ANNAMACHARYA UNIVERSITY

EXCELLENCE IN EDUCATION; SERVICE TO SOCIETY
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RAJAMPET-516126:A.P; INDIA

DEPARTMENT OF MECHANICAL ENGINEERING

LECTURE NOTES

BASIC THERMODYNAMICS
[24AMEC31T]

Prepared by
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Title of the Course: Basic Thermodynamics
Category: ES
Year: II
Semester: I
Course Code: 24AMEC31T
Branch: ME

Lecture Hours	Tutorial Hours	Practice Hours	Credits
3	0	0	3

Course Objectives:
1. To impart the awareness on laws of thermodynamics.
2. To enable the students to understand second law of thermodynamics and its applications to various systems.
3. To familiarize steam properties to understand working of steam power plants.
4. To acquire knowledge on equations of state and properties of gas mixtures.
5. To understand the inter-relationship between various air standard cycles used in gas power cycles.

Course Outcomes:
At the end of the course, the student will be able to
1. apply the first law of thermodynamics for various energy systems
2. analyze the performance of thermal engineering devices by using Second law of Thermodynamics.
3. solve the properties of pure substances by using steam tables.
4. calculate the P-V-T properties of gases and mixtures.
5. analyze the Air standard cycles by using the thermodynamic principles

Unit 1 Basic Concepts & First Law of Thermodynamics 12
System, Control Volume, Surrounding, Boundaries, Universe, Types of Systems, Macroscopic and Microscopic viewpoints, Concept of Continuum, Thermodynamic Equilibrium, State, Property, Process, Cycle – Reversibility, Quasi – static Process, Irreversible Process, Causes of Irreversibility – Energy in State and in Transition - Types, Work and Heat, Point and Path function.
Zeroth Law of Thermodynamics –Ideal Gas Scale – PMM I - Joule's Experiments – First law of Thermodynamics – Corollaries – First law applied to a Process – applied to a flow system – Steady Flow Energy Equation

Unit 2 Second Law of Thermodynamics 12
Limitations of the First Law – Thermal Reservoir, Heat Engine, Heat pump, Parameters of performance, Second Law of Thermodynamics, Kelvin-Planck and Clausius Statements and their Equivalence / Corollaries, PMM of Second kind, Carnot's principle, Carnot cycle and its specialties, Thermodynamic scale of Temperature.
Clausius Inequality, Entropy, Principle of Entropy Increase – Energy Equation, Availability and Irreversibility Elementary Treatment of the Third Law of Thermodynamics.

Unit 3 Properties of Pure Substances 10

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

Thermodynamic relations: -Thermodynamic Potentials, Gibbs and Helmholtz Functions, Maxwell Relations.

Unit 4   Perfect Gas Laws & Mixture Of Perfect Gases   13

Equation of State, specific and Universal Gas constants – various Non-flow processes, properties, end states, Heat and Work Transfer, changes in Internal Energy – Throttling and Free Expansion Processes – Flow processes – Deviations from perfect Gas Model – Vander Waals Equation of State – Compressibility charts – variable specific Heats – Gas Tables.

Mole Fraction, Mass fraction Gravimetric and volumetric Analysis – Dalton's Law of partial pressure, Avogadro's Laws of additive volumes – Mole fraction, Volume fraction and partial pressure, Equivalent Gas constant and Molecular Internal Energy, Enthalpy, specific heats and Entropy of Mixture of perfect Gases and Vapour.

Unit 5   Air Standard Cycles   06

Otto, Diesel and Dual cycles, P-V and T -S diagrams - Description and Efficiencies- Mean effective pressures. Comparison of Otto, Diesel and Dual cycles.

Prescribed Textbooks:
1. Engineering Thermodynamics. PK Nag, TMH, 6th edition,2017.
2. Thermodynamics – An Engineering Approach. Yunus Cengel& Boles, TMH. Mcgraw Higher Education 9th edition, 2019.

Reference Books:
1. Fundamentals of Thermodynamics. Sonntag, Borgnakke and Van wylen, John Wiley & sons (ASIA) Pt Ltd. Publisher: Wiley; 8 edition (December 26, 2012).
2. Thermodynamics. Mc Graw Hill J. P. Holman, McGraw-Hill College; 4th edition (January 1, 1988).
3. An introduction to Thermodynamics. YVC Rao, Universities Press, 3rd edition 2004.
4. Engineering Thermodynamics, Jones & Dugan, PHI INDIA (2011).
5. Basic Engineering Thermodynamics. A. Venkatesh, Universities Press; First edition (2007).

Web resources:
1. https://www.youtube.com/watch?v=9GMBpZZtjXM&list=PLD8E646BAB3366BC8
2. https://www.youtube.com/watch?v=pMmHdWvN_FI&list=PLyqSpQzTE6M_QOKxVxZ5nQ48gOkzg7zWP&index=1
3. https://www.youtube.com/watch?v=2LPQX4F-GoA&list=PLwdnzlV3ogoWV-_n1YItO933MxgPXfEiM
4. https://www.youtube.com/watch?v=ZXHbqJj5mk4&list=PLjA7uIhseb0-tML7elONaelFTts6xoG5B

CO-PO Mapping:

Course Outcomes	Engineering Knowledge	Problem Analysis	Design/Development of solutions	Conduct investigations of complex problems	Engineering tool usage	The Engineer and the World	Ethics	Individual and Collaborative Team work	Communication	Project management and finance	Life-long learning	PSO1	PSO2
24AMEC31T.1	3	2	1	1	-	-	-	-	1	-	1	2	2
24AMEC31T.2	3	3	1	1	-	-	-	-	1	-	1	2	3
24AMEC31T.3	3	2	1	1	-	-	-	-	1	-	1	2	1
24AMEC31T.4	3	2	1	1	-	-	-	-	1	-	1	2	1
24AMEC31T.5	3	3	1	1	-	-	-	-	1	-	1	2	2

UNIT - I   INTRODUCTION   BASIC CONCEPTS

THERMODYNAMICS :-

→ It is the science which deals with Energy.

→ Energy can be viewed as the ability to cause changes.

→ Thermodynamics includes the aspects of energy & energy transformation, energy conversions, including power generation, refrigeration. & energy savings.

→ It studies the relationship b/w the properties of system.

→ It is based upon the observation of common experience which have been formulated into thermodynamic laws.

$$\text{Thermodynamics} \atop \text{(Greek word)} \left[\begin{array}{l} \longrightarrow \text{Therme (heat)} \\ \\ \longrightarrow \text{Dynamics (power or force)} \end{array} \right.$$

(✱) Thermodynamics is based on four laws namely zeroth, first, second & third law of thermodynamics.

→ Zeroth law builds the knowledge of thermal equilibrium and establishes the concept of temperature.

→ First law introduces the concept of internal energy.

→ Second law introduces the concept of Entropy.

→ Third law enables the evaluation of absolute entropy.

Applications of Thermodynamics :-

All activities in nature involve some interactions b/w energy & matter.

→ Human body, where heart is pumping the blood to all parts of human body. Various energy conversions occur in body cells & the heat generated by the body is constantly rejected to the environment.

→ Many house hold appliances are designed by using the principles of thermodynamics. Some of the examples are

⇒ Heating & air conditioning systems

⇒ Refrigerators, humidifiers & pressure cookers

⇒ Water heater, shower & the iron

⇒ Even the computer & T.V.

→ Thermodynamics plays a major part in the design & analysis of

⇒ Automotive engines

⇒ Rockets & jet engines

⇒ Conventional or nuclear power plants & solar collectors

⇒ Design of vehicles from car to aeroplanes.

⇒ Design of turbines

⇒ In chemical process plants & many industrial applications etc

SYSTEM

A system is defined as a quantity of matter or a region in space chosen for study.

Surroundings :-

The mass or region outside the system is called surroundings.
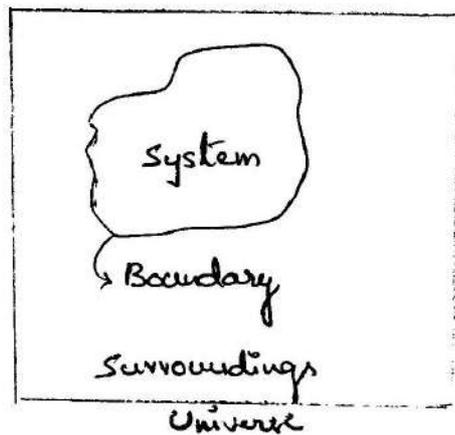
Boundary :-
The real or imaginary surface that seperates the system from its surroundings is called the boundary. It may be fixed or movable.

Boundary has zero thickness, and thus it can neither contain any mass nor occupy any volume in space.

Universe :-

System & surroundings together comprises as Universe.

Universe = System + Surroundings.

* In order to understand this concept, best example is piston & cylinder arrangement. It has 3 fixed & one movable boundary.

Types of Systems :-
① closed system ② open system ③ Isolated system.

① **Closed system** :- In this system, mass remains constant within the boundary of the system & energy
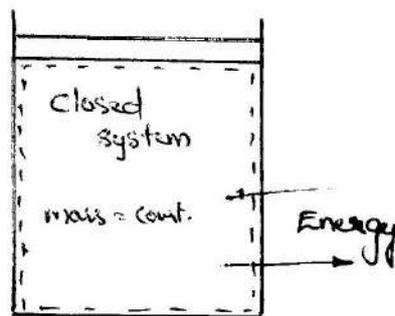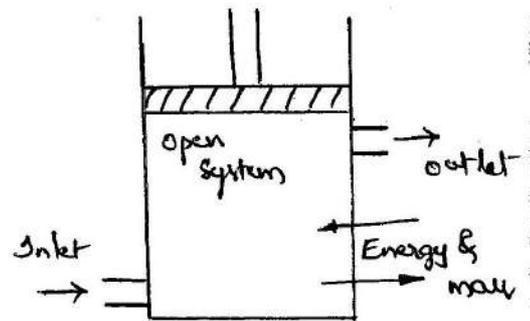
may transfer across its boundary.

Ex :- Gas contained in piston cylinder arrangement with non-flow process.

In this case when the gas is heated, no mass transfers across the boundary, but the volume may get changed. So energy transfer takes place.

② Open System :- (control volume)

Both mass & energy transfer across the boundary.

Ex :- Compressor, Gas turbines, engines etc.

③ Isolated System :-

Neither mass nor energy get transfer across its boundaries.

Ex :- A fluid enclosed in a perfectly insulated closed vessel. (thermoflask).

A system may be classified as

* Homogeneous
* Heterogeneous

(i) Homogeneous System :- If the system consists of single phase it is called as homogeneous system. It may be either solid, liquid or gaseous state.

Ex :- Mixture of gases, water + nitric acid

(ii) Heterogeneous System :- If the system consists of more than one phase it is called heterogeneous system.

Ex :- water & steam, ice & water, water & oil etc.

# Difference b/w closed systems & open systems:

| Closed System	Open System
① Only energy crosses the boundary.	① Both mass & energy crosses the boundary.
② System contains fixed or constant amount of mass.	② System contains varying amount of mass.
③ It is not very complicated.	③ It is complicated due to the movement of fluids.
④ Boundary of the system doesnot allow the matter to flow in or out of the system.	④ Boundary of the system allows the matter to flow in or out of the system.
⑤ Offenly used in analysis.	⑤ Used in most of applications.
⑥ Ex: Piston cylinder arrangement without valves.	⑥ Ex:- Engines, compressor, turbines, heaters, power plants etc.

Control volume & Control surface:

For thermodynamic analysis an open system * (compressor) is considered.
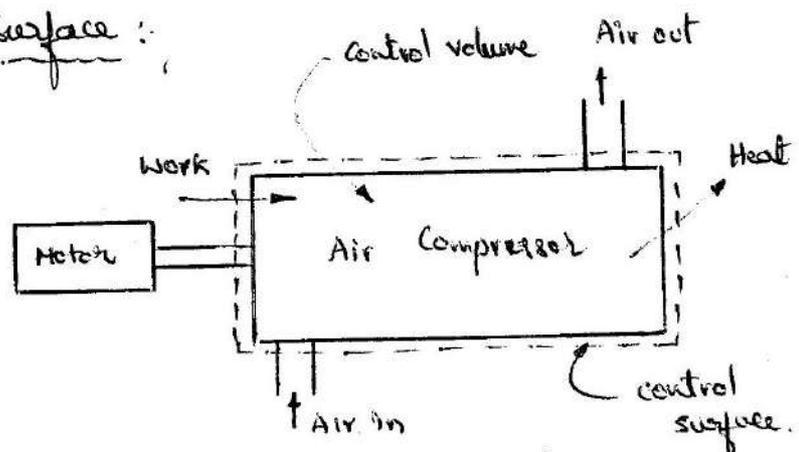

    If the volume of a system under study remains constant then that volume is called control volume. The control volume is surrounded by a control surface. Matter as well as energy crosses the control surface.

State :- State is the condition of a system at an instant of time described by its properties such as pressure, temp, density etc.
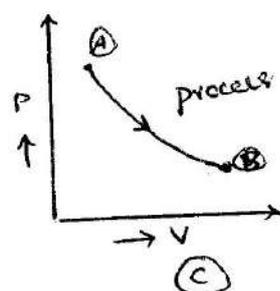
Points ① & ② in the figure shows two different states of a system.
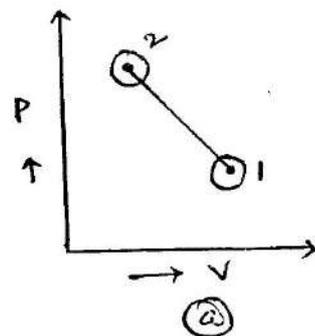
Path :- A thermodynamic system passing through a series of states constitutes a path. (or) It is a line through which system passes when it undergoes a change in state.
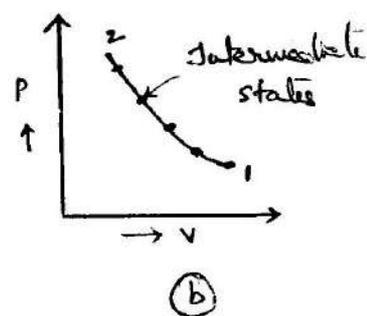
Process :- A process is defined as a transition in which a system changes from initial state to a final state.

Ex:- For example state A is the initial state of the system. Due to expansion of the system the final state is B. The line AB is the process that has taken place. as shown in the figure ©

Thermodynamic Cycling (or) Cyclic process :-

If a system undergoes a number of different processes and finally reaches to its initial state by forming a complete cycle then it is known as Cyclic process.
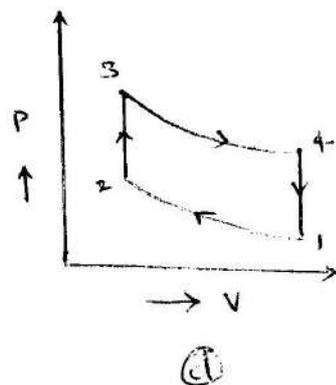
Thermodynamic Equilibrium :-

A system is said to be in a state of thermodynamic equilibrium if there is no change in any property at all points in a system.

A system will be in a state of thermodynamic equilibrium if the following equilibrium are satisfied.

① **Mechanical Equilibrium :-** A system is said to be in a state of mechanical equilibrium if there no unbalanced forces within the system and/or b/w system & surroundings. [pressure should be constant]

② **Chemical Equilibrium :-** There should not be any chemical reaction within the system and b/w system & surroundings.

③ **Thermal Equilibrium :-** If there exists an uniformity of (or) (Equality of temperature) temperature throughout system or b/w the system & surroundings.

④ **Electrical Equilibrium :-** If there exists an uniformity of electrical potential throught the system.

Quasi-Static Process :- (Quasi-Equilibrium process)

Let us consider a system of gas contained in a cylinder. The system initially is in an equilibrium state, represented by the properties P_1, V_1, t_1. The weight on the piston just balances the upward force exerted by the gas. If the weight is removed, there will be an unbalanced force b/w the system & surroundings and under gas pressure, the piston will move up till it hits the stops. The system again comes to an equilibrium

state, being described by the properties P_2, V_2, t_2. But the intermediate states passed through by the system are non-equilibrium states which cannot be described by thermodynamic coordinates. Figure shows point ① & ② as the initial & final equilibrium states joined by a dotted line, which has got no meaning otherwise.

Such a process, which is but a locus of all the equilibrium points passed through by the system, is
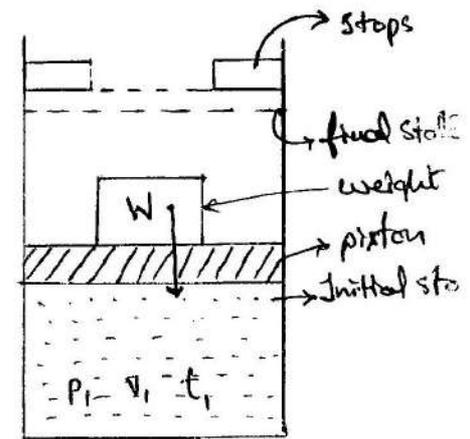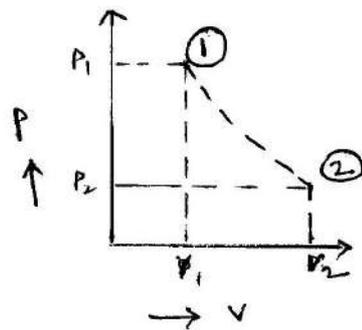
known as a quasi-static process, quasi means 'almost'. Infinite slowness is the characteristic feature of a quasi static process. A quasi-static process is then a succession of equilibrium states. A quasi-static process is also called as reversible process.

MICROSCOPIC & MACROSCOPIC APPROACHES :-

Let us consider a gas filled in the container which is containing number of molecules. These molecules will have certain characteristics like position, momentum, velocity, pressure etc

The analysis of thermodynamic system can be explained in two ways.

→ Microscopic view

→ Macroscopic view.

Microscopic Approach :-

This approach considers a system being composed of large no. of particles known as molecules. Each molecule is having different energy & velocity.

These values constantly changes with time as the molecules collide with one another. So the microscopic approach is considered with structure of matter hence it is also called as Statistical thermodynamics.

Ex:- velocity, K.E, momentum etc.

Macroscopic Approach :-

A macroscopic approach is concerned with certain quantity of matter by taking into account which is going at guage level or overall level behaviour. Hence it is referred as classical thermodynamics.

Ex:- pressure, volume, temperature etc.

If a pressure guage is fitted to the gas filled container the pressure can be measured at any instant.

It is very difficult to measure the physical parameters such as pressure, temperature, volume, impulse etc., with microscopic approach.

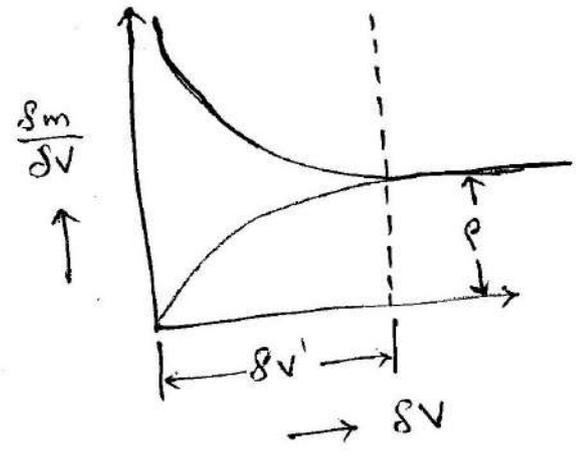| MICROSCOPIC VIEW	MACROSCOPIC VIEW
① Every molecule in the matter have its own properties & they move with independent velocities.	① It is assumed that all the molecules behave in the same manner in the system.
② Large no. of variables are required for describing a system.	② Only few variables are required to describe the system.
③ Measurement of variable is very difficult.	③ The properties are easily measured at any point of time with the help of guages.
④ Time required for measuring the variables is more.	④ Time required for measuring the variables is less.
⑤ Both mathematical & statistical methods are required for describing a system.	⑤ Simple mathematical formulae are sufficient for analysis.
⑥ It explains the structure of matter.	⑥ It don't explain the structure of matter.
⑦ It is limited to fewer applications of engineering problems.	⑦ It provides an easy way to the solution of engineering applications.
⑧ It is also known as Statistical thermodynamics.	⑧ It is also known as classical thermodynamics.

Concept of Continuum :-

It is very much useful in classical thermodynamics. From the continuum point of view, the matter is seen as being distributed through space & not as in the particle view, localised. Matter exists in big chunks having mass, energy & momentum as do particles, but it also possesses some additional continuum characteristics such as Volume, density & temp etc.

In otherwords continuum idealisation toreat the substance as being continous disregarding the action of individual molecules.
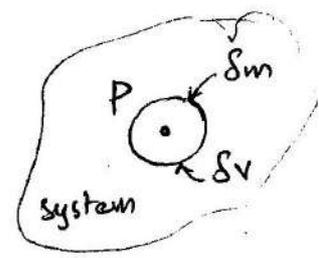
Let us consider the mass δm in a volume δv surrounding the point P. The ratio $\delta m / \delta v$ is the avg mass density of the system within the volume δv. We suppose that at first δv is rather large, and is subsequently shrunk about the point P. If we plot $\delta m / \delta v$ against δv, the avg density tends to approach an asymptote as δv increase. However when δv becomes so small as to contain relatively few molecules, the avg density fluctuates substantially with time as molecules pass into & out of the volume in random motion & so it is impossible to speak of a definite value of $\delta m / \delta v$. The smallest volume which may be regarded as continous is $\delta v'$.
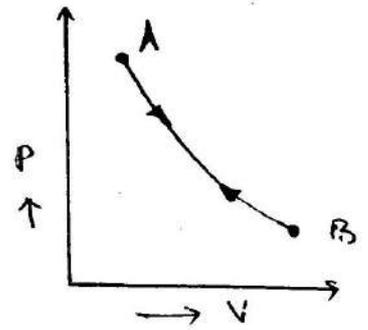
Mathematically, density at a point may be expressed as,

$$\rho = \lim_{\delta v \to \delta v'} \frac{\delta m}{\delta v} \quad Kg/m^3$$

where $\delta v'$ is the smallest volume about point P in which the fluid can be called in continuum.

REVERSIBILITY (or) IDEAL PROCESS :-

A reversible process is one which is performed in such a way that at conclusion of the process, both the system & surroundings may be restored to their initial states, without producing any changes in the rest of the universe.

Let the state of a system be represented by A & let the system be taken to state B by following the path A-B. If the system & also the surroundings are restored to their initial states & no change in the universe is produced, then the process A-B will be a reversible process.

A reversible process is carried out infinitely slowly with an infinitesimal gradient, so that every state passed through by the system is an equilibrium state. So a reversible process coincides with a quasi-static process.

Ex :-
→ Frictionless relative motion
→ Electrolysis process
→ Polytropic expansion or compression of a fluid.
→ Isothermal expansion or compression.

Irreversible Process (Irreversibility) :-

Any natural process carried out with a finite gradient is an irreversible process. A reversible process which consist

of a succession of equilibrium states, is an idealized hypothetical process, approached only as a limit. It is said to be an asymptote to reality. All spontaneous processes are irreversible. Time has an important effect on reversibility. If the time allowed for a process to occur is infinitely large, even though the gradient is finite, the process becomes reversible. However, if this time is squeezed to a finite value, the finite gradient makes the process irreversible.

Ex:-

→ Fluid flow with friction
→ Combustion of air & fuel.
→ Plastic deformation
→ Heat transfer ... etc.

Causes of Irreversibility :-

The irreversibility of a process may be due to either one or both of the following.

→ Lack of equilibrium during the process.
→ Involvement of dissipative effects.

Irreversibility due to lack of equilibrium :-

The lack of equilibrium (mechanical, thermal or chemical) b/w the system & its surroundings, or b/w two systems or two parts of the same system, causes a spontaneous change which is irreversible.

The following are specific examples in this regard.

(a) Heat transfer through a finite temp difference.

(b) Lack of pressure equilibrium within the interior of the system or b/w the system & the surroundings.

(c) Free expansion.

Irreversibility due to Dissipative Effects :-

The irreversibility of a process may be due to the dissipative effects in which work is done without producing an equivalent increase in the kinetic or potential energy of any system. The transformation of work into molecular internal energy either of the system or of the reservoir takes place through the agency of such phenomena as friction, viscosity, inelasticity, electrical resistance & magnetic hysteresis. These effects are known as dissipative effects & work is said to be dissipa[...]
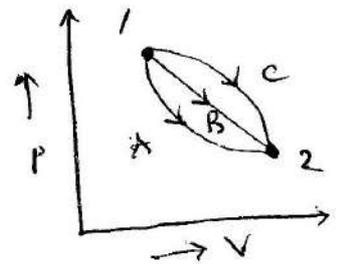
Ex:- (a) Friction
(b) Paddle-wheel work transfer
(c) Transfer of electricity through a ~~reservoir~~. resistor.

Point functions & path functions :-

→ Thermodynamic properties are the point functions for a given state where there is one & only one value for each property. This can be located on a graph with a point. This is also known as state functions. These are exact differentials.

Ex: pressure, vol, temp etc.

$$\int_1^2 dp = P_2 - P_1 \quad ; \quad \int_1^2 dV = V_2 - V_1 \quad ; \quad \int_1^2 dT = T_2 - T_1$$

→ Path functions are certain quantities which cannot be located on a graph by a point. These are generally given by area under the curve. These are inexact or partial differentials.

Ex:- Heat, work, ~~energy~~ etc.

$$\int_1^2 \delta Q \neq Q_2 - Q_1 \qquad : \qquad \int_1^2 \delta w \neq w_2 - w_1$$

Point function	Path functions
① change in function depends only on initial & final state of a process ie., point function	① The change in a function depends on a path followed by a system ie., path functions.
② Functions does not depend on path followed by the system.	② Functions depends on path followed by the system.
③ Differentials are exact & perfect.	③ Differentials are inexact or partial
④ pressure, vol, temp etc.	④ Ex: work, energy etc.

Work :-

Work is the energy transferred (with transfer of mass) because of a property difference (other than temp) that exists b/w the system & surroundings.

work = force × displacement N-m (or) Joule.

Energy :-

Energy is the capacity to do work. In other words, energy is defined as capacity to exert a force through a distance.

It can be classified into
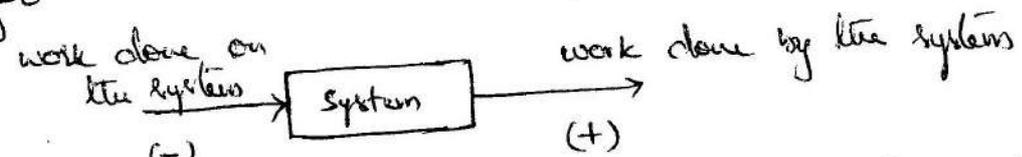
→ Stored energy (PE, KE, IE etc)

→ Energy in transit. (Heat, work, electricity etc)

Energy possessed by a system when it is static is called energy in state ie., stored energy. It is also known as internal energy.

Energy in transition are mainly

ⓐ Work transfer

ⓑ Heat transfer

Work transfer :-

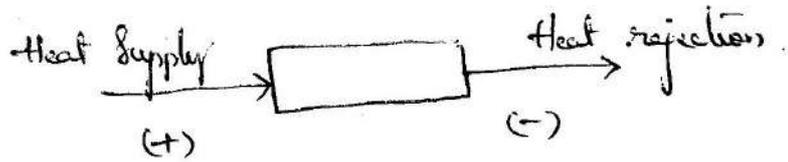Work transfer from the system to the outside is positive ie., power producing systems.

Ex:- Power plants, automobiles, ships, aeroplanes, rockets etc.

Work transfer from outside to the system is negative ie., power consuming systems.

Ex:- pumps, motors, iron box, freezers, air conditioner, compressor, etc

Heat transfer:-

Heat Supply → [ ] → Heat rejection.
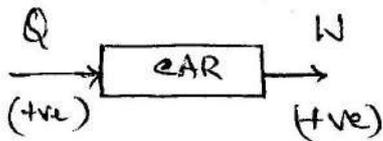   (+)   (-)

Heat transfer from the system to outside is negative

Ex:- Air conditioners, refrigerators etc.

Heat transfer from outside to system is positive.

Ex:- Heat given to a boiler drum, heat given inside the engine of an automobile etc.

Q → [CAR] → W
(+ve)   (+ve)

W → [FRIDGE] → Q
(-ve)   (-ve)

Energy Vs Heat:-

Energy	Heat
① It is the capacity to do work (or) exert the force through a distance.	① Heat is one form of energy that exists due to temperature difference b/w system & surroundings
② It is available in different forms. It changes from one form to another. ex: Mechanical to electrical	② It transfer from high temp to low temp system without mass transfer.
③ Energy is divided into two types. ⓐ Internal energy ⓑ Energy in transition	③ Heat belongs to energy in transition.
④ Energy is present in the system & at the boundary of the system.	④ Heat is present only at the boundary of the system.

Types of TD Process :-

Process	law	Relations
① Const. pressure process	$P = C$	$P_1 = P_2 = P_3$ at all state points
② const. vol. process	$V = C$	$V_1 = V_2 = V_3$, at all state points
③ const. temp process	$T = C$; $PV = C$	$P_1 V_1 = P_2 V_2$ . . . . .
④ Adiabatic process	$PV^{\gamma} = C$	$P_1 V_1^{\gamma} = P_2 V_2^{\gamma} = P_3 V_3^{\gamma}$ . . . . .
⑤ Polytropic process	$PV^n = C$	$P_1 V_1^n = P_2 V_2^n$ . . . .

workdone is given by $W = \int p \cdot dv$

Derivations for work :
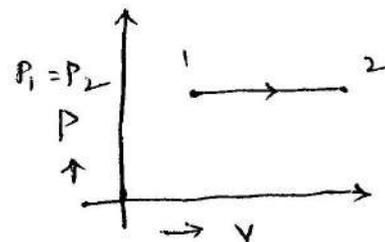
① const. Pressure process (Isobaric) :-

$P_1 = P_2$

$W = \int p \, dv$

$W_1 = \int_1^2 p \cdot dv$

$\qquad = p \int_1^2 dv = P [v]_1^2 = P(V_2 - V_1)$
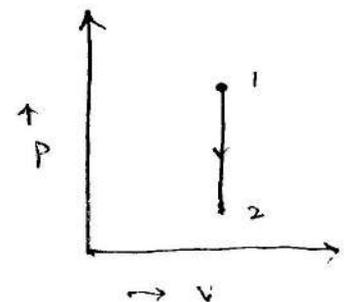
$W = P_1 (V_2 - V_1)$

② constant volume process (Isochoric) :-

$V_1 = V_2$

$W = \int p \cdot dv$

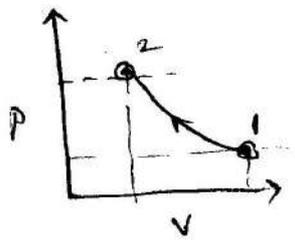$W_{1-2} = \int_1^2 p \cdot dv = p \int_1^2 dv = P[v]_1^2$

$\qquad = P(V_2 - V_1) = P(V - V) = 0$

$W = 0$ [work done by a closed system in a constant vol. process is zero]

Compression process:-

In compression process pressure increases & volume decreases. Movement of piston in upward direction increases the pressure of gas acting on piston.

In compression process $\frac{V_2}{V_1} < 1$

∴ work = Negative ie., workdone on the system.

Expansion process:-

In this process pressure decreases & volume increases.

In expansion process $\frac{V_2}{V_1} > 1$

∴ work = Positive ie., workdone by the system.

② The properties of closed systems change following relation b/w pressure & vol. as $pv = 3$, where P is in bar & V is in m^3. Calculate the workdone when pressure increases from 1.5 bar to 7.5 bar.

sol⁴: Given, $P_1 = 1.5$ bar
$P_2 = 7.5$ bar

$$P_1 V_1 = 3$$
$$1.5 V_1 = 3 \Rightarrow V_1 = 2 \ m^3$$

$$P_2 V_2 = 3$$
$$7.5 V_2 = 3 \Rightarrow V_2 = 0.4 \ m^3$$

$$W = \int_{V_1}^{V_2} p \cdot dv = \int_{2}^{0.4} \frac{3}{v} \, dv$$

$$\int \frac{1}{v} dv = \ln v$$

$$= 3 \left[\ln(0.4) - \ln(2) \right]$$

$$= -4.828 \times 10^{-3} \, bar \ m^3$$

$$= -4.828 \times 100 \ KPa \times m^3$$

$$= -483 \ KJ$$

③ Constant temperature process (Isothermal) :- $\left[T_1 = T_2 = T_3 = \right.$

$$P_1 V_1 = P_2 V_2 \cdots\cdots = C$$

$$PV = C \quad (\text{or}) \quad P = \frac{C}{V}$$

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

$$= P_0 \int_1^2 \frac{C}{V} dV = C \int_1^2 \frac{1}{V} \cdot dV$$

$$= C \left[\log V\right]_1^2 = C\left[\log V_2 - \log V_1\right]$$

$$= C \log\left(\frac{V_2}{V_1}\right)$$

$$\boxed{W = PV \log\left(\frac{V_2}{V_1}\right)} \quad (\text{or}) \quad \boxed{W = PV \log\left(\frac{P_1}{P_2}\right)}$$

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

① A mass of 1.5 kg of air is compressed in a Quasi-static process from 0.1 MPa to 0.7 MPa for which PV = C i.e., isothermal process. The initial density of air is 1.16 kg/m³. Find the workdone by the piston to compress the air.

Sol:- Given : m = 1.5 kg   req.: workdone = ?
P₁ = 0.1 MPa
$$P_2 = 0.7 \text{ MPa} \qquad PV = C$$
$$\rho_1 = 1.16 \text{ kg/m}^3$$

$$\text{Density} = \frac{m}{V} \Rightarrow \rho_1 = \frac{m}{V_1} \Rightarrow 1.16 = \frac{1.5}{V_1}$$

$$V_1 = 1.293 \text{ m}^3$$

$$\therefore P_1 V_1 = P_2 V_2$$

$$V_2 = \frac{P_1 V_1}{P_2} = \frac{0.1 \times 1.293}{0.7}$$

$$W = P_1 V_1 \, \ln\left(\frac{P_1}{P_2}\right) = 0.1 \times 1.293 \, \ln\left(\frac{0.1}{0.7}\right) \times 10^3$$

$$= -252.38 \text{ KJ}$$

③ A gas undergoes 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 m^3 to 6 m^3.

sol:- $P = -3V + 15$

$$W = \int_{V_1}^{V_2} P \cdot dV = \int_3^6 (-3V + 15) \, dV$$

$$= \left[\frac{-3V^2}{2} + 15V \right]_3^6$$

$$= \left[-\frac{3(6)^2}{2} + 15(6) \right] - \left[-\frac{3(3)^2}{2} + 15(3) \right]$$

$$= 4.5 \text{ bar} \implies 4.5 \times 100 \text{ KJ}$$

$$= 450 \text{ KJ}$$

④ During non flow reversible process a gas enclosed in a cylinder piston assembly expands from 2 m^3 to 4 m^3 with the relation $P = V^2 + \frac{6}{3}$ where P is the pressure in bar. Determine the work.

A:- $$W = \int_{V_1}^{V_2} P dV$$

$$= \int_2^4 \left(V^2 + \frac{6}{3} \right) dV = \left[\frac{V^3}{3} + \frac{6V}{3} \right]_2^4$$

$$= \left[\frac{(4)^3}{3} + \frac{6(4)}{3} \right] - \left[\frac{(2)^3}{3} + \frac{6(2)}{3} \right] = 18.66 + 4 = 22.66 \text{ KJ}$$
bar m^3

$$= 2266 \text{ KJ}$$

⑤ A gas contained in a piston cylinder arrangement expands from 0.75 m^3 to 1.35 m^3 volume while the pressure remains constant at 200 kPa. If the gaseous system recieves 30 KJ of work from a wheel, determine the net workdone by the system.
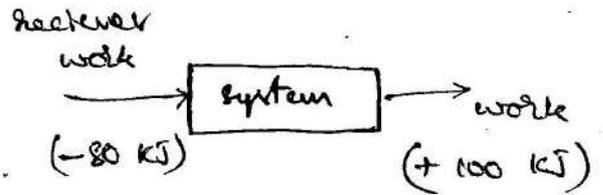
$V_1 = 0.75 \, m^3$ $P = 200 \, kPa$

$V_2 = 1.25 \, m^3$

pressure remains constant

$W = P_1 [V_2 - V_1]$

Receiver
work
system → work
(−80 KJ)   (+ 100 KJ)

$= 200 [1.25 - 0.75] = 100 \, KJ$

Since it is recieving 80 KJ of work from outside.

∴ Net workdone $= 100 - 80 = \underline{20 \, KJ}$

Air at pressure of 50 bar & 0.2 m^3 is expanded at const. pressure untill the volume is doubled, it is then expanded according to the polytropic process $pv^{1.3} = const.$, until the volume is 0.8 m^3. calculate the workdone in each process. Indicate the process on p-v diagrams.
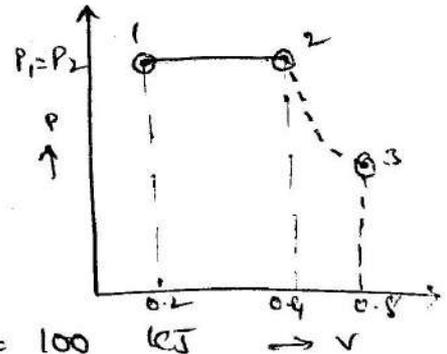
$P_1 = 50 \, bar \times 100$

$V_1 = 0.2 \, m^3$

$V_2 = 0.4 \, m^3$

$V_3 = 0.8 \, m^3$

$pv^{1.3} = const.$

$W = P_1 (V_2 - V_1)$

$= 500 (0.4 - 0.2) = 100 \, KJ$

(1−2) is constant
(2−3) is polytropic

$P_1 V_1^{1.3} = P_2 V_2^{1.3} \Rightarrow P_2 =$

$P_2 V_2^{1.3} = P_3 V_3^{1.3} \Rightarrow P_3 = 2.3 \times 10^3 \, KJ$

Polytropic process

$W = \dfrac{P_2 V_2 - P_3 V_3}{n-1}$

$W = 1251.7 \, KJ$

A gas undergoes two processes that are in series. The 1st processes is an expansion that is carried out according to the law $pv = const.$ Second process is a constant pressure process that returns the gas to the initial volume of the 1st process

The starting of the 1st process is at 400 kPa & c....... with the expansion to a pressure of 200 kPa. Sketch the process on PV diagram & determine work of combined proce..

Sol. 2 process $(1-2) \rightarrow$ PV constant

$(2-3) \rightarrow$ pressure $\Rightarrow$ constant.

$P_1 = 400$ kPa $\qquad\qquad V_1 = 0.025$ m³

$P_2 = 200$ kPa

$P_1 V_1 = P_2 V_2 \Rightarrow \dfrac{P_1 V_1}{P_2} = V_2 = 0.05$ m³
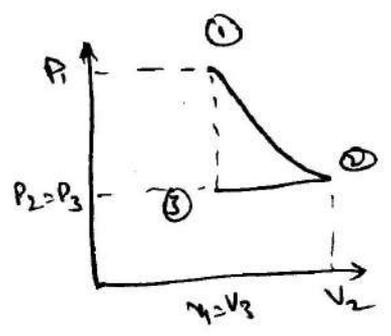
$P_2 = P_3 = 200$ kPa

$V_3 = V_1 = 0.025$ m³

workdone in 1st process

$w = P_1 V_1 \log\left[\dfrac{P_1}{P_2}\right] = 6.93$ kJ

2nd process

$w = P_2 (V_3 - V_2)$

$= 200 (0.025 - 0.05) = -5$ kJ

∴ Total workdone $= 6.93 - 5 = 1.93$ kJ

⑧ A fluid at a pressure of 3 bar in the sp. volume 0.18 m³/kg contained in a cylinder behind piston expand reversibly to a pressure of 0.6 bar it follows the law $pv^2 = $ const. Calculate the workdone by the fluid on the piston.

Sol.

$P_1 = 3$ bar $\qquad\qquad pv^2 = C$

$P_2 = 0.6$ bar

$V_1 = 0.18$ m³/kg $\qquad p = \dfrac{C}{V^2}$

$w = \int_1^2 p \cdot dv$

$= \int_1^2 \dfrac{C}{V^2} dv \qquad\qquad = C\left[\dfrac{V^{-2+1}}{-2+1}\right]_1^2$

$= \int_1^2 C V^{-2} \cdot dv \qquad\qquad = C\left(\dfrac{V^{-1}}{-1}\right)_1^2$

$\qquad\qquad\qquad = C\left[V^{-1}\right]_1^2$

$$= -c\left[V_2^{-1} - V_1^{-1}\right]$$

$$W = c\left[\frac{1}{V_1} - \frac{1}{V_2}\right]$$

$$P_1 V_1^2 = c$$

$$8 \times (0.18)^2 = c \quad \Rightarrow \quad c = 0.0972 \text{ bar} \cdot m^3/kg.$$
$$= 9.72 \text{ KJ}$$

$$P_1 V_1^2 = P_2 V_2^2$$

$$V_2^2 = \frac{P_1 V_1^2}{P_2} = \sqrt{0.162} = 0.4024 \; m^3$$

$$W = c\left[\frac{1}{V_1} - \frac{1}{V_2}\right]$$

$$= 0.2984 \text{ bar } m^3/kg \quad \Rightarrow \quad 0.298 \times 100 \text{ KPa } m^3/kg.$$
$$= 29.8 \; \frac{KN}{m} \times \frac{m^3}{kg} \qquad [NM = J]$$
$$= 29.8 \; KJ/kg.$$

Relations b/w volume, pressure & temperature :-

① Constant pressure process :-

$$\boxed{\frac{V_1}{V_2} = \frac{T_1}{T_2}}$$ where P is constant.

② constant volume process :-

$$\boxed{\frac{P_1}{P_2} = \frac{T_1}{T_2}}$$ where V is constant.

③ constant temperature process (Isothermic) :-

$$\frac{P_1 V_1}{P_2 V_2} = \frac{mRT_1}{mRT_2} \quad \Rightarrow \quad \boxed{P_1 V_1 = P_2 V_2} \qquad PV^\gamma = c$$

④ Adiabatic process :-

$$\frac{P_1 V_1}{P_2 V_2} = \frac{mRT_1}{mRT_2} \quad \Rightarrow \quad \frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)\left(\frac{V_1}{V_2}\right) \longrightarrow ①$$

$$P_1 V_1^{\mathcal{N}} = P_2 V_2^{\mathcal{N}}$$

$$\frac{P_1}{P_2} = \left[\frac{V_2}{V_1}\right]^{\mathcal{N}} \rightarrow \text{②} \qquad \text{substitute in eq ①}$$

$$\therefore \frac{T_1}{T_2} = \left[\frac{V_2}{V_1}\right]^{\mathcal{N}} \left[\frac{V_2}{V_1}\right]^{-1} = \left[\frac{V_2}{V_1}\right]^{\mathcal{N}-1}$$

$$\boxed{\frac{T_1}{T_2} = \left[\frac{V_2}{V_1}\right]^{\mathcal{N}-1}}$$

④ Polytropic process :- similar to the above derivation.

$$\boxed{\frac{T_1}{T_2} = \left[\frac{V_2}{V_1}\right]^{n-1}}$$

⑨ A quantity of air having a volume of 0.03 m^3 at a temp of 200°c & a pressure of 150 N/cm^2 is expanded at a constant pressure, a volume of 0.06 m^3, it is then expanded adiabatically to a volume of 0.12 m^3. Calculate workdone during each process, temp & pressure at the end of adiabatic process. Assume ★ ⅍ $\mathcal{N}$ is equal to 1.41, also draw the process on p-v diagrams.

Sol: $V_1 = 0.03\ m^3$

$T_1 = 200°c + 273 = 473\ K$

$P_1 = 150\ N/cm^2$

$= 1500\ kPa$

$V_2 = 0.06\ m^3$

$V_3 = 0.12\ m^3$

$\mathcal{N} = 1.41$

$\therefore PV^{\mathcal{N}} = C$
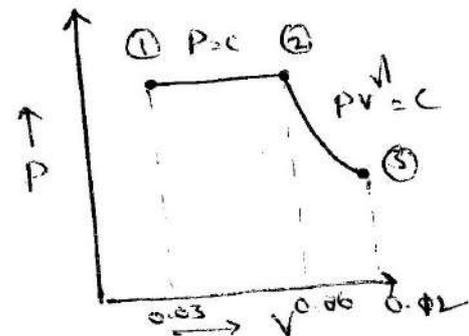
Process (1-2):

$$w = P_1 (V_2 - V_1)$$

$$= 1500 (0.06 - 0.03)$$

$$w_{(1-2)} = 45\ kPa$$

process (2-3): $\qquad pV^{\gamma} = C$

$$P_2 V_2^{\gamma} = P_3 V_3^{\gamma}$$

$$W_{(2-3)} = \frac{P_2 V_2 - P_3 V_3}{\gamma - 1}$$

$$\frac{P_2 V_2^{\gamma}}{V_3} = P_3 = 564 \ KPa$$

$$= \frac{1500 \times 0.06 - 564 \times 0.12}{1.41 - 1}$$

$$= 54.4 \ KJ$$

$$\frac{T_1}{T_2} = \frac{V_1}{V_2} \implies T_2 = \frac{V_2 T_1}{V_1} = 946 \ K$$

$$\frac{T_3}{T_2} = \left[\frac{V_2}{V_3}\right]^{\gamma - 1} \implies T_3 = 946 \left[\frac{0.06}{0.12}\right]^{(1.41-1)}$$

$$\underline{T_3 = 711.98 \ K}$$

workdone at const. pressure $W = 45 \ KPa$

pressure at final process $P_3 = 564 \ KPa$

Temperature at final process $T_3 = 711.98 \ K$

Adiabatic process:-

In adiabatic process heat transfer is zero.

The condition for adiabatic process is $pV^{\gamma} = C \implies P = \dfrac{C}{V^{\gamma}}$

$$W = \int p.dv$$

$$W_{1-2} = \int_1^2 p.dv = \int_1^2 \frac{C}{V^{\gamma}} dv$$

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

$$W = C \left[\frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1}\right]$$

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

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

Pdv - Work (or) Displacement Work!

Let P_1, V_1 are initial press & vol

& $P_2 V_2$ are final " "

when the piston moves an infittisimal
distance dl, & if 'a' be the area
of piston, the force F acting on piston,

$$F = p \cdot a$$

And the infiniterimal amount of workdone
by the gas on the piston

$$\partial w = F \cdot dl = pa\, dl = pdv$$

with change in vol from V_1 to V_2,

Amount of wd by the system

$$\boxed{W_{1-2} = \int_{V_1}^{V_2} pdv}$$

where $dv = a\, dl$
= infinitesimal
dip. vol.

The integration $\int pdv$ can be performed only on a quasistatic path.

$$1\ Pa = 1\ N/m^2$$

$$1\ bar = 10^5\ Pa = 100\ kPa$$

$$1\ atm = 101.325\ kPa = 1.01325\ bar$$

$$1\ Joule = 1\ Nm$$

$$watt = J/s$$

Polytropic Process :-

In this process the condition is $PV^n = C$

where n is known as polytropic index.

$$PV^n = C \implies P = \frac{C}{V^n}$$

$$W = \int P \, dv \implies W_{1-2} = \int_1^2 P \cdot dv$$

$$= \int_1^2 \frac{C}{V^n} dv = C \int_1^2 V^{-n} dv$$

$$= C \left[\frac{V^{-n+1}}{-n+1} \right]_1^2 = C \left[\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} \right]$$

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

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

* State or show that work is a path function & not a point function :-

In the figures shown, the system is at state ①. To move the system point ① & ②, it can follow any paths such as A (or) B (or) C. etc. The area under the curve represents the workdone.

In the diagrams, the area under each curve is not equal even though initial & final points are same.

Hence work is a path function and not a point function.

fig ⓐ

fig ⓑ

fig ⓒ
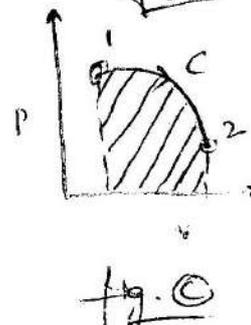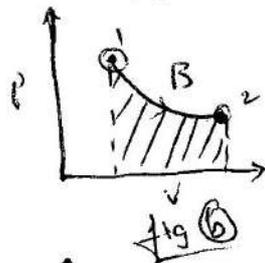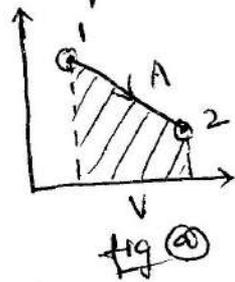
P) A piston and cylinder machine containing a fluid system has a stirring device on the cylinder. The is frictionless, and is held down against the fluid due to atm. pressure of 101.325 KPa. The stirring device is 10,000 revolutions with an average torque against the fluid 1.275 N m. Mean while the piston of 0.6m diameter move out 0.8m. Find the net work transfer for the system.
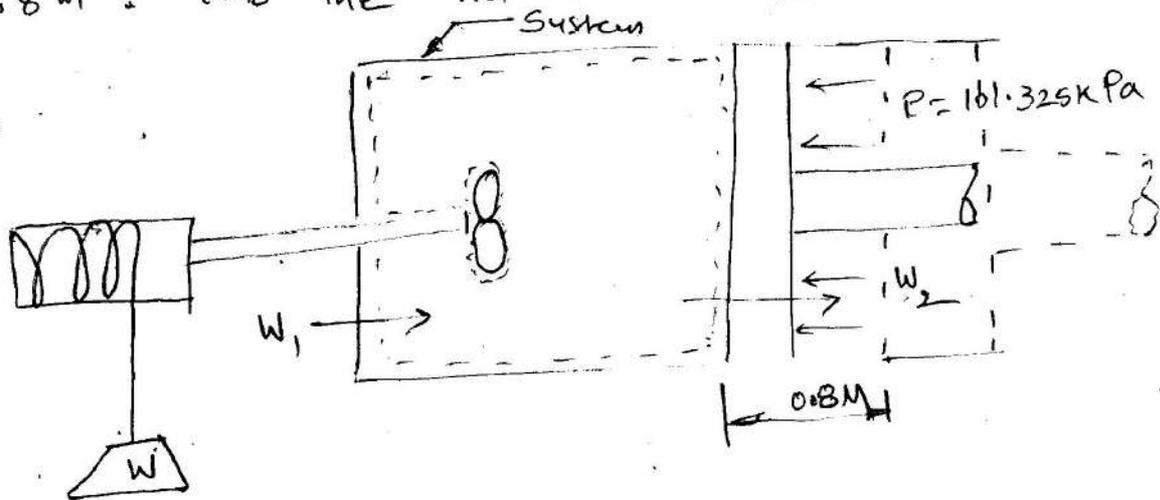
Work done by the stirring device upon system.

$$W_1 = 2\pi NT$$
$$= 2\pi \times 10000 \times 1.275 = 80 \, kJ$$

This is the negative work for system

Work done by the system upon surrounder.

$$W_2 = (PA) \cdot L$$
$$= 101.325 \times \frac{\pi}{4} (0.6)^2 \times 0.8 = 22.9 \, kJ$$

This is positive work for the system.

Hence the net work transfer for the system

$$W = W_1 + W_2 = -80 + 22.9 = \underline{-57.1 \, kJ}$$

ZEROTH LAW OF THERMODYNAMICS :-

When two bodies are in thermal equilibrium with a third body, then they are also in thermal equilibrium with eachother.

This can be stated as, when a body A is in thermal equilibrium with a body B & when B is seperately in thermal equilibrium with a body C, then A & C will also be in thermal equilibrium with each other, ie., A & C will not undergo any physical changes when brought in contact.

$$\therefore \quad A = B$$
$$B = C \quad \text{then} \quad A = C$$
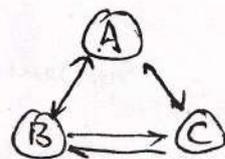
Note:- Zeroth law is the basis of temperature measurement.

Equality of temperature :-

Temperature is generally defined as the degree of hotness or intensity of heat. The physical meaning of temperature is that it describes whether the body is hot or cold.

Let two bodies, one hot (at temp θ_1) & one cold (at temp θ_2) be placed in contact with each other ($\theta_1 > \theta_2$) while isolated from all other bodies. After some time, we observe that hot body becomes colder whereas the colder one becomes hotter. It indicates that both the bodies have experienced a change in one or more of their properties. We also find that both the bodies are now at same temp θ_m. ($\theta_m < \theta_1$; $\theta_m > \theta_2$). The state, that these two bodies have attained same temp. is a state of thermal equilibrium.

The condition of equality of temp is stated as follows:

" Two systems have equal temperatures if there are no changes in their properties when they are brought in therm contact with each other."

Thermometry :- It is the science of measurement of temperature.

Principles of Thermometry :-

In order to obtain a quantitative measure of temp, a reference body is used. Besides this a certain physical characteristics is to be selected, which changes with temp. This reference body is called thermometer. & its selected characteristics is called thermodynamic metric property. The Principle of thermometer lies in the thermometric property of fluid used in it. A very common thermometer consists of a small amount of mercury in an evacuated capillary tube. The expansion of mercury in the tube when it comes in contact with hot body, is used as thermometric property.

The following properties are generally used.

1) Pressure exerted by gases.

2) volume expansion of solids, liquids & gases

3) Vapour pressure of liquids

4) Electrical resistance of solids

5) Thermo electricity.

Types of thermometers.

| Thermometer	Thermometric property	Range.
1) Hg in Glass thermometer	length	-40 to 525°C
2) Const. Vol gas thermometer	pressure	-200 to 1500°C
3) const. pressure gas thermometer	volume	-200 to 1500°C
4) Electrical resistance thermometer	Resistance	-200 to 120°C
5) Thermo couple	emf	0 to 1500°C
6) Radiation pyrometer	wave length	> 400°C

FIRST LAW OF THERMODYNAMICS :-

This is also known as law of conservation of energy. It states that energy can neither be created nor destroyed but can be convertible from one form to another form. It means two forms of energy heat & work are mutually convertable.

Whenever heat is absorbed by a system it increases its internal energy plus to do some external work.

This can be represented as follows.

$$Q = \Delta U + W$$
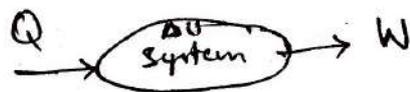
where Q is heat energy entering a system

ΔU is internal energy,

W is external work.

First law can also be stated as,

If a system undergoes a cyclic change (the end state being precisely the same as the initial state), then the algebraic sum of the work delivered to the surroundings is proportional to the algebraic sum of heat taken from the surroundings. It is expressed as

$$\oint dQ = \oint dW \qquad (or) \qquad \Sigma Q = \Sigma W$$

Internal Energy :-

Energy stored in a system which is neither heat nor work is called internal energy.

Ex:- when a gas is heated it expands producing some work but the amount of work produced will be less than heat supply. This difference b/w heat & work is known as internal energy which is stored in the system.

$$\boxed{\Delta U = Q - W}$$

Ideal gas temp Scale :-

Assume that the bulb of a constant vol. gas thermometer container certain amount of gas such that where the bulb is surrounded by water at its triple point, the pressure P_t is 1000 mm mercury. (Triple point is the temp at which substance exists in all three states.) keeping the vol. of gas V constant let the following procedure be carried out.

$$\boxed{\begin{array}{l} T = CP \\ \text{where } C = \dfrac{273 \cdot 16}{P_{tr}} \end{array}}$$

(i) Bulb of the thermometer is surrounded by steam condensing at 1 atm & pressure P_1 is determined. Then calculate the temp as

$$\theta_1 = 273 \cdot 16 \, \frac{P_1}{P_t} = 273 \cdot 16 \, \frac{P_t}{1000}$$

(ii) Some amount of gas is removed from the bulb so that when it is surrounded by water at its triple point, the pressure P_t is 500 mm of Hg. At this instant, pressure is determined, say P_2. Then θ_2 for steam condensing at 1 atm is calculated

$$\theta_2 = 273 \cdot 16 \, \frac{P_2}{500}$$

Similarly $\theta_3, \theta_4, \dots \theta_n$ are found from the experimentally determined values of $P = P_3, P_4 \dots P_n$ by going on reducing the vol. of gas against $P_t = 250, 100 \dots$ mm Hg.

Note that $\theta_t = 273 \cdot 16 \, \frac{P}{P_t}$

θ vs P_t is plotted & explorate the curve to the axis where $P_t = 0$. Read from the graph $\underset{P_t \to 0}{\lim \theta}$

[The temp of triple point of water is 273.16 k]

It may be shown that all the gases indicate the same temp as P_t is lowered & made to approach zero.

A similar series of tests can be conducted with a const pressure gas thermometer.

$$\therefore \; \theta = 273.16 \; \frac{V}{V_t}$$

θ vs P is plotted.

Replacing θ by T, the ideal gas temp is given by

$$\boxed{T = 273.16 \; \lim_{P_t \to 0} \; \frac{P}{P_t}}$$

(or)

$$\boxed{T = 273.16 \; \lim_{P \to 0} \; \frac{V}{V_t}}$$
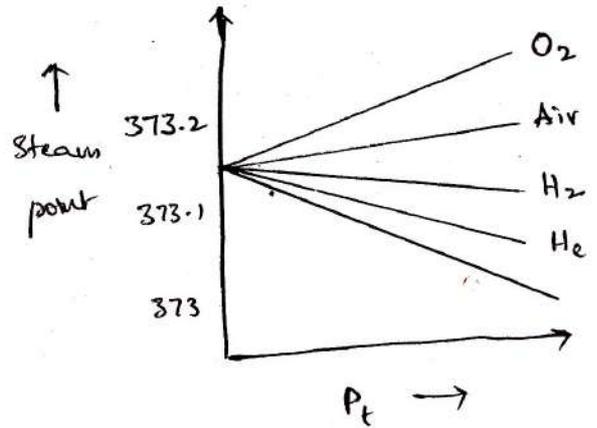
JOULE'S EXPERIMENT :

A quantity of liquid is taken in an insulated vessel. Work is done on the fluid by stirring the paddle wheel. This work input to the fluid causes a rise in temp of fluid. The amount of work done is calculated by the product of weight & the vertical height of weight displaced.

Next by removing the insulation the system is immersed in a water bath, such that heat is transferred from the fluid till the original state of fluid is reached which will be indicated by temp & pressure.
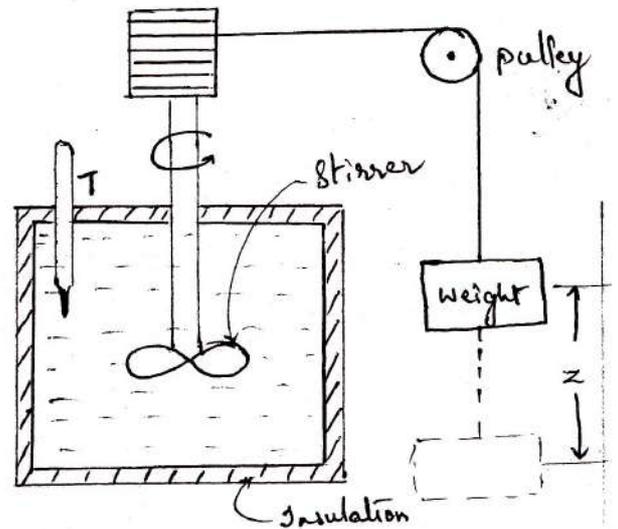
In this way system undergoes a complete cycle. The amount of heat rejected by the fluid is equal to the increase of energy of water bath.

Conclusion: The net work input W was directly proportional to the net heat Q transferred from the system regardless of the kind of workdone, the rate at which the work was done & the scheme used for transfering it into heat.

Thus for a closed system undergoing cyclic process

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

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

Perpetual Motion Machine I : PMM-I   [Perpetual → continuing forever]

PMM-I refers to the Perpetual Motion machine of first kind. It is hypothetical machine that will continuously churn out work but without absorbing heat from its surroundings.

But such a machine is not feasible from a practical point of view, for it violates law of conservation of energy (1st law TD).

$$Q=0 \longrightarrow \boxed{PMM1} \longrightarrow W$$
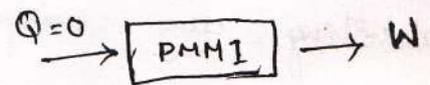
The reverse of PMM is also not true. It is a hypothetical machine which is not feasible as it violates the 1st law of TD.

$$W=0 \longrightarrow \boxed{\begin{array}{c} PMM\ I \\ (reverse) \end{array}} \longrightarrow Q$$
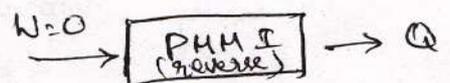
Corollaries of First law :-

Corollary → Idea that is borned from something that is proved ahead.

cor.1 :-
There exists a property of a closed system, such that a change in its value during any change of state is given by the difference b/w the heat supplied & workdone. And this property is called `Internal energy` of the system. Mathematically

$$\boxed{\Delta U = \Delta Q - \Delta W}$$

[∂u increases or decreases with change of state]

This energy equation is called Non flow energy equation (NFEE).

Col. 2 :-

"The energy of an isolated system is constant." By isolated system we mean a system which exchanges neither heat nor work with its surroundings. In otherwords both Q & W are zero and $\Delta U = 0$

Alternatebely, the second corollary may be stated as, that the "internal energy of a closed system remains unchanged if the system is isolated from the surroundings."

In a way this is Law of Conservation of Energy.

Col. 3 :-

"A perpetual machine of 1st kind is impossible". It is a machine that produces & supplies 'work' by itself without absorbing any energy from the surroundings.

Internal Energy :-

Energy stored in a system which is neither heat nor work is called internal energy.

when a gas is heated it expands producing some work, but amount of work produced will be less than heat supply. This difference b/w heat & work is known as internal energy which is stored in a system.

$$\Delta E = Q - W$$

① Write first law of TD equations for the following systems.

Q = ΔU + W
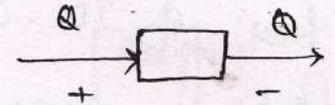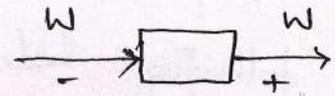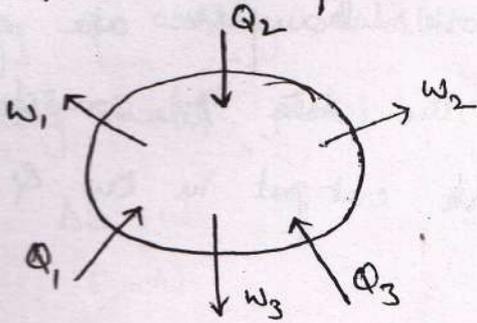
AU = W − Q ⟹ ΔU = (W₁ + W₂ + W₃) − (Q₁ + Q₂ + Q₃)

∴ (Q₁ + Q₂ + Q₃) = ΔU + (W₁ + W₂ + W₃)

② Give the relation b/w heat energy, work & internal energy for the following systems of multiple energy conversion.
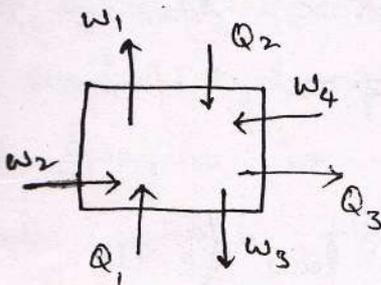
sol:- Q₁ + Q₂ − Q₃ = ΔU + (W₁ − W₂ + W₃ − W₄)

③ The system undergoes a cyclic process composed of 4 processes. The heat transfers in each process are 400 KJ, − 365 KJ, − 200 KJ, 250 KJ the respective work transfers are 140 KJ, 0 KJ, − 55 KJ & 0. Is the above data is consistant with 1ˢᵗ law of TD ?

A:- For cyclic process, ΣQ = ΣW

ΣQ = 400 − 365 − 200 + 250 = 85 KJ

ΣW = 140 + 0 − 55 + 0 = 85 KJ

∴ ΣQ = ΣW = 85 KJ

∴ the given data is consistant of the cyclic process.

& follows 1ˢᵗ law of TD.

④ A closed system undergoes a TD cycle consisting of 4 seperate processes. The heat & work transfers are given in the following table. Show that the data is consistant with 1st law of TD. Calculate net work output in kw & change in internal energy.

Process	Heat (KJ/m)	Work (KJ/m)
1-2	20000	0
2-3	-10000	30000
3-4	0	20000
4-1	15000	-25000

Sol:-

$$\Sigma Q = 20000 - 10000 + 0 + 15000 = 25000 \text{ KJ/m}$$

$$\Sigma W = 0 + 30000 + 20000 - 25000 = 25000 \text{ KJ/m}$$

$$\therefore \Sigma Q = \Sigma W$$

The data is consistent. It follows 1st law of TD.

Net work = 25000 KJ/m

$$= 416.66 \text{ KW}$$

change in ΔU,

process (1-2) : $Q_{1-2} = \Delta U_{1-2} + W_{1-2}$

$$\Delta U_{(1-2)} = 20000 - 0 = 20000 \text{ KJ/m} \rightarrow ①$$

process (2-3) $\Delta U_{(2-3)} = -10000 - 30000 = -40000 \text{ KJ/m} \rightarrow ②$

process (3-4) $\Delta U_{(3-4)} = 0 + 20000 = 20000 \text{ KJ/m} \rightarrow ③$

process (4-1) $\Delta U_{(4-1)} = 15000 + 25000 = 40000 \text{ KJ/m} \rightarrow ④$

$$\Delta U_{(1-2-3-4-1)} = \Sigma Q - \Sigma W = 25000 - 25000 = 0$$

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

A. $Q = \Delta E + W$

$\Delta E = Q - W$

$W = 2 \, kJ = 2000 \, J/5 \, kg$

$= -400 \, J/kg$

$Q = 800 \, J/5kg = -160 \, J/kg$

$\therefore \Delta E = Q - W$

$= -160 + 400$

$\Delta E = 240 \, J/kg$.
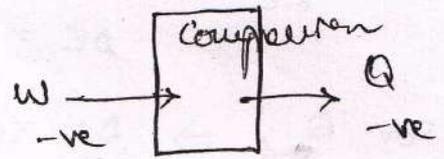
Piston & cylinder m/c contains a fluid system which possesses through complete cycle of 4 process. During the cycle sum of all heat transfers is -170 kJ. The system completes 100 cycles per minute. Complete following table showing method for each item. Calculate the net work o/p in KW.

Process	δQ (KJ/m)	δW (KJ/m)	ΔE (KJ/m)
(a-b)	0	2170	-2170
(b-c)	21000	0	21000
(c-d)	-2100	34500	-36,600
(d-a)	-35,900	-53,670	17770

$\Sigma Q = -170 \, kJ/m \times 100 = -17000$

$\Sigma Q = Q_{a-b} + Q_{b-c} + Q_{c-d} + Q_{d-a}$

$Q_{d-a} = \Sigma Q - Q_{a-b} - Q_{b-c} - Q_{c-d}$

$= -17000 - 0 - 21000 + 2100 = -35900 \, kJ/min$

for $Q_{a-b} \Rightarrow Q = \Delta E + W$

$\qquad \Delta E = Q - W$

$\qquad \Delta E = 0 - 2170 = -2170 \ KJ/min$

For $Q_{b-a} \Rightarrow \Delta E = Q - W$

$\qquad DE = 21000 - 0 = 21000 \ KJ/min$

For $Q_{c-d} \Rightarrow \Delta E = Q - W$

$\qquad Q = \Delta E + W \Rightarrow W = Q - \Delta E$

$\qquad\qquad\qquad\qquad = -2100 + 36600 = 34500 \ KJ/min$

$\sum W = \sum Q$ for cyclic process.

$\sum W = W_{a-b} + W_{b-c} + W_{c-d} + W_{d-a}$

$W_{d-a} = \sum W - W_{a-b} - W_{b-c} - W_{d-a} = -53670 \ KJ/min$

For $W_{d-a} \Rightarrow \Delta E = Q - W = -35900 + 53670$

$\qquad\qquad\qquad\qquad \Delta E = 17740 \ KJ/min$

A/c to Ist law of TD $\quad \sum Q = \sum W$

$\qquad\qquad\qquad \Delta E_{cyclic} = 0$

Total work $\Rightarrow -17000 \ KJ/mi$

$\qquad\qquad \dfrac{-17000}{60} = -283.33 \ KW$

④ A gas undergoes a thermodynamic cycle consisting of 3 process of beginning at initial stage where $P_1 = 1 \ bar$, $V_1 = 1.5 \ m^3$ & $U_1 = 512 \ KJ$. The process are as follows.

ⓐ process (1-2) $\Rightarrow$ Compression with PV = const, $P_2 = 2 \ bar$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad U_2 = 690 \ KJ$

ⓑ process (2-3) $\Rightarrow$ $W_{2-3} = 0$, $Q_{2-3} = -150 \ KJ$

ⓒ process (3-1) $\Rightarrow$ $W_{3-1} = 50 \ KJ$

Neglecting KE & PE changes, determine Q values, Q_{1-2}, Q_{3-1}

sol: ⓐ PV = const

$\qquad P_1 V_1 = P_2 V_2 \Rightarrow 1 \times 1.5 = 2 \times V_2$

$\qquad\qquad\qquad\qquad\qquad V_2 = 0.75$

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

$$= (690 - 512) + -103.972$$

$$Q_{1-2} = 74.03 \text{ kJ}$$

$$W_{1-2} = P_1 V_1 \ln\left[\frac{P_1}{P_2}\right]$$

$$= 100 \times 1.5 \ln\left(\frac{1}{2}\right)$$

$$W_{1-2} = -103.972 \text{ kJ}$$

(b) process (2-3) $\Rightarrow W_{2-3} = 0$

$$Q_{2-3} = \cancel{0} - 150 \text{ kJ (given)}$$

$$= \cancel{-150 \text{ kJ}}$$

$$\Delta U_{2-3} = Q_{2-3} - W_{2-3} = -150 - 0 = -150 \text{ kJ}$$

$$U_3 - U_2 = -150 \text{ kJ}$$

$$U_3 - 690 = -150 \Rightarrow U_3 = 540 \text{ kJ}$$

(c) $W_{3-1} = 50 \text{ kJ}$

$$Q_{3-1} = \Delta U_{3-1} + W_{3-1}$$

$$= U_1 - U_3 + W_{3-1}$$

$$= 512 - 540 + 50 \Rightarrow Q_{3-1} = 22 \text{ kJ}.$$

)

⑧ A system receives 200 kJ of heat at const. vol. process & rejects 220 kJ of heat at const. pressure & 40 kJ of work is done on the system. The system is brought to its initial condition by adiabatic. Calculate adiabatic work.

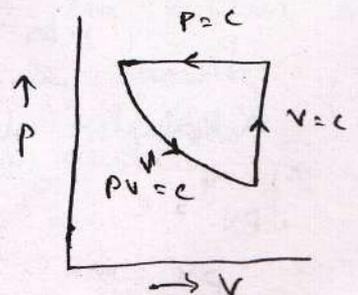· If initial internal energy is 240 kJ then what is I.E at all points. Represent cycle on p-v diagram.

1-2 $Q_{1-2} = 200 \text{ kJ}$

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

3-1

     $U_1 = 240 \text{ kJ}$

① 1-2 :- $W_{1-2} = 0$ [∵ const vol. process]

$$Q_{1-2} = 200 \text{ kJ}$$

$$\therefore Q = \Delta U_{1-2} + W$$

$$U_2 - U_1 = 200$$

$$U_2 = 200 + U_1$$

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

② 2-3 :- Const. pressure.

$$Q_{2-3} = -220 \text{ kJ} \quad ; \quad W_{2-3} = -40 \text{ kJ}$$

$$Q = \Delta U_{2-3} + W$$

$$-220 + 40 = U_3 - U_2 \quad \Rightarrow U_3 = -220 + 40 + U_2$$
$$= -220 + 40 + 440$$
$$U_3 = 260 \text{ kJ}$$

③ 3-1 :- Adiabatic process.

$$PV^\gamma = C \quad , \text{ For cyclic process } \Sigma Q = \Sigma W \quad \& \quad \Sigma E \text{ or } \Sigma U = 0.$$

$$Q_{3-1} = \Delta U_{3-1} + W_{3-1}$$
$$= U_1 - U_3 + W_{3-1}$$

In adiabatic process [heat transfer = 0].

$$\therefore Q_{3-1} = 0 \qquad \therefore U_1 - U_3 = -W_{3-1}$$

$$W_{3-1} = 20 \text{ kJ}$$

$$\therefore \text{Adiabatic process, } W_{3-1} = 20 \text{ kJ}$$

$$\therefore U_2 = 440 \text{ kJ} , U_3 = 260 \text{ kJ}.$$

④ The system is composed of 2 kg of fluid expands in a piston cylinder machine from initial state of 1 MPa, 100°C to final temp of 30°C. If there is no heat transfer find net work for process. Assume R = 0.287 kJ/kg k.

sol:-
$$m = 2 \text{ kg} \qquad T_1 = 100°C \qquad R = 0.287 \text{ kJ/kg k}.$$
$$P = 1 \text{ MPa} \qquad T_2 = 30°C$$

Adiabatic process :- (Heat transfer is zero)

$$PV^\gamma = C.$$

$$PV = MRT$$

$$(+)V = 2 \times 0.287 \times 100°C$$

$$=$$

$$W = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{mRT_1 - mRT_2}{\gamma - 1}$$

$$= \frac{mR(T_1 - T_2)}{\gamma - 1} \qquad [\gamma = 1.4]$$

$$= \frac{2 \times 0.287 (100 - 30)}{1.4 - 1}$$

$$W = 100.45 \text{ kJ}$$

First law applied to flow process: (Open System)

In open system, we know that energy (heat & work) as well as matter cross the boundary. The matter may take internal, kinetic, potential, chemical & magnetic energies along with it while crossing the boundary. However, chemical & magnetic energies are generally neglected.

In open system there are 2 types of flow process, namely.

1) Steady flow process
2) Unsteady flow process

1) In steady flow process the mass flowing into the system is equal to the mass flowing out of the system. in a given time & there is no change in the storaged energy of the system.

Ex:-

Imagine a bath tub with a closed drain & turns on water which fills the tub & starts overflowing.

2) In unsteady flow process, the mass flowing into the system is not equal to the mass flowing out from the system in a given time & there is change in storage energy of the system ie., the rate of net flow of matter is not constant.

Ex:- Imagine a bath tub with a closed drain at the bottom or with an open drain & turns on water. As the quantity of matter in the tub is not constant, it is an unsteady process.

Joules law - Internal Energy of perfect gas:-

Joules law states that internal energy of a perfect gas is independent of vol & pressure. It only depends on temperature. Thus $dU = mc_v dT$ is applicable for any

change of state b/w 1 & 2 irrespective of the process since internal energy is a point function.

From above definition we can express the sp. heat at constant vol. as

$$\boxed{C_v = \dfrac{\partial u}{\partial T}}$$

where ∂u is specific change in internal energy in KJ/kg

Heat Transfer in various Non-flow process :-

First law for a closed system is given by

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

For an ideal gas internal energy is a function of temp alone.

$$\therefore \boxed{\Delta u = mc_v (T_2 - T_1)} \rightarrow eq.$$

This eq. is applicable for any process since it is a point function & does not depend on paths of the process and depends only on the state temp's.

Let us Apply this eq. to various possible process of a closed system which changes from one state to another to develop relations for heat transfer.

(a) Constant Volume process.

Applying 1st law,

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

$$\therefore W_{1-2} = 0$$

$$Q_{1-2} = \Delta U = mc_v (T_2 - T_1)$$

change of state b/w 1 & 2 irrespective of the process since internal energy is a point function.

From above definition we can express the sp. heat at constant vol. as $\boxed{C_v = \dfrac{\partial u}{\partial T}}$

where du is specific change in internal energy in KJ/kg

Heat Transfer in various Non-flow process :-

First law for a closed system is given by

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

For an ideal gas internal energy is a function of temp alone.

$$\therefore \boxed{\Delta U = m C_v (T_2 - T_1)} \rightarrow eq.$$

This eq. is applicable for any process since it is a point function & does not depends on paths of the process and depends only on the state temp's.

Let us Apply this eq. to various possible process of a closed system which changes from one state to another to develop relation for heat transfer.
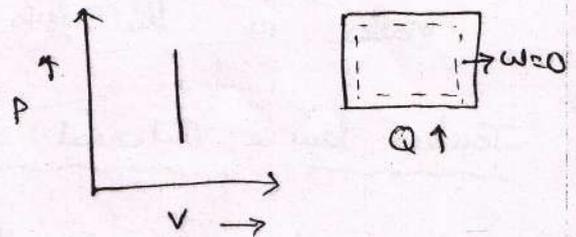
(a) Constant volume process.

Applying 1st law,

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

$$\because W_{1-2} = 0$$

$$Q_{1-2} = \Delta U = m C_v (T_2 - T_1)$$

It indicates that the total amount of energy supplied in the form of heat is stored by the system as internal energy & thus

$$\boxed{(Q_{1-2})_V = w\, c_v\, (T_2 - T_1)}$$

ⓑ **Constant Pressure process:-**

Applying 1st law,

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

$$W_{1-2} = P_1\,(V_2 - V_1) \; ; \quad \Delta U = m c_v (T_2 - T_1)$$

$$\therefore Q_{1-2} = m\, c_v\, (T_2 - T_1) + P_1\,(V_2 - V_1)$$

$$= m\, c_v\, (T_2 - T_1) + (P_2 V_2 - P_1 V_1) \qquad [\because P_1 = P_2]$$

$$= m\, c_v\, (T_2 - T_1) + m R\,(T_2 - T_1) \qquad [\because P_1 V_1 = m R T_1]$$

$$m\, c_p\,(T_2 - T_1) = m\,(T_2 - T_1)\,(c_v + R) \qquad \left[\because Q_{1-2} = m\, c_p (T_2 - T_1)\right]$$

$$c_p = c_v + R$$

$$\boxed{c_p - c_v = R} \qquad \longrightarrow eq.$$

This indicates that c_p is always greater than c_v & the amount of heat required in a const. pres. process is greater than the const. vol. process to bring the same change in temp.

ⓒ **Isothermal process:-** $[PV = C]$

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

$$\Delta U = m\, c_v\, (T_2 - T_1) \quad [\because Temp = const]$$

$$\Delta U = 0$$

It indicates that the total amount of energy supplied in the form of heat is stored by the system as internal energy & thus

$$\boxed{(Q_{1-2})_v = w\, C_v\, (T_2 - T_1)}$$

ⓑ Constant Pressure process :-

Applying 1ˢᵗ law,

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

$$W_{1-2} = P_1\,(V_2 - V_1)\; ; \quad \Delta u = m c_v (T_2 - T_1)$$

$$\therefore\ Q_{1-2} = m\, C_v\,(T_2 - T_1) + P_1\,(V_2 - V_1)$$

$$= m\, C_v\,(T_2 - T_1) + (P_2 V_2 - P_1 V_1) \qquad [\because P_1 = P_2]$$

$$= m\, C_v\,(T_2 - T_1) + m R\,(T_2 - T_1) \qquad \left[\because P_1 V_1 = mRT_1\right]$$

$$m\, C_p\,(T_2 - T_1) = m\,(T_2 - T_1)\,(C_v + R) \qquad \left[\because Q_{1-2} = m\, C_p (T_2 - T_1)\right]$$

$$C_p = C_v + R$$

$$\boxed{C_p - C_v = R} \qquad \longrightarrow eq.$$

This indicates that C_p is always greater than C_v & the amount of heat required in a const. press. process is greater than the const. vol. process to bring the same change in temp.

ⓒ Isothermal process :- $[PV = C]$

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

$$\Delta U = m c_v (T_2 - T_1) \quad [\because Temp = const]$$

$$\Delta U = 0$$

$$\therefore \ Q_{1-2} = W_{1-2}$$

$$\boxed{Q_{1-2} = P_1 V_1 \ ln \ \frac{V_2}{V_1}}$$

i.e., In isothermal process the system will not store any energy & total amount of heat supplied will convert into work.

Though the temp is constant in isothermal process $Q \neq 0$, moreover it is equal to W.

① Adiabatic Process :- (Reversible)

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

$$\Delta U = m \, C_v (T_2 - T_1) \ ; \quad W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\vartheta - 1} = \frac{mR(T_1 - T_2)}{\vartheta - 1}$$

$$W_{1-2} = m C_v (T_1 - T_2) \quad \left[\therefore \frac{R}{\vartheta - 1} = C_v \right.$$

$$\therefore \ Q_{1-2} = \Delta U + W_{1-2} \qquad\qquad\qquad \text{from } C_p - C_v = R$$

$$= m C_v (T_2 - T_1) + m C_v (T_1 - T_2) \qquad \left. C_p / C_v = \vartheta \right]$$

$$\boxed{Q_{1-2} = 0}$$

In adiabatic process heat transfer is zero i.e., the system does work without any heat interaction but at the expense of its own internal energy. So the temp changes.

" In adiabatic process heat transfer is zero but temp changes."

④ Polytropic process :-

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

$$= \frac{P_1 V_1 - P_2 V_2}{n-1} + m c_v (T_2 - T_1)$$

$$= \frac{mR(T_1 - T_2)}{n-1} + \frac{mR}{\lambda - 1}(T_2 - T_1) \qquad \left[\because c_v = \frac{R}{\lambda - 1} \right]$$

$$= mR(T_1 - T_2)\left[\frac{1}{n-1} - \frac{1}{\lambda - 1} \right]$$

$$= mR(T_1 - T_2)\left[\frac{(\lambda - 1) - (n - 1)}{(n-1)(\lambda - 1)} \right]$$

$$\therefore \frac{mR(T_1 - T_2)}{n-1}\left[\frac{\lambda - n}{\lambda - 1} \right]$$

$$Q_{1-2} = \frac{\lambda - n}{\lambda - 1} \times \text{work done}$$

$$= \frac{mR}{\lambda - 1} \cdot \frac{\lambda - n}{n-1}(T_1 - T_2)$$

$$= m c_v \frac{n - \lambda}{n-1}(T_2 - T_1)$$

$$Q_{1-2} = m c_N (T_2 - T_1) \qquad \left[c_N = c_v \left[\frac{n - \lambda}{n-1}\right] \text{ is polytropic specific heat} \right]$$

$$\boxed{Q = m c_N \Delta T}$$

First law for an isolated system :

In an isolated system $dQ = 0$ & $dW = 0$ & hence $\Delta E \ll 0$. These $E = $ constant. Then it states that in an isolated system energy remains constant. For example universe is an isolated system for which the energy remain constant.

⑨ A domestic refrigerator is loaded with vegetable food extra and their door is closed, during a certain period of the m/c consumed 1 kw-hr of energy & I.E of a system drops by 5000 KJ. Find the net heat transfer for the system ?

Sol: Given Internal energy $\Delta E = -5000$ KJ

$$W = 1 \text{ kw-hr}$$
$$= -3600 \text{ KJ}$$

$$\Delta Q = \Delta E + W$$
$$= -5000 - 3600 = -8600 \text{ KJ}$$

⑩ An air reservoir of vol. $5.5 \, m^3$ contains air at 16 bar & $42°c$ a wall is opened & some quantity of air escape to atmosphere. The pressure of air in the reciever reduced to 12 bar, when the valve is closed. Calculate the mass of the air left in the reservoir receiver. Assume adiabatic process.

Sol:
$V_1 = 5.5 \, m^3$

$P_1 = 16 \text{ bar} = 1600 \text{ KPa}$

$P_2 = 12 \text{ bar} = 1200 \text{ KPa}$

$T_1 = 42 + 273 = 315 \text{ K}$

$$PV^{\gamma} = \text{Const.}$$
$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$$
$$P_1 V_1 = MRT_1$$

① $m_1 = \dfrac{P_1 V_1}{RT_1} = \dfrac{1600 \times 5.5}{0.287 \times 315} = 97.34 \text{ kg.}$

② $P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{\gamma} \Rightarrow \left(\frac{V_2}{V_1}\right) = \left(\frac{P_1}{P_2}\right)^{1/\gamma}$$

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

$$\Rightarrow \frac{315}{T_2} = \left[\frac{1600}{1200}\right]^{\frac{1.4-1}{1.4}} \Rightarrow T_2 = 291.6 \text{ k}$$

$$V_1 = V_2 = 5.5 \, m^3.$$

$$P_2 V_2 = m_2 R T_2$$

$$m_2 = \frac{1200 \times 5.5}{0.287 \times 291} = 79.02 \text{ kg}.$$

$$m = m_1 - m_2 = 18.3 \text{ kg} \quad (\text{left mass})$$

Steady Flow Energy Equation :-

Consider a control vol of a thermodynamic open system through which working fluid is flowing at a steady state.

The fluid enters with an internal energy (U_1), pressure (P_1), vol (V_1), with a velocity (C_1) & at a height of (z_1) from the datum. Due to its velocity it possess K.E & due to its height it possesses P.E. Q is heat supplied & W is the work produced. If fluid leaves system with U_2, P_2, V_2 & C_2 at a height z_2. A/c to 1st law of TD energy i/p must be equal to energy o/p. Assume $m = 1$ kg of fluid.

Energy	Input	output
① Internal energy	U_1	U_2
② K.E	$\frac{1}{2} C_1^2$	$\frac{1}{2} C_2^2$
③ P.E	$g z_1$	$g z_2$
④ flow work	$P_1 V_1$	$P_2 V_2$

Total energy entering = Total energy leaving

$$Q + \left[U_1 + P_1 V_1 + \frac{1}{2} C_1^2 + g z_1 \right] = \left[U_2 + P_2 V_2 + \frac{1}{2} C_2^2 + g z_2 \right] + W$$

$$\left[h_1 + \frac{1}{2} C_1^2 + g z_1 \right] + Q = \left[h_2 + \frac{1}{2} C_2^2 + g z_2 \right] + W \quad \left[\begin{array}{l} \text{where } h = U + pV \\ \text{enthalpy} \end{array} \right]$$

Enthalpy is defined as the sum of IE & flow work.

$$h = U + pV$$

Neglecting changes in K.E & P.E. i.e., $c_1 = c_2$ and $z_1 = z_2$ neglect

$$\therefore h_1 + Q = h_2 + W$$

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

$$\boxed{Q = \Delta H + W}$$

Applications of SFEE :-

Most of the engineering applications are steady flow process.

All devices can be divided into 3 categories.

① work producing devices [$W = +ve$]

→ Automobiles, gas turbines, steam engines, turbines, rockets etc.

② work consuming devices [$W = -ve$]

→ Pumps, Air compressor, motors, fridges, A.C, fans etc.

③ No work interacted devices [$W = 0$]. These are also known as neutral devices mainly used heat exchanger etc.,

→ Boilers, condensers, radiators, cooling towers, nozzles, throttle valve etc.

Many Energy Analysis are derived steady energy flow equations for following devices :-

(1) Turbine   (2) Compressor   (3) Heat exchangers

                                ④ Boilers (or) evaporators (or) steam generator

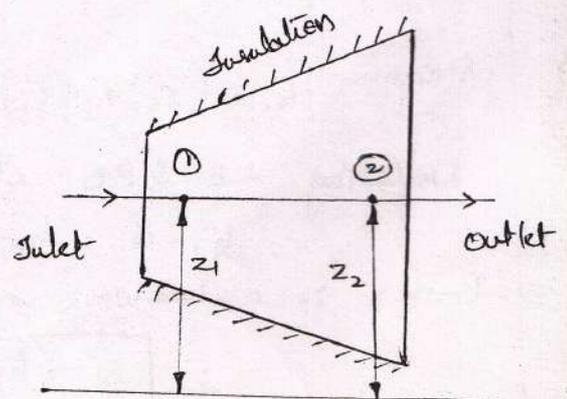(4) Nozzle   ⑤ Condenser

(5) Throttle valve .

Turbine :-

Turbine is a rotary device used for producing mechanical energy. Considering one kg of fluid & applying steady flow energy equation.

$$\left[h_1 + \tfrac{1}{2}c_1^2 + gz_1\right] + Q = \left[h_2 + \tfrac{1}{2}c_2^2 + gz_2\right] + W$$

Assume that change in velocity is very less & hence K.E changes will be neglected.

From diagram $z_1 = z_2$.

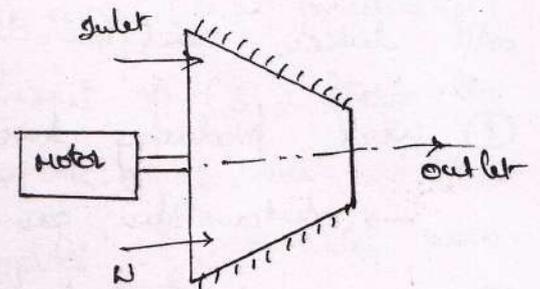$\therefore h_1 + Q = h_2 + W \implies Q = (h_2 - h_1) + W$

Since system is insulated heat transfer is zero.

$$Q = 0$$

$$\boxed{W = h_1 - h_2}$$

② Compressor :-

Compressor is a device which is used to increase the pressure of air, considering 1 kg of fluid & applying SFEE.

$$\left(h_1 + \tfrac{1}{2}c_1^2 + gz_1\right) + Q = \left(h_2 + \tfrac{1}{2}c_2^2 + gz_2\right) - W$$

Neglecting K.E & P.E changes, then

$$h_1 + Q = h_2 - W \qquad \left[\because \text{Bcoz of insulation } Q = 0\right]$$

$$\therefore \boxed{W = h_2 - h_1}$$

③ Heat Exchangers :-

ⓐ Boiler or Evaporator
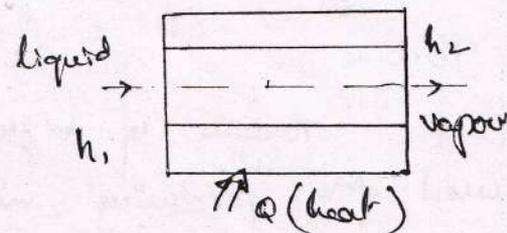
Boiler is a device which is used to convert liquid into vapour convection ie., to evaporate liquid (or) to produce steam.

$$\left[h_1 + \tfrac{1}{2}c_1^2 + gz_1\right] + Q = \left[h_2 + \tfrac{1}{2}c_2^2 + gz_2\right] + W$$

Neglecting KE & PE changes then

$$h_1 + Q = h_2 + W$$

Boiler is a non work interaction device. Hence workdone $W = 0$.

$$\therefore \boxed{Q = h_2 - h_1}$$

③ Condenser :-

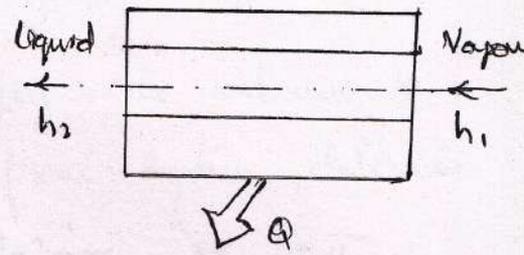$$\left[h_1 + \frac{1}{2} c_1^2 + g z_1 \right] - Q = \left(h_2 + \frac{1}{2} c_2^2 + g z_2 \right) + w$$

Neglecting KE & PE,

$$h_1 - Q = h_2 + w$$

[$w = 0$, Since No work interaction device]

$$\therefore -Q = h_2 - h_1$$

$$\boxed{Q = h_1 - h_2}$$

Condenser is a device to convert vapour to liquid ie., heat rejection process.
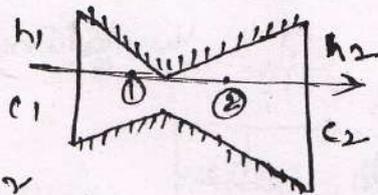
④ Nozzle :-

$$\frac{1}{2} c_1^2 + h_1 + Q = h_2 + w + \frac{1}{2} c^2$$

$$\boxed{w = 0} \qquad NO \ WORK$$

The function of nozzle is to increase velocity of fluid i.e KE considering 1 kg of fluid.

and $Q = 0$ since it is insulated heat Transfer is '0'

$$\frac{1}{2} c_1^2 + Q = h_2 - h_1 + \frac{1}{2} c_2^2$$

$$\frac{1}{2} c_1^2 + h_1 = \frac{1}{2} c_2^2 + h_2$$

$$h_1 - h_2 = \frac{1}{2} \left(c_2^2 - c_1^2 \right)$$

$$c_1^2 + 2 \left[h_1 - h_2 \right] = c_2^2$$

$$\boxed{c_2 = \sqrt{2 \left(h_1 - h_2 \right) + c_1^2}}$$

⑤ Throotal valves:-

This is mainly used in Refrigirator and A.c's throotle valve is used to reduce temp of fluid.
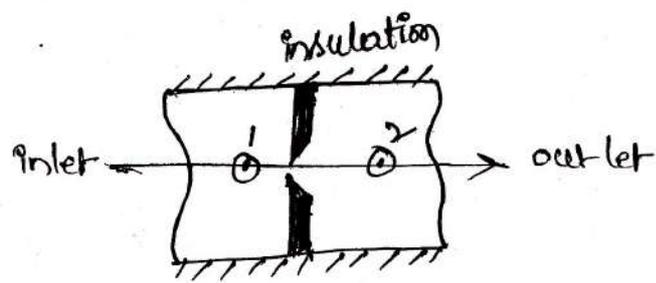
When fluid flows through a very small passage like orifice. There is decreasing pressure & flow is said to be "throttled."

Consider in 1 kg of fluid & applying energy equations.

$$\left[h_1 + \tfrac{1}{2}c_1^2 + g z_1\right] + Q = \left[h_2 + \tfrac{1}{2}c_2^2 + g z_2\right] + W$$

$$Q = 0 \quad [\because \text{insulation}]$$

$$W = 0$$

$$\boxed{\therefore h_1 = h_2}$$

Throttling process is also known as Constant enthalpy process
(Isoenthalpy process)

① Steam enters the steam condenser with an enthalpy of 2090 kJ/kg & velocity 510 m/s & after the condensation process ... ... at enthalpy of 209 kJ/kg & with a velocity of 10 m/s.
Determine heat rejected to cooling water per kg of steam condenser

Sol.
$$\left[h_1 + \tfrac{1}{2}c_1^2 + g z_1\right] + Q = \left[h_2 + \tfrac{1}{2}c_2^2 + g z_2\right] + W$$

$$Q = -ve$$

$$h_1 = 2090 \ kJ/kg \qquad h_2 = 209 \ kJ/kg$$

$$c_1 = 510 \ m/s \qquad c_2 = 10 \ m/s$$

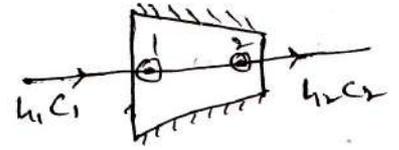$$2090 + \tfrac{1}{2}(510)^2 + Q = 209 + \tfrac{1}{2}(10)^2 + W \qquad [W = 0]$$

$$Q = 2011 \ kJ/kg$$

$$Q = -2011 \ kJ/kg$$

$$\tfrac{1}{2} = mv^2$$
$$= kg \ \tfrac{m^2}{sec^2}$$
$$= \tfrac{kg \ m}{sec^2} \cdot m$$
$$= N \cdot m = J$$

② A gas leaving turbojet engine flows into jet pipe with an enthalpy of 960 kJ/kg & velocity of 250 m/s. The exit from pipe is at an enthalpy of 800 kJ/kg. The exhaust is inline with intake. Neglecting heat losses from system, determine velocity of gas leaving the pipe.

sol: $h_1 = 960$ kJ/kg $\qquad C_1 = 250$ m/s

$h_2 = 800$ kJ/kg $\qquad C_2 = ?$

$$\left[h_1 + \tfrac{1}{2} c_1^2 + g z_1 \right] + Q = \left[h_2 + \tfrac{1}{2} c_2^2 + g z_2 \right] + W$$

$$\left[\begin{array}{l} Q = 0 \Rightarrow \text{Insulated} \\ W = 0 \Rightarrow \text{No work interacting device} \end{array} \right]$$

$$C_2 = \sqrt{c_1^2 + 2(h_1 - h_2)}$$

$$= \sqrt{(250)^2 + 2(960-800) \times 1000}$$

? $\qquad C_2 = 542.34$ m/s. $\qquad 250.63$ m/s

③ A steam turbine operates under steady flow conditions, it receives 7200 kg/hr of steam from boiler. Steam enters turbine at an enthalpy of 2800 kJ/kg. The velocity of steam is 4000 m/min at an elevation of 4 m. The velocity of steam is leaves turbine at an enthalpy of 2000 kJ/kg with an velocity 8000 m/min at an elevation of 1 m. Due to radiation heat losses from the turbine to the surrounding is 1580 kJ/hr. Calculate o/p. of turbine.

sol:- $h_1 = 2800$ kJ/kg $\qquad h_2 = 2000$ kJ/kg $\qquad : m = 7200$ kg/hr

$\qquad C_1 = 4000$ m/min $\qquad C_2 = 8000$ m/min $\qquad\qquad = 2$ kg/sec

$\qquad = 66.67$ m/s $\qquad\qquad = 133.33$ m/s.

$\qquad Z_1 = 4$ m $\qquad\qquad Z_2 = 1$ m.

$\qquad Q = -1580$ kJ/hr

$\qquad = \dfrac{-1580}{3600}$ kJ/sec

$\qquad = -0.438$ kJ/sec
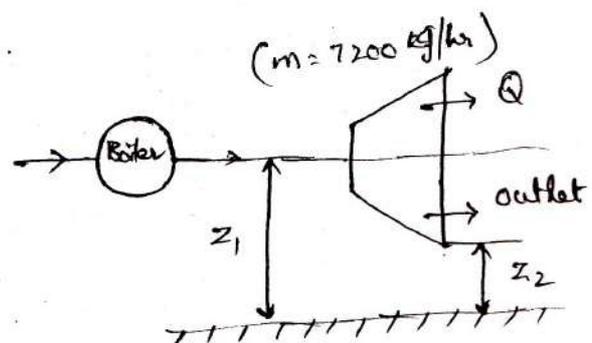
$W = ?$

$$\left[h_1 + \frac{1}{2}c_1^2 + gz_1\right] + Q = \left[h_2 + \frac{1}{2}c_1^2 + gz_2\right] + W$$

$$\therefore W = \left[(h_1-h_2) + \frac{1}{2}\frac{(c_1^2-c_2^2)}{1000} + \frac{g(z_1-z_2)}{1000}\right] + Q$$

-- heat loss per kg of steam $= \frac{Q}{m} = \frac{-0.438}{2} = -0.219$ kJ/kg

$W = 800 + \frac{1}{2}(444$

$W = 793.64 \text{ kJ/kg} \quad - 5832 \text{ kJ/kg}$

output of the turbine $W = 793.6 \times 2$ kg/sec

$$W = 1587.2 \text{ kW.}$$

③ Refrigerant vapour enters condenser of refrigeration plant with enthalpy of 223.75 kJ/kg & leaves with an enthalpy of 64.6 kJ/kg. Cooling water enters at 15°C & leaves at 20°C. Calculate mass flow rate of water per unit flow rate of refrigerant.

Condenser

Sol:-
$h_1 = 223.75$ kJ/kg
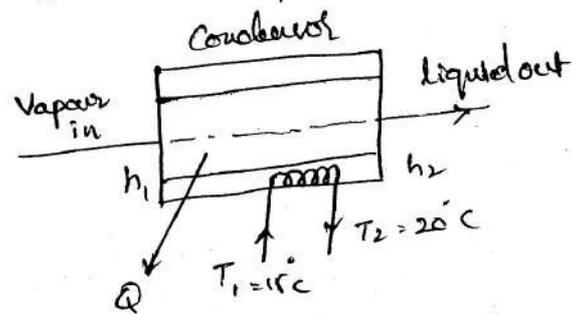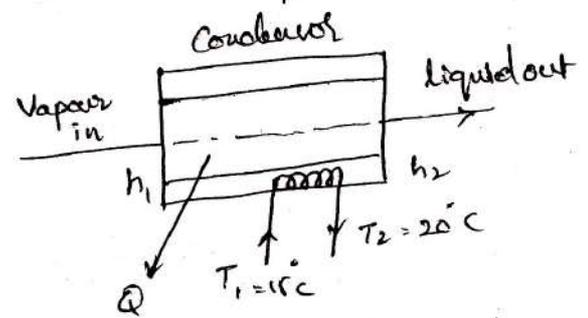
$h_2 = 64.6$ kJ/kg

$T_1 = 15+273 = 288$ K; $T_2 = 20+273 = 293$ K

A/c to 1st law heat loss by refrigerant = heat gained by water.

$$m_r (h_2-h_1) = m_w C_{pw}(T_2-T_1)$$

$$1(64.6-223.75) = m_w(4.187)(293-288)$$

$$\left[\begin{array}{l} m_r = 1 \\ C_{pw} = 4.187 \text{ kJ/kg K} \\ C_{pair} = 1.005 \text{ kJ/kg k} \end{array}\right]$$

$$m_w = -7.602 \text{ kg/sec}$$

④ Show that I.E of a system is a point function & thermo dynamic property of a system ?

Sol:- Internal Energy:- Energy stored in the body is called I.E. It is neither heat nor work. It is associated with

$N = ?$

$$\left[h_1 + \tfrac{1}{2}c_1^2 + g z_1\right] + Q = \left[h_2 + \tfrac{1}{2}c_1^2 + g z_2\right] + W$$

$$\therefore W = \left[(h_1 - h_2) + \tfrac{1}{2}\frac{(c_1^2 - c_2^2)}{1000} + \frac{g(z_1 - z_2)}{1000}\right] + Q$$

heat loss per kg of steam $= \dfrac{Q}{m} = \dfrac{-0.438}{2} = -0.219$ kJ/kg

$w = 800 + \tfrac{1}{2}(~\cancel{4444}$

$w = \cancel{793.64~kJ/kg}$ $\quad - 5832 \underset{\cancel{kJ/kg}}{kJ/kg}$

output of the turbine $W = 793.6 \times 2$ kg/sec

$$W = 1587.2 \text{ kw.}$$

+ Feb

(3) Refrigerant vapour enters condenser of refrigiralion plant with enthalpy of 223.75 kJ/kg & leaves with an enthalpy of 64.6 kJ/kg. Cooling water enters at 15°C & leaves at 20°C. Calculate mass flow rates of water per unit flow rate of refrigerant.

Sol:-

$h_1 = 223.75$ kJ/kg

$h_2 = 64.6$ kJ/kg

$T_1 = 15 + 273 = 288$ K ; $T_2 = 20 + 273 = 293$ K

Condenser — Vapour in, h_1, $T_1 = 15°C$, Q, $T_2 = 20°C$, liquid out, h_2

A/c to 1st law heat loss by refrigerant = heat gained by water.

$$m_r (h_2 - h_1) = m_w \, C_{pw}(T_2 - T_1)$$

$$1(64.6 - 223.75) = m_w(4.187)(293 - 288)$$

$\left[\begin{array}{l} m_r = 1 \\ C_{pw} = 4.187 \text{ kJ/kg K} \\ C_{pair} = 1.005 \text{ kJ/kg K} \end{array}\right]$

$$m_w = -7.602 \text{ kg/sec}$$

(4) Show that I.E of a system is a point function & thermo dynamic property of a system?

Sol: **Internal Energy:** Energy stored in the body is called I.E. It is neither heat nor work. It is associated with

motion of molecules, atoms & sub-atomic particles.

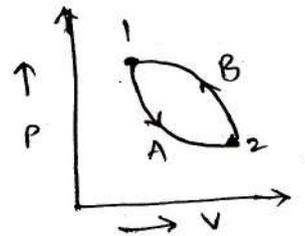Consider a closed system from ① to ② through paths A & returned to its initial state through B. The cycle is 1-A-2-B-1

A/c to 1st law of TD for cyclic process

$$\Sigma Q = \Sigma W$$
$$Q_A + Q_B = W_A + W_B \longrightarrow ①$$

Applying 1st law for states A & B

$$Q_A = \Delta E_A + W_A \longrightarrow ②$$
$$\underline{Q_B = \Delta E_B + W_B \longrightarrow ③}$$
$$Q_A + Q_B = (\Delta E_A + \Delta E_B) + (W_A + W_B)$$
$$W_A + W_B = (\Delta E_A + \Delta E_B) + (W_A + W_B)$$
$$\Delta E_A + \Delta E_B = 0$$
$$\boxed{\Delta E_A = - \Delta E_B} \longrightarrow ④$$

Change in I.E of system of paths A & B is same.

((-ve) sign is due to change in directions).

checking for one more paths or process
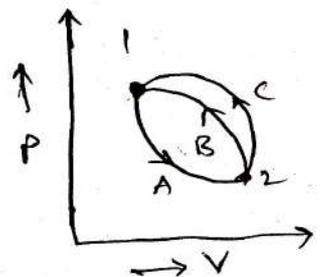
considering a system returning to its initial state through path C. Now the cycle is 1-A-2-C-1.

$$\Sigma Q = \Sigma W$$
$$Q_A + Q_C = W_A + W_C \longrightarrow ⑤$$
$$Q_A = \Delta E_A + W_A \longrightarrow ⑥$$
$$Q_C = \Delta E_C + W_C \longrightarrow ⑦$$
$$Q_A + Q_C = (\Delta E_A + \Delta E_C) + (W_A + W_C)$$
$$\boxed{\Delta E_A = - \Delta E_C} \longrightarrow ⑧$$

From eq. (P) it is evident that change in I.E. is same for path A & path C.

From eq (④) & eq. (8), we can write as follows

$$\boxed{\Delta E_A = \Delta E_B = \Delta E_C} \quad (\text{Neglecting sign})$$

Hence I.E is a point function. From above I.E is same b/w two fixed state point & it is not depend on paths (or) process. Hence the I.E of system is point function & properties of system.

④ A cylinder contains 0.115 m³ of gas at 1 bar & 90°c. The gas is compressed to a volume of 0.0288 m³, the final pressure being 5.67 bar. Calculate ⓐ the mass of gas. ⓑ the value of index of compression ⓒ the increase in internal energy of gas ⓓ the heat transfer during the compression.

If after the above compression, the gas is to be cooled at constant pressure to its original temp of 90°c, find the further work of compression required, assume $\gamma = 1.4$ & R = 0.3 KJ/kg k.

Soln:
$V_1 = 0.115 \ m^3$

$P_1 = 1 \times 10^2 \ KPa$

$T_1 = 90°c = 363 \ k$

$V_2 = 0.0288 \ m^3$

$P_2 = 567 \ KPa$

$\gamma = 1.4$

$R = 3 \ KJ/kg \ k$

find m = ?

n = ?

$\Delta U_{1-2} = ?$

$Q_{1-2} = ?$

If $P_3 = P_2$

$T_3 = T_1 = 363 \ k$

$W_{2-3} = ?$

we have,

$$P_1 V_1 = MRT_1$$

$$m = \frac{P_1 V_1}{RT_1} = 1.056 \times 10^{-1} \text{ kg}.$$

$$P_1 V_1^n = P_2 V_2^n \Rightarrow \left(\frac{V_1}{V_2}\right)^n = \left(\frac{P_2}{P_1}\right) \qquad \left[n = \log_{(0.25)} 0.176\right]$$

$$\left(\frac{0.115}{0.0288}\right)^n = \left(\frac{567}{100}\right) \Rightarrow n = 1.253.$$

$$\& \quad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1} = \left(\frac{0.115}{0.0288}\right)^{0.253}$$

$$T_2 = 515.27 \text{ K}$$

$$C_v = \frac{R}{\gamma - 1} = \frac{0.3}{1.4 - 1} = 0.75 \quad \text{kJ/kg K}$$

$$C_p = R + C_v = 1.05 \quad \text{kJ/kg K} \qquad \left[R = C_p - C_v\right]$$

$$\Delta U_{1-2} = m C_v (T_2 - T_1)$$

$$= 12.059 \text{ kJ}$$

$$W_{(1-2)} = \frac{P_1 V_1 - P_2 V_2}{n-1} = -19.08 \text{ kJ}$$

$$\therefore Q = \Delta U + W = 12.059 - 19.08 = -7.03 \text{ kJ}$$

$$W_{2-3} = m C_p (T_3 - T_2) = 1.056 \times 10^{-1} \times 1.05 (363 - 515.27)$$

$$= -24.94 \text{ kJ } /\!/$$

⊛ show that $pv^n = c$ for reversible adiabatic process.

Ⓐⓝⓢ:-
$$PV = mRT$$

Differentiating on both sides, we get

$$pdv + Vdp = mR\,dT$$

$$mR\,dT = pdv + vdp$$

$$dT = \frac{pdv + vdp}{mR} \quad\rightarrow\; \textcircled{1}$$

In adiabatic, heat transfer $\delta Q = 0$

$$\delta Q = \delta u + \delta w \Rightarrow \delta w = -\delta u$$

$$pdv = -mc_v\,dT$$

$$pdv + mc_v\,dT = 0 \quad\rightarrow\; \textcircled{2}$$

Substitute eq $\textcircled{1}$ in $\textcircled{2}$

$$pdv + mc_v\left(\frac{pdv + vdp}{mR}\right) = 0$$

$$\frac{PRdv + c_v(pdv + vdp)}{R} = 0 \Rightarrow c_v(pdv + vdp) + PRdv = 0$$

$$c_v(pdv + vdp) + P(c_p - c_v)\,dv = 0 \qquad [\because R = c_p - c_v]$$

$$c_v\,pdv + c_v\,vdp + Pc_p\,dv - Pc_v\,dv = 0$$

$$c_v\,vdp + c_p\,Pdv = 0 \quad;\quad \text{Dividing both sides by } c_v\,PV$$

$$\frac{c_v\,vdp}{c_v\,PV} + \frac{c_p\,Pdv}{c_v\,PV} = 0 \qquad \left[\frac{c_p}{c_v} = \gamma\right]$$

$$\frac{dP}{P} + \gamma\frac{dv}{V} = 0 \quad (\text{Integrate})$$

$$\log_e P + \gamma\log_e V = C_1 \qquad \left[\begin{array}{l}\text{Assume}\\ \because C_1 = \log_e c\end{array}\right]$$

$$\log_e P + \log_e V^\gamma = C_1$$

$$\log_e(PV^\gamma) = C_1$$

$$\log_e(PV^\gamma) = \log_e c$$

$$\boxed{\therefore PV^\gamma = C}$$

To a closed system 150 KJ of work is supplied. At initial vol 1, is 0.6 m³ & pressure of system changes as P=8-4V where P is in bar & V is in m³. Determine final volume & pr. of system

$$-150\times10^3 = \int (8-4V)\,dV = 8(V_2-V_1) - \frac{4}{2}(V_2^2-V_1^2)$$

$$V_A = \frac{}{} \times 10^5$$

$$V_2 = 0.353 \, m^3$$

final press $P_2 = 8-4V_2 = 6.588\,bar$

The pressure & sp. volume of atm. are related accordly to eqⁿ $PV^{1.4} = 2.5\times10^5$, where $P = N/m^2$ & $V = m^3/kg$

what depth of atmosphere is req'd to produce a pressure of 1.033 bar at earth surface. Assume $g = 9.81 \, m/s^2$. Consider the atmosphere as fluid column

a) $P V^{1.4} = 2.5\times10^5$
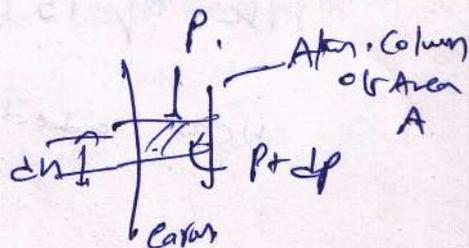
consider an element of length dh by force balance

$$A(P+dP) = mg + PA$$

$$PA + A\,dP = \rho A\,dh + PA$$

$$dh = \frac{1}{g}V\,dP \quad \int_0^{1.033\times10^5}\frac{1}{g}\left(\frac{2.5\times10^5}{P}\right)^{1/1.4}dP$$

$$\int_0^H dh = \quad \Rightarrow H = 69462 y$$

P) The flow energy of 0.124 m³/min of a fluid crossing a boundary to a system is $18KW$ find the pressure at first point

$P_1 = $ Pressure

$A_1 = $ Area

$V_1 = $ velocity

Volume flow rate $(Q) = A_1 V_1$

∴ Power = Force × volume

$= P_1 A_1 \times V_1$

$= P_1 \times Q$

$18 = P_1 \times \dfrac{0.124}{60}$

$P_1 = \dfrac{18 \times 60}{0.124} = $ ② $8.71 MPa$
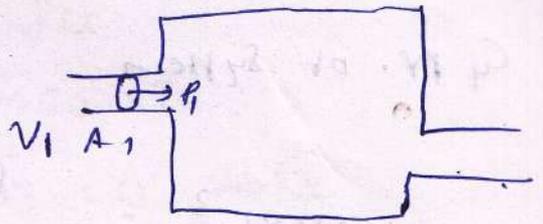
1.5 kg of liquid having a const. sp. heat of $2.5 KJ/kgk$ is stirred in a well insulated chamber causing temp. to rise by $15°C$. find ΔE & W for process

Heat added $= 1.5 \times 2.5 \times 15 = 56.25 KJ$

$\Delta E = 56.25 KJ$

As it is insulated $\Delta Q = 0$

$\Delta Q = \Delta E + W$

$0 = 56.25 + W$

$W = -56.25 KJ$

P) An engine is tested by means of water brake at 1000 rpm. The measured torque of engine is 10000 mN & water consumption of brake is 0.5 m³/s. its inlet temp. being 20°C. Calculate water temp. at exit, assuming that whole of engine power is ultimately transformed into heat which is absorbed by cooling water

$$p = T \cdot \omega$$

$$= 10000 \times \left(\frac{2\pi \times 1000}{60}\right) = 1.0472 \times 10^6 W$$

let final temp. = t°C
Heat absorbed by cooling water/unit = $m \, C_p \, \Delta T$
$$= V \cdot \rho \, C_p \, \Delta T$$
$$= 0.5 \times 1000 \times 4.2(t-20)$$

$$\therefore \quad 0.5 \times 1000 \times 4.2 \times (t-20) = 1.0472 \times 10^6$$

$$\underline{t = 20 + 0.5 = 20.5°C}$$

P) A system composed of 2kg of above air expands in a frictionless piston & cylinder machine from Init. State of 1. MPa 100°C to a final temp. of 30°C. If there is no heat transfer, find net work for process

$$Q = 0$$
$$Q = W + \Delta E \implies W = -\Delta E$$
$$= -\Delta U = -\int_1^L C_v dT$$
$$= -0.718 \, (T_2 - T_1)$$
$$= -0.718 \, (100 - 30) = -50.26 \, kJ/kg$$

total work $W = 2 \times (-50.26)$
$$= -100.52 \, kJ$$

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$$= 0.5 \times 1000 \times 4.2 (t-20)$$

$$\therefore \quad 0.5 \times 1000 \times 4.2 \times (t-20) = 1.0472 \times 10^6$$

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$$= -0.718\,(100-30) = -50.26\ kJ/kg$$

total work $W = 2 \times (-50.26)$

$$= -100.52\ kJ$$

Limitation

1) No Restriction on dir^n of flow of heat : The First law establishes definite relationship b/w heat & work. The first law doesn't indicate whether heat can flow from cold end to hot end or not. ex¹ we can't extract heat from Ice by cooling ∧ get to low temp. Some ext. work has to be done

2) Doesn't specify the feasibility of process :- First law doesn't specify that process is feasible or not. for ex¹ when rod is heated at one end when equil. has to be obtained which is possible only by some expeddure of energy. (Heat can't flow from low temp. Body to high temp. body. It is silent about it

3) Practically it is not possible to convert heat energy quite equiv. amount of work. To overcome this limitation another law known as IInd law of T.D. which helps to predict reaction is feasible or not & also tell direction of flow of heat

4)   Q —> W   — Feasibility
     W can't be converted into heat. equally

5) Entropy

Limitations of First law of TD :-

(i) According to 1st law of TD, heat & work are mutually convertable. This is not true in real practice.

(ii) There is no restriction on the direction of flow of work & heat which is not true.

(iii) In general heat is not completely converted into work.

(iv) High pressure gas expands to low pressure, but the reverse is not possible in general i.e., some external energy is required which violets the 1st law of TD.

(v) In an automobile, if brakes are applied the brake work is converted into heat & dissipated into the atmosphere. If reverse process is considered i.e., by giving the heat to brakes wheel, it should rotate, which is not possible.

(vi) A/c to Joule's experiment work can be completely converted into heat but in general complete conversion of heat into work is not possible becoz of losses.

$$W \longrightarrow Q$$
$$Q \longrightarrow W$$

Thermal Reservoir :-

→ It is a reservoir having infinite amount of heat quantity in it such that when we add or remove finite amount of heat from it. Its temp will not change.

→ Thermal reservoir is a body of infinite heat capacity,

which is capable of absorbing or rejecting unlimited qty of heat without affecting its temperature.

→ All the process associated with a thermal reservoir are assumed to be quasi-static. [ex:- ocean water, atm.air]

Heat Source :

The thermal reservoir from which heat is transfered to a system during a cycle is called 'heat source'.

Ex: Boiler furnace, Sun, Nuclear reactors, combustion chamber of an engine or turbine etc.

Heat Sink :-

The thermal reservoir to which heat is rejected from the system during a cycle is called as "heat sink."

Ex: Atmospheric air, river, sea (or) ocean water etc.

Heat Engine :-

A heat engine is a device which converts heat energy (low grade) into mechanical work (High grade energy) [ex:- Steam power plant]

Thermal efficiency $\eta_{th} = \dfrac{O/P}{I/P} = \dfrac{Net\ workdone}{Heat\ supplied.}$

$Q_H \Rightarrow$ heat supply from source

$Q_L \rightarrow$ heat rejected to sink

$T_H \rightarrow$ highest (or) hot body temp

$T_L \rightarrow$ lowest (or) cold body temp

T_H | Source
Q_H
→ work (W)
Q_L
T_L | Sink

$\eta = \dfrac{O/P}{I/P} = \dfrac{W}{Q}$ where $W = Q_H - Q_L$

$Q = Q_H$

$\therefore \boxed{\eta = \dfrac{Q_H - Q_L}{Q_H}}$ (or) $\boxed{\eta = \dfrac{T_H - T_L}{T_H}}$
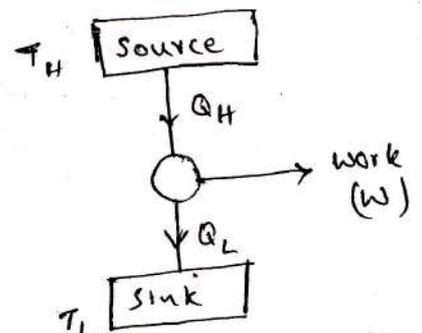
Refrigerator :-

Refrigerator is a device which is used to produce cooling effect & maintaining at low temp.

The efficiency of refrigerator is generally expressed in terms COP (coefficient of performance).

Efficiency $\eta = \dfrac{O/P}{I/P}$

$$= \dfrac{\text{cooling effect}}{\text{work}} = \dfrac{Q_L}{W}$$

$$COP = \dfrac{Q_L}{Q_H - Q_L} \qquad \left[\begin{array}{l} Q_L + W = Q_H \\ \therefore W = Q_H - Q_L \end{array}\right]$$
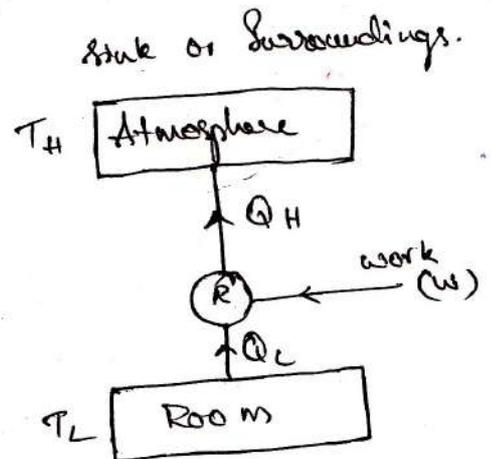
(or) $COP = \dfrac{T_L}{T_H - T_L}$ Ex: Refrigerators, A.c's etc.,

Sink or Surroundings.

T_H | Atmosphere |

Q_H ↑

work (W) ←

R

Q_L ↑

T_L | Rooms |

Heat Pump :-

Heat pump is a device which delivers heat energy from low temp to high temp while working in a cycle.

COP of heat pump can be represented as follows.

$COP_{HP} = \dfrac{O/P}{I/P} = \dfrac{\text{heating effect}}{\text{work}} = \dfrac{Q_H}{W}$

$$Q_H = Q_L + W$$

$$W = Q_H - Q_L$$

$\boxed{(COP)_{HP} = \dfrac{Q_H}{Q_H - Q_L}}$ (or) $\boxed{(COP)_{HP} = \dfrac{T_H}{T_H - T_L}}$

T_H | ROOM |

Q_H ↑

← W

Q_L ↑

T_L | Atmosphere |
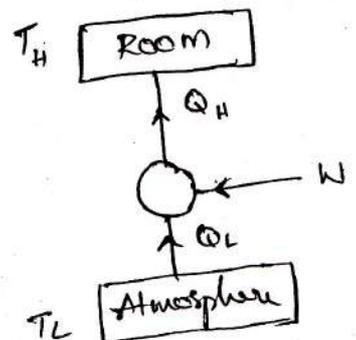
Note :- Derive the relation b/w COP of heat pump & COP of Refrigerator. $\dfrac{Q_H}{Q_H - Q_L} - \dfrac{Q_L}{Q_H - Q_L} = 1$

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

① A heat engine, one heat pump & a refrigerator are working b/w two heat reservoir one at 600 K, the other at 300 K calculate ① Efficiency of heat engine

② COP_{HP}

③ COP_R

Sol:

① Efficiency of HE $= \dfrac{T_H - T_L}{T_H} = \dfrac{600 - 300}{600} = \dfrac{3}{6} = 0.5 = 50\%$

② $COP_{HP} = \dfrac{T_H}{T_H - T_L} = \dfrac{600}{600 - 300} = 2$

③ $COP_R = \dfrac{T_L}{T_H - T_L} = \dfrac{300}{600 - 300} = 1$

② A Heat engine receives heat at the rate of 1500 KJ/min & given an o/p of 8.2 kw. Determine

② Thermal efficiency

⑥ Rate of heat rejection
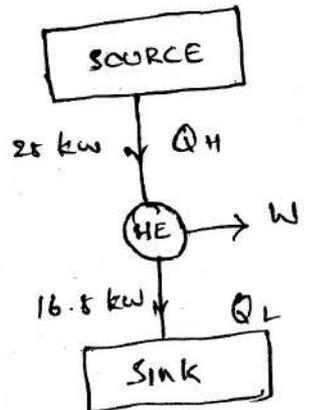
Sol:

$Q_H = 1500$ KJ/min

$Q_H = \dfrac{1500}{60}$ KJ/sec $= 25$ kw

$W = 8.2$ kw

$\eta = \dfrac{Q_H - Q_L}{Q_H} = \dfrac{W}{Q_H} = \dfrac{8.2}{25} = 32.8\%$

$W = Q_H - Q_L \Rightarrow -Q_L = -16.8$ kw

$$\boxed{Q_L = 16.8 \text{ kw}}$$

③ A H.E, H.P & refrigerator receiver 500 KJ of heat each but they reject 250 KJ, 600 KJ & 600 KJ of heat respectively. Determine ① η of HE ② COP_R ③ COP_{HP}

Represent these values with the help of diagrams.

Sol:- Efficiency HE, (η) :-

$$\eta = \frac{O/P}{I/P} = \frac{Q_H - Q_L}{Q_H}$$

$$= \frac{500 - 250}{500} = 0.5$$

$$\eta = 50\%.$$
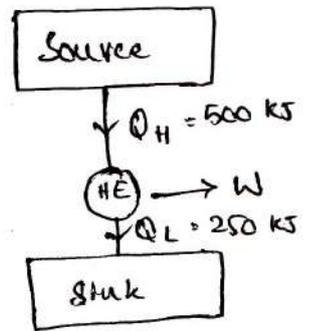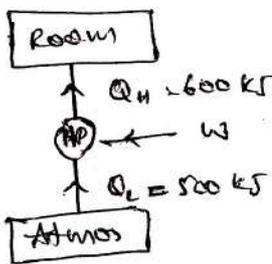
② $COP_R = \dfrac{O/P}{I/P} = \dfrac{Q_L}{Q_H - Q_L} = \dfrac{500}{100} = 5$

③ $COP_{HP} = \dfrac{O/P}{I/P} = \dfrac{Q_H}{Q_H - Q_L} = \dfrac{600}{100} = 6$

✓
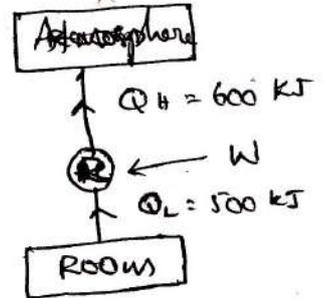
④ Calculate COP & Heat transfer to condensor of a refrigerator in KJ/hr which has refrigeration capacity 12000 KJ/hr when power input is 0.75 kW.

Sol:- $Q_L = 12000$ KJ/hr

$\quad = 200$ KJ/min

$W = 0.75$ kW

$\quad = 0.75 \times 3600 = 2700$ KJ/hr

$Q_H = Q_L + W$

$\quad = 12000 + 2700 = 14700$ KJ/hr

$COP = \dfrac{Q_L}{Q_H - Q_L} = \dfrac{12000}{2700} = 4\cdot 44.$

✓
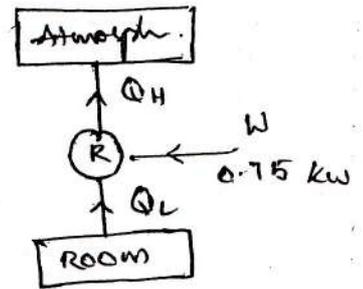
⑤ Reversible H.E operates b/w 2 reservoirs at 420 K & 280 k. If o/p from engine is 2.5 kJ. Determine efficiency of engine and its heat interaction with reservoirs. Subsequently engine is made to operate as a heat pump b/w same reservoir. Calculate COP_{HP}. and power input required when heat transfer rate from 280 k reservoir is 5 kW.

Sol:- $\eta = \dfrac{T_H - T_L}{T_H} = \dfrac{480 - 280}{420} = 0.33$

$\eta = 33.3\%.$

$$W = 2.5 \text{ kJ}$$

$$Q_H = Q_L + W$$

$$\eta = \frac{O/P}{I/P}$$
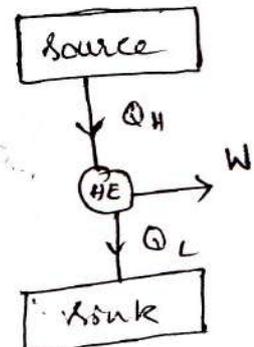
$$0.333 = \frac{W}{Q_H} = \frac{2.5}{Q_H}$$

$$\therefore Q_H = 7.5 \text{ kJ}$$

$$W + Q_L = Q_H \implies Q_L = Q_H - W = 5 \text{ kJ}$$

$$COP_{HP} = \frac{420}{420 - 280} = 3.$$

$$3 = \frac{Q_H}{Q_H - Q_L} \implies Q_H = 3Q_H - 3Q_L$$

$$2Q_H = 3Q_L$$

$$Q_H = \frac{3}{2} \times 5 = 7.5 \text{ kW}.$$

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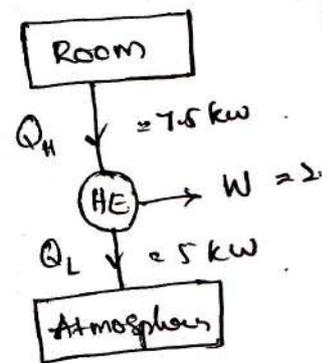
⑥ A reversible heat engine operating b/w 900 k & 300 k is used to a reversible refrigerator for which temp limits are 300 k & 250 k. The engine absorbs 1800 kJ of energy as heat from reservoir at 900 k. The net output from engine & refrigerator system is 360 kJ. Make calculations for heat extracted from refrigerator cabinet & total heat rejected at 300 k.

Sol:

$$\eta = \frac{T_H - T_L}{T_H} = \frac{900 - 300}{900}$$

$$\eta = 66.67 \, \%.$$

$$0.667 = \frac{1800 - Q_L}{1800}$$

$$Q_L = 600 \text{ kJ}$$

$$COP_R = \frac{T_L}{T_H - T_L} = \frac{250}{300 - 250}$$

$$COP_R = 5$$
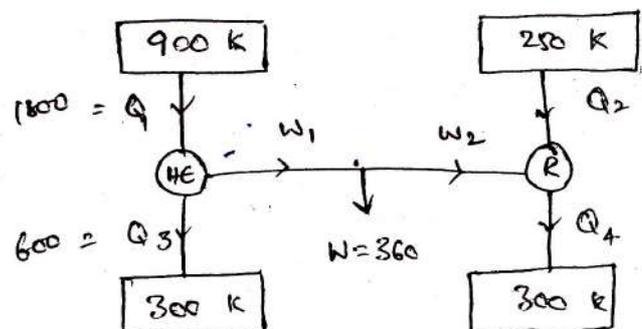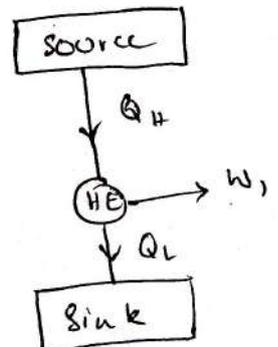
$$COP_R = \frac{Q_L}{Q_H - Q_L} \implies 5 = \frac{Q_2}{Q_4 - Q_2} \rightarrow \text{①}$$

$$W_1 = Q_1 - Q_3$$

$$W_1 = 1800 - 600 = \underline{1200 \text{ KJ}}$$

Given, $W = W_1 - W_2$

$$W_2 = 360 - 1200 = -840$$

$$W_2 = \underline{840 \text{ KJ}}$$

$$\therefore Q_4 - Q_2 = W_2 = \underline{840 \text{ KJ}}$$

$$\therefore 5 = \frac{Q_2}{Q_4 - Q_2} \implies 5 = \frac{Q_2}{840} \implies Q_2 = 4200 \text{ KJ} \rightarrow \text{②}$$

$$\therefore Q_4 - Q_2 = 840$$

$$Q_4 = 840 + 4200 = 5040 \text{ KJ} \rightarrow \text{③}$$

Heat extracted from refrigerator $Q_2 = 4200 \text{ KJ} \rightarrow \text{④}$

Total heat rejected at 300k reservoir,

$$\underset{HE}{Q_3} + \underset{R}{Q_4} = 5040 + 600 = 5640 \text{ KJ} \rightarrow \text{⑤}$$

✓ ⑦ Cyclic HE operator b/w source temp of 800°C & sink temp of 30°C, what is the least rate of heat of rejections per KW, net o/p of engine.

$$\eta = \frac{o/p}{i/p} = \frac{N}{Q_H} = \frac{Q_4 - Q_L}{Q_4}$$

$$= \frac{T_H - T_L}{T_H} = \frac{1073 - 303}{1073}$$

$$\eta = 71.76\%.$$

$$\eta = \frac{W}{Q_4} \implies 0.7176 = \frac{W}{Q_4} \implies Q_H = 1.3927$$

$$W = Q_H - Q_L \implies Q_L = 1 - 1.3935$$

$$Q_L = 0.3927 \text{ kW}.$$
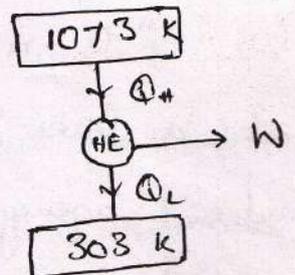
SECOND LAW OF TD :-

It is stated in two ways ie., through

(i) Kelvin - Planck Statement

(ii) Clausius Statement

It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with body at single fixed rep's

Kelvin - Planck's Statement :-

"It is impossible to construct an engine working on a cyclic process, whose sole purpose is to convert all the heat supplied to it into equivalent amount of work."

$$\text{If } Q_2 = 0 \left(\text{ie., } W_{net} = Q_1 \text{ or } \eta = 100\% \right)$$

$$W = Q_1 - Q_2$$
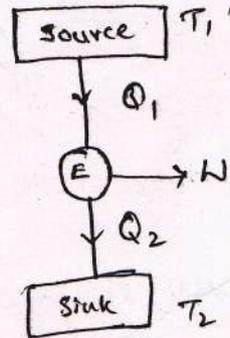
the heat engine will produce net work in a complete cycle by exchanging heat with only one reservoir, thus violating the Kelvin- Planck Statement.

Such a heat engine is called a Perpetual motion machine of the second kind (PMM2). A PMM2 is impossible.

Clausius Statement :-

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

"Heat flows from a hot body to a cold body."
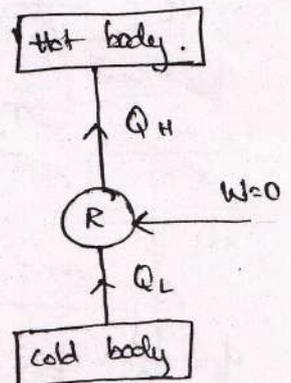
(or) It is impossible to construct a device which operating in a cycle, will produce no effect other than transfer of heat from cooler body to higher body

Corollaries of Second law :-

① NO engine, working on a cyclic process is more efficient than (Carnot's) reversible engine when working b/w the same two limits of temperature.

② All reversible engines have the same efficiency when working b/w the same two reservoirs of heat.

③ Whenever a system executes a complete cyclic process the $\oint dQ/T$ around the cycle is less than zero or in the limit is equal to zero. This shows the inequality of Clausius.

④ $\oint dQ/T = 0$ for any reversible cyclic process & consequently for any reversible process b/w reference states ① & ② is a property of the system in state ②. This property is called 'entropy.'

⑤ A true absolute TD temp. scale may be defined which is independent of the characteristics of the thermodynamic medium. A scale of temp. can be defined which is independent of any particular thermometric substance & which provides abs. zero of temp.

Equivalence of the two statements :-

The Kelvin Planck & the Clausius statements are equivalent in their consequence, & either statement can be used as the expression of II law of TD. Any device that violates the Kelvin-Planck statement also violates the clausius statement & vice versa.

Consider the heat engine - refrigerator combinations as shown in fig., operating b/w the same two reservoirs. The heat engine is assumed to have, in violation of Kelvin-Planck statement, a thermal η of 100%. & therefore it converts

High temp. reservoir at T_H

Q_H

$Q_H + Q_L$

H.E. $\eta = 100\%$

$W_{net} = Q_H$

R

Q_L

Low temp. reservoir at T_L

(a) A refrigerator that is powered by a 100% efficient heat engine.

High temp reservoir at T_H

Q_L

R

Q_L

Low temp. reservoir at T_L

(b) The equivalent refrigerator

all the heat Q_H it receives to work W. This work is now supplied to a refrigerator that removes heat in the amount of Q_L from the low temp reservoir & rejects heat in the amount of $Q_L + Q_H$ to the high temp reservoir. During this process, the high temp. reservoir receives a net amount of heat Q_L (the diff b/w $Q_L + Q_H$ and Q_H). Thus, the combination of these two devices can be viewed as a refrigerator, that transfers heat in an amount of Q_L from a cooler body to a warmer one without requiring any input from outside. This is clearly a violation of the Clausius statement.

It can also be shown in a similar manner that a violation of the Clausius statement leads to the violation Kelvin-Planck statement. Therefore, both are two equivalent expressions of II law of TD.

(a) A refrigerator that is powered by a 100% efficient heat engine.

(b) The equivalent refrigerator

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It can also be shown in a similar manner that a violation of the clausius statement leads to the violation Kelvin-Planck statement. Therefore, both are two equivalent expressions of II law of TD.

Perpetual Motion Machine of Second Kind (PMM II) :-

It is impossible to construct a PMM II. It is a hypothetical m/c that continuously supply heat from low temp reservoir to high temp without taking any input or work from surroundings.

But such a m/c is not feasible from practical point of view. It violates II law of TD. (clausius statement)

Carnot Cycle / Engine :-

It is a reversible cycle which consists of all reversible process. i.e.,

→ Reversible isothermal heat addition
→ Reversible adiabatic expansion
→ Reversible isothermal heat rejection
→ Reversible adiabatic compression.

fig: CARNOT ENGINE

Carnot has proposed a piston cylinder arrangement with working medium & two covers as shown in fig.

Process (1-2) : $T_H = C$

By replacing diathermic cover an amount of heat Q_1 is supplied from the source at constant temp T_1.

Process (2-3) :- (drops T_H to T_L) The diathermic cover is replaced by an adiabatic cover & thus medium with its stored energy pushes the piston forward by developing work W_E adiabatically & reversibly & the temp of medium decreases from T_1 to T_2

Process (3-4) :- $(T_L = c)$ The adiabatic cover is replaced by diathermic cover & Q_2 amount of heat is made to leave the system at T_2 to a sink at T_2 reversibly.

Process (4-1) :- $(T_L$ to $T_H)$ The diathermic cover is again replaced by adiabatic cover & pump work W_P is done on the medium reversibly & adiabatically till the temp rises to T_1 & system returns to its initial state, as shown in PV diagram.

For a steady flow process,

A/c to I law of TD for a cycle,

$$\Sigma Q = \Sigma W$$

$$Q_H - Q_L = W_E - W_c$$

$\therefore$ Efficiency of Carnot engine $= \dfrac{\text{Net work output}}{\text{Heat supply}}$

$$\eta_{carnot} = \dfrac{W_E - W_c}{Q_H} = \dfrac{Q_H - Q_L}{Q_H}$$

$$\boxed{\therefore \quad \eta_{carnot} = \dfrac{T_H - T_L}{T_H}}$$

Reversible Carnot Heat Engine :-

Since all the process in the Carnot cycle are reversible, it is possible to reverse the engine. Let individually all the process are reversed then

Process (1-2) $\longrightarrow$ Isothermal heat rejection

(2-3) $\longrightarrow$ Adiabatic pumping

(3-4) $\longrightarrow$ Isothermal heat addition

(4-1) $\longrightarrow$ Adiabatic expansion.

Thus all the energy transfers associated with the process are reversed in direction but their magnitude remains the same.

Thus the Wnet. is negative & heat is transferred from lower temp reservoir to higher temp reservoir thus acts as a heat pump or refrigerator.

⊕ Development of Carnot cycle is practically impossible becoz.,

→ All process in nature are irreversible.

→ It is not possible to replace the covers diathermic & adiabatic continuously.

→ Isothermal heat addition & rejection requires infinite time i.e., piston has to move infinitely slow where adiabatic process must be completed very quickly. Two kinds of motions cannot be obtained.

→ Frictionless motion of piston is not possible.

→ The curves isothermal & adiabatic when drawn on P-V diagram due to the small diff. in their slope they will not converge easily & requires a large stroke. Thus V_s will be very high with less enclosed area i.e., work development.

Thermodynamic temp Scale :-

we know that η of reversible carnot heat engine is a function of temp only.

The absolute temp scale is also known as kelvin scale. It depends on heat absorbed & heat rejected & is independent of peculiar characteristics of working substance.

In defining kelvin scale the triple point of water ($0°C = 273.16 K$) is taken as standard reference point.

Thus the Work is negative & heat is transferred from lower temp reservoir to higher temp reservoir thus acts as a heat pump or refrigerator.

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→ It is not possible to replace the covers diathermic & adiabatic continuously.

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we know that η of reversible carnot heat engine is a function of temp only.

The absolute temp scale is also known as kelvin scale. It depends on heat absorbed & heat rejected & is independent of peculiar characteristics of working substance.

In defining kelvin scale the triple point of water ($0°C = 273.16 k$) is taken as standard reference point.

$$\Rightarrow \frac{Q_2}{Q_1} = \frac{T_2}{T_1} \quad \text{(or)} \quad T = 273.16 \frac{Q}{Q_t} \cdot \left[\frac{Q}{Q_{tp}} \cdot \frac{T}{T_{tp}} \right]$$

Thus the absolute TD temp scale has a definite zero point of water which can be attained by imaging a series of reversible engine contending from source T_1 to a lower temp. If enough engines are placed in series to make the total work output equal to Q_1, then the heat rejected by last engine is zero. However 2nd law do not allow to develop such an engine.

When the heat rejected approaches zero the temp of heat rejection also approaches a zero limit. Thus it appears a definite zero point exists an absolute temp scale but the point can't be reached without violation of second law.

① An engine operating on Carnot cycle works within temp limit of 600 K & 300 K. If engine receiver 2000 KJ of heat. Calculate workdone & thermal efficiency of engine.

sol:-

$T_1 = 600$ K
$T_2 = 300$ K
$Q_H = 2000$ KJ

$$\eta_{carnot} = \frac{T_H - T_L}{T_H} = \frac{W}{Q_H}$$

$$\Rightarrow \frac{600 - 300}{600} = \frac{W}{2000}$$

$Q_H - Q_L = W$

$2000 - Q_L = 1000$

$Q_L = 1000$ KJ

$W = 1000$ KJ

$\eta_{th} = 0.5 = 50\%$

② Determine power required to run refrigerator that transfers 2000 KJ/min heat from a cooled space at 0°c to the surrounding atmosphere at 27°c. The refrigerator operates on reverse Carnot cycle.

80/

$$\text{COP } \eta_{ref} = \frac{T_L}{T_H - T_L} = \frac{Q_L}{W}$$

$$\text{COP} = \frac{273}{300 - 273} = 10.111$$

$$10.111 = \frac{Q_L}{Q_H - Q_L} \qquad \left[\because Q_L = 2000 \text{ kJ/min}\right]$$

$$Q_H = 2197.8 \text{ kJ/min}$$

$$W = Q_H - Q_L = 2197.8 - 2000$$
$$= 197.8 \text{ kJ/min}$$

$$\boxed{W = 3.297 \text{ kW}}$$
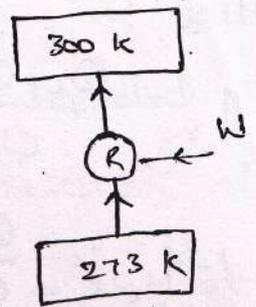
③ HE_1, HE_2, HE_3 are connected in series ar shown. They are working with same thermal efficiency. Calculate W_1, W_2, W_3. (carnot engine).

Q⅄:- Given

$$\eta_1 = \eta_2 = \eta_3$$

HE_1 :-

$$\eta_1 = \frac{Q_H - Q_L}{Q_H} = \frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1}$$

$$= 1 - \frac{Q_2}{Q_1}$$

$$1 - \eta = \frac{Q_L}{Q_1} \longrightarrow ①$$

HE_2 :-

$$\eta_2 = \frac{Q_2 - Q_3}{Q_2} = 1 - \frac{Q_3}{Q_2}$$

$$1 - \eta_2 = \frac{Q_3}{Q_2} \longrightarrow ②$$

HE_3 :-
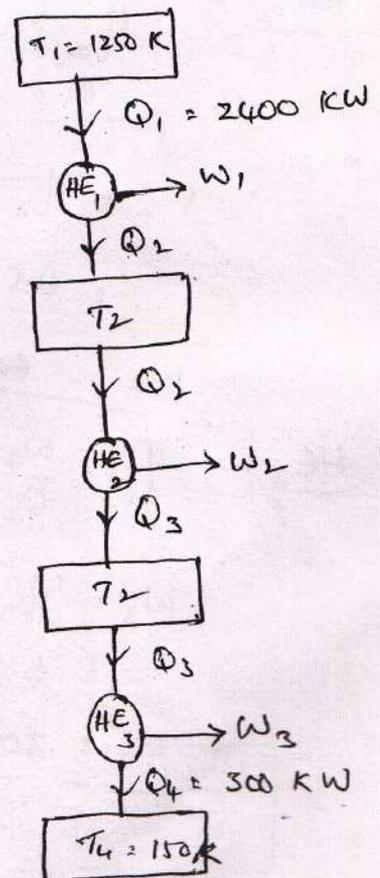
$$\eta_3 = \frac{Q_3 - Q_4}{Q_3} = 1 - \frac{Q_4}{Q_3}$$

$$1 - \eta_3 = \frac{Q_4}{Q_3} \longrightarrow ③$$

Multiplying ①,② & ③ , we get.

$$(1-\eta)^3 = \frac{\cancel{Q_2}}{Q_1} \times \frac{\cancel{Q_3}}{\cancel{Q_2}} \times \frac{Q_4}{\cancel{Q_3}} = \frac{Q_4}{Q_1}$$

$$(1-\eta)^3 = \frac{300}{2400}$$

$$1 - \eta = 0.5$$

$$\eta = 0.5 = 50\,\%.$$

$\underline{HE_1}$:-

$$\eta_1 = \frac{Q_1 - Q_2}{Q_1} = \frac{W_1}{Q_1}$$

$$W_1 = \eta_1 \times Q_1 = 2400 \times 0.5 = \underline{1200 \;\; kW}$$

$\underline{HE_2}$:-

$$\eta_2 = \frac{W_2}{Q_2} \qquad\qquad \frac{Q_1 - Q_2}{Q_1} = 0.5$$

$$\therefore W_2 = \eta_2 \times Q_2 \qquad\qquad 1 - \frac{Q_2}{Q_1} = 0.5 \Rightarrow 1 - \frac{Q_2}{2400} = 0.5$$

$$= 0.5 \times 1200 \qquad\qquad\qquad\qquad \underline{Q_2 = 1200 \;\; kW}$$

$$\underline{W_2 = 600 \;\; kW}$$

$\underline{HE_3}$:-

$$\eta_3 = \frac{W_3}{Q_3} \qquad\qquad\qquad 1 - \frac{Q_4}{Q_3} = 0.5$$

$$W_3 = \eta_3 \times Q_3 \qquad\qquad 1 - \frac{300}{Q_3} = 0.5 \Rightarrow \underline{Q_3 = 600 \;\; kW}$$

$$= 0.5 \times 600$$

$$\underline{W_3 = 300 \;\; kW.}$$

④ 2 Reversible heat engines A & B are connected 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 & engine 'B' is in thermal communication with a sink at 4.4°C. If work output of 'A' is twice of 'B', calculate

(1) Intermediate temp b/w A & B.

(2) η of each engine.

(3) Heat rejected to cold sink.

Draw the operating systems for the above data.

Sol: Given

$$W_A = 2 \times W_B$$

$\underline{HE_1 :-}$

$$\eta_A = \frac{T_1 - T_2}{T_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\frac{T_1 - T_2}{T_1} = \frac{W_A}{Q_1}$$

$$W_A = Q_1 \left[\frac{T_1 - T_2}{T_1} \right] \longrightarrow ①$$

$$\underline{HE_B :-} \quad \eta_B = \frac{T_2 - T_3}{T_2} = \frac{Q_2 - Q_3}{Q_2}$$

$$W_B = Q_2 \left[\frac{T_2 - T_3}{T_2} \right] \longrightarrow ②$$

we know that $W_A = 2W_B$

$$Q_1 \left[\frac{T_1 - T_2}{T_1} \right] = 2 Q_2 \left[\frac{T_2 - T_3}{T_2} \right]$$

$$\frac{Q_2 \, T_1}{T_2} \times \frac{T_1 - T_2}{T_1} = 2 Q_2 \frac{T_2 - T_3}{T_2}$$

$$T_1 - T_2 = 2T_2 - 2T_3$$

$$T_1 + 2T_3 = 3T_2$$
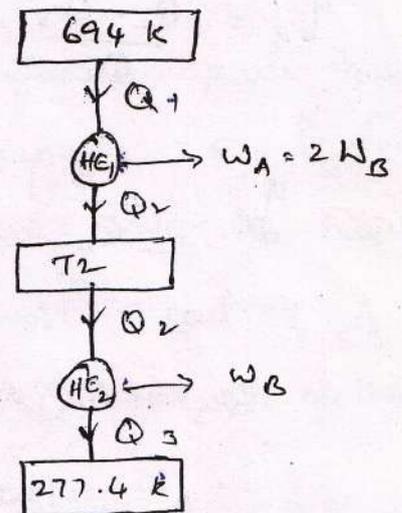
$Q_1 = T_1 \; ; \; Q_2 = T_2$

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$

$$\boxed{Q_1 = \frac{Q_2 \, T_1}{T_2}}$$

$$694 + 554.8 = T_2$$

$$\boxed{T_2 = 416.26 \ K}$$

$$\therefore \eta = \frac{T_1 - T_2}{T_1}$$

HE$_A$:

$$\eta_A = \frac{694 - 416.26}{694} = 40 \%.$$

$$\eta_A = \frac{W_A}{Q_1} \Rightarrow W_A = 200 \times 0.4 = 800 \ KJ$$

HE$_B$:

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$

$$Q_2 = \frac{Q_1}{T_1} \times T_2 = \frac{200}{694} \times 416.26$$

$$Q_2 = 119.96 \ KW$$

$$\eta_B = \frac{Q_2 - Q_3}{Q_2} = \frac{T_2 - T_3}{T_2} = \frac{416.26 - 277.4}{416.26} = 33.3 \%.$$

$$\eta_B = \frac{W_B}{Q_2} \Rightarrow W_B = \eta_B \times Q_2$$
$$= 0.333 \times 119.96 = 39.946 \ KJ$$

$$\therefore Q_3 = Q_2 - W_B$$

$$Q_3 = 120 - 39.6 = 80.4 \ KJ.$$

⑤ Consider 3 hypothetical heat engines A, B & C, each operating b/w 1000 k & 300 k. when each engine involves itself with a heat interaction of 1000 kJ with high temp reservoir, it is claimed that while A develops a work of 600 kJ, B & C develops 700 & 800 kJ. Use Carnot statement & identify the engines A, B, & C are reversible, irreversible or impossible.

Sol:
$$T_1 = 1000 \ k \qquad W_A = 600 \ kJ$$
$$T_2 = 300 \ k \qquad W_B = 700 \ kJ$$
$$Q_1 = 1000 \ kJ \qquad W_C = 800 \ kJ$$

All the engines are operating b/w same two temp reservoirs,

$$\therefore \; \eta_{max} = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{1000} = 0.7$$

Consider engine (A)

$$\eta_A = \frac{W_A}{Q_1} = \frac{600}{1000} = 0.6$$

As $\eta_A < \eta_{max}$, the heat engine is irreversible.

engine (B) :-

$$\eta_B = \frac{W_B}{Q_1} = \frac{700}{1000} = 0.7$$

$$\eta_{max} = \eta_B = 0.7, \quad \text{so it is reversible}.$$

engine (C) :-

$$\eta_C = \frac{W_C}{Q_1} = \frac{800}{1000} = 0.8$$

$$\eta_{max} < \eta_C, \quad \text{so it is impossible}.$$

(E) A direct heat engine A & a reversed heat engine B operate b/w 177°C & 27°C. The COP of B as a heat pump is 2.5. A driver B. The magnitude of heat interaction of A & B with the reservoir at 27°C are 200 & 50 KJ. The combined work output of A & B is 20 KJ. Identify whether the heat engine A is reversible or irreversible.

sol. $T_1 = 450$ k

$T_2 = 300$ k

$Q_{2A} = 200$ KJ

$Q_{2B} = 50$ KJ

$(COP)_B = 2.5$

$$(COP)_{HP,B} = \frac{Q_{1B}}{W_B} = 2.5$$

$$\Rightarrow Q_{1B} = W_B \times 2.5 \rightarrow \text{①}$$

Also $W_B = Q_{1B} - Q_{2B} \Rightarrow Q_{1B} = W_B + Q_{2B} \rightarrow \text{②}$

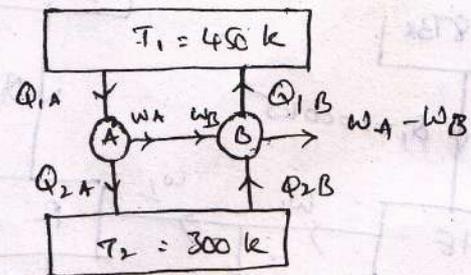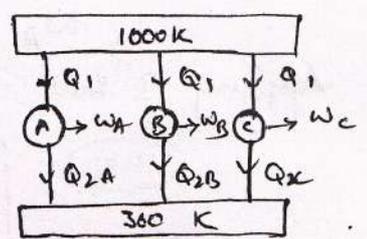Equate ① & ②, we get $W_B \times 2.5 = W_B + Q_{2B}$

$$W_B \times 2.5 = W_B + 50$$

$$W_B = 33.3 \; KJ$$

From data $W_A = W_B + W_{output}$

$$W_A = 33.3 + 20 = 53.3 \text{ kJ}$$

Applying I law to engine A,

$$Q_{1A} = Q_{2A} + W_A = 200 + 53.3 = 253.3 \text{ kJ}$$

$$\eta_A = \frac{W_A}{Q_{1A}} = \frac{53.3}{253.5} = 0.21$$

but $\eta_{max} = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{450} = 0.33$.

As $\eta_A < \eta_{max}$, engine A is irreversible.

P) A reversible heat engine operates b/w 2 reservoirs at temp\tof 60°C & 40°C. The engine drives a reversible refrigerator which operates b/w reservoirs at temp.s of 40°C & -25°C. The heat transfer to heat engine is 2000kJ & net w/output of combined engine refrigerator plant is 360kJ.

a) Evaluate heat transfer to refrigerant & net heat transfer to reservoir at 40°C

b) Reconsider (a) given that η_{HE} & COP of ref. are each 40% of their max. possible values

a) max. η of H.E. cycle

$T_1 = 873K$
$T_3 = 253K$
$Q_1 = 2000kJ$
Q_4
W_1 W_2
HE   →   R
Q_2 $W = 360kJ$ $Q_3 = Q_4 + W_2$
$T_2 = 313K$
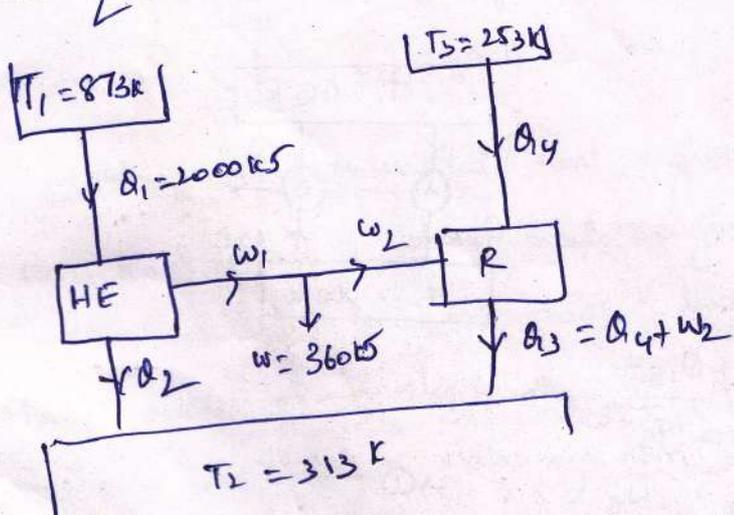
$$\eta_{max} = 1 - \frac{T_2}{T_1} = 1 - \frac{313}{873} = 1 - 0.358 = 0.642$$

Again $\frac{W_1}{Q_1} = 0.642 \Rightarrow W_1 = Q_1 \times 0.642 = 1284 \text{ kJ}$

Max. COP of Ref. Cycle

$$COP_{max} = \frac{T_3}{T_2 - T_3} = \frac{253}{313 - 253} = 4.22$$

Also $COP = \frac{Q_4}{W_2} = 4.22$

Since $W = W_1 - W_2$

$$W_2 = W_1 - W = 1284 - 360 = 924 \text{ kJ}$$

$$Q_4 = W_2 \times COP = 4.22 \times 924 = 3899 \text{ kJ}$$

$$\therefore Q_3 = Q_4 + W_2 = 3899 + 924 = 4823 \text{ kJ}$$

$$Q_2 = Q_1 - W_1 = 2000 - 1284 = 716 \text{ kJ}$$

Heat Rejected to 40°C reservoir
$$= Q_2 + Q_3 = 716 + 4823 = 5539 \text{ kJ}$$

b) $\eta = 0.4 \times \eta_{max} = 0.4 \times 0.642$

$$W_1 = 0.4 \times 0.642 \times 2000 = 513.6 \text{ kJ}$$

$$W_2 = W_1 - W = 513.6 - 360 = 153.6 \text{ kJ}$$

COP of actual ref. cycle $= \frac{Q_4}{W_2}$

$$= 0.4 \times 4.22 = 1.69$$

$$\therefore Q_4 = 153.6 \times 1.69 = 259.6 \text{ kJ}$$

$$Q_3 = 259.6 + 153.6 = 413.2 \text{ kJ}$$

$$Q_2 = Q_1 - W = 2000 - 513.6 = 1486.4 \text{ kJ}$$

Heat rejected to 40°C reservoir $= Q_3 + Q_2 = 413.2 + 1486.4 = 1899.6 \text{ kJ}$

Entropy is a measure of molecular disorder.

Consider a tank containing gas. The molecules of gas are in random motion & they move in different directions with different velocities colliding with each other.

entropy

↑

(gases)

(liquids)

(solids)

Degree of disorder →

Let us heat the gas, random motion of gas molecules further increases which leads to more irregularity (or) more disorderness. This degree of disorderness existing in a system is known as entropy.

The units of entropy $s = \dfrac{Q}{T} = KJ/kg\,k$

* I law of TD ⇒ $\boxed{Q = \Delta U + W}$

II law of TD ⇒ $\boxed{Q = Tds}$

Uses of Study of Entropy :-

→ Since entropy is a property, it can be used to determine state of a substance.

→ Entropy represents maximum amount of work obtainable per degree drop in temperature.

→ Entropy is generally assumed as zero at $-273.15°C$ ie at $0°k$

→ Since it depends on mass, entropy is an extensive property

→ entropy/unit-mass = sp. entropy (intensive property)

→ A change in entropy shows that heat energy has been transferred to or from a system & the temp level at which that heat is transferred.

→ $\oint \dfrac{dQ}{T} \leq 0$ is called Clausius Inequality.

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Applications :-

Heat transfer through finite temp difference :-

let A & B are two bodies
with temp's T_1 & T_2 resp.
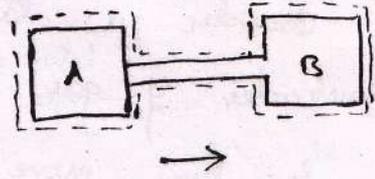
change in entropy of body A $= \Delta S_A = \dfrac{-Q}{T_1}$

$\qquad\qquad\qquad\qquad B = \Delta S_B = \dfrac{Q}{T_2}$

For total isolated system $\Delta S = \Delta S_A + \Delta S_B$

$$\Delta S = -\dfrac{Q}{T_1} + \dfrac{Q}{T_2} \qquad \Rightarrow \qquad \boxed{\Delta S = Q\left[\dfrac{T_1 - T_2}{T_1 T_2}\right]}$$

case(i): if $T_1 > T_2$ then $\Delta S > 0$ ie., irreversible process

$\qquad\quad T_1 < T_2$ then $\Delta S < 0$ ie., impossible

$\qquad\quad T_1 = T_2$ then $\Delta S = 0$ ie., reversible process

Ⓐ I law of TD $\rightarrow$ Internal energy (extensive property)

Ⓑ II law of TD $\rightarrow$ Entropy (extensive property)

Limitations of First law of TD

1) when a closed system undergoes a thermodynamic cycle the net heat transfer is equal to net work transfer, this statement does not specify the direction of flow of heat and work

not given dir'n
not given condition

2) the heat energy & mechanical work are mutually convertible through mechanical work can be fully converted into heat energy, but only a part of heat energy can be converted into mechanical work this means heat energy & mechanical work are not fully mutually convertible. No 100%.
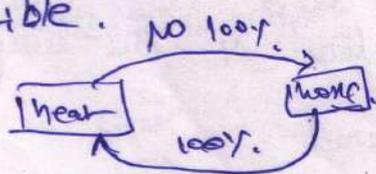
Entropy :- (S)

→ It is a measure of molecular disorder

→ It is a thermodynamic property

→ It is a point function ie., its value does not change when the state of the system changes.

→ Therefore entropy change of a system is zero, if state of system does not change during the process.

Ex:- Nozzles, compressor, turbines, pumps etc.

CLASIUS INEQUALITY :-

It is defined as,

"whenever a system executes a complete cycle, the cyclic integral of $\frac{\delta Q}{T}$ is less than or in the limit equal to zero."

consider an engine operating b/w two fixed temp reservoirs. Let dQ_1 units of heat be supplied at temp T_1 & dQ_2 units of heat be rejected at temp T_2 during a cycle. Then thermal efficiency of this engine,

$$\eta_E = \frac{dQ_1 - dQ_2}{dQ_1}$$

thermal efficiency of a reversible engine operating b/w same temp is given by $\eta_R = \frac{T_1 - T_2}{T_1}$

We know that $\eta_E \not> \eta_R$ or in limiting case $\eta_E \leq \eta_R$ since no engine can be more efficient than a reversible engine (Carnot's theorem)

$$\therefore \quad \frac{dQ_1 - dQ_2}{dQ_1} \leq \frac{T_1 - T_2}{T_1}$$

$$1 - \frac{dQ_2}{dQ_1} \leq 1 - \frac{T_2}{T_1}$$

$$\frac{dQ_2}{dQ_1} \leq \frac{T_2}{T_1}$$

$$\Rightarrow \quad \frac{dQ_2}{T_2} - \frac{dQ_1}{T_1} \leq 0$$

Hence, in the limit $\boxed{\oint \frac{dQ}{T} \leq 0}$ in case of reversible cycle where the equality applies in case of irreversible cycle.
& inequality applies in case of irreversible cycle.

Meaning & concept of Entropy:-

Entropy literally means 'transformations'. It is a thermodynamic state property of matter which is held constant if no heat is supplied in a reversible adiabatic process."

Entropy increases as heat is supplied to a system & decreases as heat is rejected from a system. But it remains constant if no heat is supplied nor rejected. That is why adiabatic process is called 'isentropic' process.

If dQ = a small change in heat transfer at T

T = absolute temp

$d\phi$ = change in entropy

Then $d\phi = \frac{dQ}{T}$ or $\phi = \int \frac{dQ}{T}$

For a reversible cycle, $\boxed{\oint \frac{dQ}{T} = 0}$

Further we have $\eta_{carnot} = \dfrac{\Delta T}{T} = \dfrac{W}{Q}$

If $\Delta T = 1$, then $W = \dfrac{Q}{T}$ (or) $dw = \dfrac{dQ}{T}$

But $\dfrac{dQ}{T} = d\phi$

$\therefore \ d\phi = dw$

Hence entropy is regarded as a measure of rate of availability of heat for transformation into work.

Entropy — A Property :-

Let us consider two equilibrium states ① & ② connected by two reversible paths A & B as shown.
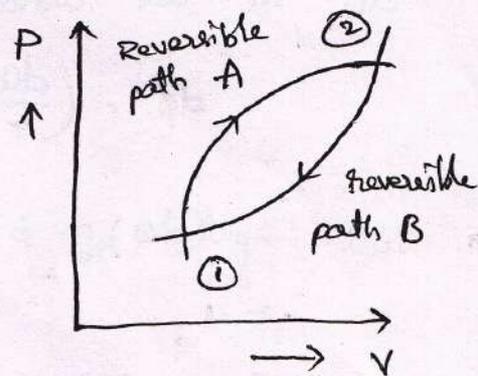
Now, if path B is reversed then the two paths makes the cycle a reversible cycle.

Then $\oint \dfrac{dQ}{T} = 0$

we have $\oint \dfrac{dQ}{T} = \displaystyle\int_1^2 \left(\dfrac{dQ}{T}\right)_A + \int_2^1 \left(\dfrac{dQ}{T}\right)_B = 0$

$\displaystyle\int_1^2 \left(\dfrac{dQ}{T}\right)_A = - \int_2^1 \left(\dfrac{dQ}{T}\right)_B$

$\displaystyle\int_{1,A}^2 \left(\dfrac{dQ}{T}\right) = \int_{1}^2 {}_B\left(\dfrac{dQ}{T}\right)$

From the above it is clear that the expression $\int \dfrac{dQ}{T}$ is independent of the paths. It is a point function & hence represents a property of the system. This property is called entropy.

$$d\phi = \left(\frac{dQ}{T}\right)_{rev} \quad \& \quad \int_1^2 d\phi = \phi_2 - \phi_1$$

Temperature entropy (T-φ) diagrams :-

A reversible TD process may be plotted on Temp Vs Entropy diagrams.

Consider an elemental increase in entropy $d\phi$ due to a small amount of heat transfer dQ at an absolute temp T.
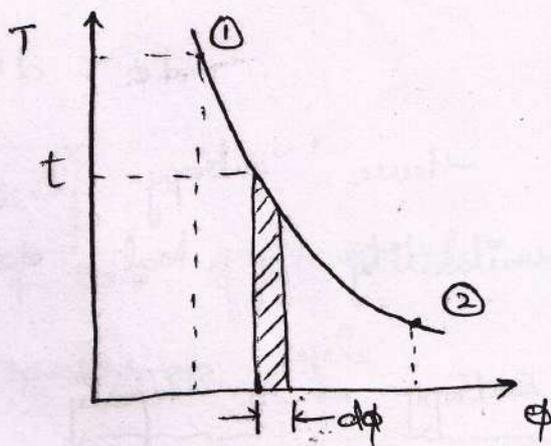
$$d\phi = \left(\frac{dQ}{T}\right)_{rev}$$

$$(dQ)_{rev} = T \times d\phi \quad (or) \quad simply \quad \boxed{dQ = T \times d\phi}$$

$$\boxed{dQ = T\,ds}$$

Thus area under a curve for a reversible process plotted on T-φ diagram, gives the quantity of heat transfered during the process.

Principle of Entropy Increase :-

The entropy of an isolated system increases in all real processes & is conserved in reversible process. *
(constant)

In order to prove this let us consider an irreversible process 1-2 along paths A shown in fig.

Let the cycle be completed by a reversible proc 2-1 along path B, so that process 1-A-2 & 2-B-1 together forms an irreversible cycle. From the Clausius Inequality,

$$\oint \frac{\delta Q}{T} < 0 \quad \text{for irreversible process}$$

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

path-A .... path-B

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

path-B .... path-B

But since path-B is reversible, the limits of the integral can be reversed & therefore

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

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

path-A .... path-B

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

(or)
$$ds > \left(\frac{\delta Q}{T}\right)_{inrev} \qquad \text{But } ds = \left(\frac{\delta Q}{T}\right)_{rev}$$

Hence in general, we may write $ds \geq \frac{\delta Q}{T}$

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

where equality & inequality signs shows the reversibility & irreversibility respectively.

For adiabatic process whether reversible or irreversible $\delta Q = 0$
hence $\Delta S \geq 0$.

This means that entropy is zero in reversible adiabatic & greater than zero in irreversible adiabatic.

Although entropy changes b/w two fixed states is the same for any paths, reversible or irreversible, the heat transfer to the system is less (more, if heat is transferred from the system) for irreversible paths than for the reversible one.

This is obvious from the fact that entropy increases in irreversible process & is conserved in reversible process.

① A qty of 400 KJ of heat is supplied per second to a heat engine at a fixed temp of 580 K. The heat rejection takes place at 280 K. The following results are obtained.

ⓐ 320 KJ/s are rejected   ⓑ 193 KJ/s are rejected.

ⓒ 80 KJ/s are rejected

Classify which of results report a reversible cycle or irreversible cycle or impossible results.

Sol: Applying clausius Inequality to the cycle in each case, we have

ⓐ $\oint \dfrac{dQ}{T} = \dfrac{400}{580} - \dfrac{320}{280} = -0.4532 < 0$

Since $\oint \dfrac{dQ}{T} < 0$, cycle is irreversible.

ⓑ $\oint \dfrac{dQ}{T} = \dfrac{400}{580} - \dfrac{193}{280} = 0$ $\therefore \oint \dfrac{dQ}{T} = 0$, cycle is reversible.

ⓒ $\oint \dfrac{dQ}{T} = \dfrac{400}{580} - \dfrac{80}{280} = 0.4039 > 0$ $\therefore \oint \dfrac{dQ}{T} > 0$, cycle is impossible

This shows clausius inequality.

② One kg of air is heated reversibly from an initial state of 1 atm & 15°C to 1 atm & 75°C. For reversible heating of air at const. pressure, $\frac{dQ}{dT}$ = 1.2 KJ/K. Determine the change in entropy.

Sol. For a closed system undergoing a reversible process, change of entropy, by definition $ds = \frac{dQ}{T}$

$$\frac{dQ}{dT} = 1.2 \text{ KJ/K (given)}$$

$$dQ = 1.2 \ dT$$

$$\therefore \ ds = \frac{dQ}{T} = \frac{1.2 \ dT}{T}, \quad \text{Integrating}$$

$$\int_1^2 ds = 1.2 \int \frac{dT}{T}$$

$$(s)_1^2 = 1.2 \left[\log_e T\right]_{T_1}^{T_2}$$

$$S_2 - S_1 = ds = 1.2 \left[\log_e T_2 - \log_e T_1\right]$$

$$ds = 1.2 \ \log_e \frac{T_2}{T_1}$$

$$ds = 1.2 \ \log_e \frac{348}{288}$$

$$= 0.227 \text{ KJ/kg K}.$$

| $T_1 = 15 + 273 = 288$ K
| $T_2 = 75 + 273 = 348$ K

AVAILABLE ENERGY :-

Heat energy derived from combustion of fossil fuels or from nuclear fusion is said to be low grade energy.

On the other hand, mechanical (shaft) work, electrical energy, water power, tidal power etc are rated as high grade energy.

The bulk of high grade energy is obtained from sources of low grade energy. But the complete conversion of low grade energy i.e., 'heat' into high grade energy i.e., 'shaft work' is impossible a/c to II law of TD.

" That part of low grade energy which is available for conversion into high grade energy is called "available energy."

Available energy is also called as Exergy.

Obviously the other part of energy, a/c to II law, must be rejected. It is known as Unavailable energy, which is also known as Unavailable Anergy.

In a thermodynamically reversible cycle engine, max. work o/p obtainable from a certain heat input is called available energy (A.E.). The minimum energy that has to be rejected to the sink is called Unavailable energy (U.E.). If Q_1 is heat input,

$$Q_1 = A.E + U.E$$

(or) $W_{max} = A.E.$

$$= Q_1 - U.E$$

$$\boxed{Energy = Exergy + Anergy}$$

If T_1 & T_2 are temp's of source & sink,
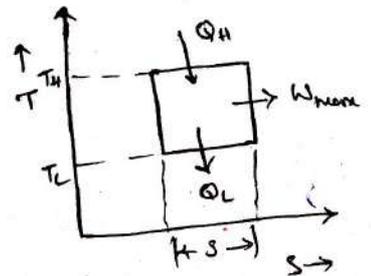
$$\eta_{rev} = 1 - \frac{T_2}{T_1}$$

For a given T_1, the efficiency of reversible engine η_{rev}, will increase with the decrease of T_2. The lowest practicable value of temp of heat rejection is the temp of surrounding T_0.

Then, $\eta_{max} = 1 - \dfrac{T_0}{T_1} = \dfrac{W_{max}}{Q_1}$

$\therefore W_{max} = Q_1 \left[1 - \dfrac{T_0}{T_1} \right]$

$AE = Q \left[1 - \dfrac{T_0}{T_1} \right]$

$= Q - T_0 \left(\dfrac{Q}{T} \right)$

$\boxed{AE = Q - T_0 \cdot ds}$

we know,
$W_{max} = AE$
$Q_1 = Q$ (say)

$\left[\begin{array}{l} T_0 = \text{dead state} \\ PE = 0 \\ KE = 0 \end{array} \right]$
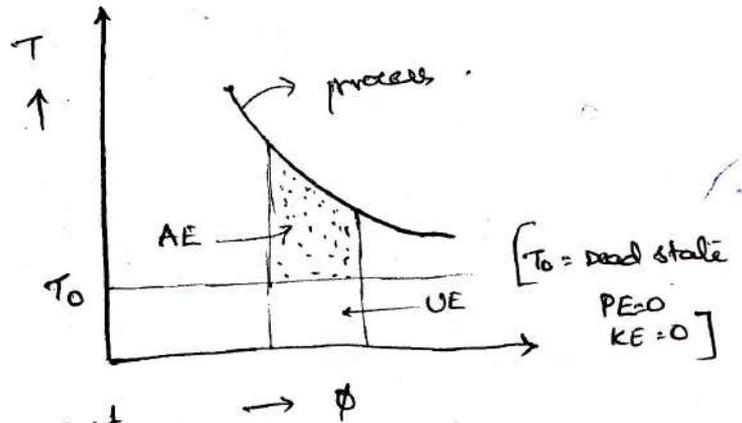
Figure shows the availability concept.

T_0 is the dead state which is a level below which the system cannot by itself go down, like atm. temp, zero altitude ($PE = 0$), zero velocity ($KE = 0$).

① Calculate AE & UE of a system that absorbs 15000 KJ of heat from heat source at 500 k, while environment temp is 290 k.

sol: $AE = Q_H - \dfrac{Q_H \, T_L}{T_H} \quad = 15000 - \dfrac{15000 \times 290}{500} = 6300 \text{ kJ}$

$UE = 8700 \text{ kJ}$

(or)
$Q_H = T_H \, ds$
$ds = \dfrac{Q_H}{T_H} = \dfrac{15000}{500} = 30 \text{ kJ/k}$
$UE = T_L \, ds = 290 \times 30 = 8700 \text{ kJ}$

$\begin{array}{l} \text{(or)} \\ \eta = \dfrac{T_H - T_L}{T_H} = \dfrac{W_{max}}{Q_H} \\[2mm] W_{max} = \dfrac{(T_H - T_L) \, Q_H}{T_H} \\[2mm] = 6300 \cdot KJ \end{array}$

② In a Carnot cycle heat is supplied at 350°c & rejected at 27°c. Working fluid is water which absorbs heat and evaporates liquid at 350°c to steam at 350°c. The associated entropy change is 1.44 KJ/kg k.

1. cycle operates with mass flow rate of 1 kg of water.

$T_H = 628 \, k$ Calculate ① Heat supplied, workdone

$T_L = 300 \, k$ ② cycle operates in steady flow

with power output of 20 kw. Determine mass flowrate of the system.

Sol:

$$\eta = \frac{T_H - T_L}{T_H} = \frac{623 - 300}{623} = 52\%.$$

$$ds = 1.44 \, KJ/kg \, k$$

$$Q_H = T_H \, ds = 632 \times 1.44 = 897.12 \, KJ$$

$$Q_L = T_L \, ds = 300 \times 1.44 = 432 \, KJ$$

$$W = Q_H - Q_L = 465 \, KJ/kg = AE$$

Power = Maxximum flow rate × work

$$\text{Mass flow rate} = \frac{Power}{work} = \frac{20}{465} = 0.043 \, kg/sec$$

③ Air at 1 bar & 30°C is heated in reversible manner at constant pressure until its temp reaches to 205°C.

① Calculate amount of heat added per kg of air.

② Available energy if sink temp is 4°C.

④ 0.2 kg of air initially at 575 k temp receives 300 kJ of heat reversibly at const. pressure. Determine the available & unavailable energy's of the heat added. C_p of air = 1.005 kJ/kg surrounding temp = 300 k.

Sol:

$T_1 = 575$ k

$Q = 300$ kJ

$C_p = 1.005$ kJ/kg k

$dS = \dfrac{dQ}{T}$

$= m \, C_p \, \ln\left(\dfrac{T_2}{T_1}\right)$

$= 0.2 \times 1.005 \, \ln\left(\dfrac{2067.5}{575}\right)$

$= 0.2572$ kJ/kg k

$dQ = m c_p \, \Delta T$

$300 = 0.2 \times 1.005 \times (T_2 - 575)$

$T_2 = 2067.5$ k

unavailable energy $= T_0 \times ds \implies UE = 2067.5 \times 0.2572$

$= 531.81$ kJ/kg

Entropy change during a Process :-

$dQ = du + dw$

$= du + pdv$

entropy $ds = \dfrac{dQ}{T} \implies T \cdot ds = dQ$

$\boxed{T \cdot ds = du + pdv} \rightarrow ①$

we know

$h = u + pv$

$dh = du + d(pv)$

$dh = du + pdv + vdp$

$dh - vdp = du + pdv$

$[T \, ds = du + pdv]$

$\boxed{T \cdot ds = dh - vdp} \rightarrow ②$

① Constant volume Process :-

$$dQ = m c_v dT$$

$$ds = \frac{dQ}{T} = m c_v \frac{dT}{T} \qquad \text{Integrate on both sides,}$$

$$\int_1^2 ds = \int_1^2 m c_v \frac{dT}{T}$$

$$S_2 - S_1 = m c_v (lnT)_1^2 \qquad \qquad \left| \; \frac{P_1}{P_2} = \frac{T_1}{T_2} \right.$$

$$\boxed{S_2 - S_1 = m c_v \; ln\left(\frac{T_2}{T_1}\right) \; (or) \; = m c_v \; ln\left(\frac{P_2}{P_1}\right)}$$

② Constant Pressure process :-

$$dQ = m c_p dT$$

$$ds = \frac{dQ}{T} = m c_p \frac{dT}{T} \qquad \text{Integrate,} \qquad \left| \; \frac{T_2}{T_1} = \frac{V_2}{V_1} \right.$$

$$\int_1^2 ds = \int_1^2 m c_p \frac{dT}{T}$$

$$\boxed{S_2 - S_1 = m c_p \; ln\left(\frac{T_2}{T_1}\right) \quad or \quad m c_p \; ln \frac{V_2}{V_1}}$$

③ Isothermal process :-

$$dQ = du + dw \qquad \left[\text{For isothermal } du = 0 \right] \qquad \left| \; \begin{aligned} P_1 V_1 &= P_2 V_2 \\ \frac{P_1}{P_2} &= \frac{V_2}{V_1} \end{aligned} \right.$$

$$= du + pdv$$

$$\therefore \; dQ = pdv \qquad \qquad \qquad PV = RT$$

$$ds = \frac{dQ}{T} = \frac{pdv}{T} \qquad \qquad P = \frac{RT}{v} . \left[\text{where } T = C \right]$$

$$ds = \frac{R}{v} dv \quad , \text{Integrate}$$

$$\int_1^2 ds = \int_1^2 \frac{R}{v} dv \quad \Rightarrow \quad \boxed{ds = R \; ln\left(\frac{V_2}{V_1}\right) \; (or) \; R \; ln\left(\frac{P_1}{P_2}\right)}$$

④ Reversible Adiabatic process :-

$$dQ = 0$$

$$ds = \frac{dQ}{T} = 0 \quad \Rightarrow \quad S_2 - S_1 = 0 \quad \Rightarrow \quad S_2 = S_1$$

Entropy is constant. This is also known as Isentropic Process.

⑤ Polytropic Process :- $[PV^n = C]$

Case(i):- $ds = \dfrac{dQ}{T}$ $dQ = du + dw$

$\qquad\qquad\qquad = C_v dT + p dv$

$ds = \dfrac{C_v dT}{T} + p \dfrac{dv}{T}$;   Integrate

$\qquad\qquad\qquad\qquad$ | $PV = RT$
$\qquad\qquad\qquad\qquad$ | $P = \dfrac{RT}{V}$

$\displaystyle\int_1^2 ds = \int_1^2 C_v \dfrac{dT}{T} + \int_1^2 p \dfrac{dv}{T}$

$$\boxed{S_2 - S_1 \;=\; C_v \ln\left(\dfrac{T_2}{T_1}\right) + R \ln\left(\dfrac{V_2}{V_1}\right)} \rightarrow ①$$

This is in terms of temp & volume.

$\therefore \dfrac{PV}{T} = $ constant $\Rightarrow \dfrac{P_1 V_1}{T_1} = \dfrac{P_2 V_2}{T_2} \Rightarrow \dfrac{T_2}{T_1} = \dfrac{P_2 V_2}{P_1 V_1}$

$\therefore$ Eq ① can be written as,

Case(ii):-
$S_2 - S_1 = C_v \ln\left[\dfrac{P_2 V_2}{P_1 V_1}\right] + R \ln\left(\dfrac{V_2}{V_1}\right)$

$\qquad\qquad = C_v \ln\left(\dfrac{P_2}{P_1}\right) + C_v \ln\left(\dfrac{V_2}{V_1}\right) + R \ln\left(\dfrac{V_2}{V_1}\right)$

$\qquad\qquad = C_v \ln\left(\dfrac{P_2}{P_1}\right) + (C_v + R) \ln\left(\dfrac{V_2}{V_1}\right)$

$\qquad\qquad\qquad\qquad\qquad$ $[\because C_p = C_v + R]$

$$\boxed{S_2 - S_1 = C_v \ln\left(\dfrac{P_2}{P_1}\right) + C_p \ln\left(\dfrac{V_2}{V_1}\right)} \rightarrow ②$$

Case(iii):- $\dfrac{PV}{T} = $ const $\therefore \dfrac{P_1 V_1}{T_1} = \dfrac{P_2 V_2}{T_2} \Rightarrow \dfrac{V_2}{V_1} = \dfrac{P_1 T_2}{P_2 T_1}$

$\therefore$ Eq ① can be written as,

$S_2 - S_1 = C_v \ln\left(\dfrac{T_2}{T_1}\right) + R \ln\left(\dfrac{P_1 T_2}{P_2 T_1}\right)$

$\qquad\qquad = C_v \ln\left(\dfrac{T_2}{T_1}\right) + R \ln\left(\dfrac{P_1}{P_2}\right) + R \ln\left(\dfrac{T_2}{T_1}\right)$

$\qquad\qquad = (C_v + R) \ln\left(\dfrac{T_2}{T_1}\right) + R \ln\left(\dfrac{P_1}{P_2}\right)$

$$\boxed{S_2 - S_1 = C_p \ln \dfrac{T_2}{T_1} + R \ln\left(\dfrac{P_1}{P_2}\right)} \rightarrow ③$$

Case IV : In terms of n & γ

$$P = \frac{RT}{V}$$

$$dQ = \left[\frac{\gamma - n}{\gamma - 1}\right] dw$$

$$ds = \frac{dQ}{T} = \left[\frac{\gamma - n}{\gamma - 1}\right] \frac{dw}{T} = \left[\frac{\gamma - n}{\gamma - 1}\right] \frac{pdv}{T}$$

$$ds = \left[\frac{\gamma - n}{\gamma - 1}\right] R \frac{dv}{v} \quad , \quad \text{Integrate} \ldots$$

$$\int_1^2 ds = \int_1 \left[\frac{\gamma - n}{\gamma - 1}\right] R \frac{dv}{v}$$

$$\boxed{S_2 - S_1 = \frac{\gamma - n}{\gamma - 1} R \ln\left(\frac{V_2}{V_1}\right)} \rightarrow \text{④}$$

$$\frac{C_p}{C_v} = \gamma$$
$$\gamma C_v = C_p$$

But $\dfrac{R}{\gamma - 1} = C_v$

$$\therefore \ S_2 - S_1 = (\gamma - n) C_v \ln\left(\frac{V_2}{V_1}\right)$$

$$= (\gamma \cdot C_v - n C_v) \ln\left(\frac{V_2}{V_1}\right)$$

$$\boxed{S_2 - S_1 = (C_p - n \cdot C_v) \ln(V_2/V_1)} \rightarrow \text{⑤} \quad \left[\text{in terms of vol}\right]$$

$PV^n = \text{const.}$

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{1/n} , \quad \text{then eq ⑤ becomes,}$$

$$S_2 - S_1 = (C_p - n \cdot C_v) \ln\left(\frac{P_1}{P_2}\right)^{1/n}$$

$$\boxed{S_2 - S_1 = (C_p - n \cdot C_v) \frac{1}{n} \ln\left(\frac{P_1}{P_2}\right)} \rightarrow \text{⑥} \quad \left[\text{in terms of pressure}\right]$$

we know,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{n-1/n} , \quad \text{take log on both sides,}$$

$$\ln\left(\frac{T_2}{T_1}\right) = \left(\frac{n-1}{n}\right) \ln\left(\frac{P_2}{P_1}\right)$$

$$\therefore \quad \ln\left(\frac{P_2}{P_1}\right) = \left(\frac{n}{n-1}\right)\ln\left(\frac{T_2}{T_1}\right) \implies \ln\left(\frac{P_1}{P_2}\right) = -\left(\frac{n}{n-1}\right)\ln\left(\frac{T_2}{T_1}\right)$$

$\therefore$ Eq. ⑥ can the written as,

$$S_2 - S_1 = (C_p - n.C_v)\cdot\frac{1}{\gamma}\cdot -\left(\frac{\gamma}{n-1}\right)\ln\left(\frac{T_2}{T_1}\right)$$

$$= \frac{n\,C_v - C_p}{n-1}\cdot\ln\left(\frac{T_2}{T_1}\right) \qquad\qquad \left| \quad \frac{C_p}{C_v} = \gamma \right.$$

$$S_2 - S_1 = \frac{C_v\left(n - \frac{C_p}{C_v}\right)}{n-1}\,\ln\left(\frac{T_2}{T_1}\right)$$

$$\boxed{\therefore \quad S_2 - S_1 = \left(\frac{n-\gamma}{n-1}\right)C_v\,\ln\left(\frac{T_2}{T_1}\right)} \rightarrow ⑦$$

① Heat flows from a reservoir at 800 k to another reservoir at 250 k. If entropy change of the heat reservoir is -4 kJ/kg K. Determine the entropy change of cold-reservoir
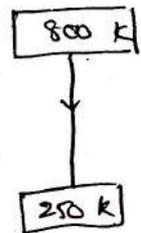
Sol:
$$\frac{dQ}{T} = (ds)_H$$

$$\frac{dQ}{800} = -4 \implies dQ = -3200 \text{ kJ}$$

800 K
↓
250 K

Same amount of heat is supplied to cold body.

For cold body,
$$\frac{dQ}{T} = (ds)_c \implies \frac{+3200}{250} = ds$$

$$(ds)_c = 12.8 \text{ kJ/kg k}.$$

② Heat flows from a hot reservoir at 800 k to another reservoir at 250 k. If the entropy change of overall process is 4.25 kJ/kg k. Make calculations for heat flowing out of high temp reservoir.
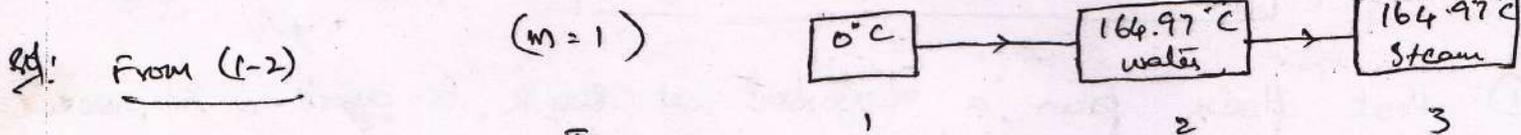
2⁴! change of entropy of hot & cold body = 4.25 KJ/kg k

$$\left(\frac{dQ}{T}\right)_H + \left(\frac{dQ}{T}\right)_c = 4.25$$

$$-\frac{dQ}{800} + \frac{dQ}{250} = 4.25$$

$$Q = 1545.45 \, KJ.$$

③ Water is heated at const pressure of 0.7 MPa, boiling point is 164.97°c. The initial temp of water is 0°c. Latent heat of evaporation is 2066.3 KJ/kg. Find the increase in entropy of water if final state is steam at 164.97°c. Cp of water = 4.2 KJ/kg k.

2⁴! From (1-2)   (m = 1)

| 0°C | → | 164.97°C water | → | 164.97°C Steam |

1   2   3

$$S_2 - S_1 = m C_p \ln \frac{T_2}{T_1}$$

$$= 4.2 \times 10^3 \times \ln \left(\frac{437.97}{2.73}\right)$$

$$= 1.985 \, KJ/kg \, k$$

From (2-3)

$$S_3 - S_2 = \frac{Q}{T} = \frac{latent \, heat}{T} = \frac{2066.3}{437.97} = 4.717 \, KJ/kg \, k$$

Total change in entropy

$$S_2 - S_1 + S_3 - S_2 = 1.985 + 4.717$$

$$= 6.7029 \, KJ/kg \, k$$

4) 2 kg of water at 80°c is mixed adiabatically with 3kg of water at 30°c at a constant pressure process of 1 atm. Find the increase in entropy of total mass of water due to mixing process.

Ans:

$$ds = \left(\frac{\partial s}{\partial T}\right)_p dT + \left(\frac{\partial s}{\partial p}\right)_T dp$$

Multiply with T,

$$\left[c_p = T\left(\frac{\partial s}{\partial T}\right)_p \right]$$

$$Tds = T\left(\frac{\partial s}{\partial T}\right)_p dT + T\left(\frac{\partial s}{\partial p}\right)_T dp$$

From M.W.R $\left(\frac{\partial s}{\partial p}\right)_T = \left(\frac{\partial v}{\partial T}\right)_p$, substitute

$$\boxed{Tds = c_p \, dT - T\left(\frac{\partial v}{\partial T}\right)_p dp} \longrightarrow ②$$

③ Consider combustion of fuel-air mixture in an IC engine which generates hot gases at 2773 K in cylinder. The gas expands a/c to polytropic process $pv^{1.38} = C$. volume ratio is 9. & Surrounding air temp is 293 K. Determine ⓐ work transfer ② change in I.E ③ Heat Transfer. Assume $R = 0.26$ kJ/kgk

$c_v = 0.82$ kJ/kgk

Sol:

$T_H = 2773$ K

$T_L = 293$ K

① work transfer $= \dfrac{P_1 V_1 - P_2 V_2}{n-1} = \dfrac{mRT_1 - mRT_2}{1.38 - 1}$

Given $\dfrac{V_2}{V_1} = 9$

In polytropic process

$$\left(\frac{V_2}{V_1}\right)^{n-1} = \frac{T_1}{T_2} = \left(\frac{9}{1}\right)^{1.38-1} = 2.3024$$

$T_2 = 1203$ K

$T_1 = 2773$ K

$T_2 = \dfrac{2773}{2.3024} = 1203$ K

work $= \dfrac{mR(T_1 - T_2)}{n-1}$

$= \dfrac{0.26(2773 - 1203)}{1.38 - 1} = \underline{\underline{1074 \text{ kJ}}}$

② $\Delta u = m \, c_v (T_2 - T_1)$

$= 1 \times 0.82(1203 - 2773) = \underline{\underline{-1287 \text{ kJ}}}$

③ $Q = \Delta u + w$

$$= -1287 + 1074 = -213 \text{ kJ}$$

Heat transfer $Q = 213$ kJ (rejected).

④ A cylinder contains $0.115 \, m^3$ of gas at 1 bar & 90°C. The gas is compressed to a vol. of $0.0288 \, m^3$. The final pressure of gas is 5.67 bar. Calculate

(i) Mass of gas   (ii) Value of index of Compression

(iii) Increase in internal energy of the gas

(iv) Heat transfer during Compression.

Assume $\gamma = 1.4$, $R = 0.3$ kJ/kgk, $c_v = 0.75$ kJ/kg k.

Sol:- $V_1 = 0.115 \, m^3$

$P_1 = 1$ bar $= 100$ kP

$V_2 = 0.0288 \, m^3$

$P_2 = 5.67 \times 10^2$ kP

$T_1 = 90°C = 363$ k.

(i) we have $P_1 V_1 = MRT_1$

$$m = \frac{P_1 V_1}{RT_1}$$

$$m = 0.1056 \text{ kg}$$

(ii) $PV^n = C$ i.e., $P_1 V_1^n = P_2 V_2^n$

$$100 \times (0.115)^n = 567 \times (0.0288)^n$$

$$n = 1.253.$$

(iii) $\Delta u = m c_v (T_2 - T_1)$

$$= 0.1056 \times 0.75 \, (515.27 - 363)$$

$$\Delta u = 12.06 \text{ kJ}$$

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

$$\frac{363}{T_2} = \left[\frac{0.0288}{0.115}\right]^{1.253-1}$$

$$T_2 = 515.27 \text{ k}$$

(iv) $Q = \Delta u + w$

$$= 12.06 - 19.089 \text{ kJ}$$

$$Q = -7.029 \text{ kJ}$$

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

$$= -19.089 \text{ kJ}$$

Heat Transfer $Q = 7$ kJ

③ $Q = \Delta u + w$

$= -1287 + 1074 = -213 \; kJ$

Heat Transfer $Q = 213 \; kJ$ (rejected).

④ A cylinder contains $0.115 \; m^3$ of gas at 1 bar & 90°C. The gas is compressed to a vol. of $0.0288 \; m^3$. The final pressure of gas is 5.67 bar. Calculate

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(iv) Heat transfer during Compression.

Assume $\gamma = 1.4$, $R = 0.3 \; kJ/kg\,k$, $C_v = 0.75 \; kJ/kg\,k$.

Sol: $V_1 = 0.115 \; m^3$

$P_1 = 1 \; bar = 100 \; kP$

$V_2 = 0.0288 \; m^3$

$P_2 = 5.67 \times 10^2 \; kP$

$T_1 = 90°C = 363 \; K$.

(i) we have $P_1 V_1 = M R T_1$

$$m = \frac{P_1 V_1}{R T_1}$$

$$m = 0.1056 \; kg$$

(ii) $PV^n = C$ i.e., $P_1 V_1^n = P_2 V_2^n$

$$100 \times (0.115)^n = 567 \times (0.0288)^n$$

$$n = 1.253.$$

(iii) $\Delta u = m C_v (T_2 - T_1)$

$= 0.1056 \times 0.75 \, (515.27 - 363)$

$\Delta u = 12.06 \; kJ$

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

$$\frac{363}{T_2} = \left[\frac{0.0288}{0.115}\right]^{1.253-1}$$

$$T_2 = 515.27 \; k$$

(iv) $Q = \Delta u + w$

$= 12.06 - 19.089 \; kJ$

$Q = -7.029 \; kJ$

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

$$= -19.089 \; kJ$$

Heat Transfer $Q = 7 \; kJ$

① The HE receiver heat at the rate of 500 kw, from a source temp of 1200 k. It rejects waste heat at 300 k. In this process it delivers a power o/p of 180 kw. Determine

① η of engine ② Ideal power o/p ③ Irreversibility.

Sol:

① $\eta = \dfrac{T_H - T_L}{T_H} = \dfrac{1200 - 300}{1200} = \underline{75\%}$

② Ideal power o/p = heat i/p = $\underline{500}$ kw

③ Wactual

$$\eta = \dfrac{Q_H - Q_L}{Q_H} = \dfrac{W}{Q_H}$$

$W = 0.75 \times 500 = \underline{375}$ kw

Irreversibility = Ideal power − Actual power

$= 375 - 180$

$= \underline{195}$ kw.

Heat lost by 2 kg of   Heat gained by 3 kg of water at
water at 80°C = 30°C.

$$\therefore \quad 2\,c_p\,(80-t) = 3\,c_p\,(t-30) \qquad \left[Q = m c_p \,\Delta T \right]$$

$$t = \underline{50}°C \qquad \left[c_{p\,water} = 4.2 \ kJ/kg\,k \right]$$

$$(\Delta s)_1 = \int_{T_1}^{T_2} \frac{\delta Q}{T} = \int_{353}^{323} m \frac{c_p\,dT}{T}$$

$$= 2 \times 4.2 \ ln \left(\frac{T_2}{T_1}\right)_{353}^{323} = 8.4 \ ln \left(\frac{323}{353}\right)$$

$$= -0.746 \ kJ/kg\,k$$

Entropy change for 3 kg of water,

$$(\Delta s)_2 = \int_{P_1}^{T_2} \frac{\delta Q}{T} = \int_{303}^{323} \frac{m c_p\,dT}{T}$$

$$= 3 \times 4.2 \times ln \left(\frac{323}{303}\right) = 0.8054 \ kJ/kg\,k$$

Entropy increase of total mass of water due to mixing,
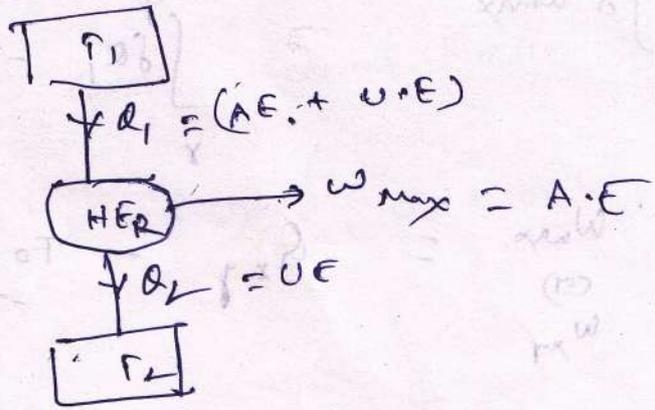
$$= (\Delta s)_1 + (\Delta s)_2$$

$$= -0.746 + 0.8054$$

$$= 0.059 \ kJ/kg\,k$$

Exergy — Available energy [A.E.]

- The energy which we are actually going to utilize is called Exergy also called Available energy

- The energy which we are not going to actually utilize is called Anergy also called unavailable energy

- Basically the [source or heat contain both things] i.e. A.E & U.A.E.

Take an example

Some part of energy is utilized to produce useful work & called Available energy
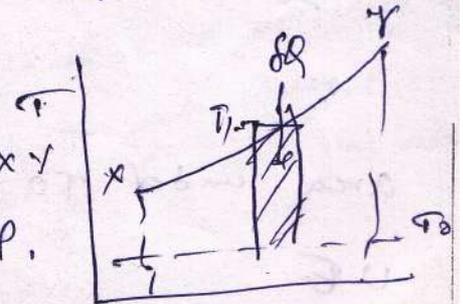
Some part of energy which is not utilized to produce work is called U.E.

W.K.T. $\eta_{H.E} = 1 - \dfrac{T_2}{T_1} = \dfrac{W_{max}}{Q_1}$

$W_{max} = Q_1 \left[1 - \dfrac{T_2}{T_1} \right]$

$Q_1 = (A.E. + U.E)$

$W_{max} = A.E$

$Q_2 = UE$

To understand concept of A.E. which is consider a finite process b/w X & Y

The final temp. is assumed as T_0 for X Y which is surrounding temp. or amb. Tep.

Assuming Tep. T_1 During process X & Y Assuming elementary strip... δQ is heat added to for of elementary strip for rev. process.

for elem. strip. for fin. x y process

write W_{max}.

$$\delta W_{max} = \delta Q_1 \left[1 - \frac{T_0}{T_1} \right]$$

$$= \delta Q_1 - \delta Q_1 \frac{T_0}{T_1}$$

$$= \delta Q_1 - T_0 \left[\frac{\delta Q_1}{T_1} \right]$$

for total work is max

$$\int_x^y \delta W_{max} = \int_x^y \delta Q_1 - T_0 \int_x^y \frac{\delta Q_1}{T_1}$$

$\frac{\delta Q_1}{T_1} = dS$

$$W_{max} = Q_{xy} - T_0 (S_y - S_x)$$
(or)
W_{xy}

W_{max},
or
AE

$Q_1 = U.E$

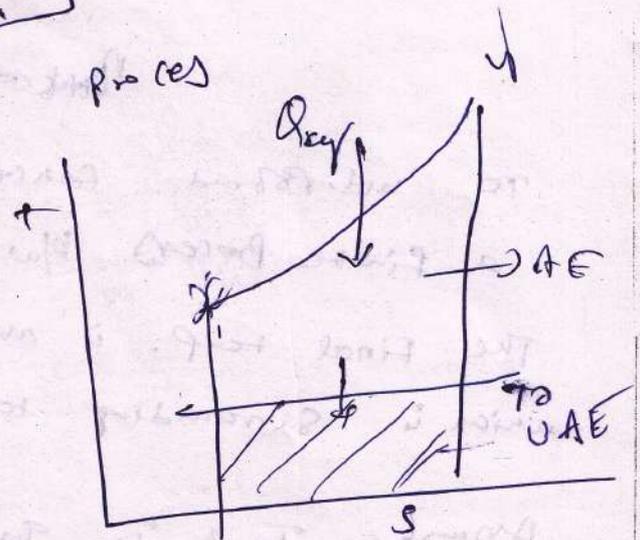$$\therefore U E = T_0 \left[S_y - S_x \right]$$

If we draw for whole process

area under T0 part show

U E

area un shaded is A E

Summation $A E + U E$ gives input energy

Reversible work by an open system exchanging heat only with Surroundings.

$$dW_{max} = dm_1 \left[h_1 - T_0 S_1 + \frac{V_1^2}{2} + gz_1 \right] - dm_2 \left[h_2 - T_0 S_2 + \frac{V_2^2}{2} + gz_2 \right]$$

$$- d \left[U - T_0 S + \frac{mv^2}{2} + mgz \right]$$

Reversible work in a steady flow Process

$$W_{max} = \left(H_1 - T_0 S_1 + \frac{mv_1^2}{2} + mgz_1 \right) - \left(H_2 - T_0 S_2 + \frac{mV_2^2}{2} + mgz_2 \right)$$

where $H - T_0 S$ is called Keenan function rep. by B

$$\therefore W_{max} = \left(B_1 + \frac{m_0 V_1^2}{2} + mgz_1 \right) - \left(B_2 + \frac{mV_2^2}{2} + mgz_2 \right)$$

$$W_{max} = \psi_1 - \psi_2.$$

$\psi = $ Availability function of steady flow process

$$\psi = B + \frac{mv^2}{2} + mgz$$

useful work — All the work 'W' of system would not be available for deliver, since a certain portion of it would be spent in pushing out the atmosphere.

The useful work is defined as the actual work delivered by a system less the work performed on the atmosphere.

Let V_1 & V_2 are init. & final volume & P_0 is the atmospheric

Reser: w.D. on Atmosphere $= P_0 (V_2 - V_1)$

then useful work $= W_U = W_{act} - P_0 (V_2 - V_1)$

max. useful work $= (W_U)_{max} = W_{max} - P_0 (V_2 - V_1)$

this is for closed system.

In case of open system $(W_U) = W_{act}$ (Becart no change

$(W_u)_{max} = E_1 - E_2 + P_0(V_1 - V_2) - T_0(S_1 - S_2)$

If K.E & P.E changes are neglected

$(W_u)_{max} = U_1 - U_2 + P_0(V_1 - V_2) - T_0(S_1 - S_2)$

$(W_u)_{max} = [U_1 + P_0 V_1 - T_0 S_1] - [U_2 + P_0 V_2 - T_0 S_2]$

$$= \phi_1 - \phi_2$$

Here ϕ is Called Availability function for a closed System

where $\phi = U + P_0 V - T_0 S$

Irreversibility :- The actual work done by system is always less

than Idealised rev. work & diff. b/w two is called Irreversibility

of the process.

$$I = W_{max} - W$$

Irreversibility also Called degradation of Dissipation.

$$I = T_0 (\Delta S_{sytm} + \Delta S_{surround})$$

$$I = T_0 [\Delta S_{univ}]$$

Gouy - Stodola Theorem :- The Rate of loss of Available energy or exergy

in a process is proportional to rate of entropy generation $(\dot{S}_{gen})$

$$\dot{I} = W_{lost} = T_0 \Delta S_{univ} = T_0 \dot{S}_{gen}$$

P) Air expands through a Turbine from 500kPa, 520°C to 100kPa, 300°C. During

expⁿ 10 KJ/kg of heat is lost to surrounding which is at 98 KPa, 20°C Neglecting

KE & P.E changes. Determine Per kg of air 1) The decrease in availability

2) The max. work 3) Irreversibility. for air take Cp = 1.005 kJ/kg·k.

From Ist law

$T ds = dH - V dP$

entropy change of air in ⟹ $\int_1^2 dS = \int_1^2 \frac{m \, Cp \, dT}{T} - \int_1^2 \frac{mR \, dP}{P}$

expⁿ process

$S_2 - S_1 = m Cp \ln \frac{T_2}{T_1} - mR \ln \frac{P_2}{P_1}$

for 1kg of air

$S_2 - S_1 = Cp \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$

Change in availability $= \phi_1 - \phi_2 = b_1 - b_2$

$= (h_1 - T_0 S_1) - (h_2 - T_0 S_2)$

$= Cp(T_1 - T_2) - T_0 (S_1 - S_2)$

$= Cp(T_1 - T_2) - T_0 \left[R\ln \frac{P_2}{P_1} - Cp \ln \frac{T_2}{T_1} \right]$

$= 1.005(520-300) - 293 \left[0.287 \ln \left(\frac{1}{5}\right) - 1.005 \ln \frac{513}{793} \right]$

$= 260.7 KJ/kg$

Max. work = Wmax = Change in availability $= \phi_1 - \phi_2$

$= 260.7 KJ/kg$

From SFEE

$Q + h_1 = W + h_2$

$W = (h_1 - h_2) + Q$

$W = Cp(T_1 - T_2) + Q$

$W = 1.005(520-300) - 10$

$W = 221.1 + 211.1 KJ/kg$

Irreversibility

$I = W_{max} - W$

$= 260.7 - 211.1$

$= 49.6 KJ/kg$

(or)

$I = T_0 (\Delta S_{sytm} + \Delta S_{surr})$

$I = 293 \left[1.005 \ln \left(\frac{573}{793}\right) - 0.287 \ln\left(\frac{1}{5}\right) + \frac{10}{293} \right]$

$I = 49.6 KJ/kg$