

LECTURE NOTES

ON

**THERMODYNAMICS
ACADEMIC YEAR 2021-22**

I B.Tech.–II SEMESTER(R20)

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DEPARTMENT OF HUMANITIES AND BASIC SCIENCES

**V S M COLLEGE OF ENGINEERING
RAMCHANDRAPURAM
E.G DISTRICT
533255**



JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY KAKINADA
KAKINADA – 533 003, Andhra Pradesh, India

DEPARTMENT OF MECHANICAL ENGINEERING

I Year - II Semester		L	T	P	C
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THERMODYNAMICS					

Course Objectives:

To impart the knowledge of the thermodynamic laws and principles so as to enable the student to prepare an energy audit of any mechanical system that exchange heat and work with the surroundings.

UNIT – I

Introduction: Basic Concepts : System, boundary, Surrounding, Universe, control volume, Types of Systems, Macroscopic and Microscopic viewpoints, Concept of Continuum, Thermodynamic Equilibrium, State, Property, Process - Reversible, Quasi static & Irreversible Processes, cycle, Causes of Irreversibility. Energy in State and in Transition - Types, Work and Heat, Point and Path function.

Zeroth Law of Thermodynamics – Concept of Temperature – Principles of Thermometry – Reference Points – Const. Volume gas Thermometer – Scales of Temperature.

UNIT – II

Joule’s Experiments – First law of Thermodynamics – Corollaries – First law applied to a Process – applied to a flow system –Energy balance for closed systems-Specific heats-Internal energy, Enthalpy and Specific heats of Solids, liquids and Ideal gases, Some steady flow energy equation applied to Nozzle, Turbine, Compressor and heat exchanger devices, PMM-I.

UNIT III

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 cycle and its specialties, Carnot’s theorem, Thermodynamic scale of Temperature.

Clausius Inequality, Entropy, Principle of Entropy Increase, Availability and Irreversibility (Basic definitions) – Thermodynamic Potentials, Gibbs and Helmholtz Functions, Maxwell Relations – Elementary Treatment of the Third Law of Thermodynamics.

UNIT IV

Pure Substances, P-V-T- surfaces, T-S and h-s diagrams, Mollier Charts, Phase Transformations – Triple point and critical point, properties during change of phase, Dryness Fraction – Clausius – Clapeyron Equation, Property tables. Various Thermodynamic processes and energy Transfer – Steam Calorimetry.

UNIT – V

Ideal Gas equation of state- Compressibility factor- Van der Waals equation of state- Beattie-Bridgeman equation of state- Benedict-Webb-Rubin equation of state- Viral equation of state-compressibility charts – variable specific heats .

Mixtures of perfect Gases – Dalton’s Law of partial pressure, Avogadro’s Laws of additive volumes- Equivalent Gas constant and Molecular Internal Energy, Enthalpy, Specific Heat and Entropy of Mixture of Perfect Gases and Vapour.



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KAKINADA – 533 003, Andhra Pradesh, India

DEPARTMENT OF MECHANICAL ENGINEERING

Psychrometric Properties – Dry bulb Temperature, Wet Bulb Temperature, Dew point Temperature, Thermodynamic Wet Bulb Temperature, Specific Humidity, Relative Humidity, Saturated Air, Vapour pressure, Degree of saturation – Adiabatic Saturation , Carrier's Equation – Psychrometric chart.

TEXT BOOKS:

1. Engineering Thermodynamics, PK Nag 6th Edn , McGraw Hill.
2. Fundamentals of Thermodynamics – Sonntag, Borgnakke, Van Wylen, 6th Edn, Wiley

REFERENCES:

1. Thermodynamics by Prasanna Kumar, Pearson Publishers
2. Engineering Thermodynamics – Jones & Dugan PHI
3. Thermodynamics, an Engineering Approach, Yunus A Cengel, Michael A Boles, 8th Edn inSI Units, McGraw Hill.
4. Thermodynamics – J.P.Holman , McGrawHill
5. An Introduction to Thermodynamics - Y.V.C.Rao – Universities press.
6. Thermodynamics – W.Z.Black & J.G.Hartley, 3rd Edn Pearson Publ.
7. Engineering Thermodynamics – D.P.Misra, Cengage Publ.
8. Engineering Thermodynamics – P.Chattopadhyay – Oxford Higher Edn Publ.

COURSE OUTCOMES:

After undergoing the course the student is expected to learn

CO1: Basic concepts of thermodynamics

CO2: Laws of thermodynamics

CO3: Concept of entropy

CO4: Property evaluation of vapors and their depiction in tables and charts

CO5: Evaluation of properties of perfect gas mixtures.

VSM COLLEGE OF ENGINEERING
RAMACHANDRAPRUM-533255
DEPARTMENT OF HUMANITIES AND BASIC SCIENCES

Course Title	Year-Sem	Branch	Contact Periods/Week	Sections
THERMODYNAMICS	2-1	Mechanical engineering	6	-

COURSE OUTCOMES: Students are able to

- To impart the knowledge of the thermodynamic laws and principles so as to enable the student to prepare an energy audit of any mechanical system that exchange heat and work with the surroundings..(K1)
- Understand the concept of first law of thermodynamics K2)
- Analyze the problems on second law of thermodynamics. (K4)
- Determine the parameters of heat engine and refrigerators.(K3)
- Estimate work and heat transfer parameters.(K2)

Unit/ item No.	Outcomes	Topic	Number of periods	Total periods	Book Refer ence	Delive ry Metho d	
1	CO1: Identify the unique vocabulary associated with thermodynamics and Explain the basic concepts of thermodynamics like system, properties, equilibrium, pressure, specific volume, temperature, zeroth law of thermodynamics, temperature measurement and temperature scales.	Title of the Chapter : Fundamental Concepts & Definitions		15	T1, R1	Chalk & Talk, PPT, Active Learning & Tutorial	
		1.1	Explain the basic concepts of thermodynamics such as system, state, state postulate, equilibrium, properties, process and cycle				4
		1.2	Distinguish between Open, Closed and Isolated systems, Microscopic and Macroscopic approaches, Intensive and Extensive properties				4
		1.3	Define zeroth law of thermodynamics and explain the concept of pressure, temperature, specific volume and temperature scales.				4
		1.4	Apply the above concepts to solve simple engineering problems	3			
2	CO2: Explain the concept of thermodynamic work. Calculate and compare work in case of a closed system executing different thermodynamic processes or different thermodynamic cycles, State and apply the first law of thermodynamics	Title of the Chapter : Work and Heat, First Law of thermodynamics for closed systems		15	T1, R1	Chalk & Talk, Active Learning & Tutorial	
		2.1	Derive an expression for thermodynamic work at the moving boundary of a simple compressible system				4
		2.2	Calculate and compare work in case of a system executing a thermodynamic cycle with different combinations of				4

	for closed and open systems undergoing different thermodynamic processes. Evaluate the performance of steam power plants, refrigeration plants and their components using the first law of thermodynamics for open systems		thermodynamic processes and suggest the most economical cycle				
		2.3	Calculate work in case of a system executing various thermodynamic processes that involve either ideal gas or pure substance as working fluid	2			
		2.4	Apply the first law of thermodynamics for a closed system executing a thermodynamic process and calculate change in internal energy or work transfer or heat transfer in typical engineering problems that involve either ideal gas or pure substance as working fluid	2			
		2.5	Explain the development of concept of enthalpy, calculate enthalpy of pure substances & ideal gases knowing two independent properties and apply it in solving problems that involve thermodynamic processes	2			
		2.6	Define constant pressure and constant volume specific heats & Obtain expressions for enthalpy change and internal energy change of ideal gases from the conclusions drawn from Joule's experiment	1			
3	CO3: State and apply the first law of thermodynamics for closed and open systems undergoing different thermodynamic processes. Evaluate the performance of steam power plants, refrigeration plants and their components using the first law of thermodynamics for open systems	Title of the Chapter : Second law of thermodynamics			10	T1, R1	Chalk & Talk, Active Learning & Tutorial
		3.1	Explain the limitations of first law of thermodynamics,	4			
		3.2	State & explain Kelvin-Planck & Clausius statements of second law of thermodynamics, Prove the equivalence of two statements of second law	4			
		3.3	Apply the efficiency and COP expressions of Carnot cycle to solve typical engineering problems	2			
4	CO4: Distinguish between ideal gas and	Title of the Chapter : Properties of pure substances					
		4.1	Illustrate the T-v, P-T diagrams and P-v-T surfaces of pure substances.	4		T1, R1	

	pure substance. Calculate thermodynamic properties using tables of thermodynamic properties and analyze the processes on T-v diagrams to solve advanced engineering problems	4.2	Analyze the processes on T-v diagrams to solve advanced engineering problems	3	10		Chalk & Talk, Active Learning & Tutorial
		4.3	Explain the compressibility factor and compressibility chart for nitrogen & Conclude from this chart as to when the ideal gas equation can be applied and when real gas equation is applicable	3			
5	CO5: Quantify the second law of thermodynamics for a cycle by establishing the inequality of Clausius. Apply the inequality of Clausius and establish the property entropy of a system. Derive and apply principle of increase of entropy to evaluate the feasibility of a thermodynamic process.		Title of the Chapter : Ideal Gas equation of state- Mixtures of perfect Gases	1	10	T1, R1	Chalk & Talk, Active Learning & Tutorial
		5.1	Calculate entropy changes that take place during processes for pure substances and ideal gas				
		5.2	Establish the increase of entropy principle. Apply the same to evaluate the feasibility of a thermodynamic process	2			
		5.3	Mixtures of perfect Gases	1			
		5.4	Low Pass Filter, High Pass Filter, Band Pass Filter, Band Elimination Filter, m-Derived Filter, Composite filters	3			
		5.5	Design of Filters	2			
		5.6	Problems on Filters	1			
				TOTAL	60		

LIST OF TEXT BOOKS AND AUTHORS

Text Books:

T1. Engineering Thermodynamics, PK Nag 6th Edn , McGraw Hill.

T2. Fundamentals of Thermodynamics – Sonntag, Borgnakke, Van Wylen, 6th Edn, Wiley

Reference Books:

R1. Thermodynamics -RK rajput

R2. Engineering Thermodynamics – Jones & Dugan PHI.

R3. Thermodynamics, an Engineering Approach, Yunus A Cengel, Michael A Boles, 8th Edn inSI Units, McGraw Hill.

R4. Thermodynamics – J.P.Holman , McGrawHill

R5. An Introduction to Thermodynamics - Y.V.C.Rao – Universities press.

Introduction:- Thermodynamics is the science of energy transfer and its effect on the physical properties of substances.

It is a classical (or) macroscopic science, which studies heat and work transfer with matter which bring about changes in the macroscopic properties of a substance that are measurable.

Based upon observations of common experience, changes in the properties of substance have been formulated into 4 Thermodynamic laws. These laws govern the principle of energy conversion.

The application of the thermodynamic laws and principles are found in all fields of energy technology.

- Example:-
- 1) Steam and Nuclear power plants
 - 2) I.C engines
 - 3) Gas turbines
 - 4) Refrigeration & Air-conditioning
 - 5) Compressors etc.,

Four Laws

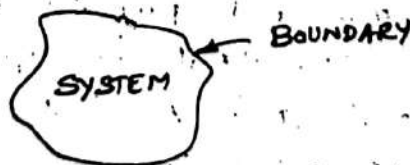
- 1) First Law - Concept of internal energy
- 2) Zeroth Law - Concept of Temperature
- 3) Second Law - Limit of converting heat into work principle of increase entropy
- 4) Third Law - Absolute zero of Entropy

Terms (or) definitions:-

1) Thermodynamic system:- It is a prescribed region (or) space (or) finite quantity of matter on which we focus our attention to study its properties.

2) Surroundings:- Other than the system everything else is known as surroundings.

3) Boundary:- An imaginary closed curve which separates system from its surroundings is called Boundary. The boundary may be either fixed (or) moving.



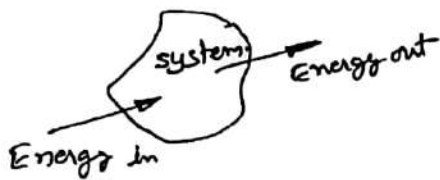
4) Universe:- System plus surroundings put together is known as universe. Hence it has no boundaries and is of infinite size.

Types of Thermodynamic Systems:-

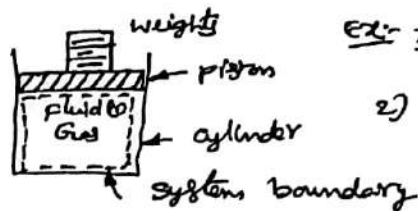
Based on the mass and energy transfer across the boundary, the systems are divided into three types:

- 1) Closed system
- 2) open system
- 3) Isolated system

1) closed system:- In a closed system, the mass is fixed. There is no mass transfer across the boundaries but energy transfer may take place into (or) out of the system.



No mass transfer.

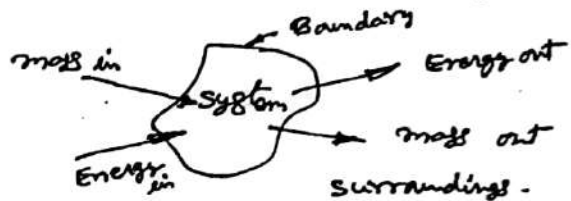


Ex:- 1) Hot coffee in a steel tumbler
2) Heating the Gas in a cylinder.

Certain quantity of fluid in a cylinder bounded by a piston constitutes a closed system.

② Open system:- In an open system both mass and energy crosses the boundary.

Ex:- 1) Compressor
2) Nozzle.



③ Isolated system:- In isolated system, there is neither energy transfer nor mass transfer occurs across the boundaries. i.e., Not having any interaction with surroundings.

Ex:- 1) Thermo flask
2) Insulated chamber



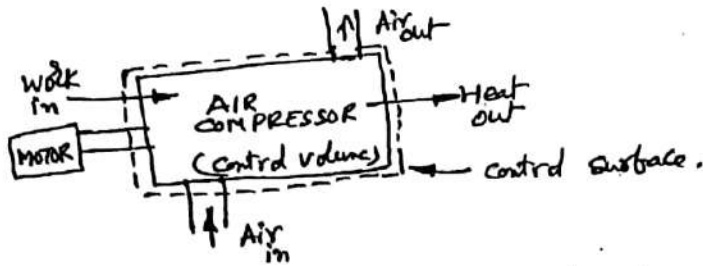
Type of thermodynamic System	Mass Transfer	Energy Transfer
1) closed	X	✓
2) open	✓	✓
3) Isolated	X	X

Another Types of Systems:-

① Homogeneous system:- A quantity of matter uniform throughout in chemical composition and physical structure is called a phase. Every substance can exist in any of the three phases i.e., solid, liquid and gas. A system consisting of a single phase is called a homogeneous system.

② Heterogeneous system:- A system consisting of more than one phase is known as heterogeneous system.

control volume For thermodynamic analysis of an open system such as an air compressor, attention is focussed on a certain volume in space surrounding the compressor. Known as the control volume bounded by a surface called control surface.



Thermodynamic properties, processes and A cycles:-

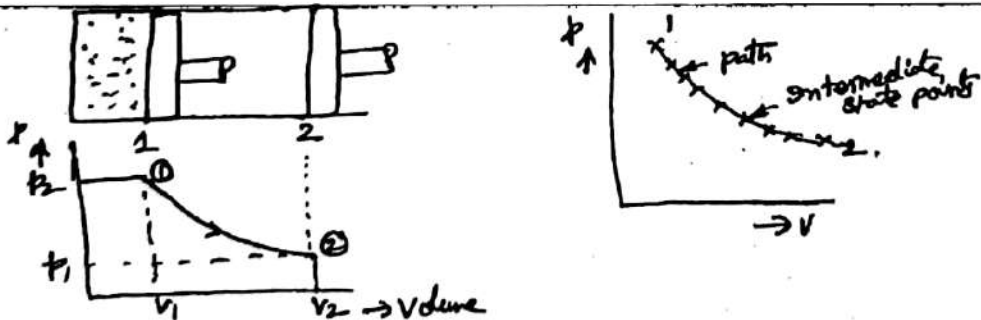
properties:- Every system has certain characteristics by which its physical condition may be described. EX: volume, temperature, pressure such characteristics are called properties of the system.

State- state is a unique condition of system described at any instant of time described by its properties such as pressure, temperature, volume etc.,

Change of state- Any operation in which one or more of the properties of a system changes is called a change of state.

path- When a system undergoes change in its state, the line joining the series of intermediate states through which the system has passed is known as path.

process:- When the path is completely specified, the change of state is called a process. EX: Isobaric process (pressure, $P = \text{const.}$)



Thermodynamic cycle (Cyclic process):-

If a system undergoes a series of processes from one state to another state and returns to its initial state by following a complete cycle, then the system is said to be undergo a cyclic process. A cyclic process may have 2 or more than two processes.



Types of properties:-

1) Intensive properties:- Intensive properties are those which are independent of the mass of the system.

Ex:- pressure, Temperature, density

2) Extensive properties:- Extensive properties are those which are dependant on the mass of the system.

Of the mass is increased, the values of Intensive properties are not changed. But the values of extensive properties also increases. Ex:- Total mass, Total volume, Total energy.

The extensive properties per unit mass, are intensive properties.

I.e., Volume \rightarrow Extensive property

Specific Volume \rightarrow Intensive property.

All specific extensive properties are intensive properties.

Ex:- specific volume, specific heat, Specific density.

MACROSCOPIC and MICROSCOPIC POINT OF VIEW:

Thermodynamic studies are undertaken by the following two different approaches.

1. Macroscopic approach (Classical Approach)

1. In this approach, a certain quantity of matter is considered without taking into account the events occurring at molecular level. In other words, this approach to thermodynamics is concerned with overall behaviour. This is known as Classical Thermodynamics.

2. The analysis of macroscopic system requires simple mathematical formulae.

2. Microscopic approach (Statistical Approach)

The approach considers that the system is made up of a large no. of discrete particles known as molecules. These molecules have different velocities and energies. The values of these energies are constantly changing with time. This approach to thermodynamics which is concerned directly with the structure of matter is known as Statistical Thermodynamics.

The behaviour of the system is found by using statistical methods as the no. of molecules is very large. So advanced statistical mathematical methods are needed to explain changes in the system.

3. The value of the properties of the system are their average values. For example consider a sample of gas in a closed container, the pressure of the gas is the average value of the pressure exerted by millions of individual molecules. The properties can be measured very easily. The change in properties can be felt by our senses.

The properties like, velocity, momentum, impulse etc, which describes the molecule can not be easily measured by instruments. Our senses can not feel them.

4. In order to describe a system, only few properties are needed

Large no. of variables are needed to describe a system, so the approach is complicated.

Thermodynamic equilibrium:-

A system will be in a state of thermodynamic equilibrium, if the conditions for the following three types of equilibrium are satisfied.

- a) Mechanical Equilibrium
- b) Chemical Equilibrium
- c) Thermal Equilibrium.

Mechanical Equilibrium:- If all the forces in the system and between the system and surroundings are balanced, then the system is said to be in mechanical equilibrium. This is possible only when pressure is same throughout the system and also equal to that of surroundings.

Chemical Equilibrium:- If no chemical reaction @ transfer of matter takes place throughout the system, then the system is said to be in chemical equilibrium.

Thermal Equilibrium:- If the temperature is uniform throughout the system and between the system and surroundings, then the system is said to be in thermal equilibrium.

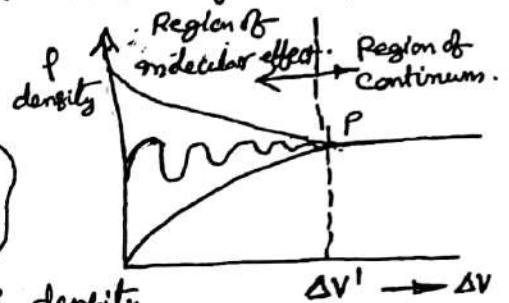
Criteria for an Equilibrium.

Equilibrium	Criteria
Thermal	Equilibrium of Temperature
Mechanical	Equilibrium of pressure and free
Chemical	Equilibrium of chemical potential
Thermodynamic	All the above.

Concept of Continuum:-

To study about a system and its properties, it is always convenient to consider the system as a continuous distribution of matter. This continuous distribution of matter is known as continuum. The concept of continuum is to treat the matter as continuous by disregarding the behaviour of individual molecules. In classical thermodynamics, the concept of continuum is very useful.

Let us consider the mass Δm in a volume ΔV surrounded the point P as shown in figure.



The ratio $\Delta m / \Delta V$ is the average mass density of the system with in the volume ΔV . The volume $\Delta V'$ is the smallest volume about the point P, for which the mass can be considered continuous. Any volume smaller than this volume will lead to discontinuity in the particles, atoms and electrons in the matter and the density becomes unpredictable.

$$\rho \text{ density} = \lim_{\Delta V \rightarrow \Delta V'} \left(\frac{\Delta m}{\Delta V} \right)$$

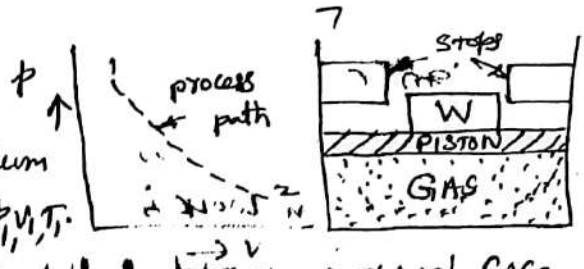
This continuum holds good from volume $\Delta V'$ and is non-continuum for a volume less than $\Delta V'$. This is due to the variation in the density of fluid from one point to another point with entering and leaving the molecules from the system in random manner.

Quasi-static process

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

A quasi-static process is viewed as a sufficiently slow process in which system changes its state very slowly under the influence of an infinitesimally small driving force. The system adjusts itself internally, so that the properties in one part of the system do not change any faster than those in the other part.

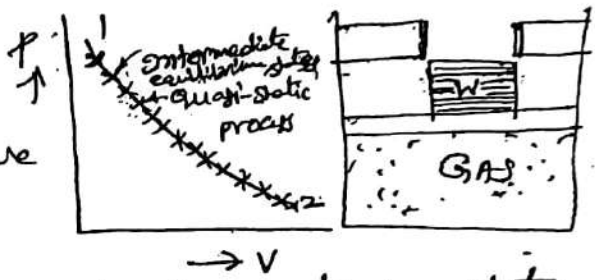
Let us consider a system of gas contained in a cylinder. The system is initially in equilibrium state, represented by properties p_1, V_1, T_1 .



The weight (W) on the piston just ~~balances~~ the upward force exerted by the gas.

If the weight (W) is removed, the piston will move up due to gas pressure. The system ~~will~~ comes to an equilibrium state by properties p_2, V_2, T_2 . But the intermediate states passed through by the system are non-equilibrium states, which can be described by points 1, 2.

Now, if single weight W is made up of small pieces of weights and these weights are removed one by one very slowly from top of piston,



the gas will pass through a series of equilibrium states. If the ~~weights~~ mass are made negligibly small, the gas would undergo a quasi-equilibrium expansion process.

Classification of Thermodynamic processes:-

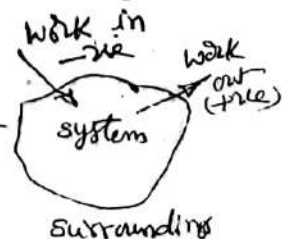
1. Non-flow processes & flow processes.

1. Non-flow processes:- The processes occur in closed system which don't permit the transfer of mass across their boundaries, are known as non-flow processes. Energy crosses the system boundary in the form of heat & work.
ex:- constant volume process, constant pressure process etc.

2. Flow processes:- The processes occurring in open system which permit the transfer of mass to and from the system are known as flow processes.

ex:- steady flow process through nozzles, turbines & compressors etc.
non-steady flow processes are filling (or) evacuation of vessels.

WORK:- work is transient quantity which only appears at the boundary while a change of state is taking place within a system. units are Joules (J).



Sign convention:-

- When work is done by the system, the sign is +ve.
- When work is done on the system, the sign is -ve.

PdV work (or) displacement work:-

Consider a gas enclosed in a frictionless cylinder arrangement.

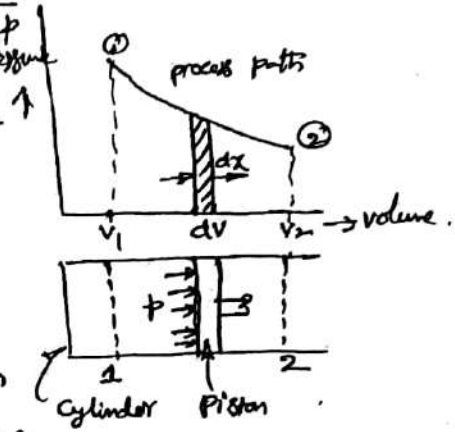
Let the gas pressure is p , volume V and piston cross-sectional area is A . If the piston is allowed to move through a distance ' dx ' in a quasi-equilibrium manner, the force applied on the piston is

$F = \text{pressure} \times \text{cross-sectional area of piston} = pA$

Then work transfer through the distance of dx , during the process, $\delta W = pA dx = p dV$.

Total work transfer during a process is equal to area under p - V diagram.

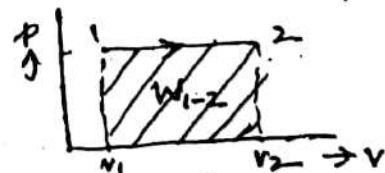
$\therefore W = \int_1^2 p dV$ KJ.



Now find work in various quasi-static processes

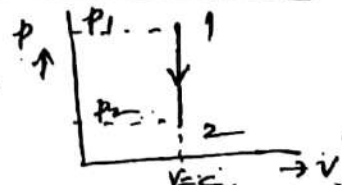
- 1) Constant pressure process ($p=c$) (or) $pV^0=c$.
(isochoric process)

$W_{1-2} = \int_1^2 p dV = p [v_2 - v_1]$



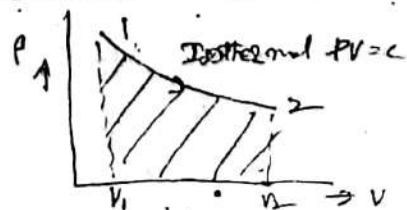
- 2) Constant volume process (or) Isochoric process ($V=c$); $pV^\infty=c$

$W_{1-2} = \int_1^2 p dV = 0$ [since $dV = \text{constant}$, $dV = 0$]



- 3) Constant temperature process (or) Isothermal process ($T=c$) (or) $pV^1=c$

$pV = p_1V_1 = p_2V_2 = c$
 $W = \int_1^2 p dV = \int_1^2 \frac{c}{V} dV = c \int_1^2 \frac{1}{V} dV$
 $= c \ln V \Big|_1^2 = c \ln \frac{V_2}{V_1}$
 $\therefore W = p_1V_1 \ln \frac{V_2}{V_1} = \frac{p_2}{p_1} V_1 \ln \frac{p_1}{p_2}$



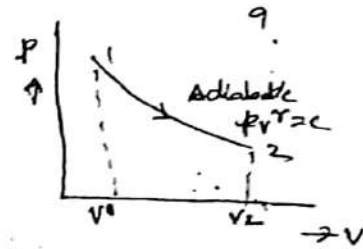
Adiabatic process $PV^\gamma = c$

$$P_1 V_1^\gamma = P_2 V_2^\gamma = c$$

$$W = \int_1^2 P dV$$

$$= \int_1^2 \frac{c}{V^\gamma} dV = c \left[\frac{V^{-\gamma+1}}{-\gamma+1} \right]_1^2$$

$$= \frac{c V_2^{-\gamma+1} - c V_1^{-\gamma+1}}{-\gamma+1} = \frac{P_2 V_2^\gamma \cdot V_2^{-\gamma+1} - P_1 V_1^\gamma \cdot V_1^{-\gamma+1}}{-\gamma+1}$$



$$\therefore W = \frac{P_2 V_2 - P_1 V_1}{-\gamma+1} \quad (a) = \frac{P_1 V_1 - P_2 V_2}{\gamma-1}$$

Polytropic process $PV^n = c$
 $P_1 V_1^n = P_2 V_2^n = c$

$$W = \int_1^2 P dV, \text{ by solving.}$$

$$W = \frac{P_1 V_1 - P_2 V_2}{n-1}$$

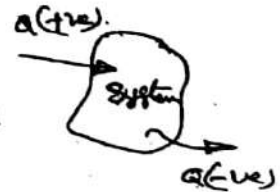
A Gas in a closed system can undergo the following processes.

process	Law	Relation	Total Wk (1-2)
1) constant pressure	$P = c @ PV^0 = c$	$P_1 = P_2 = P$ at all state points	$W_{1-2} = P(V_2 - V_1)$
2) constant volume	$V = c @ PV^n = c$	$V_1 = V_2 = V_3 = \dots$	$W_{1-2} = 0$
3) constant temperature	$T = c @ PV^1 = c$	$P_1 V_1 = P_2 V_2 = \dots$	$W_{1-2} = P_1 V_1 \ln \frac{V_2}{V_1}$
4) Adiabatic	$PV^\gamma = c$	$P_1 V_1^\gamma = P_2 V_2^\gamma = \dots$	$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\gamma-1}$
5) polytropic	$PV^n = c$	$P_1 V_1^n = P_2 V_2^n = \dots$	$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n-1}$

Heat:- Heat is something which appears at the boundary when system changes its state due to a difference in temperature between the system and its surroundings. Symbol is Q .

Sign convention

- When heat flows in to the system, Q is +ve
- When heat flows from out of system, Q is -ve



PROBLEMS

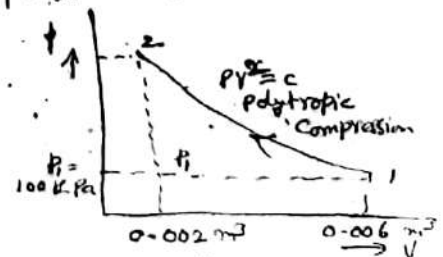
① A gas of volume 6000 cm^3 and at a pressure of 100 kPa is compressed quasi-statically to $PV^\gamma = c$ until the volume becomes 2000 cm^3 . Calculate the final pressure and work transfer.

Given data:-

$$P_1 = 100 \text{ kPa} = 1 \text{ bar} = 10^5 \text{ N/m}^2$$

$$V_1 = 6000 \text{ cm}^3 = 0.006 \text{ m}^3$$

$$V_2 = 2000 \text{ cm}^3 = 2000 \times 10^{-6} = 0.002 \text{ m}^3$$



Final pressure (P_2)

10

We know that for polytropic process, $PV^n = c = P_1V_1^n = P_2V_2^n$.

$$\therefore P_2 = P_1 \left(\frac{V_1}{V_2} \right)^n = 1 \left(\frac{0.006}{0.002} \right)^2 = 9 \text{ bar.}$$

Work done (W_{1-2}): polytropic compression
 we know that $W = \int_{V_1}^{V_2} P dV = \frac{(P_2V_2 - P_1V_1)}{n-1}$ for polytropic process.
 $= \frac{(9 \times 0.002 - 1 \times 0.006)}{2-1} \times 100 \text{ kJ.}$

work done, $W = 1.2 \text{ kJ}$ Ans. ✓

② A mass of 2.5 kg of air is compressed in a quasi-static process from 0.1 MPa to 0.7 MPa for which $PV = \text{constant}$. The initial volume is $0.8 \text{ m}^3/\text{kg}$. Find the work done by the piston to compress the air.

Sol:- mass, $m = 2.5 \text{ kgs.}$

$P_1 = 0.1 \text{ MPa}$

$P_2 = 0.7 \text{ MPa}$

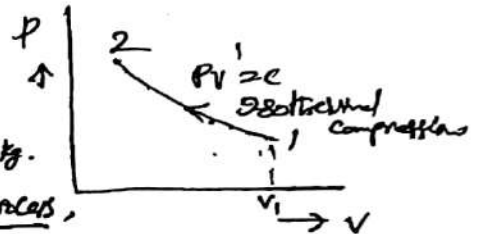
process, $PV = c$, $v_{s1} = 0.8 \text{ m}^3/\text{kg}$.

We know that work done in $PV = c$ process,

$$W = P_1 V_1 \ln \left(\frac{V_2}{V_1} \right) = P_1 V_1 \ln \frac{P_1}{P_2}$$

$$= 0.1 \times 10^3 \times 2 \ln \frac{0.1}{0.7}$$

$W = -389.182 \text{ kJ}$ ✓



State
 $V_1 = \text{specific volume} \times \text{mass}$
 $= 0.8 \times 2.5$
 $= 2 \text{ m}^3$.

③ An engine cylinder has piston of area 0.12 m^2 and contains gas at a pressure of 1.5 MPa . The gas expands according to a process which is represented by a straight line on a P - V diagram. The final pressure is 0.15 MPa . Calculate the W-D by the gas on the piston if the stroke is 0.3 m .

Sol:- Given, Area = 0.12 m^2
 of piston

Initial gas pressure, $P_1 = 1.5 \text{ MPa}$

Final gas pressure, $P_2 = 0.15 \text{ MPa}$

Length of stroke, $L = 0.3 \text{ metres.}$

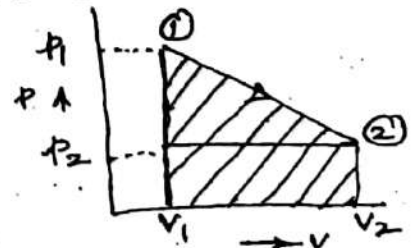
Stroke volume, $(V_2 - V_1) = \text{Area of piston (or) cylinder} \times \text{Stroke Length}$

$= 0.12 \times 0.3 = 0.036 \text{ m}^3$.

\therefore Work done on the piston is equal to shaded Area in P - V diagram.

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

$W = \frac{1}{2} (1.5 - 0.15) \times 10^6 (0.036) + 0.15 \times 10^6 \times 0.036$
 $W = 0.0297 \times 10^6 \text{ Joules.} = 29.7 \text{ kJ}$ ✓

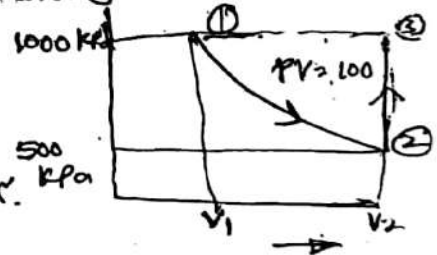


Prob A gas undergoes a reversible non-flow process according to the relation $p = (-3V + 15)$ where V is the volume in m^3 and p is the pressure in bar. Determine the workdone when the volume changes from 3 to 6 m^3 .

Sol. pressure, $p = (-3V + 15)$
 initial volume, $V_1 = 3 m^3$
 Final volume, $V_2 = 6 m^3$
 We know, workdone = $\int_1^2 p dV = \int_1^2 (-3V + 15) dV$
 $= \left[-3 \frac{V^2}{2} + 15V \right]_3^6 = -1.5 (6^2 - 3^2) + 15(6 - 3)$
 $= -40.5 + 45 = 4.5 \times 10^5 \text{ Joules. } [\because p \text{ in bar } 10^5]$
 $W = 450 \text{ kJ.}$

Prob A gas expands according to the equation $pV = 100$, where p is the pressure in kPa and V is the specific volume in m^3/kg . The initial pressure of gas is 1000 kPa and final pressure is 500 kPa. The gas is then heated at constant volume back to its original pressure of 1000 kPa. Determine the work of combined process. Also sketch the process on p - V co-ordinates.

Sol. $pV = 100$
 initial pressure, $p_1 = 1000 \text{ kN/m}^2$
 At state 2 pressure, $p_2 = 500 \text{ kN/m}^2$
 At state 3, Final pressure, $p_3 = p_1 = 1000 \text{ kN/m}^2$



Workdone during 1-2 process

We know, $pV = 100 = p_1 V_1 = p_2 V_2$ (constant temperature $T = c$ process)

$$V_1 = \frac{100}{1000} = 0.1 \text{ m}^3/\text{kg} \quad V_2 = \frac{100}{500} = 0.2 \text{ m}^3/\text{kg}$$

$$W_{1-2} = p_1 V_1 \ln \frac{V_2}{V_1} = 1000 \times 0.1 \times \ln \frac{0.2}{0.1} = 69.315 \text{ kJ/kg}$$

Workdone during 2-3 process (constant volume process $V = c$)

$$W_{2-3} = 0, \text{ since } 2-3 \text{ process line is vertical.}$$

$$\therefore W_{1-3} = W_{1-2} + W_{2-3} = 69.315 \text{ kJ/kg}$$

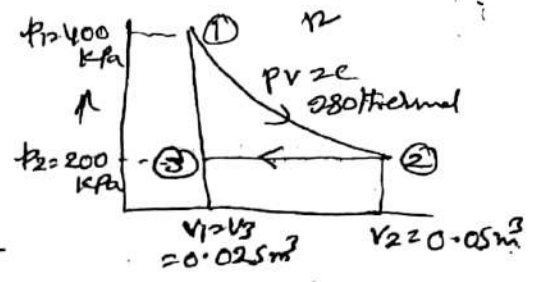
Prob A gas undergoes two processes that are in series. The first process is an expansion process that is carried out according to the law $pV = c$ and the second process is a constant pressure process that returns to the gas to the initial volume of the first process. The start of first process is at 400 kPa and 0.025 m^3 with an expansion to 200 kPa. Sketch the process p - V diagram and determine the work of the combined process.

SOL.

$$\begin{aligned}
 PV &= C \\
 P_1 &= 400 \text{ KPa} \\
 V_1 &= 0.025 \text{ m}^3 \\
 P_2 &= 200 \text{ KPa}
 \end{aligned}$$

We know that $PV=C \Rightarrow P_1V_1 = P_2V_2$

$$\therefore V_2 = \frac{P_1}{P_2} \times V_1 = \frac{400}{200} \times 0.025 = 0.05 \text{ m}^3$$



Work done during isothermal process, $T=C$ (1) $PV=C$ (1-2) process

$$W_{1-2} = P_1V_1 \ln \frac{P_1}{P_2} = 400 \times 0.025 \ln \frac{400}{200} = 6.93 \text{ KJ}$$

$$W_{2-3} = P_2(V_3 - V_2) = 200(0.025 - 0.05) = -5 \text{ KJ}$$

$$\therefore \text{net work done } W_{1-3} = W_{1-2} + W_{2-3} = 6.93 - 5 = 1.93 \text{ KJ}$$

Q.214 On a reversible non-flow process, the work is done by a substance in accordance with $V = \frac{2.80}{P} \text{ m}^3$, where P is pressure in bar. Find the work done (or) by system as pressure increases from 0.7 bar to 7 bar.

SOL. A reversible non flow process with

$$P_1 = 0.7 \text{ bar} = 70 \text{ kPa}, P_2 = 7 \text{ bar} = 700 \text{ kPa}$$

$$V = \frac{2.80}{P} \text{ m}^3$$

To find: work interaction by the system,

Analysis The initial and final volume of working substance, $V_1 = \frac{2.80}{P_1} = \frac{2.80}{0.7} = 4 \text{ m}^3$.

$$V_2 = \frac{2.80}{P_2} = \frac{2.8}{7} = 0.4 \text{ m}^3$$

For a given relation, pressure P can be expressed as
 $P = \frac{2.80}{V} \text{ bar} = 100 \times \frac{2.8}{V} \text{ kPa}$
 The work done by a system can be calculated as
 $W = \int_{V_1}^{V_2} P dV = 100 \times 2.8 \int_{4}^{0.4} \frac{1}{V} dV$
 $= 280 \times \ln V \Big|_{4}^{0.4} = 280 \ln \left(\frac{0.4}{4} \right)$
 $W = -6447 \text{ J}$

Pr. 11 On a piston-cylinder arrangement, the pressure is inversely proportional to the square of the volume. The initial pressure is 10 bar in the cylinder and the initial volume is 0.1 m³. The volume is now changed so that the final pressure is 2 bar. Find the work done in KJ.

SOL.

$$\begin{aligned}
 \text{The relation } P &\propto \frac{1}{V^2} \\
 P_1 &= 10 \text{ bar} = 1000 \text{ kPa} \\
 V_1 &= 0.1 \text{ m}^3 \\
 P_2 &= 2 \text{ bar} = 200 \text{ kPa}
 \end{aligned}$$

To find work done during the process

Analysis The given relation $P \propto \frac{1}{V^2}$ (or) $P = \frac{K}{V^2}$

At state 1, $P_1 = \frac{K}{V_1^2}$, where K is constant of proportionality.

$$K = P_1 V_1^2 = (1000 \text{ kPa}) \times (0.1 \text{ m}^3)^2 = 10 \text{ kPa} \cdot \text{m}^6$$

Now at state 2,

$$P_2 = \frac{K}{V_2^2} \Rightarrow V_2 = \sqrt{\frac{K}{P_2}} = \sqrt{\frac{10}{200}} = 0.223 \text{ m}^3$$

Now, the work done during the process,

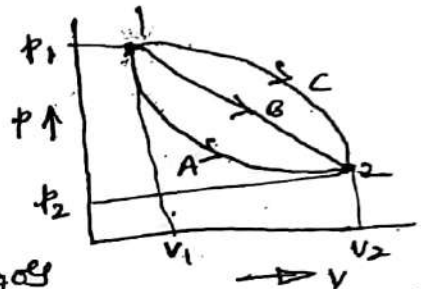
$$\begin{aligned}
 W &= \int_{V_1}^{V_2} P dV = \int_{V_1}^{V_2} \frac{K}{V^2} dV \\
 &= K \left[\frac{1}{V_1} - \frac{1}{V_2} \right] \\
 &= 10 \times \left[\frac{1}{0.1} - \frac{1}{0.223} \right] \\
 &= 57.1 \text{ KJ}
 \end{aligned}$$

* path function and point function 13

- ① path function:- The function which depends on the path of system passed and not on the end states is known as path function.
Example:- Work transfer, Heat transfer.
- ② point function:- The function which depends on the end states not on the path of the system is known as point function.
Example:- property of system i.e., volume, temp, pressure etc.

'properties' are point functions:-

Thermodynamic properties are point functions. Since for a given state, there is a definite value for each property. When a system undergoes a change from one state to another, the properties of the system also changes, which depends only on end states and not on the path followed between these two states. Therefore, these properties are called state functions (or) point functions. point functions can be represented by a point on any plot eg., Temperature, pressure, volume etc., these properties have exact differentials designated by d (symbol). Therefore change in volume (or) pressure represented by dV (or) dP .



The differentials of point functions are exact (or) perfect differentials, and the integration is simple

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

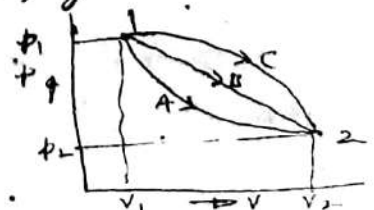
→ The change in volume this depends only on the end states of the system irrespective of the path followed.

→ For a cyclic process, the initial and final states of the system are the same and hence change in any property is zero.

$$\oint dV = 0, \quad \oint dP = 0, \quad \oint dT = 0$$

WORK TRANSFER - 'PATH' FUNCTION

A quantity whose value depends on the particular path followed during the process is called a path function.



It requires a particular path and direction to represent the quantity on any plot. eg, heat, work etc.

With reference to figure, it is possible to take a system from state 1 to state 2 along many quasi-static paths such as A, B, C.

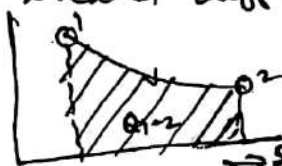
Since the area under the each curve represents the work for each process, the amount of work involved in each case is not a function of the end states of the process and it depends on the path, the system follows in going from state 1 to state 2.

The path functions have inexact differentials represented by the symbol δ . Therefore, a differential amount of work or heat is written by δW or δQ .

HEAT TRANSFER - A 'PATH' FUNCTION -

Heat transfer is a path function, that is the amount of heat transferred when a system changes from state ① to ② depends on the intermediate states through which the system passes. i.e., its path. Therefore δQ is an inexact differential and we write

$$\int_1^2 \delta Q = Q_{1-2}$$



Path function

1. If the change in function depends on the path followed by a system then that function is called path function.

2. The function depends on path followed by the system.

3. Examples: work, energy (heat) etc.

4. The differentials of path functions are inexact (or) imperfect differentials.

5. This function does not satisfy the equation $dz = Mdx + Ndy$

1. If the change in function depends only on initial and final state of process, then that function is called point function.

2. This function does not depend on path followed by the system.

3. Example, pressure, volume, temp, (thermodynamic properties)

4. The differentials of point functions are exact (or) perfect differentials.

5. This function satisfies $dz = Mdx + Ndy$

Prob A gas contained in a piston cylinder arrangement expands from 0.75 m^3 volume to 1.25 m^3 volume until the pressure remains constant at 200 kPa if the gaseous system receives 80 kJ of work from a paddle wheel, determine net work done by the system.

SOL Given, $V_1 = 0.75 \text{ m}^3$, $V_2 = 1.25 \text{ m}^3$
 $p_2 = p_1 = 200 \text{ kPa}$.
 Paddle wheel work = $-80 \text{ kJ} = W_1$ (work supplied).

$$\text{Rate, } W_2 = \text{work done by the system} = \int_{V_1}^{V_2} p \, dV = p(V_2 - V_1)$$

$$W_2 = 200 \times 10^3 [1.25 - 0.75] = 100 \text{ kJ (ve)}$$

$$\therefore \text{Net work done, } W.D = W_1 + W_2 = -80 + 100 = 20 \text{ kJ (ve)}$$

Prob A vacuum gauge connected to a tank reads 30 kPa at a location where the barometer reads 755 mm of Hg. Calculate the absolute pressure in the tank assuming the density of Hg (mercury) to be $13,590 \text{ kg/m}^3$.

SOL. Vacuum gauge reading, $p_v = 30 \times 10^3 \text{ Pa}$
 density of mercury, $\rho = 13,590 \text{ kg/m}^3$.

$$\therefore \text{We know that, } \text{vacuum pressure, } p_v = \rho g h.$$

$$30 \times 10^3 = 13,590 \times 9.81 \times h.$$

$$\text{vacuum gauge height, } \therefore h = \frac{30 \times 10^3}{13,590 \times 9.81} = 0.225 \text{ m of Hg}$$

$$= 225 \text{ mm of Hg.}$$

$$\therefore \text{Absolute pressure} = \text{Barometric pressure} - \text{vacuum gauge pressure}$$

$$= 755 - 225 = 530 \text{ mm of Hg.}$$

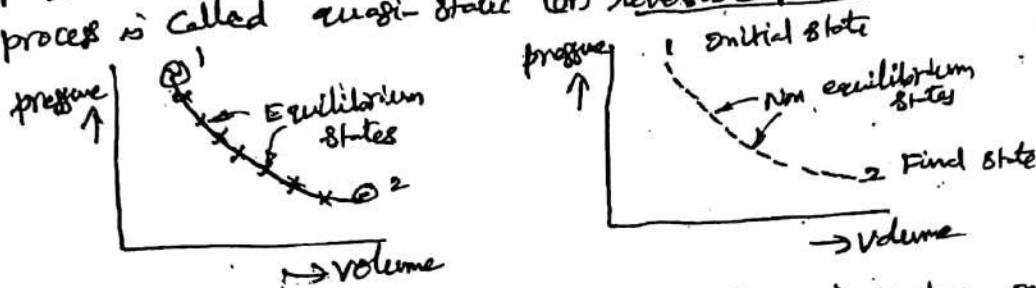
Differences:

Adiabatic process & isobaric process, isochoric process, isobaric process, isobaric process.

Adiabatic process:- on an adiabatic process, the gas changes its condition without the transfer of heat to (or) from the surroundings: pressure, volume and temperature of the gas may vary during an adiabatic process. During an adiabatic process, no heat is transferred to the gas from an external source and the gas must do the external work at the expense of its own energy. An adiabatic expansion is always accompanied by a decrease in the temperature of the gas as the gas gives up its own internal energy to do work.

Isentropic process:- A reversible adiabatic process is called isentropic process.

Reversible process: If the process is assumed to take place sufficiently slowly so that the deviation of the properties at the intermediate states is infinitesimally small, then every state passed through by the system will be in equilibrium. Such a process is called quasi-static (or reversible process).



Irreversible process: If the process takes place in such a manner that the properties at the intermediate states are not in equilibrium state (except the initial and final state), then the process is said to be non-equilibrium (or irreversible process). This process is represented by broken line on the property diagram.

All the processes occurring in nature are irreversible. When these processes are reversed, they cannot return to their initial state of the system without changing the surroundings.

* Irreversibility: - When ^{an} actual process occurs, it produces certain effects, therefore, the process cannot be reversed and the system and its surroundings cannot be restored to their initial states. During an irreversible process, the total energy remains constant but capacity to do work is lost due to degradation of some portion of available energy.

This degradation of energy is responsible for entropy generation with in the system during a process. The entropy generation is always equal to irreversibilities involved in the process.

\therefore Irreversibility, $I = W_{max} - W_{useful}$ (KJ).

* Causes of Irreversibility: - Irreversibility of the process may be caused due to

- (1) Mechanical (or) thermal irreversibility
- (2) Internal and external irreversibility.

- (i) Mechanical Irreversibility:- is associated with friction. When two bodies have relative movement, a frictional force opposes the motion at the interface of these two bodies and some work is lost to overcome this friction. When direction is reversed, some work is further required to overcome friction. Friction is also involved between solid and fluid, & layers of fluid due to different velocities.
- (ii) Thermal Irreversibility:- is associated with transfer of heat due to finite temperature difference between a system and its surroundings. An amount of heat lost from a system during compression can not be regained during expansion process causes irreversibility.
- (iii) Internal Irreversibility:- is also caused due to mixing of different layers of fluid at different temperatures. It is also due to free (or) unrestrained expansion of fluid.
- (iv) External Irreversibility:- is associated with friction at bearings and friction between atmospheric air and rotating members.

* Conditions for a Reversible process:-

- 1) The process should not involve friction of any kind.
- 2) Heat transfer should not take place due to finite temperature difference between system and surroundings.
- 3) There should not be a mixing of fluid layers at different temperatures.
- 4) There should not be free and unrestrained expansion.
- 5) The process must pass through a series of equilibrium states.

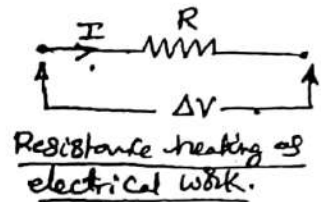
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* Forms of Work Transfer (Other Types of Work Transfer):- 18

There are forms of work other than $p \cdot dV$ (or) displacement work. The following are the additional types of work transfer which may get involved in system - surroundings interactions.

① Electrical work:-

Electrical work is the energy interaction due to crossing of electrons at the system boundary. on an electric field, the electrons in a wire move under the effect of electromotive forces for doing work [driving a motor, fan etc.]. The resistance heating as an electrical work.



② Rate of ~~work~~ electrical work transfer

$W_E = VI$ watts.

The work done W_E in time Δt is, $W_E = VI \Delta t$ (Joules).

② MECHANICAL WORK:-

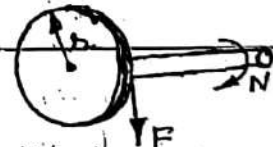
on mechanics, the work done by a system is expressed as a product of force (F) and displacement (S).

$W = FS$.

If force is not constant, the work done is obtained by adding the differential amounts of work, $W = \int_1^2 F ds$.

③ SHAFT WORK:-

The shaft work is the work associated with energy transmission with a rotating shaft. It is the product of torque (product of force and radius of shaft) and angular displacement.



Work of a moving shaft

Torque, $T = F \times r$ (or) $F = \frac{T}{r}$

This force acts through a displacement per unit time,

$S = 2\pi r \times \frac{N}{60}$

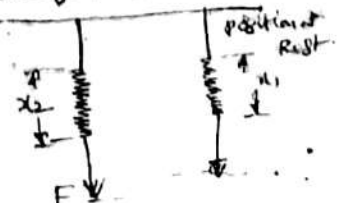
Shaft work per unit time, $W_{shaft} = FS = 2\pi r \times \frac{N}{60} \times \frac{T}{r}$

$W_{shaft} = \frac{2\pi NT}{60}$ Watts.

④ Spring work:-

When force is applied on a spring, its length changes.

Elongation of spring under force



If dx is change in the length of a spring under the influence of a force F , then the work done by the spring is

$$\delta W_{\text{spring}} = F dx.$$

where the force F exerted can be defined in terms of spring constant k (N/m) as.

$$F = kx, \text{ Newtons.}$$

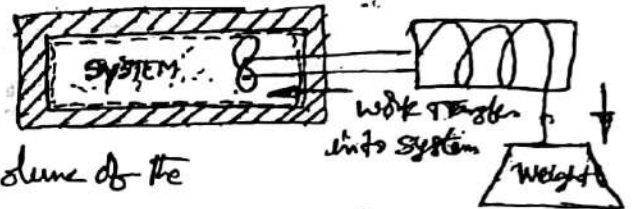
Then spring work $\delta W = kx dx$.

If spring length changes from x_1 to x_2

$$W_{\text{spring}} = k \int_{x_1}^{x_2} x dx = \frac{1}{2} k (x_2^2 - x_1^2)$$

paddle wheel work (or) stirring work:

As the weight is lowered and the paddle wheel turns, there is work transfer into the fluid system



which gets stirred. Since the volume of the system remains constant $\int p dv = 0$.

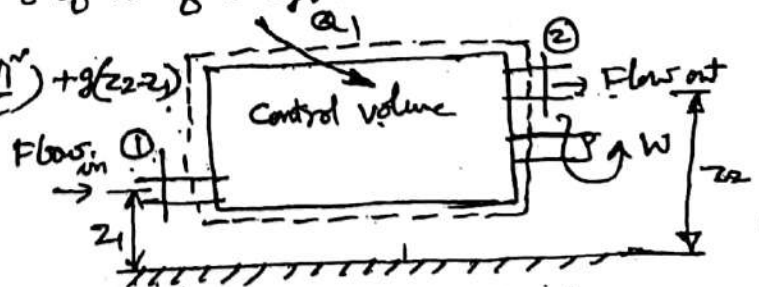
If m is the mass of the weight lowered through a distance dz and T is the torque transmitted by the shaft in rotating through an angle $d\theta$, the differential work transfer to the fluid is

$$dW = mg dz = T d\theta.$$

$$\text{total work transfer, } W = \int_1^2 mg dz.$$

Flow work (or) flow energy: refers to work required to push a certain mass of fluid into and out of the control volume. A flow process constitutes an open system, in which the working substance enters and leaves the control surface of a system.

$$q_{1-2} - W_{1-2} = (h_2 - h_1) + \left(\frac{V_2^2 - V_1^2}{2} \right) + g(z_2 - z_1)$$



HEAT: - It is a transfer form of energy that flows between two systems (or a system and its surroundings) by virtue of the temperature difference between them. The temperature difference is the potential for heat transfer. Therefore there would be no heat transfer between two systems if they are at the same temperature.

The amount of heat transferred from the state 1 to the state 2 is designated by Q_{1-2} (or Q) and it is measured in Joules (or) Kilo Joules (kJ).

Heat transfer per unit mass of a system is defined by

$$q_f = \frac{Q}{m} \text{ (kJ/kg)}.$$

The heat (or) heat energy is generally referred to as heat transfer.

The transfer of heat into a system is called heat addition (or) heat supply.

The transfer of heat from the system is called heat rejection.

Similarities between Heat and Work

1. Both are recognized at the boundary of the system as they cross it, thus both heat and work are boundary phenomena.
2. A system may have energy, but not heat (or) work because, heat and work are transient phenomena.
3. Both are associated with a process, not a state. Therefore, unlike properties heat (or) work has no meaning at a state.
4. Both are path functions. They are represented by a path followed during the process.
5. The equations for heat and work transfer can not be differentiated exactly. The differential quantities of heat and work are represented by δQ and δW , respectively.

Dissimilarities between Heat and Work transfer

1. Heat is a low-grade energy, whereas the work is a high grade energy.
 2. Heat transfer takes place due to temperature difference only, while work transfer may take place due to any potential difference in pressure, voltage, height, velocity and temperature etc.
 3. A stationary system can not do work, while such a restriction is imposed on heat transfer.
 4. The entire quantity of work can be converted into heat (or) any other form of energy, while conversion of the entire quantity of heat into work is not possible.
 5. Conversion of work into heat (or) any other form of energy is possible with a single process, while conversion of heat into work requires a complete cyclic process, like a steam power plant.
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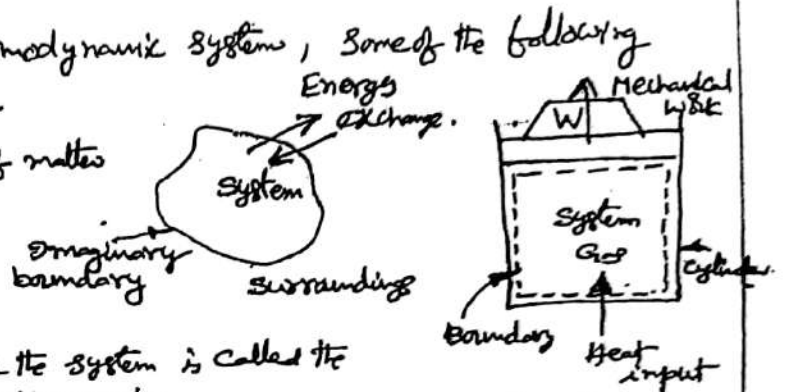
Q-B UNIT-1

PROB Explain thermodynamic system, surroundings and universe, illustrate the same with examples.

SOL Thermodynamic system:- A thermodynamic system (or) simply a system is defined as a certain quantity of matter (or) a prescribed region in space considered for thermodynamic study (or) we focus our attention to study its properties. The study also involves changes in properties due to exchange of energy in the form of heat and work. The system may be a quantity of steam, a mixture of vapour and gas (or) a piston-cylinder assembly of an I.C. engine and its contents.

For the description of a thermodynamic system, some of the following quantities need to be specified.

- (i) quantity as well as composition of matter
- (ii) measurable properties such as pressure, temp and volume of the system.
- (iii) Energy of the system.



Surroundings:- The region outside the system is called the surroundings (or) environment.

Boundary:- The real (or) imaginary surface that separates the system from its surroundings is called the boundary. The boundary may be fixed (or) movable. The boundary may change shape, volume, position and (or) orientation with respect to observer. For example, an elastic balloon changes in shape & volume during a certain process.

Universe:- System plus surroundings put together is known as universe. Hence it has no boundaries and is of infinite size.

PROB Distinguish between closed system, open system & isolated system with suitable examples.

SOL ① closed system:- on a closed system, the mass is fixed.

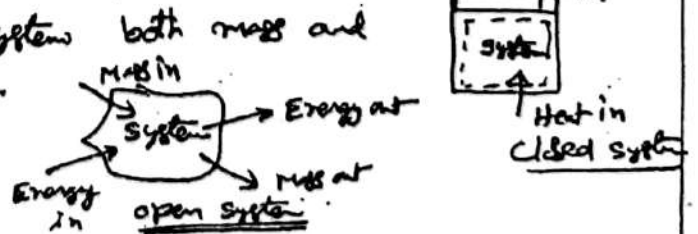
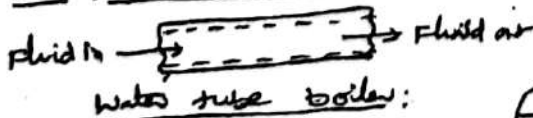
There is no mass transfer across the boundary but energy transfer may take place into (or) out of the system.

EX:- i) Heating the gas in a cylinder ii) Hot coffee in a steel tumbler
iii) steam power plant etc.



② open system:- on an open system both mass and energy cross the boundary.

EX:- flow through tubes & pipes:



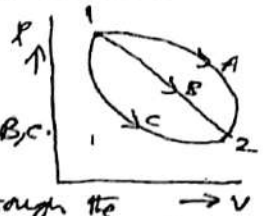
③ Isolated system:- on isolated system, there is neither energy transfer nor mass transfer occurs across the boundaries. Not having any interaction with surroundings.

EX:- i) Thermo flask 2) Insulated chamber.



PROB Show that work is a path function and not a state function

SOL Work is a path function and not a state function. This can be proved with the help of the P-V diagram. On the P-V diagram, a system is at state 1. To move the system from state 1 to 2, it can follow any path such as A, B, C, etc. The area under the curve represents the work done. Here the area under the each curve is not equal to even though the initial and final states are same. From this, we can conclude that work is a path function and not a state function.



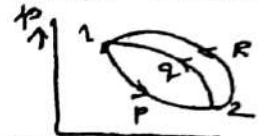
PROB Justify the statement that work and heat are not properties.

SOL Consider a volume of (V) gas enclosed in a piston cylinder assembly as shown in figure. If the gas is allowed to expand by changing its pressure from p_1 to p_2 . Increase in volume of the gas causes the piston to move outwards and hence work is done by the gas. The expansion of the process from p_1 to p_2 is plotted on P-V diagram.



Now, if the gas initially was allowed to expand by a different process, say B, it would have followed the path 1B2. Therefore, it makes clear that work done by the gas while following path 1A2 is different from that of path 1B2 as both processes follow different paths. Hence, it can be said that work is not a point function but a path function. The differential of path function is inexact and hence work done should be written as δW instead of dW .

Heat is a path function:- Consider a system of gas in a piston cylinder arrangement. Let the gas be taken to a state 2 from state 1 to 2 through process P and back to initial state through process Q. The gas can also be taken to initial state by another process R.



Apply first law to both cycles [1P2Q1, 1P2R1]

$$\int_{1P2} \delta Q + \int_{2Q1} \delta Q - \int_{1P2} \delta W - \int_{2Q1} \delta W = 0 \quad \text{--- (1)}$$

$$\int_{1P2} \delta Q + \int_{2R1} \delta Q - \int_{1P2} \delta W - \int_{2R1} \delta W = 0 \quad \text{--- (2)}$$

Subtracting 2 in equation 1,

$$\int_{2Q1} \delta Q - \int_{2R1} \delta Q - \left[\int_{2Q1} \delta W - \int_{2R1} \delta W \right] = 0$$

We know work is a path function

$$\text{Hence } \int_{2Q1} \delta W - \int_{2R1} \delta W \neq 0$$

$$\text{Similarly } \int_{2Q1} \delta Q - \int_{2R1} \delta Q \neq 0$$

$\therefore \int_{2Q1} \delta Q \neq \int_{2R1} \delta Q$ Heat is path function not point function.

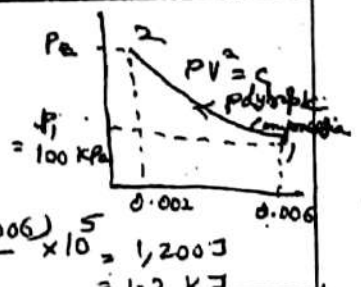
PROB If a gas of volume 6000 cm^3 and at a pressure of 100 kPa , is compressed quasi-statically to $PV^2 = \text{constant}$ until the volume becomes 2000 cm^3 . Calculate the final pressure & work transfer.

SOL $P_1 = 100 \text{ kPa} = 1 \text{ bar} = 10^5 \text{ N/m}^2$
 $V_1 = 6000 \text{ cm}^3 = 0.006 \text{ m}^3$; $V_2 = 2000 \text{ cm}^3 = 0.002 \text{ m}^3$.

Final pressure (P_2): $P_1 V_1^2 = P_2 V_2^2$

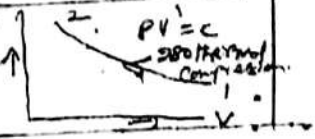
$$P_2 = P_1 \left(\frac{V_1}{V_2} \right)^2 = 1 \left(\frac{0.006}{0.002} \right)^2 = 9 \text{ bar}$$

$$\text{Workdone } (W_{1-2}) = \int_{V_1}^{V_2} P dV = \frac{P_2 V_2 - P_1 V_1}{n-1} = \frac{(9 \times 0.002 - 1 \times 0.006)}{2-1} \times 10^5 = 1,200 \text{ J} = 1.2 \text{ kJ}$$



PROB A mass of 2.5 kg of air is compressed in a quasi-static process from 0.1 MPa to 0.7 MPa for which $PV = \text{constant}$. The initial volume is $0.8 \text{ m}^3/\text{kg}$. Find the work done by the piston to compress the air.

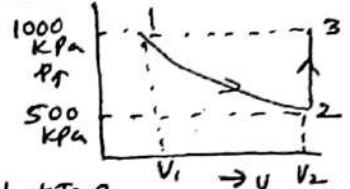
SOL mass, $m = 2.5 \text{ kg}$, $P_1 = 0.1 \text{ MPa} = 0.1 \times 10^6 \text{ Pa}$; $P_2 = 0.7 \times 10^6 \text{ Pa}$
 Isothermal process; $V_1 = 0.8 \text{ m}^3/\text{kg}$; $V_1 = m \times V_1 = 0.8 \times 2.5 = 2 \text{ m}^3$
 Work, $W_{1-2} = P_1 V_1 \ln \frac{V_2}{V_1} = P_1 V_1 \ln \frac{P_1}{P_2}$



Workdone in isothermal process, $W_{1-2} = p_1 V_1 \ln \frac{p_1}{p_2} = 0.1 \times 10^6 \times 2 \ln \frac{0.1 \times 10^6}{0.7 \times 10^6}$
 $= -389,182 \text{ J} = -389.182 \text{ kJ}$

PROB A gas expands according to the equation $pV=100$, where p is the pressure in kPa and V is the specific volume in m^3/kg . The initial pressure of the gas is 1000 kPa and final pressure is 500 kPa. The gas is then heated at constant volume back to its original pressure of 1000 kPa. Determine the work of combined process. Also sketch on p - V co-ordinates.

SOL $pV = 100$; initial pressure, $p_1 = 1000 \text{ kN/m}^2$
 At state 2, pressure, $p_2 = 500 \text{ kN/m}^2$, At state 3, final pressure, $p_3 = p_1 = 1000 \text{ kN/m}^2$



Workdone during (1-2) process $pV = 100 = p_1 V_1 = p_2 V_2$ (Constant Temp. process)

$p_1 V_1 = 100$; $V_1 = \frac{100}{1000} = 0.1 \text{ m}^3/\text{kg}$; $V_2 = \frac{100}{500} = 0.2 \text{ m}^3/\text{kg}$.

$W_{1-2} = p_1 V_1 \ln \frac{V_2}{V_1} = 1000 \times 0.1 \ln \frac{0.2}{0.1} = 69.315 \text{ kJ/kg}$

Workdone (W_{2-3}) during (2-3) constant volume process, $W_{2-3} = 0$.

\therefore total workdone, $W_{1-3} = W_{1-2} + W_{2-3} = 69.315 + 0 = 69.315 \text{ kJ/kg}$.

PROB Explain about quasi-static process.

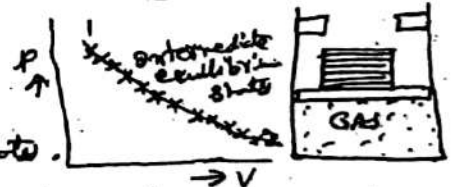
SOL When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium states at all times, it is called quasi-static (or) quasi-equilibrium process.

Let the gas initially at properties p_1, V_1, T_1 . The weight just balances on piston with upward force by gas.



If the weight (W) is removed, piston will move upwards and attains equilibrium state with properties p_2, V_2, T_2 . The intermediate states are non-equilibrium states.

Now, if the single weight (W) is made up of small pieces of weights and these weights are removed one by one slowly from the top of piston, the gas will pass through a series of equilibrium states.



If masses are very small, the gas would undergo quasi-equilibrium expansion process.

Quasi-static work in a closed system:

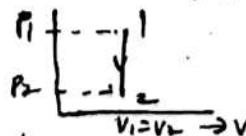
1) Constant pressure process ($P=C$) ;

$W_{1-2} = \int_1^2 p dv = P[V_2 - V_1]$



2) Constant volume process ($V=C$)

$W_{1-2} = \int_1^2 p dv = 0$ since $dv=0$

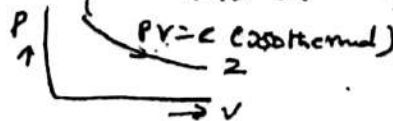


3) Constant temperature process ($T=C$)

$pV = C = p_1 V_1 = p_2 V_2$

$W_{1-2} = \int_1^2 p dv = \int_1^2 \frac{C}{v} dv = C \int_1^2 \frac{1}{v} dv$

$= p_1 V_1 \ln \frac{V_2}{V_1} = p_1 V_1 \ln \frac{p_1}{p_2} = mR T_1 \ln \frac{p_1}{p_2}$



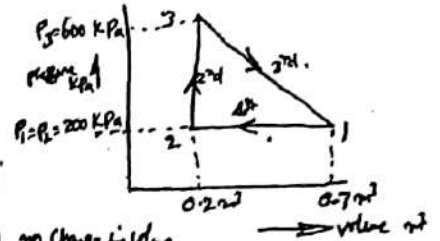
4) Adiabatic process $pV^\gamma = C$, $p_1 V_1^\gamma = p_2 V_2^\gamma = p V^\gamma = C$

$W_{1-2} = \int_1^2 p dv = \int_1^2 \frac{C}{v^\gamma} dv = C \left[\frac{v^{-\gamma+1}}{-\gamma+1} \right]_1^2$

$= \frac{C \cdot v_2^{-\gamma+1} - C \cdot v_1^{-\gamma+1}}{-\gamma+1} = \frac{p_1 V_1 - p_2 V_2}{\gamma - 1} = \frac{mR(T_1 - T_2)}{\gamma - 1}$

PROB A cycle consists of three processes. The first is constant pressure compression at 200 kPa from an initial volume of 0.7 m³ to a final volume of 0.2 m³. The second process takes place at constant volume with pressure increasing to 600 kPa. The third process to the beginning of the first process. Sketch the cycle on P-V co-ordinates and calculate the net work transfer.

SOL process (1-2) :- constant pressure compression process.
 $p_1 = p_2 = 200 \text{ kPa}$; $V_1 = 0.7 \text{ m}^3$ & $V_2 = 0.2 \text{ m}^3$
 \therefore Work done on the system, $W_{1-2} = p_1 [V_1 - V_2] = 200 [0.7 - 0.2] = 100 \text{ kPa}$.
 (-ve)



process (2-3) :- constant volume compression process, $W_{2-3} = 0$ [since $p dV = 0$, no change in volume during the process 2-3].

process (3-1) :- Expansion process follows straight inclined line from 3 to 1.

$$W_{3-1} = \frac{1}{2} (p_3 - p_1)(V_1 - V_3) = \frac{1}{2} [600 - 200][0.7 - 0.2] = 100 \text{ kPa (+ve)}$$

since process 3-1 is expansion process

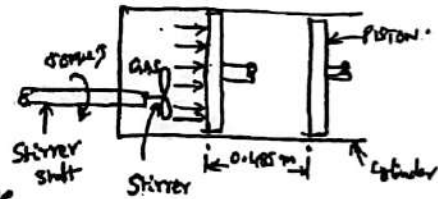
$$\therefore \text{Total Workdone, } W = W_{1-2} + W_{2-3} + W_{3-1} = -100 + 0 + 100 = 0.$$

PROB A fluid contained in a horizontal cylinder fitted with a frictionless leak-proof piston, is continuously agitated by means of stirrer passing through cylinder cover. The cylinder diameter is 0.4 m. During the stirring process lasting 10 minutes, the piston slowly moves out a distance of 0.485 m against the atmosphere. The net work done by the fluid during the process is 2 kJ. The speed of the electric motor driving the stirrer is 840 rpm. Determine the torque in shaft and power output of the motor.

SOL ① Paddle work (-ve work) because work is done by stirrer on fluid system, $W_p = -2\pi r N T \times 10$

$$= 2 \times 3.1416 \times 840 \times T \times 10 \quad (-ve) \text{ work}$$

② Displacement work (+ve) piston moves against atmosphere (atmosphere) work is positive



$$W_p = W_d = p \cdot pA = 1.01325 \times 10^5 \times \frac{\pi}{4} (0.4)^2 \times 0.485 = 6174.2 \text{ Joules.}$$

③ Net work done by the fluid, $W_{net} = 2 \text{ kJ} = 2000 \text{ Joules}$.

$$\therefore W_{net} = W_{paddle} + W_{displacement} \rightarrow 2000 = -521768T + 6174.2$$

$$\text{Power, } P = \frac{2\pi r N T}{60} = \frac{2 \times 3.1416 \times 840 \times 0.08}{60} = 7.03 \text{ Watts.} \quad \therefore T = 0.08 \text{ Joules}$$

PROB A spherical balloon contains 5 kg of air at 200 kPa and 500 K. The balloon material is such that pressure inside is always proportional to the square of the diameter. Determine the work done for the volume of the balloon doubles as a result of heat transfer.

SOL mass, $m = 5 \text{ kg}$, initial pressure, $p_1 = 200 \text{ kPa}$; initial temp $T_1 = 500 \text{ K}$; Final volume, $V_2 = 2V_1$.

consider the diameter of the balloon as D , then according to given condition, $p = KD^2$, where $K = \text{constant of proportionality}$

from the perfect gas relation, $p_1 V_1 = mRT_1$; $V_1 = \frac{mRT_1}{p_1} = \frac{5 \times 0.287 \times 500}{200} = 3.5875 \text{ m}^3$.

we know that volume of the balloon, $V_1 = \frac{4}{3} \pi r^3 = \frac{1}{6} \pi D^3$; $3.5875 = \frac{1}{6} \pi D_1^3$; $D_1 = 1.899 \text{ m}$

$$\therefore V_2 = 2V_1 = 2 \times 3.5875 = 7.175 ; V_2 = \frac{1}{6} \pi D_2^3 ; 7.175 = \frac{1}{6} \pi D_2^3 ; D_2 = 2.393 \text{ m}$$

similarly from the relation; $p = KD^2 \Rightarrow p_1 = K D_1^2$; $K = \frac{p_1}{D_1^2} = \frac{200}{(1.899)^2} = 55.44$.

work done by the system, $W = \int p dV = \int K D^2 dV = K \int D^2 d(\frac{1}{6} \pi D^3)$
 $= \frac{K}{6} \pi \int D^2 \times 3D^2 dD = \frac{1}{2} \pi \times 55.44 \int D^4 dD = 87.08 \left[\frac{D^5}{5} - \frac{D_1^5}{5} \right]$
 $= 87.08 \left[\frac{(2.393)^5}{5} - \frac{(1.899)^5}{5} \right] = 936.22 \text{ kJ}$

Unit 1

- 1.(a) What are the differences between system and control volume. Explain different types of systems with examples.
- (b) A gas undergoes a reversible non-flow process according to the relation $P = (-15V+17)$ where V is the volume in m^3 and P is the pressure in bar. Determine the work done when the volume changes from 2.8 to 5.6 m^3 .

sol: (a)

SYSTEM	CONTROL VOLUME
1) System is defined as definite region or area or space where thermodynamic process takes place	1) Control volume is defined as an open system in which mass and energy flows into and out of system.
2) System is focussed to study its properties	2) Control volume is keeping interest for flow energies and matter.
3) System has boundaries and boundary may be fixed or movable. Ex: - A gas enclosed in cylinder bounded by piston with weight on the piston. The piston moves upwards due to heat addition	3) Control volume is fixed. An open system called Control volume. Ex: - Air compressor, turbines, engines etc. have mass and energy both take place across boundaries.
4) System classified to open, closed, isolated systems.	4) Control volume is open system. It is one of thermodynamic system.

Thermodynamic systems → classification with examples. See First question.

sol: (b)

$P = (-15V+17)$ $V_1 = 2.8 \text{ m}^3$; $V_2 = 5.6 \text{ m}^3$

For reversible non-flow process, $W = \int P dV = \int_{V_1}^{V_2} (-15V+17) dV = -15 \int_{V_1}^{V_2} V dV + 17 \int_{V_1}^{V_2} dV$

$$= -15 \left[\frac{V^2}{2} \right]_{V_1}^{V_2} + 17 [V]_{V_1}^{V_2}$$

$$= -15 \left[\frac{V^2}{2} \right]_{2.8}^{5.6} + 17 [V]_{2.8}^{5.6}$$

$$= -176.4 + 47.6$$

$$= (-128.8) \times 10^5 = -128.8 \times \frac{10^5}{10^3} = -12880 \text{ kJ}$$

→ -ve sign due to work done on the system.

- 1.(a) Differentiate between Macroscopic Microscopic view points from thermodynamics.
- (b) A gas expands according to the equation $PV = 98$, where P is the pressure in kPa and V is the specific volume in m^3/kg . The initial pressure of the gas is 993 kPa and the final pressure is 488 kPa. The gas is then heated at constant volume back to its original pressure of 993 kPa. Determine the work of the combined process. Also sketch the process on P-V and T-S coordinates.

sol: (a)

MACROSCOPIC APPROACH (CLASSICAL APPROACH)	MICROSCOPIC APPROACH (STATISTICAL APPROACH)
1) A certain quantity of matter is considered without taking into account, the events occurring at molecular level. It called overall behaviour classical thermodynamics	1) System considered made up of large no. of molecules. These molecules have different velocities and energies constantly change with time. So, this approach study structure of matter. Statistical thermodynamics.
2) Requires simple mathematical formulae for analysis.	2) Requires advanced statistical mathematical formulae.
3) properties are their average values Ex: pressure of gas is average of pressure exerted by millions of individual molecules. Measured easily by instruments.	3) properties like velocity, momentum, impulse can not be easily measured by instruments
4) In order to describe a system, only few properties are required.	4) Large no. of variables needed to describe a system. So, this approach is complicated.

sol: (b)

isothermal process, $PV = 98$

$P_1 = 993 \text{ kPa}$, $P_2 = 488 \text{ kPa}$

$P_3 = P_1 = 993 \text{ kPa}$ $PV = 98 = PV_1$

Work done during isothermal process (1-2)

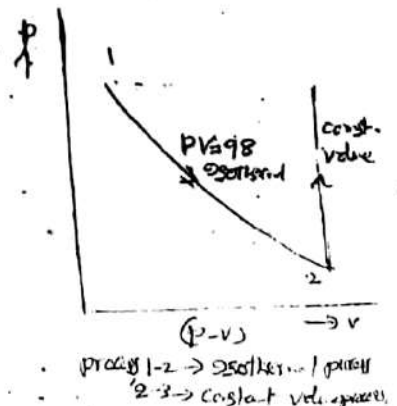
$$W_{1-2} = P_1 V_1 \ln \frac{V_2}{V_1} = P_1 V_1 \ln \frac{P_1}{P_2} = 98 \ln \frac{993}{488}$$

$$= 69.62 \text{ Joules}$$

Work done during constant volume process (2-3)

$$W_{2-3} = \int P dV = 0 \quad [\because \text{since } dV=0]$$

∴ Total work, $W = W_{1-2} + W_{2-3} = 69.62 \text{ Joules}$ ✓



1. (a) What are different types of thermodynamic systems? Explain them with suitable examples.
 (b) A fluid contained in a horizontal cylinder fitted with a frictionless leak-proof piston, is continuously agitated by means of a stirrer passing through cylinder cover. The cylinder diameter is 0.4 during the stirring process lasting 10 minutes, the piston moves out a distance of 0.485 m against a atmosphere. The net work done by the fluid during the process is 2 KJ. The speed of the electric motor driving the stirrer is 840 rpm. Determine torque in the shaft and power output of the motor.

sol(a) A Thermodynamic system is defined as a certain quantity of matter (or) a prescribed region in space considered for thermodynamic study (or) we focus our attention to study its properties. The study involves changes in properties due to exchange of energy in the form of heat and work. The system may be a quantity of steam, a mixture of vapour and gas etc.

(i) **closed system**:- In closed system, the mass is fixed. There is no mass transfer across its boundaries, but energy transfer takes place in to (or) out of system in form of heat and work.
 Ex:- (A) Heating the gas in a cylinder (B) Hot coffee in a steel tumbler (C) steam power plant (D) closed cycle gas turbine power plant.

(ii) **OPEN SYSTEM**:- In open system both mass and energy cross the boundaries.
 Ex: Degas through tubes and nozzle.
 (A) water tube boiler
 (iii) **isolated system**:- In isolated system, there is neither energy transfer nor mass transfer across boundaries. (i) Thermoflask (ii) insulated chamber.

sol (b) $W_{net} = W_{displace} - W_{paddle} = 2000 \text{ J}$

$W_{paddle} = \frac{2\pi NT}{60} = \frac{2\pi \times (840 \times 10) T}{60} = 879.48 T$ — (1)

$W_{displace} = p \Delta V = (1.01325 \times 10^5) \times \frac{\pi}{4} (0.4)^2 \times (0.485) = 6174.2$ — (2)

$\therefore W_d - W_p = 2000$; $6174.2 - 879.48 T = 2000$; $T = 4.746 \text{ Nm}$
 \therefore Power of paddleshaft, $P = \frac{2\pi NT}{60} = \frac{2\pi \times 8400 \times 4.746}{60} = 4.174 \text{ kWatts}$

1. (a) What do you understand by a state function and path function
 (b) If a gas of volume 6000 cm^3 and at a pressure of 100 kPa, is compressed quasistatically to $PV^2 = \text{Constant}$ until the volume becomes 2000 cm^3 . Calculate the final pressure the work transfer.

(a) **state function**:- (or) **point function**:- The function which depends only on the end states and not on the path followed during a thermodynamic process is known as state function. Ex:- properties of system, i.e. pressure, volume, temp, enthalpy, entropy, internal energy.
change of state function:- dP, dV, dH, dU etc.
path function:- The function which depends on the path of system passed and not on end states known as path function. Ex:- Heat transfer and work transfer.
 The area under each path on (P-V) diagram represents work transferred for each path, so work is path function. Similarly, Heat also changes according to the process which is followed. Heat and work are represented by SQ (or) SW.

sol (b) Given, $V_1 = 6000 \text{ cm}^3$; $P_1 = 100 \text{ kPa}$; $V_2 = 2000 \text{ cm}^3$.

We know $PV^n = C$; so $P_1 V_1^2 = P_2 V_2^2$

(i) Final pressure (P_2) $\Rightarrow P_2 = P_1 \left(\frac{V_1}{V_2}\right)^2 = 100 \left[\frac{6000}{2000}\right]^2 = 900 \text{ kPa}$

(ii) Work transfer (W_{1-2}) $= \int_{V_1}^{V_2} P dV = \frac{P_1 V_1 - P_2 V_2}{2-1} = \frac{100 \times 6000 \times 10^{-6} - 900 \times 2000 \times 10^{-6}}{2-1}$
 $= -1200 \text{ Joules}$
 $= -1.2 \text{ KJ}$ [-ve sign, work is done on gas]

* FIRST LAW OF THERMODYNAMICS

The first law of thermodynamics, also known as the conservation of energy principle. It states that during any process, if the energy disappears in one form, it appears in other form, but its total quantity remains always constant.

That is, the energy can be neither created nor destroyed, it can only change its form.

For example, for the energy interaction between a system and its surroundings, the energy lost by a system must be exactly equal to the amount of energy gained by the surroundings.

The first law can be proved mathematically, but no process in nature is known to have violated the first law of thermodynamics.

It is the relation of energy balance and is applicable to any kind of system [open or closed] undergoing any kind of process.

Example 1:-

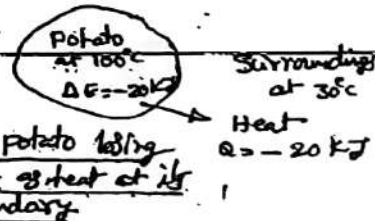
Let us consider a process that involves only heat transfer but no work interaction. A hot potato taken from oven is exposed to room air. As a result of heat transfer from the hot potato, its energy will decrease. In absence of other effects, the decrease of total energy of the potato becomes equal to the amount of heat transferred to its surroundings. Therefore,

the principle of conservation of energy becomes can be expressed as $-\Delta E = -Q$

where $\Delta E = E_2 - E_1$.

In the absence of any work interaction between a system and its surroundings, the amount of net heat transfer is equal to change in the energy of a system.

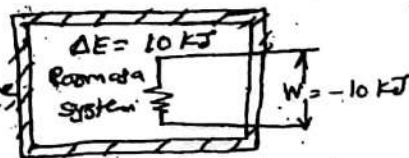
$Q = \Delta E$ when $W = 0$.



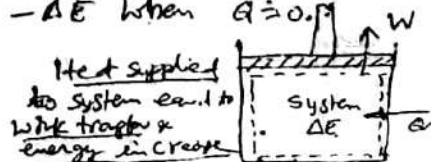
Example 2:- Consider a well-insulated room heated by an electric heater. As a result of electrical work done,

the energy of the room will increase. Since the room is adiabatic and cannot have any heat interaction with its surroundings, the conservation of energy principle dictates that electrical work done on the room must be equal to increased energy of the room. $-W = \Delta E$.

For an adiabatic process, the amount of work done is equal to the change in energy of the system. $W = -\Delta E$ when $Q = 0$.



Example 3:- Consider work and heat transfer simultaneously. The gas in cylinder is heated. As the energy of the gas increases, its pressure and volume also increases.



As then the gas will expand and work will be done at the boundary of the system. The conservation of energy principle reveals that

$$Q = W + \Delta E \quad \text{where } Q = \text{Net heat transfer across system boundaries}$$

$$Q - W = \Delta E$$

$$W = \text{Net work transfer}$$

$$\Delta E = \text{Net change in total energy of the system } (E_2 - E_1)$$

The total energy of the system is the sum of internal energy U , potential energy PE and kinetic energy KE .

$$\Delta E = \Delta U + \Delta PE + \Delta KE \quad (KJ)$$

Mostly closed systems in practice are stationary, they don't have kinetic energy and potential energy during a process.

The first law of thermodynamics is reduced to

$$\boxed{Q - W = \Delta U} \quad KJ.$$

Mechanisms of Energy Transfer:-

The energy can be transferred to or from a system in three forms. heat, work and mass flow.

① Heat Transfer:- (a) Heat transferred to a system increases the energy of the molecules and thus an increase in the internal energy of the system, and heat transfer from a system decreases the energy of molecules and this results in decrease of internal energy.

② Work Transfer (W):- Work refers to the transfer of energy due to potential difference other than temperature difference between a system and its boundary.

A rising piston, rotating shaft and an electric wire carrying current crossing the system boundary - all these energy transfers are associated with work interactions. The work transfer to a system increases the energy of the system and work transfer from a system decreases energy.

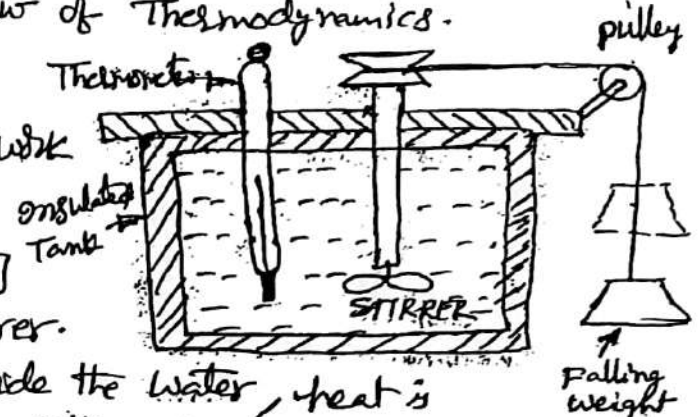
③ Mass flow m :- When mass enters the system, the energy of the system increases because mass carries energy with it. Similarly, when some mass leaves the system, the energy of the system decreases, because the leaving mass takes some energy with it.

First Law of Thermodynamics for a cyclic process

Joule's Experiment

Joule conducted several experiments which led to the formulation of the First law of Thermodynamics.

When weight is allowed to fall to a certain distance, work is done on the water [product of weight and distance moved] through the rotation of stirrer.



When the stirrer rotates inside the water, heat is produced due to friction and this heat generation is measured by the measurement of rise in temperature using thermometer fixed in container.

Further, the insulation from the tank was removed and the whole system was ~~transferred~~ placed in a water bath. The heat was transferred from the system in order to bring same initial state conditions.

During a complete cycle, there was net work input and net heat output from the system.

"Joule" found in his experimental observations that, Whenever a closed system undergoes a cycle, the work input to the system is proportional to the net heat output.

It is expressed as $\oint \delta W \propto \oint \delta Q$
 $\text{or } \oint \delta W = J \oint \delta Q$; $\frac{\text{meas. unit}}{\text{unit}}$ $\oint \delta W = \oint \delta Q$

Where, J = constant of proportionality called mechanical equivalent of heat. = 25 Value 8 1 in S.I units.

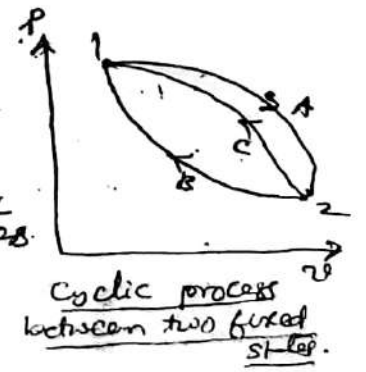
⊗ Internal Energy (E) - A property of system

Consider a system undergoing a change of state from 1 to 2 along path A and returning from 2 to 1, along path B. Thus complete cycle (A-B-A).

Applying first law of thermodynamics for cyclic process.

$$\int_1^2 \delta Q_A + \int_2^1 \delta Q_B = \int_1^2 \delta W_A + \int_2^1 \delta W_B$$

$$\int_1^2 \delta Q_A - \int_1^2 \delta Q_B = \int_1^2 \delta W_A - \int_1^2 \delta W_B$$



Re-arranging, we get

$$\int_1^2 \delta Q_A - \int_1^2 \delta W_A = \int_1^2 \delta Q_B - \int_1^2 \delta W_B ; \text{The quantity } \delta Q - \delta W \text{ is de.}$$

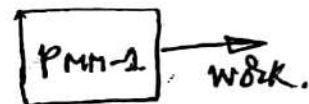
(Q) $\Delta E_A = \Delta E_B$; similarly for cyclic process 1-A-2-C-1,
 $\Delta E_A = \Delta E_C$.

The change in energy between two states ^{does not} depends up on path followed by process, depends between two states 1 & 2

Perpetual Motion Machine of First Kind - PMM 1

A device that violates the first law of Thermodynamics by producing work from nothing is called a perpetual motion machine of the first kind. PMM1.

It is defined as a machine which produces work energy without consuming an equivalent of energy from other source - it is impossible in actual practice, because no machine can produce energy of its own without consuming any other form of energy.



PROB. A system is composed of a gas contained in a cylinder fitted with a piston. The gas expands from state 1 for which $E_1 = 75 \text{ kJ}$ to a state 2 for which $E_2 = -25 \text{ kJ}$. During the expansion, the gas does 60 kJ of work on the surroundings. Determine the heat transferred to (Q) from the system during the process.

SOL. To find, the amount of heat transferred,
Analysis, according to the First law of Thermodynamics for a process,

$$Q - W = \Delta E$$

(Q) $Q = W + \Delta E$ — (1)
 where $\Delta E = E_2 - E_1 = -25 - 75 = -100 \text{ kJ}$

using the equation (1), $Q = W + \Delta E$

here $W = \text{work done by gas} = +60 \text{ kJ}$.

$$\therefore Q = 60 - 100 = -40 \text{ J (Heat is rejected)}$$

PROB A system undergoes a cyclic process composed of four processes 1-2, 2-3, 3-4 and 4-1. The energy transfers are tabulated as

process	Q kJ/min	W kJ/min	ΔU kJ/min
1-2	400.0	150.0	—
2-3	200.0	—	300.0
3-4	-200	—	—
4-1	0	75	—

Complete the table and determine the power output.

For process 1-2; $Q - W = \Delta U$
 $400 - 150 = \Delta U$; $\Delta U_{1-2} = 250$ kJ/min.

For process 2-3; $Q - W = \Delta U$; $W_{2-3} = Q - \Delta U = 200 - 300 = -100$ kJ/min.

For process 4-1; $Q - W = \Delta U$; $\Delta U_{4-1} = 0 - 75 = -75$ kJ/min.

For a cyclic process, $\oint \delta Q = \oint \delta W$

$$Q_{1-2} + Q_{2-3} + Q_{3-4} + Q_{4-1} = W_{1-2} + W_{2-3} + W_{3-4} + W_{4-1}$$

$$400 + 200 - 200 + 0 = 150 - 100 + W_{3-4} + 75$$

$$\therefore W_{3-4} = 275 \text{ kJ/min.}$$

For process 3-4; $Q - W = \Delta U$; $-200 - 275 = \Delta U_{3-4} = -475$ kJ/min.

process	Q kJ/min	W kJ/min	ΔU kJ/min
1-2	400	150	250
2-3	200	-100	300
3-4	-200	275	-475
4-1	0	75	-75

Limitations or restrictions of First Law of Thermodynamics:

- When a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to the net work transfer. This statement does not satisfy the direction of flow of heat and work [i.e., whether the heat flows from a hot body to a cold body (or) from a cold body to a hot body]. It does not give any condition under which these transfers take place.
- The heat energy and mechanical work are mutually convertible. Though the mechanical work can be fully

Converted into heat energy, but only a part of heat energy can be converted into mechanical work. This means that the heat energy and mechanical work are not fully mutually convertible. In other words, there is a limitation on conversion of one form of energy into other.

A machine which violates the first law of Thermodynamics is known as perpetual motion machine of the first kind PMM-1. It is defined as a machine which produces work energy without consuming an equivalent energy from other source. Such a machine is impossible.

PROB. A stationary mass of gas is compressed without friction from an initial state of 0.3 m^3 and 0.105 MPa to a final state of 0.15 m^3 and 0.105 MPa . The pressure is remaining constant during process. There is a transfer of 37.6 kJ of heat from the gas during the process. How much does the internal energy of the gas change.

SOL. First law for a system in a process

$$Q = \Delta U + W$$

$$Q_{1-2} = \Delta U_{1-2} + W_{1-2} = \Delta U + P(V_2 - V_1)$$

$$\text{Since } W_{1-2} = P(V_2 - V_1) = 0.105 \times 10^6 (0.15 - 0.3) = -15,750 \text{ J} \quad (\text{negative})$$

$$Q_{1-2} = -37.6 \times 10^3 \text{ J} \quad (\text{negative}) \text{ since transfer of heat from gas.}$$

$$\therefore -37.6 \times 10^3 = \Delta U + (-15,750)$$

$$\therefore \Delta U = -37.6 \times 10^3 + 15,750 = -21,850 \text{ J only} \quad (\text{decrease})$$

PROB. In a general compression process 2 kJ of mechanical work is supplied to 5 kg of working substance and 800 J of heat is rejected to the cooling jacket. Calculate the change in specific internal energy.

SOL. For first law of thermodynamic process.

$$Q = \Delta U + W$$

$$Q = 800 \text{ J} \quad (\text{negative}) \text{ rejected, } \quad -800 = \Delta U - 2000$$

$$W = 2000 \text{ J} \quad (\text{negative}) \text{ supplied,} \quad \Delta U = 1200 \text{ J.}$$

$$\text{change in internal energy} \quad \Delta U = 1200 \text{ J.}$$

$$\text{Specific internal energy change} = \frac{\Delta U}{m} = \frac{1200}{5} = 240 \text{ J/kg}$$

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[PROB.] A fluid confined in a cylinder by a spring-loaded frictionless piston so that the pressure in the fluid is a linear function of the volume $p = a + bV$. The internal energy of the fluid is given by the following equation $U = 34 + 3.15 pV$ where U is in kJ, p is in kPa and V is in m^3 . If the fluid changes from an initial state of 170 kPa, $0.03 m^3$ to a final state of 400 kPa & $0.06 m^3$, without any work other than that done on the piston. Find the direction & magnitude of the work and heat transfer.

[SOL.] $p_1 = 170 \text{ kPa}$, $V_1 = 0.03 m^3$ $U = 34 + 3.15 pV$
 $p_2 = 400 \text{ kPa}$, $V_2 = 0.06 m^3$

Change in internal energy, $U_2 - U_1 = 3.15 [p_2 V_2 - p_1 V_1]$
 $= 3.15 [400 \times 10^3 \times 0.06 - 170 \times 10^3 \times 0.03] = 59.5 \text{ kJ}$

The relation between p and V is given by,

$p = a + bV$
 at p_1, V_1 ; $170 = a + b \times 0.03$ — ①
 at p_2, V_2 ; $400 = a + b \times 0.06$ — ② Solving ① & ②,

$a = -60$; $b = 7667$
 \therefore work transfer, $W_{1-2} = \int_{V_1}^{V_2} p dV = \int_{V_1}^{V_2} (a + bV) dV$
 $= a(V_2 - V_1) + b \left[\frac{V_2^2 - V_1^2}{2} \right]$

$= (V_2 - V_1) \left[a + b \left(\frac{V_2 + V_1}{2} \right) \right]$
 $= (0.06 - 0.03) \left[-60 + \frac{7667}{2} (0.092) \right]$
 $= 8.55 \text{ kJ}$

Work done by the system, the magnitude being 8.55 kJ.

Heat transfer involved is given by

$Q_{1-2} = U_2 - U_1 + W_{1-2} = 59.5 + 8.55 = 68.05 \text{ kJ}$

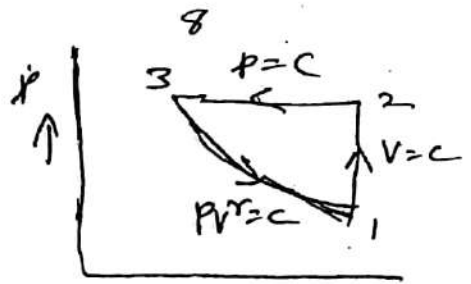
[PROB.] A system receives 200 kJ of heat at constant volume process and rejects 220 kJ of heat at constant pressure and 40 kJ of work is done on the system. The system is brought to its original state by an adiabatic process. Calculate the adiabatic work if the initial & internal energy is 240 kJ, then calculate the value of internal energy at all points.

$$Q_{1-2} = 200 \text{ kJ, heat is received}$$

$$Q_{2-3} = -220 \text{ kJ (heat rejected)}$$

initial internal energy,
 $U_1 = 240 \text{ kJ}$

Work done during the process, $W_{2-3} = -40 \text{ kJ}$.
(20 kJ done on the system)



process 1-2 constant volume process
 $W_{1-2} = 0$ since $\int p dV \Rightarrow \because V_1 = V_2$

$$\therefore Q_{1-2} = \Delta U + W = \Delta U$$

$$200 = U_2 - U_1$$

$$\therefore U_2 = 200 + U_1 = 200 + 240 = 440 \text{ kJ}$$

process 2-3 $Q_{2-3} = -220 \text{ kJ}$

According to first law for a process 2-3,

$$Q_{2-3} = \Delta U + W_{2-3}$$

$$-220 = \Delta U - 40$$

$$\therefore \Delta U = -220 + 40 = -180 \text{ kJ}$$

$$U_3 - U_2 = -180 \text{ kJ}$$

initial energy at state 3, $\therefore U_3 = -180 + U_2 = -180 + 440 =$

$$U_3 = 260 \text{ kJ}$$

for process (3-1) adiabatic process:-

$$Q_{3-1} = 0$$

For cyclic process 1-2-3, we have

$$\oint da = \oint dw$$

$$Q_{1-2} + Q_{2-3} + Q_{3-1} = W_{1-2} + W_{2-3} + W_{3-1}$$

$$200 - 220 + 0 = 0 - 40 + W_{3-1}$$

Adiabatic work: $W_{3-1} = -20 + 40 = 20 \text{ kJ}$

TEMPERATURE:-

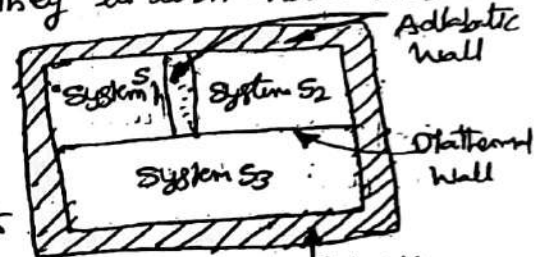
Temperature can be defined as a measure of hotness or coldness. The property which distinguishes Thermodynamics from other sciences is temperature. One might say that temperature bears as important a relation to Thermodynamics as force to statics or velocity to dynamics. Temperature is associated with the ability to distinguish hot from cold.

When two bodies are at different temperatures are brought into contact, after some time, they attain a common temperature and are then said to exist in thermal equilibrium.

* Zeroth Law of Thermodynamics

It states that when two systems are in thermal equilibrium with a third system, they in turn have thermal equilibrium with each other.

Consider two systems S_1 and S_2 which are separated by an adiabatic wall, and a third system S_3 is in contact with both the systems S_1 and S_2 .



These systems are in thermal equilibrium.

If systems S_1 and S_2 are individually in thermal equilibrium

with a third system S_3 , then the systems S_1 and S_2 will also be in thermal equilibrium with each other, even though they are not in contact.

Measurement of Temperature:-

The measurement of temperature depends upon establishment of thermal equilibrium between a system and the device used to measure the temperature. The sensing device should have at least one measurable property that changes with change in temperature. Such a property is called a thermometric property. The substance which shows the changes in the thermometric property is called Thermometric Substance. List of Thermodynamic Thermometric properties and devices are given below

- ① Change in dimension:- Expansion or Contraction of metal such as mercury-in-glass thermometer.
- ② Change in electrical resistance of metals & semi-conductors such as Resistance thermometers & thermistors

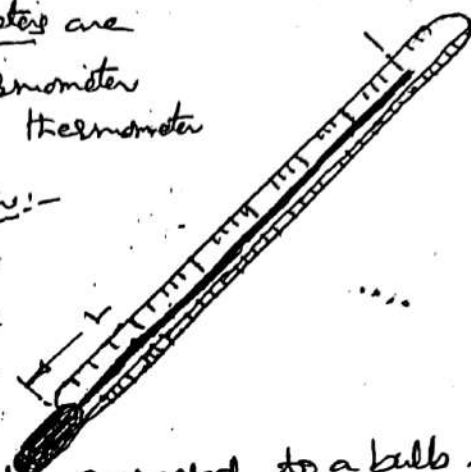
- ⑤ Thermoelectric emf between cold and hot junctions, such as thermocouples.
- ⑥ Change in intensity and colour of emitted radiation such as pyrometers.

Commonly used thermometers are

- a) liquid-in-glass thermometer
- b) constant volume gas thermometer
- c) liquid-in-glass thermometer:-

It works on expansion (or) contraction of a thermometric substance with temperature.

It consists of a uniform diameter glass capillary tube connected to a bulb filled with a liquid at one end [mercury]. As the temperature increases, the liquid expands in volume and rises in the capillary. The height of liquid column is calibrated into a temperature scale, which may be read. Mercury, Alcohol, ether are commonly used.



Constant Volume Gas Thermometer

The thermometer consists of a

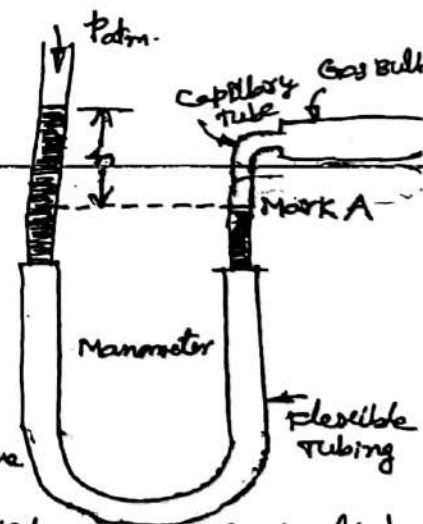
- i) bulb which encloses a fixed mass of an ideal gas
- ii) capillary tube
- iii) U-tube manometer with flexible bend.

The capillary tube connects the gas bulb to one limb of the manometer; the other limb being open to atmosphere.

The flexible bend of the manometer helps to raise (or) lower the limb open to atmosphere

so that mercury can be made to stand at fixed mark A in the limb communicating with the bulb. This is to ensure that volume of the gas in the bulb is maintained at constant value.

During operation, the bulb communicates with a constant temperature bath. There is exchange of heat between the bath and bulb until both attain the thermal equilibrium [Equality of temp]. Due to heat transfer to the bulb, the gas in the bulb expands and pushes the mercury downwards in right limb. The flexible tubing is then adjusted so that mercury level again attains the position of fixed mark A.



The difference in the level of mercury in the two limbs is recorded, and absolute pressure p , is determined by hydrostatic equation.

$$p = p_{\text{atm}} + \rho g h, \text{ where } \rho = \text{density, } h = \text{difference of mercury level}$$

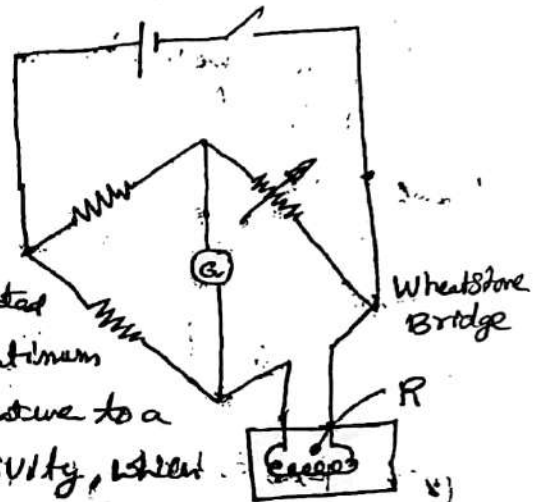
Firstly, the gas bulb is placed in a constant temp. bath at the triple point (273.15K) temp and corresponding pressure p_p is calculated.

Now, the bulb is brought in contact with a system whose temp. T is to be measured and measure the pressure, p .

∴ The new temperature, $T = 273.15 \times \frac{p}{p_p}$

Electrical Resistance Thermometer

In the resistance thermometer, the change in resistance of a metal wire due to its change in temperature is the thermometric property. The wire, frequently platinum, may be incorporated in a Wheatstone bridge circuit. The platinum resistance thermometer measures temperature to a high degree of accuracy and sensitivity, which makes it suitable as a standard for the calibration of other thermometers.



On a restricted range, the following quadratic equation is often used.

$$R = R_0 (1 + At + Bt^2)$$

where R_0 = resistance of platinum wire when it is surrounded by melting ice

A, B are constants.

TEMPERATURE SCALE:— To measure the temperature of a system, some numerical values are assigned on the thermometer. These numerical values on thermometer together are called temperature scale.

To give numerical value to the temperature of a body we have to define a scale of temperature. This is to choose two fixed point temperatures are the melting point of ice and the other boiling point of water (steam) at 1 atm of fixed temperature point.

We assign arbitrary T_1 to ice point and T_2 to steam point, correspondingly let the length of the mercury column are l_1 and l_2 respectively. The temperature correspondingly to any length l may be defined assuming linear relation—

$$\therefore t = a l + b$$

Thus a change of one degree in temperature ^{measures} means a change of $\frac{l_2 - l_1}{l_2 - l_1}$ in the length of mercury column.

There are four different scales:-

① Centigrade scale:- It is also known as Celsius scale.

on this, melting point of ice is marked as 0°C and boiling point of water as 100°C , under atmospheric pressure. Space between two points is divided into 100 equal parts. It is denoted by $^\circ\text{C}$.

Linear Equation

$$t = at + b$$

$$0 = a l_1 + b$$

$$100 = a l_2 + b$$

$$a = \frac{100}{l_2 - l_1}; \quad b = -a l_1 = -\frac{100}{l_2 - l_1} \times l_1$$

$$t^\circ\text{C} = \frac{100 \times l - 100 l_1}{l_2 - l_1} = \frac{100 (l - l_1)}{l_2 - l_1} \checkmark$$

② Fahrenheit scale

32 and 212°F are ice point and steam point respectively.

$$^\circ\text{F} = \frac{180}{l_2 - l_1} (l - l_1) + 32$$

③ Absolute temperature (Kelvin)

$$T(\text{K}) = T(^{\circ}\text{C}) + 273.15$$

④ Rankine scale $T(\text{R}) = T(^{\circ}\text{F}) + 459.67$

PROB The pressure in a constant gas thermometer is measured as 32 mm of Hg above atmospheric pressure at triple point. Determine the temp in $^\circ\text{C}$, when the pressure is 76 mm of Hg above atmospheric pressure. The barometer reads 752 mm of Hg.

SOL Absolute pressure at triple point, $P_{TP} = 752 + 32 = 784$ mm of Hg.

Absolute pressure at given pressure, $p = 752 + 76 = 828$ mm of Hg.

Triple point temperature, $T_{TP} = 273.15\text{K}$.

To find Temperature T at pressure p .

Analysis:- For constant volume gas thermometer, $\frac{P_{TP}}{T_{TP}} = \frac{p}{T}$

$$\text{①), } T = T_{TP} \times \frac{p}{P_{TP}} = 273.15 \times \frac{828}{784} = 288.48\text{K}$$

$$\text{Celsius temperature, } T = 288.48 - 273.15 = 15.33^\circ\text{C}$$

Prob. The temperature scale of a certain thermometer is given by the relation $t = A \ln p + B$, where A and B are constants and p is the thermometric property of the fluid in thermometer. At ice point and steam point, if the thermometric property is found to be 1.5 and 7.5 respectively, what will be the temperature corresponding to the thermometric property of 3.5 on Celsius scale?

Sol.
 Initial property $p_1 = 1.5$
 Final property $p_2 = 7.5$
 Ice-point temperature $T_1 = 0^\circ\text{C}$
 Steam-point temperature $T_2 = 100^\circ\text{C}$
 Thermometric property $p_3 = 3.5$

To find The temperature corresponding to thermometric property of 3.5

Analysis - The relation for temperature is given as
 $t = A \ln p + B$

At ice point, $0 = A \ln(1.5) + B$ — (1)

(1) $0 = 0.405 A + B$

At steam point, $100 = A \ln(7.5) + B$

(2) $100 = 2.015 A + B$ — (2)

Solving (1) & (2); subtracting equation (1) from (2), we get

$100 = 1.61 A$; $A = 62.13$; $B = -25.2$

Using A and B for thermometric property at 3.5

$t = 62.13 + \ln(3.5) - 25.2 = 54.64^\circ\text{C}$ ✓

Prob. A new temperature scale in degree N is to be defined with boiling and freezing points on the scale are 400°N and 100°N respectively. Correlate this with (i) Centigrade scale (ii) Fahrenheit scale

(b) What will be the reading on new scale corresponding to 60°C .

Sol. Centigrade scale Melting point is 0°C ; Boiling point 100°C .
 under Atmospheric pressure.

The relationship between temperature & length is given by

$t = a l + b$ — (1)

$0 = a l_1 + b$ — (2)

$100 = a l_2 + b$ — (3)

Subtracting (3) from (2), we get; $a = \frac{100}{l_2 - l_1}$, $b = -\frac{100 l_1}{l_2 - l_1}$

Substituting a & b in equation (1), $t^\circ\text{C} = \frac{100 (l - l_1)}{l_2 - l_1}$

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For given temperature scale, the boiling and freezing points are $400^\circ N$ and $100^\circ N$ respectively.

We have $t = at + b$.

$$100 = a l_1 + b \quad \text{--- (4)}$$

$$400 = a l_2 + b \quad \text{--- (5)}$$

By solving the above equation,

$$a = \frac{300}{l_2 - l_1}; \quad b = 100 - \frac{300 l_1}{l_2 - l_1}$$

Now substituting the values of a and b in equation (1), we get

$$\begin{aligned} t^\circ N &= \frac{300}{l_2 - l_1} l + 100 - \frac{300 l_1}{l_2 - l_1} = \frac{300}{l_2 - l_1} (l - l_1) + 100 \\ &= 3 \left(\frac{100}{l_2 - l_1} \right) (l - l_1) + 100 \end{aligned}$$

By substituting $\frac{100}{(l_2 - l_1)} (l - l_1) = t^\circ C$

$$\therefore \boxed{t^\circ N = 3t^\circ C + 100}$$

For a Fahrenheit scale, the boiling and freezing points are $212^\circ F$ and $32^\circ F$ respectively.

We have $t = at + b$

$$32 = a l_1 + b \quad \text{--- (7)}$$

$$212 = a l_2 + b \quad \text{--- (8)}$$

$$a = \frac{180}{l_2 - l_1} \quad b = 32 - \frac{180 l_1}{l_2 - l_1}$$

Solve the above equation,

$$t^\circ F = \frac{180 l}{l_2 - l_1} + 32 - \frac{180 l_1}{l_2 - l_1} = \frac{180 (l - l_1)}{l_2 - l_1} + 32 \quad \text{--- (9)}$$

we have $t^\circ N = 3 \left(\frac{100}{l_2 - l_1} \right) (l - l_1) + 100$

$$= 300 \left(\frac{t^\circ F - 32}{180} \right) + 100$$

$$\therefore \boxed{t^\circ N = \frac{5}{3} (t^\circ F - 32) + 100}$$

(b) The reading on new scale corresponding to $60^\circ C$ is

$$t^\circ C = 60^\circ C$$

relationship between $t^\circ N$ and $t^\circ C$ is

$$t^\circ N = 3t^\circ C + 100 = 3 \times 60 + 100 = \underline{280 N}$$

A perfect gas (or an ideal gas) may be defined as a state of a substance, whose evaporation from its liquid state is complete, and strictly obey all the gas laws under all conditions of temperature & pressure.

Laws of perfect gases:-

The physical properties of a gas are controlled by the following three variables.

- 1) pressure exerted by the gas
- 2) temperature
- 3) Volume occupied by gas.

Laws: 1) Boyle's Law 2) Charles's Law 3) Gay-Lussac's Law.

Boyle's Law:- The volume of absolute pressure of a given mass of a perfect gas varies inversely as its absolute volume, when the temperature remains constant.

$$p \propto \frac{1}{V} \quad \text{or} \quad pV = \text{constant} \quad \text{or} \quad p_1V_1 = p_2V_2 = p_3V_3 = \text{constant}$$

Charles's Law:- The volume of a given mass of a perfect gas varies directly as its absolute temperature when absolute pressure remains constant.

$$V \propto T \quad \text{or} \quad \frac{V}{T} = \text{constant} \quad \text{or} \quad \frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V_3}{T_3} = \text{constant}$$

Gay-Lussac's Law:- The absolute pressure of a given mass of a perfect gas varies directly as its absolute temperature when volume remains constant.

$$p \propto T \quad \text{or} \quad \frac{p}{T} = \text{constant} \quad \text{or} \quad \frac{p_1}{T_1} = \frac{p_2}{T_2} = \frac{p_3}{T_3} = \text{constant}$$

General gas equation:- Which obeys both Boyle's & Charles's Laws.

$$p \propto \frac{1}{V} \quad \text{or} \quad V \propto \frac{1}{p} \rightarrow \text{Boyle's Law}$$

$$V \propto T \rightarrow \text{Charles's Law}$$

$$\text{or} \quad V \propto \frac{T}{p} \quad \text{or} \quad \frac{pV}{T} = \text{constant}$$

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2} = \frac{p_3V_3}{T_3} = \text{constant}$$

Characteristic gas equation:- $pV = nRT$

where $R =$ characteristic gas constant. 0.287 kJ/kg K

Joule's Law:- The change of internal energy is proportional to change of temperature $\Delta U \propto \Delta T$

$$\therefore \Delta U = m c_p c_v \Delta T$$

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Specific heats:- The amount of heat required to raise the temperature of its unit mass through one degree. Solids & liquids have one specific heat while gases have two specific heats (C_p & C_v).

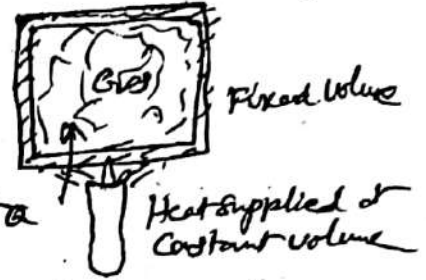
Specific heat at constant volume (C_v):-

It is the amount of heat required to raise the temperature of a unit mass of gas through one degree when it is heated at constant volume. C_v , kJ/kgK .

Heat supplied at constant volume

$$Q_{1-2} = m \times \text{sp. heat at constant vol} \times \text{rise in temperature}$$

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



Specific heat at constant pressure (C_p):-

It is the amount of heat required to raise the temperature of a unit mass of a gas through one degree when it is heated at constant pressure.

Heat supplied, $Q = m C_p (T_2 - T_1)$.



Enthalpy of a Gas, h : It is the sum of the internal energy (U) and the product of pressure and volume (PV).

Since $(U + PV)$ is made entirely of properties, therefore enthalpy (h) is also a property.

Relation Between two specific heats:-

Consider a gas enclosed in a container and being heated at constant pressure from initial state 1 to final state 2.

Heat supplied at constant pressure:-

$$Q_{1-2} = m C_p (T_2 - T_1)$$

Heat utilized for external work, $W_{1-2} = P(V_2 - V_1)$

increase in internal energy, $dU = m C_v (T_2 - T_1)$

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

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

$$C_p - C_v = R$$

$$\frac{C_p}{C_v} = \gamma \text{ (adiabatic index)}$$

Non-Flow processes:- The thermodynamic processes which do not involve the mass flow across their boundary (closed systems).

The commonly used non-flow processes are

- 1) constant-volume process
- 2) constant-pressure process
- 3) constant-temperature process
- 4) polytropic process
- 5) Adiabatic process. (Isentropic process)

1) Constant volume process (Isochoric process) :-

if a gas is confined in a closed cylinder, its volume cannot change when heated (or) cooled.

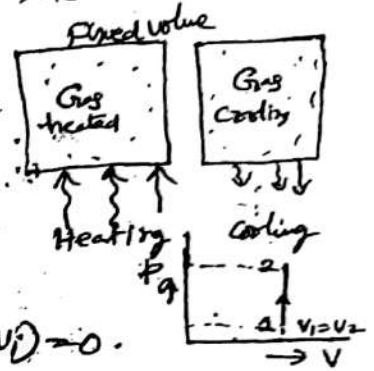
The temperature & pressure increased with heat addition. The internal energy of gas increases.

Charles Law for constant volume process.

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \Rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Work done by gas $W_{1-2} = \int P dV = P(V_2 - V_1) = 0$.

Heat supplied $Q_{1-2} = (U_2 - U_1) + W_{1-2} = U_2 - U_1 = m C_V (T_2 - T_1)$.



2) Constant pressure process (Isobaric process) :-

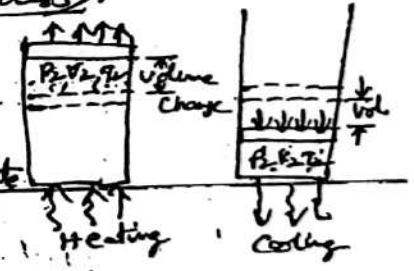
if heat is supplied to a gas under constant pressure, the volume of the gas will increase in direction proportion to the change in the absolute temperature of the gas.

The relationship between pressure, volume and temperature is

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} ; \text{ since } P_1 = P_2 ; \frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V}{T} = \text{const.}$$

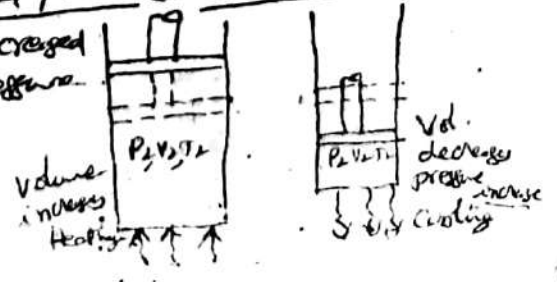
Work done by the gas $W_{1-2} = P(V_2 - V_1) = m R (T_2 - T_1)$

Heat supplied $Q_{1-2} = (U_2 - U_1) + W_{1-2}$
 $= m C_V (T_2 - T_1) + m R (T_2 - T_1)$
 $= m C (T_2 - T_1) \text{ (} C_V + R \text{)}$
 $= m C_P (T_2 - T_1)$



3) Constant Temperature process (Isothermal process) (Boyle's process) :-

if the volume of a gas is increased (or) decreased with constant temperature, the absolute pressure will vary inversely with volume. This is Boyle's Law for constant temperature process.



The process is also called as isothermal (constant temperature) process.

Boyle's law for a constant temperature process is

$$P_1 V_1 = P_2 V_2$$

The relationship between pressure, volume and temperature is

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad \text{Since } T_1 = T_2 \quad P_1 V_1 = P_2 V_2 = PV = \text{constant}$$

Work done by the gas $W_{1-2} = \int_{V_1}^{V_2} \frac{c}{V} dV = c \int_{V_1}^{V_2} \frac{1}{V} dV$

$$= P_1 V_1 \left[\log_e V \right]_{V_1}^{V_2} = P_1 V_1 \log_e \frac{V_2}{V_1}$$

Heat supplied, $Q_{1-2} = W_{1-2} + \Delta U$ $\because \Delta U = m C_V (T_2 - T_1) = 0; T_1 = T_2$

$$= W_{1-2} = P_1 V_1 \log_e \frac{V_2}{V_1}$$

ADIABATIC PROCESS: In an adiabatic process, the gas changes its condition without the transfer of heat to (or) from the surroundings. Pressure, volume and temperature of the gas vary during adiabatic process.

The relationship between pressure, volume & temperature is $P_1 V_1^\gamma = P_2 V_2^\gamma = c$, constant

Work done during adiabatic process $W_{1-2} = \int P dV$

$$= \int \frac{c}{V^\gamma} dV = c \int \frac{1}{V^\gamma} dV = c \int \frac{1}{V^{\gamma}} dV = c \left[\frac{V^{-\gamma+1}}{-\gamma+1} \right]_{V_1}^{V_2}$$

$$= \frac{c}{-\gamma+1} \left[V_2^{-\gamma+1} - V_1^{-\gamma+1} \right] = \frac{P_2 V_2^\gamma \cdot V_2^{-\gamma+1} - P_1 V_1^\gamma \cdot V_1^{-\gamma+1}}{-\gamma+1}$$

(Take $C_V = \frac{R}{\gamma-1}$)

$$= - \left(\frac{P_2 V_2 - P_1 V_1}{\gamma-1} \right), \text{ -ve sign denotes work done on the gas.}$$

Heat supplied (or) Heat transferred, $Q_{1-2} = 0$ (Adiabatic process $Q = 0$)

POLYTROPIC PROCESS:

An expansion process in which the energy to do the work is supplied partly from an external source and partly from the gas itself is known as polytropic process that will follow a path which will fall in between those of the isothermal and adiabatic processes.

$$PV^n = c \quad ; \quad P_1 V_1^n = P_2 V_2^n = PV^n = c$$

Work done during polytropic process, $W_{1-2} = \frac{P_2 V_2 - P_1 V_1}{n-1} = \frac{m R (T_2 - T_1)}{n-1}$

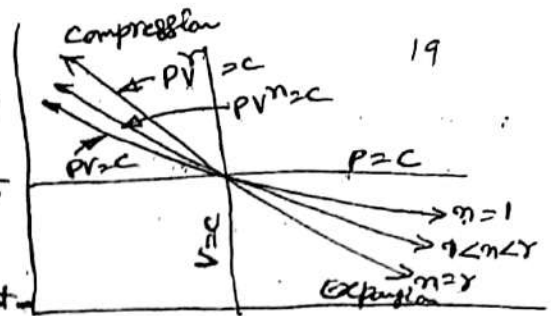
$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2} \right)^{\frac{n-1}{n}} ; \quad \frac{T_1}{T_2} = \left(\frac{V_2}{V_1} \right)^{n-1}$$

Heat transferred, $Q_{1-2} = W_{1-2} + \Delta U_{1-2}$

$$= \frac{m R (T_2 - T_1)}{n-1} + m C_V (T_2 - T_1) = \frac{m R (T_2 - T_1)}{n-1} + m \times \frac{R}{\gamma-1} (T_2 - T_1)$$

$$= \frac{m R (T_2 - T_1)}{n-1} \left[\frac{1}{n-1} + \frac{1}{\gamma-1} \right] = \frac{\gamma-n}{\gamma-1} \times \frac{m R (T_2 - T_1)}{n-1}$$

an isothermal compression process, ↑ energy is transferred as heat from the gas to an external sink at the same rate that work is being done on the gas. The internal energy is constant.

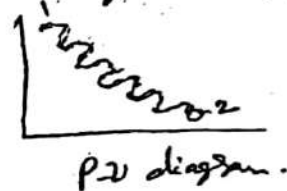
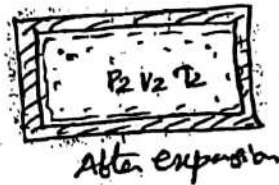
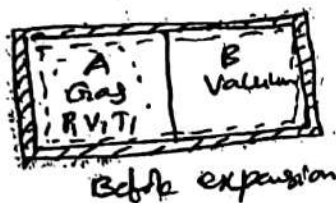


During an adiabatic process, there is no transfer of heat energy. Hence an amount of energy is equal to the amount of work done on the gas is set up in the gas as an increase in the internal energy and temperature of gas increases.

Comparison of isentropic, isothermal & polytropic process.

Free Expansion [or Unrestricted Expansion] process:-

The free expansion process is an irreversible non-flow process. A free expansion occurs when a fluid is allowed to expand suddenly into a vacuum chamber through an orifice of large dimensions.



Consider two chambers A and B separated by a partition.

If the partition is removed, the gas will expand freely and occupy the whole space. By this volume increases to V_2 , pressure & temp. decreases to P_2, T_2 .

Since there is no expansion of boundary of the system, no work is done. $\therefore Q_{1-2} = 0, W_{1-2} = 0$ and $dU = 0; dH = 0$.

S.No.	Type of reversible non-flow process	P-2-T relation	Work done W_{1-2}	Change in internal energy $\Delta U = U_2 - U_1$	Heat supplied $Q = W + \Delta U$	Change in enthalpy $dH = dh$
1.	Constant volume process	$\frac{P_1}{T_1} = \frac{P_2}{T_2}$	0	$mC_V(\Delta T)$	$mC_V(\Delta T)$	$mC_P(\Delta T)$
2.	Constant pressure process	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$	$P(V_2 - V_1)$	$mC_V(\Delta T)$	$mC_P(\Delta T)$	$mC_P(\Delta T)$
3.	Constant temp (or) isothermal	$P_1V_1 = P_2V_2$	$P_1V_1 \log_e \frac{V_2}{V_1}$	0	$P_1V_1 \log_e \frac{V_2}{V_1}$	0
4.	Adiabatic (or) isentropic $PV^\gamma = c$	$P_1V_1^\gamma = P_2V_2^\gamma$ $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$ $= \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$	$\frac{P_2V_2 - P_1V_1}{\gamma-1}$	$mC_V(\Delta T)$	0	$mC_P(\Delta T)$
5.	polytropic process $PV^n = c$	$P_1V_1^n = P_2V_2^n$	$\frac{P_2V_2 - P_1V_1}{n-1}$	$mC_V(\Delta T)$	$\frac{r-n}{\gamma-n} W$	$mC_P(\Delta T)$

PROB. A certain gas occupies a space of 0.3 m^3 at a pressure of 2 bar and a temperature of 77°C . It is heated at constant volume, until the pressure is 7 bar. Determine 1) Temperature at end of the process 2) mass of gas 3) change in internal energy 4) change in enthalpy during the process.
 Assume $C_p = 1.005 \text{ kJ/kgK}$, $C_v = 0.712 \text{ kJ/kgK}$, $R = 287 \text{ J/kgK}$

SOL.
 $V_1 = 0.3 \text{ m}^3$, $P_1 = 2 \text{ bar} = 2 \times 10^5 \text{ N/m}^2$, $T_1 = 77^\circ\text{C} = 350 \text{ K}$
 $P_2 = 7 \text{ bar} = 7 \times 10^5 \text{ N/m}^2$, $C_p = 1.005 \text{ kJ/kgK}$, $R = 287 \text{ J/kgK}$

1) Temperature at the end of the process, T_2

We know that, $\frac{P_1}{T_1} = \frac{P_2}{T_2}$

$$\therefore T_2 = \frac{P_2}{P_1} \times T_1 = \frac{7 \times 10^5}{2 \times 10^5} \times 350 = 1225 \text{ K} = 1225 - 273 = 952^\circ\text{C}$$

2) Mass of the gas,

Let $m =$ mass of the gas

We know that, $P_1 V_1 = mRT_1$; $m = \frac{P_1 V_1}{RT_1} = \frac{2 \times 10^5 \times 0.3}{287 \times 350} = 0.597 \text{ kg}$

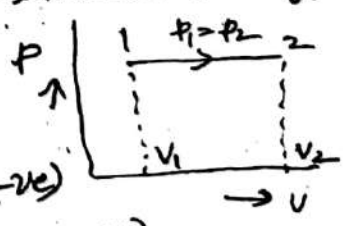
3) change in internal energy:-

$$\Delta U = U_2 - U_1 = m C_v (T_2 - T_1) = 0.597 \times 0.712 (1225 - 350) = 372 \text{ kJ}$$

4) change in enthalpy, $\Delta H = H_2 - H_1 = m C_p (T_2 - T_1)$

$$= 0.597 \times 1.005 (1225 - 350) = 525 \text{ kJ}$$

PROB. A closed system undergoes a reversible process at a constant pressure process of 3.5 bar and its volume changes from 0.15 m^3 to 0.06 m^3 . 25 kJ of heat is rejected by the system during the process. Determine the change in internal energy of the system.



SOL. pressure, $p = 3.5 \text{ bar} = 3.5 \times 10^5 \text{ N/m}^2$
 $V_1 = 0.15 \text{ m}^3$, $V_2 = 0.06 \text{ m}^3$

Heat rejected by system, $Q = -25 \text{ kJ}$ (-ve)

Work done = $p(V_2 - V_1) = 3.5 \times 10^5 (0.06 - 0.15) = -31,500 \text{ J} = -31.5 \text{ kJ}$ (-ve) (work done on the system)

According to First law of thermodynamics.

$$Q = \Delta U + W$$

$$-25 = \Delta U + (-31.5) \Rightarrow \Delta U = 31.5 - 25 = 6.5 \text{ kJ}$$

PROB A quantity of air has a volume of 0.4 m^3 at a pressure of 5 bar and a temperature of 80°C . It is expanded in a cylinder at a constant temperature to a pressure of 1 bar . Determine the amount of work done by the air during expansion.

SOL Given, $v_1 = 0.4 \text{ m}^3$, $p_1 = 5 \text{ bar} = 5 \times 10^5 \text{ N/m}^2$, $T_1 = 80^\circ\text{C} = 80 + 273 = 353 \text{ K}$
 $p_2 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$.

Work done by the air during (expansion)

$$W_{1-2} = p_1 v_1 \ln \frac{v_2}{v_1} = p_1 v_1 \ln \frac{p_1}{p_2} = 5 \times 10^5 \times 0.4 \ln \frac{5}{1}$$

$$= 3.218 \times 10^5 \text{ J} = 321.8 \text{ kJ} \quad \checkmark \text{ (work done by system is +ve)}$$

PROB 0.1 m^3 of air at a pressure of 1.5 bar is expanded isothermally to 0.5 m^3 . Calculate the final pressure of the gas and heat supplied during the process.

SOL Given, $v_1 = 0.1 \text{ m}^3$, $p_1 = 1.5 \text{ bar} = 1.5 \times 10^5 \text{ N/m}^2$, $v_2 = 0.5 \text{ m}^3$.

Final pressure of the gas,

We know that, $p_1 v_1 = p_2 v_2$

$$p_2 = \frac{p_1 v_1}{v_2} = \frac{1.5 \times 10^5 \times 0.1}{0.5} = 0.3 \times 10^5 \text{ N/m}^2 = 0.3 \text{ bar}$$

Work done by the system, $W_{1-2} = p_1 v_1 \ln \frac{v_2}{v_1} = p_1 v_1 \ln \frac{p_1}{p_2}$

$$= 1.5 \times 10^5 \times 0.1 \ln \left(\frac{1.5}{0.3} \right) = 24.115 \text{ J}$$

$$= 24.115 \text{ kJ} \quad \checkmark$$

Heat supplied, $Q = \Delta U + W = 0 + 24.115$ $\Delta U = 0$, since $T_1 = T_2$

$$= 24.115 \text{ kJ} \quad \checkmark$$

PROB A system contains 0.15 m^3 of a gas at a pressure of 3.8 bar and 150°C . It is expanded adiabatically till the pressure falls to 1 bar . The gas is then heated at a constant pressure till its enthalpy increases by 70 kJ . Determine the total work done. Take, $C_p = 1 \text{ kJ/kgK}$, $C_v = 0.714 \text{ kJ/kgK}$.

SOL Adiabatic index, $\gamma = \frac{C_p}{C_v} = \frac{1}{0.714} = 1.4$

For an Adiabatic process 1-2, p, v, T relations are

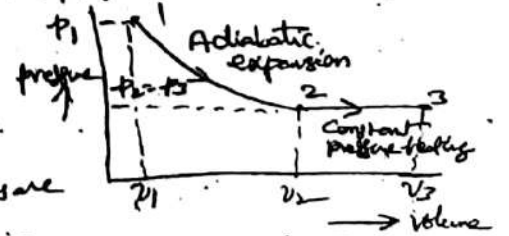
$$p_1 v_1^\gamma = p_2 v_2^\gamma \quad \text{or} \quad \frac{v_1}{v_2} = \left(\frac{p_2}{p_1} \right)^{\frac{1}{\gamma}}$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}}$$

Final volume, $v_2 = v_1 / \left(\frac{p_2}{p_1} \right)^{\frac{1}{\gamma}}$

$$= 0.15 / \left(\frac{1}{3.8} \right)^{\frac{1}{1.4}}$$

$$= 0.39 \text{ m}^3$$



Given, $v_1 = 0.15 \text{ m}^3$
 $p_1 = 3.8 \text{ bar} = 3.8 \times 10^5 \text{ N/m}^2$
 $T_1 = 150^\circ\text{C} + 273 = 423 \text{ K}$
 $p_2 = 1 \text{ bar}$ enthalpy
 $\Delta H = +70 \text{ kJ}$ (increased)

gas constant, $R = C_p - C_v = 1 - 0.714 = 0.286 \text{ kJ/kg} \cdot \text{K}$

Temperature at state 2, $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$; $T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

$$\Rightarrow T_2 = 423 \left(\frac{1}{3.8}\right)^{\frac{1.4-1}{1.4}} = 288.7 \text{ K}$$

mass of the gas, $P_1 V_1 = nRT_1$
 $m = \frac{P_1 V_1}{RT_1} = \frac{0.28 \times 10^6 \times 0.15}{286 \times 423} = 0.47 \text{ kg}$

Increase in enthalpy during the constant pressure process 2-3,

$$dH = m C_p (T_3 - T_2)$$

$$70 = 0.47 \times 1 (T_3 - 288.7); T_3 = \frac{70}{0.47} + 288.7 = 437.6 \text{ K}$$

Since the heating is at constant pressure, therefore,

$$\frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3} \Rightarrow \frac{V_2}{T_2} = \frac{V_3}{T_3} \text{ since } P_2 = P_3$$

$$V_3 = \frac{V_2 T_3}{T_2} = \frac{0.39 \times 437.6}{288.7} = 0.59 \text{ m}^3$$

Work done during adiabatic expansion,

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{3.8 \times 10^5 \times 0.15 - 1.4 \times 10^5 \times 0.39}{1.4 - 1}$$

$$= 45,000 \text{ J} = 45 \text{ kJ} \checkmark$$

Work done during constant pressure heating,

$$W_{2-3} = P_2 (V_3 - V_2) = 1.4 \times 10^5 (0.59 - 0.39)$$

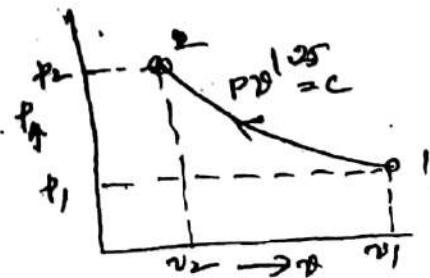
$$= 20,000 \text{ J} = 20 \text{ kJ}$$

$$\text{Total Work done, } W = W_{1-2} + W_{2-3} = 45 + 20 = 65 \text{ kJ} \checkmark$$

Prob. A gas mixture obeying perfect gas law has a molecular mass of 26.7. The gas mixture is compressed through a compression ratio of 12 according to the law $PV^{1.25} = \text{constant}$, from initial conditions of 0.9 bar and 333K. Assuming a mean molar specific heat at constant volume of 21.1 kJ/kg. find per kg of mass, the work done and heat flow across the cylinder walls. For the above gas, determine the values of characteristic gas constant, molar specific heat at a constant pressure and ratio of specific heats.

Sol. Given, Molecular mass, $M = 26.7$
 Compression ratio, $\gamma = \frac{V_1}{V_2} = 12$
 Initial pressure, $P_1 = 0.9 \text{ bar} = 0.9 \times 10^5 \text{ N/m}^2$
 Initial temperature, $T_1 = 333 \text{ K}$

Plot find V_2, P_2 ;
 We know that $P_1 V_1^\gamma = P_2 V_2^\gamma$
 $P_2 = P_1 \left(\frac{V_1}{V_2}\right)^\gamma = 0.9 (12)^{1.25} = 20.1 \text{ bar}$



characteristic gas constant, $R = \frac{\text{universal gas constant}}{\text{molecular weight}}$ ²³
 $= \frac{8314}{26.7} = 311.4 \text{ J/kgK}$

and $p_1 v_1 = mRT_1$

$$v_1 = \frac{mRT_1}{p_1} = \frac{1 \times 311.4 \times 333}{0.9 \times 10^5} = 1.15 \text{ m}^3$$

$$v_2 = \frac{v_1}{12} = \frac{1.15}{12} = 0.096 \text{ m}^3 \quad \left[\text{Since mass of gas} = 1 \text{ kg, given.} \right]$$

~~Work done~~ Work supplied during compression,

$$W_{1-2} = \frac{p_2 v_2 - p_1 v_1}{n-1} = \frac{20.1 \times 10^5 \times 0.096 - 0.9 \times 10^5 \times 1.15}{1.25-1}$$

$$= 357840 \text{ J} \quad \text{or} \quad \underline{357.84 \text{ kJ}} \checkmark$$

Heat flow across cylinder walls:

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1}$$

$$p_2 = p_1 \left(\frac{v_1}{v_2} \right)^{\gamma-1} = 333 \left(\frac{1.15}{0.096} \right)^{1.25-1} = 620 \text{ k}$$

specific heat at constant volume, $c_{v2} = \frac{C_{v,m}}{M} = \frac{21.1}{26.7} = 0.79 \text{ kJ/kgK}$

change in internal energy, $dU = U_2 - U_1 = m c_v (T_2 - T_1) = 1 \times 0.79 (620 - 333) = 226.7 \text{ kJ}$

Heat flow, $Q = \Delta U + W = 226.7 + (-357.84)$ [\because W is -ve, work supplied]
 across cylinder walls, $= \underline{-131.1 \text{ kJ}}$ Heat rejected

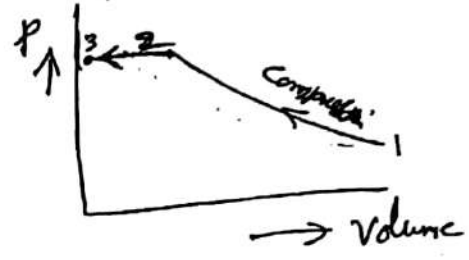
$C_p - C_v = R$; $C_p - 0.79 = 0.3114$; $C_p = 1.1014 \text{ kJ/kgK}$

Mean specific heat at constant pressure, $C_{p,m} = M C_p = 26.7 \times 1.1014 = 29.4 \text{ kJ/kgK}$

Ratio of specific heats, $\gamma = \frac{C_p}{C_v} = \frac{1.1014}{0.79} = \underline{1.394} \checkmark$

PROB A cylinder contains 0.115 m^3 of gas at 1 bar and 90°C . The gas is compressed to a volume 0.0288 m^3 . The final pressure being 5.67 bar. Calculate

- (a) mass of the gas
 - (b) value of index of compression
 - (c) increase in internal energy
 - (d) Heat transfer during compression.
- of ~~the~~ after compression, the gas is to be cooled at constant pressure to its original temperature of 90°C , find the work of compression required. Assume $\gamma = 1.4$ & $R = 0.3 \text{ kJ/kgK}$.



SOL Given, $V_1 = 0.115 \text{ m}^3$
 $P_1 = 1 \text{ bar}$
 $T_1 = 90 + 273 = 363 \text{ K}$
 $V_2 = 0.0288 \text{ m}^3$
 $P_2 = 5.67 \text{ bar}$
 $\gamma = 1.4 ; R = 0.3 \text{ kJ/kgK}$

(a) mass of the gas:- $P_1 V_1 = m R T_1 ; m = \frac{P_1 V_1}{R T_1}$
 $= \frac{1 \times 10^5 \times 0.115}{(0.3 \times 1000) \times 363}$
 $= 0.1056 \text{ Kgs} \checkmark$

(b) value of index of compression:-
 $P_1 V_1^n = P_2 V_2^n$
 $\therefore n = \frac{\log_e (P_2/P_1)}{\log_e (V_1/V_2)} = \frac{\log_e (5.67/1)}{\log_e (0.115/0.0288)} = 1.253$

(c) increase in internal energy:-
 $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1} ; T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{n-1} = 363 \left(\frac{0.115}{0.0288}\right)^{1.253-1} = 515.17 \text{ K}$
 $\Delta U = \text{change in internal energy} = m C_v (T_2 - T_1) = m \left(\frac{R}{\gamma - 1}\right) (T_2 - T_1)$
 $= 0.1056 \times \frac{0.30}{1.4 - 1} (515.17 - 363)$
 $= 12.05 \text{ kJ} \checkmark$

(d) Heat Transfer-
 $Q = \Delta U + W ; W = \frac{P_2 V_2 - P_1 V_1}{n-1} = \frac{5.67 \times 0.0288 - 1 \times 0.115}{1.253 - 1} 10^5$
 $= 19.05 \text{ kJ} \text{ (-ve) work done on system}$
 $\therefore Q = \Delta U + W$
 $= 12.05 - 19.05 = -7 \text{ kJ} \checkmark$

(e) After compression, it required to cool gas to original temp of 90°C
 $\frac{P_3 V_3}{T_3} = \frac{P_2 V_2}{T_2} ; P_3 = P_2 ; V_3 = V_2 \times \frac{T_3}{T_2} = \frac{363 \times 0.0288}{515.17} = 0.0202 \text{ m}^3$
 Additional work required, $W = P_2 (V_3 - V_2) = 5.67 \times 10^5 (0.0202 - 0.0288)$
 $= -4.87 \text{ kJ} \checkmark$

* Application of First law of Thermodynamics to a steady flow process.

A flow process constitutes an open system, in which the working substance enters and leaves the control surface of a system. Energy interaction in the form of heat and work may also take place with in the system.

Flow energy (or) flow work refers to work required to push a certain mass of fluid into and out of the control volume.

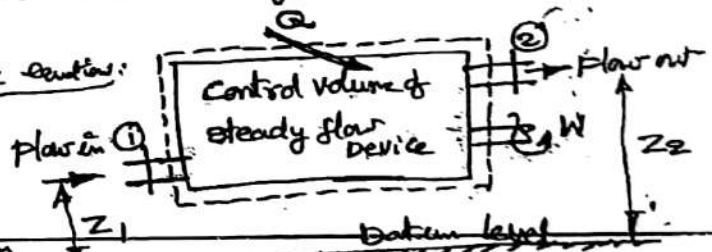
On a steady flow process, the following conditions must be satisfied.

- The rate of mass flow at inlet and outlet is same.
- The rate of heat transfer is constant.
- The rate of work transfer is constant.
- State of the working substance at any point with in the system is same at all points.
- There is no change in the chemical composition of the systems.

If any one of these conditions are not satisfied, then the process is said to be non-steady flow process. In engineering mainly concerned with steady flow process.

Steady flow Energy Balance equation:

Consider an open system through which the working substance flows at a steady rate as shown in figure. The working substance enters the system at section (1) and leaves the system at section (2).



- Let
- p_1 = pressure of the working substance entering the system, N/m²
 - v_{s1} = specific volume of the substance entering the system, m³/kg.
 - V_1 = velocity of the working substance entering the system, m/sec.
 - u_1 = specific internal energy of the working substance entering the system in J/kg.
 - z_1 = Height above datum level for inlet in metres.

Similarly p_2, v_{s2}, V_2, u_2 & z_2 are corresponding values for the working substance leaving the system.

- Let
- q_{1-2} = Heat supplied to the system J/kg
 - w_{1-2} = work delivered by the system J/kg.

The total energy of entering the system per kg of working substance

$$E_1 = \text{internal energy} + \text{flow work} + \text{Kinetic energy} + \text{potential energy} + \text{Heat supplied.}$$

$$= u_1 + P_1 v_{s1} + \frac{V_1^2}{2} + g z_1 + q_{1-2}$$

Similarly, Total energy leaving the system per kg of working substance

$$E_2 = u_2 + P_2 v_{s2} + \frac{V_2^2}{2} + g z_2 + W_{1-2}$$

Assuming no loss of energy during flow, According to First law of Thermodynamics, $E_1 = E_2$

$$u_1 + P_1 v_{s1} + \frac{V_1^2}{2} + g z_1 + q_{1-2} = u_2 + P_2 v_{s2} + \frac{V_2^2}{2} + g z_2 + W_{1-2}$$

$$\boxed{m \left(h_1 + \frac{V_1^2}{2} + z_1 g + q_{1-2} \right) = m \left(h_2 + \frac{V_2^2}{2} + g z_2 + W_{1-2} \right)}$$

This is known as steady flow energy equation (SFEE).

Note:- on steady flow, mass flow rate is constant entering & leaving the working substance.

- ① $m = \frac{A_1 V_1}{v_{s1}} = \frac{A_2 V_2}{v_{s2}}$
- ② If K.E & P.E are neglected, SFEE, $q_{1-2} - W_{1-2} = h_2 - h_1$
- ③ SFEE may be written as, $q_{1-2} - W_{1-2} = h_2 - h_1 + \left(\frac{V_2^2}{2} - \frac{V_1^2}{2} \right) + g(z_2 - z_1)$

* Application of steady flow energy equation (SFEE)

① BOILER:- A boiler is a device which supplies heat to water and generates steam. on this system, there is no change in kinetic and potential energies and also there is no work done by the system. KE & P.E & work done is zero.

The SFEE equation,

$$q_{1-2} - W_{1-2} = (h_2 - h_1) + \left(\frac{V_2^2}{2} - \frac{V_1^2}{2} \right) + (z_2 g - z_1 g)$$

$$\therefore \boxed{q_{1-2} = h_2 - h_1}$$

This shows that heat supplied to a boiler increases the enthalpy of the system.

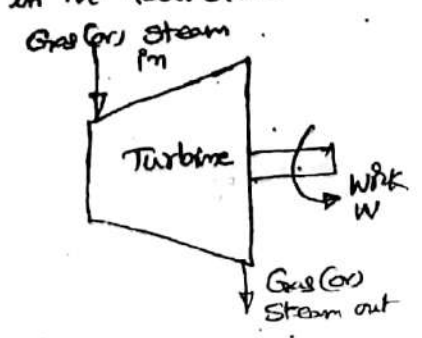


② STEAM TURBINE:- on steam turbine, steam is passed through the turbine and part of its energy is converted into work in the turbine.

The steam leaves the turbine at lower pressure and temperature.

$$q_{1-2} - W_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

Here, $q_{1-2} = 0$, if turbine is insulated,
 = -ve, if turbine not insulated.



Value

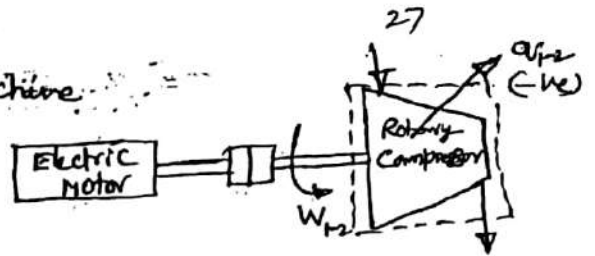
A steady-flow process can be defined as a process during which all properties of fluid at each location within the system remain constant with respect to time. That is, the fluid properties can change from point to point within the control volume but at any fixed location they remain the same during the entire process. Steady flow means no change with time.

Conditions for steady-flow process:

1. The fluid properties (intensive (or Extensive) within the control volume remain constant at each location with respect to time.
2. The properties of the fluid crossing the boundary (inlet and outlet) remain constant at each point of the boundary.
3. The Mass-flow rate into the system is always equal to the mass flow rate out of the system.
4. Heat and work interactions with the surroundings occur at a steady state.

③ ROTARY COMPRESSOR:-

A rotary compressor is a machine which compresses air (or) gas and supplies the same at moderate pressure in large quantity.



- on compressor, $z_1 = z_2$, and heat rejected from system

so, $q_{1-2} = -ve$

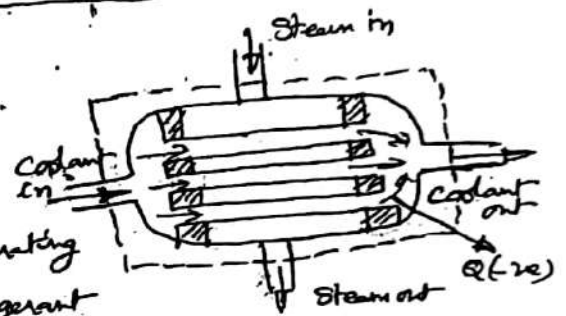
W_{1-2} work supplied to the system, $-ve$.

$$q_{1-2} - W_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2}$$

$$\therefore -q_{1-2} - (-W_{1-2}) = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2}$$

④ CONDENSER:-

A condenser is a device used to condense steam in case of steam power plants using water as the cooling medium, where as in refrigerating systems, it is used to condense refrigerant vapour using air as the cooling medium. For such a systems, there is no change in KE and P.E. Also, there is no work done by the system.



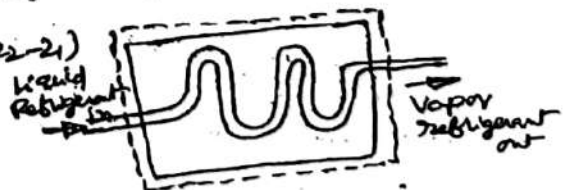
$$\therefore -q_{1-2} = h_2 - h_1$$

$$-q_{1-2} = h_2 - h_1 \quad \text{OR} \quad q_{1-2} = h_1 - h_2$$

⑤ EVAPORATOR:- Evaporator is a device used in refrigeration systems in which liquid refrigerant passes, receives heat and leaves as vapour refrigerant. For such a system, K.E & P.E, work done is zero.

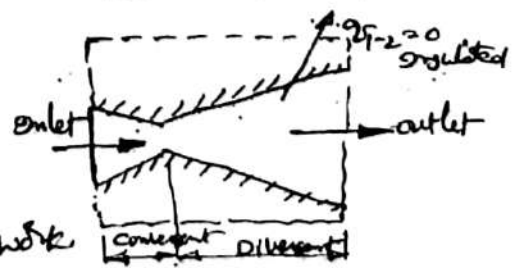
$$q_{1-2} - W_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$\therefore q_{1-2} = h_2 - h_1$$



⑥ NOZZLE:-

A nozzle is a device which increase the velocity of the working substance at the expense of its pressure drop. The nozzle is insulated, so that no transfer of heat from the system, Further, the system does not deliver any work. There is no change in P.E



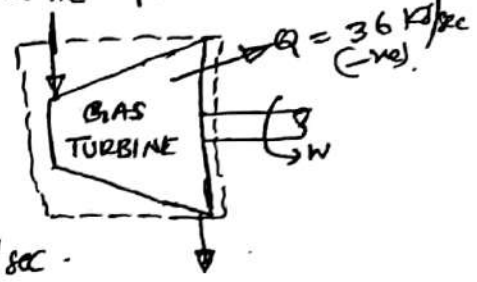
$$q_{1-2} - W_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$0 = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} \quad \therefore V_2 = \sqrt{V_1^2 + 2(h_1 - h_2)}$$

of initial velocity, V_1 is neglected

velocity of steam at exit, $V_2 = \sqrt{2(h_1 - h_2)}$

PROB. A gas turbine receives gas at an enthalpy of 800 kJ/kg and a velocity of 100 m/sec. The gas leaves the turbine at an enthalpy of 380 kJ/kg and a velocity of 150 m/sec. Heat lost to surroundings from the gas is 36 kJ/sec. If the rate of gas flow is 10 kg/sec, Find the power developed by the turbine.



SOL. Given, Enthalpy at inlet of turbine,

$h_1 = 800 \text{ kJ/kg}$

velocity at inlet, $V_1 = 100 \text{ m/sec}$

$h_2 = 380 \text{ kJ/kg}, V_2 = 150 \text{ m/sec}$

Heat rejected, $Q_{1-2} = -36 \text{ kJ/sec}$

rate of gas flow, $\dot{m} = 10 \text{ kg/sec}$

SFEE is

$$Q_{1-2} - W_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$\frac{Q_{1-2}}{\dot{m}} - \frac{W_{1-2}}{\dot{m}} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + 0$$

$$\frac{-36 \times 10^3}{10} - \frac{W_{1-2}}{10} = (380 \times 10^3 - 800 \times 10^3) + \frac{150^2 - 100^2}{2}$$

$$-36 \times 10^3 - \frac{W_{1-2}}{10} = (-420 \times 10^3 + 6250) = (-413,750)$$

$$W_{1-2} = 4101500 \text{ kJ/sec} \text{ (or) } 410 \text{ kW}$$

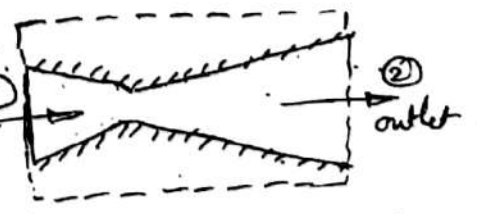
PROB. A nozzle receives 1200 kg/hr of steam at 13 MN/m², specific volume v_{s1} is 142 litres/kg, internal energy 4400 kJ/kg and negligible speed. At exit, the pressure is 100 kN/m², specific volume 1660 litres/kg and internal energy 2200 kJ/kg. Calculate the exit velocity of steam.

SOL. Given, mass of steam, $m = 1200 \text{ kg/hr}$, inlet pressure at inlet, $p_1 = 1.3 \text{ MN/m}^2 = 1.3 \times 10^6 \text{ N/m}^2$

specific volume at inlet, $v_{s1} = 142 \text{ lit/kg} = 0.142 \text{ m}^3/\text{kg}$

internal energy at inlet, $u_1 = 4400 \text{ kJ/kg}$

similarly, $p_2 = 100 \times 10^3 \text{ N/m}^2$
 $v_{s2} = 1660 \text{ lit/kg} = 1.66 \text{ m}^3/\text{kg}$
 $u_2 = 2200 \text{ kJ/kg}$



$$\text{or S.F.E.E, } q_{1-2} - h_{1-2} = (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1)$$

$$0 = (h_2 - h_1) + \frac{v_2^2}{2}; \quad q_{1-2} = 0, W = 0$$

$$v_1 = 0; z_1 = z_2$$

$$\therefore v_2 = \sqrt{2(h_1 - h_2)}$$

$$h_1 = u_1 + p_1 v_{s1} = 4400 \times 10^3 + 1.3 \times 10^6 \times 0.142 = 4584600 \text{ J/kg}$$

$$h_2 = u_2 + p_2 v_{s2} = 2200 \times 10^3 + 100 \times 10^3 \times 1.66 = 2366000 \text{ J/kg}$$

$$\therefore v_2 = \sqrt{2(h_1 - h_2)} = \sqrt{2(4584600 - 2366000)} = 2106 \text{ m/sec}$$

Prob A blower handles 1 kg/s of air at 20°C and consumes 15 kW. Its inlet and outlet velocities of air 100 m/sec and 150 m/sec respectively. Find the exit air temperature. Assume adiabatic conditions ($q=0$)

Sol. Given: mass of air = 1 kg/sec. Power consumed, $W = -15 \text{ kW}$ (-ve)
inlet temperature of air, $T_1 = 20^\circ\text{C}$, $V_1 = 100 \text{ m/sec}$, $V_2 = 150 \text{ m/sec}$

= The S.F.E.E

$$q_{1-2} - W_{1-2} = (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1)$$

$$\frac{Q}{m} - \frac{W_{1-2}}{m} = (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2}$$

$$- \frac{(-15) \times 10^3}{1} = (h_2 - h_1) + \frac{150^2 - 100^2}{2}$$

$$\therefore (h_2 - h_1) = 15000 - 6250 = 8750 \text{ J/kg}$$

$$8750 = m c_p [T_2 - T_1] = 1 \times 1005 \times (T_2 - 293)$$

$$\therefore \text{Exit air temperature, } T_2 = 301.706 \text{ K (or } 28.7^\circ\text{C)}$$

Prob A steady flow apparatus 140 kJ of work is done by each kg of fluid. The specific volume of fluid, pressure and velocity at the inlet are $0.37 \text{ m}^3/\text{kg}$, 600 kPa and 16 m/sec. The inlet is 32 mm above floor and the discharge pipe is at the floor level. The discharge conditions are $0.62 \text{ m}^3/\text{kg}$, 100 kPa and 300 m/sec. The total heat loss between inlet and discharge is 9 kJ/kg of fluid. Find whether specific internal energy increase or decrease.

Sol Given, work done by fluid, $W = 140 \text{ kJ}$ (+ve)

$$v_{s1} = 0.37 \text{ m}^3/\text{kg}$$

$$p_1 = 600 \text{ kPa}$$

$$V_1 = 16 \text{ m/sec}$$

$$z_1 = 32 \text{ mm}$$

$$z_2 = 0$$

$$v_{s2} = 0.62 \text{ m}^3/\text{kg}$$

$$p_2 = 100 \text{ kPa}$$

$$V_2 = 300 \text{ m/sec}$$

$$Q = \text{total heat loss}$$

$$= 9 \text{ kJ/kg (-ve)}$$

We have SFEE is,

$$q_{1-2} - W_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$\frac{Q_{12}}{m} - \frac{W_{12}}{m} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$\frac{-9 \times 10^3}{1} - \frac{(140 \times 10^3)}{1} = (h_2 - h_1) + \frac{300^2 - 16^2}{2} + 9.81[0 - 32]$$

$$\therefore (h_2 - h_1) = 104441.92 \text{ J/kg}$$

$$(u_2 + p_2 v_2 - (u_1 + p_1 v_1)) = 104441.92$$

$$\therefore (u_2 - u_1) = 104441.92 - p_2 v_2 + p_1 v_1$$

$$= 104441.92 - 100 \times 10^3 \times 0.62 + 600 \times 10^3 \times 0.37$$

$$\therefore u_2 - u_1 = 264441.7 \text{ (or } 264.4 \text{ kJ (in drop))}$$

PROB Steam enters a steam condenser with an enthalpy of 2090 kJ/kg and velocity of 510 m/sec. The condensate leaves the condenser with an enthalpy of 209 kJ/kg and with a velocity of 10 m/sec. determine the heat received by cooling water per kg of steam condensed.

SOL: Given, $h_1 = 2090 \text{ kJ/kg}$ The SFEE is
 $v_1 = 510 \text{ m/sec}$
 $h_2 = 209 \text{ kJ/kg}$
 $v_2 = 10 \text{ m/sec}$

$$q_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$\therefore q_{1-2} = (209 - 2090) + \frac{10^2 - 510^2}{2}$$

$$\therefore \text{Heat rejected from steam} = -2011 \text{ kJ/kg} \checkmark$$

PROB A gas leaving the turbine jet engine flows steadily into the jet pipe with an enthalpy 960 kJ/kg and velocity 250 m/sec. The exit from the pipe is at enthalpy 860 kJ/kg and exhaust is in line with intake. Neglect heat losses from the system; determine the velocity of the gas leaving the pipe.

SOL: Given, $h_1 = 960 \text{ kJ/kg}$ The SFEE is
 $v_1 = 250 \text{ m/sec}$
 $h_2 = 860 \text{ kJ/kg}$
 $v_2 = ?$

$$q_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + 0$$

$$= (860 - 960) \times 10^3 + \frac{V_2^2 - 250^2}{2}$$

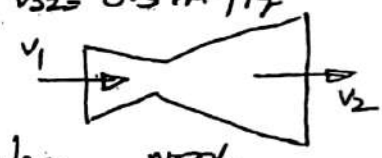
$$\therefore v_2 = 512.34 \text{ m/sec}$$

PROB One kg of fluid enters a nozzle with a velocity of 300 m/min and enthalpy of 2990 KJ/kg. The enthalpy of fluid at exit is 2760 KJ/kg. The nozzle is placed horizontally and neglect heat loss from the nozzle.

- Determine
- (a) The Velocity of the fluid at the exit
 - (b) The mass flow rate, if the area of the nozzle is 0.095 m² and the specific volume at inlet is 0.19 m³/kg.
 - (c) The exit area of the nozzle, if specific volume at exit is 0.5 m³/kg.

SOL: Given, $m = 1 \text{ kg}$
 $V_1 = 300 \text{ m/min} = 5 \text{ m/sec}$
 $h_1 = 2990 \text{ KJ/kg}$
 $h_2 = 2760 \text{ KJ/kg}$

$A_1 = 0.095 \text{ m}^2$
 $v_{s1} = 0.19 \text{ m}^3/\text{kg}$
 $v_{s2} = 0.5 \text{ m}^3/\text{kg}$



i) Exit velocity,

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

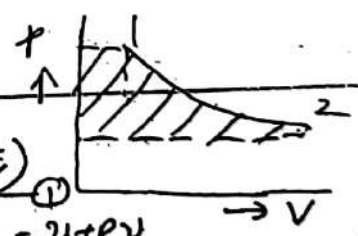
$$= \sqrt{5^2 + 2(2990 - 2760)10^3} = 678 \text{ m/sec}$$

ii) Mass flow rate, $m = \frac{A_1 V_1}{v_{s1}} = \frac{0.095 \times 5}{0.19} = 2.5 \text{ kg/sec}$

iii) Exit area A_2 ; $m = \frac{A_2 V_2}{v_{s2}}$; $A_2 = \frac{m v_{s2}}{V_2} = \frac{2.5 \times 0.5}{678} = 0.00184 \text{ m}^2$

Work done in a steady flow process

We know that the steady flow equation for unit mass flow, the differential form is



$\delta q - \delta w = dh + d(ke) + d(pe)$ ①

We also know that, $h = u + pv = u + pu$

differentiating the expression, $dh = du + d(pv) = du + v dp + p dv$

According to first law, $\delta q - \delta w = du + v dp + p dv$

$\delta q = du + p dv$

Substituting the dh value in equation ①,

$\delta q - \delta w = \delta q + v dp + d(ke) + d(pe)$ ②

neglecting ke and pe .

The equation ② becomes, $-\delta w = v dp$

$\therefore \delta w = -v dp$
 on integrating $W = -\int_1^2 v dp$

Work done for various steady flow processes

32

① Constant volume process,

$$W_{1-2} = - \int_1^2 v dp = -v(p_2 - p_1) = v(p_1 - p_2)$$

② Constant pressure process

$$W_{1-2} = - \int_1^2 v dp = v(p_1 - p_2) = 0 \text{ since } p_1 = p_2.$$

③ Constant temperature process ($p_1 v_1 = p_2 v_2 = p v$).

$$\begin{aligned} W_{1-2} &= - \int_1^2 v dp = \int_1^2 \frac{p_1 v_1}{p} dp = -p_1 v_1 \int_1^2 \frac{dp}{p} \\ &= -p_1 v_1 [\ln p_2 - \ln p_1] = p_1 v_1 \ln \frac{p_1}{p_2} = p_1 v_1 \ln \frac{v_2}{v_1} \end{aligned}$$

④ Adiabatic process: - $p v^\gamma = p_1 v_1^\gamma = p_2 v_2^\gamma = c$; $v = v_1 \left(\frac{p_1}{p}\right)^{\frac{1}{\gamma}}$

$$\begin{aligned} W &= - \int_1^2 v dp = - \int_1^2 v_1 \left(\frac{p_1}{p}\right)^{\frac{1}{\gamma}} dp \\ &= v_1 p_1^{\frac{1}{\gamma}} \int_1^2 p^{-\frac{1}{\gamma}} dp = -v_1 p_1^{\frac{1}{\gamma}} \left[\frac{p^{-\frac{1}{\gamma} + 1}}{-\frac{1}{\gamma} + 1} \right]_1^2 \\ &= \frac{\gamma}{\gamma - 1} v_1 p_1^{\frac{1}{\gamma}} [p_2^{\frac{\gamma-1}{\gamma}} - p_1^{\frac{\gamma-1}{\gamma}}] \\ &= \frac{\gamma}{\gamma - 1} (p_1 v_1 - p_2 v_2) \checkmark \end{aligned}$$

⑤ polytropic process

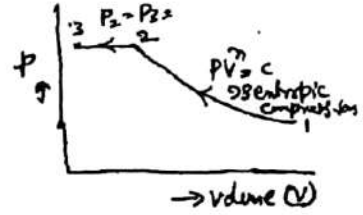
$$p_1 v_1^n = p_2 v_2^n = p v^n = c$$

$$W_{1-2} = \frac{n}{n-1} (p_1 v_1 - p_2 v_2)$$

PROB A cylinder contains 0.115 m^3 of gas at 1 bar and 90°C . The gas is compressed to a volume 0.0288 m^3 , the final pressure being 5.67 bar. calculate (i) mass of the gas (ii) value of index of compression (iii) increase in internal energy of the gas (iv) heat transfer during compression.

After above compression, gas is to be cooled at constant pressure to its original temperature of 90°C , find work of compression required. Assume, $\gamma = 1.4$ and $R = 0.3 \text{ kJ/kg K}$.

SOL Given, $V_1 = 0.115 \text{ m}^3$, $P_1 = 1 \text{ bar}$, $T_1 = 90 + 273 = 363 \text{ K}$
 $V_2 = 0.0288 \text{ m}^3$, $P_2 = 5.67 \text{ bar}$, $\gamma = 1.4$; $R = 0.3 \text{ kJ/kg K}$.



(i) mass of the gas (m) we know, $P_1 V_1 = mRT$

$$m = \frac{P_1 V_1}{RT_1} = \frac{1 \times 10^5 \times 0.115}{0.3 \times 1000 \times 363} = 0.1056 \text{ kg}$$

(ii) Value of index of compression (n):
 $P_1 V_1^n = P_2 V_2^n$

$$n = \frac{\log_e P_2/P_1}{\log_e V_1/V_2} = \frac{\log_e \frac{5.67}{1}}{\log_e \frac{0.115}{0.0288}} = 1.253$$

(iii) Increase in internal energy (ΔU)
 For polytropic compression, $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$; $T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{\gamma-1} = 363 \left[\frac{0.115}{0.0288}\right]^{1.4-1} = 515.17 \text{ K}$

$$\Delta U = m C_v [T_2 - T_1] = m \frac{R}{\gamma-1} (T_2 - T_1) = 0.1056 \times \frac{0.30}{1.4-1} [515.17 - 363] = 12.05 \text{ kJ}$$

(iv) Heat Transfer (Q) $Q = \Delta U + W$; $W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\gamma-1} = \frac{1 \times 0.115 - 5.67 \times 0.0288}{1.253-1} \times 10^5 = -19.05 \text{ kJ}$

$$\therefore Q = 12.05 - 19.05 = -7 \text{ kJ}$$

(v) After compression, it is required to cool gas to original temp. of 90°C , $T_3 = T_1$

$\frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_1}$; $P_2 = P_3$; $V_3 = V_2 \times \frac{T_1}{T_2} = 0.0288 \times \frac{363}{515.17} = 0.0202 \text{ m}^3$

Additional work required, $W = P_2 [V_3 - V_2] = 5.67 \times 10^5 [0.0202 - 0.0288] = -4.87 \text{ kJ}$

PROB 2 Define the first laws of Thermodynamics and discuss why it is known as law of conservation of energy.

SOL First law of Thermodynamics states that "heat and work are mutually convertible". It can also be stated as whenever a system undergoes a cyclic process, the net heat supplied to the system is equal to the net work done by the system. Mathematically, $\oint \delta Q = \oint \delta W$. The above statement valid for system undergoing cycles.

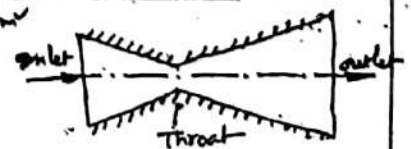
For a system undergoing change of state where both heat and work transfer takes place, the net energy is stored in the system in the form of internal energy.

Mathematically, $Q - W = \Delta U$ where $Q =$ Heat supplied to system, $W =$ Work done by system, $\Delta U =$ change in internal energy.

Therefore, energy is conserved in this operation, it leads to a conclusion that, First law of thermodynamics is just another statement of law of conservation of energy and perfectly goes by the statement that "the energy neither be created nor destroyed but changes one form to another form."

PROB A nozzle receives 1200 kg/hr of steam at 1.3 MN/m^2 , specific volume 142 lit/sec kg , internal energy 4400 kJ/kg and negligible speed. At exit, the pressure is 100 kN/m^2 , specific volume, 1660 lit/kg and internal energy 2200 kJ/kg . calculate exit velocity of steam.

SOL mass of steam, $m = 1200 \text{ kg/hr}$; $P_1 = 1.3 \text{ MN/m}^2 = 1.3 \times 10^6 \text{ N/m}^2$
 $v_{s1} = 142 \text{ lit/sec kg} = 142 \times 10^{-3} \text{ m}^3/\text{kg}$; $u_1 = 4400 \text{ kJ/kg}$
 similarly, $P_2 = 100 \text{ kN/m}^2 = 100 \times 10^3 \text{ N/m}^2$; $v_{s2} = 1660 \text{ lit/kg} = 1.66 \text{ m}^3/\text{kg}$
 $u_2 = 2200 \text{ kJ/kg}$



SPEE for nozzle, $g(h_1 - h_2) = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$

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

$$\therefore \text{since } h_1 = u_1 + P_1 v_{s1} = 4400 \times 10^3 + 1.3 \times 10^6 \times 142 \times 10^{-3} = 4584600 \text{ J/kg}$$

$$h_2 = u_2 + P_2 v_{s2} = 2200 \times 10^3 + 100 \times 10^3 \times 1660 \times 10^{-3} = 2366000 \text{ J/kg}$$

Exit velocity; $V_2 = \sqrt{2(h_1 - h_2)} = \sqrt{2(4584600 - 2366000)} = 2106 \text{ m/sec}$

Prob Show that energy is a property of the system.

Sol Consider a system undergoing a change of state 1 to 2 along path A. ↑

Thus complete cycle 1-A-2-B-1, Applying first law for cyclic process,

$$\int_1^2 \delta Q_A + \int_2^1 \delta Q_B = \int_1^2 \delta W_A + \int_2^1 \delta W_B; \int_1^2 \delta Q_A - \int_1^2 \delta Q_B = \int_1^2 \delta W_A - \int_1^2 \delta W_B, \text{ cyclic process}$$

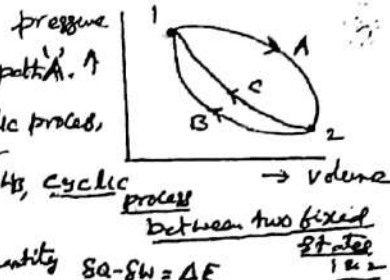
By re-arranging, we get

$$\int_1^2 \delta Q_A - \int_1^2 \delta W_A = \int_1^2 \delta Q_B - \int_1^2 \delta W_B;$$

$$\therefore \Delta E_A = \Delta E_B$$

$$\text{Similarly } \Delta E_A = \Delta E_C,$$

The change in energy does not depend on path followed but only depends on state 1 and 2.



Prob A closed system undergoes a reversible process at a constant pressure process of 3.5 bar and its volume changes from 0.15 m³ to 0.06 m³. 25 kJ of heat is rejected by system during the process. Determine the change in internal energy of the system.

Sol Pressure, $p_1 = p_2 = 3.5 \text{ bar} = 3.5 \times 10^5 \text{ N/m}^2$; $V_1 = 0.15 \text{ m}^3$, $V_2 = 0.06 \text{ m}^3$

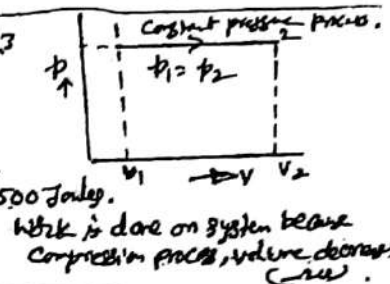
$$\text{Heat rejected by system, } Q = -25 \text{ kJ} = -25 \times 10^3 \text{ J}$$

$$\text{Workdone, } W_{1-2} = p[V_2 - V_1] = 3.5 \times 10^5 [0.06 - 0.15]$$

$$= -31,500 \text{ Joules.}$$

According to First law, $Q = \Delta U + W$; $-25 \times 10^3 = \Delta U + (-31,500)$

$$\therefore \Delta U = 6,500 \text{ Joules.}$$



Work is done on system because compression process, volume decreases.

Prob What do you understand by thermometric property and thermometric substance?

Sol The measurement of temperature depends on establishment of thermal equilibrium between a system and the device used to measure the temperature.

Thermometric property:- The sensing device should have at least one measurable physical property, that changes with change in temp. Such a property called Thermometric property.

Thermometric substance:- The substance which shows changes in thermometric property, called Thermometric substance, at its reference body like thermocouple, thermometer.

S.No.	Physical Property	Thermometric substance (Application)
1.	Pressure, P	Constant volume gas thermometer
2.	Volume, V	Constant pressure gas thermometer
3.	Resistance, R	Electrical resistance thermometer
4.	Thermal emf, E	Thermo-couple
5.	Length, l	Mercury-in-glass thermometer

Prob What are the different scales of temperature? Establish a relationship between centigrade scale & Fahrenheit scale.

Sol **Temperature Scale**:- To measure the temp. of a system, some numerical values are assigned on the thermometer, these numerical values on thermometer together called temp. scale.

Scale of temperature between two fixed points is one is melting point and other boiling point at 1 atmosphere.

$$t = a \cdot t_c + b$$

There are 4 different scales: (i) Centigrade scale (ii) Fahrenheit scale (iii) Absolute Kelvin scale (iv) Reamur scale

(i) **Centigrade (or) Celsius scale**:- On this, melting point of ice marked as 0°C and boiling point of water at 100°C, under atmospheric pressure. It is divided into 100 equal parts, denoted by °C.

$$t = a \cdot t_c + b \quad \text{--- (1)}$$

$$0 = a \cdot 0 + b \quad \text{--- (2)}$$

$$100 = a \cdot 100 + b \quad \text{--- (3)}$$

$$\text{From (2) \& (3), } a = \frac{100}{100-0}; \quad b = -a \cdot 0 = -\frac{100 \cdot 0}{100-0}$$

$$\therefore t_c = a \cdot t_c + b = \frac{100}{100-0} \cdot t_c - \frac{100 \cdot 0}{100-0} = \frac{100(t_c - 0)}{(100-0)} \quad \checkmark$$

(ii) **Fahrenheit scale (°F)**: 32°F & 212°F are ice point & steam point respectively.

$$t = a \cdot t_f + b \quad \text{--- (1)}$$

$$32 = a \cdot 0 + b \quad \text{--- (2)}$$

$$212 = a \cdot 100 + b \quad \text{--- (3)}$$

$$\text{From (2) \& (3), } a = \frac{180}{100-0}; \quad b = 32 - \frac{180 \cdot 0}{100-0}$$

$$t_f = a \cdot t_c + b = \frac{180}{100-0} \cdot t_c + 32 - \frac{180 \cdot 0}{100-0} = \frac{180(t_c - 0)}{(100-0)} + 32 \quad \checkmark$$

$$\text{Relation between } ^\circ\text{C} \text{ \& } ^\circ\text{F} \text{ are; } t_f = 180 \frac{(t_c - 0)}{(100-0)} + 32 = 180 \times \frac{t_c}{100} + 32 = \frac{9}{5} t_c + 32$$

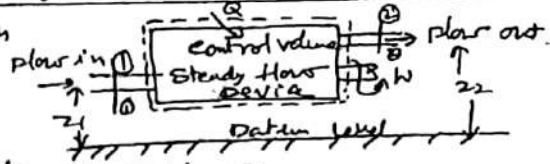
Prob What is Mechanical equivalent of heat?

Sol Joule's experiment concluded that there exists a relationship between heat and work, and both are two forms of energy. Joule conducted experiments with different amounts of work with various systems, and concluded that the work input is always proportional to the heat transferred from the system. $W \propto Q$ (or) $W = JQ$ where, J = constant of proportionality called Joule's constant.

$$\text{Sign S.I units; } J = 1$$

PROB Derive the expression for steady flow energy equation

SOL Consider an open system through which the working substance flows at a steady rate as shown in figure. The working substance enters at section ① and leaves system at section ②.



Let p_1 = pressure of working substance entering the system, N/m^2
 v_{s1} = specific volume " " " " , m^3/kg
 V_1 = velocity of working substance " " " " , m/sec
 u_1 = specific internal energy of working substance at inlet, J/kg
 z_1 = Height above datum level for inlet in metres.

Similarly p_2, v_{s2}, V_2, u_2 & z_2 are corresponding values at exit

Let Q_{1-2} = Heat supplied into system J/kg
 W_{1-2} = Work delivered by the system, J/kg .

Total energy of the system entering per kg working substance = Total energy per kg at exit

$$e_1 = e_2$$

$$\frac{u_1 + p_1 v_{s1}}{m_1} + \frac{V_1^2}{2} + g z_1 + Q_{1-2} = \frac{u_2 + p_2 v_{s2}}{m_2} + \frac{V_2^2}{2} + g z_2 + W_{1-2}$$

$$\therefore Q_{1-2} - W_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

PROB A blower handles $1 kg/sec$ of air at $20^\circ C$ and consumes $1.5 kW$. Its inlet and outlet velocities of air are $100 m/sec$ and $150 m/sec$ respectively. Find the exit air temperature. Assume adiabatic conditions ($Q=0$)

SOL Power consumed, $W = -15 kW$ ($-ve$)

SFEE, $Q_{1-2} - W_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$

$$\frac{Q_{1-2}}{mass} - \frac{W_{1-2}}{mass} = (h_2 - h_1) + \frac{150^2 - 100^2}{2}$$

$$- (-15) \times 10^3 = (h_2 - h_1) + \frac{150^2 - 100^2}{2}$$

$$\therefore (h_2 - h_1) = m c_p [T_2 - T_1] = 8750 \text{ J/kg}$$

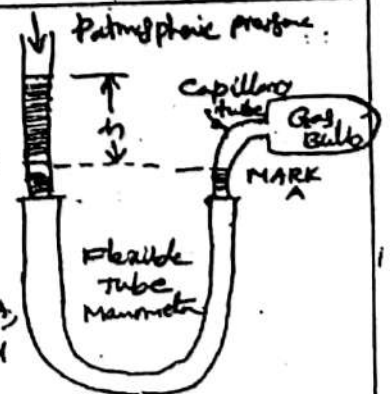
$$= 1 \times 1.005 \times 10^3 [T_2 - (20 + 273)] = 8750$$

Exit Air temp: $T_2 = 301.706 K$ (or) $28.7^\circ C$

PROB Explain the working of constant volume gas thermometer.

SOL The thermometer consists of (i) bulb consists of fixed mass of ideal gas (ii) capillary tube (iii) U-tube manometer.

During operation, the bulb gas bulb communicates with a constant temp. bath. Due to heat exchange between bath and bulb, heat transfer to the gas in bulb takes place and gas will expand and pushes mercury below Mark A. By adjusting flexible tube up to Mark A, the difference in level of mercury in two limbs (h) recorded



$$\therefore p = p_{atm} + \rho g h$$

Firstly, the gas bulb is placed at triple point temperature ($273.15 K$) and p_{tp} is calculated. [$p_{tp} = p_{atm} + \rho g h_{tp}$]. Now, the bulb is brought in contact with a system whose temp (T) is to be measured and measure p .

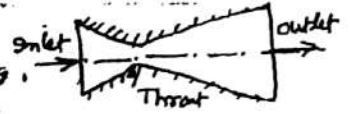
$$\therefore \text{The new temperature, } T = 273.15 \times \frac{p}{p_{tp}}$$

2. (a) Define First law of Thermodynamics and What are the limitations of first law of thermodynamics?
 (b) A nozzle receives 1200 kg/hr of steam at 1.3 MN/m², specific volume 142lit/kg, internal energy 4400 kJ/kg and negligible speed .At the exit ,the pressure is 100 kN/m²,specific volume 1660 lit/kg and internal energy 2200 kJ/kg. Calculate the exit velocity of the steam.

SOL (a) First law states that "heat and work are mutually convertible". It can be also stated that as whenever a system undergoes a cyclic process, the net heat supplied to system is equal to net work done by system. Mathematically, $\oint \delta Q = \oint \delta W \rightarrow$ The statement valid for systems undergoing cyclic processes. For systems undergoing change of state (or process) where heat and work transfer takes place, the net energy (ΔU) is stored in the form of internal energy. Mathematically, $Q - W = \Delta U$. Where, Q = Heat supplied to the system, W = work done by system, ΔU = change in internal energy. Therefore, energy is conserved [Converted from Q to W]. Therefore, it is called Law of Conservation of energy.

LIMITATIONS OF First Law: ① Limitation on conversion of one form of energy to other form ② According to 1st law, no restriction on direction of flow of work and heat, which is not true in reality ③ Work can be completely into heat but reverse is not possible completely. ④ Heat can not flow from cold body to hot body without external work. ⑤ Gas expands from high pressure to low pressure. But reverse is not automatically true.

SOL (b) Given, $m = 1200 \text{ kg/hr}$, $p_1 = 1.3 \text{ MN/m}^2 = 1.3 \times 10^6 \text{ N/m}^2$
 specific volume, $v_{s1} = 142 \text{ lit/kg} = 142 \times 10^{-3} \text{ m}^3/\text{kg}$, $u_1 = 4400 \text{ kJ/kg} = 4400 \times 10^3 \text{ J/kg}$
 Similarly, $p_2 = 100 \text{ kN/m}^2 = 100 \times 10^3 \text{ N/m}^2$, $v_{s2} = 1660 \times 10^{-3} \text{ m}^3/\text{kg}$, $u_2 = 2200 \times 10^3 \text{ J/kg}$.



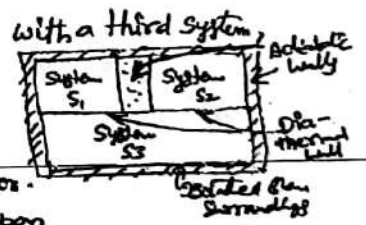
According to SFEE, $g v_1^2 - g v_2^2 = (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1)$; $v_2 = \sqrt{v_1^2 + 2(h_1 - h_2)}$
 since $h_1 = u_1 + p_1 v_{s1} = 4400 \times 10^3 + 1.3 \times 10^6 \times 142 \times 10^{-3} = 4584600 \text{ J/kg}$, $h_2 = u_2 + p_2 v_{s2} = 2200 \times 10^3 + 100 \times 10^3 \times 1660 \times 10^{-3} = 2366000 \text{ J/kg}$.
 \therefore Exit velocity, $v_2 = \sqrt{2(h_1 - h_2)} = \sqrt{2(4584600 - 2366000)} = 2106 \text{ m/sec}$.

2. (a) What is the Zeroth law of Thermodynamics? Explain how it is applied for the measurement of temperature.

(b) Define the thermometric property? Explain the working of constant volume thermometer.
 (c) Establish the correlation between Centigrade and Fahrenheit scale

SOL (a)

It states that when two systems are in thermal equilibrium with a third system, then they mutually have thermal equilibrium with each other. If systems S₁ and S₂ are individually in thermal equilibrium with a third system S₃, then systems S₁ & S₂ also in equilibrium with each other.



Measurement of Temperature

The measurement of temperature depends upon establishment of thermal equilibrium between a system and a the sensing device to measure temperature.

SOL (b) THERMOMETRIC PROPERTY: The sensing device should have atleast one measurable property that changes with change in temperature called thermometric property.

Ex- change in dimension, change in electrical resistance, Thermoelectric emf, change in length of

Constant Volume Gas Thermometer consists of (i) Bulb consists of fixed mass of ideal gas.

(ii) Capillary tube (iii) U-tube manometer.

During operation, Gas bulb communicates with constant temp bath.

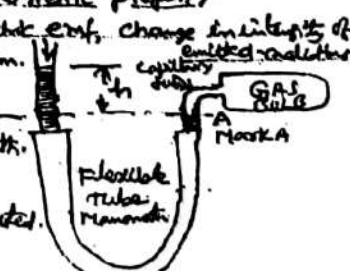
Due to heat transfer, gas expands pushes mercury below Mark A.

By adjusting flexible tube; mercury again up to Mark A, difference 'h' noted.

$p = p_{atm} + \rho g h$

Firstly, the gas bulb placed placed at Triple point (273.15K); $p = p_{atm} + \rho g h_{tp}$

Now, The gas bulb at unknown temp. bath, pressure measured, $p = p_{atm} + \rho g h$.



SOL (c)

Centigrade Scale:

Melting point 0°C; Boiling point 100°C at atmospheric pressure & water. It is divided into 100 equal parts.

$t = a_1 t_1 + b$ ①; $0 = a_1 \cdot 0 + b$ ②; $100 = a_1 \cdot 100 + b$ ③; By solving ② & ③, $a_1 = \frac{100}{100}$; $b = -\frac{100 \cdot 0}{100 - 0}$

Fahrenheit Scale:

Melting point 32° & Boiling point 212°F

$t = a_2 t_2 + b$ ④; $32 = a_2 \cdot 0 + b$ ⑤; $212 = a_2 \cdot 100 + b$ ⑥; By solving ⑤ & ⑥, $a_2 = \frac{180}{100}$; $b = 32 - \frac{180 \cdot 0}{100}$

Relation between 2 scales: $t_{°F} = \frac{180}{100} t_{°C} + 32$; $t_{°C} = \frac{180}{5} t_{°F} - 32$

2. A cylinder contains 0.115 m^3 of gas at 1 bar and 90°C . The gas is compressed to a volume 0.0288 m^3 , the final pressure being 5.67 bar. Calculate

- (i) The mass of the gas
- (ii) The value of index of compression
- (iii) The increase in internal energy of the gas
- (iv) The heat transferred during the process

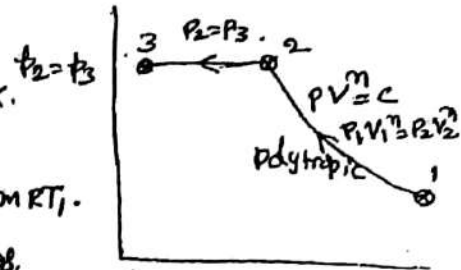
Take, $\gamma = 1.4$; $R = 0.3 \text{ kJ/kgK}$.

$$C_V = \frac{R}{\gamma - 1}; C_P = \frac{\gamma R}{\gamma - 1}$$

If, after above compression, the gas is to be cooled at constant pressure to its original temperature of 90°C , find the work of compression required

Sol: Given, initial volume, $V_1 = 0.115 \text{ m}^3$
 initial pressure, $p_1 = 1 \text{ bar}$, $T_1 = 90 + 273 = 363 \text{ K}$.

Final Volume, $V_2 = 0.0288 \text{ m}^3$, $p_2 = 5.67 \text{ bar}$.



(a) **MASS OF THE GAS (m):** - we know Equation of state, $pV = mRT_1$.

$$\therefore m = \frac{p_1 V_1}{R T_1} = \frac{(1 \times 10^5) \times 0.115}{(0.3 \times 1000) \times 363} = 0.104 \text{ kg}$$

(b) **Value of index of compression (n):** $p_1 V_1^n = p_2 V_2^n$; $n = \frac{\log_e (p_2/p_1)}{\log_e (V_1/V_2)} = \frac{\log_e (5.67/1)}{\log_e (0.115/0.0288)} \rightarrow \text{Volume}$

(c) **Increase in Internal energy:** - (ΔU)

we know, $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1}$; $T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{n-1} = 363 \left(\frac{0.115}{0.0288}\right)^{1.253-1} = 515.17 \text{ K}$

$\therefore \Delta U = \text{change in Internal energy} = m c_v (T_2 - T_1) = m \left(\frac{R}{\gamma - 1}\right) (T_2 - T_1)$
 $= 0.1056 \times 0.3 \frac{(515.17 - 363)}{1.4 - 1} = 12.0 \text{ kJoule}$

(d) **Heat Transfer (Q)**

$Q = \Delta U + W$; $W = \frac{p_1 V_1 - p_2 V_2}{\gamma - 1} = \frac{(1 \times 0.115 - 5.67 \times 0.0288) \times 10^5}{1.253 - 1} = -19,089 \text{ J} = -19.09 \text{ kJ}$
 (=ve) work done on system.

AFTER COMPRESSION, IT IS REQUIRED TO COOL GAS TO ORIGINAL TEMPERATURE OF 90°C ($T_3 = T_1$)

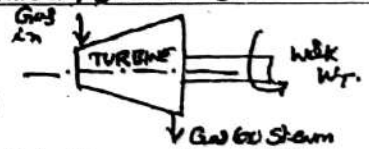
\therefore PROCESS (2-3) $\frac{p_2 V_2}{T_2} = \frac{p_3 V_3}{T_3 = T_1} \Rightarrow p_2 = p_3$; $\therefore V_3 = V_2 \frac{T_2}{T_1} = \frac{363 \times 0.0288}{515.17} = 0.0202 \text{ m}^3$

\therefore Additional work required, $W_{2-3} = p_2 [V_3 - V_2] = 5.67 \times 10^5 [0.0202 - 0.0288] = -4,870 \text{ J} = -4.87 \text{ kJ} (=ve)$

2. (a) Derive the steady flow energy equations for steam turbine and rotary compressor.
- (b) The gas leaving the turbine jet engine flows steadily in to the jet pipe with enthalpy 800 kJ/kg and velocity 123 m/s. The exit from the pipe is at enthalpy 450 kJ/kg, and exhaust in line with intake. Neglect heat losses from the system determine the velocity gas leaving the pipe.

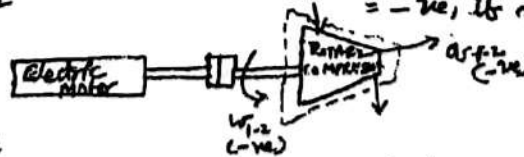
(a) **SOLUTION:**

STEAM TURBINE: - In steam turbine, steam (or) gas is passed through turbine, converted into work. The steam leaves with low pressure and low temperature.



$q_{1-2} - w_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$; Here $q_{1-2} = 0$, $z_1 = z_2$, $z_1 = z_2$ if not regulated. $= -ve$, its not regulated.

ROTARY COMPRESSOR: -



A rotary compressor is a machine which compresses air (or) gas and supplies at high pressure in large quantity.

In compressor, $q_{1-2} = -ve$ (heat rejected by system)
 $w_{1-2} = -ve$ (work supplied to system).

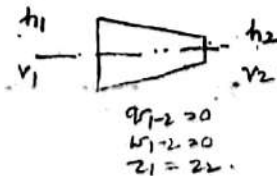
$q_{1-2} - w_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \Rightarrow -q_{1-2} - (-w_{1-2}) = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2}$

(b) **SOLUTION:** - Given, $h_1 = 800 \text{ kJ/kg} = 800 \times 10^3 \text{ J/kg}$, $V_1 = 123 \text{ m/sec}$; $h_2 = 450 \text{ kJ/kg} = 450 \times 10^3 \text{ J/kg}$.

According to SFEE, $q_{1-2} - w_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$

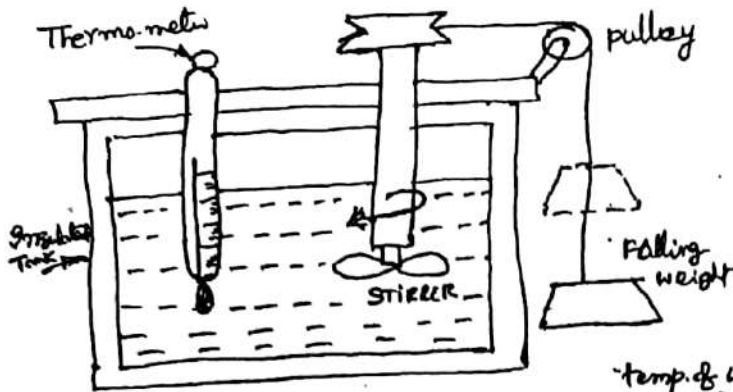
$0 = 0 = (860 - 760) \times 10^3 + \frac{V_2^2 - 250^2}{2}$

$\Rightarrow V_2 = 512.74 \text{ m/sec}$



UNIT-2

Explain Joule's experiments with suitable sketches.



Joule conducted several experiments which led to the formulation of first law.

When weight is allowed to fall to a certain distance, work is done on water through rotation of stirrer. When stirrer rotates inside the water, heat is produced due to friction and is measured by rise in

temp. of water. Further, insulation from tank was removed and the whole system placed in water bath.

The heat transferred from the system in order to bring some initial conditions.

Whenever a closed system undergoes a cycle, the work input to the system is proportional to the net heat output.

$$\oint \delta W = \oint \delta Q \quad (\text{or}) \quad \oint \delta W = \oint \delta Q \quad T = 1 \text{ in SI units.}$$

PROB. Air flows steadily at the rate of 0.5 kg/sec through an air compressor, entering at 7 m/sec velocity, 100 kPa pressure and 0.95 m³/kg volume, and leaving at 5 m/s, 700 kPa and 0.19 m³/kg. The internal energy of air leaving is 90 kJ/kg greater than that of the air entering. Cooling water in the compressor jacket absorbs heat from the air at the rate of 58 kW. Compute the rate of shaft work input to the air in kW and find

SOL. At inlet, $m = 0.5 \text{ kg/sec}$
 velocity $V_1 = 7 \text{ m/sec}$
 pressure, $P_1 = 100 \text{ kPa} = 100 \times 10^3 \text{ Pa}$
 specific volume, $v_{s1} = 0.95 \text{ m}^3/\text{kg}$

At exit; $v_2 = 5 \text{ m/s}$; $P_2 = 700 \times 10^3 \text{ Pa}$, $v_{s2} = 0.19 \text{ m}^3/\text{kg}$

u_2 is greater than u_1 by 90 kJ/kg; so $u_2 - u_1 = 90 \text{ kJ/kg}$.

By applying SPEC; $q_{1-2} - w_{1-2} = (h_2 - h_1) + \frac{1}{2} [v_2^2 - v_1^2] + g(z_2 - z_1)$

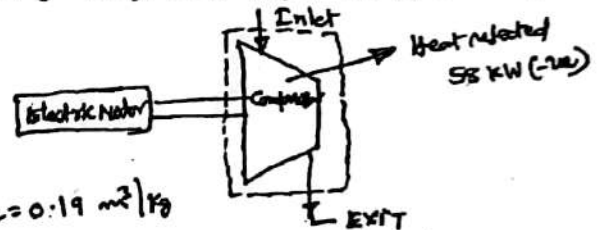
$$\text{here, } q_{1-2} = \frac{Q_{1-2}}{m} = \frac{-58 \times 10^3}{0.5} = -116 \times 10^3 \text{ J/kg (neg)}$$

$$\therefore q_{1-2} - w_{1-2} = (u_2 - u_1) + (P_2 v_{s2} - P_1 v_{s1}) + \frac{1}{2} [v_2^2 - v_1^2] + 0$$

$$-116 \times 10^3 - w_{1-2} = 90 \times 10^3 + (700 \times 10^3 \times 0.19 - 100 \times 10^3 \times 0.95) + \frac{1}{2} [5^2 - 7^2]$$

$$= 90 \times 10^3 + 38 \times 10^3 + (-12)$$

$$\therefore w_{1-2} = 243,988 \text{ W} = 243.98 \text{ kW}$$



PROB. What is steady flow process?

SOL. In steady flow process the flow rate of mass and energy don't vary with time and properties within the system are invariant with time at every point. The analysis of steady flow process is based on the principle of Conservation of energy.

consider an open system through which the working substance flows at a steady rate as shown in figure. The working substance enters at section (1) and leaves system at section (2).

Let p_1 = pressure of working substance entering the system, N/m^2

v_{s1} = sp. volume of working substance entering the system, m^3/kg

V_1 = velocity at inlet, m/sec

e_1 = specific internal energy at inlet, J/kg

z_1 = Height above datum level at inlet in metres.

Similarly, $p_2, v_{s2}, V_2, z_2, z_2'$ are corresponding values at exit.

Let q_{1-2} = Heat supplied into the system, J/kg

w_{1-2} = Work delivered by the system, J/kg

Total energy of the system entering per kg of working substance

= Total energy per kg at exit

$$e_1 = e_2$$

$$e_1 + p_1 v_{s1} + \frac{V_1^2}{2} + g z_1 + q_{1-2} = e_2 + p_2 v_{s2} + \frac{V_2^2}{2} + g z_2 + w_{1-2}$$

$$\therefore q_{1-2} - w_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

PROB. A turbo compressor delivers $2.33 \text{ m}^3/\text{s}$ at 0.276 MPa , 43°C which is heated at this pressure to 430°C and finally expanded in a turbine which delivers 1860 kW . During the expansion there is a heat transfer of 0.09 MJ/s to the surroundings. Calculate the turbine exhaust temperature if changes in KE and PE negligible.

Soln

pressure after compressor, $p_c = 0.276 \times 10^6 \text{ Pa}$

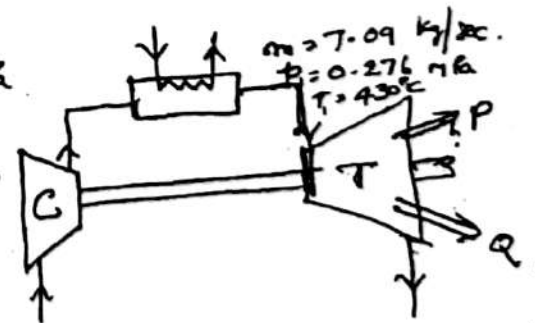
volume flow rate, $V = 2.33 \text{ m}^3/\text{s}$

temperature, $T = 43 + 273 = 316 \text{ K}$

\therefore we know, $pV = mRT$

\therefore mass flow rate, $m = \frac{pV}{RT}$

$$= \frac{0.276 \times 10^6 \times 2.33}{287 \times 316} = 7.09 \text{ kg/sec} \quad [\text{Take, } R = 287 \text{ J/kgK}]$$



power developed by turbine, $P = 1860 \text{ kW}$ (given)

$$\text{power developed by turbine per unit mass, } w_{1-2} = \frac{(1860 \times 10^3)}{m} = \frac{1860 \times 10^3}{7.09} = 262.3 \times 10^3 \text{ J/kg}$$

Heat transfer from turbine, $Q = 0.09 \text{ MJ/s}$

$$\text{Heat transfer from turbine per unit mass, } q_{1-2} = \frac{Q}{m} = \frac{0.09 \times 10^6}{7.09} = 12.64 \times 10^3 \text{ J/kg}$$

Take negative of $q_{1-2} = -12.64 \times 10^3 \text{ J/kg}$

Apply SFEE to the turbine,

$$q_{T-2} - w_{T-2} = (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1) \quad [\because KE \& PE \text{ negligible}]$$

$$\therefore q_{T-2} - w_{T-2} = \dots c_p [T_2 - T_1]$$

$$-12.69 \times 10^3 - 262.3 \times 10^3 = 1.005 \times 10^3 [T_2 - (43 + 273)]$$

$$-274.99 = 1.005 [T_2 - 316]$$

$$\therefore T_2 = -273.63 + 316 = \underline{42.37 \text{ K}} \checkmark$$

PROB. A nozzle is a device for increasing the velocity of a steadily flowing stream. At the inlet to a certain nozzle, the enthalpy of the fluid passing is 3000 kJ/kg and the velocity is 60 m/s . At the discharge end, the enthalpy is 2762 kJ/kg . The nozzle is horizontal and there is negligible heat loss from it. Find the velocity at exit from the nozzle. If the inlet area is 0.1 m^2 and the specific volume at inlet is $0.187 \text{ m}^3/\text{kg}$. Find the mass flow rate.

SOLUTION

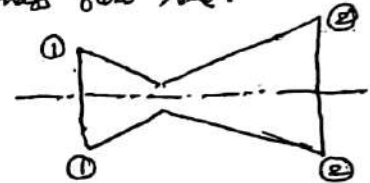
At inlet, $h_1 = 3000 \text{ kJ/kg}$, $v_1 = 60 \text{ m/s}$

At exit, $h_2 = 2762 \text{ kJ/kg}$, $v_2 = ?$

\therefore Apply SFEE to the nozzle, $q_{T-2} - w_{T-2} = (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1)$

$$0 = (2762 - 3000) \times 10^3 + \frac{v_2^2 - 60^2}{2}$$

$$\therefore v_2 = \sqrt{238 \times 10^3 + (60)^2} = \sqrt{238000 + 3600} = 491.5 \text{ m/sec.}$$



mass flow rate, $m = \frac{A_1 v_1}{v_{s1}} = \frac{A_2 v_2}{v_{s2}} = \frac{0.1 \times 60}{0.187} = 32 \text{ kg/sec.}$

PROB. During one cycle, the working fluid in an engine engages in two work interactions: 15 kJ to the fluid and 44 kJ from the fluid, and three heat interactions: two of which are known: 75 kJ to the fluid and 40 kJ from the fluid. Evaluate the magnitude and direction of third heat transfer?

SOL. $w_{1-2} = -15 \text{ kJ}$; $w_{2-3} = 44 \text{ kJ}$; $w_{3-1} = 0$ (No work transfer).

$q_{1-2} = 75 \text{ kJ}$; $q_{2-3} = -40 \text{ kJ}$; $q_{3-1} = ?$ to find.

We know for cyclic process; Apply First law: $\oint \delta w = \oint \delta q$.

$$w_{1-2} + w_{2-3} + w_{3-1} = q_{1-2} + q_{2-3} + q_{3-1}; -15 + 44 = 75 + (-40) + q_{3-1}$$

$$\therefore q_{3-1} = -6 \text{ kJ} \text{ (Heat rejected by the fluid).}$$

PROB. Air at 1 bar is a cylinder compressed isothermally from 85 kPa , 29°C to 380 kPa . The initial volume is 0.423 m^3 . Find heat transfer and change in Entropy of air.

\therefore Heat transfer, $q =$ work required for compression in isothermal process $= p_1 v_1 \ln \frac{p_2}{p_1} = 85 \times 0.423 \ln \frac{380}{85} = -53.8 \text{ kJ}$ (Heat rejected)

change in Entropy $(s_2 - s_1) = \frac{dq}{T} = \frac{p_1 v_1}{T_1} \ln \frac{p_2}{p_1} = \frac{85 \times 0.423}{(29+273)} \ln \frac{380}{85} = -0.178 \text{ kJ/kgK}$

Thermodynamic process table.

S.No:	Thermodynamic process	P-V-T relation	Equi-state work	Change in internal energy	Heat Transfer	Change in Enthalpy	Change in Entropy
1	Constant Volume process	$V_1 = V_2 = C$ (or) $\frac{P_1}{T_1} = \frac{P_2}{T_2}$	$W_{1-2} = 0$	$\Delta U = m C_V [T_2 - T_1]$	$Q = W + \Delta U$ $m C_V [T_2 - T_1]$	$m C_P [T_2 - T_1]$	$m C_V \ln \frac{T_2}{T_1}$
2	Constant pressure process	$P_1 = P_2 = C$ (or) $\frac{V_1}{T_1} = \frac{V_2}{T_2}$	$W_{1-2} = P [V_2 - V_1]$	$m C_V [T_2 - T_1]$	$m C_P [T_2 - T_1]$	$m C_P [T_2 - T_1]$	$m C_P \ln \frac{T_2}{T_1}$
3	Isobaric (or) constant Temperature process	$T_1 = T_2 = C$ $P_1 V_1 = P_2 V_2$	$W_{1-2} = P_1 V_1 \ln \frac{V_2}{V_1}$ $= P_1 V_1 \ln \frac{P_2}{P_1}$	0	$P_1 V_1 \ln \frac{V_2}{V_1}$ $P_1 V_1 \ln \frac{P_1}{P_2}$	0	$m R \ln \frac{V_2}{V_1}$ $m R \ln \frac{P_1}{P_2}$
4	polytropic process	$P_1 V_1^n = P_2 V_2^n = C$ $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{V_1}{V_2}\right)^{n-1}$	$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n-1}$ (or) $m R \frac{C_V (T_1 - T_2)}{n-1}$	$m C_V [T_2 - T_1]$	$\frac{\gamma-1}{\gamma} \times W_{1-2}$	$m C_P [T_2 - T_1]$	$\frac{\gamma-1}{\gamma} m R \ln \frac{V_2}{V_1}$
5	Adiabatic process (or) isentropic process	$P_1 V_1^\gamma = P_2 V_2^\gamma = C$ $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$	$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\gamma-1}$ $= \frac{m R C_V (T_1 - T_2)}{\gamma-1}$	$m C_V [T_2 - T_1]$	0	$m C_P [T_2 - T_1]$	0

UNIT-2: PERFECT GASES

PERFECT GAS:-

Gases which do not change their phase during thermodynamic process and obey Boyle's law, Charles law and characteristic gas equation, are known as ideal (or) perfect gases.

A gas can be modeled as an ideal gas when it has following features.

- 1) It has no intermolecular forces of attraction (or) repulsion
- 2) It does not change its phase during a thermodynamic process.
- 3) It obeys Boyle's, Charles laws and the characteristic gas equation.

The internal energy of gases decreases rapidly with decreasing pressure and disappears when absolute pressure approaches zero. At zero pressure, all real gases behave in a similar manner and the state of identical behaviour is called ideal state.

Ideal gases:- In actual practice, no gas is completely ideal gas, but many gases treated as an ideal gases like Air, Nitrogen, oxygen, hydrogen, helium, argon, neon, krypton, carbon dioxide.

Boyle's law:- volume (or) specific volume of a gas is inversely proportional to absolute pressure
 $v \propto \frac{1}{p}$ (or) $p v = \text{constant}$; If a gas changes its state

Charles law:- The specific volume is directly proportional to absolute temperature.
 $v \propto T$ (or) $\frac{v}{T} = C$; (or) $\frac{v_1}{T_1} = \frac{v_2}{T_2}$ for a gas changes its state.

Equation of state:- It is observed that thermodynamic properties are interrelated.

Any equation that relates the pressure, temperature and specific volume of a substance is known as an equation of state.

$f(p, v, T) = 0$ (or) $p = f(v, T)$; $v = f(p, T)$ (or) $T = f(p, v)$.

Characteristic gas equation:- In any thermodynamic system of an ideal gas, the pressure, temperature and specific volume vary simultaneously. On the basis of the characteristic, an equation is derived with the help of Boyle's and Charles laws.

Boyle's law $v \propto \frac{1}{p}$ when $T = \text{constant}$

Charles law, $v \propto T$ when $p = \text{constant}$

By combining both relations, $v \propto \frac{T}{p}$ (or) $v = \frac{R \cdot T}{p}$

(or) $p v = R T$ where $R = \text{characteristic (or) specific gas constant}$.
 $v = \text{specific volume}$.

(or) $P V = m R T$ $\rightarrow V = \text{Volume of a gas}$.

(or) $P V = m R_u T$ where $m = \text{No. of moles of a gas} = \frac{\text{mass}}{\text{molar wt}}$.
 $R_u = \text{Universal gas constant}$

* $R_u = 8314 \text{ J/kg mol} \cdot \text{K}$.

$R_u = M \cdot R$; $M = \text{molecular mass of any gas}$.

The relationship between two principle specific heats and characteristic gas constant for

a perfect gas: Let us consider a perfect gas being heated from a temperature T_1 to T_2 at constant pressure.

From a non-flow equation $Q = \Delta U + W$

$Q = (u_2 - u_1) + p d v$

$Q = (u_2 - u_1) + p [v_2 - v_1]$; $m c_p (T_2 - T_1) = m c_v (T_2 - T_1) + m R (T_2 - T_1)$ (Heat supplied)



$\therefore \boxed{C_p - C_v = R}$ on dividing both sides by C_v ,

$$\frac{C_p}{C_v} - 1 = \frac{R}{C_v} \quad ; \quad C_v = \frac{R}{\left(\frac{C_p}{C_v} - 1\right)} = \frac{R}{\gamma - 1}$$

Similarly $\frac{C_p}{C_p} = \frac{C_v}{C_p} = \frac{R}{C_p} \quad ; \quad 1 - \frac{1}{\gamma} = \frac{R}{C_p}$

$$\therefore \boxed{C_p = \frac{\gamma R}{(\gamma - 1)}} \quad ; \quad \therefore \boxed{\frac{C_p}{C_v} = \gamma}$$

Relationship between absolute temperature (T) and absolute pressure (P) in Adiabatic process ($PV^\gamma = C$)

The thermodynamic properties for a perfect gas are related as

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad \text{and} \quad \frac{T_2}{T_1} = \frac{P_2 V_2}{P_1 V_1} \quad \text{--- (1)}$$

For an isentropic process, $PV^\gamma = C$ and $P_1 V_1^\gamma = P_2 V_2^\gamma$

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}} = \left(\frac{P_2}{P_1}\right)^{-\frac{1}{\gamma}} \quad \text{--- (2)}$$

Substitute (2) in (1)

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right) \left(\frac{V_2}{V_1}\right) = \left(\frac{P_2}{P_1}\right) \left(\frac{P_1}{P_2}\right)^{-\frac{1}{\gamma}} = \left(\frac{P_2}{P_1}\right)^{1 - \frac{1}{\gamma}} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}$$

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

Similarly ; $P_1 V_1^\gamma = P_2 V_2^\gamma \quad ; \quad \left(\frac{P_1}{P_2}\right) = \left(\frac{V_1}{V_2}\right)^\gamma \quad \text{--- (3)}$

Substitute (3) in (1)

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right) \left(\frac{V_1}{V_2}\right) = \left(\frac{V_1}{V_2}\right)^\gamma \cdot \left(\frac{V_2}{V_1}\right) = \left(\frac{V_1}{V_2}\right)^{\gamma - 1} = \left(\frac{V_1}{V_2}\right)^{\frac{\gamma - 1}{\gamma}}$$

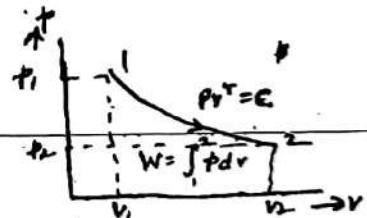
$$\therefore \boxed{\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\frac{\gamma - 1}{\gamma}}}$$

Work done during Adiabatic process The work done during a

non-linear process is expressed as

$$W_{1-2} = \int_1^2 P dV = \int_1^2 \left(\frac{C}{V^\gamma}\right) dV = C \int_1^2 V^{-\gamma} dV$$

$$= C \left[\frac{V^{-\gamma+1}}{-\gamma+1} \right]_1^2 = \frac{C \cdot V_2^{-\gamma+1} - C \cdot V_1^{-\gamma+1}}{-\gamma+1} = \frac{P_2 V_2 - P_1 V_1}{\gamma - 1} = \frac{mR(T_2 - T_1)}{\gamma - 1}$$



Equations for change of entropy of an ideal gas:-

Let 1 kg of gas at a pressure P_1 , volume V_1 , absolute temperature T_1 & Entropy S_1 , be heated to P_2, V_2, T_2 & S_2 respectively. By law of conservation of energy

$$dq = du + dw = C_v dT + P dV$$

Dividing on both sides by T ; $\frac{dq}{T} = C_v \frac{dT}{T} + \frac{P dV}{T}$ [since $\frac{PV}{T} = \frac{R}{C_v}$]

$$ds = C_v \frac{dT}{T} + \frac{R}{V} dV$$

Integrating on both sides, $\int ds = C_v \int \frac{dT}{T} + R \int \frac{dV}{V}$

$$\boxed{S_2 - S_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}} \quad \rightarrow (T, V) \quad \text{--- (1)}$$

Similarly $S_2 - S_1 = C_v \ln \frac{P_2 V_2}{P_1 V_1} + R \ln \frac{V_2}{V_1}$ [$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \Rightarrow \frac{P_2 V_2}{P_1 V_1} = \frac{T_2}{T_1}$]

$$= C_v \ln \frac{P_2}{P_1} + (C_v + R) \ln \frac{V_2}{V_1}$$

$$\boxed{S_2 - S_1 = C_v \ln \frac{P_2}{P_1} + C_p \ln \frac{V_2}{V_1}} \quad \rightarrow (S, V) \quad \text{--- (2)}$$

Similarly $S_2 - S_1 = C_p \ln \frac{T_2}{T_1} + R \ln \frac{P_1}{P_2}$ (T, P) \rightarrow (3)

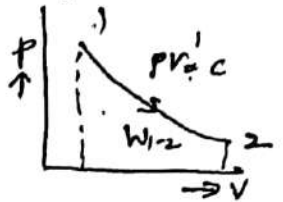
PROB 1.5 Kgs of air at pressure of 6.75 bar occupies a volume of 0.23 m³.
 If this air is expanded to a volume of 1.13 m³, find the workdone and heat absorbed (or) rejected by the air for each of the following methods of carrying out the process (i) isothermally (ii) Adiabatically.

SOL: Mass of air, $m = 1.5$ Kgs.

Initial pressure of air, $P_1 = 6.75$ bar = 6.75×10^5 Pa.

Initial volume of air, $V_1 = 0.23$ m³.

Final volume of air, $V_2 = 1.13$ m³.



(i) Isothermal process

To find final pressure, P_2 ; $P_1 V_1 = P_2 V_2$ for isothermal process.

$$P_2 = \frac{P_1 V_1}{V_2} = \frac{6.75 \times 10^5 \times 0.23}{1.13} = 1.37 \times 10^5 \text{ Pa.}$$

$$\text{Workdone, } W_{1-2} = P_1 V_1 \ln \left(\frac{V_2}{V_1} \right) = 6.75 \times 10^5 \times 0.23 \ln \left(\frac{1.13}{0.23} \right) = 247.14 \text{ KJ/Kg.}$$

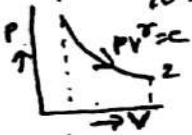
$$\text{Total workdone, } W_{1-2} = \text{mass} \times W_{1-2} = 1.5 \times 247.14 = \frac{370.71 \text{ KJ}}{10^3}$$

$$\text{Heat transfer, } Q = W_{1-2} + \Delta U = W_{1-2} = 370.71 \text{ KJ} \quad [\because \Delta U = 0 \text{ for constant temperature process}]$$

(ii) Adiabatic process

To find final pressure, P_2 ; $P_1 V_1^\gamma = P_2 V_2^\gamma$

$$P_2 = P_1 \left(\frac{V_1}{V_2} \right)^\gamma = 6.75 \times 10^5 \left[\frac{0.23}{1.13} \right]^{1.4} = 0.726 \times 10^5 \text{ bar.}$$



$$\text{Workdone, } W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{(6.75 \times 0.23 - 0.726 \times 1.13) \times 10^5}{10^3} = 183 \text{ KJ/Kg.}$$

$$\text{Total workdone} = \text{mass of air} \times W_{1-2} = 1.5 \times 183 = 274.5 \text{ KJ}$$

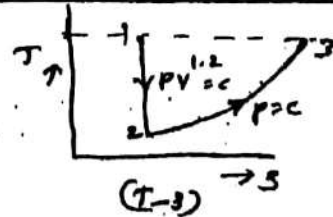
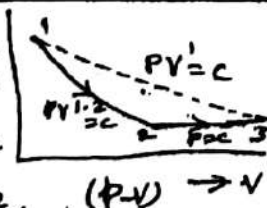
For an Adiabatic process, $Q = 0$.

PROB. A gas occupies 0.034 m³ at 600 KPa and 85°C. It is expanded in the non-flow process according to the law $PV^{1.2} = \text{constant}$ to a pressure of 60 KPa after which it is heated at constant pressure back to its original temperature. Sketch the process on P-V and T-s diagrams and calculate the whole process the workdone, the heat transferred.

Take, $C_p = 1.047$ and $C_v = 0.775$ KJ/KgK for the gas.

SOL:

Take
 $C_p = 1.047$ KJ/KgK
 $C_v = 0.775$ KJ/KgK



Given,
 $P_1 = 600 \text{ KPa} = 600 \times 10^3 \text{ Pa}$
 $V_1 = 0.034 \text{ m}^3$
 $T_1 = 85 + 273 = 358 \text{ K}$
 $P_2 = 60 \text{ KPa} = 60 \times 10^3 \text{ Pa}$
 $P_3 = P_2$
 $T_3 = T_1 = 85^\circ\text{C} = 358 \text{ K}$

Process (1-2) $PV^{1.2} = c$

$$P_1 V_1^{1.2} = P_2 V_2^{1.2}$$

$$V_2 = V_1 \left(\frac{P_1}{P_2} \right)^{1/1.2} = 0.034 \left[\frac{600 \times 10^3}{60 \times 10^3} \right]^{1/1.2} = 0.2316 \text{ m}^3$$

$$W_{1-2} = \int P dV = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{600 \times 10^3 \times 0.034 - 60 \times 10^3 \times 0.2316}{1.2 - 1} = 32,152 \text{ J} = 32.152 \text{ KJ}$$

$$Q_{1-2} = \frac{\gamma - 1}{\gamma} \times W_{1-2} = \frac{1.4 - 1.2}{1.4 - 1} \times 32.152 = 16.26 \text{ KJ.}$$

For process (1-2) $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}}$; $T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} = 358 \left[\frac{60 \times 10^3}{600 \times 10^3} \right]^{\frac{1.2 - 1}{1.2}} = 244 \text{ K.}$

For process (2-3)

$$\frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3}; \quad \frac{V_2}{T_2} = \frac{V_3}{T_3}; \quad V_3 = \frac{T_3}{T_2} \times V_2 = \frac{T_1}{T_2} \times V_2$$

$$V_3 = \frac{T_1}{T_2} \times V_2 = \frac{358}{244} \times 0.2316 = 0.3398 \text{ m}^3$$

Work done in the process (2-3) Constant pressure process

(*)

$$W_{2-3} = P_2 [V_3 - V_2] = 60 \times 10^3 [0.3398 - 0.2315] = 6492 \text{ J} = \underline{6.492 \text{ KJ}}$$

$$Q_{2-3} = m C_p [T_3 - T_2] = 1 \times 1.047 \times [358 - 244] = \underline{119.35 \text{ KJ}}$$

$$\therefore \text{Total Work done, } W_{1-3} = W_{1-2} + W_{2-3} = 32.52 + 6.492 = \underline{39.01 \text{ KJ}}$$

$$\text{Total Heat transferred, } Q_{1-3} = Q_{1-2} + Q_{2-3} = 16.26 + 119.35 = \underline{135.61 \text{ KJ}}$$

Prob A gas in a cylinder fitted with a piston undergoes a cycle composed of three processes. First, the gas expands at constant pressure with a heat addition of 42 KJ and a work output of 12.0 KJ. Then, it is cooled at constant volume by a removal of 48 KJ of heat. Finally, an adiabatic process returns the gas to its initial state. Determine,

- The work of the adiabatic process
- The stored energy of the gas at each of the other two states if its stored energy in the initial state is assigned the value of zero.

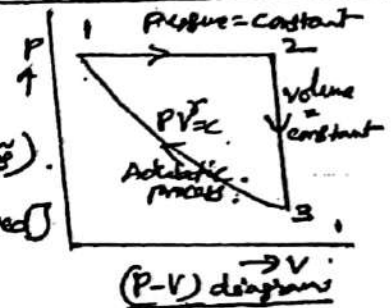
Sol Process (1-2) Constant pressure process :-

Heat addition, $Q_{1-2} = 42.0 \text{ KJ}$ (+ve, heat added to system gas)

Work output, $W_{1-2} = 12.0 \text{ KJ}$ (+ve, work done by system gas)

Process (2-3) constant volume process

Heat removed, $Q_{2-3} = -48 \text{ KJ}$ [-ve, due to heat removed from system]



From process (1-2) $Q_{1-2} = \Delta U_{1-2} + W_{1-2}$

$$\therefore \Delta U_{1-2} = Q_{1-2} - W_{1-2} = 42 - 12 = 30 \text{ KJ}$$

From process (2-3)

$$Q_{2-3} = \Delta U_{2-3} + W_{2-3} = \Delta U_{2-3} + 0 \quad [\because W_{2-3} = 0 \text{ for constant volume}]$$

$$\therefore Q_{2-3} = \Delta U_{2-3} = -48 \text{ KJ}$$

From process (3-1)

Adiabatic work process

$$Q_{3-1} = 0 \text{ for adiabatic process}$$

For cyclic process $\sum F_n$ Three thermodynamic processes [1-2, 2-3, 3-1]

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

$$W_{1-2} + W_{2-3} + W_{3-1} = Q_{1-2} + Q_{2-3} + Q_{3-1}$$

$$12.0 + 0 + W_{3-1} = 42 + (-48.0) + 0$$

$$\therefore W_{3-1} = \text{Adiabatic work} = -18 \text{ KJ} \quad [\text{work is done on the system, compression process}]$$

From process (3-1)

$$Q_{3-1} = W_{3-1} + \Delta U_{3-1}$$

$$\therefore \Delta U_{3-1} = Q_{3-1} - W_{3-1} = 0 - (-18) = 18 \text{ KJ}$$

From process (2-3)

$$Q_{2-3} = W_{2-3} + \Delta U_{2-3}$$

$$\Delta U_{2-3} = -48 \text{ KJ}$$

Since, $U_1 = 0$ (given) ; $\therefore U_2 = U_1 + 30 \text{ KJ} ; U_2 = 30 \text{ KJ}$

$$\Delta U_{2-3} = U_3 - U_2 = -48 \text{ KJ} ; U_3 = -48 + U_2 = -48 + 30 = -18 \text{ KJ}$$

Real Gases:- The ideal gas equation of state, $PV = RT$ can be used with the assumption of no attraction (or) very little attraction force of molecules with in the gas and the volume of molecules is negligibly small compared to volume of gas.

For many gases, at very low pressure & high temperature, the force of attraction and volume of molecules compared to volume of gas are small and real gases obey very close to ideal gas equation.

But at higher pressure, the forces of attraction and volume of molecules are higher (appreciable). Then, the real gas behaviour deviates from ideal-gas behaviour.

Compressibility factor (Z)

The slight modification in the ideal gas equation ($PV = RT$) of state to fit real-gas behaviour with introduction of a correction factor (Z) is called compressibility factor (Z). It is defined as

$$Z = \frac{PV}{RT} = \frac{\text{Actual volume of the gas}}{\text{Volume as predicted by ideal gas equation}} = \frac{V}{\left(\frac{RT}{P}\right)} = \frac{PV}{RT}$$

For an ideal gas, $Z = 1$.

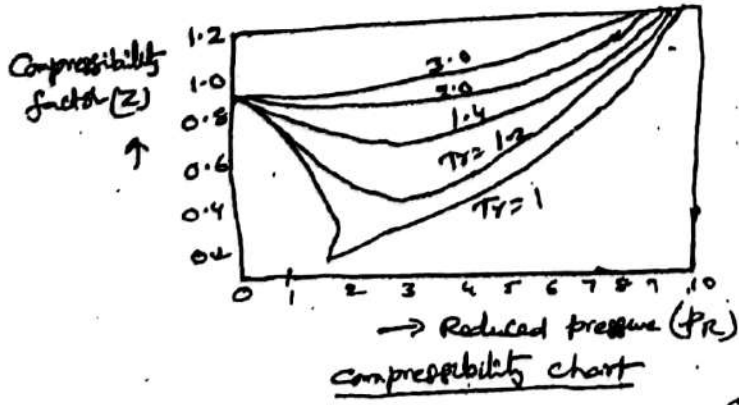
For a real gas Z is a function of pressure and temperature. The real gases behave differently at a given temperature and pressure, but they behave very closely at their reduced pressure and reduced temperature.

Reduced pressure, $P_R = \frac{P_{\text{actual}}}{P_{\text{critical}}} = \frac{P}{P_c}$

Reduced temperature, $T_R = \frac{T_{\text{actual}}}{T_{\text{critical}}} = \frac{T}{T_c}$

Reduced specific volume, $v_R = \frac{v_{\text{actual}}}{v_{\text{critical}}} = \frac{v}{v_c}$

Disadvantage of Compressibility chart factor chart:- That a separate chart is needed for each gas. But at the same reduced co-ordinates, the compressibility factor Z is approximately same for all gases. It is called law of corresponding states. Thus $v_R = f(P_R, T_R)$.



→ Reduced pressure (P_R)
compressibility chart

Compressibility factor (Z)

$Z = \frac{PV}{RT}$ for ideal gas

$$Z = \frac{P_c v_c}{RT_c} \times \frac{P_2 v_2}{T_2} = Z_c \times \frac{P_2 v_2}{T_2} \rightarrow \text{for real gas.}$$

This chart is useful when the properties of the gas at critical point are known. The deviation of the real gases from ideal gases can be known by this chart. Accuracy is $\pm 5\%$ by this chart. If the compressibility factor Z is less than unity, the gas is more compressible than perfect gas.

Vander Waal's Equation of State:-

Vander Waal's Equation:- In 1873, J.D. Vander Waal's presented an equation of state which was of interest on physical reasoning, introduced two correction constants in the equation of ideal gas equation of state.

$$\left(p + \frac{a}{\bar{v}^2}\right) (\bar{v} - b) = R_u T \quad \text{where } \bar{v} = \text{molar volume in } \text{m}^3/\text{kg mol}$$

$$R_u = \text{universal gas constant} = 8.314 \text{ kJ/kg mol K.}$$

The constant 'a' was introduced to account for the existence of intermolecular attraction, the constant 'b' was introduced to account for volume of molecules and R_u is universal gas constant. These constants are evaluated from the behaviour of the gas at critical point.

$$\frac{R_u T_c}{p_c \bar{v}_c} = \frac{8}{3}$$

Except at higher pressures, the real gases don't obey Vander Waal's equation in all range pressures and temperatures. Despite of its limitations, the Vander Waal's equation has historical importance because it was the first attempt to model the behaviour of real gases.

PROB Determine the pressure of air at 190°C having a specific volume of $0.00295 \text{ m}^3/\text{kg}$ by means of
 (1) Ideal gas equation (2) Vander Waal's equation
 Take, $a = 135522 \text{ N}\cdot\text{m}^4/(\text{kg}\cdot\text{mole})^2$, $b = 0.0362 \text{ m}^3/\text{kg}\cdot\text{mole}$, $R = 8314 \text{ J/kg}\cdot\text{mol}\cdot\text{K}$.

SOL Let: $p =$ pressure of air
 $T =$ Temperature of air $= 190^\circ\text{C} = 190 + 273 = 463 \text{ K}$
 $\bar{v} =$ specific volume of air $0.00295 \text{ m}^3/\text{kg}$
 $R_u =$ Universal gas constant of air $= 8314 \text{ J/kg}\cdot\text{mol}\cdot\text{K}$

Vander Waal's equation constants are
 $a = 135522 \text{ N}\cdot\text{m}^4/(\text{kg}\cdot\text{mole})^2$; $b = 0.0362 \text{ m}^3/\text{kg}\cdot\text{mole}$.

Take molecular weight of air, $M = 29$.

Ideal gas equation $pV = mRT$. Perfect gas equation.

$$pV = mRT$$

$$\Rightarrow p\bar{v} = RT \quad [\text{where, } \bar{v} = \text{specific volume} = \text{volume/mass}]$$

$$p\bar{v} = \left(\frac{R_u}{M}\right) \times T \quad [\text{where } R_u = M \times R; M = \text{molecular mass of gas}]$$

$$\therefore p = \frac{R_u \times T}{\bar{v} \times M} = \frac{8314 \times 463}{29 \times 0.00295} = \frac{44.996 \times 10^6 \text{ N/m}^2}{105} = 449.9 \text{ bar} \checkmark$$

Vander Waal's equation:-

$$\left(p + \frac{a}{\bar{v}^2}\right) (\bar{v} - b) = R_u T \quad [\bar{v} = \bar{v} \times M = 0.00295 \times 29]$$

$$\therefore p = \frac{R_u T}{\bar{v} - b} - \frac{a}{\bar{v}^2} = \left[\frac{8314 \times 463}{0.00295 \times 29 - 0.0362} - \frac{135522}{(0.00295 \times 29)^2} \right]$$

$$= 780 \times 10^5 - 180 \times 10^5 = 595 \times 10^5 \text{ Pa}$$

$$\therefore \text{pressure, } p = \frac{595 \times 10^5}{10^5} = 595 \text{ bar} \checkmark$$

PROB Determine the pressure of 2 moles of air at 400°C with a total volume of 0.5 m³. Use the ideal gas law and Vander Waals law.

SOL: Let p = pressure of air ; n = No. of moles of air = 2
 T = Temperature of air = 400°C = 400 + 273 = 673 K ; V = total volume = 0.5 m³
 R_u = universal gas constant of air = 8314 J / kg-mole K.
 Vander Waals equation constants for air

Take constants as Assumptions:
 $a = 1.368 \text{ bar} \left[\frac{\text{m}^3}{\text{kgmol}} \right]^2$; $b = 0.0367 \text{ m}^3 / \text{kgmol}$
 $= 1.368 \times 10^5 \text{ Pa} \left[\frac{\text{m}^3}{\text{kgmol}} \right]^2$

Ideal gas equation $pV = n \cdot R_u T$ ✓

pressure of air, $p = \frac{n \cdot R_u \cdot T}{V} = \frac{2 \times 8314 \times 673}{0.5} = 22,381,288 \text{ N/m}^2$

$p = \frac{22,381,288}{10^5} = 223.81 \text{ bar}$

Vander Waals equation:

$\left(p + \frac{a}{v^2} \right) (v - b) = R_u T$

where $\bar{v} = \frac{V (\text{total volume})}{n (\text{No. of moles})} = \frac{0.5}{2} = 0.25 \text{ m}^3 / \text{kgmol}$

∴ pressure, $p = \frac{R_u \cdot T}{(\bar{v} - b)} - \frac{a}{\bar{v}^2} = \frac{8314 \times 673}{(0.25 - 0.0367)} - \frac{1.368 \times 10^5}{(0.25)^2}$
 $= 26,232,170 - 2,188,800$
 $= 24,043,370 \text{ N/m}^2$
 $= 240.43 \text{ bar} ✓$

PROB Find the molecular weight and gas constant for the gas whose specific heats are as follows. $C_p = 1.967 \text{ kJ/kgK}$, $C_v = 1.507 \text{ kJ/kgK}$.

SOL: Given that, $C_p = 1.967 \text{ kJ/kgK}$ and $C_v = 1.507 \text{ kJ/kgK}$.

We know, Gas constant, $R = C_p - C_v = 1.967 - 1.507 = 0.46 \text{ kJ/kgK}$.

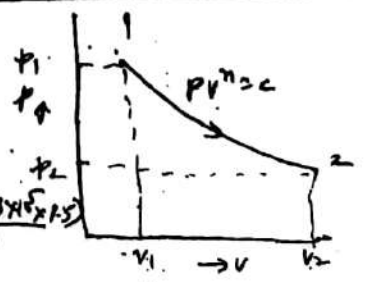
We know universal gas constant, $R_u = 8.314 \text{ kJ/kgK}$

∴ Molecular weight of the gas, $M = \frac{R_u}{R} = \frac{8.314}{0.46} = 18.07 \text{ kg/kgmol} ✓$

PROB. 0.3 m³ of air at pressure 8 bars expands to 1.5 m³. The final pressure is 1.3 bar. Assuming the expansion to be polytropic, calculate the heat supplied and change of internal energy. Take, $\gamma = 1.4$

SOL: We know for polytropic expansion process, $p v^n = c$
 $p_1 v_1^n = p_2 v_2^n$; $\frac{p_1}{p_2} = \left(\frac{v_2}{v_1} \right)^n$; $n = \frac{\log_e p_1/p_2}{\log_e v_2/v_1}$
 $\therefore n = \frac{\log_e 8/1.3}{\log_e 1.5/0.3} = 1.129$

(i) Heat supplied, $Q = \frac{\gamma - n}{\gamma - 1} \times \frac{p_1 v_1 - p_2 v_2}{n - 1} = \frac{(1.4 - 1.129)}{1.4 - 1} \times \frac{(8 \times 10^5 \times 0.3 - 1.3 \times 10^5 \times 1.5)}{1.129 - 1}$
 $= 236340 \text{ J/kg} = 23.63 \text{ kJ/kg}$



③

Change in internal energy; $\Delta U = C_v [T_2 - T_1]$ $[C_v = \frac{R}{\gamma - 1}]$

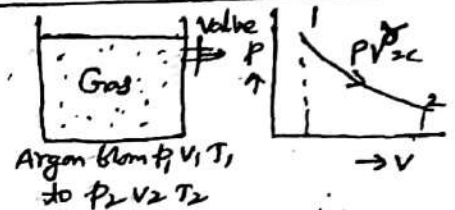
$$\Delta U = \frac{R}{\gamma - 1} \times (T_2 - T_1) = \frac{RT_2 - RT_1}{\gamma - 1} = \frac{P_2 V_2 - P_1 V_1}{\gamma - 1}$$

$$= \frac{1.3 \times 10^5 \times 1.5 - 8 \times 10^5 \times 0.3}{1.4 - 1} = -112,500 \text{ J/kg}$$

$$= -112.5 \text{ kJ/kg}$$

PROB. A tank of volume 1.3 m^3 is filled with argon gas at 6 bar and 260°C . If the gas within the tank changes its state isentropically when it flows from the tank until the pressure drops to the atmospheric pressure of 1 bar, determine the mass of the gas that has left the tank during the process.

SOL. Volume, $V_1 = 1.3 \text{ m}^3$, pressure, $P_1 = 6 \text{ bar}$
 Temperature, $T_1 = 260^\circ\text{C} = 533 \text{ K}$
 pressure, $P_2 = 1 \text{ bar}$



The gas flows isentropically from 6 bar to 1 bar. From the expansion process of the gas from state 1 to state 2 isentropically, we have,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}; \quad T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}} = 533 \left(\frac{1}{6}\right)^{\frac{0.4}{1.4}} = 319.44 \text{ K.}$$

Assume R for argon = 0.2081 kJ/kgK

$$P_1 V_1 = m_1 R T_1$$

Initial mass, $m_1 = \frac{P_1 V_1}{R T_1} = \frac{6 \times 10^5 \times 1.3}{0.2081 \times 10^3 \times 533} = 7.0322 \text{ kg.}$

Final mass, $m_2 = \frac{P_2 V_2}{R T_2} = \frac{1 \times 10^5 \times 1.3}{0.2081 \times 319.44} = 1.9556 \text{ kg.}$

Mass of the gas which left the tank during the process, $m = m_1 - m_2$
 $= 7.0322 - 1.9556$
 $= 5.0766 \text{ kg.}$

PROB Show that $C_p - C_v = \frac{\beta^2 T V}{K}$

SOL From First law of Thermodynamics, $dQ = du + PdV$.
 Since we may write, $u = \phi(T, V)$.

$$du = \left(\frac{\partial u}{\partial T}\right)_V \cdot dT + \left(\frac{\partial u}{\partial V}\right)_T \cdot dV.$$

$$\therefore dQ = du + PdV = \left(\frac{\partial u}{\partial T}\right)_V \cdot dT + \left\{P + \left(\frac{\partial u}{\partial V}\right)_T\right\} dV = C_v dT + \left\{P + \left(\frac{\partial u}{\partial V}\right)_T\right\} dV.$$

This is true for any reversible process, and so, for a reversible constant pressure process,

$$dQ = C_p (dT)_p = C_v (dT)_p + \left\{P + \left(\frac{\partial u}{\partial V}\right)_T\right\} (dV)_p$$

Hence, $C_p - C_v = \left\{P + \left(\frac{\partial u}{\partial V}\right)_T\right\} \left(\frac{\partial V}{\partial T}\right)_p$

From thermodynamic function: $dF = -SdT - PdV$; $\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T = \frac{1}{T} \left\{P + \left(\frac{\partial u}{\partial V}\right)_T\right\}$

$$\therefore C_p - C_v = T \cdot \left(\frac{\partial P}{\partial T}\right)_V \cdot \left(\frac{\partial V}{\partial T}\right)_p$$

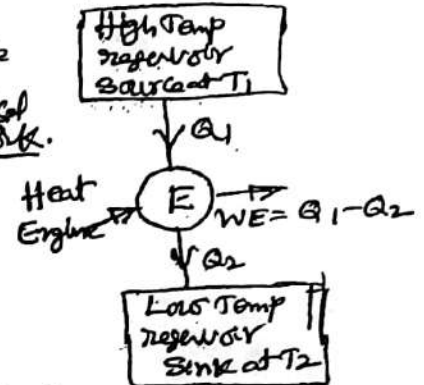
From $\beta = \frac{1}{V} \left(\frac{\partial V}{\partial P}\right)_T$; $K = -\frac{1}{V} \left(\frac{\partial V}{\partial P}\right)_T$; we have $C_p - C_v = \frac{\beta^2 T V}{K}$

* Second Law of Thermodynamics

UNIT-III

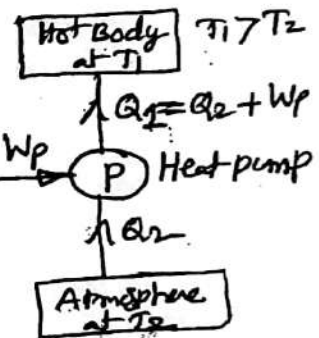
The second law of thermodynamics recognizes that the mutual conversion of heat into work during a process is impossible, while its opposite is possible [complete conversion of work into heat is possible].

Heat Engine:- A heat engine is a device used for converting heat energy into mechanical work.
 heat energy (Q_1) from high temperature reservoir at temperature T_1 is supplied to the engine. After doing work (W_E), a part of this heat energy is rejected to sink (or low temperature reservoir).



$$\eta_{H-E} = \frac{\text{Maximum work obtained}}{\text{total heat supplied}} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

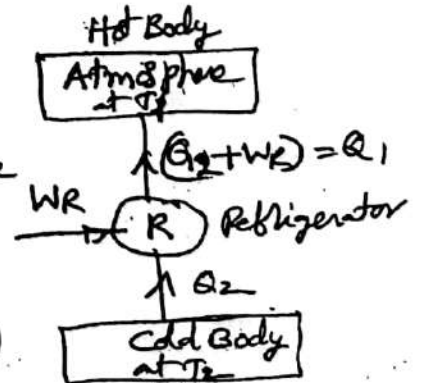
Heat pump:- A heat pump is device used for to transfer heat from atmosphere [Cold] at temperature T_2 to hot body (space at T_1), W_p with the help of mechanical pump.



The performance of heat pump is expressed by the coefficient of performance (COP)

$$(C.O.P)_p = \frac{\text{Amount of heat delivered } (Q_1)}{\text{Amount of work supplied to pump } (W_p)} = \frac{Q_1}{Q_1 - Q_2} = \frac{T_1}{T_1 - T_2}$$

Refrigerator:- A refrigerator is a reversed heat engine which either cool (or) maintain the temperature lower than the temperature of surroundings. This is done by extracting heat (Q_2) from cold body and rejecting heat to the atmosphere ($Q_1 + W_R$) with the help of mechanical work supplied to refrigerator.



$$(C.O.P)_R = \frac{\text{Amount of heat taken from cold body } (Q_2)}{\text{Amount of work required } (W_R)}$$

$$(COP)_{\text{pump}} = 1 + (COP)_{\text{refrigerator}} = \frac{Q_1}{W_R} = \frac{Q_1}{Q_1 - Q_2} = \frac{T_1}{T_1 - T_2}$$

Statements of the second Law of Thermodynamics

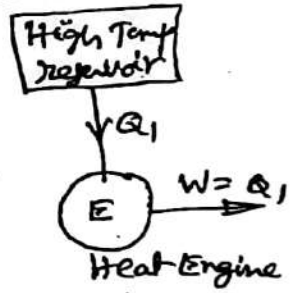
Kelvin-Planck Statement:- It relates the working of heat engines.

"It is impossible to construct an engine which while operating in a cycle, produces no other effect except to extract the heat from a single temperature reservoir and do equivalent amount of work."

According to the Kelvin-Planck statement, a heat engine can not be 100 percent efficient. In practice, no heat engine can convert all heat supplied to useful work. The heat engine receives heat from a high temperature reservoir and it must reject some amount of heat to a low-temperature reservoir. The work done by a cyclic heat engine is the difference between heat supplied and heat rejection.

perpetual motion machine of the second kind (PMM-II):-

A 100% percent efficient machine, which is impossible to obtain in actual practice, because no machine can convert whole of the heat energy supplied to it, into its equivalent amount of work. A PMM-II is impossible.



Clausius Statement:-

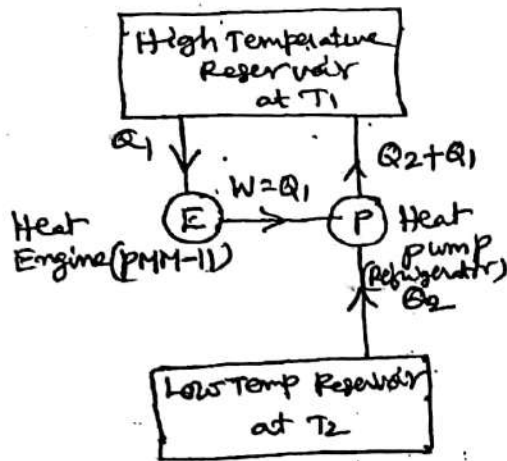
It relates the working of the refrigerators and heat pumps.

"It is impossible for any device that operates in a cycle, and produce no effect other than the transfer of heat energy from a lower temperature body to higher temperature body."

The heat energy can not flow by itself from a low-temperature body to a high-temperature body without addition of work.

Refrigerators and heat pumps transfer energy from a low-temperature region to a higher temperature region at the cost of work input to their compressors.

Equivalence of Kelvin-Planck and Clausius statements.



Any device that violates one statement also leads to violation of the other statement.

Consider a heat engine (PMM2) and an actual refrigerator, operating between a high temperature T_1 & low temperature T_2 . The heat engine is receiving heat Q_1 from high temperature reservoir at T_1 and it converts all heat in to net work $W=Q_1$. It does not reject any amount of heat to low temperature reservoir, thus violating the Kelvin-Planck statement of second law.

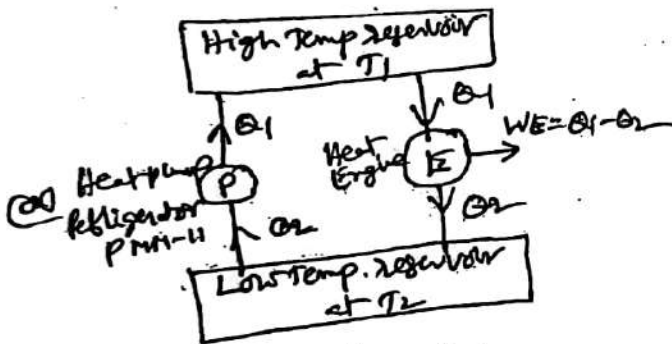


Figure (b)

This device

The work produced by heat engine is supplied to a refrigerator (Heat pump) that removes heat Q_2 and discharges (Q_1+Q_2) to high temperature reservoir. The refrigerator and heat engine together constitute a device, whose sole effect is to transfer heat energy Q_2 to a high temperature reservoir (Q_2+Q_1) . This device clearly violates Kelvin-Planck statement leads to violation of Clausius statement.

Figure (b) shows violation of Clausius statement leads to violation of Kelvin-Planck statement.

* Carnot cycle, (∞) Carnot Engine :-

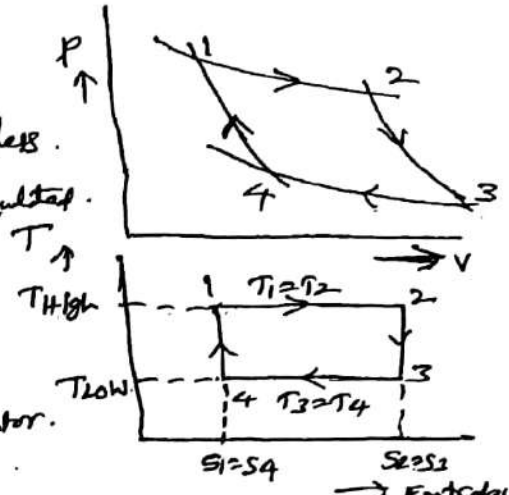
A French engineer, Sadi Carnot in 1824 proposed an engine which works on a reversed cycle. It is theoretically a heat engine that converts the maximum amount of energy in to mechanical work. Carnot showed that the efficiency of any engine depends on the difference between the highest temperature and lowest temperature reached during one cycle. The greater the temperature difference, higher the efficiency.

It comprises four reversible processes given below.

- ① Reversible isothermal expansion
- ② Reversible adiabatic expansion
- ③ Reversible isothermal compression
- ④ Reversible adiabatic compression

Carnot Cycle Assumptions

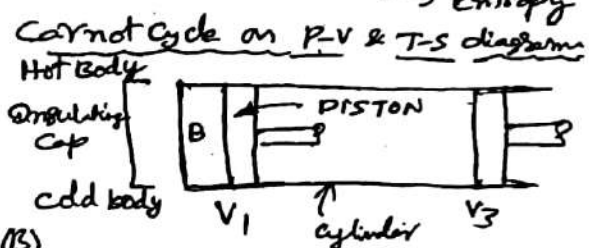
- 1) Working substance is perfect gas.
- 2) piston movement in cylinder is frictionless.
- 3) Walls of cylinder & piston are perfectly insulated.
- 4) Heat supply and Heat rejection are at constant temperatures.
- 5) cylinder head is very good conductor of heat and partially perfect insulator.



Working of a Carnot Engine:-

1. First Stage (isothermal expansion)

The hot body at a temperature T_1 is brought in contact with bottom (B) of the cylinder. The air expands reversibly at constant temperature process (1-2).



Heat supplied, $Q_{12} = \dots$ Work done by air during isothermal expansion.

$$= P_1 V_1 \ln \frac{V_2}{V_1} = nRT_1 \ln \frac{V_2}{V_1} = nRT_1 \ln r$$

2. Second Stage [Adiabatic expansion]:- The hot body is removed from the bottom of the cylinder B and the insulating cap is brought in contact. The air now allowed to expand reversibly and adiabatically. process (2-3). No heat supplied. The temperature falls from T_2 to T_3 .
So, decrease in internal energy = Work done by air during adiabatic expansion.

$$= \frac{P_2 V_2 - P_3 V_3}{\gamma - 1} = \frac{nR(T_2 - T_3)}{\gamma - 1} = \frac{nR(T_1 - T_3)}{\gamma - 1}$$

3. Third Stage [isothermal compression]

Remove the insulating cap from bottom of cylinder and bring the cold body in its contact. The air is compressed at constant temperature $T_3 = T_4$. During this process, heat is rejected to cold body. Heat rejected = Work done on air during isothermal compression.

$$Q_{3-4} = P_3 V_3 \ln \frac{V_3}{V_4} = nRT_3 \ln \frac{V_3}{V_4} = nRT_3 \ln r$$

Where, $r =$ Compression ratio = Expansion ratio, $\frac{V_2}{V_1} = \frac{V_3}{V_4}$.

4. Fourth Stage:- (Adiabatic compression):- Now insulating cap is brought in contact with bottom of cylinder, and air is allowed to be compressed adiabatically. Increase in internal energy due to increase in temperature from T_4 to T_1 .

increase in internal energy = work done on air during adiabatic compression.

$$= \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{mR(T_1 - T_2)}{\gamma - 1} = \frac{mR(T_1 - T_3)}{\gamma - 1}$$

∴ Efficiency of Carnot cycle $\eta_{Carnot} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}}$

$$= \frac{mR T_1 \ln \frac{V_2}{V_1} - mR T_3 \ln \frac{V_2}{V_1}}{mR T_1 \ln \frac{V_2}{V_1}}$$

$$= \frac{T_1 - T_3}{T_1} = 1 - \frac{T_3}{T_1} = 1 - \frac{T_{Low}}{T_{High}}$$

Alternative proof:-

Heat supplied during isothermal expansion 1-2, $Q_{1-2} = T_1(S_2 - S_1)$

Heat rejection during isothermal compression 3-4, $Q_{3-4} = T_3(S_2 - S_1)$

$$\eta_{Carnot\ cycle} = \frac{H.S - H.R}{H.S} = \frac{T_1(S_2 - S_1) - T_3(S_2 - S_1)}{T_1(S_2 - S_1)} = 1 - \frac{T_3}{T_1}$$

For adiabatic expansion 2-3,

$$\frac{T_2}{T_3} = \left(\frac{V_3}{V_2}\right)^{\gamma-1} \quad \text{or} \quad \frac{V_3}{V_2} = \left(\frac{T_2}{T_3}\right)^{\frac{1}{\gamma-1}}$$

For adiabatic compression 4-1,

$$\frac{T_1}{T_4} = \left(\frac{V_4}{V_1}\right)^{\gamma-1} \quad \text{or} \quad \frac{V_4}{V_1} = \left(\frac{T_1}{T_4}\right)^{\frac{1}{\gamma-1}}$$

Since $T_1 = T_2$ and $T_3 = T_4$
 so, $\frac{V_3}{V_2} = \frac{V_4}{V_1}$ or $\frac{V_2}{V_1} = \frac{V_3}{V_4}$

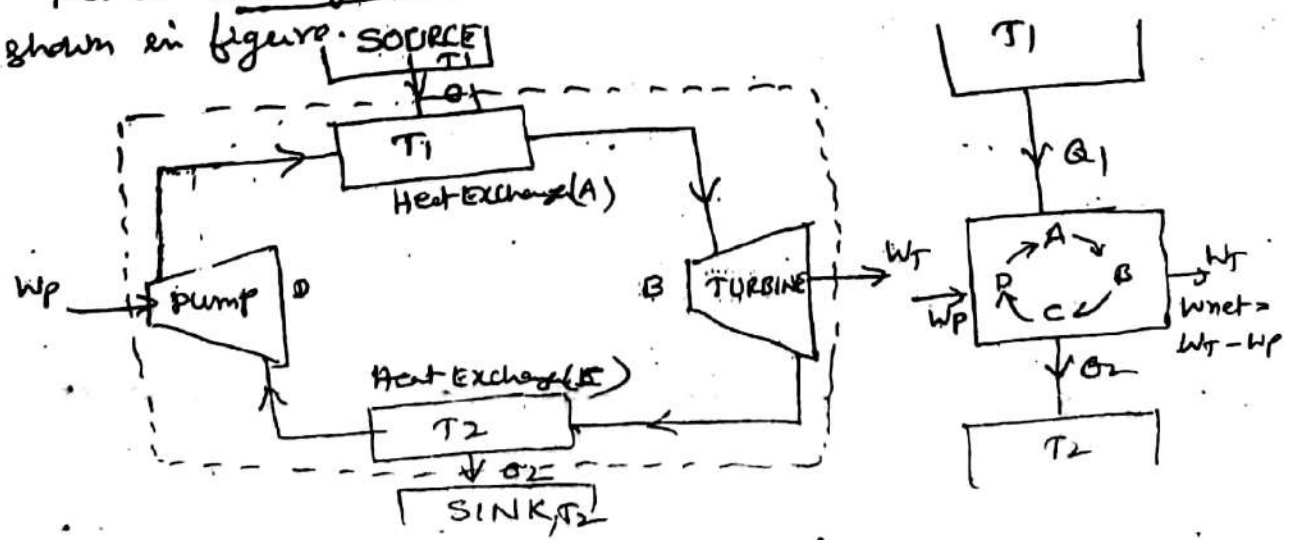
$$\frac{T_1}{T_4} = \frac{T_1}{T_3} = \left(\frac{V_4}{V_1}\right)^{\gamma-1}$$

$$\eta_{Carnot} = 1 - \frac{T_3}{T_1} = 1 - \frac{1}{\gamma^{\frac{1}{\gamma-1}}}$$

Carnot Heat Engine:-

A cyclic heat engine operating on the Carnot cycle is called a Carnot heat engine.

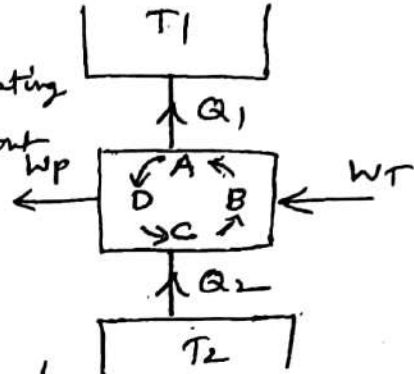
For a steady flow system, the Carnot cycle is represented as shown in figure.



- $Q_1 \rightarrow$ heat transferred to system reversibly and isothermally
- $W_T \rightarrow$ Workdone by Turbine
- $Q_2 \rightarrow$ heat rejected to sink at temp T_2
- $W_P \rightarrow$ Work is done on the system by pump.
- \therefore Net Workdone by system, $W_{net} = W_T - W_P$

Reversed Heat Engine:-

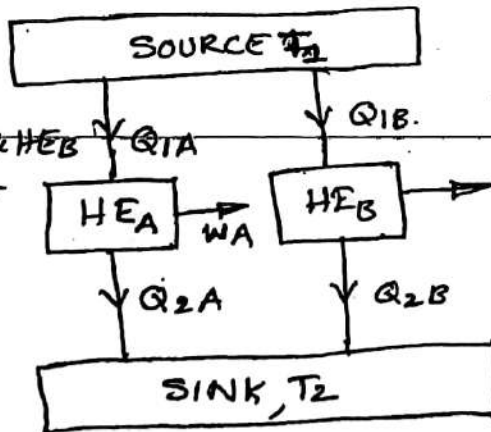
A reversed heat engine is operating reversibly (reversed direction) without any friction.



Carnot's Theorem (or) Carnot principle:

- No engine can be more efficient than a reversible engine operating between the same two reservoirs.
(or) Carnot (reversible) engine among all the engines is the most efficient.
- The efficiency of all reversible heat engines operating between the same two temperatures & reservoirs are the same.

Two cyclic heat engines HEA & HEB operating between the source and sink, of which HEB is reversible.



HEA & HEB are two engines operating between the given source at temp T_1 and sink at temp T_2 .

Let HEA be any heat engine and HEB be any reversible heat engine. We have to prove efficiency of HEB is more than that of HEA. Let us assume that $\eta_A > \eta_B$.
Let the rate of working of the engines be such that

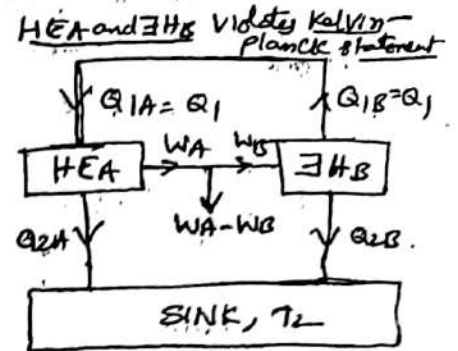
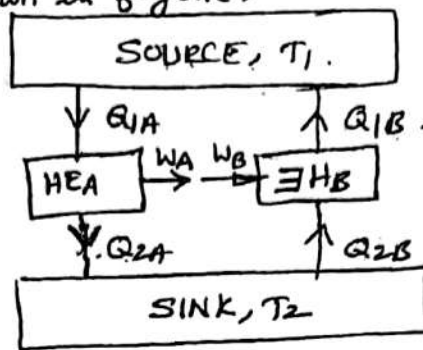
$$Q_{1A} = Q_{1B} = Q_1$$

since $\eta_A > \eta_B$

$$\frac{W_A}{Q_{1A}} > \frac{W_B}{Q_{1B}}$$

$$W_A > W_B \quad \left[\text{since } Q_{1A} = Q_{1B} \right]$$

Now, let HEB be reversed. Since HEB is a reversible heat engine, the magnitudes of heat and work transfer quantities will remain the same, but their directions will be reversed as shown in figure.



Since $W_A > W_B$, some part of W_A (equal to W_B) may be fed to drive the reversed heat engine HEB . Since $Q_{1A} = Q_{1B} = Q_1$, the heat discharged by HEB may be supplied to HEA . The source may therefore, be eliminated. The net result is that HEA and HEB together constitute a heat engine which operating in a cycle produces net work $W_A - W_B$ while exchanging heat with a single reservoir at T_2 . This violates the Kelvin-Planck statement of the second law. Hence the assumption that $\eta_A > \eta_B$ is wrong.

Collapses of Carnot Theorem:-

- ① All reversible heat engines operating between the same constant temperature limits will have the same efficiency. None have higher than other.
- ② The efficiency of the reversible Carnot cycle engine does not depend on the working medium. It depends only on the temperature limits.
- ③ No engine can be more efficient than a reversible Carnot engine which operating between the same temperature limits.

Absolute Thermodynamic Temperature Scale:-

A temperature scale that is independent of the properties of the substances that are used to measure temperature is called Thermodynamic temperature scale.

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

By the second law, it is necessary to have a temp difference $(T_1 - T_2)$ to obtain efficiency for any cycle. We know that the efficiency of all heat engines between the same temperature levels is the same, and is independent of the working substance. Therefore, for a reversible cycle, the efficiency will depend solely upon the temperature T_1 and T_2 at which heat is transferred.

$$\eta_{rev} = f(T_1, T_2)$$

$$\frac{Q_1}{Q_2} = f(T_1, T_2)$$

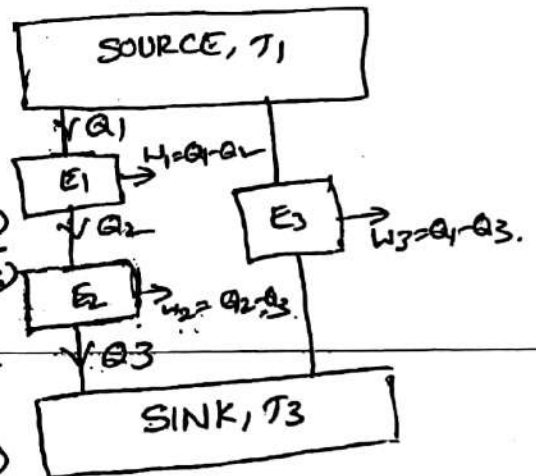
Let us consider two reversible heat engines E_1 receiving heat from the source T_1 and rejecting heat at T_2 to E_2 which in turn rejects heat to the sink at T_3 .

$$\text{Now } \frac{Q_1}{Q_2} = f(T_1, T_2) ; \frac{Q_2}{Q_3} = f(T_2, T_3)$$

E_1 and E_2 together constitute another heat engine E_3 operating between T_1 and T_3 .

$$\therefore \frac{Q_1}{Q_3} = f(T_1, T_3)$$

$$\text{Now } \frac{Q_1}{Q_2} = \frac{Q_1}{Q_3} \cdot \frac{Q_3}{Q_2} ; f(T_1, T_2) = \frac{f(T_1, T_3)}{f(T_2, T_3)}$$



The ratio $\frac{Q_1}{Q_2}$ depends only on T_1 and T_2

not on T_3 .

So the ratio can be written, $\frac{Q_1}{Q_2} = \frac{f(T_1)}{f(T_2)}$

$$\therefore \boxed{\frac{Q_1}{Q_2} = \frac{T_1}{T_2}} \text{ Thermodynamic temperature scale.}$$

Efficiency of Reversible heat engine

$$\eta_{\text{Heat Engine}} = 1 - \frac{Q_2}{Q_1}$$

$$\eta_{\text{Reversible}} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

$$\boxed{\eta_{\text{Max}} = \frac{T_1 - T_2}{T_1}}$$

Refrigerator : C.O.P = $\frac{T_2}{T_1 - T_2}$

Heat pump : C.O.P = $\frac{T_1}{T_1 - T_2}$

PROB A reversible heat engine operates between -13°C and 37°C . Calculate its C.O.P as a refrigerator and a heat pump.

SOL. Given, $T_1 = T_{\text{High}} = 37^{\circ}\text{C} = 37 + 273 = 310\text{K}$
 $T_2 = T_{\text{Low}} = -13 + 273 = 260\text{K}$

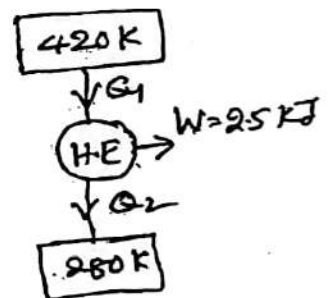
(C.O.P) Refrigerator = $\frac{T_2}{T_1 - T_2} = \frac{260}{(310 - 260)} = 5.2$

(C.O.P) Heat pump = $\frac{T_1}{T_1 - T_2} = \frac{310}{310 - 260} = 6.2$

PROB A reversible heat engine operates between two reservoirs at 420K and 280K its output from the engine is 2.5KJ . determine the efficiency of the engine and its heat interactions with heat reservoirs. subsequently the engine is reversed and made to operate as heat pump between the same reservoirs. Make calculations for the COP of heat pump and power input required when the heat transfer rate from the 280K reservoir is 5KW .

For a reversible heat engine

SOL. Given, $T_1 = 420\text{K}$
 $T_2 = 280\text{K}$
 Workout = 2.5KJ



$\eta_{\text{reversible}} = \frac{T_1 - T_2}{T_1} = \frac{420 - 280}{420} = 0.33$ (or $\frac{33}{100}$)

$\frac{W}{Q_1} = 0.33$; $Q_1 = \frac{W}{0.33} = \frac{2.5}{0.33} = 7.57\text{KJ}$

$Q_1 - Q_2 = W$
 $\therefore Q_2 = Q_1 - W = 7.57 - 2.5 = 5.07\text{KJ}$

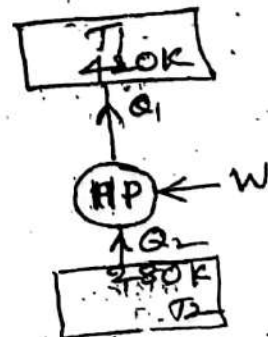
For Heat pump

Given, $T_1 = 420\text{K}$; $T_2 = 280\text{K}$.
 Heat removed from 280K reservoir: 5KW .

$\therefore (\text{C.O.P})_{\text{HP}} = \frac{T_2}{T_1 - T_2} = \frac{280}{420 - 280} = 2$

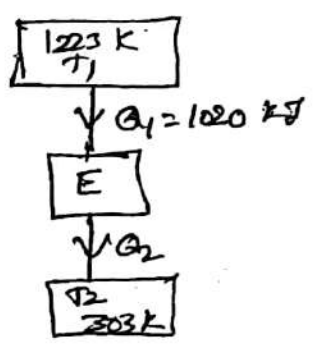
$\text{C.O.P} = \frac{\text{Desired effect } (Q_2)}{\text{work input}}$

$\therefore \text{Work input} = \frac{Q_2}{\text{COP}} = \frac{5}{2} = 2.5\text{KW}$ ✓



PROB An engine working on Carnot cycle receives 1020 kJ heat from a heat reservoir at a constant temp of 950°C and rejected heat to a heat sink at a constant temp of 30°C. Calculate.

- (1) the thermal efficiency of the heat engine
- (2) Workdone.

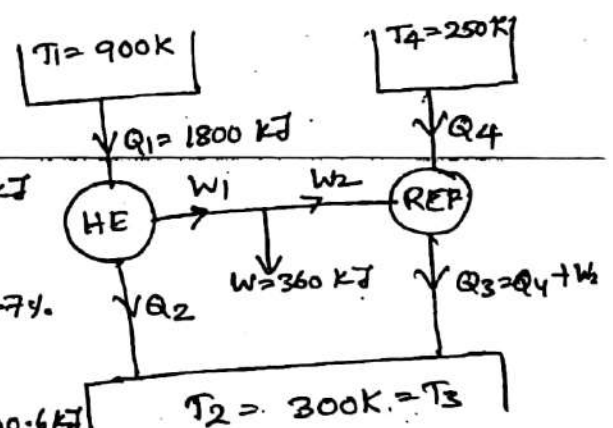


SOL. Given, $T_1 = 950 + 273 = 1223 \text{ K}$
 $T_2 = 30 + 273 = 303 \text{ K}$
 $Q_1 = 1020 \text{ kJ}$.

- (1) $\eta_{HE} = \frac{T_1 - T_2}{T_1} = \frac{1223 - 303}{1223} = 0.75$ (75%)
- (2) Workdone = $\eta \times Q_1 = 0.75 \times 1020 = 765 \text{ kJ}$.

PROB A reversible heat engine operating between thermal reservoirs at 900K and 300K is used to drive a reversible refrigerator for which temperature limits are 300K and 250K. The engine absorbs 1800 kJ of energy as heat from the reservoir at 900K and net output engine - refrigerator system is 360 kJ. Make calculations for the heat extracted from the refrigerator and the net heat rejected to the reservoir at 300K.

SOL. Given, $T_1 = 900 \text{ K}$
 $T_2 = 300 \text{ K}$
 $Q_1 = 1800 \text{ kJ}$



Net work output, $W = W_1 - W_2 = 360 \text{ kJ}$

For a reversible heat engine (HE)
 $\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{900} = 0.667$ (66.7%)
 $\eta = \frac{W_1}{Q_1} = 0.667$; $W_1 = 0.667 \times Q_1 = 0.667 \times 1800 = 1200.6 \text{ kJ}$

We know that, $W_{net} = W_1 - W_2 = 360 \text{ kJ}$
 $\therefore W_2 = W_1 - 360 = 1200.6 - 360 = 840.6 \text{ kJ}$

For a reversible refrigerator, $(C.O.P)_R = \frac{Q_4}{Q_3 - Q_4} = \frac{T_4}{T_3 - T_4}$
 $= \frac{250}{300 - 250} = 5$

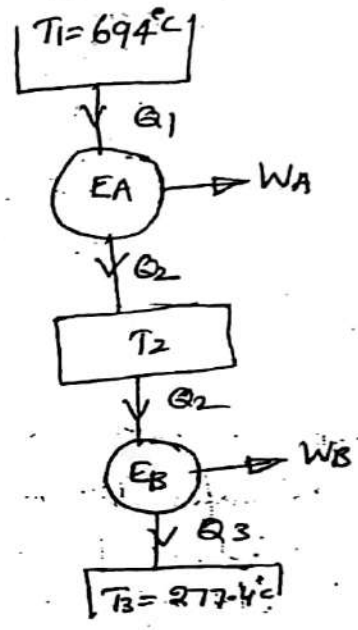
From $(C.O.P)_R = \frac{Q_4}{W_2}$; $5 = \frac{Q_4}{840.6}$; $Q_4 = 5 \times 840.6 = 4203 \text{ kJ}$

$Q_3 = Q_4 + W_2 = 4203 + 840.6 = 5043.6 \text{ kJ}$
 $Q_2 = Q_1 - W_1 = 1800 - 1200.6 = 599.4 \text{ kJ}$
 \therefore Heat rejected to 300K reservoir, $Q_3 + Q_2 = 5043.6 + 599.4 = 5643 \text{ kJ}$

PROB Two reversible heat engine A and B are arranged in series with A rejecting heat directly to B through an intermediate reservoir. Engine A receives 200 kJ of heat from a reservoir at 421°C and engine B is in thermal communication with a sink at 4.4°C. If the work output of A is twice that of B, find

- The intermediate temperature between A and B.
- Efficiency of heat engine
- Heat rejected to the cold sink.

SOL. Given,
 Two heat engines are arranged in series.
 $Q_1 = 200 \text{ kJ}$
 $T_1 = 421^\circ\text{C} = 421 + 273 = 694 \text{ K}$
 $T_3 = 4.4^\circ\text{C} = 4.4 + 273 = 277.4 \text{ K}$
 $W_A = 2W_B$



For two reversible heat engines arranged in series

$$\frac{T_1}{Q_1} = \frac{T_2}{Q_2} = \frac{T_3}{Q_3}$$

$$\Rightarrow \frac{T_1}{Q_1} = \frac{T_3}{Q_3} ; Q_3 = \frac{T_3}{T_1} Q_1 = \frac{277.4}{694} \times 200 = 79.9 \text{ kJ}$$

Given that,

$$W_A = 2(W_B)$$

$$Q_1 - Q_2 = 2(Q_2 - Q_3) = 2Q_2 - 2Q_3$$

$$3Q_2 = Q_1 + 2Q_3$$

$$Q_2 = \frac{(Q_1 + 2Q_3)}{3} = \frac{(200 + 2 \times 79.9)}{3} = 119.93 \text{ kJ}$$

$$\frac{T_1}{Q_1} = \frac{T_2}{Q_2} ; T_2 = T_1 \times \frac{Q_2}{Q_1} = 694 \times \frac{119.93}{200} = 416.16 \text{ K}$$

$$\textcircled{2} \quad \eta_A = \frac{Q_1 - Q_2}{Q_1} = \frac{200 - 119.93}{200} = 0.400 \text{ (or } 40\%)$$

$$\eta_B = \frac{Q_2 - Q_3}{Q_2} = \frac{119.93 - 79.9}{119.93} = 0.33 \text{ (or } 33.7\%)$$

$\textcircled{3}$ Heat rejected to cold sink, $Q_3 = 79.9 \text{ kJ}$

PROB A reversible heat engine receives heat from a reservoir at 700°C and rejects heat to another reservoir at temp T_2 . A second heat engine receives the heat rejected by the first engine and rejects heat to a sink at 37°C. calculate temp T_2 for

- Equal efficiency for both engines
- Equal work for both engines.

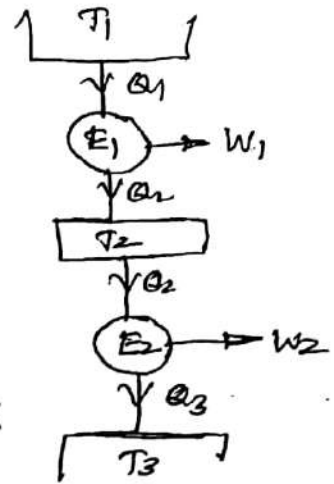
SOL. Given, $T_1 = 700^\circ\text{C} = 973\text{ K}$
 $T_3 = 37^\circ\text{C} = 310\text{ K}$

(i) For equal efficiency of both the engines

$$\eta_1 = \eta_2$$

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

$$T_2^2 = T_1 T_3 ; T_2 = \sqrt{T_1 T_3} = \sqrt{973 \times 310} = 549.21\text{ K}$$



(ii) Equal work

$$W_1 = Q_1 - Q_2 ; W_2 = Q_2 - Q_3$$

$$W_1 = W_2 ; Q_1 - Q_2 = Q_2 - Q_3$$

$$Q_1 - 2Q_2 + Q_3 = 0$$

$$\frac{Q_1}{Q_2} - 2 + \frac{Q_3}{Q_2} = 0 ; \frac{Q_1}{Q_2} + \frac{Q_3}{Q_2} = 2$$

$$\frac{T_1}{T_2} + \frac{T_3}{T_2} = 2$$

$$\therefore T_2 = \frac{T_1 + T_3}{2} = \frac{973 + 310}{2} = 641.5\text{ K}$$

PROB. A heat engine is used to drive a heat pump. The heat transfer from the heat engine and from the heat pump are used to heat the water circulating through the radiators of a building. The efficiency of a heat engine is 27% and COP of heat pump is 4. Evaluate the ratio of heat through

SOL. $\eta_{HE} = 27\%$

$$(COP)_{HP} = 4$$

The work produced by heat engine is utilized to heat the water from the pump.

$$W_{HE} = W_{HP}$$

$$\eta_{HE} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} = 0.27$$

$$Q_2 = 0.73 Q_1 \quad \text{--- (1)}$$

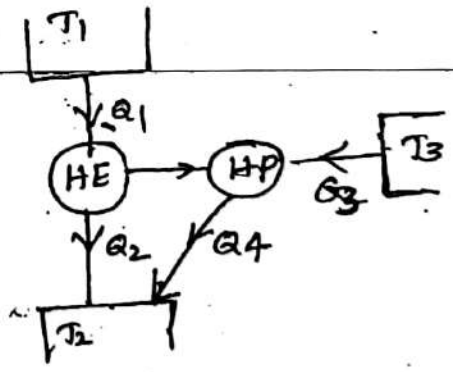
$$(C.O.P)_{HP} = \frac{Q_4}{Q_4 - Q_3} = 4 ; Q_4 = 4(Q_4 - Q_3) \quad \text{--- (2)}$$

$$W_{HE} = W_{HP}$$

$$Q_1 - Q_2 = Q_4 - Q_3 \quad \text{--- (3)}$$

Substituting equation (3) in (2), $Q_4 = 4(Q_1 - Q_2) = 4Q_1 - 4Q_2$

Ratio of heat transfer to cooling water ($Q_4 + Q_2$)
heat transfer to the heat engine Q_1



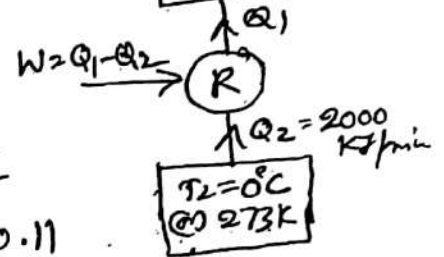
$$= \frac{Q_2 + 4Q_1 - 4Q_2}{Q_1} = \frac{4Q_1 - 3Q_2}{Q_1}$$

$$= \frac{4Q_1 - 3 \times 0.73Q_1}{Q_1} = 1.81 \checkmark$$

PROB. Determine the power required to run a refrigerator that transfers 2000 kJ/min of heat from a cooled space at 0°C to the surrounding atmosphere at 27°C. The refrigerator operates on reversed Carnot cycle.

SOL.

For a refrigeration system,



$$(C.O.P)_{Ref} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

$$= \frac{273}{300 - 273} = 10.11$$

We know, $(C.O.P) = 10.11 = \frac{Q_2}{Q_1 - Q_2} = \frac{2000}{Q_1 - 2000}$

$$\therefore (Q_1 - 2000) 10.11 = 2000$$

$$\therefore Q_1 = \frac{2000}{10.11} + 2000 = 2197.8 \text{ kJ/min}$$

Power required, $W = (Q_1 - Q_2) = 2197.8 - 2000 = 197.8 \text{ kJ/min}$

PROB. An engine operating on a Carnot cycle works with its temperatures of 600K and 300K. If the engine receives 2000 kJ of heat, evaluate workdone and Thermal eff of the engine.

SOL. For a Carnot cycle,

$$\eta_{Carnot} = \frac{\text{Workdone}}{\text{Heat supplied}} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

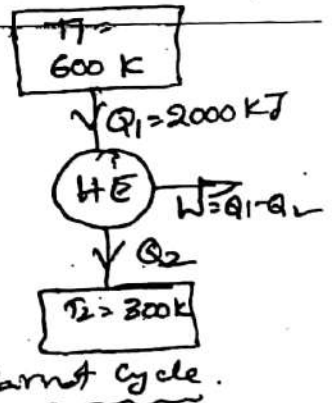
$$= 1 - \frac{T_2}{T_1} = 1 - \frac{300}{600} = 0.5 \text{ (or) } 50\%$$

\therefore We know, $\eta_{Carnot} = 0.5 = \frac{\text{Workdone}}{\text{Heat supplied}}$

$$= \frac{Q_1 - Q_2}{Q_1} = \frac{2000 - Q_2}{2000}$$

$$\therefore Q_2 = 2000 - 1000 = 1000 \text{ kJ}$$

\therefore Workdone, $W = Q_1 - Q_2 = 2000 - 1000 = 1000 \text{ kJ}$
 $= 1 \text{ MJ} \checkmark$



Entropy (ENTROPY)

The first law of thermodynamics was stated in terms of cycles first and it was shown that the cyclic integral of heat to the cyclic integral of work. When first law applied for thermodynamic processes, the existence of a property, the internal energy.

Similarly, the second law was also first stated in terms of cycles executed by systems [heat engine cycle].

When second law applied for thermodynamic processes, leads to definition of a property called Entropy.

Entropy of a system is a measure of the degree of molecular disorder existing in the system. It is an important thermodynamic property of a working substance, which increases with the addition of heat and decreases with its removal. It is ~~not~~ difficult to define the term entropy, but it is easy to define the change of entropy of a working substance.

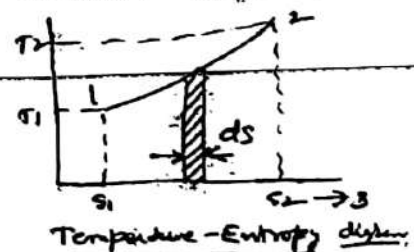
On a reversible process, over a small range of temperature, the increase (or) decrease of entropy, when multiplied by the absolute temperature gives the heat absorbed (or) rejected by the working substance.

$$\therefore \delta Q = T ds \quad \text{or} \quad \boxed{ds = \frac{\delta Q}{T}}$$

ds = Change of entropy
 T = Absolute temperature
 δQ = Heat added (or) rejected.

Relation between Heat and Entropy :-

Consider the heating of a working substance by a reversible process shown by a curve from 1 to 2 on T-S diagram.



Let a small quantity of heat (δQ) is added (or) supplied to the working substance, which increases entropy by (ds). Let the absolute temperature at this instant be T . According to definition of entropy

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

total heat supplied (or) rejected, $\int \delta Q = \int T ds$.

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

The change in entropy may be regarded as a measure of the rate of the availability (or) unavailability of heat for transformation into work.

The increase in entropy is obtained from a given quantity of heat at low temperature.

Available and unavailable Heat energy :-

Available heat energy :- is that part of the heat energy (or) heat supplied which can be converted into mechanical work.

Unavailable heat energy :- is that part of heat energy which cannot be converted into mechanical work.

The common term used for unavailable heat energy, according to second law of Thermodynamics, is the heat rejected by the system to the surroundings.

-- Total heat to energy supplied to the system

$$SQ = \text{Available heat energy} + \text{Unavailable heat energy}$$

$$= A.H.E + U.H.E = \text{Workdone} + \text{Heat rejected.}$$

The maximum possible efficiency obtainable by the engine working on a Carnot cycle is given by

$$\eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

$T_1 =$ Maximum Absolute temperature
 $T_2 =$ Lowest absolute temperature

$$= \frac{\text{Max. Work obtained}}{\text{Heat supplied @ absorbed}} = \frac{\delta W}{\delta Q} = 1 - \frac{T_2}{T_1}$$

$$(1) \quad \delta W = \delta Q \left[1 - \frac{T_2}{T_1} \right]$$

w. Since, Lowest practical temp of heat rejection is the temp. of surroundings (T_0).

$$\therefore \delta W = \delta Q \left[1 - \frac{T_0}{T_1} \right] = \delta Q - \delta Q \times \frac{T_0}{T_1}$$

We also know, workdone, $\delta W = \text{Heat supplied} - \text{Unavailable heat energy}$
 $= \delta Q - U.H.E$

$$\therefore U.H.E = T_0 \left(\frac{\delta Q}{T_1} \right) = T_0 \cdot ds.$$

The unavailable heat energy (U.H.E) (or) heat rejected is the product of the lowest temperature of heat rejection and change of entropy of the system during the process of supplying heat.

Change in entropy may be regarded as a measure of Unavailable form of heat energy (or) irreversibility of the process.

Clausius inequality:-

The Clausius inequality states that whenever a closed system undergoes a cyclic process, the cyclic integral of $\frac{\delta Q}{T}$ is less than zero for an irreversible process and is equal to zero for a reversible cyclic process.

$$\oint \frac{\delta Q}{T} < 0, \text{ for an irreversible cyclic process} \quad \text{--- (1)}$$

$$\oint \frac{\delta Q}{T} = 0, \text{ for a reversible cyclic process.} \quad \text{--- (2)}$$

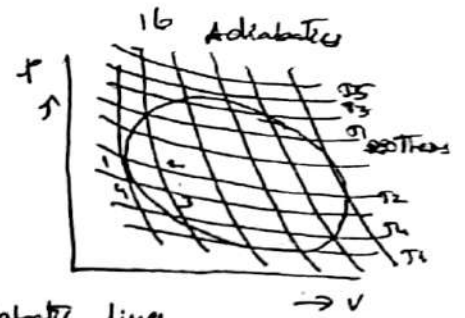
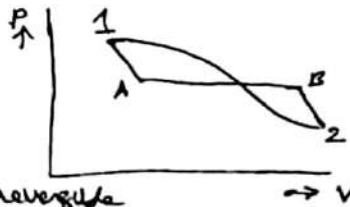
The Clausius inequality is written as $\oint \frac{\delta Q}{T} \leq 0$.

Units of Entropy $ds = \frac{\delta Q}{T}$ $\frac{KJ}{K}$ units.

The entropy of a substance is zero at absolute zero temperature.

Clausius Theorem

It states that a reversible line can be replaced by two reversible adiabatic lines and a reversible isothermal line



1-2 process \rightarrow reversible process, 1-A, B-2 \rightarrow two adiabatic lines, A-B \rightarrow isothermal line.

$$Q_{1-2} = W_{1-2} + U_2 - U_1$$

$$\text{For process 1, 1-A, A-B and B-2, } Q_{1-A-B-2} = W_{1-A-B-2} + U_2 - U_1$$

$$\text{Since } W_{1-2} = W_{1-A-B-2}$$

$$Q_{1-2} = W \cdot Q_{1-A} + Q_{A-B} + Q_{B-2}$$

$$Q_{1-A} = Q_{B-2} = 0 \text{ two adiabatic processes.}$$

$$\boxed{Q_{1-2} = Q_{A-B}}$$

From figure B, consider a smooth closed curve representing a reversible cycle.

A reversible closed cycle curve is divided into no. of small Carnot cycles.

For a small Carnot cycle, Q_1 is heat supplied at T_1 and Q_2 is heat rejected at T_2 .

Thus according to absolute temperature scale for a reversible cycle,

$$\frac{\delta Q_1}{T_1} = \frac{\delta Q_2}{T_2}$$

Consider a sign convention for heat transfer, $-ve$ is for heat rejection.

$$\frac{\delta Q_1}{T_1} + \frac{\delta Q_2}{T_2} = 0$$

$$\text{For all small Carnot cycles, } \left(\frac{\delta Q_1}{T_1} + \frac{\delta Q_2}{T_2} \right) + \left(\frac{\delta Q_3}{T_3} + \frac{\delta Q_4}{T_4} \right) + \dots = 0$$

$$\boxed{\oint \frac{\delta Q}{T} = 0} \rightarrow \text{Clausius Theorem.}$$

Principle of increase of Entropy

The Clausius inequality states that whenever a closed system undergoes a cyclic process, the cyclic integral of $\frac{\delta Q}{T}$ is less than zero for an irreversible process. For reversible process, $\frac{\delta Q}{T}$ is zero.

$$\therefore \oint \frac{\delta Q}{T} \leq 0 \quad \text{--- (1)}$$

Let us know that change in entropy, $ds = \frac{\delta Q}{T}$

Since, entropy is a thermodynamic property and the cyclic integral of a thermodynamic property is zero, therefore (1) can be written \rightarrow

$$\oint \frac{\delta Q}{T} \leq \oint ds$$

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

$$ds \geq \frac{\delta Q}{T} \quad \text{--- (2)}$$

When the process is reversible, $ds = \frac{\delta Q}{T}$

When the process is irreversible, $ds > \frac{\delta Q}{T}$

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If we apply equation (2) to an isolated system like universe for which $\delta Q = 0$, then the equation (2) can be written as $ds > 0$

For a reversible cyclic process, $ds = 0$ (or) $s = \text{constant}$

For an irreversible process, $ds > 0$

Since in practice all processes are irreversible, therefore the entropy of such a system like universe goes on increasing \therefore This is known as principle of increase in entropy.

General Case for Change of Entropy of a Gas

Let 1 kg of gas at a pressure p_1 , volume v_1 , absolute temp T_1 , & Entropy s_1 , be heated to p_2, v_2, T_2 & s_2 respectively. By Law of Conservation of energy.

$$dq = du + dw = C_v dT + p dv$$

Dividing on both sides by T , we get

$$\frac{dq}{T} = \frac{C_v dT}{T} + \frac{p dv}{T}$$

$$ds = \frac{C_v dT}{T} + \frac{R dv}{v}$$

$$\therefore pv = RT$$

$$\frac{p}{T} = \frac{R}{v}$$

Integrating both sides, we get

$$\int_1^2 ds = C_v \int_{T_1}^{T_2} \frac{dT}{T} + R \int_{v_1}^{v_2} \frac{dv}{v}$$

$$\therefore s_2 - s_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} \quad (P.V) \text{ --- (1)}$$

$$s_2 - s_1 = C_v \ln \frac{p_2 v_2}{p_1 v_1} + R \ln \frac{v_2}{v_1} \quad \left[\because \frac{T_2}{T_1} = \frac{p_2 v_2}{p_1 v_1} \right]$$

$$= C_v \ln \frac{p_2}{p_1} + C_v \ln \frac{v_2}{v_1} + R \ln \frac{v_2}{v_1}$$

$$= C_v \ln \frac{p_2}{p_1} + (C_v + R) \ln \frac{v_2}{v_1}$$

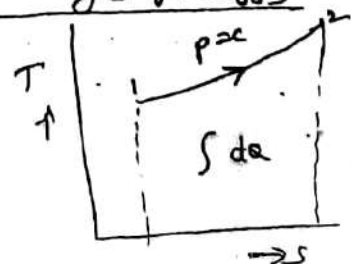
$$\therefore s_2 - s_1 = C_v \ln \frac{p_2}{p_1} + C_p \ln \frac{v_2}{v_1} \quad (P.V) \text{ --- (2)}$$

Simplifying, $s_2 - s_1 = C_p \ln \frac{T_2}{T_1} + R \ln \frac{p_1}{p_2} \text{ --- (3)}$

Entropy change in different reversible gas processes

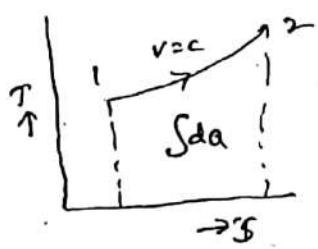
(i) Reversible Constant pressure process

$$ds = \int \frac{dq}{T} = \int \frac{m C_p dT}{T} = m C_p \ln \frac{T_2}{T_1}$$



② Reversible constant volume process

$$ds = \int \frac{dq}{T} = \int m c_v \frac{dT}{T} = m c_v \ln \frac{T_2}{T_1}$$



③ Reversible isothermal process

$$ds = \int \frac{dq}{T} = \int \frac{p dv}{T} = \int \frac{mR}{v} dv$$
$$S_2 - S_1 = mR \ln \frac{v_2}{v_1} = mR \ln \frac{p_1}{p_2}$$



④ Reversible adiabatic process

$$ds = \int \frac{dq}{T} = 0$$

⑤ Reversible polytropic process

$$ds = \int \frac{dq}{T} = \frac{\gamma - \eta}{\gamma - 1} \int \frac{dw}{T} = \frac{\gamma - \eta}{\gamma - 1} mR \ln \frac{v_2}{v_1} = \frac{\gamma - \eta}{\gamma - 1} m c_v \ln \frac{T_2}{T_1}$$
$$(S_2 - S_1) = \frac{\gamma - \eta}{\gamma - 1} \int \frac{p dv}{T} = \frac{\gamma - \eta}{\gamma - 1} mR \int \frac{dv}{v} = \frac{\gamma - \eta}{\gamma - 1} mR \ln \frac{v_2}{v_1}$$

Third Law of Thermodynamics:

Entropy is a measure of the uncertainty of molecular position in matter in either phase. This uncertainty of molecular position in matter is a function of temperature and it decreases as temperature decreases. It is due to different energy levels of molecules in the matter. The molecules of a substance becomes motionless at absolute zero temperature, thus having zero entropy.

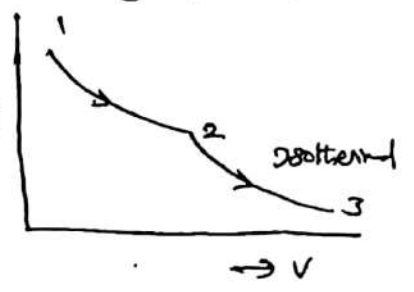
The entropy of a pure substance at absolute zero temperature is zero. This statement is known as Third law of Thermodynamics.

$$\lim_{T \rightarrow 0} S = 0$$

This law is useful in calculating the absolute entropy of a substance. This is also useful in calculating thermodynamic properties such as heat, temperature and is also useful in analysing chemical and phase equilibrium. This law is significant in explaining the behaviour of solids at low temperature.

PROB: The volume of 1 kg of air increases from 0.5 m³ to 1.3 m³ while its pressure decreases from 1 MPa to 250 kPa. Then 420 kJ of heat were added to it isothermally. Calculate the total entropy change for the system for the combined process. Assume for air $C_p = 1.005 \text{ kJ/kgK}$, $C_v = C_p - R = 0.718 \text{ kJ/kgK}$, $R = 0.287 \text{ kJ/kgK}$.

SOL: Process 1-2 (general process)
 $S_2 - S_1 = m C_v \ln \frac{P_2}{P_1} + m C_p \ln \frac{V_2}{V_1}$
 $= 1 \times 0.718 \ln \frac{250 \times 10^3}{1 \times 10^6} + 1 \times 1.005 \ln \frac{1.3}{0.5}$
 $= -0.035 \text{ kJ/K}$



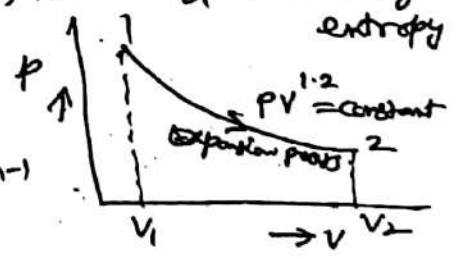
Process 2-3 Isothermal process

To find $\frac{V_3}{V_2}$, we know $Q_{2-3} = P_2 V_2 \ln \frac{V_3}{V_2}$
 $+ (420) \times 10^3 = 250 \times 10^3 \times 1.3 \ln \frac{V_3}{V_2}$
 $\therefore \frac{V_3}{V_2} = 3.64$
 $\therefore S_3 - S_2 = m R \ln \frac{V_3}{V_2} = 1 \times 0.287 \ln 3.64$
 $= 0.37 \text{ kJ/K}$

\therefore Total entropy change $= (S_3 - S_1) = (S_2 - S_1) + (S_3 - S_2)$
 $= -0.035 + 0.37 = 0.335 \text{ kJ/K}$

PROB: A closed system consists of 1 kg of air which is initially at 1.5 bar and 67°C. The volume doubles as the system undergoes a process according to the law $PV^{1.2} = c$. Find work done, heat transfer and change in entropy.

SOL: $m = 1 \text{ kg}$, $P_1 = 1.5 \text{ bar}$, $T_1 = 67 + 273 = 340 \text{ K}$
 $V_2 = 2V_1$; $\frac{V_2}{V_1} = 2$
 polytropic relation, $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$; $T_2 = \frac{T_1}{\left(\frac{V_2}{V_1}\right)^{\gamma-1}}$
 $T_2 = \frac{340}{(2)^{1.2-1}} = 295 \text{ K}$



(i) Work done $= \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{m R (T_1 - T_2)}{\gamma - 1} = 1 \times 0.287 \frac{[340 - 295]}{1.2 - 1}$
 $= 64.5 \text{ kJ}$ $[\because \text{take } R = 0.287 \text{ kJ/kgK}]$

(ii) Heat Transfer $Q = \frac{\gamma - \gamma_1}{\gamma - 1} \times \text{Work done} = \frac{1.4 - 1.2}{1.4 - 1} \times 64.5 = 32.25 \text{ kJ}$

(iii) Change of entropy, $(S_2 - S_1) = \frac{\gamma - \gamma_1}{\gamma - 1} \times m R \ln \frac{V_2}{V_1}$
 $= \frac{1.4 - 1.2}{1.4 - 1} \times 1 \times 0.287 \ln(2) = 0.099 \text{ kJ/K}$

PROB. A thermal energy source at 800 K loses 2000 kJ of heat to a sink at (a) 500 K and (b) 750 K. Determine which heat transfer is more irreversible.

SOL $T_{source} = 800 K$; $Q_{source} = 2000 kJ$; $T_{sink} = 750 K$.

The entropy change for each reservoir can be determined as $\Delta S = \frac{Q}{T}$

$$\Delta S_{source} = \frac{Q_{source}}{T_{source}} = \frac{-2000}{800} = -2.5 kJ/K$$

$$\Delta S_{sink} = \frac{Q_{sink}}{T_{sink}} = \frac{+2000}{500} = 4 kJ/K$$

$$\therefore \Delta S_{total} = \Delta S_{source} + \Delta S_{sink} = -2.5 + 4 = 1.5 kJ/K$$

(b) When heat is transferred to a sink at 750 K.

$$\Delta S_{source} = -2.5 kJ/K$$

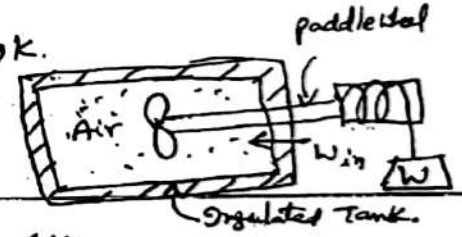
$$\Delta S_{sink} = \frac{2000}{750} = 2.7 kJ/K$$

$$\therefore \Delta S_{total} = -2.5 + 2.7 = +0.2 kJ/K$$

PROB. 1.5 kgs of air at 1 bar, 300 K is contained in a rigid insulated tank. During the process, 18 kJ of work is done on the gas through a paddle-wheel mechanism. Determine the final temp, final pressure of air in the tank and change in entropy. Assume specific heats of air to be constant.

SOL $C_p = 1.005 kJ/kgK$; $C_v = 0.716 kJ/kgK$.

For an insulated tank, heat transfer is zero. Paddle-wheel work is added to a system.



From a first law to a process,

$$Q = W_{paddle} + \Delta U; 0 = -18 kJ + \Delta U$$

$$\therefore \Delta U = 18 kJ = m C_v (T_2 - T_1)$$

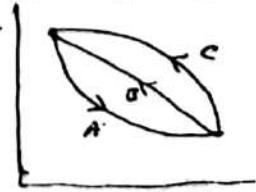
$$18 = 1.5 \times 0.716 [T_2 - 300]; T_2 = 316.76 K \text{ (or) } 43.76^\circ C$$

From constant volume process, $\frac{P_1}{T_1} = \frac{P_2}{T_2}; P_2 = P_1 \times \frac{T_2}{T_1} = 1 \times \frac{316.76}{300} = 1.0558 \text{ bar}$

Change of entropy, $\Delta S = m C_v \ln \frac{T_2}{T_1} = 1.5 \times 0.716 \ln \frac{316.76}{300} = 0.0584 kJ/K$

Entropy is a point (or) property function:-

The mathematical quantity $\int \frac{\delta Q}{T}$ is the property of a reversible line and is the a point function. Consider a system taken from initial state 1 to final state 2 by a reversible path A. Subsequently, the system may be brought back to initial state by the following reversible paths B (or) C. The paths A & B together constitute a reversible cycle and so A & C.



For a reversible cycle, $\int_1^2 \frac{\delta Q}{T} + \int_2^1 \frac{\delta Q}{T} = 0$; $\int_1^2 \frac{\delta Q}{T} + \int_2^1 \frac{\delta Q}{T} = 0$; $\int_1^2 \frac{\delta Q}{T} = - \int_2^1 \frac{\delta Q}{T}$

$\therefore \int_1^2 \frac{\delta Q}{T} = \int_1^2 \frac{\delta Q}{T}$; So, paths B & C, $\int \frac{\delta Q}{T}$ is same and is independent of path followed and depends only end states 1 & 2. So, Entropy is a point function.

GENERAL THERMODYNAMIC RELATIONS

The thermodynamic properties [pressure, volume and temperature] are directly measurable while the other properties [internal energy, enthalpy and entropy, U, H, S] are evaluated in terms of these measurable properties.

Thus, it is very important to develop the thermodynamic relations for properties which cannot be measured directly in terms of the combination of properties which can be measured directly (or) evaluated experimentally. There are other two important properties also which are known as Helmholtz function (F) and Gibbs function (G).

Helmholtz function (F):- is a property of a system and is given by subtracting the product of absolute temperature (T) and entropy (S) from the internal energy (U). Mathematically

$$\text{Helmholtz function, } F = U - TS.$$

Since $(U - TS)$ is made up entirely of properties, therefore, Helmholtz function is also a property.

Gibbs function (G):- The Gibbs function (also known as thermodynamic potential) is also a property of a system and is

denoted by G .

Mathematically, Gibbs function $G = (H - TS)$.

Exact differential. Suppose, Z is a function of two independent properties x and y .

$$Z = f(x, y)$$

According to condition of exact differentials,

$$dZ = \left(\frac{\partial Z}{\partial x}\right)_y dx + \left(\frac{\partial Z}{\partial y}\right)_x dy = M dx + N dy.$$

According to calculus,

$$\boxed{\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y}$$

* MAXWELL'S Equations

① Internal energy, $dU = \delta Q - \delta W$
 $= T ds - P dv$ [$\because \delta Q = T ds$ & $\delta W = P dv$]

The above equation is in the form,
 $dZ = M dx + N dy$

∴ Exact differential form, $\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$ — (1)

(2) Enthalpy $dH = dU + d(PV)$
 $= dU + PdV + VdP$ [∵ $dU = Tds + PdV$]
 $= (Tds + PdV) + PdV + VdP =$
 $\therefore dH = Tds + VdP.$

in exact differential form, $\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$ — (2)

(3) Helmholtz function $F = U - TS$
 $dF = dU - d(TS) = dU - Tds - SdT$
 $= (Tds + PdV) - Tds - SdT =$
 $= -PdV - SdT$

in exact differential form, $\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T$ — (3)

(4) Gibbs function $G = H - TS$
 $dG = dH - d(TS) = dH - Tds - SdT$
 $= Tds + VdP - Tds - SdT =$
 $= VdP - SdT$

in exact differential form, $\left(\frac{\partial V}{\partial T}\right)_P = \left(\frac{\partial S}{\partial P}\right)_T$ — (4)

These 4 equations are known as Maxwell's equations.

Isothermal coefficient of compressibility (K)

It is the ratio of rate of change of volume w.r. to its original volume to that of change in pressure at a given temperature.

$K = -\left(\frac{dV}{V}\right)_T = -\frac{1}{V} \left(\frac{dV}{dP}\right)_T$ —ve sign due to increase in pressure decreases volume.

Adiabatic compressibility (K_S): It is the ratio of rate of change of volume w.r. to its original volume to that of change in pressure under adiabatic conditions.

$K_S = -\left(\frac{dV}{V}\right)_S = -\frac{1}{V} \left(\frac{dV}{dP}\right)_{S=const.}$

Coefficient of volume expansion (β): It is the ratio of change of volume w.r. to original volume to that of change in temperature at const. pressure.

$\beta = \frac{1}{V} \left(\frac{dV}{dT}\right)_P$

* Tds equations :-

Since entropy may be expressed as a function of any other two properties e.g. temperature T and specific volume v. Then,

$$s = f(T, v)$$
$$ds = \left(\frac{\partial s}{\partial T}\right)_v \cdot dT + \left(\frac{\partial s}{\partial v}\right)_T \cdot dv \quad \text{--- (1)}$$

By multiplying with T, we get, $Tds = T \left(\frac{\partial s}{\partial T}\right)_v \cdot dT + T \left(\frac{\partial s}{\partial v}\right)_T \cdot dv$

But for a reversible constant volume change,
 $dq = C_v \cdot (dT)_v = T(ds)_v$

$$C_v = T \cdot \left(\frac{\partial s}{\partial T}\right)_v$$

$\Psi = U - TS = -SdT - PdV$
Helmholtz equation,

But $\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial p}{\partial T}\right)_v$ From Maxwell's

$$\therefore Tds = C_v \cdot dT + T \left(\frac{\partial p}{\partial T}\right)_v \cdot dv$$

This is First Tds equation.

Similarly,

$$s = f(T, p)$$

$$ds = \left(\frac{\partial s}{\partial T}\right)_p \cdot dT + \left(\frac{\partial s}{\partial p}\right)_T \cdot dp$$

By multiplying with T, $Tds = T \cdot \left(\frac{\partial s}{\partial T}\right)_p \cdot dT + T \cdot \left(\frac{\partial s}{\partial p}\right)_T \cdot dp$

For a constant pressure change,

$$dq = C_p (dT)_p = T(ds)_p$$

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

\therefore But, $\left(\frac{\partial s}{\partial p}\right)_T = -\left(\frac{\partial v}{\partial T}\right)_p$, from Gibbs' equation.
 $G = H - TS = -SdT + vdp$

$$\therefore Tds = C_p dT - T \left(\frac{\partial v}{\partial T}\right)_p \cdot dp \rightarrow \text{2nd Tds equation.}$$

Joule Thomson Co-efficient :- The change in temperature with drop in pressure at constant enthalpy is termed as Joule-Thomson Co-efficient. $\mu = \left(\frac{dT}{dp}\right)_h$. It varies with both temperature and pressure of the gas.

* The magnitude of the Joule Thomson Coefficient is a measure of the imperfection of a gas (or its deviation from perfect gas behaviour). When $\mu = 0$, temperature remains constant (Throttling).

PROB. Derive the equation $\left(\frac{\partial v}{\partial T}\right)_s \Big/ \left(\frac{\partial v}{\partial T}\right)_p = \frac{1}{\gamma - 1}$.

SOL.

For Thermodynamic properties, p, v, T , the cyclic relation is

given by $\left(\frac{\partial p}{\partial v}\right)_T \cdot \left(\frac{\partial v}{\partial T}\right)_p \cdot \left(\frac{\partial T}{\partial p}\right)_v = -1$ $\left[\because \left(\frac{\partial x}{\partial y}\right)_z \cdot \left(\frac{\partial y}{\partial z}\right)_x \cdot \left(\frac{\partial z}{\partial x}\right)_y = -1 \right]$ — (1)

Similarly for s, v, T $\cdot \left(\frac{\partial s}{\partial v}\right)_T \cdot \left(\frac{\partial v}{\partial T}\right)_s \cdot \left(\frac{\partial T}{\partial s}\right)_v = -1$ — (2)

From the equation (1), $\left(\frac{\partial v}{\partial T}\right)_p = -\frac{1}{\left(\frac{\partial p}{\partial v}\right)_T \cdot \left(\frac{\partial T}{\partial p}\right)_v}$ — (3)

From the equation (2), $\left(\frac{\partial v}{\partial T}\right)_s = -\frac{1}{\left(\frac{\partial s}{\partial v}\right)_T \cdot \left(\frac{\partial T}{\partial s}\right)_v}$ — (4)

By,

Equation (4) / Equation (3), we get $\frac{\left(\frac{\partial v}{\partial T}\right)_s}{\left(\frac{\partial v}{\partial T}\right)_p} = \frac{\left(\frac{\partial p}{\partial v}\right)_T \cdot \left(\frac{\partial T}{\partial p}\right)_v}{\left(\frac{\partial s}{\partial v}\right)_T \cdot \left(\frac{\partial T}{\partial s}\right)_v}$

* Since, from $dF = -sdT - pdv$

$\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial p}{\partial T}\right)_v$

$= \frac{\left(\frac{\partial s}{\partial T}\right)_v}{\left(\frac{\partial p}{\partial T}\right)_v} \times \left(\frac{\partial v}{\partial p}\right)_T$

But for, $\left(\frac{\partial s}{\partial T}\right)_v = \frac{C_v}{T}$, $\left(\frac{\partial p}{\partial T}\right)_v = \frac{p}{K}$, $\left(\frac{\partial v}{\partial p}\right)_T = -\gamma K$.

$\therefore \frac{\left(\frac{\partial v}{\partial T}\right)_s}{\left(\frac{\partial v}{\partial T}\right)_p} = \frac{C_v/T}{\left(\frac{p}{K}\right) \times (-\gamma K)} = \frac{C_v}{-T \cdot \frac{p}{K} \cdot \gamma}$

$= \frac{C_v}{C_p - C_v}$ $\left[\because -T \cdot \frac{p}{K} \cdot \gamma = C_p - C_v \right]$

$\therefore \frac{1}{\frac{C_p}{C_v} - \frac{C_v}{C_v}} = \frac{1}{\gamma - 1}$ proved

II B. Tech I Semester Regular Examinations, March - 2021
THERMODYNAMICS
 (Com to ME, AME)

Time: 3 hours

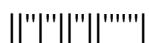
Max. Marks: 75

Answer any **FIVE** Questions each Question from each unit

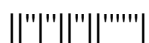
All Questions carry **Equal** Marks

- ~~~~~
- 1 a) What is a thermodynamic system? Explain different classes of systems with suitable examples. [8M]
 b) Compare macroscopic and microscopic approaches in thermodynamic studies? [7M]
 Or
- 2 a) What is a quasi-static process with example? [8M]
 b) The properties of a closed system will change following the relation between pressure and volume as $PV = 3.0$ where P is in bar, V is in m³. Calculate the work done when the pressure increases from 1.5 bar to 7.5 bar. [7M]
- 3 Write down the general equation for steady flow systems and simplify when applied for the following systems: [15M]
 (a) Steam turbine.
 (b) Steam nozzle.
 (c) Centrifugal compressor.
 (d) Condenser.
 Or
- 4 a) Define the first law of thermodynamics? [5M]
 b) A heat engine receives heat at the rate of 1500 kJ/min and gives an output of 8.2 kW. Determine: [10M]
 (i) The thermal efficiency.
 (ii) The rate of heat rejection
- 5 a) Define Carnot efficiency and which is the more effective way to increase the efficiency of a Carnot cycle: to increase T_1 keeping T_2 constant; or to decrease T_2 , keeping T_1 constant? Where T_1 is upper temperature and T_2 is lower temperature. [8M]
 b) Discuss the significance of Gibbs and Helmholtz functions. [7M]
 Or
- 6 a) Prove that entropy is a property of a system. [7M]
 b) 5 kg of air at 550 K and 4 bar is enclosed in a closed system. [8M]
 (i) Determine the availability of the system if the surrounding pressure and temperature are 1 bar and 290 K respectively.
 (ii) If the air is cooled at constant pressure to the atmospheric temperature, determine the availability
- 7 a) A mass of wet steam at temperature 165°C is expanded at constant quality 0.8 to pressure 3 bar. It is then heated at constant pressure to a degree of superheat of 66.5°C. Find the enthalpy and entropy changes during expansion and during heating. Draw the T-s and h-s diagrams. [8M]
 b) Explain about phase transformation and various properties involved during phase change? [7M]

Or



- 8 a) Discuss about triple point & critical point. [7M]
b) A pressure cooker contains 1.5 kg of saturated steam at 5 bar. Find the quantity of heat which must be rejected so as to reduce the quality to 60% dry. Determine the pressure and temperature of the steam at the new state. [8M]
- 9 a) Explain about adiabatic mixing of perfect gases. [7M]
b) A mixture of hydrogen (H_2) and oxygen (O_2) is to be made so that ratio of H_2 to O_2 is 2:1 by volume. If the pressure and temperature are 1 bar and 25 respectively, calculate: [8M]
(i) The mass of O_2 required.
(ii) The volume of the container
- Or
- 10 a) Explain about compressibility charts. [7M]
b) Explain the following [8M]
i) Heating and humidification
ii) Cooling and dehumidification.



II B. Tech I Semester Regular Examinations, March - 2021
THERMODYNAMICS
 (Com to ME, AME)

Time: 3 hours

Max. Marks: 75

Answer any **FIVE** Questions each Question from each unit
 All Questions carry **Equal** Marks

- ~~~~~
- 1 a) Briefly discuss about the work and heat transfer. [8M]
 b) A Gas of volume 6000CC at a pressure of 100 kPa is compressed quasi statically according to $PV^2 = \text{constant}$ until the volume becomes 2000CC. Determine the final pressures and work transfer. [7M]
- Or
- 2 a) Show that work is a path function and not a property. [7M]
 b) A gas under goes two processes: Process 1-2 expansion from pressure $P_1 = 340$ kPa and volume $V_1 = 0.0425 \text{ m}^3$ to pressure $P_2 = 136$ kPa, during which the P-V relation is given by $PV^2 = \text{constant}$. Process 2-3 constant pressure compression to volume $V_3 = V_1$. Sketch the processes on a P-V diagram and determine the work done. [8M]
- 3 a) Apply first law to a process and a cycle. [8M]
 b) A cyclic heat engine operates between a source temperature of 800°C and a sink temperature of 30°C . What is the least rate of the heat rejection per kW net output of the engine? [7M]
- Or
- 4 a) Define internal energy and prove that it is a property of the system. [7M]
 b) A system executes a cyclic process during which there are four transfers of heat as given below: $Q_{1-2} = 880$ kJ; $Q_{2-3} = 100$ kJ; $Q_{3-4} = -720$ kJ; $Q_{4-1} = 200$ kJ. The work transfers during the processes are given as: $W_{1-2} = 60$ kJ; $W_{2-3} = -40$ kJ; $W_{3-4} = 80$ kJ. Find W_{4-1} . [8M]
- 5 a) Explain in detail about Clausius inequality. [7M]
 b) Derive the Maxwell relations. [8M]
- Or
- 6 a) Explain the working of car not cycle and derive the expression for its thermal efficiency. [8M]
 b) Define about thermal reservoir and heat engine performance parameters? [7M]
- 7 a) Derive Clausius Clapeyron equation [8M]
 b) Using Clausius Clapeyron equation, estimate the enthalpy of vaporization at 220 saturation temperature. Take the following data $T_s = 220^\circ\text{C}$, $v_g = 0.086 \text{ m}^3/\text{kg}$, $v_f = 0.001109 \text{ m}^3/\text{kg}$, $(dP/dT) = 52 \text{ kPa/K}$. [7M]
- Or
- 8 a) A rigid vessel of capacity 0.2 m^3 holds 10 bar steam at 250°C . The vessel is slowly cooled till the steam pressure drops to 3.5 bar. Determine the (i) final temperature and dryness fraction of steam; (ii) change in entropy. [8M]
 b) Define critical-point phase transformation? [7M]

- 9 a) A mixture of ideal gases consists of 3 kg of nitrogen and 5 kg of carbon dioxide and at a pressure of 300 KPa and temperature of 20° C. Find (i) the mole fraction of each constituent, [10M]
(ii) the equivalent molecular weight of the mixture,
(iii) the equivalent gas constant of the mixture,
(iv) the partial pressures and partial volumes,
(v) the volume and density of mixture, and
(vi) the C_p and C_v of the mixture. If the mixture is heated at constant volume to 40° C, find the changes in internal energy, enthalpy and entropy of the mixture. If heating is done at constant pressure, calculate the changes in internal energy, enthalpy and entropy of the mixture. Take γ for CO_2 and N_2 to be 1.286 and 1.4 respectively.
- b) State van-der-Waals equation of state? [5M]
- Or
- 10 a) Explain about adiabatic mixing of perfect gases. [7M]
- b) State Dalton's law of partial pressures and Avogadro's laws of additive volumes. [8M]

II B. Tech I Semester Regular Examinations, March - 2021
THERMODYNAMICS
 (Com to ME, AME)

Time: 3 hours

Max. Marks: 75

Answer any **FIVE** Questions each Question from each unit
 All Questions carry **Equal** Marks

- ~~~~~
- 1 a) What is a system? Explain different types of systems with example. [8M]
 b) Explain the zeroth law of thermodynamics with neat sketch. Explain how it is important in establishing the temperature scale? [7M]
- Or
- 2 a) Explain the working of constant volume gas thermometer. [7M]
 b) A three process cycle operating with nitrogen as the working substance has constant temperature compression at 34°C with initial pressure 100 kPa. Then the gas undergoes a constant volume heating and then polytropic expansion with 1.35 as index of expansion. The isothermal compression requires -67 kJ/kg of work. Determine
 i) pressure, volume and temperature around the cycle
 ii) Heat in and out
 iii) Net work For Nitrogen gas $C_X=0.7431$ kJ/kg-K. [8M]
- 3 a) Explain Joule's experiment? [7M]
 b) Derive the steady flow energy equation and apply it to a Heat exchanger? [8M]
- Or
- 4 a) At the inlet to a certain nozzle the enthalpy of fluid passing is 2800 kJ/kg and velocity is 50 m/s. At the discharge end the enthalpy is 2600 kJ/kg. The nozzle is horizontal and there is negligible heat loss from it.(10m) [10M]
 (i) Find the velocity at exit of the nozzle.
 (ii) If the inlet area is 900 cm^2 and specific volume at inlet is $0.187\text{ m}^3/\text{kg}$ find mass flow rate.
 (iii) If the specific volume at the nozzle exit is $0.498\text{ m}^3/\text{kg}$, find the exit area of the nozzle.
 b) Write the corollaries of first law of thermodynamics? [5M]
- 5 a) Establish the equivalence of Kelvin- Planck and Clausius statements. [7M]
 b) Discuss about Carnot theorem with neat diagram. [8M]
- Or
- 6 a) Prove that entropy is a property of a system. [7M]
 b) 1 kg of air initially at 8 bar pressure and 380 K expands polytropically ($p v^{1.2} = \text{constant}$) until the pressure is reduced to one -fifth value. Calculate: [8M]
 (i) Final specific volume and temperature.
 (ii) Change of entropy, work done and heat interaction.
 (iii) Change in entropy.

- 7 a) Sketch the H-S and P-T diagram of a pure substance. [7M]
b) Describe with a neat sketch, separating throttling calorimeter for measuring the degree fraction of steam. [8M]

Or

- 8 a) A large, insulated vessel is divided into two chambers one containing 5 kg of dry saturated steam at 0.2 MPa and the other 10 kg of steam, 0.8 quality at 0.5 MPa. If the partition between the chambers is removed and the steam is mixed thoroughly and allowed to settle, find the final pressure, steam quality and entropy change in the process. [7M]
b) Draw the phase equilibrium diagram for a pure substance on T-s plot with relevant constant property lines. [8M]
- 9 a) A gaseous mixture consists of 1 kg of oxygen and 2 kg of nitrogen at a pressure of 150 kPa and a temperature of 20°C. Determine the changes in internal energy, enthalpy and entropy of the mixture when the mixture is heated to a temperature of 100°C (i) at constant volume and (ii) at constant pressure.. [8M]
b) Define the following [7M]
(i) Thermodynamic wet bulb temperature
(ii) Specific humidity
(iii) Saturated air

Or

- 10 a) State and prove Avogadro's law of additive volumes.. [8M]
b) Atmosphere air at 1.0132 bar has a dbt of 32°C and wbt of 26°C, compute i) the partial pressure of water vapour, ii) specific humidity, iii) dew point temperature, iv) relative humidity, v) degree of saturation, vi) density of air in the mixture, vii) density of vapour in the mixture, viii) enthalpy of the mixture. [7M]

II B. Tech I Semester Regular Examinations, March - 2021
THERMODYNAMICS
 (Com to ME, AME)

Time: 3 hours

Max. Marks: 75

Answer any **FIVE** Questions each Question from each unit
 All Questions carry **Equal** Marks

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- 1 a) Explain quasi – static process? What is its characteristic feature? [8M]  
 b) Which property of a system increases when heat is transferred. [7M]  
     i). at constant volume,  
     ii).at constant pressure.
- Or
- 2 a) A mass of 1.5 kg of air is compressed in a quasi-static process from 0.1 MPa to 0.7 MPa [8M]  
 for which  $pv = \text{constant}$ . The initial density of air is  $1.16 \text{ kg/m}^3$ . Find the work done by  
 the piston to compress the air.  
 b) Show that work is a path function and not a property [7M]
- 3 a) Define internal energy. How is energy stored in molecules and atoms? [7M]  
 b) A gas of mass 1.5 kg undergoes a quasi-static expansion which follows a relationship [8M]  
 $p = a + bV$ , where  $a$  and  $b$  are constants. The initial and final pressures are 1000 kPa and  
 200 kPa respectively and the corresponding volumes are  $0.20 \text{ m}^3$  and  $1.20 \text{ m}^3$ . The  
 specific internal energy of the gas is given by the relation:  $u = 1.5 pv - 85 \text{ kJ/kg}$ . Where  
 $P$  is the kPa and  $V$  is in  $\text{m}^3/\text{kg}$ . Calculate the net heat transfer and the maximum internal  
 energy of the gas attained during expansion.
- Or
- 4 a) Distinguish between reversible process and cyclic process. Write the causes of [7M]  
 irreversibility?  
 b) Derive the steady flow energy equation and apply in to steam nozzle and turbine. [8M]
- 5 a) A reversible heat engine operates between two reservoirs at temperatures of  $600^\circ\text{C}$  and [10M]  
 $40^\circ\text{C}$ . The engine drives a reversible refrigerator which operates between reservoirs at  
 temperatures of  $40^\circ\text{C}$  and  $-20^\circ\text{C}$ . The heat transfer to the engine is 2000 kJ and the net  
 work output of the combined engine-refrigerator plant is 360 kJ.  
     (i) Evaluate the heat transfer to the refrigerant and the net heat transfer to the  
     reservoir at  $40^\circ\text{C}$ .  
     (ii) Reconsider (i) given that the efficiency of the heat engine and the COP of the  
     refrigerator are each 40% of their maximum possible value.  
 b) Explain about heat engine and heat pump [5M]
- Or
- 6 a) What is the absolute thermodynamic temperature scale? Show that a definite point [8M]  
 exists on the absolute temperature scale but that this point cannot be reached without the  
 violation of the second law.  
 b) Write the Maxwell's equations and derive the first and second Tds equations. [7M]



- 7 a) Why cannot a throttling calorimeter measure the quality if the steam is very wet? [8M]  
How is the quality measured then?
- b) A steam boiler initially contains  $5 \text{ m}^3$  of steam and  $5 \text{ m}^3$  of water at 1 MPa. [7M]  
Steam is taken out at constant pressure until  $4 \text{ m}^3$  of water is left. What is the  
heat transferred during the process?
- Or
- 8 a) Describe with a neat sketch, separating throttling calorimeter for measuring the [8M]  
degree fraction of steam?
- b) Explain the properties during phase-change? [7M]
- 9 a) Define Compressibility factor 'Z'. Discuss the significance of the [7M]  
compressibility factor.
- b) Explain Beattie – Bridgeman equation of state? [8M]
- Or
- 10 a) Derive the expressions for the internal energy and specific heats for mixtures of [7M]  
ideal gases.
- b) Explain Psychometric properties of atmospheric air. [8M]

## I B. Tech II Semester Regular Examinations, September- 2021

**THERMODYNAMICS**

(Only ME)

Time: 3 hours

Max. Marks: 70

**Answer any five Questions one Question from Each Unit**  
**All Questions Carry Equal Marks**

**UNIT-I**

- 1 a) What is a thermodynamic system? Explain different classes of systems with suitable examples. (7M)
- b) A balloon is filled with air (200 kPa and 300K) such that it becomes as sphere of diameter 1m. It is then gradually heated till the pressure rises to 500 kPa. Determine the amount of work done during the process, assuming that the pressure inside the balloon is proportional to the diameter of the balloon. (7M)

Or

- 2 a) Discuss exact and inexact differentials. (7M)
- b) Explain what do you understand by concept of continuum? How will you define density and pressure using this concept? (7M)

**UNIT-II**

- 3 a) State the first law of thermodynamics and prove that for a non-flow process, it leads to the energy equation. (7M)
- b) Explain joule's Experiment. (7M)

Or

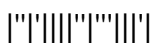
- 4 a) Define internal energy and prove that it is a property of the system. (7M)
- b) A system executes a cyclic process during which there are four transfers of heat as given as follows:  $Q_{12} = 880$  kJ;  $Q_{23} = 100$  kJ;  $Q_{34} = -720$  kJ;  $Q_{41} = 200$  kJ. The work transfers during the processes are given as:  $W_{12} = 60$  kJ;  $W_{23} = -40$  kJ;  $W_{34} = 80$  kJ. Find  $W_{41}$ . (7M)

**UNIT-III**

- 5 a) Given an expression for entropy changes for an open system. (5M)
- b) An ice plant working on a reversed Carnot cycle heat pump produces 15 ton of ice per day. The ice is formed from water at  $0^{\circ}\text{C}$  and the formed ice is maintained at  $0^{\circ}\text{C}$ . The heat is rejected to the atmosphere at  $25^{\circ}\text{C}$ . The heat pump used to run the ice plant is coupled to a Carnot engine which absorbs heat from a source which is maintained at  $220^{\circ}\text{C}$  by burning liquid fuel of 44500 kJ/kg calorific value and rejects the heat to the atmosphere. Determine: (i) Power consumed by the engine. (9M)  
(ii) Fuel consumed per hour. Take enthalpy of fusion of ice = 334.5 kJ/kg.

Or

- 6 a) Two blocks of metal, each having a mass of 10 kg and having a specific heat of 0.4 kJ/kg.K, are at a temperature of  $40^{\circ}\text{C}$ . A reversible refrigerator receives heat from one block and rejects heat to the other. Calculate the work required to cause a temperature difference of  $100^{\circ}\text{C}$  between the two blocks. (7M)
- b) Define Kelvin –Planck and Clausius statements. Prove that violation one Statement leads to a violation of the other Statement. (7M)



## UNIT-IV

- 7 a) Write the clapeyron equation and point out its utility. (7M)  
b) Steam initially at 0.3 MPa, 250°C is cooled at constant volume. (7M)  
i) At what temperature will steam become superheated vapour?  
ii) What is the quality of steam at 80°C?  
iii) What is the heat transferred per kg of steam in cooling from 250°C to 80°C.  
Or
- 8 a) In a separating and throttling calorimeter the pressure of the steam before throttling is 10bar. The pressure and temperature of steam after throttling is 1.1 bar and 110°C respectively. At the separator 0.6 kgs of water is trapped and 3.4 kgs of condensed water is collected from the condenser. Determine the dryness fraction of steam in the main pipeline. Take  $C_p$  for superheated steam as 2.1 kJ/kg k. (7M)  
b) Discuss about triple point, critical temperature and critical pressure. (7M)

## UNIT-V

- 9 a) Define the terms Specific humidity, Relative humidity and Degree of saturation. (7M)  
Draw the same on Psychometric chart.  
b) Methane has a specific heat at constant pressure given by  $C_p = 17.66 + 0.06188T$  (7M)  
kJ/kg mol K when 1 kg of methane is heated at constant volume from 27°C to 500°C. If the initial pressure of the gas is 1 atm, calculate the final pressure, the heat transfer, the work done and the change in entropy.  
Or
- 10 a) State and explain the importance of internal energy and enthalpy of gas mixtures. (7M)  
b) A sling psychrometer reads 39°C dry bulb Temperature and 35°C wet bulb (7M)  
Temperature. Find the humidity ratio, Relative humidity, dew point Temperature, specific volume, and enthalpy of air.



**II B. Tech I Semester Supplementary Examinations, September - 2021**  
**THERMODYNAMICS**  
 (Com to ME, AME)

Time: 3 hours

Max. Marks: 75

Answer any **FIVE** Questions each Question from each unit  
 All Questions carry **Equal** Marks

- 1 a) Define the following terms: i) Thermodynamics ii) Macroscopic approach iii) Continuum.  
 b) A gas initially at 100 kPa and 6000 cm<sup>3</sup>. The final volume is 2000 cm<sup>3</sup>. Determine the moving boundary work for each of the following processes.  
 (i) P is inversely proportional to V (ii) PV<sup>2</sup> = constant (iii) P is inversely proportional to V.

Or

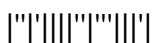
- 2 a) Classify the types of systems; explain with examples.  
 b) A fluid at a pressure of 3 bar and with specific volume of 0.18 m<sup>3</sup>/kg contained in a cylinder behind a piston expands reversibly to a pressure of 0.6 bar according to a law,  $p=c/v^3$  where c is a constant. Calculate the work done by the fluid on the piston.
- 3 a) Define enthalpy. How is it related to internal energy?  
 b) Calculate the power developed and diameter of the inlet pipe, if a gas enters the gas turbine at 5 kg/sec, 50 m/s with an enthalpy of 0.9 MJ/kg. The heat loss to the surrounding is 0.025 MJ/kg. The heat loss to the surrounding is 0.025 MJ/kg. The heat loss to the surrounding is 0.025 MJ/kg. Assume 100 kPa and 300 K at the inlet.

Or

- 4 a) Describe the classic paddle wheel experiment performed by Joule. What conclusion was drawn based on the experimental observations (Joule experiment).  
 b) Calculate the power developed and diameter of the inlet pipe, if a gas enters into the gas turbine at 5 kg/sec, 50 m/s with an enthalpy of 0.9 MJ/kg. The heat loss to the surrounding is 0.025 MJ/kg. The heat loss to the surrounding is 0.025 MJ/kg. The heat loss to the surrounding is 0.025 MJ/kg. Assume 100 kPa and 300 K at the inlet.
- 5 a) Explain the Availability in a thermodynamic system with example.  
 b) A heat engine working on Carnot cycle converts 1/5th of the heat input into work. When the temperature of the sink is reduced by 80°C, the efficiency gets doubled. Determine the temperature of sink?

Or

- 6 a) Define Gibb's and Helmholtz's functions? Compare the importance of them?  
 b) A domestic food freezer maintains a temperature of -15°C, the ambient air temperature is 30°C, if heat leaks into the freezer at the continuous rate of 1.75 kJ/sec. State the least power necessary to pump this heat out continuously?



- 7 a) Why can not a throttling calorimeter measure the quality, if the steam is wet? Explain how the quality is been measured?  
b) 1 kg of water fills a 150 L rigid container at an initial pressure of 2MPa. The container is then cooled to 40<sup>0</sup>C. Determine the initial temperature and final pressure of the water.

Or

- 8 a) Explain the saturation temperature, the changes in specific volume, enthalpy and entropy during evaporation at 1MPa.  
b) A vessel of volume 0.04 m<sup>3</sup> contains a mixture of saturated water and steam at a temperature of 250<sup>0</sup>C. The mass of the liquid present is 9 kg. Find the pressure, mass, specific volume, enthalpy, entropy.
- 9 a) Explain the Mole fraction and Mass fraction in the Mixture of Perfect gas? Derive a relation between them.  
b) Saturated air at 210<sup>0</sup>C is passed through a dryer, so that its final relative humidity is 20%. The dryer uses silica gel absorbent. The air is then pass through a cooler until its final temperature is 210<sup>0</sup>C without a change in specific humidity. Find out i) the temperature of air at the end of the drying process, ii) the relative humidity at the end of the cooling process, iii) The dew point temperature at the end of the drying process?

Or

- 10 a) Air at 10bar and a DBT of 400<sup>0</sup>C and WBT of 360<sup>0</sup>C. Compute degree of saturation, dew point temperature and enthalpy of the mixture?  
b) Enumerate different psychometric processes.

