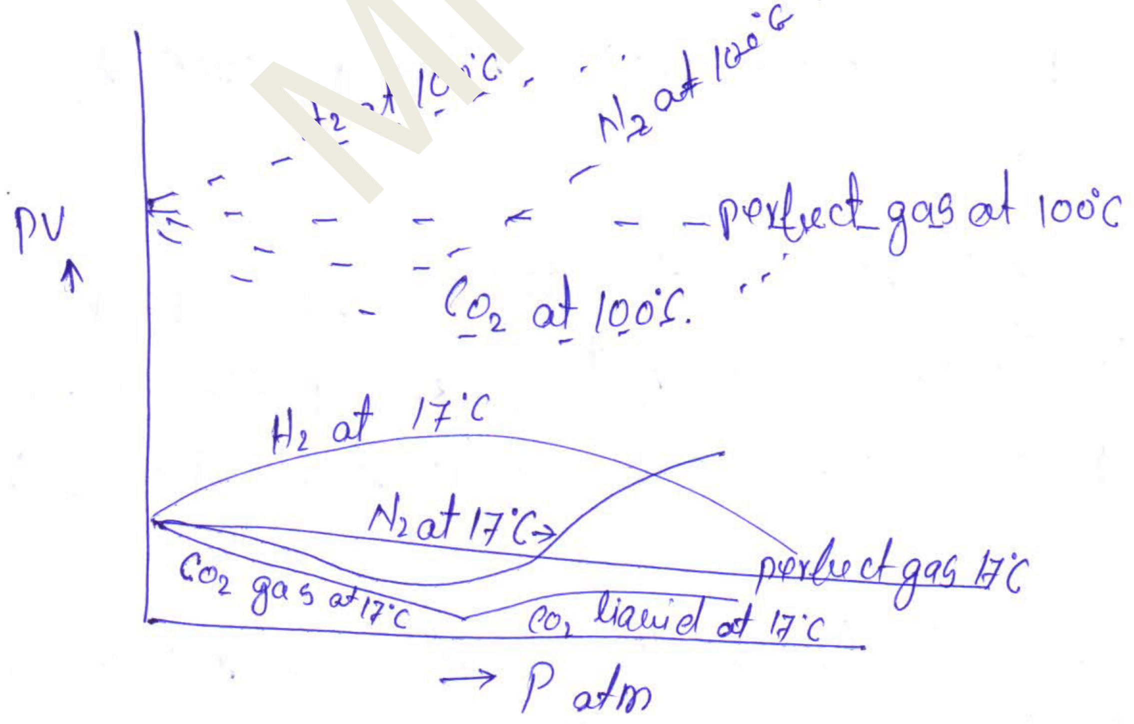
According to kinetic theory of gases, assumptions are made for analysis of perfect gas.

### 3.5.3 Deviations from perfect gas model.

But if pressure and temp are such that above assumptions are not satisfied behaviour of real gas deviates from that of ideal gas.

Main reasons for deviation are:

- * shape factors and inter molecular forces
- * Electrical forces
- * Hydrogen bonding
- * Quantum effects.



# Vanderwalls Equation of State

Since real gases deviate from perfect gases, vander waal proposed an equation which would applicable to real gases also.

Equation of state was derived based on assumptions of kinetic theory of gases

① There is no intermolecular forces between particles

② The volume of molecules is negligible in comparison with the gas.

But in real gases as pressure increases, the inter molecular force between particles increase and there by volume occupied by particles is also important to consider in comparison with total volume.

The internal pressure is proportional to number of attracting molecules per unit volume and to the number of attracting molecules that strike the unit area of wall per unit time.

Both these factors are proportional to number of molecules in unit volume of gas (or) density of gas

Vander Waal suggested that the reduction of pressure is proportional to square of moral density and in turn is equal to $a/v^2$ where $v$ is total volume and $a$ is proportionality constant

$$\text{Reduction of pressure} \propto = a/v^2$$

Pressure exerted by gas = kinetic pressure - Internal pressure

$$P = P_1 - a/v^2$$

$$P_1 = P + a/v^2$$

where $a$ is constant that is responsible for reduction of pressure due to long range attractive force.

The volume occupied by molecules ($v$) is replaced by $(v-b)$ by vander Waals where $b$ is a constant that is responsible for reduction in volume also causes increase in pressure.

Thus deviation of real gases over perfect gases is given by Vander Waal's equation $\left(P+\frac{a}{v^2}\right)(v-b) = RT$

$$P = \frac{RT}{v-b} - \frac{a}{v^2}$$

P → $N/m^2$, V → molar volume $m^3/kg$. mole

T → Temp. K   R → 8.314 kJ/kg. mole

a → const $N \cdot m^4/(kg\ mole)^2$

when pressure approaches zero and volume approaches infinity, the vanderwaal's eq of state reduces to $PV = RT$.

## Compressibility Chats

The equation of state is applicable to perfect gases. To apply equation of state for non-perfect gases compressibility factor is introduced so that

$$Z = PV/RT \qquad Z \rightarrow \text{compressibility factor}$$

for perfect gases $Z = 1$

The virial equation of state represents an expansion of product PV in finite series form.

$$PV = RT\left(1 + \frac{B}{V} + \frac{C}{V^2} + \frac{D}{V^3} + \cdots\right)$$

const. B, C, D are called virial coefficients and they depend on temp

The virial equation with pressure as independent variable can be written as

$$PV = RT(1 + B'P + C'P^2 + D'P^3 + \cdots)$$

The virial coefficients provide series correction to ideal gas behaviour. This can be done by using compressibility factor.

$$Z^3 - \left(\frac{P_r}{8T_r}+1\right)Z^2 + \left(\frac{27P_r}{64T_r^2}\right)Z - \frac{27P_r^2}{512T_r^3} = 0$$

This equation is another form of vanderwaal's equation and it can be solved by Z in terms of $P_r$, $T_r$, $Z = f(P_r, T_r)$

This law of corresponding states is basis of generalised compressibility chart

$P_a = P/P_c$ → reduced pressure

$V_r = V/V_c$ → " volume

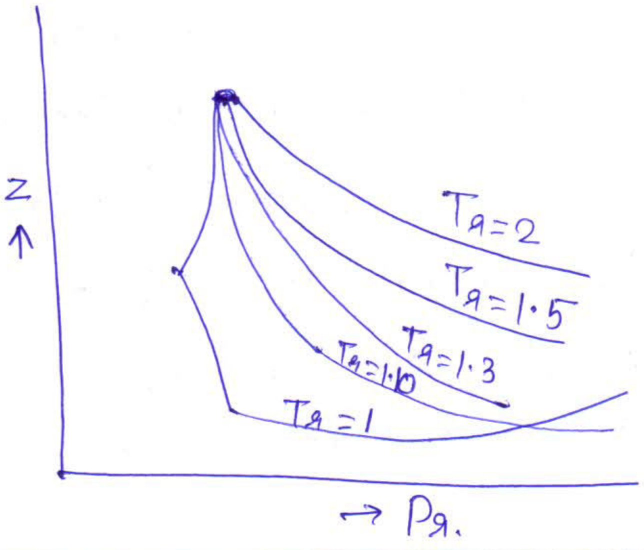
$T_r = T/T_c$ → " temp

we know that $Z = PV/RT$

$\therefore P_r = P/P_c \Rightarrow P = P_r \cdot P_c$

||y $V = V_r \cdot V_c$

$T = T_r \cdot T_c$.



# Variable Specific heats

The specific heat of any gas increase with increase in temp.

At high temp due to collisions among molecules of gas vibrations are caused.

These vibrations of molecules causes increases in specific heat

For gases in a temp range of 300k to 1500k, sp. heat varies linearly with temp and is given by

$C_p = a + KT$ & $C_v = b + KT$ where a & b and K are const

$R = C_p - C_v = (a + KT) - (b + KT) = a - b$

Above 1500k specific heat varies very rapidly and is given by

$$C_p = a + K_1 T + K_2 T^2$$

$$C_v = b + K_1 T + K_2 T^2$$

### 3.6.3 Gas Tables:

The enthalpy and internal energy of a gas which obeys equations of state $PV = RT$ are functions of only temp can be calculated by appropriate relation for specific heats as given in table. These calculations are done by Keenan and Kaye and tabulated as Gas tables.

For these tables zero reference level for enthalpy and internal energy is taken as zero degrees absolute

* change in entropy: $s_2 - s_1 = \phi_2 - \phi_1 - R \ln \frac{P_2}{P_1}$

* Relative pressure $(P_r)$: $P_r = P/P_0$ $\therefore \ln P_r = \phi/R$

For reversible adiabatic process, the relative pressure is a function of temp alone since $\phi$ is dependent only on temp $P_1/P_2 = (P_{r_1})/(P_{r_2})_{s=const}$

* Relative volume:

Similarly the relative volume $(V_r)$ for isentropic process is derived $\ln V_r = \ln V/V_0 = -1/R \int_{T_0}^{T} C_v dT/T$

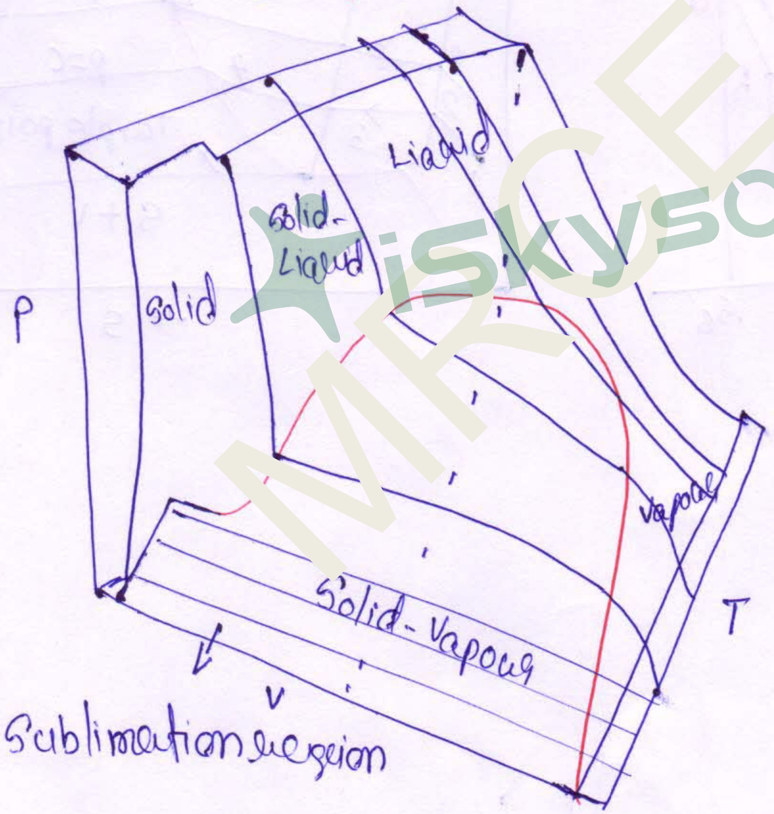
$V_r$ is relative volume $V_r = V/V_0$ and also $\frac{V_1}{V_2} = \left(\frac{V_{r_1}}{V_{r_2}}\right)_{s=const}$

values of relative pressure and relative volume are tabulated for air tables.

# Pure Substance

Pure substance is the working substance for power plants. Pure substance is defined as one which is having constant chemical composition through out its phase.

## 3.7.1 P-V-T Surfaces.

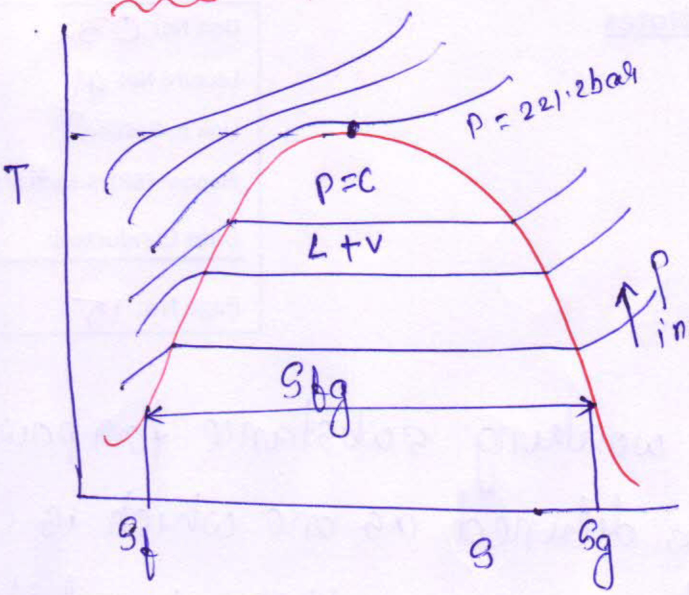


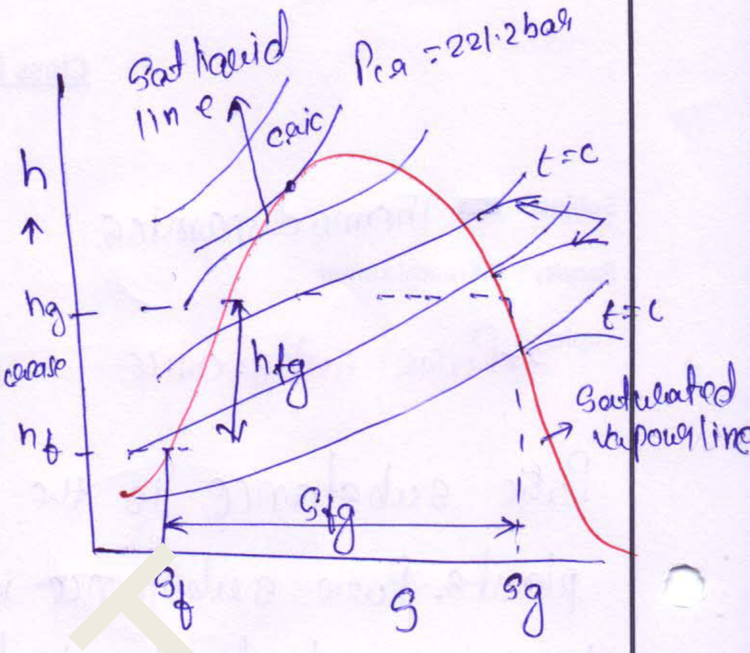
$P_c = 221.2 \text{ bar}$

$V_c = 0.00317 \text{ m}^3/\text{kg}$

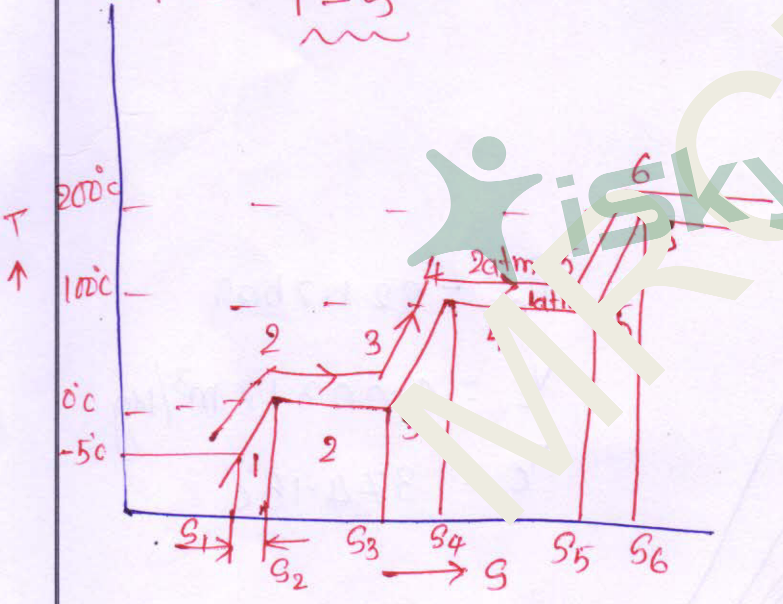
$T_c = 374.15^\circ\text{c}$

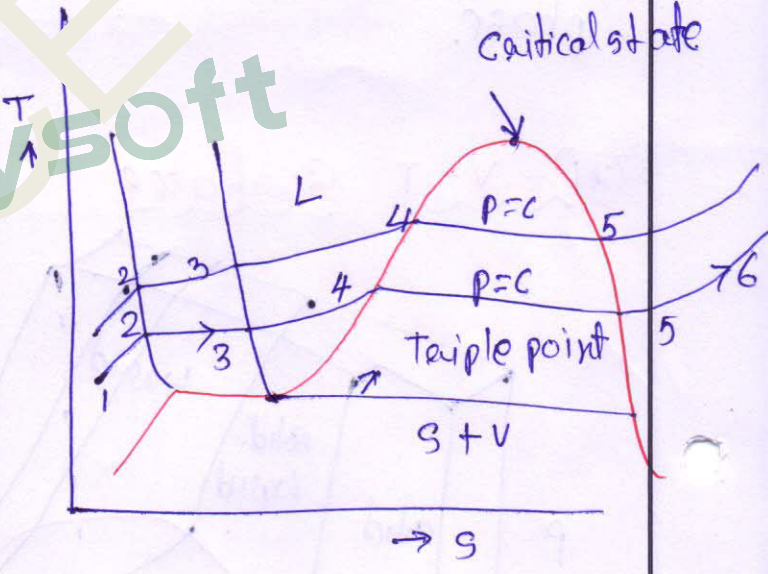
## 3.7.2 T-S & h-S





## 3.7.3 T-S





# Mollier Diagram

Mollier diagram indicating only the liquid and vapour phases.

As the pressure increases, the saturation temp increases and so the slope of the isobar also increases. Hence the constant pressure lines diverge from one another and the critical isobar is a tangent at the critical point.

Isothermal bends towards the right and its slope decreases asymtropically to zero, because the ideal gas region it becomes horizontal and const enthalpy implies const temp.

At a particular pressure $h_f$ is the specific enthalpy of saturated water, $h_g$ is that of saturated vapour and $h_{fg} = (h_g - h_f)$ is the latent heat of vapourisation at that pressure. As the pressure increases $h_{fg}$ decreases and the critical pressure, $h_{fg}$ becomes zero.

## 3.7.5 phase transformations

phase is defined as homogeneous, chemical and physical state of molecules.

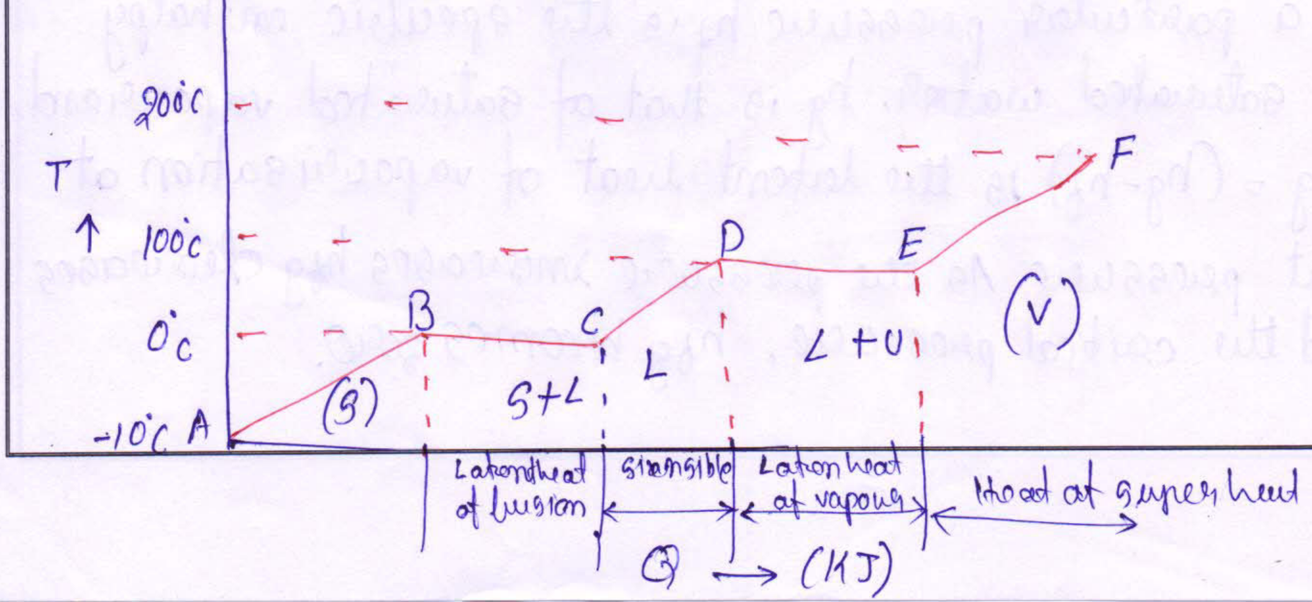
A pure substance exists in three phases:
(i) Solid (ii) Liquid (iii) Vapour (or) gaseous phase.
ex: Water has three phases.

* when ice melts, there is change of phase from solid to liquid which is called melting (or) fusion of the ice.

* If water changes from liquid to solid phase again it is called freezing (or) solidification

* change of phase from liquid to vapour phase is called vaporization

* change of phase from vapour phase to liquid phase condensation.



## Tripple Point at various Critical States

Triple point is defined as the point at which solid, liquid, and vapour phases of a substances coexist in equilibrium.

Ex: Consider phase transformation in ice to steam there exists fusion line, vaporization line, Sublimation line.

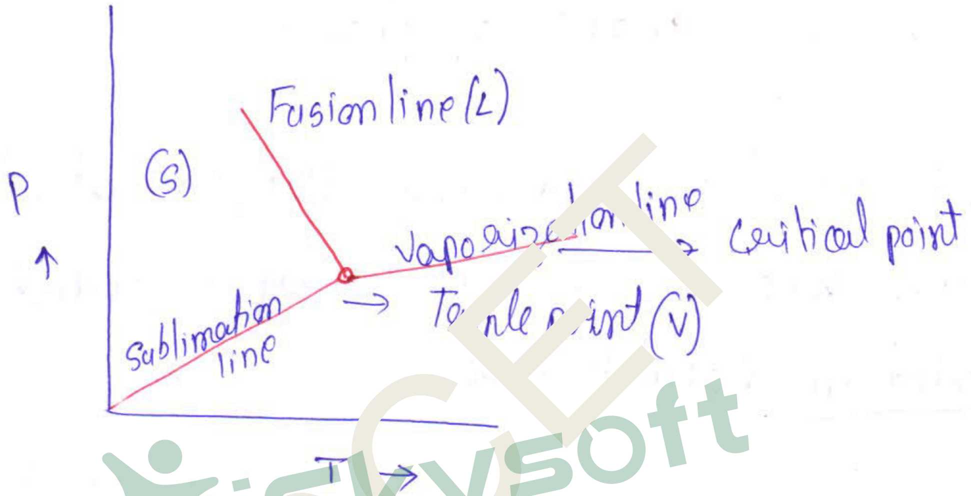
Along fusion line solid and liquid phases are in equilibrium

Along vaporization line liquid and vapour phases are in equilibrium.

The vaporization line ends at critical point.

Along sublimation line, the solid and vapour phases are in equilibrium

The fusion line, the vaporization line and sublimation line meet at a point. The point is called Triple point.



During phase transformations like melting, vapourisation and sublimation, the temp and pressure remain constant while the entropy and volume change. If $x$ is the fraction of initial phase $i$ which has been transferred into final phase $f$.

S & V are linear functions of $x$.

$$S = (1-x)\,s(i) + x \cdot s(f)$$

For reversible phase transformations the heat transferred per mole (or per kg) is the latent heat

$$l = T\{s(f) - s(i)\}$$

which indicates the change in entropy

$$dg = -s\,dT + v\,dp$$

$$s = -\left(\frac{\partial g}{\partial T}\right)_p$$

$$v = (\partial g/\partial p)_T$$

A phase change of the first order is known as any phase changes that satifies the following requirements

- * There are changes of entropy and volume
- * The first-order derivates of Gibbs function change discontinuosly.

Let us consider the first order phase transition of one mole of a substance from phase 'i' to phase 'f' using the first Tds equation

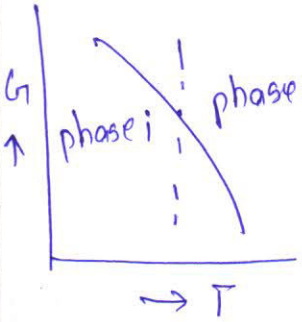
$$T ds = C_v dT + T\left(\frac{\partial P}{\partial T}\right)_v dv$$

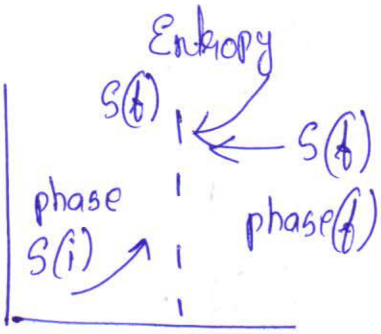
for the phase transition which is reversible, isothermal and isobaric and integrating over the whole change of phase and since $(\partial P/\partial T)_v$ is independent of v.

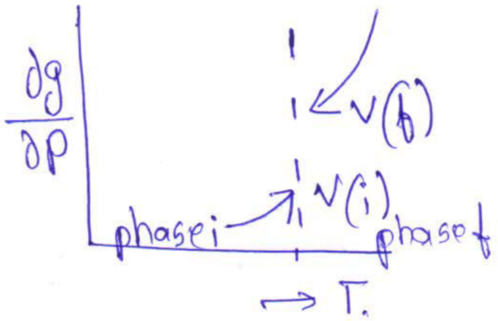
$$T\{s^{(f)} - s^{(i)}\} = T\frac{dp}{dT}\{v^{(f)} - v^{(i)}\}$$

$$\therefore \frac{dp}{dT} = \frac{s^{(f)} - s^{(i)}}{v^{(f)} - v^{(i)}} = \frac{l}{T\{v^{(f)} - v^{(i)}\}}$$

The above eq is called clausius - clapeyron equation







# Dryness Fraction

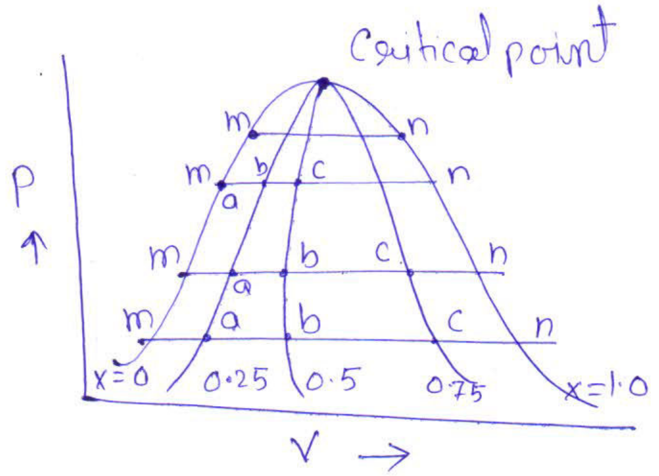
If 1kg of liquid-vapour mixture, $x$ kg is the mass of vapour and $(1-x)$ kg is the mass of liquid, then $x$ is known as the quantity (or) dryness fraction of the liquid vapour mixture. Therefore quality (or) dryness indicates the mass fraction of vapour in a liquid vapour mixture

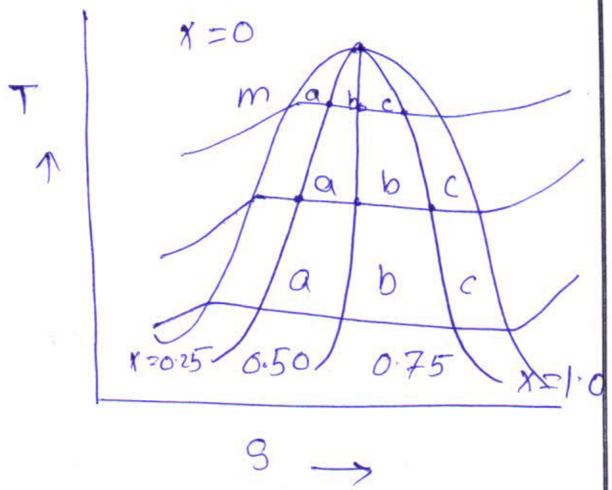
(or) $x = m_v / m_v + m_l$

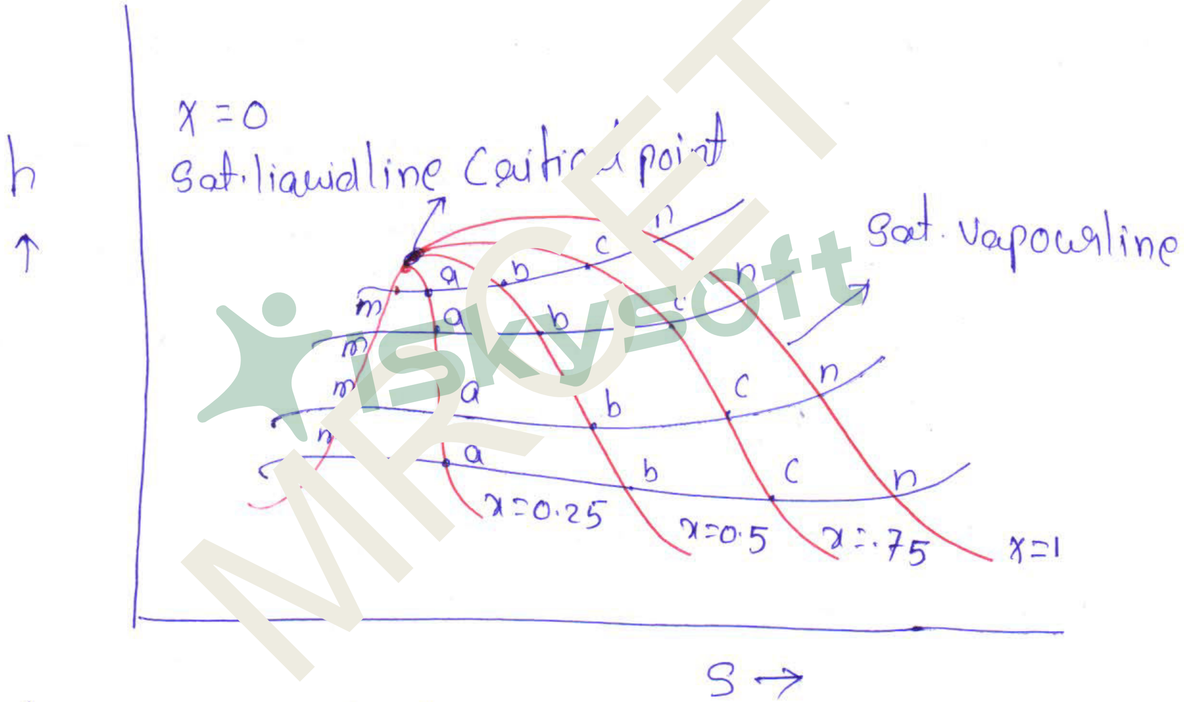
where $m_v$ & $m_l$ are the masses of vapour and liquid respectively in the mixture. The values of $x$ varies between 0 and 1

$x = 0$ for saturated water, $x = 1$ for saturated vapour.

Points m indicate the saturate liquid states with $x=0$,
Points n indicate the saturate vapour states with $x=1$.







* The lines mn indicate the saturate liquid states x=0 transition from liquid to vapour. Points a, b, c at various pressure indicate the situations when the masses of vapour reached 25%, 50% 75% of the total mass.

## Dryness Fraction ( Extension)

Let v be the volume of a liquid vapour mixture of quality x, $v_f$ be the volume of the saturated liquid, $v_g$ the volume of the saturated vapour, the corresponding masses being m, $m_f$ & $m_g$ respectively.

$$m = m_f + m_g$$

$$V = V_f + V_g$$

$$mv = m_f v_f + m_g v_g$$

$$= (m - m_g) v_f + m_g v_g$$

$$v = \left(1 - \frac{m_g}{m}\right) v_f + \frac{m_g}{m} v_g$$

$$v = (1-x) v_f + x v_g$$

$x = m_g / m$

$v_f$ = sp.vol of sat liquid

$v_g$ = sp.vol of sat. vapour

$v$ = sp.vol of mix of quality 'x'

Similarly

$$s = (1-x) s_f + x \cdot s_g$$

$$h = (1-x) h_f + x \cdot h_g$$

$$u = (1-x) u_f + x \cdot u_g$$

where s, h & u refer to the mixture of quality 'x'. the suffix f and suffix g indicate the conditions.

$$v = (1-x)\, v_f + x\, v_g$$

$$= v_f + x\,(v_g - v_f)$$

$$= V_f + x\, V_{fg}$$

$$V = v_f + x\, v_{fg}$$

Similarly $h = h_f + x\, h_{fg}$

$$s = s_f + x\, s_{f \cdot g}$$

$$u = u_f + x\, u_{fg}.$$

Mollier Charts.

# Mollier Cheats

steam tables are also represented on a graph in which enthalpy (h) is plotted against entropy (s).

This was done by Dr. Mollier and hence is known as mollier chart.

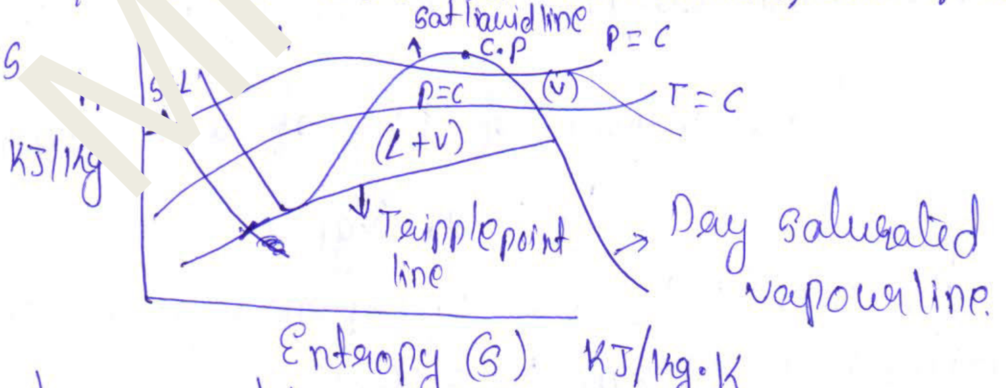
we know that $Tds = dh - vdp$

$$\frac{dh}{ds} - vdp = T$$

At const pressure $dp = 0$

$$\therefore \left(\frac{\partial h}{\partial s}\right)_p = T$$

This equation forms the basis for moiller diagram of a pure substances



shows the phase equilibrium diagram of pure substance of h-s co-ordinates indicating saturated solid line, vapour line, various phases and transition zones.

6M

## 3.9.1 Various thermodynamic process and energies transfered.

Various thermodynamic process for heating and cooling of vapour are:

- * Isochoric process
- * Isobaric process
- * Isothermal process
- * Isentropic process
- * polytropic process
- * Throttling process.

Consider 1kg of wet steam is heated from intial state 1 and final state 2.

$P_1$ = Intial pressure of wet steam.

$V_{g_1}$ = Sp. volume of dry saturated steam corresponding to pressure P.

$x_1$ = Intial dryness fraction of wet steam

Intial volume of 1kg of wet steam

$$V_1 = x_1 \cdot V_{g_1}$$

Let $P_2$, $V_{g2}$, $x_2$, $V_2$ are corresponding values for final conditions of steam $V_2 = x_2 \cdot V_{g2}$.

**Topic:** 3.9.2 Energies transfered & steam Calorimetry

* If the value of $x_2$ is less than and i.e $x_2 < 1$ final condition of steam is wet.

* If the value of $x_2$ is equal to one i.e $x_2 = 1$ final condition of steam is dry and saturated then $V_2 = x_2 \cdot V_{g2}$.

* If the value of $x_2$ is greater than one i.e $x_2 > 1$ final condition of steam is super heated.

$$V_2 = V_{sup}$$

$$= V_{g2}\left(\frac{T_{sup}}{T_2}\right)$$

$V_{sup}$ = volume of super heated steam.

$T_{sup}$ = is temp of sup heat steam.

### 3.9.3 Steam Calorimetry:

Steam calorimeters are used to determine the dryness fraction of wet steam.

Commonly used steam calorimeters are

- * Barrel calorimeter
- * Seperating calorimeter
- * Throttling calorimeter
- * Combined seperating and throttling calorimeter.

# Mixtures of Perfect Gases

## Introduction : (6.1) :

A mixture is defined as combination. If a mixture remains ~~and~~ homogeneous in composition throughout the process then it is considered to be pure substance. The mixture of pure substance is classified into two types

1) Mixture of perfect gas
2) Mixture of perfect gas and vapour (or) psychrometry.

The thermodynamic behaviour of mixture of perfect gases and psychrometry depends on the individual properties of gases involved in mixture.

A gas mixture may be analysed (1) on the basis of mass (2) on the basis of number of moles.

## Mole fraction: $x$ (6.2)

The ratio $n_i/n = n_i/\Sigma n_i$ is defined as mole fraction of component of mixture is denoted by $x_i$

$$\text{Mole fraction} = \frac{\text{No. of moles of component}}{\text{Total no of moles of mixture}}$$

$$x_1 = \frac{n_1}{n}, \quad x_2 = \frac{n_2}{n} \quad x_N = \frac{n_N}{n}$$

one gm mol of oxygen has a 32 gm. 1 kg mol of oxygen has a masses of 32 kg.
1 kg mol of nitrogen has mass of 28 kg

$$\therefore x_1 + x_2 + x_3 + \dots + x_N = 1$$

The sum of mole fractions of all the components present in the mixture is unity.

Avogadro's law → volume of a g mol of all gases at the pressure of 760 mm of Hg, 1 g mol of a gas has a volume of 22.4×10³ cm³. 1 kg mol of a gas has volume 22.4 m³

Mass fraction: (6.1.3)

The ratio of $\frac{m_i}{m_{tot}} = \frac{m_i}{\Sigma m_i}$ is defined as the mass fraction of component of mixture and is denoted by $y_i$.

Mass fraction = Mass of component / Total mass.

$$y_1 = \frac{m_1}{m_{tot}}, \quad y_2 = \frac{m_2}{m_{tot}} \quad \dots \quad y_N = \frac{m_N}{m_{tot}}$$

$$\therefore y_1 + y_2 + \dots y_N = 1$$

The sum of mass fractions of all components present in mixture is unity

Gravimetric analysis – mass fraction: (6.1.4)

If a gas is analysed on the basis of mass (or) weight it is called gravimetric analysis.

Consider a general mixture of N components. $m_{tot}$ is total sum of masses of each of N components Then $= \frac{m_i}{m_{tot}}$.

## Topic: Volumetric analysis - mole fraction: (6.15)

when analysis of gas mixture is based on number of moles of each component present, it is called volumetric analysis

Consider a general mixture of N components then total no of moles n then n is given by ⇒ $n = n_1 + n_2 + n_3 + \dots + N$.

$$= \sum_{n=1}^{N} n_i$$

The ratio $\frac{n_i}{n} = \frac{n_i}{\sum n_i}$

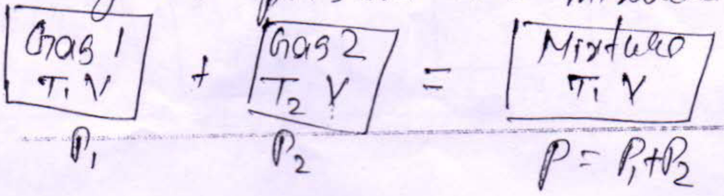
## Dalton's law of partial pressures. (6.2)

The total pressure of a mixture of perfect gases is equal to sum of the partial pressures of the components each measured alone at volume and temp of mixture.

The partial pressure of a gas in the mixture is the pressure it would exert if it alone occupied the total volume of mixture at the same temp

mathematically $P = P_1 + P_2 + P_3 + \dots P_N = \sum_{i=1}^{N} P_i$

Consider two gases present in a mixture



For perfect gas $P_1V = n_1RT$

$$P_2V = n_2RT$$

1 (+) 2 $\Rightarrow$ $P_1V + P_2V = n_1RT + n_2RT$

$$(P_1+P_2)V = (n_1+n_2)RT$$

$$PV = nRT$$

∴ Mixture of perfect gas 1 and 2 also acts like a perfect gas $\frac{(1)}{(3)} \Rightarrow P_1 = \frac{n_1}{n}P = x_1P$

$$P_2 = \frac{n_2}{n}P = x_2P$$

$P_1, P_2$ are called partial pressures

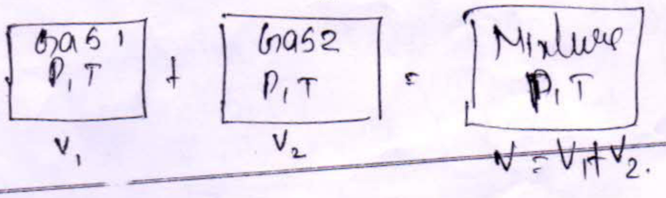
As each component occupies same volume and has same temp $\therefore \frac{P_1}{n_1} = \frac{P_2}{n_2} = \dots = \frac{P}{n}$

## Avogadro's law of Additive volumes: (6.2.1)

"Under identical conditions of pressure and temp, equal volumes of all gases contain same number of molecules.

According to Amagat's law of additive volumes, the total volume of a mixture of gases is equal to sum of partial volumes of component gases, each measured alone at pressure and temp of mixture

$$V = V_1 + V_2 + V_3 + \dots V_N = \sum_{i=1}^{N} V_i$$



**Topic:** Amagat's law point of view: (6·2·1·a)

for 1st perfect gas $PV_1 = n_1RT$ — ①

for 2nd perfect gas $PV_2 = n_2RT$ — ②

$$① + ② \quad PV_1 + PV_2 = n_1RT + n_2RT$$

$$P(V_1 + V_2) = (n_1 + n_2)RT$$

$$PV = nRT \; — ③$$

The mixture of gases also behave like perfect gas

$$①/③ \Rightarrow \frac{V_1}{V} = \frac{n_1}{n}$$

$$V_1 = x_1 V$$

$$V_2 = x_1 V$$

or $x_1 = V_1/V$, $x_2 = V_2/V$

∴ The ratio of partial volume of a gas component to total volume is mole fraction. As each component occupies same pressure and has same temp.

$V_1/n_1 = V_2/n_2 = \text{----} \; V/n$

Since Dalton's law $P_1 = x_1 \cdot P$

$P_2 = x_2 \cdot P$

From Amagat's law $V_1 = x_1 V$, $V_2 = x_2 V$

$x_1 = n_1/n = V_1/V = P_1/P \quad x_2 = n_2/n = V_2/V = P_2/P$

∴ $x_i = n_i/n = V_i/V = P_i/P$

Mole fraction of component is equal to volume fraction and ratio of partial pressure to total pressure.

## Mole fraction: (6·2·2)

The ratio of partial volume of gas component to total volume is mole fraction

## volume fraction: (6·2·3) & Partial pressure:

Mole fraction of component is equal to volume fraction of partial pressure to total pressure.

## Equivalent gas constant of mixture · (6·2·4)

For mixture of two perfect gas

$$PV = mRT$$

and for each component at same volume and temp.

$$P_1 V = m_1 R_1 T$$

$$P_2 V = m_2 R_2 T$$

According to Dalton's law

$$P = P_1 + P_2$$

$$PV = P_1 V + P_2 V$$

$$PV = m_1 R_1 T + m_2 R_2 T = (m_1 R_1 + m_2 R_2) T$$

$\therefore$ since $PV = mRT$

$$mR = m_1 R_1 + m_2 R_2 \qquad R = \frac{m_1}{m} R_1 + \frac{m_2}{m} R_2$$

$$= y_1 R_1 + y_2 R_2$$

$$R = \Sigma \frac{m_i}{m} R_i = \Sigma y_i R_i$$

where $y_i$ is mass fraction.

## Topic: Molecular internal energy of mixture of perfect gas (6·3)

For a mixture of two perfect gas, on the basis of Gibbs Dalton's law, the total molecular internal energy of the mixture is given by $U = U_1 + U_2$

The total molecular internal energy of each component can be expressed on gravimeteric basis.

$$mu = m_1 u_1 + m_2 u_2$$

where $u$ is specific internal energy

$$\therefore u = \frac{m_1}{m} u_1 + \frac{m_2}{m} u_2$$

$$= y_1 u_1 + y_2 u_2$$

On volumeteric basis, the total molecular internal energy of each component can be expressed

$$\therefore nu = n_1 u_1 + n_2 u_2$$

$$u = \frac{n_1}{n} u_1 + \frac{n_2}{n} u_2$$

$$= x_1 u_1 + x_2 u_2$$

where $\underline{u}$ is molar Specific internal energy.

## Enthalpy of mixture of perfect gases: (6·3·1)

The enthalpy of mixture of two perfect gases $H = H_1 + H_2$

On gravimeteric basis $mh = m_1 h_1 + m_2 h_2$ $h = y_1 h_1 + y_2 h_2$

On volumeteric basis $nh = n_1 h_1 + n_2 h_2$ $h = x_1 h_1 + x_2 h_2$.

## Specific heats of mixture of perfect gases: (6·3·2)

From molecular internal energy of mixture of two perfect gas on Gravimetric basis $mu = m_1 u_1 + m_2 u_2$ $\quad u = C_v \cdot dT$

$$\therefore m C_v dT = m_1 C_{v1} \cdot dT + m_2 C_{v2} dT$$

$$C_v = \frac{m_1}{m} C_{v_1} + \frac{m_2}{m} C_{v_2}$$

$$= y_1 C_{v_1} + y_2 C_{v_2}$$

Simillarly of volumetric basis $C_v = \frac{n_1}{n} C_{v_1} + \frac{n_2}{n} C_{v_2} = x_1 C_{v_1} + x_2 C_{v_2}$

from enthalpy of mixture of two perfect gases on gravimetric basis.

$$mh = m_1 h_1 + m_2 h_2 \qquad h = C_p dT$$

$$m C_p dT = m_1 C_{p1} dT + m_2 C_{p2} dT$$

$$C_p = \frac{m_1}{m} C_{p_1} + \frac{m_2}{m} C_{p_2} \qquad C_p = y_1 C_{p1} + y_2 C_{p2}$$

$\therefore$ similarly on volumetric basis

$$C_p = \frac{n_1}{n} C_{p_1} + \frac{n_2}{n} C_{p2}$$

$\therefore$ Specific heat at constant volume of mixture of two perfect gases is given by $C_v = y_1 C_{v_1} + y_2 C_{v_2} = x_1 C_{v_1} + x_2 C_{v_2}$

Specific heat at constant pressure of mixture of two perfect gases is given by $C_p = y_1 C_{p1} + y_2 C_{p2} = x_1 C_{p1} + x_2 C_{p2}$

## Entropy of mixture of perfect gases (6·3·3)

The entropy of mixture of two perfect gases is given by $S = S_1 + S_2$

on Gravimetric basis $ms = m_1 s_1 + m_2 s_2$ $\quad s = \frac{m_1}{m} s_1 + \frac{m_2}{m} s_2 = y_1 s_1 + y_2 s_2$

on volumetric basis $= n s = x_1 s_1 + x_2 s_2$

The entropy change of perfect gas $= C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$,

where two gases are mixed adiabatically

$$(S_2 - S_1)_1 = -n_1 R_0 \ln P_1/P \qquad (S_2 - S_1)_2 = -n_2 R_0 \ln P_2/P$$

$$S_2 - S_1 = -R_0 \left[ n_1 \ln P_1/P + n_2 \ln \frac{P_2}{P} \right] = -R_1 \left[ n_1 \ln x_1 + n_2 \ln x_2 \right]$$

Therefore it can be concluded that the increase in entropy of mixture of perfect gases depends only on number of moles of component gas.

## Topic: Mixtures of perfect gases and vapour: (6.4)

The vapour in mixtures of perfect gas and vapour can be treated as perfect gas. Therefore the general rules applicable to mixture of perfect gases applies to mixture of perfect gas and vapour.

The composition of former may change on heating or cooling whereas in latter doesnot change normally. when the temp of gas-vapour mixture is lowered below a certain limit, it may condense (or) solidify resulting in change of composition of mixture

The vapour condenses to liquid form if its partial pressure is above triple point pressure and solidifies directly if the pressure is below triple point pressure.

Atmospheric air is a good example for mixture of perfect gas and vapour.

### Atmospheric air (6.4.1):

Atmospheric air is usually moist air which is actually a mixture of dry air and water vapour. The science which deals with properties of air-water vapour mixture is called as psychrometry.

## Psychrometric terms & properties : (6.5)

### (a) Moist air: (6.5.1)

Atmospheric air is moist air. Moist air is mixture of dry air and water vapour. Dry air is from moisture $O_2$ - 20.99%. $N_2$ - 78.03%, Argon - 0.94%, $CO_2$ - 0.03% and tracess of rare gas by volume. The amount of water vapour present in moist air depends upon the absolute pressure and temperature of mixture.

### (b) Saturated air : (6.5.2)

It is the mixture of dry air and water vapour when the partial pressure of vapour is equal to saturation pressure of water at temp of mixture. At this condition the mixture is said to be saturated with vapour.

### (c) Dry bulb temperature $(T_D)$ : (6.5.3)

The temperature of air recorded by conventional thermometer when it is not abbected by moisture present in air

### (d) Wet bulb temperature $(T_{wb})$ : (6.5.4)

The wet bulb temp is measured by a thermometer when bulb is covered with a wick standard with water and placed in moist air. Always wet bulb temp is less than dry bulb temp

### (e) Wet bulb depression : (6.5.4a)

wet bulb depression = $T_{wb} - T_{db}$

Topic: **Dew point temperature (6.5.5)**

It is the saturation temp corresponding to partial pressure of water vapour ($P_v$). It is the temp of air recorded by a thermometer when water vapour present in moist air begins to condense and is denoted by $t_{dp}$.

**Dew point Depression: (6.5.6)**

It is the difference between the dry bulb temp and dew point temp of air.

**Vapour pressure (6.5.7)**

$$P_v = P_w - \frac{(P_b - P_w)(t_d - t_w)}{1544 - 1.44 t_w}$$

$P_w$ → Saturation pressure corresponding to wetbulb temp from steam tab. les.

$P_b$ → Barometric pressure, $t_d$ = Dry bulb temp $t_w$ = Wet bulb temp.

**Relative Humidity (6.5.8)**

It is the ratio of actual mass of water vapour ($m_v$) in a given volume of moist air to mass of water vapour ($m_s$) in same volume of saturated air at same temp and pressure. Relative humidity = $\phi = m_v / m_s$

$\phi = P_v / P_s$ Partial pressure of water vapour in moist air ($P_v$) Temperature to saturation pressure ($P_s$) of water vapour at same temp

## Specific humidity: (6.5.9)

Specific humidity is the mass of water vapour present in 1kg of dry air. Specific humidity also termed as humidity, absolute humidity, humidity ratio, moisture content is also defined as the ratio of mass water vapour to mass of dry air in a given volume of air mixture

Specific humidity $= \omega = 0.622\, P_v/P_a$

$\omega = 0.622\, P_v / P_b - P_v$

$P_v \rightarrow$ Partial pressure of water vapour

$P_b \rightarrow$ Barometric pressure

$P_a \rightarrow$ Partial pressure of dry air

For saturated air specific humidity $= \omega = 0.622\, P_s / P_b - P_s$

$P_s$ = Partial pressure of saturated air from steam tables at dry bulb temp.

## Degree of saturation: (6.6

It is the ratio of actual mass of water vapour in a unit mass of dry air to mass of water vapour in same mass of dry air when it is saturated at same dry bulb temp.

It is also defined as the ratio of actual specific humidity to the specific humidity of saturated air at same dry bulb temp $\mu = \omega/\omega_s = 0.622\, P_v/P_b - P_v / 0.622 \cdot \frac{P_s}{P_b - P_s} = \frac{P_v (P_b - P_s)}{P_s (P_b - P_v)}$

$\mu = \phi\, (P_b - P_s)/P_b - P_v$

if relative humidity $\phi = 0$ then degree of saturation is zero and specific humidity is also zero $\mu = \phi\, (P_b - P_s)/P_b - P_v$

$= \phi \frac{1 - P_s/P_b}{\left(1 - \frac{P_v}{P_b}\right)}$, $\mu = \phi \left[\frac{1 - P_s/P_b}{1 - \frac{P_v}{P_s} \cdot \frac{P_s}{P_b}}\right]$ $\mu = \phi \left[\frac{1 - \frac{P_s}{P_b}}{1 - \phi \cdot \frac{P_s}{P_b}}\right]$ $\phi = \frac{\mu}{1 - (1 - \mu)\frac{P_s}{P_b}}$

so if relative humidity is equal to 1, then degree of saturation is $= 1$.

Topic: Enthalpy of moist air: (6·6·1)

The enthalpy of moist air is given by Gibb's Dalton law since moist air is mixture of dry air and water vapour.

Enthalpy of moist air = Enthalpy of dry air + water vapour + enthalpy of water vapour when moisture is super heated.

Enthalpy of dry air = $h_a = C_{pa} \cdot t_d$

$C_{pa}$ = sp. heat of dry air = 1.005 kJ/kg·K

$t_d$ = dry bulb temp

Enthalpy of water vapour $h_v = \omega \cdot h_s$

$\omega$ = sp. humidity

$h_s$ = enthalpy of water vapour at dew point temp

Enthalpy of water vapour, when moist air is super heated.

$h_{vs} = \omega\, C_{ps}(t_d - t_{dp})$

$C_{ps}$ = sp. heat of super heated water vapour = 1.9 kJ/kg. K

$t_d - t_{dp}$ = Degree of super heated of water vapour

∴ Total enthalpy of moist air

$$h = h_a + h_v + h_{vs}$$

$$h = C_{pa}\, t_d + \omega h_s + \omega C_{ps}(t_d - t_{dp})$$

$$= C_{pa} t_d + \omega[h_s + C_{ps}(t_d - t_{dp})]$$

$$h_s = h_{fdp} + h_{fgdp}$$

$$= 4{\cdot}2 t_{dp} + h_{fgdp}$$

$$h = C_{vm}\, t_d + \omega[h_{fgdp} + (4{\cdot}2 - C_{ps})t_{dp}]$$

$C_{vm}$ = Humid specific heat = 1.022 kJ/kg. K

$C_{ps}$ = 1.9 kJ/kg K

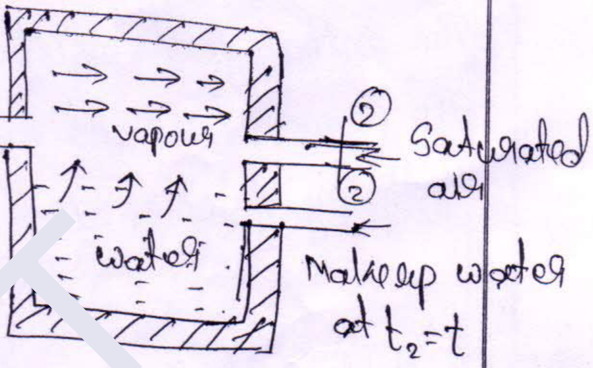
$$h = 1{\cdot}022 t_d + \omega[h_{fgdp} + (4{\cdot}2 - 1{\cdot}9)t_{dp}]$$

$$h = 1{\cdot}022 t_d + \omega[h_{fgdp} + 2{\cdot}3\, t_{dp}]\ \text{kJ}$$

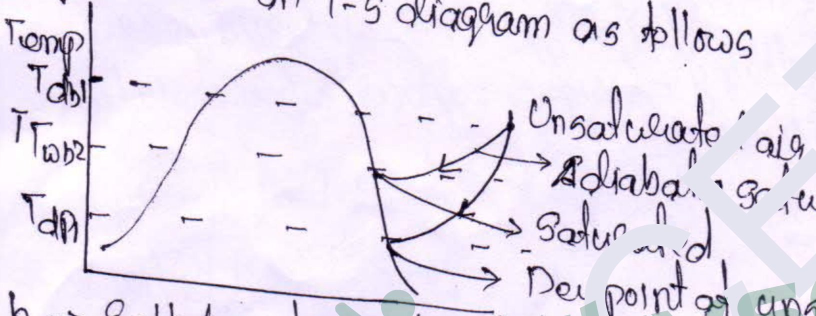
$h_{fgdp}$ = Latent heat of vapourisation of water corresponding to dewpoint temp obtained from steam tables.

# Adiabatic Saturation temp : (6·6·2)

An adiabatic saturation temp is defined as the temp which results from adding water adiabatically to the air in a steady flow untill it beomes saturated. the water being supplied at the final temp of mixture.



An adiabatic saturation can be represented on T-S diagram as follows



$h_1$ → Enthalpy of unsaturated air at section (1)

$\omega_1$ → sp. humidity of air at section (1)

$h_2$ = enthalpy at saturated air at section (2)

$\omega_2$ → sp. humidity of air at section (2)

$h_{fw}$ → Sensible heat of water at adiabatic saturation temp

Enthalpy at section (1) = Enthalpy at section (2)

$$h_1 + (\omega_2 - \omega_1) h_{fw} = h_2$$

$$h_1 - \omega_1 h_{fw} = h_2 - \omega_2 h_{fw}$$

$$h_1 = h_{a1} + \omega_1 h_{s1}$$

$$h_2 = h_{a2} + \omega_2 h_{s2}$$

$h_{a1}$ – enthalpy of 1kg of dry air at bulb temp $t_{db1}$

$h_{s1}$ – enthalpy of superheated vapour $t_{db1}$ per 1kg of vapour

$h_{a2}$ = enthalpy of 1kg of air at wet bulb temp $t_{wb2}$

$$(h_{a1} + \omega_1 h_{s1}) - \omega_1 h_{fw} = (h_{a2} + \omega_2 h_{s2}) - \omega_2 h_{fw}$$

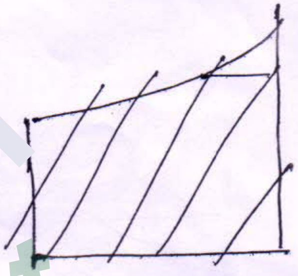
$$\omega_1 = \omega_2 (h_{s2} - h_{fw}) + h_{a2} - h_{a1} \,/\, h_{s1} - h_{fw}$$

$h_{s2}$ = enthalpy of saturated vapour at wet bulb temp $t_{wb2}$.

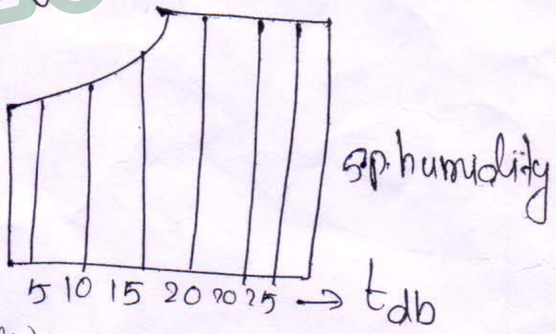
Topic: Psychrometric chart: (6.7)

Psychrometric chart shows various properties of moist air. It is a graphical representation of thermodynamic properties of moist air. The psychrometric chart is drawn for standard atmo-spheric pressure of 1.01325 bar. The dry bulb temp is abscissa and specific humidity, partial pressure are ordinates.

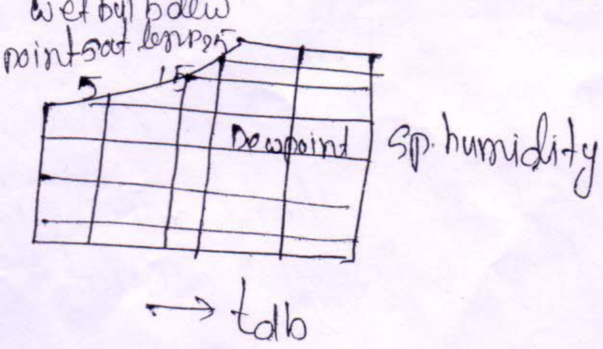
constant specific humidity lines: (a)



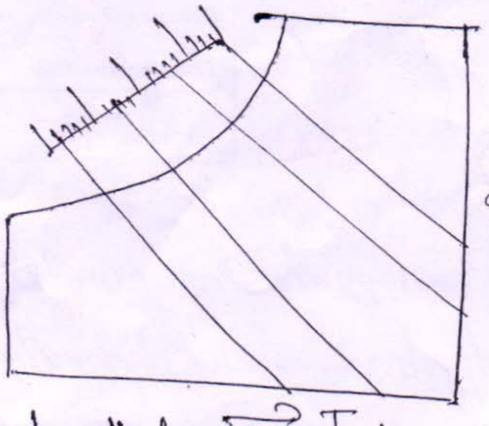
constant Dry bulb temp lines: (b)

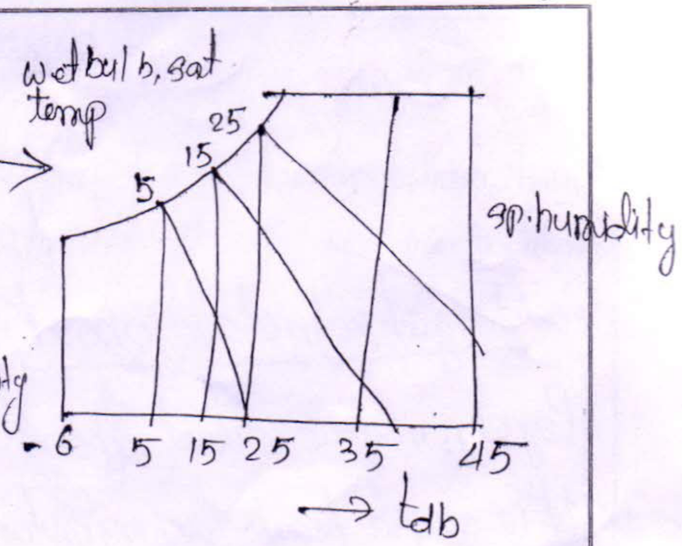


Dewpoint temp lines: (c).

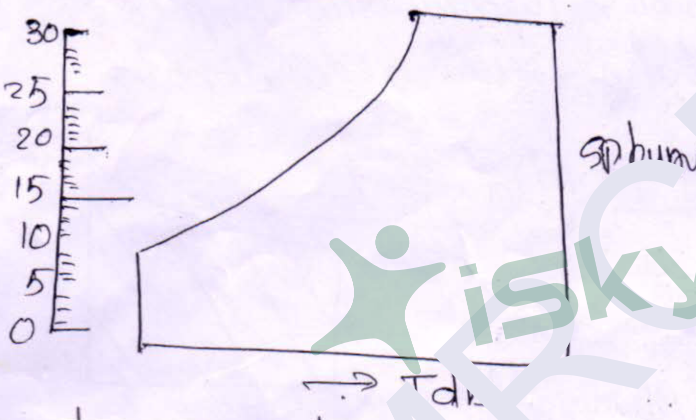


constant wet bulb temp lines:

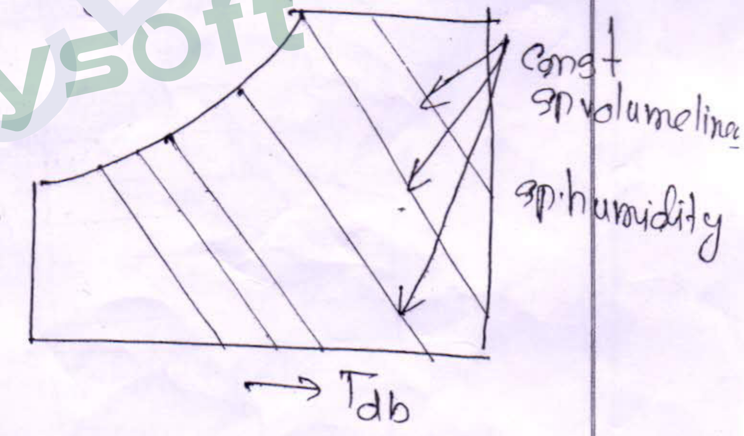


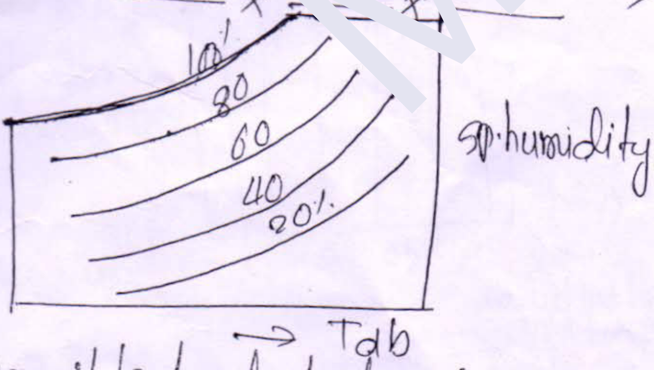


const enthalpy lines



const specific volume lines: →

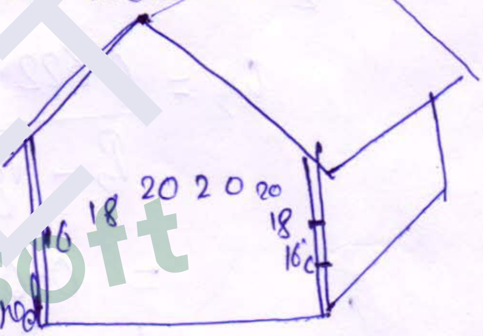




sensible heat factor (S.H.F) scale: $\frac{\text{Sensible heat}}{\text{sensible heat + Latent heat}}$

In psychrometric chart, S.H.F scale is on right side of chart
This is drawn with resp. to point at 50% R.H. line near 27°C dbt.

① In cold weather, condensation frequently occurs on the inner surface of the windows due to the lower air temp near the window surface. Consider a house that contains air at 20°c and 75% relative humidity. At what window temp will the moisture in the air start condensing on the inner surface of the windows?



Sol The window temp at which fogging starts is to be determined

20°c $P_{sat} = 2.392$ kpa

$P_v$ = const cooling process untill the moisture in the air starts condensing.

$$T_{dp} = T_{sat} @ P_v$$

$$P_v = \phi P_g @ 20°c = (0.75)(2.392 \text{kpa}) = 1.754 \text{kpa}$$

$$T_{dp} = T_{sat} @ 1.754 \text{kpa} = 15.4°c$$

Inner temp at window should be maintained above 15.4°c.

② The dry & wet bulb temp of atmospheric air at 1atm (101.325 kpa) pressure are measured with a sling psychrometer and determined to be 25°, 15°C. Determine.

<u>Sol</u> Tsat of water is 1.7057 kpa at 15°C
3.1698 " at 25°C.

$C_p = 1.005$ kJ/kg.K

Sp. humidity $\omega_1 = C_p(T_2 - T_1) + \omega_2 h_{fg_2} / h_{g_1} - h_{f_2}$

where $T_2$ is the wet bulb temp and $\omega_2$ is

$$\omega_2 = \frac{0.622 P_{g_2}}{P_2 - P_{g_2}} = \frac{(0.622)(1.7057 \text{ kpa})}{(101.325 - 1.7057)\text{ kpa}}$$

$= 0.01065$ kg $H_2O$/kg dry air.

$$\omega_1 = \frac{(1.005 \text{ kJ/kg}°C)[(15 - 25)°C] + (0.01065)(2465.4 \text{ kJ/kg})}{(2546.5 - 62.982) \text{ kJ/kg}}$$

$= 0.00653$ kg $H_2O$/kg dry air

$$\phi_1 = \omega_1 P_2 / (0.622 + \omega_1) P_{g_1} = \frac{(0.00653)(101.325 \text{ kpa})}{(0.622 + 0.00653)(3.1698 \text{ kpa})}$$

$= 0.332$ or 33.2%

$h_1 = h_{a_1} + \omega_1 h_{v_1} \cong C_p T_1 + \omega_1 h_{g_1}$

$= (1.005 \text{ kJ/kg}°C)(25°C) + (0.00653)(2546.5 \text{ kJ/kg})$

$= 41.8$ kJ/kg dry air.

③ Room temp at 1 atm 35°C and 40% RH.

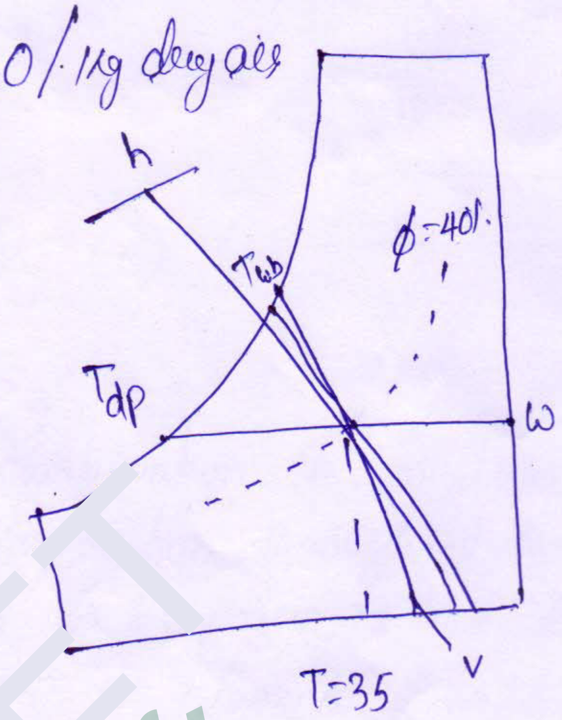
Sp. humidity $(\omega) = 0.0142$ kg $H_2O$/kg dry air

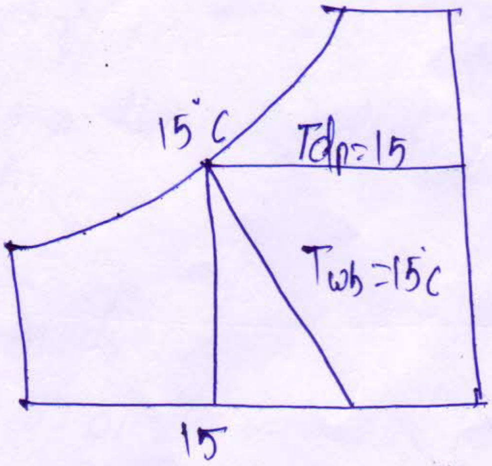
$h = 71.5$ kJ/kg dry air

$T_{wb} = 24°C$

$T_{dp} = 19.4°C$

$v = 0.893$ $m^3$/kg dry air.





For saturated air the dry bulb - wb - dp are identical.

tmospheric air at 100 kPa, 30°c has a relative humidity f 70%. Compute ① Humidity ratio ② Dew point temp.

Sol: Relative humidity $\phi = 0.7$

$P_g$ corresponding to $30°c = 4.246\,kPa$

$$\phi = P_v / P_g$$

$$\therefore P_v = 0.7 \times 4.246 = 2.97\ KPa.$$

Humidity ratio.

$$\omega = \frac{0.622\,P_v}{P - P_v} = \frac{0.622 \times 2.97}{100 - 2.97}$$

$$= 0.019\ kg/kg\ \text{of dry air}$$

Dew point temp

$$t_{dp} = t_{sat}\ \text{at}\ P_v$$

From steam table, $t_{sat}$ corresponding to

2.97 kpa = 24°C

∴ Dew point temp = 24°C.

---

② ⓒ Degree of Saturation.

$$\mu = \frac{P_v}{P_g}\left[\frac{1 - \frac{P_g}{P}}{1 - \frac{P_v}{P}}\right] = \frac{0.0297}{0.04246}\left[\frac{1 - \frac{0.04246}{1}}{1 - \frac{0.0297}{1}}\right]$$

$$= 0.6903\,//.$$

② A room of dimensions 5m × 3m × 3m contains an air water vapour mixture at 1bar 30°C and 70% relative humidity. Calculate ① mass of air ② mass of water vapour ③ also degree of saturation.
$R = 8.3143$ KJ/kg mole K and molecular mass of air and water vapour is 29 and 18.

Sol: Volume of a room $= 5 \times 3 \times 3 = 45 \, m^3$

$P_g$ at 30°C $= 0.04246$ bar

Partial pressure of vapour $P_v = \phi P_g = 0.7 \times 0.04246$
$= 0.0297$ bar

" " of air $P_a = P - P_v = 1 - 0.0297$
$= 0.9703$ bar

The volume of each gas is equal to the volume of room

$V_a = V_{vap} = 45 \, m^3$

For air $= R = 8.3143/29 = 0.2867$ KJ/kg·K

Vapour $= R = 8.3143/18 = 0.4619$ KJ/kg·K

Mass of air $m_a = \frac{P_a V_a}{R_a T} = \frac{10^2 \times 0.9703 \times 45}{0.2867 \times 303}$

$= 50.26$ kg

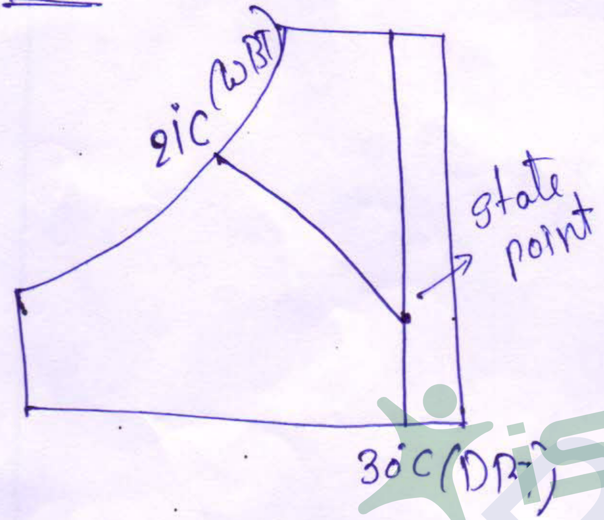
Mass of vapour $m_v = \frac{P_v V_v}{R_v T} = \frac{10^2 \times 0.0297 \times 45}{0.4619 \times 303}$

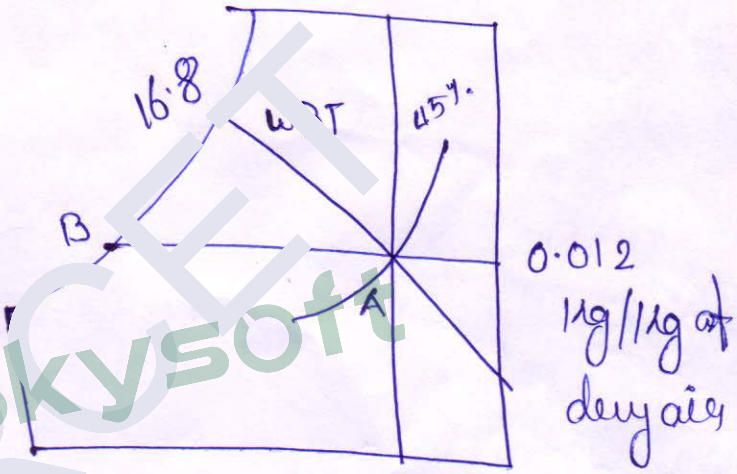
$= 0.9549$ kg.

**Topic:** ③

Find ⓐ Dew point temp (b) relative humidity ⓒ Moisture content if dry bulb temp is 30°C and wet bulb temp is 21°C. Represent the above on psychrometric chart.

Sol:





④

$$d = d_1 + \frac{\theta - \theta_1}{\theta_2 - \theta_1}(d_2 - d_1).$$

$\theta_1 = 35°C$ $d_1 = 5.6281 kpa$

$\theta_2 = 40°C$ $d_2 = 7.3841 kpa$

$$d = 5.628 + \frac{38 - 35}{40 - 30}(7.384 - 5.628)$$

$= 6.6821 kpa.$

Non-saturated sp. volume.

At 20 kpa → 100°C.

10 kpa = $d_2$ = 3.4183 50 kpa = $d_1$ = 17.19561.

$$d = 17.19561 \frac{m^3}{kg} + \frac{(20kpa - 10kpa)}{(50kpa - 10kpa)}(3.41833 - 17.19561)$$

$= 13.75129.$

$x_1 = 1$ $x_2 = 2$ $x_3 = 3$

$y_1 = 4$ $y_2 = ?$ $y_3 = 6$

$$y_2 = y_1 + \frac{(x_2 - x_1)}{(x_3 - x_1)} \times (y_3 - y_1)$$

$$= 4 + \frac{(2-1)}{(3-1)}(6-4)$$

$$= 4 + \frac{1}{\cancel{2}}(\cancel{2})$$

$y_2 = 5$

267 + 267 ⇒

$\boxed{334}$

$\boxed{267 + 40}$

317 +

84

~~450~~ 9

~~300~~

~~8~~

$\boxed{1.3}$

267

+40

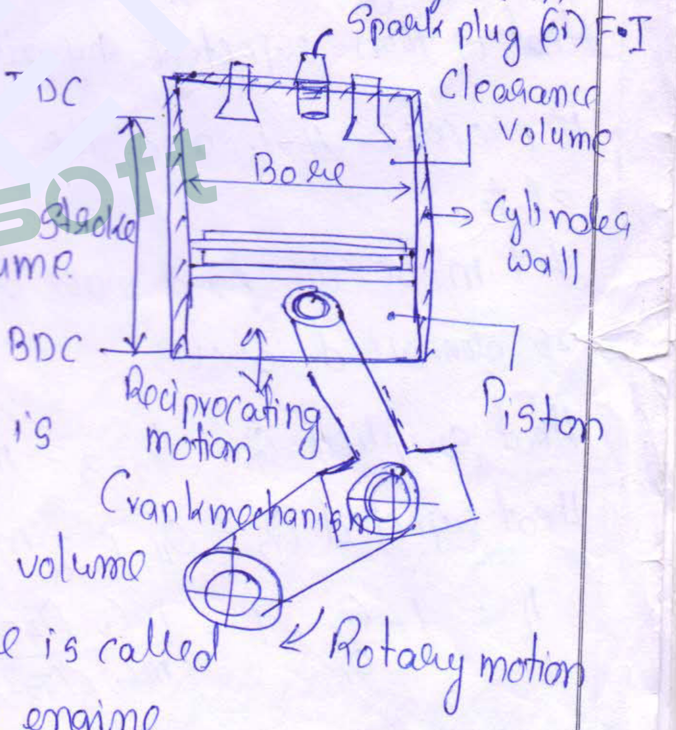
307

$\boxed{57}$ +

# Power Cycles: (07)

## Otto Cycle: (7.1)

The Otto cycle is the air standard cycle of the SI engine. It is named after Nikolaus A. Otto a German engineer, who first built a succesful four stroke SI engine in 1876.



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

The volume displaced by the piston as it moves between TDC and BDC is called the displacement volume.

The ratio of the maximum formed volume to the minimum clearance volume is called the compression ratio $r_K$ of the engine

$$r_K = V_{max}/V_{min} = V_{BDC}/V_{TDC}$$

Mean effective pressure of the cycle is given by $P_m = \frac{\text{Network o/p}}{\text{Swept volume}}$

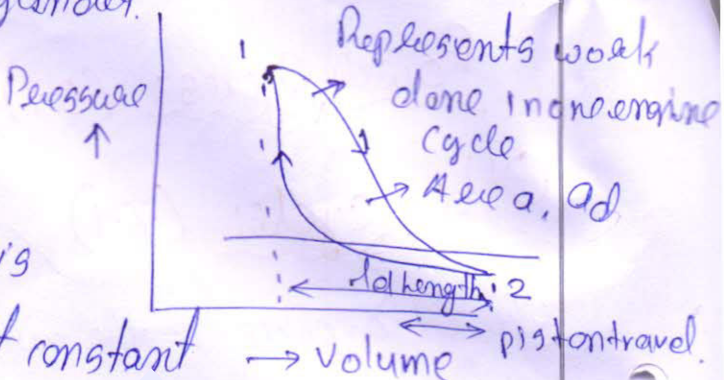
$$P_m = a_d/l_d \times K$$

where K is the indicator spring constant (N/cm² × cm travel)

work done in one engine cycle $= (P_m \cdot A) L$

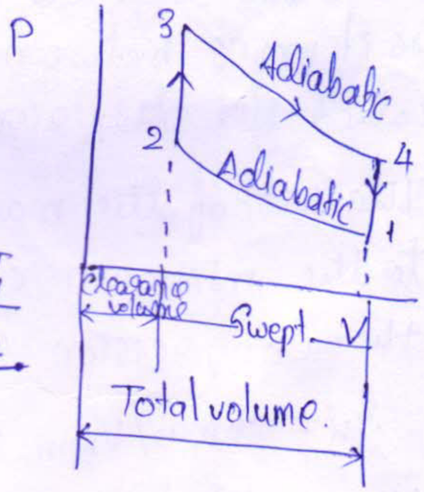
$A$ = cross section area of the cylinder $= \frac{\pi}{4} D^2$ $D$ = cylinder dia

$L$ = stroke of piston or length of cylinder.



Air is compressed in process 1-2 reversibly and adiabatically. Heat is then added to air reversibly at constant volume in process 2-3. work is done by air in expanding reversibly and adiabatically in process 3-4. Heat is then rejected by air reversibly at constant volume in process 4-1. and the system (air) comes back to its initial state.

Let m be the fixed mass of air undergoing the cycle of operations as described above.



Heat supplied $Q_1 = Q_{2-3} \quad mC_v(T_3 - T_2)$

Heat rejected $Q_2 = Q_{4-1} = mC_v(T_4 - T_1)$

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

process 1-2 $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{r-1}$

process 3-4 $\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{r-1} = \left(\frac{V_1}{V_2}\right)^{r-1}$

$\therefore \frac{T_2}{T_1} = T_3/T_4$ (or) $\frac{T_3}{T_2} = \frac{T_4}{T_1}$

**Topic:** Otto cycle: (7·1·a)

Compression ratio , Expansion ratio

$r_c = (r) = \frac{V_1}{V_2}$ $\qquad r_e = r = \frac{V_4}{V_3}$

(or) $T_3 = T_4 \cdot (r)^{\gamma-1}$

$$\eta = 1 - \frac{T_4 - T_1}{T_4 \cdot (r)^{\gamma-1} - T_1 (r)^{\gamma-1}}$$

$$= 1 - \frac{T_4 - T_1}{r^{(\gamma-1)} (T_4 - T_1)} = 1 - 1/(r)^{\gamma-1}$$

Mean effective pressure: → (7·1·b) The mean effective pressure may be defined as the ratio of work done to displacement volume of piston considering [illegible] of working fluid.

Displacement volume $= V_1 - V_2$

Mean effective pressure = workdone per cycle / Displacement work

$$= C_v (T_2 - T_3) - C_v (T_4 - T_1) / V_1 - V_2$$

$$V_1 - V_2 = V_1 (1 - 1/r) = \frac{RT_1}{P_1}\left(\frac{r-1}{r}\right) = C_v \frac{(\gamma-1)}{P_1}\left(\frac{r-1}{r}\right) T_1$$

$$= P_1 r \cdot \left(\frac{T_4}{T_1} - 1\right)(r^{\gamma-1} - 1) / (r-1)(\gamma-1)$$

Net work o/p: $W_{net} = \frac{P_3V_3 - P_4V_4}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}$

$$\frac{v_1}{v_2} = \frac{V_1}{V_2} = r_k \quad (\text{or}) \quad V_1 = V_2\, r_k = V_4$$

$$\frac{P_2}{P_1} = P_3/P_4 = \left(\frac{V_1}{V_2}\right)^{\gamma} = r_k^{\gamma}$$

$$P_3/P_2 = P_4/P_1 = r_p \text{ (say)}$$

$$W_{net} = \frac{P_1V_1}{\gamma - 1}\left(\frac{P_3V_3}{P_1V_1} - \frac{P_4V_4}{P_1V_1} - \frac{P_2V_2}{P_1V_1} + 1\right)$$

$$= \frac{P_1V_1}{\gamma-1}\left(\frac{r_p\, r_k^{\gamma}}{r_k} - r_p - \frac{r_k^{\gamma}}{r_k} + 1\right)$$

$$= \frac{P_1V_1}{\gamma-1}\left(r_p\, r_k^{\gamma-1} - r_p - r_k^{\gamma-1} + 1\right)$$

$$W_{net} = \frac{P_1V_1}{\gamma-1}(r_p - 1)(r_k^{\gamma-1} - 1)$$

Mean effective pressure

$$P_m = \text{Net work o/p / Swept volume}$$

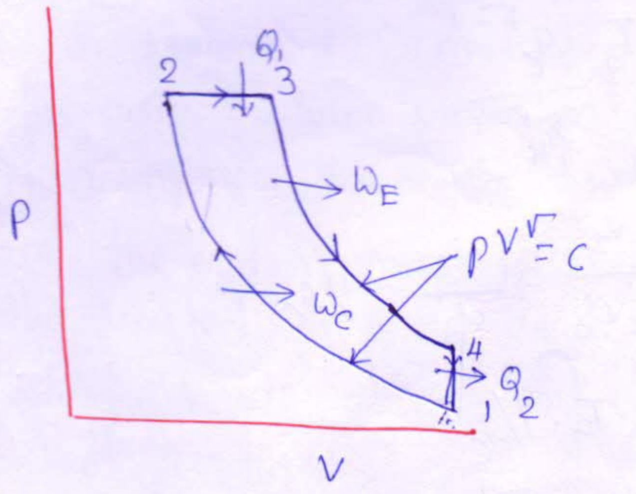
where Swept volume $= V_1 - V_2 = V_2(r_k - 1)$

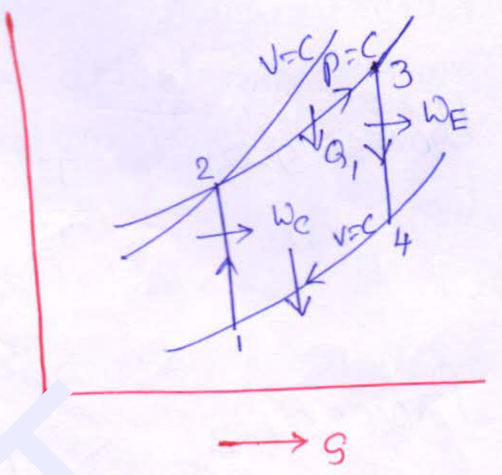
$$P_m = \frac{P_1V_1}{\gamma-1}(r_p - 1)/(r_k^{\gamma-1} - 1)/V_2\,(r_k - 1)$$

$$= P_1 r_k (r_p - 1)\,(r_k^{\gamma-1} - 1)/(\gamma-1)(r_k - 1)$$

Net workoutput is directly proportional to the pressure ratio ($r_p$). For given values of $r_k$ & $\gamma$, $P_m$ increase with $r_p$. Otto cycle, an increase in $r_k$ leads to an increase in $P_m$, $W_{net}$ and cycle efficiency.

Topic: Diesel cycle: (1892) (7.2)





For m kg of air in the cylinder the efficiency analysis of the cycle can be made

Heat supplied $Q_1 = Q_{2-3} = mC_p(T_3 - T_2)$

$$Q_2 = Q_{4-1} = mC_v(T_4 - T_1)$$

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)}$$

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

The η can be expressed in terms of any two of the following

Compression ratio $r_k = \frac{V_1}{V_2} = \frac{v_1}{v_2}$

Expansion ratio $r_e = V_4/V_3 = \frac{v_4}{v_3}$

Cut-off ratio $r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2}$ Ratio of cylinder volume after and before the combustion process.

$$r_k = r_e \cdot r_c$$

Process 3-4

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{r-1} = 1/r_e^{r-1}$$

$$T_4 = T_3 \frac{r_c^{r-1}}{r_k^{r-1}}$$

Process 2-3

$$\frac{T_2}{T_3} = \frac{P_2 v_2}{P_2 v_3} = \frac{v_2}{v_3} = 1/r_c$$

$$T_2 = T_3 \cdot 1/r_c$$

Process 1-2

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{r-1} = 1/r_k^{r-1}$$

$$T_1 = T_2 \cdot \frac{1}{r_k^{r-1}} = \frac{T_3}{r_c} \cdot \frac{1}{r_k^{r-1}}$$

Substituting the value of $T_1$, $T_2$ & $T_4$ in the expression of $\eta$

$$\eta = 1 - \left. \frac{T_3 r_c^{r-1}}{r_k^{r-1}} - \frac{T_3}{r_c} \frac{1}{r_k^{r-1}} \right/ r\left(T_3 - T_3 \cdot \frac{1}{r_c}\right)$$

$$\eta_{Diesel} = 1 - \frac{1}{r} \cdot \frac{1}{r_k^{r-1}} \cdot \frac{r_c^{r} - 1}{r_c - 1}$$

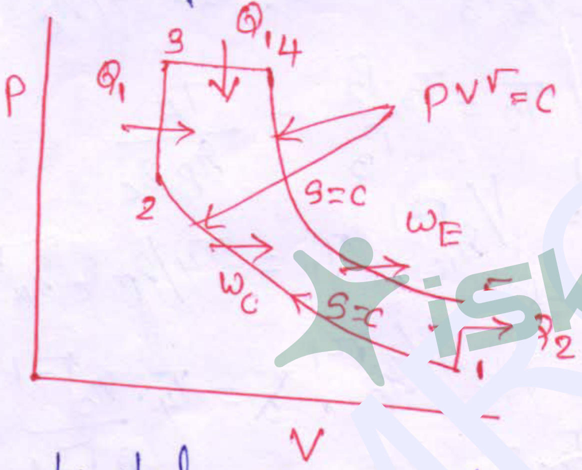
As $r_c > 1$, $\frac{1}{r}\left(\frac{r_c^{r} - 1}{r_c - 1}\right)$ is also greater than unity.

$\therefore$ The $\eta$ of Diesel cycle is less than the $\eta$ of the Otto Cycle.

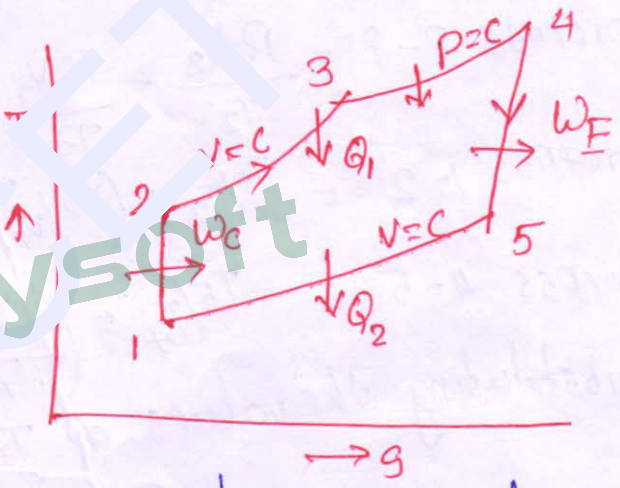
Topic:

# Dual cycle (7.3)

The air standard Diesel cycle does not simulate exactly the pressure - volume variation in the actual compression ignition engine, where the fuel injection is started before the end of compression stroke. A closer approximation is the limited pressure cycle in which some part of heat is added to air at constant volume, and the remainder at constant pressure.



Limited pressure cycle



Mixed cycle (or) Dual cycle.

P-V & T-s diagrams of the dual cycle. Heat is added reversibly, partly at constant volume (2-3) and partly at constant pressure (3-4)

Heat supplied $Q_1 = mC_v(T_3 - T_2) + mC_p(T_4 - T_3)$

Heat rejected $Q_2 = mC_v(T_5 - T_1)$

$$\eta = 1 - Q_2/Q_1$$

$$= 1 - \frac{mC_v (T_5 - T_1)}{mC_v (T_3 - T_2) + mC_p (T_4 - T_3)}$$

$$= 1 - \frac{T_5 - T_1}{(T_3 - T_2) + r (T_4 - T_3)}$$

Compression ratio $r_k = v_1/v_2$

Expansion ratio $r_e = v_5/v_4$

Cut-off-ratio $r_c = v_4/v_3$

constant volume pressure ratio $r_p = P_3/P_2$

$r_k = r_c \cdot r_e$

$r_e = r_k / r_c$

process 3-4 = $r_c = v_4/v_3 = \frac{T_4 P_3}{P_4 \cdot T_3} = T_4/T_3$, $T_3 = T_4/r_c$

process 2-3 = $\frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3}$, $T_2 = \frac{P_2}{P_3} = \frac{T_4}{r_p \cdot r_c}$

process 1-2 = $T_1/T_2 = (V_2/V_1)^{r-1} = 1/r_k^{r-1}$, $T_1 = T_4 / r_p \cdot r_c \, r_k^{r-1}$

process 4-5 = $T_5/T_4 = \left(\frac{v_4}{v_5}\right)^{r-1} = 1/r_e^{r-1}$, $T_5 = T_4 \cdot \frac{r_c^{r-1}}{r_k^{r-1}}$

Substituting the values of $T_1, T_2, T_3$ & $T_5$

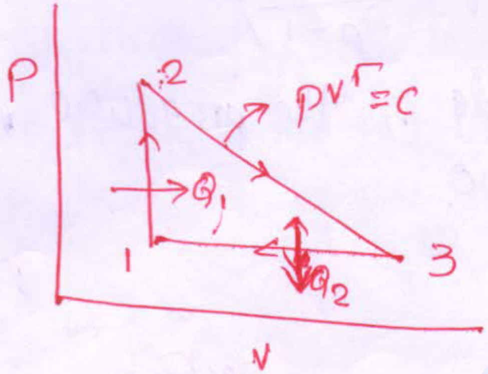
$$\eta = 1 - \frac{T_4 \cdot \frac{r_c^{r-1}}{r_k^{r-1}} - \frac{T_4}{r_p \cdot r_c \, r_k^{r-1}}}{\left(\frac{T_4}{r_c} - \frac{T_4}{r_p \cdot r_c}\right) + r \left(T_4 - \frac{T_4}{r_c}\right)}$$

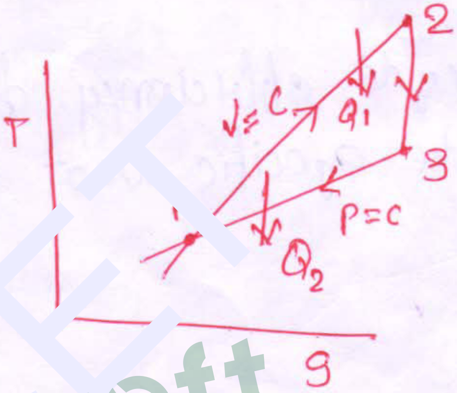
$$\eta_{Dual} = 1 - \frac{1}{r_k^{r-1}} \frac{r_p \cdot r_c^{r} - 1}{r_p - 1 + r \, r_p (r_c - 1)}.$$

Topic: Lenoir cycle (7·4)

The cycle consists of an constant-volume heat addition (1-2), reversible adiabatic expansion (2-3); and constant pressure heat rejection (3-1).

It is applicable to pulse jet engines.





For 1 kg gas

$$Q_1 = c_v (T_2 - T_1)$$

$$Q_2 = c_p (T_3 - T_1)$$

$$\eta_{cycle} = 1 - Q_2/Q_1 = 1 - \frac{c_p (T_3 - T_1)}{c_v (T_2 - T_1)} = 1 - \frac{\gamma (T_3 - T_1)}{T_2 - T_1}$$

$$r_p = P_2/P_1 \qquad \boxed{\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}} \qquad \boxed{V_1 = V_2}$$

$$\boxed{\therefore T_2 = T_1 \, P_2/P_1} = r_p \cdot T_1$$

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

$$\therefore \underline{T_3} = T_2 \left(1/r_p\right)^{\gamma-1/\gamma} = T_1 r_p \left(1/r_p\right)^{\gamma-1/\gamma}$$

$$\underline{\eta_{Lenoir}} = 1 - \gamma\left[T_1 r_p^{1/\gamma} - T_1\right] / T_1 r_p - T_1$$

$$= 1 - \gamma\left(\frac{r_p^{1/\gamma} - 1}{r_p - 1}\right)$$

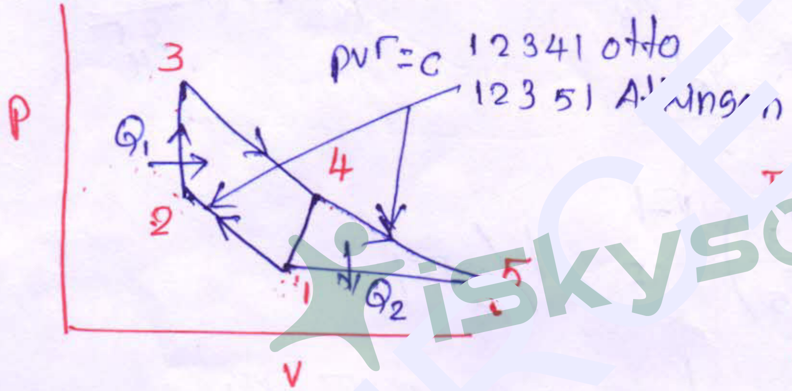
The cycle efficiency depends on the pressure ratio and the specific heat ratio.

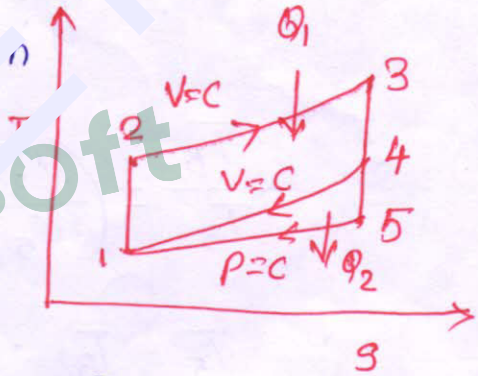
$\gamma = 1.4$

$pv^\gamma$ = Adiabatic ind

Topic: # ATKINSON CYCLE (7.5)

Atkinson cycle is an ideal cycle for an Otto engine exhausting to a gas turbine. In this cycle, the isentropic expansion (3-4) of an otto cycle is allowed to further expand to the lowest cycle pressure (3-5) so as to increase the work output.



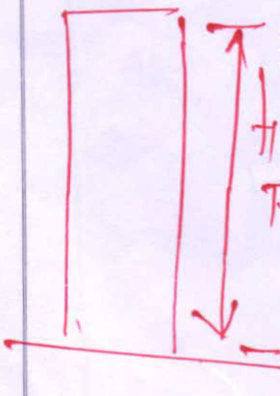


For 1kg gas $Q_1 = C_v(T_3 - T_2)$

$Q_2 = C_p(T_5 - T_1)$

$\frac{C_p}{C_v} = \gamma$

$$\eta = 1 - \frac{C_p(T_5 - T_1)}{C_v(T_3 - T_2)} = 1 - \frac{\gamma(T_5 - T_1)}{T_3 - T_2}$$



$r_k$ = compression ratio = $v_1/v_2$

$r_e$ : expansion ratio = $v_5/v_3$

$$\frac{T_2}{T_1} = \frac{v_1}{v_2} \quad \therefore \quad T_2 = T_1 r_k^{\gamma-1}$$

$$\frac{T_3}{T_2} = \frac{P_3}{P_2} = \frac{P_3}{P_5} \cdot \frac{P_5}{P_2} = \frac{P_3}{P_5} \cdot \frac{P_1}{P_2}$$

$$\frac{P_3}{P_5} = \left(\frac{V_5}{V_3}\right)^{\gamma} = r_e^{\gamma}$$

$$\frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^{\gamma} = 1/r_k^{\gamma}$$

$$\therefore T_3 = T_2 \cdot r_e^{\gamma} \cdot \frac{1}{r_k^{\gamma}} = T_1 r_k^{\gamma-1} \cdot r_e^{\gamma} \cdot \frac{1}{r_k^{\gamma}}$$

$$= T_1 \cdot \frac{r_e^{\gamma}}{r_k}$$

$$\frac{T_5}{T_3} = \left(\frac{v_3}{v_5}\right)^{\gamma-1} = 1/r_e^{\gamma-1}$$

$$\therefore T_5 = T_3 \cdot \frac{1}{r_e^{\gamma-1}} = T_1 \cdot \frac{r_e^{\gamma}}{r_k} \cdot \frac{1}{r_e^{\gamma-1}} = T_1 \frac{r_e}{r_k}$$

Substituting $T_2$, $T_3$, & $T_5$

$$\eta_{Atkinson} = 1 - \gamma \frac{T_1 \cdot \frac{r_e}{r_k} - T_1}{T_1 \frac{r_e^{\gamma}}{r_k} - T_1 r_k^{\gamma-1}}$$

$$= 1 - \gamma \frac{r_e - r_k}{r_e^{\gamma} - r_k^{\gamma}}$$

Topic: 
# Stirling Cycle (7-6)

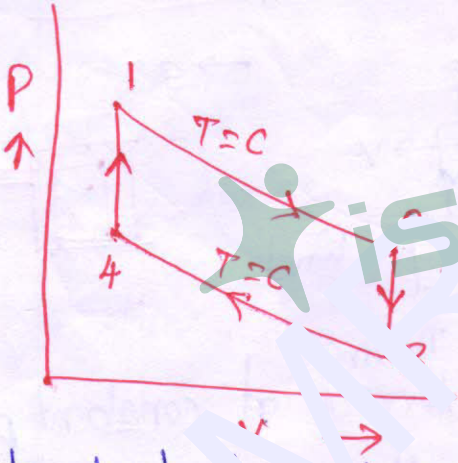
The cycle consists of two reversible isothermal and two reversible isochores for 1kg of ideal gas.

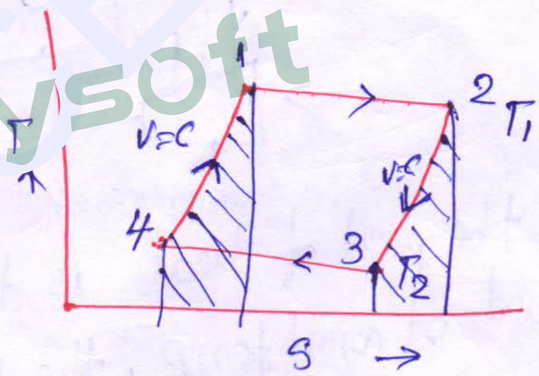
$$Q_{1-2} = W_{1-2} = RT_1 \ln \frac{v_2}{v_1}$$

$$Q_{2-3} = -C_v (T_2 - T_1) ; \quad W_{2-3} = 0$$

$$Q_{3-4} = W_{3-4} = -RT_2 \ln v_3/v_4$$

$$Q_{4-1} = C_v (T_1 - T_2) ; \quad W_{4-1} = 0$$





Due to heat transfer at const volume process, the η of the stirling cycle is less than that of the carnot cycle. However, if a regenerative arrangement is used such that $Q_{2-3} = Q_{4-1}$ i.e... the area under 2-3 is equal to area under 4-1

$$\eta = RT_1 \ln v_2/v_1 - RT_2 \ln v_3/v_4 / RT_1 \ln \frac{v_2}{v_1}$$

$$= T_1 - T_2/T_1$$

So, the regenerative stirling cycle has the η as the carnot cycle.

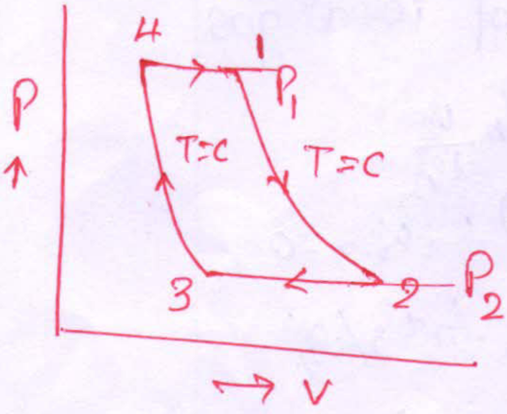
## Ericsson cycle (1850) (For 1kg of ideal gas) — (7.7)

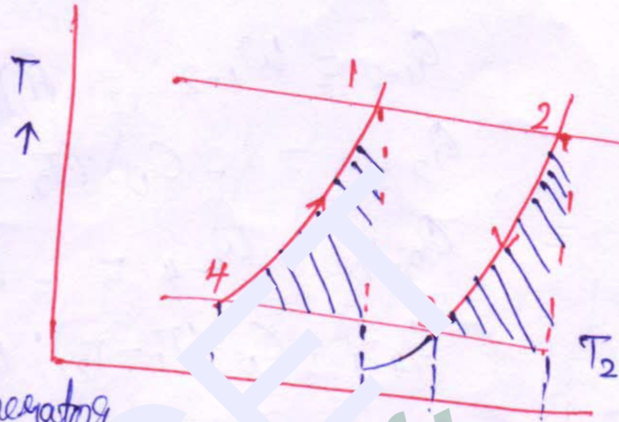
$$Q_{1-2} = W_{1-2} = RT_1 \ln P_1/P_2$$

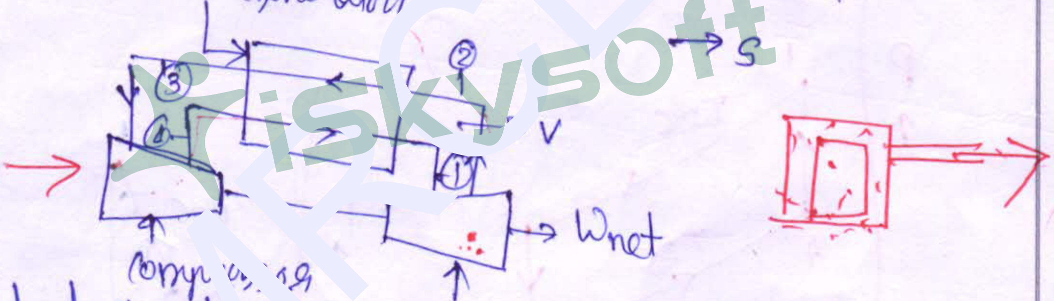
$$Q_{2-3} = C_p(T_2 - T_1);\ W_{2-3} = P_2(v_3 - v_2) = R(T_2 - T_1)$$

$$Q_{3-4} = W_{3-4} = -RT_2 \ln P_1/P_2$$

$$Q_{4-1} = C_p(T_1 - T_4);\ W_{4-1} = P_1(v_1 - v_4) = R(T_1 - T_2)$$







Since the part of [illegible] is transferred at constant pressure and part at const temp, the η of the ericson cycle less than that of the carnot cycle. But with ideal regeneration $Q_{2-3} = Q_{4-1}$ so that all heat is added from the external source at $T_1$ and all the heat is rejected to an external sink at $T_2$ the η of the cycle becomes equal to the carnot cycle η

$$\eta = 1 - Q_2/Q_1 = 1 - \frac{RT_2 \ln P_1/P_2}{RT_1 \ln P_1/P_2} = 1 - \frac{T_2}{T_1}.$$

Topic:

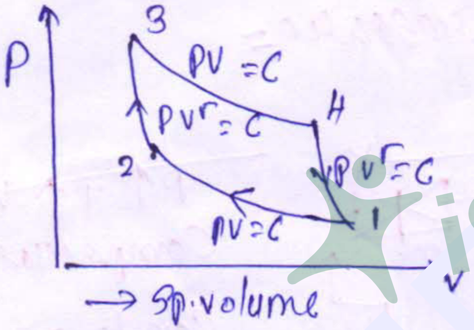
# Comparison of Cycles: (7·8)

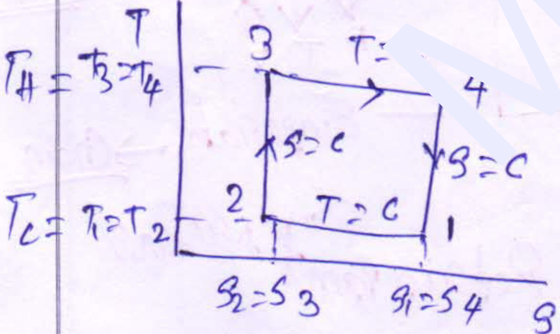
## Carnot Cycle

① It consists of two reversible isothermal & two isentropic

② It is used as an ideal cycle for heat engines

③ Regenerator is not ~~valid~~ involved to make process reversible





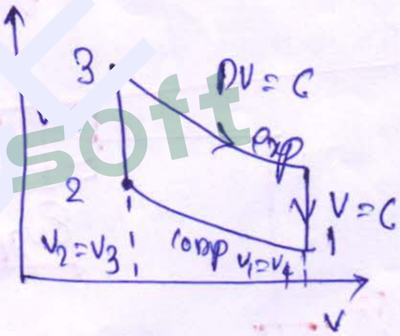
$$\eta_c = 1 - \frac{T_L}{T_H}$$

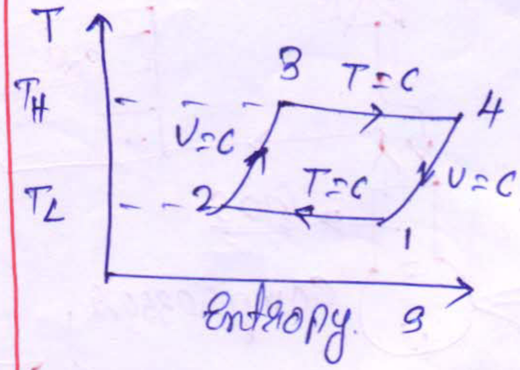
## Sterling cycle

① It consists of two reversible isothermal & two isochoric process

② It used as an ideal cycle for air engines.

③ Regenerator is used to make cycle reversible



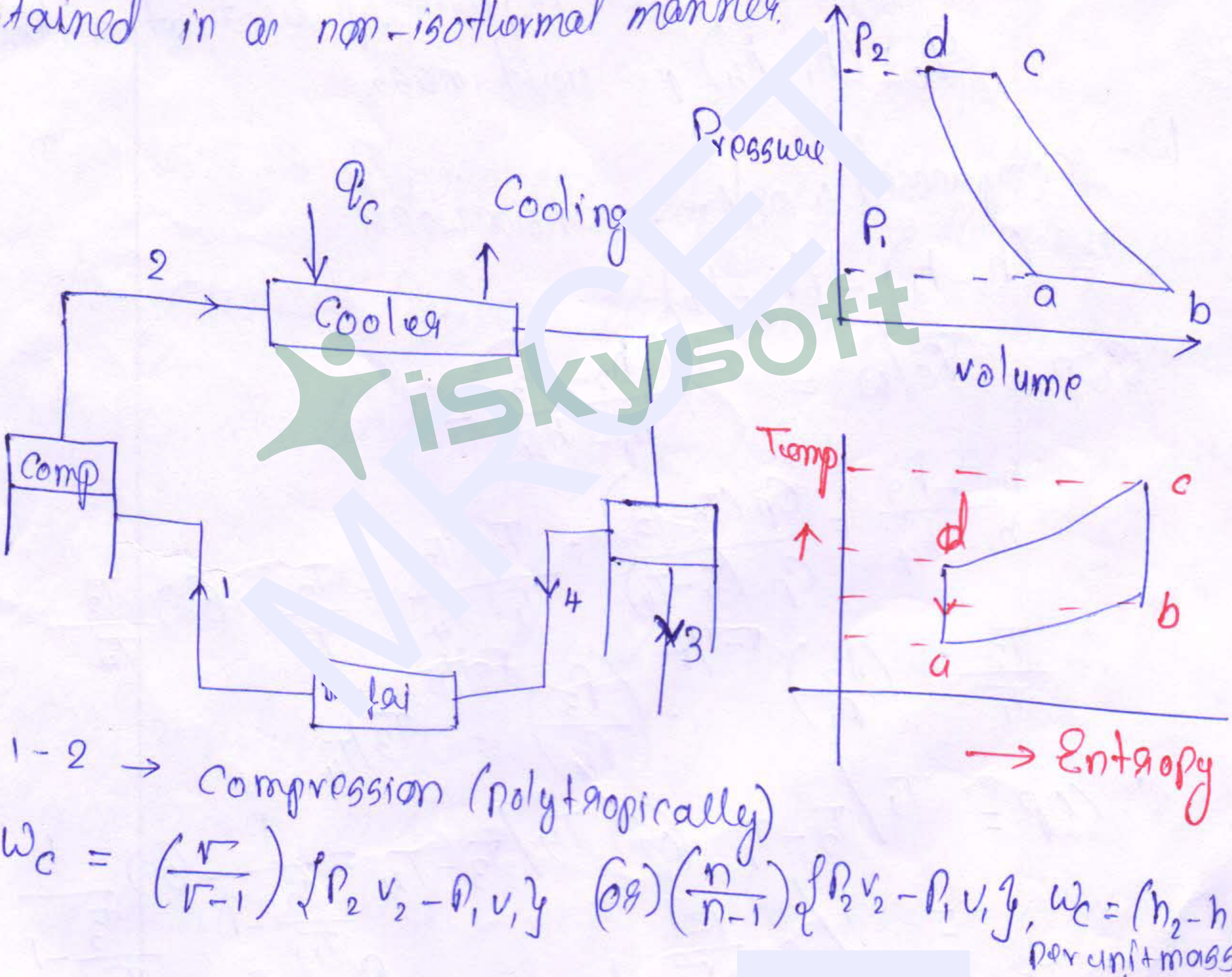


$$\eta_s = 1 - \frac{T_L}{T_H}$$

Topic:

# Bell Coleman Cycle:

Air refrigeration system is also called as gas cycle refrigeration system. as in this cycle the working substance remains in a gaseous phase through out. In such a cycle refrigeration is obtained in a non-isothermal manner.



1 - 2 → Compression (polytropically)

$W_c = \left(\frac{\gamma}{\gamma-1}\right)\{P_2 V_2 - P_1 V_1\}$ (or) $\left(\frac{n}{n-1}\right)\{P_2 V_2 - P_1 V_1\}$, $W_c = (h_2 - h_1)$ per unit mass compressed in entropy process

2-3 → Cooling $q_c = (h_2 - h_3)$ per unit mass

3-4 → high pressure low temp air ($P_2 = P_3, V_3, T_3$) is expanded isentropically in the expander

$$W_c = \left(\frac{\gamma}{\gamma-1}\right)(P_4V_4 - P_3V_3)$$

$$= \left(\frac{n}{n-1}\right)(P_4V_4 - P_3V_3) \text{ if polytropic}$$

$$= (h_3 - h_4) \text{ per unit mass}$$

4-1 → Low pressure, low temp air ($P_1 = P_3, V_1, T_4$) is now sent to the refrigerator where it picks up heat at constant

$$q_c = (h_1 - h_4) \text{ per unit mass.}$$

W = compressed work - expansion work

$$= (h_2 - h_1) - (h_3 - h_4)$$

$$COP = q_c/w = 1\Big/\frac{h_2 - h_3}{h_1 - h_4} - 1$$

$$\frac{h_2 - h_3}{h_1 - h_4} = \frac{C_p(T_2 - T_3)}{C_p(T_1 - T_4)} = \frac{T_2 - T_3}{T_1 - T_4} = \frac{T_2}{T_1} \text{ (or) } \frac{T_3}{T_4}$$

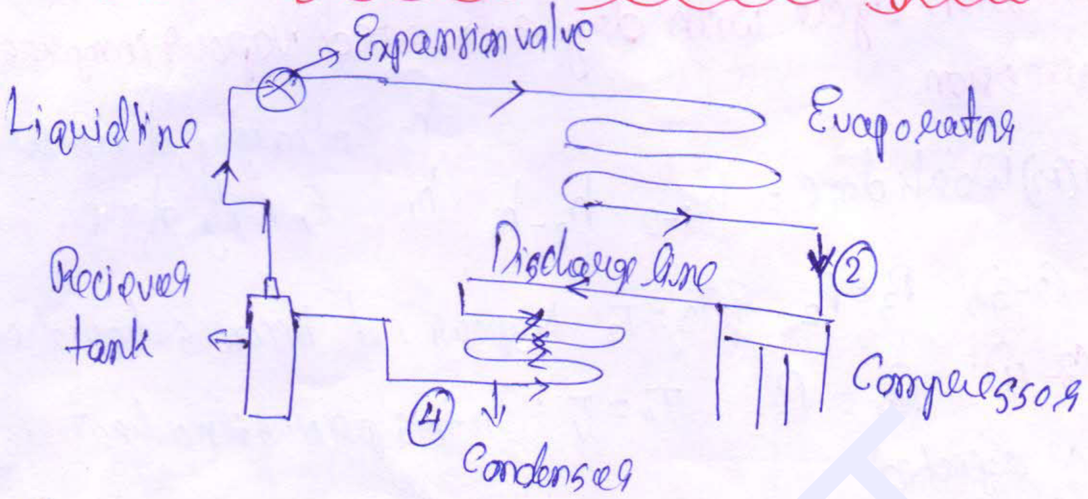
$$\therefore \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} = \left(\frac{P_3}{P_4}\right)^{\gamma-1/\gamma} = T_3/T_4$$

$$\therefore COP = T_1/T_2 - T_1 \text{ (or) } T_4/T_3 - T_4 = \frac{1}{\frac{T_2}{T_1} - 1} \text{ (or) } \frac{1}{\frac{T_3}{T_4} - 1}$$

$$= 1\Big/ r_p^{\frac{\gamma-1}{\gamma}} - 1$$

$$r_p = \frac{P_2}{P_1} = P_3/P_4$$

Topic: # Vapour Compression Refrigeration System



Compressor → Remove the vapour from the evaporator

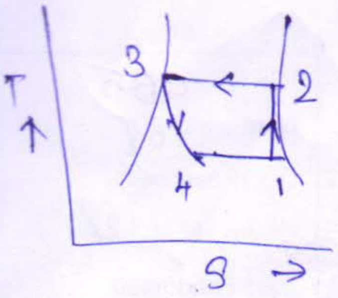
Dischargeline → Delivers the liquid from the compressor

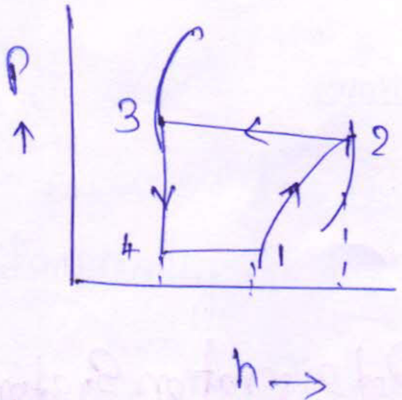
Condenser: The function of a condenser is to remove the heat

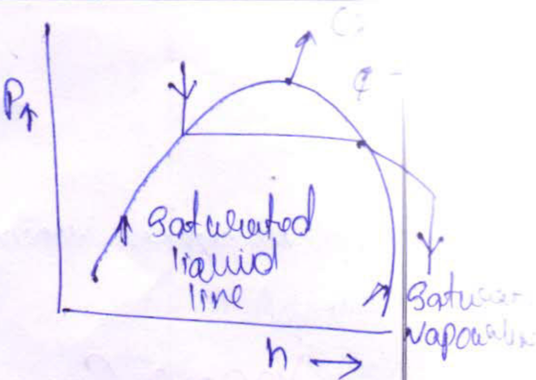
Receiver tank → Used for storage of liquid.

Expansion valve → The amount of liquid to send in proper proportion of mixture

Evaporator : which changes from liquid to vapour







## Vapour compression cycle with dry saturated vapour compression after compression.

$h_2$ Enthalpy of vap. sat at $T_2$

$h_1$ Enthalpy of vap at $T_1$

Compressor (1-2) Work done = $W_{1-2} = h_2 - h_1$

Condensation: (2-3); $P_3 = P_2$ & $T_3 = T_2$ Vapour ref becomes liquid refrigerant

Expansion: (3-4); $P_4 = P$ $T_4 = T_1$, in this process no heat is absorbed or rejected.

Vaporising process: The liquid & vap or mixture of refrigerant

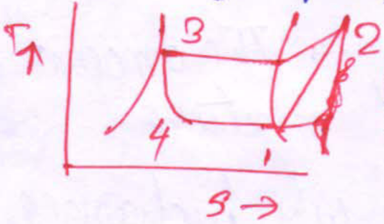
Refrigerating effect $h_1 - h_4 = h_1 - h_{f3}$

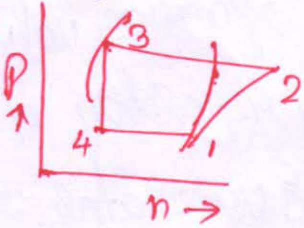
$\therefore$ COP = Refrigerating effect/work done = $\dfrac{h_1 - h_{f3}}{h_2 - h_1}$

Superheated vapour after compression: COP = $\dfrac{\text{Refrigerating effect}}{\text{work done}}$ $= h_1 - h_{f3}/h_2 - h_1$ $h_2$ is calculated by using degree of superheat.

$h_2 = h_2' + C_p \times$ degree of superheat $= h_2' + C_p(T_2 - T_2')$

$S_2 = S_2' + C_p \ln T_2/T_1$

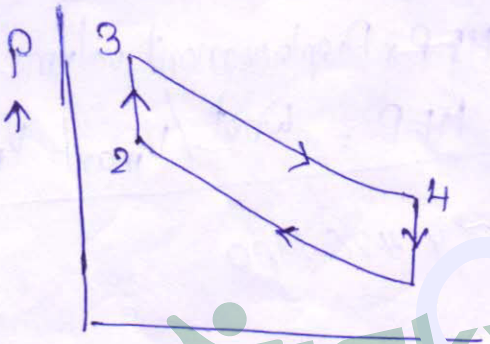


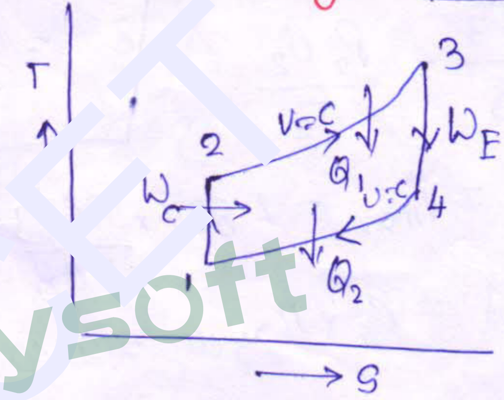


Topic:

① An engine working on the otto cycle is supplied with air at 0.1 MPa, 35°C. The compression ratio is 8. Heat supplied is 2100 KJ/kg. Calculate the maximum pressure and Temperature of the cycle, the cycle efficiency, and the mean effective pressure. For air $C_p = 1.005$, $C_v = 0.718$, $R = 0.287$ KJ/kg.K $\boxed{\text{NOV-2009}}$

Sol:





$T_1 = 273 + 35 = 308\,K$

$P_1 = 0.1\,MPa = 100\,KN/m^2$

$Q_1 = 2100\,KJ/kg$

$r_k = 8, \quad \gamma = 1.4$

$$\eta_{cycle} = 1 - \frac{1}{r_k^{\gamma-1}} = 1 - \frac{1}{8^{0.4}} = 0.565 = 56.5\%$$

$$\frac{v_1}{v_2} = 8, \quad v_1 = \frac{RT_1}{P_1} = \frac{0.287 \times 308}{100} = 0.844\,m^3/kg$$

$$v_2 = \frac{0.884}{8} = 0.11\,m^3/kg$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = (8)^{0.4} = 2.3$$

$$T_2 = 2.3 \times 308 = 708.4\,K$$

$$Q_1 = C_v(T_3 - T_2) = 2100\ kJ/kg$$

$$T_3 - 708.4 = \frac{2100}{0.718} = 2925\,K$$

$$T_3 = T_{max} = 3633\,K$$

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = (8)^{1.4} = 18.37$$

$$P_2 = 1.873\ Mpa$$

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2}$$

$$P_3 = P_{max} = 1.837 \times \frac{3633}{708} = 9.426\ Mpa$$

$$W_{net} = Q_1 \times \eta_{cycle} = 2100 \times 0.565 = 1186.5\ kJ/kg$$

$$= P_m(v_1 - v_2) = P_m(0.884 - 0.11)$$

$$P_m = m.e.p = \frac{1186.5}{0.774} = 1533\,kpa = 1.533\,Mpa$$

$$\boxed{\begin{aligned} W_{net} &= MEP \times \text{piston area} \times \text{stroke} \\ &= MEP \times \text{Displacement volume} \\ MEP &= W_{net} / V_{max} - V_{min} \end{aligned}}$$

Adiabatic (closed)

$- \; PV^{\gamma} = c$

$- \; \boxed{TV^{\gamma-1} = c}$

$- \; T \propto \frac{1}{V^{\gamma-1}}$

Pol

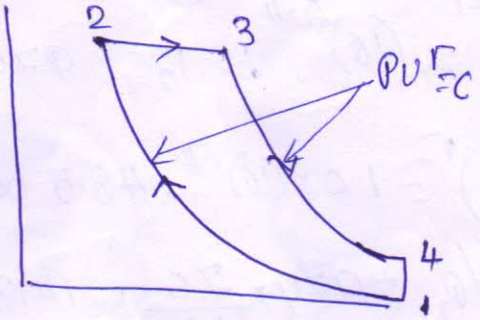
$PV^{n} =$

$TV^{n-1} =$

② A Diesel engine has an compression ratio of 14 and cutt-off takes place at 6% of the stroke. Find the air standard efficiency?

<u>Sol:</u> $r_k = v_1/v_2 = 14$

$$v_3 - v_2 = 0.06(v_1 - v_2) = 0.06(14v_2 - v_2) = 0.78v_2$$



$v_3 = 1.78\, v_2$

∴ Cutt-off ratio $r_c = v_3/v_2 = 1.78$

$$\eta_D = 1 - \frac{1}{\gamma}\cdot\frac{1}{r_k^{\gamma-1}}\cdot\frac{r_c^{\gamma}-1}{r_c-1}$$

$$= 1 - \frac{1}{1.4}\,\frac{1}{(14)^{0.4}}\,\frac{(1.78)^{1.4}-1}{1.78-1}$$

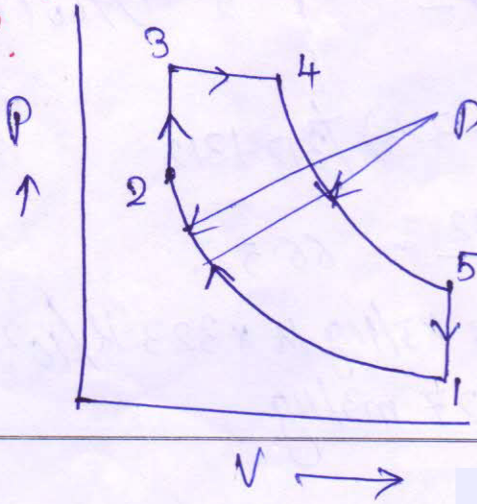
$$= 1 - 0.248\cdot\frac{1.24}{0.78} = 0.605$$

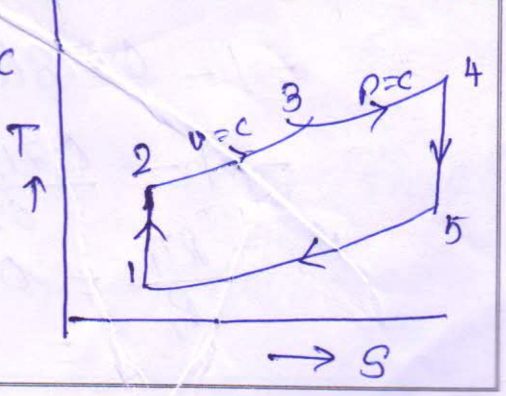
$$= 60.5\%$$

③ An air standard cycle has a compression ratio of 16, and compression begins at 1 bar, 50°C. The maximum pressure is 70 bar, the heat transferred to air at constant pressure is equal to that at constant volume. Estimate the pressures and temp at the cardinal points of the cycle.

$\boxed{\text{June-08}}$

<u>Sol:</u>





$T_1 = 273+50 = 323K$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = (16)^{0.4}, \therefore T_2 = 979K$$

$$P_2 = P_1\left(\frac{v_1}{v_2}\right)^{\gamma} = 1.0\times(16)^{1.4} = 48.5 \text{ bar}$$

$$T_3 = T_2 \cdot P_3/P_2 = 979\times\frac{70}{48.5} = 1413\,K$$

$$Q_{2-3} = C_v\,(T_3-T_2) = 0.718(1413-979) = 312 \text{ kJ/kg}$$

$$Q_{2-3} = Q_{3-4} = C_p\,(T_4-T_3)$$

$$T_4 = \frac{312}{1.005}+1413 = 17233K$$

$$\frac{v_4}{v_3} = \frac{T_4}{T_3} = \frac{1723}{1413} = 1.22$$

$$\therefore \frac{v_5}{v_4} = \frac{v_1}{v_2}\times\frac{v_3}{v_4} = 16/1.22 = 13.1$$

$$\therefore T_5 = T_4\left(\frac{v_4}{v_5}\right)^{\gamma-1} = 1723\times 1/(13.1)^{0.4} = 615K$$

$$P_5 = P_1\,(T_5/T_1) = 1.0\times 615/323 = 1.9 \text{ bar.}$$

④ The cycle efficiency when the pressure 1.9 bar and the maximum pressure 70 bar find the $\eta$

Sol:
$$\eta = 1-Q_2/Q_1 = 1 - C_v(T_5-T_1)/C_v(T_3-T_2)+C_p(T_4-T_3)$$

$$= 1-0.718(615-323)/312+312$$

$$= 1-\frac{0.718\times292}{624} = 66.5\%$$

$$v_1 = \frac{RT_1}{P_1} = 0.287 \text{ kJ/kg K}\times 323\text{ K}/10^2 \text{ kN/m}^2$$

$$= 0.927 \text{ m}^3\text{/kg}$$

Topic:

$$v_1 - v_2 = v_1 - \frac{v_1}{16} = \frac{15}{16} v_1$$

$$W_{net} = Q_1 \times \eta_{cycle}$$

$$= 0.665 \times 624 \text{ KJ/kg}$$

∴ mean effective pressure $= \frac{W_{net}}{v_1 - v_2}$

$$= \frac{0.665 \times 624 \text{ KJ/kg}}{\frac{15}{16} \times 0.927 \text{ m}^3/\text{kg}}$$

$= 476$ KN/m² = 4.76 bar

⑤ Find the ideal thermal η of a petrol engine working on otto cycle at maximum temp of 2000°C and the temp at the end of expansion is 800°C? Find also the ratio of compression. $\gamma = 1.4$

Sol: $T_3 = 2000 + 273 = 2273$ K

$T_4 = 800 + 273 = 1073$ K

$\eta = 1 - T_4/T_3 = 1 - 1073/2273 = 0.528 = 52.8\%$

$T_3/T_4 = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = r^{\gamma-1}$ ; r = ratio of expansion

$$r = (T_3/T_4)^{1/\gamma-1} = \left(\frac{2273}{1073}\right)^{1/0.4} = (2.118)^{2.5} = 6.53.$$

In otto cycle ratio of expansion = ratio of compression

∴ Ratio of compression = 6.53.