SWAMI VIVEKANANDA SCHOOL OF

ENGINEERING & TECHNOLOGY

LECTURE NOTE

THERMAL -II

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HEAT TRANSFER

(1) Introduction:

Heat transfer means transmission of heat energy from one region to another due to difference of temperature between this two region.

Mechanical engineer have to face the Problem of heat transfer in designing of boilers, condensers, furnaces, Piping system, steam turbine, I.C engine, reciprocating steam engine, gas turbines, space craft engineering, solar system, nuclear reactor etc.

(2) Modes of heat transfer:

(i) conduction, (ii) convection, (iii) Radiation.

(i) conduction: conduction is the transfer of heat from one part of a substance to another part of the same substance, or from one substance to another in physical contact with it, without appreciable displacement of molecules forming the substance.

(ii) convection: convection is the process of heat transfer during which heat energy is carried from one part of a fluid to another part of it by the actual movement of heated mass of the fluid. The motion of the fluid is caused by the differences in density which results from temperature difference. Heat transfer by convection can occur only in fluids.

(iii) Radiation: Radiation is the transfer of heat through space or matter by means other than conduction or convection. Radiation of heat is through of as electromagnetic waves or quanta (as convenient) as light and radio waves. Radiant energy requires no medium for Propagation, and will Pass through a vacuum.

(i) **compressor :** A refrigerant compressor, as the name indicates, is a machine used to compress the vapour refrigerant from the evaporator and to raise its pressure so that the corresponding saturation temp is higher than that of the cooling medium. It also continually circulates the refrigerant through the refri-gerating system.

(ii) **classification of compressors :**

(1) According to the method of compression :

(a) Reciprocating compressor.

(b) Rotary compressors and

(c) centrifugal compressors.

(2) According to the number of working strokes:

(a) single acting compressors and

(b) double acting compressors.

(3) According to the number of stages:

(a) Single stage (or single cylinder) compressors

(b) and multi stage (or multi cylinder) compressors.

(4) According to the method of drive employed:

(a) Direct drive compressors and

(b) belt drive compressors.

(5) According to the location of the prime mover:

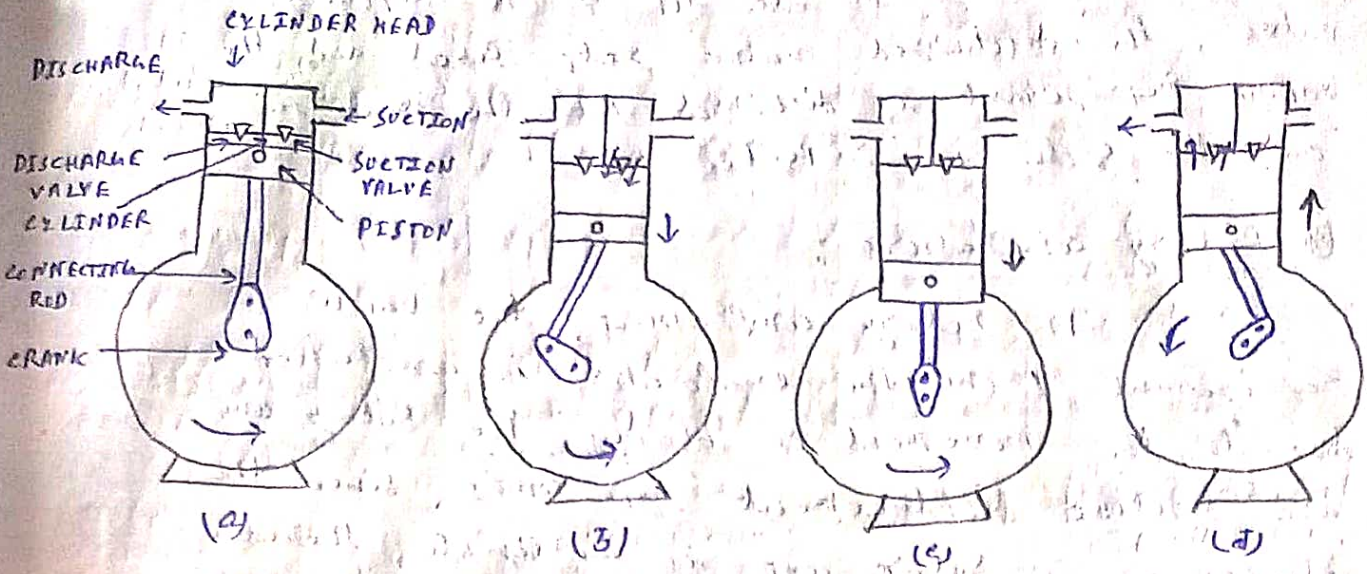
(a) Semi-hermetic compressors (direct drive, motor and compressor in separate housings) and

(b) Hermetic compressors (" in same housing)

① Reciprocating compressors:

These compressors are used for refrigerants which have comparatively low volume per kg and a large differential pressure, such as ammonia (R-717), R-12, R-22, and methyl chloride (R-40). The reciprocating compressors are available in sizes as small as 1/12 kW which are used in small domestic refrigerators and up to about 150 kW for large capacity installations.

The two types of reciprocating compressors in general use are single acting vertical compressors and double acting horizontal compressors. The single acting compressors have their cylinder arranged vertically, radially or in a V or W form. The double acting comp usually have their cylinders arranged horizontally.



PRINCIPLE OF OPERAN OF A SINGLE STAGE, SINGLE ACTING RECI COMP

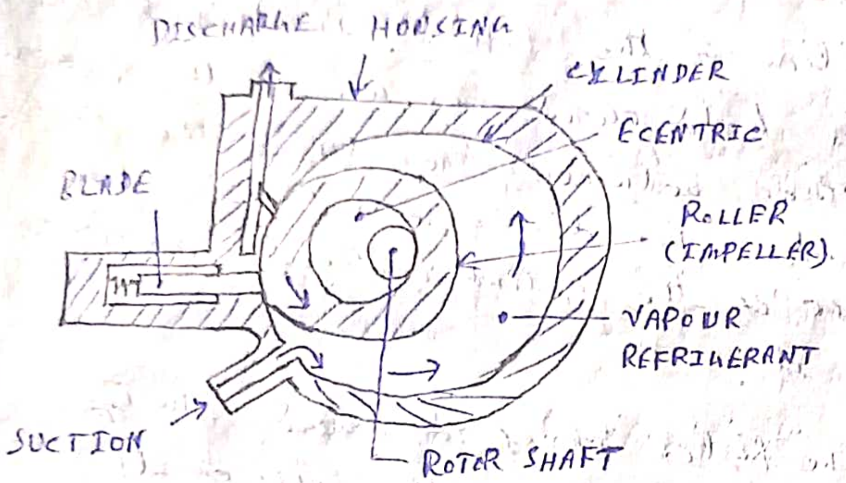
Let us consider the piston is at the top of its stroke as shown in figure (a). This is called top dead centre position of the piston. In this position, the suction valve is held closed because of the pressure in the clearance space between the top of the piston and the cylinder head. The discharge valve is also held closed because of the cylinder head pressure acting on the top of it.

When the piston moves downward (during suction stroke) as shown in fig (b), the refrigerant left in the clearance space expands. Thus the volume of the cylinder (above the piston) increases and the pressure inside the cylinder decreases. when the pressure becomes slightly less than the suction pressure or atm pressure, the suction valve gets opened and the vapour refrigerant flows into the cylinder. This flow continues until the piston reaches the bottom of its stroke (bottom dead centre)
At the bottom of the stroke as shown in fig (c), the suction valve closes because of spring action. Now the piston moves upward (during compⁿ stroke) the volᵐ of cylinder decreases and the Pr inside the cylinder increases. When the Pr inside the cylinder becomes

greater than that on the top of the discharge valve, the discharged valve gets opened and the vapour refrigerant is discharged into the condenser and the cycle is repeated.

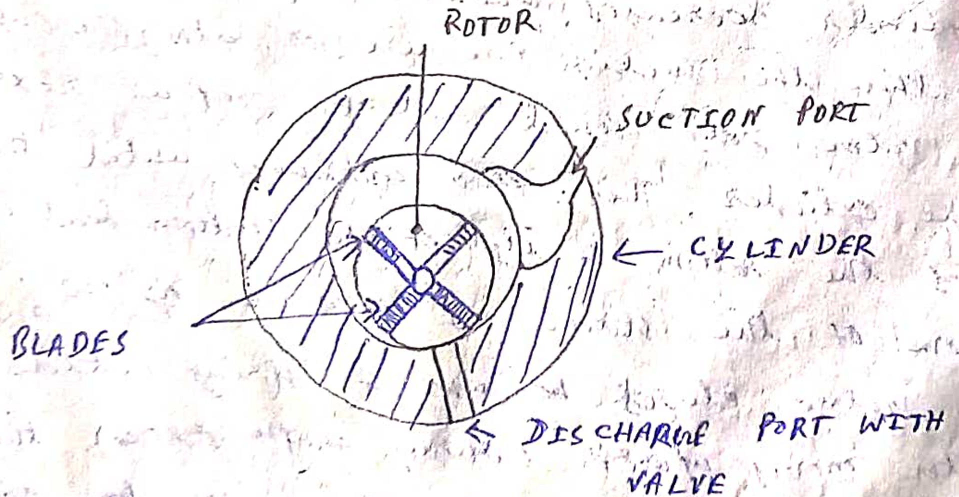
② Rotary compressors :

In rotary compressors, the vapour refrigerant from the evaporator is compressed due to the movement of blades. The rotary comp are positive displacement type comp's. Since the clearance in rotary comp is negligible, therefore they have high volumetric efficiency. These compressors may be used with refrigerants R-12, R-22, R-114 and ammonia.



(a) COMPLETION OF INTAKE STROKE AND BEGINNING COMP

STATIONARY SINGLE BLADE ROTARY COMP

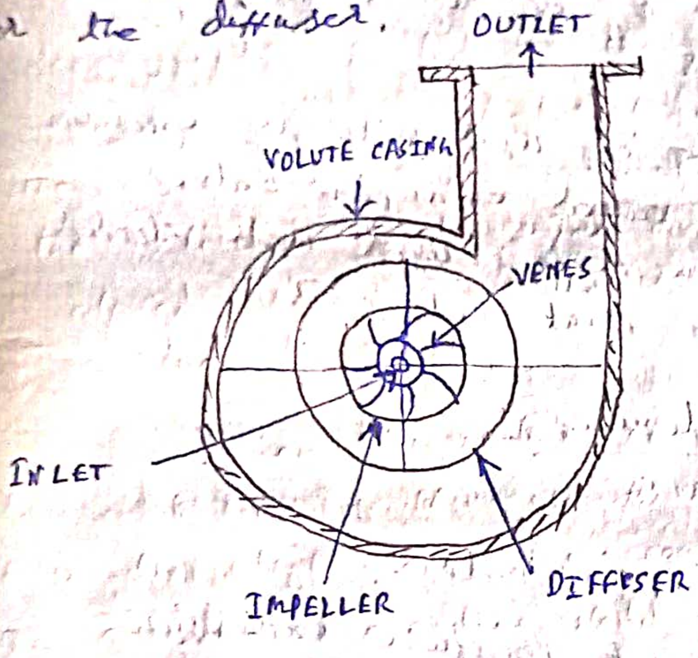


ROTATING BLADE TYPE ROTARY COMP

① centrifugal compressor :

The centrifugal art for refrigeration system was designed and developed by Dr. Willis H. Carrier in 1922. This compressor increases the pressure of low pr vapour refrigerant to a high pressure by centrifugal force. This is generally used for refrigerants that require large displacement and low condensing pressure, such as R-11 and R-113. However, the refrigerant R-12 is also employed for large capacity applications and low temp applications.

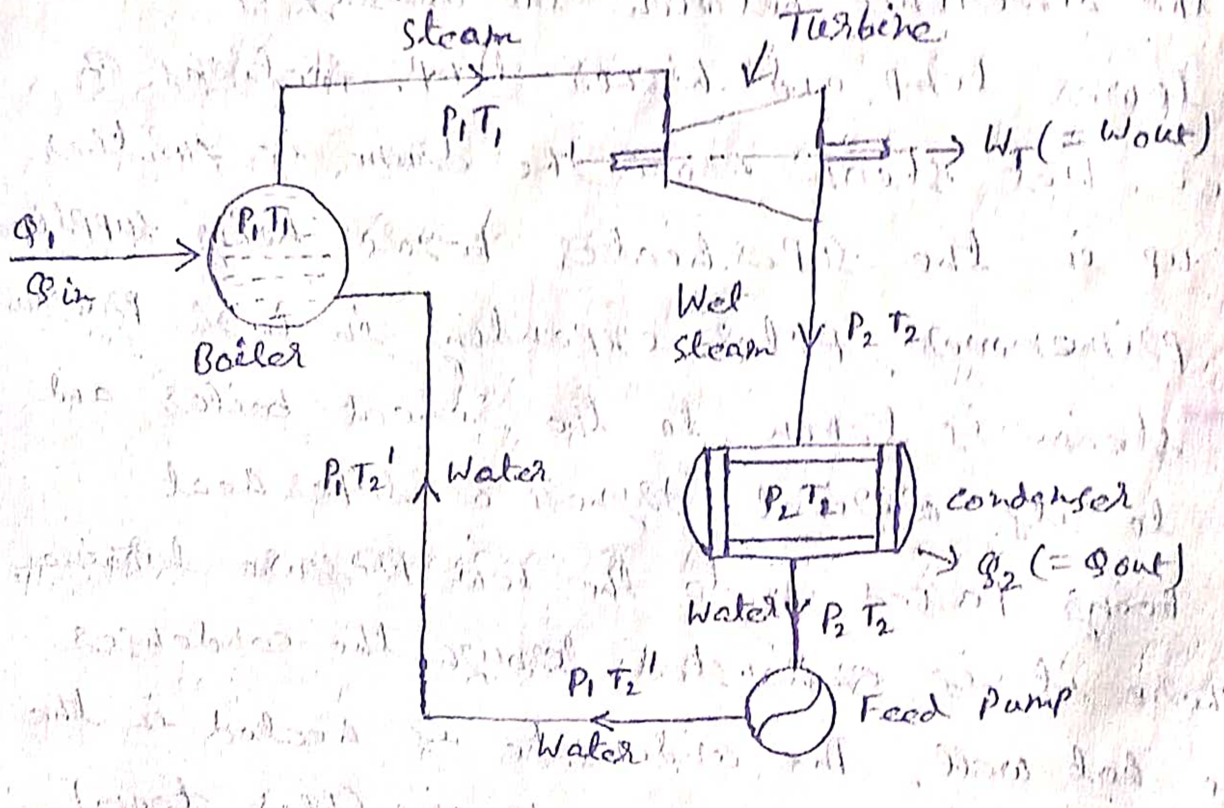
The kinetic energy they attained at the impeller outlet is converted into pressure energy when the high velocity pressure vapour refrigerant passes over the diffuser.



CENTRIFUGAL COMPRESSOR

(iii) Steam Power cycle (Rankine cycle):

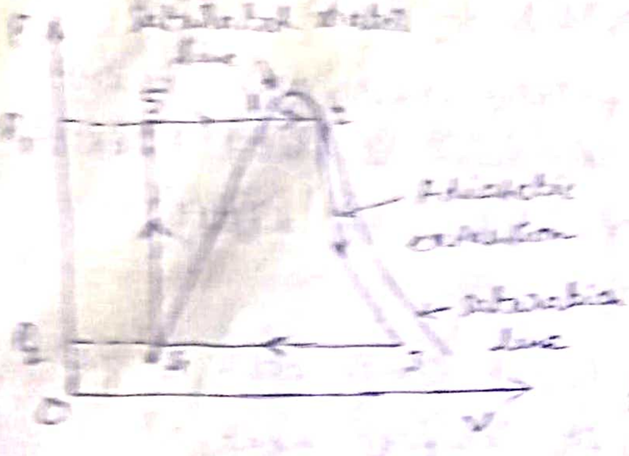
Rankine cycle is a modification of carnot cycle using steam as the working medium. Rankine cycle is the theoretical cycle on which the steam turbine (or engine) works.



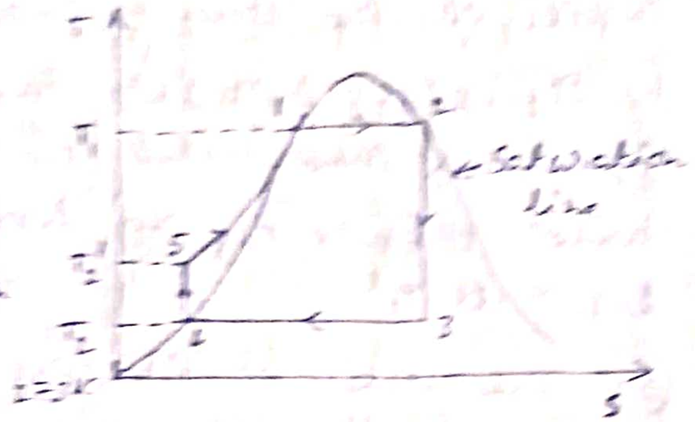
Schematic diagram for Rankine cycle

Representation of Rankine cycle with the help of P-V diagram, T-S diagram and H-S diagram:

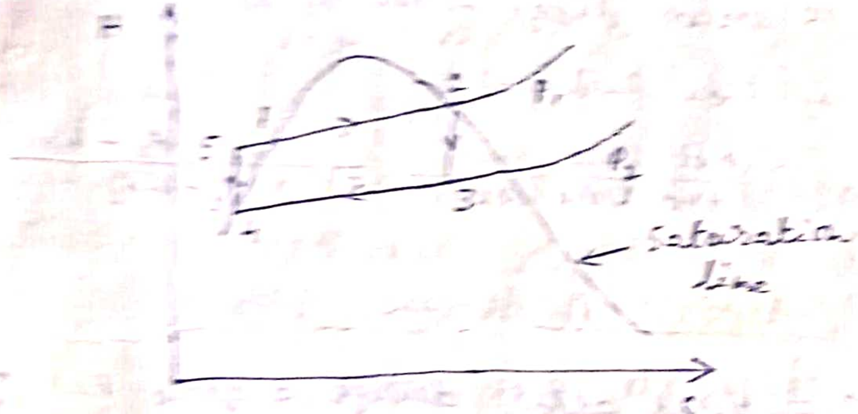
Steam used in the steam turbine has been assumed to be dry saturated steam.



P-V diagram



T-S diagram



H-S diagram

The following is the sequence of operations of Rankine cycle:

(1) Process 1-2 Isothermal addition of heat to water in a boiler. Water has already reached saturation temperature T_1 corresponding to boiler pressure P_1. Heat is added to water at constant temperature T_1 and constant pressure P_1 untill water is completely converted into steam (may dry steam at 2).

(2) Process 2-3 Isentropic adiabatic expansion of steam in a steam turbine untill pressure of steam drops to back

Pressure (or condenser pressure) P_2. T_2 the temperature of steam at P_2. Evidently, T_2 is the saturation temp. corresponding to back pressure P_2.

(3) Process 3-4 represents condensation of steam in a condenser at constant pressure P_2 and constant temp. T_2 untill all the steam is converted into water at 4.

(4) Process 4-5 represents isentropic compression of water by a feed pump untill the pressure of water rises to boiler pressure P_1, and temperature also sligntly rises to T_2'.

(5) This water at pressure P_1 and temperature T_2' now enters into the boiler where it receives heat at constant pressure P_1 along the line 5-1 untill the temperature of water rises from T_2' to T_1.

The cycle is then repeated.

$$\text{Work ratio} = \frac{\text{Net work done}}{\text{+ve work done}} = \frac{H_1 - hf_2 - W_P}{H_2 - hf_2}$$

Thermal efficiency of Rankine cycle:

Let Q_1 = Head added during a cycle per kg of steam.

Q_2 = Head rejected " " " " steam.

Then $Q_1 - Q_2$ = Heat utilised during the cycle per kg of steam.

Now, Thermal efficiency of a cycle is given by,

$$\eta_{th} = \frac{\text{Heat utilised}}{\text{Heat supplied}} = \frac{Q_1 - Q_2}{Q_1} \quad \text{--- (i)}$$

Let, H_1 = Total heat of 1 kg steam at 2. where pressure of steam is P_1 (admission pressure to the turbine) in KJ.

H_2 = Total heat of 1 kg steam in KJ at 3, where the pressure is P_2.

W_p = Work required to operate the feed pump.

The work is called feed pump work $= (P_1 - P_2) \times V_4$ (see P-V diagram) KJ/kg

Here, V_4 = SP. volume of water at P_2 in m^3/kg.

Then, $Q_1 = H_1 - h_{f_2} - W_p$

Where, h_{f_2} = Heat of the liqued corresponding to back pressure P_2.

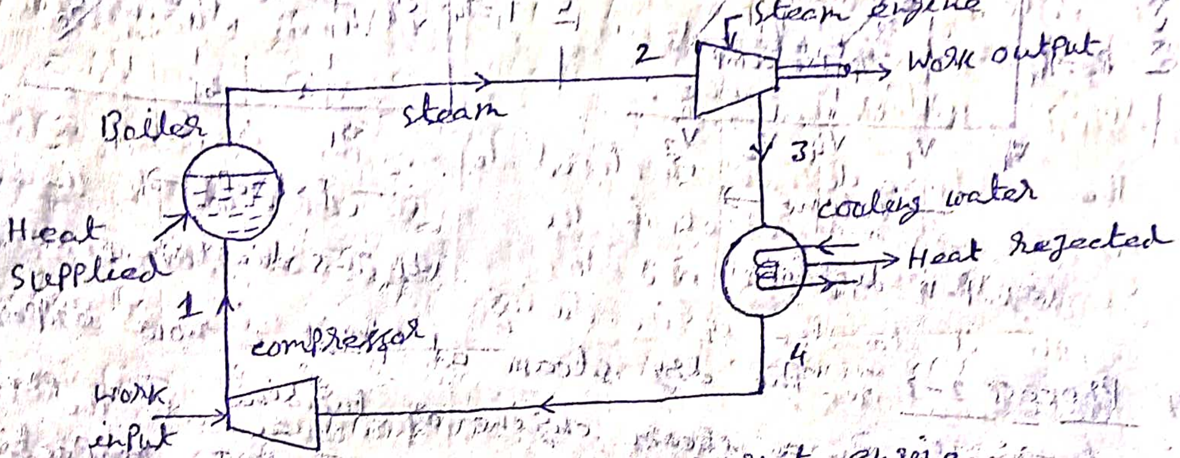
$$Q_2 = H_2 - h_{f_2}$$

$$\eta_{th} = \frac{(H_1 - h_{f_2} - W_p) - (H_2 - h_{f_2})}{H_1 - h_{f_2} - W_p}$$

$$\therefore \eta_{th} = \frac{H_1 - H_2 - W_p}{H_1 - h_{f_2} - W_p}$$

(11) Carnot cycle with steam as working substance:

The schematic diagram of a carnot engine is shown in below figure and the carnot cycle using steam as the working substance is represented on P-V and T-S diagrams as shown in figures (a) and (b) respectively.



Schematic diagram of a carnot engine.

Consider 1 kg of saturated water at pressure P_1 and absolute temperature T_1 as represented by in figure (a) and (b). The cycle is completed by the following four processes:

(1) Process 1-2: The saturated water at ~~Pressure P_1 and absolute temp T_1 as represented by~~ point 1 is isothermally converted into dry saturated steam in a boiler and the heat is absorbed at a constant temp T_1 and pressure P_1. The dry state of steam is represented by point 2. It means that the temp T_2 (i.e at point 2) and pressure P_2 (i.e at point 2) is equal to temperature T_1 and pressure P_1 respectively. This isothermal process is represented by curve 1-2 on P-v and T-S diagrams in figure (a) and (b).

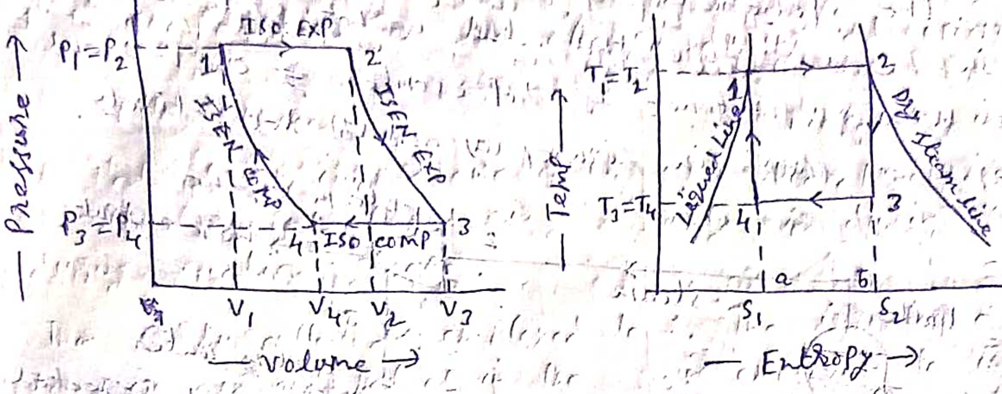
We know that the heat absorbed by the saturated water during its conversion into dry steam it is latent heat of evaporization (i.e, $h_{fg1} = h_{fg2}$) corresponding to a pressure P_1 or P_2 ($\because P_1 = P_2$).

We also know that the area a-b-1-2-b-a in the T-s diagram represents the heat absorbed to some scale, during the isothermal process.

Heat absorbed during isothermal process (area 1-2-b-a),

$$q_{1-2} = \text{change in entropy} \times \text{Absolute temperature}$$

$$= (S_2 - S_1) T_1 = (S_2 - S_1) T_2 \quad \ldots (\because T_1 = T_2) \quad \text{---(i)}$$



(a) P-v diagram (b) T-s diagram

(2) Process 2-3 :- The dry steam at point 2 now expands isentropically in a steam engine or turbine. The pressure and temp falls from P_2 to P_3 and T_2 to T_3 respectively. Since no heat is supplied or rejected during this process, therefore there is no change of entropy. The isentropic expansion is represented by the curve 2-3 as shown in figure (a) and (b).

(3) Process 3-4 :- The wet steam at point 3 is now isothermally condensed in a condenser and the heat is rejected at constant temp T_4 (i.e at point 4) and pressure P_4 (i.e, at point 4) is equal to the temp T_3 and pressure P_3 respectively. This isothermal process is represented by the curve 3-4 on P-v and T-s diagrams as shown in figure (a) and (b).

We know that the area 3-4-b-a in the T-s diagram represents the heat rejected to some scale during the isothermal process.

$\therefore$ Heat rejected during isothermal compression (area 3-4-b-a),

$$q_{3-4} = (S_2 - S_1) T_3 = (S_2 - S_1) T_4 \quad \ldots (\because T_3 = T_4) \quad \text{---(ii)}$$

(4) Process 4-1 : The wet steam is at point 4 is finally compressed isentropically in a compressor, till it returns back to its original state (point 1). The pressure and temp rises from P_4 to P_1 and T_4 to T_1 respectively. The isentropic compression is represented by the curve 4-1 as shown in fig. (a) and (b). Since no heat is absorbed or rejected during this process, therefore entropy remains constant. This completes the cycle.

We know that work done during the cycle

$$= \text{Heat absorbed} - \text{Heat rejected}$$

$$= (S_2 - S_1) T_1 - (S_2 - S_1) T_3$$

$$= (S_2 - S_1)(T_1 - T_3)$$

and efficiency of the carnot cycle,

$$\eta = \frac{\text{Work done}}{\text{Heat absorbed}}$$

$$= \frac{(S_2 - S_1)(T_1 - T_3)}{(S_2 - S_1) T_1} = \frac{T_1 - T_3}{T_1} = 1 - \frac{T_3}{T_1}$$

Where, T_1 = Highest temp. corresponding to the boiler pressure $P_1 = P_2$ and

T_3 = Lowest temp corresponding to the condenser pressure $P_3 = P_4$

Notes: (1) Since the heat absorbed is the highest temp and rejected at the lower temp, the carnot cycle would give a maximum possible efficiency.

(2) It may be noted that it is impossible to make a steam engine working on carnot cycle. The simple reason for the same is that the isothermal expansion 1-2 will have to be carried out extremely slow to ensure that the steam is always at temp T_1. Similarly isothermal compression 3-4 will have to be carried out extremely slow. But isentropic expn and compression 2-3 and 4-1 will should be carried out as quickly as possible in order to approach ideal isentropic conditions. We know that sudden changes in the speed of an engine are not possible in actual practice. Moreover it is impossible to completely eliminate friction between the various moving

(iii) Fourier's law of conduction :

This is the imperical law based on observation and states that the rate of flow of heat through a single homogeneous solid is directly proportional to the area of the section at right angles to the direction of heat flow, and the change of temperature with respect to the length of the path of the heat flow.

It is be represented by the equation,

$$Q \propto A$$

Thus, $Q = -kA \frac{dt}{dx}$

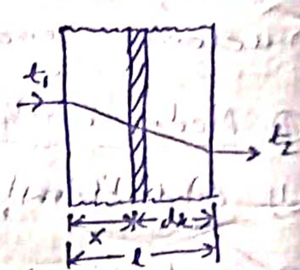
where, k = constant of proportionality and is known as thermal conductivity of the body (W/mK).

$\frac{dt}{dx}$ = Temperature gradient.

(iii) Thermal conductivity :

Thermal conductivity of a material is the amount of heat conducted through the material per unit time having unit area of heat exposure area, unit thickness and unit difference of temperature.

Rate of heat flow, $Q = \frac{kA(t_1 - t_2)}{l}$



$\therefore k = \frac{Ql}{A(t_1 - t_2)}$

If $l = 1$, $A = 1$ and $t_1 - t_2 = 1$

Then, $k = Q$

(iii) Heat exchanger :

A device used for transferring heat from fluid to another is called a heat exchanger. Its use is made in radiators in automobile, intercoolers and preheaters condensers and boilers in steam plants, condensors and ~~refrigerator~~ evaporators in refrigeration and air conditioning units. The following two types of heat exchangers are common in use :

(1) Parallel flow heat exchanger :

In parallel flow heat exchangers, the fluid flow in the same direction. The temp. difference is maximum at inlet and consequently the rate of flow of heat and the rate of decrease of temperature are maximum here.

(2) Counter current flow heat exchanger :

In counter current flow heat exchangers the fluid flow in the opposite directions.

The heat transfer takes place between the fluids at the moment when each is in its coldest state or when each is in its hottest state. The average temperature between the two fluids is greater than in parallel flow heat exchanger.

(iii) Natural or free convection:

Free convection is that convection in which movement of fluid is caused merely by differences in density resulting from temperature difference.

(iii) Forced convection:

Forced convection is that convection in which movement of fluid is caused by an external force applied by a pump or fan.

(iii) Properties of heat radiation:

$$\frac{Q_a}{Q_i} + \frac{Q_r}{Q_i} + \frac{Q_t}{Q_i} = 1$$

$$\alpha + \beta + \gamma = 1 \quad \text{----(i)}$$

Q_i = Incident radiation energy.
Q_a = " absorbed.
Q_r = " reflected.
Q_t = " transmitted.

where, α = absorptivity of a body,
β = reflectivity of the body and
γ = transmissivity of the body.

On the basis of radiation properties, a solid body is classified as:
(i) Black body, (ii) White body, (iii) Transparent body, and
(iv) Opaque body.

A black body absorbs all the radiation heat energy received by it. So from eqn (i) we get $\beta = 0$, $\gamma = 0$ so that $\alpha = 1$. So, absorptivity of a black body = 1.

A white body is that body which reflects all the radiation heat energy received by it. So from eqn (i) $\alpha = \beta$ and $\gamma = 0$, so that $\beta = 1$. So reflectivity of a white body = 1.

A transparent body is that body which transmits all the radiation heat energy received by it. So from eqn (i) $\alpha = 0$, $\beta = 0$. So that $\gamma = 1$, so transmissivity of a transparent body = 1.

An opaque body is that body in which does not transmit any ~~proportion~~ portion of radiation heat energy received by it. So for an opaque body $\gamma = 0$, so that, $\alpha + \beta = 1$

(ii) Kirchhoff's law :

According to Kirchhoff's law, the ratio of the emmisive power and absorptive power of all bodies is the same and is equal to the emmisive power of a perfectly black body.

(iii) Stefan Boltzman law :

According to Stefan Boltzman law, the emissive power of a black body (i.e, the total radiations emitted by a black body per unit area and time is directly proportional to the fourth power of the absolute temperature.

Mathematically, emmissive power of a black body,

$$E_b = \sigma T^4$$

where, σ = Stefan Boltzman constant $= 5.67 \times 10^{-8} \, W/m^2K^4$.

(iv) Air standrad cycle :

It may be defined as the ratio of workdone to the heat supplied during a cycle. mathematically, efficiency of a cycle,

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}}$$

This efficiency, as given above is known as theoritical thermal efficiency.

In order to compare the efficiency of the thermodynamic cycles air is assumed to be the working substance inside the engine cylinder. moreover air is assumed to behave as a perfect gas. The efficiency, thus, obtained is known as air standrad efficiency. It is also called ideal efficiency.