Unit 1 Fundamental of Thermodynamic

• Pure Substance :

A pure substance is one that has a homogeneous and invariable chemical composition even though there is a change of phase.

Ex. Liquid, water, mixture of liquid, water and steam. mixture of ice & water.

• Process :-

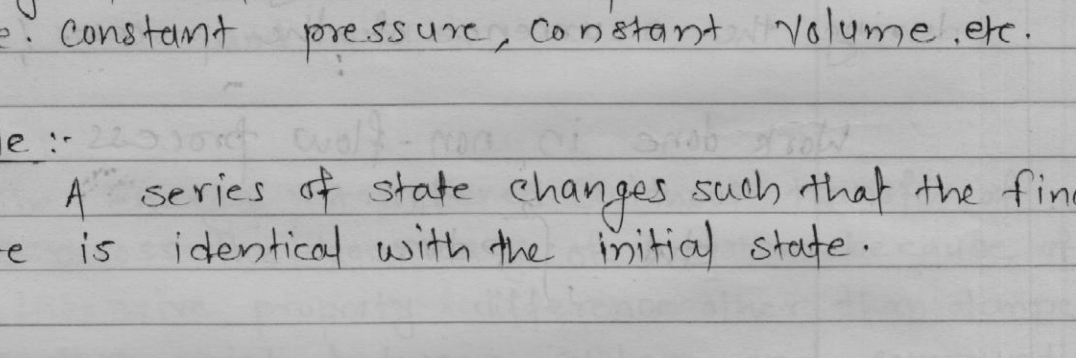
When the path is completely specified, the change of state is called a process.
i.e. Constant pressure, Constant Volume, etc.

• Cycle :-

A series of state changes such that the final state is identical with the initial state.

• Quasi-Static Process :

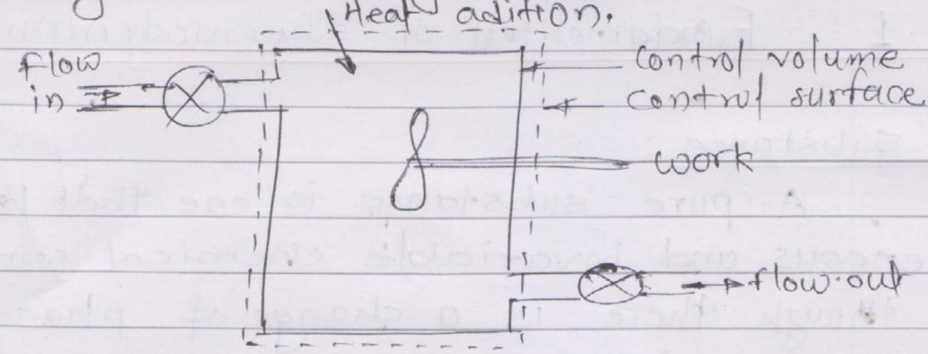
When a process is carried out in such a way that at every instant, the system deviation from the thermodynamic equilibrium is infinitesimal, then the process is known as quasi-static or quasi-equilibrium.



• Flow Process :

Flow process is the one in which fluid enters the system and leaves it after work interaction, which means that such processes occur in the system having

The system boundary.



a) steady flow process : Nozzle, turbine
b) Unsteady flow process : filling or emptying any vessel

- Non - Flow Process :

Non - flow process is one in which there is no mass interaction across the system boundaries during the occurrence of the process.

Work done in non - flow process

$$dW = \int_1^2 p\,dv.$$

- Thermodynamic Equilibrium :

System is said to be in thermodynamic equilibrium if the value of property is the same at all points in the system.

To be in thermodynamic equilibrium the system have to ~~sy~~ satisfy following three types of equilibrium.

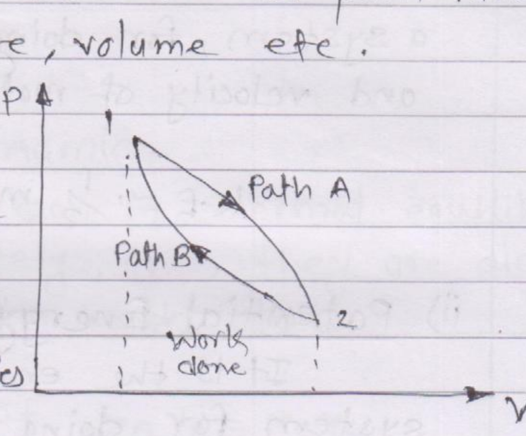
1. Mechanical Equilibrium : If there is no umbalance forces acting within the system or between the system & surroundings.
2. Chemical equilibrium : If there is no chemical reaction or transfer of matter from one part of the system to another, the system is said to exist in a state of chemical equilibrium.
3. Thermal Equilibrium : The temperature of a system does not change with time and has same

Point function :

Each property has single value at each state i.e properties of system depends upon state of system. There fore these properties are called as point function.

Ex. pressure, Temperature, volume etc.

Path Function :



Thermodynamic system passing through a series of states constitutes a path.

There are certain quantities which can not be located on a graph by a point but are given by area or so on the graph

Ex. Heat and work.

Work :

The energy tranfered (without transfer of mass) across the boundary of a system because of an intensive property difference other than temperature that exist between system and surrounding.

Work done by system on its surrounding taken as positive work.

Work done on the system by surrounding taken as negative work.

- High grade energy.
- Entire work can be converted into heat

Heat :

The energy interaction between system and surrounding due to temperature difference.

Heat added to system: +ve

Heat removed from system: - ve.

- low grade energy.
- Entire heat cannot be converted to work.

- Energy :-

Capacity to do work. (stored / Transit)

i) Kinetic energy :-

It is the energy possessed by a body or a system, for doing work, by virtue of its mass and velocity of motion.

$$K.E = \frac{1}{2} mv^2 \qquad [\text{Joule} (J)]$$

ii) Potential Energy :-

It is the energy possessed by a body or system for doing work, by virtue of its position above ground level.

$$PE = mgz.$$

iii) Internal Energy :-

It is the energy possessed by a body or a system due to its molecular arrangement and motion of the molecules.

- Enthalpy :-

The algebric sum of the internal energy and the product of pressure and volume. is called as enthalpy. It is denoted by 'H'.

$$\therefore \quad H = U + pV.$$

- Entropy :

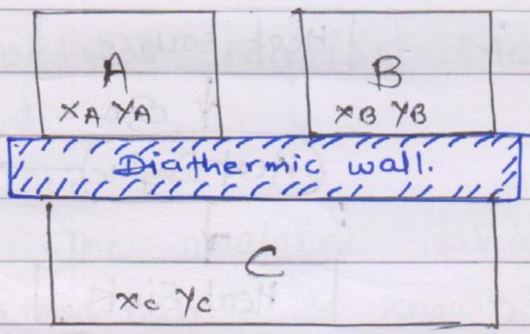
Entropy means 'Transformation'. It is a Thermodynamic property increases with the addition of heat and decreases with the removal of heat.

In a reversible process, over a small range of temperature, the increase or decrease of entropy, when multiplied by the absolute temperature, gives the heat absorbed or rejected by the working substance.

Characteristics of entropy
- point function.
- definite property of substance.
- For all substance zero at ice point.
- for reversible process zero.

• Zeroth Law of thermodynamic.

"If two system are each in thermal e
with a third system seperately, then they ar
in thermal equilibrium with each other".



If $x_A y_A = x_c y_c$,
$x_B y_B = x_c y_c$
Then
$x_A y_A = x_B y_B$.
(x & y are thermodynamic

• First law of thermodynamic:

Law of conservation of energy state
"Energy can neither be created nor be destro
but it can be converted into on form to
First law:-
"If a system undergoes a cyclic change
algebric sum of work delivered to the surrour
is directly proportional to the algebric sum
heat taken from surrounding".

$$dW \propto dQ.$$

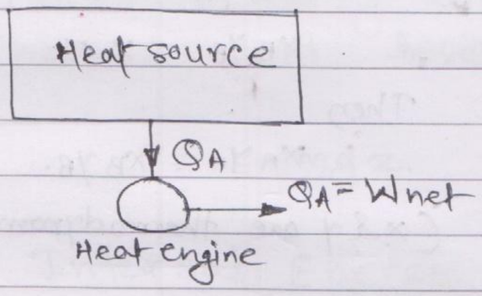
→ heat and work are mutually convertible
into another.
→ It is impossible to construct a perpetual motio
machine of first kind.

• Second Law of Thermodynamic :

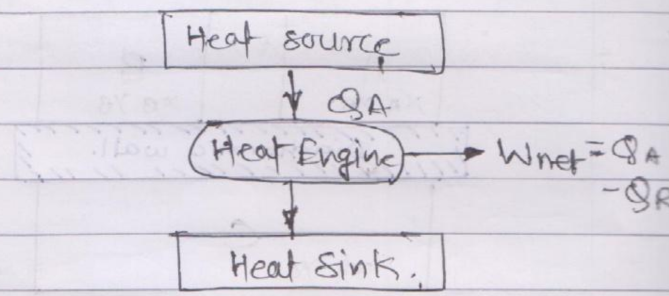
1. Kelvin - Plank statement :

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

i.e. only part of heat is converted into work, and remaining part is rejected to low temperature reservoir.



Satisfy first law

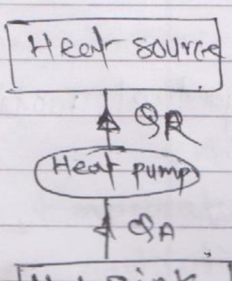


Satisfy first and second law

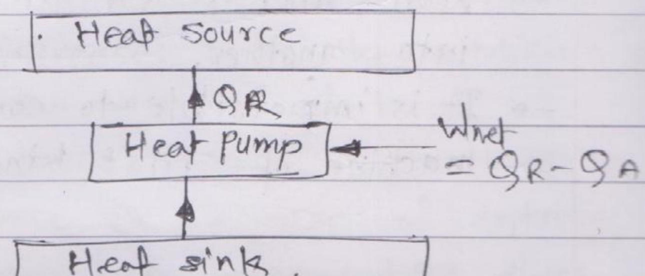
2. Clausius statement :

"It is impossible for a self acting machine, working in a cyclic process, to transfer heat from a body at a lower temperature to a body at a higher temperature without the aid of external energy".

In other word heat cannot flow itself from a cold body to a hot body without the help of an external agency (i.e. without the expenditure of mechanical work).



satisfy first law



1. It is not clear about the direction of heat and work transfer.
2. First law does not describe whether or not system will undergo change.
3. No clarity that how much percentage of one form of energy converted into another form of energy.
4. No restriction on possibility of ~~conversion~~ conservation of energy from one from to another.

Perpetual Motion Machine of first and second Kind.

- PMM 1.

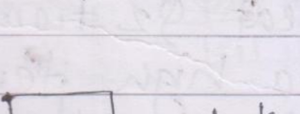
The machine which voiletes the first law of thermodynamic is known as perpetual motion machine of first kind.

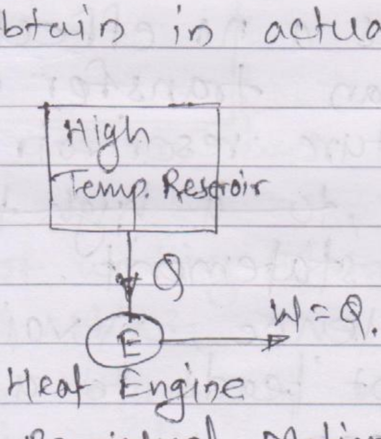
It is defined as the machine which produces work energy without consuming an equivalent of energy from other source.

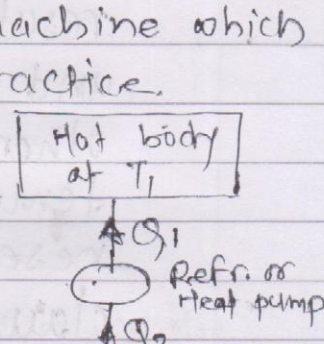
It is impossible in actual practice.

- PMM 2.

A heat engine which voiletes second law of thermodynamic is known as perpetual motion machine of second kind. or 100% efficient machine which is impossible to obtain in actual practice.







Perpetual Motion Machine (second kind).

- Equiravalance of Kelvin-Plonk and Clausius Statement.

The equiravalance of the kelvin-planks and clausius statement can be proved if it can be shown that the voilation of kelvin-planks statement implies the voilation of clasius statement and vice-versa. This is discussed as follows.

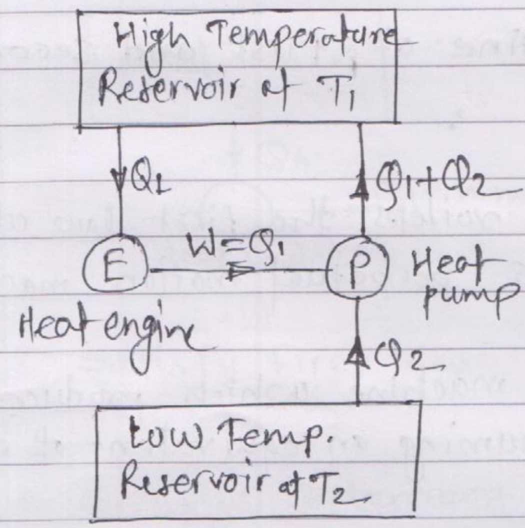


Fig (a)

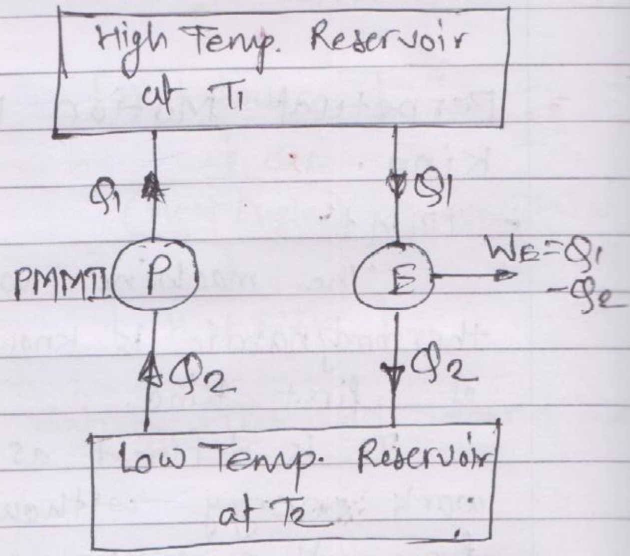


Fig. (b)

1. If the combination of a heat engine and a heat pump (or refrigerator) is considered as a single system, as shown in fig(a), then the result is a device that operates in a cycle and has a no effect on the surrounding other than transfer of heat Q_2 from a low temperature reservoir to a high temperature reservoir, ~~to a high tem~~ thus voilating the clausius statement.

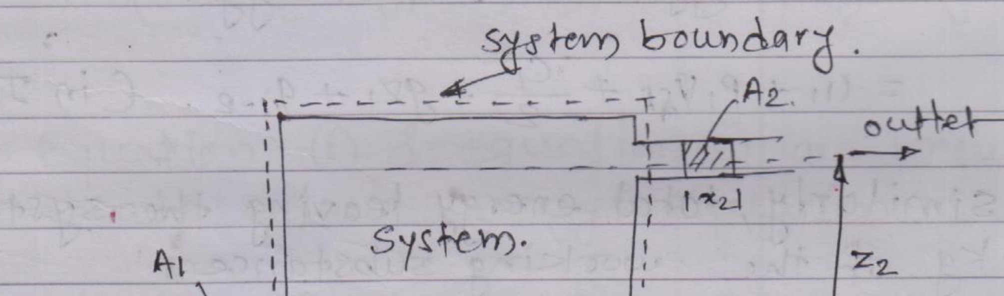
Hence, a voilation of kelvin-plank statement leads to a voilation of clausius statement.

2. If the combination of the heat pump (or refrigerator) and the heat engine is considered as a single system, as shown in fig.(b), then the result is a device that operates in a cycle whose sole effect is to remove heat at the rate of $(Q_1 - Q_2)$ and convert it completely into an equivalent amount of work, thus voilating the kelvin-planks statement. Hence a voilation of Clausius statement leads to a voilation of kelvin-plank statement.

Application of Laws of Thermodynamics.

- Steady Flow Energy Equation.

Consider an open system through which the working ~~sto~~ substance flows at steady rate. The working substance enters the system at section 1 and leaves the system at section 2.



Let P_1 - Pressure of working substance entering the system in N/m^2

v_{s1} - specific volume of w.s. entering the system in m^3/Kg.

C_1 - Velocity of the working substance entering the system in m/s.

u_1 - specific internal energy of the working substance entering the system in J/kg.

Z_1 - Height above datum level for inlet in meters.

P_2, v_{s2}, C_2, U_2 and Z_2 - Corresponding values for the working substance leaving the system.

q_{1-2} - Heat supplied to the system in J/kg; &

w_{1-2} - Work delivered by the system in J/kg.

Considering 1 kg of mass of the working substance.

We know the energy entering the system per kg of working substance.

e_1 = internal energy + Flow energy + Kinetic energy + Potential Energy + Heat supplied.

$$= u_1 + P_1 v_{s1} + \frac{C_1^2}{2} + gZ_1 + q_{1-2} \quad (\text{in J/kg}).$$

similarly, total energy leaving the system per kg of the working substance.

$$e_2 = u_2 + P_2 \cdot v_{s2} + \frac{C_2^2}{2} + gZ_2 + w_{1-2} \quad (\text{in J/kg}).$$

Assuming no loss of energy during flow, then according to first law of Thermodynamic

$e_1 = e_2$ --- (Law of conservation of energy).

$$\therefore u_1 + P_1 v_{s1} + \frac{C_1^2}{2} + gz_1 + q_{1-2} = u_2 + P_2 v_{s2} + \frac{C_2^2}{2} + gz_2 + W_{1-2}$$

We know that, $u_1 + P_2 v_{s1} = h_1$ &

$u_2 + P_2 v_{s2} = h_2$.

h_1 & h_2 are the enthalpies of working substance entering and leaving the system. respectively. in (J/kg)

$$\therefore h_1 + \frac{C_1^2}{2} + gz_1 + q_{1-2} = h_2 + \frac{C_2^2}{2} + gz_2 + W_{1-2} \quad (1)$$

or $h_1 + ke_1 + pe_1 + q_{1-2} = h_2 + ke_2 + pe_2 + W_{1-2}$.

In The above equation all the terms represent the energy flow per unit mass.

If it is multiplied by the mass of the working substance (m) in kg/s. Then all the terms will represents the energy flow per unit time. (in J/s).

$$\therefore m\left(h_1 + \frac{C_1^2}{2} + gz_1 + q_{1-2}\right) = m\left(h_2 + \frac{V_2^2}{2} + gz_2 + W_{1-2}\right) \quad (2)$$

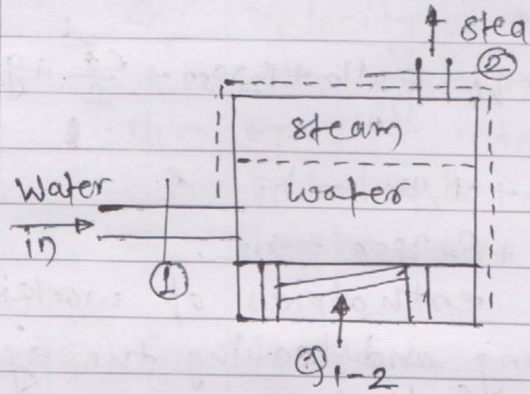
Equation (1) & equation (2) are known as steady flow energy equation.

- Application of Steady Flow Energy Equation.

(1). Boiler: A boiler is a device which supplies heat to water and generates steam.

In this system there is no change in Kinetic & potential energies.

The boiler does not give any work output.



$\therefore ke_2 - ke_1 = 0$
$pe_2 - pe_1 = 0$. and
$w_{1-2} = 0$.

Applying steady flow energy equation.

$$q_{1-2} - W_{1-2} = (h_2 - h_1) + (ke_2 - ke_1) + (pe_2 - pe_1)$$

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

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

② <u>Nozzle</u> :- A device which increases the velocity or kinetic energy of the working substance at the expense of its pressure drop.

The nozzle is insulated so that no heat enters or leaves the system. (i.e. $q_{1-2} = 0$) Further the system does not deliver any work ($W_{1-2} = 0$) and there is no change in potential energy.

Hence applying steady flow energy equation.

$$q_{1-2} - W_{1-2} = (h_2 - h_1) + (ke_2 - ke_1) + (pe_2 - pe_1) = 0$$

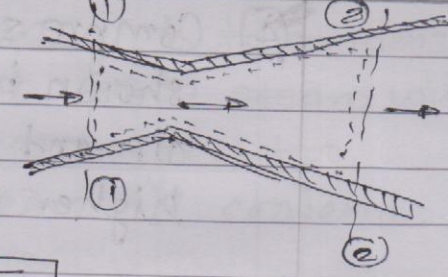
$$0 = (h_2 - h_1) + (ke_2 - ke_1)$$

or $$h_1 - h_2 = ke_2 - ke_1$$

$$h_1 - h_2 = \frac{c_2^2}{2} - \frac{c_1^2}{2}.$$

$$2(h_1 - h_2) = c_2^2 - c_1^2$$

$$\therefore c_2^2 = c_1^2 + 2(h_1 - h_2)$$



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

③ <u>Turbine</u>: A device which converts energy of the working substance into work is the turbine.

The turbine is insulated so that there is no transfer of heat ($q_{1-2} = 0$).

$$\therefore \quad q_{1-2} - W_{1-2} = (h_2 - h_1) + (ke_2 - ke_1) + (pe_2 - pe_1).$$

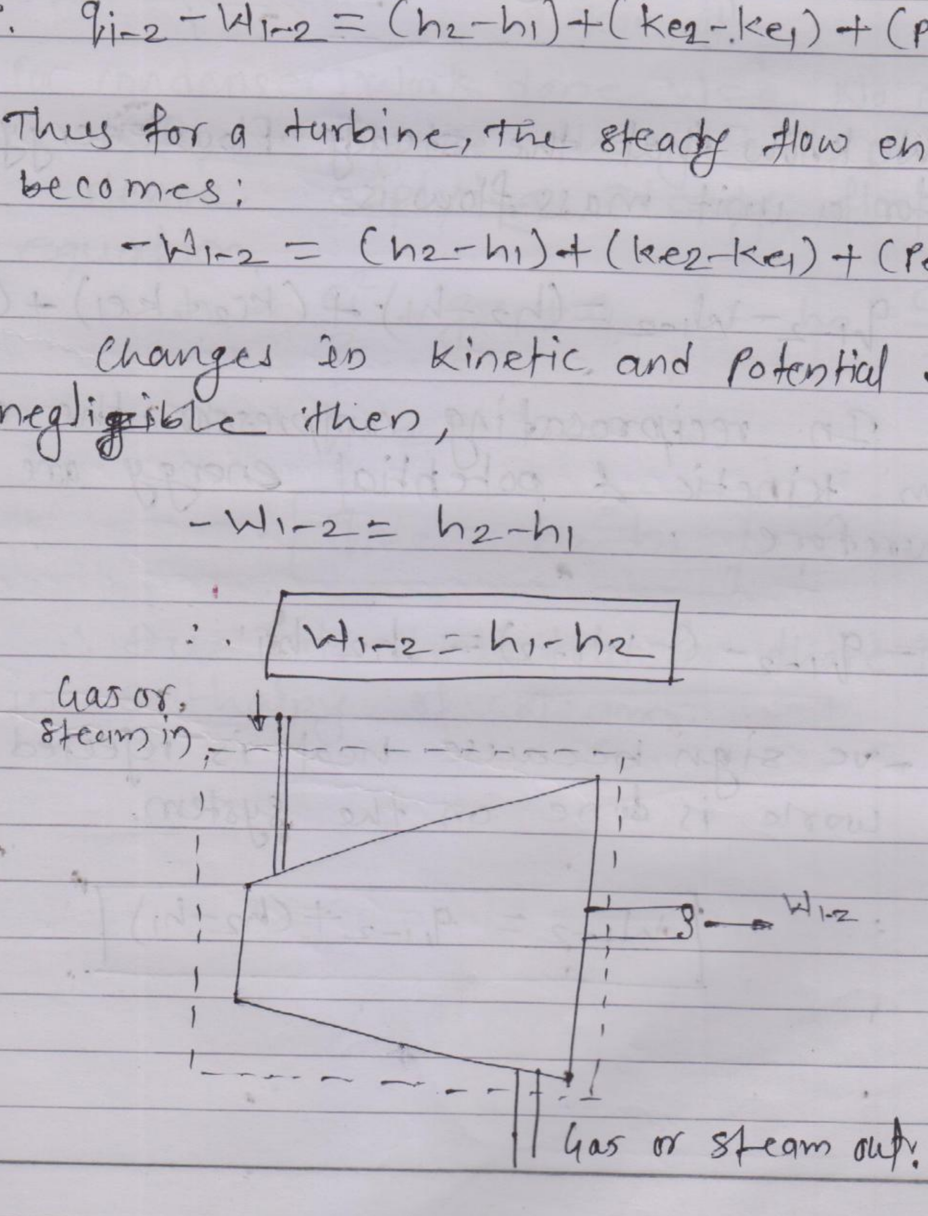
Thus for a turbine, the steady flow energy equation becomes:

$$-W_{1-2} = (h_2 - h_1) + (ke_2 - ke_1) + (pe_2 - pe_1).$$

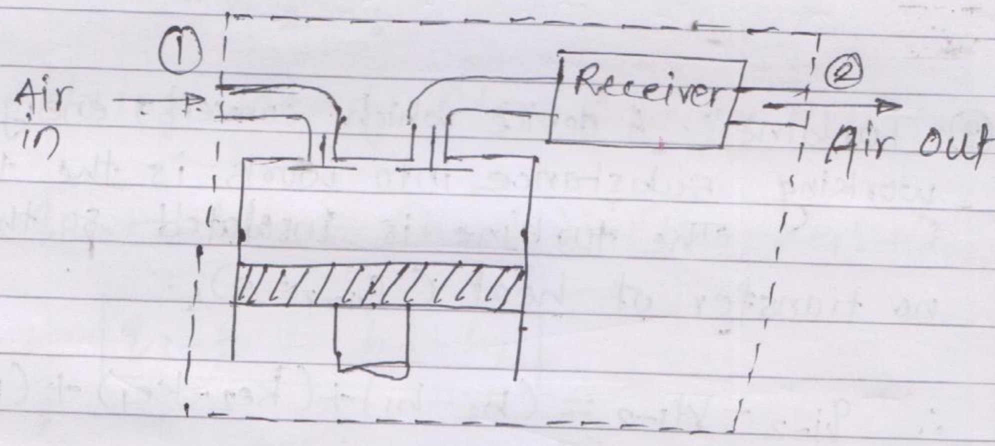
Changes in kinetic and potential energy are negligible then,

$$-W_{1-2} = h_2 - h_1$$

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



④ Compressor: A reciprocating compressor, as shown in fig. is a device which compresses air and supplies the same at a considerable higher pressure and in small quantities.



We know that the steady flow energy equation for a unit mass flow is.

$$q_{1-2} - W_{1-2} = (h_2 - h_1) + (ke_2 - ke_1) + (Pe_2 - Pe_1)$$

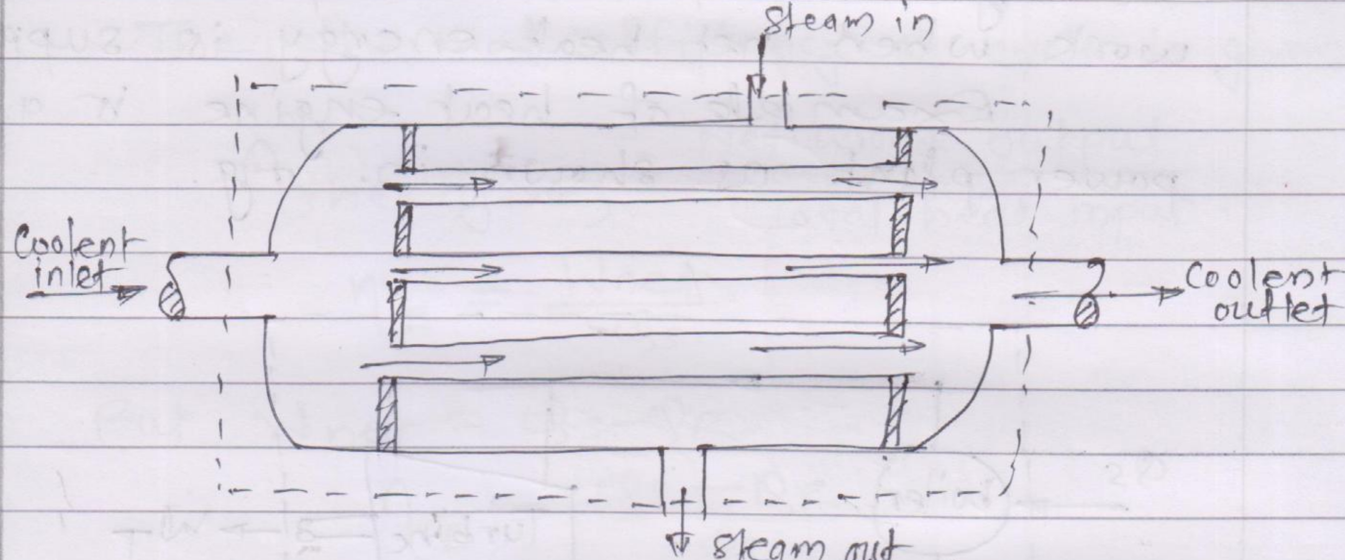
In reciprocating compressor, the changes in kinetic & potential energy are negligible therefore.

$$-q_{1-2} - (-W_{1-2}) = h_2 - h_1$$

-ve sign because heat is rejected and work is done on the system.

$$\therefore \boxed{W_{1-2} = q_{1-2} + (h_2 - h_1)}$$

(5) <u>Condenser</u>: Function of condenser is to condense the steam by absorbing heat from steam with the help of coolent. In heat exchanger, two steady flow streams are steam & coolent.



for condenser, work done W=0, No change in K.E, Negligible change in P.E.

Hence applying steady flow energy equation.

$$h_1 + \frac{c_1^2}{2} + gz_1 + q_{1-2} = h_2 + \frac{c_2^2}{2} + gz_2 + W_k$$

$$h_1 + q_{1-2} = h_2$$

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

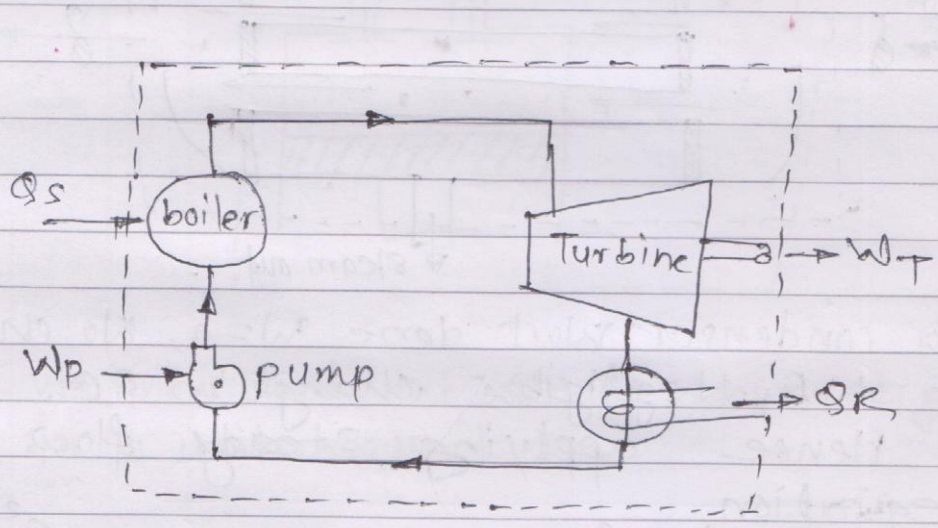
∴ Due to heat transfer there is decrease in enthalpy of steam.

Application of Second Law of Thermodynamic

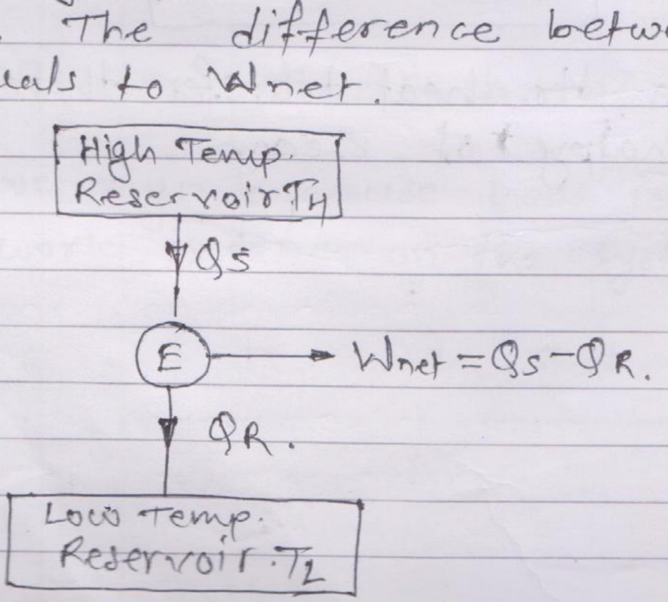
- **Heat Engine.**

Heat engine is a device working in a thermodynamic cycle which produces a net work when net heat energy is supplied.

Example of heat engine is a steam power plant as shown in fig.



When boiler, Turbine, condenser and pump are put together, they satisfy the definition of heat engine. We note that heat enters the system at boiler and leaves at the condenser. The difference between these two, equals to Wnet.



Let, Q_S & Q_R are heat supplied and heat rejected at temperature T_H & T_L respectively.

W_{net} is the net work produced by the heat engine.

The thermal efficiency of cycle is given by.

$$\eta_{(Th\,engine)} = \frac{\text{Net work output}}{\text{Total heat input}}$$

$$\eta_E = \frac{W_{net}}{Q_S}$$

But $W_{net} = Q_S - Q_R$

$$\therefore \quad \eta_E = \frac{Q_S - Q_R}{Q_S}$$

$$= 1 - \frac{Q_R}{Q_S}$$

$$= 1 - \frac{T_L}{T_H}$$

$$\boxed{\eta_E = \frac{T_H - T_L}{T_H}}$$

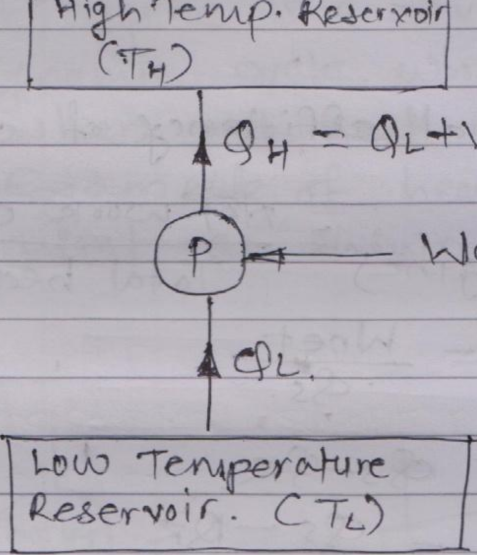
T_H - temperature of high temperature Reservoir

T_L - temperature of low temperature reservoir.

- Heat Pump

Heat pump is a device which is operating in a cycle, maintains a body at a temperature higher than the temperature of surrounding.

For maintaining body at higher temperature than surrounding, heat is removed from lower temperature body and supplied to higher temperature body with expenditure of some work.



Performance of heat pump is measured by EPR (Energy Performance Ratio)

$$EPR = \frac{Q_H}{W} = \frac{\text{Heat supplied to Hot body}}{\text{Work Required}}$$

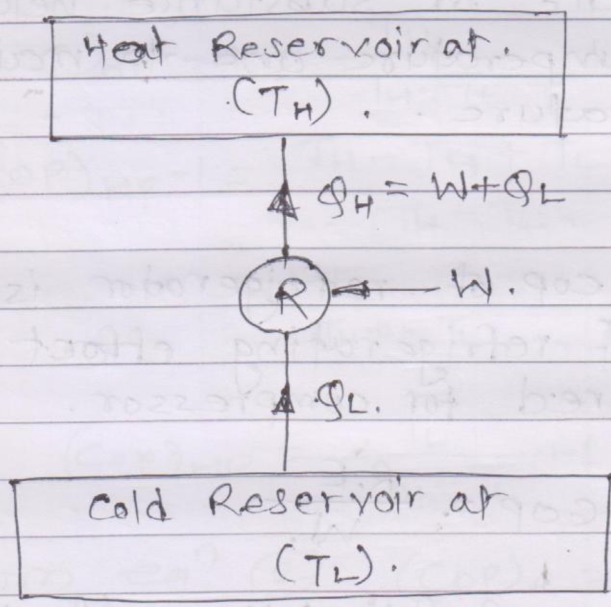
but $Q_H = Q_L + W$, $W = Q_H - Q_L$

$$EPR = \frac{Q_H}{Q_H - Q_L}$$

$$\boxed{EPR = \frac{T_H}{T_H - T_L}}$$

- The purpose of heat pump is to maintain higher temperature of body than surrounding.
- It is used in winter season to maintain the temperature of room at higher than that of surrounding.

- **Refrigerator:** Refrigerator works on clausius statement of second law of thermodynamics.
- → A refrigerator is a device which, operating in a cycle, maintains a body temperature lower than that of the surrounding.
- → Lower temperature of body than surrounding is maintained by removing heat from low temperature body (surrounding) with expenditure of work. Fig shows a block diagram of refrigerator.



- → Cold reservoir is maintained at low temperature (T_L) than surrounding or hot reservoir at T_H, by continuously extracting Q_L and rejecting to hot reservoir (surrounding).
- → The performance of refrigerator is given by, coefficient of performance (COP) $= \frac{Q_L}{W}$.

  Q_L - Heat removed from low temperature reservoir (body).

  W - Work supplied.

  but $Q_H = W + Q_L \Rightarrow W = Q_H - Q_L$.

then, $COP = \frac{Q_L}{Q_H - Q_L}$.

COP can be written in terms of temp. of hot body (T_H) & cold body (T_L)

$$COP = \frac{T_L}{T_H - T_L}$$

→ The purpose of refrigerator is to cool the space or substance below is surrounding temperature and to maintain that temperature.

→ COP: cop of refrigerator is defined as ratio of refrigerating effect to work required for compressor.

$$COP = \frac{R.E}{W}.$$

R.E. = Refrigerating effect.
W = Work required for compression.
It has no unit.

- Relationship between COP of Heat pump and COP of Refrigerator.

COP or EPR of Heat pump is given by

$$EPR \text{ or } (COP)_{HP} = \frac{T_H}{T_H - T_L} \quad — ①$$

COP of refrigerator is given by;

$$(COP)_R = \frac{T_L}{T_H - T_L} \quad -(2).$$

where,

T_H - Temperature of high temp. body.

T_L - Temperature of low temp. body.

Substract unity from body sides of eqⁿ (1), then we get;

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

$$(COP)_{HP} - 1 = \frac{T_H - T_H + T_L}{T_H - T_L}$$

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

$$\therefore \ (COP)_{HP} = \frac{T_L}{T_H - T_L} + 1$$

but from eqⁿ (2) $(COP)_R = \frac{T_L}{T_H - T_L}$.

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

- Difference between Heat engine and heat pump.

SN	Heat Engine	Heat Pump.
1.	Heat engine is a device working in a cycle produces work when heat is supplied.	Heat pump is a device working in cycle maintain a body at a temperature higher than that of surrounding

2.	It is a work developing device	It is a work ~~producing~~ absorbing device.
3.	It obeys Kelvin Plank's statement of second law of thermodynamics	It obeys Clausius statement of second law of Thermodynamics
4.	It's energy performance is measured in terms of efficiency.	It's performance is measured in terms of energy performance Ratio (EPR)
5.	$\eta_E = \frac{T_H - T_L}{T_H}$	$EPR = \frac{T_H}{T_H - T_L}$
6.	Efficiency of heat engine is always less than one	EPR of heat pump is always greater than one.

- Difference between Heat pump & Refrigerator

SN	Heat Pump	Refrigerator.
1.	Heat pump is a device working in a cyclic process maintain a body at temperature higher than that of its surrounding.	Refrigerator is a device which operating in a cycle maintains a body at a temperature lower than that of its surrounding.
2.	It is used in winter season to heat the room	It is used in summer season to cool the space
3.	In heat pump attention is concentrated on high body temperature	In refrigerator attention is concentrated on low body temperature

4.	$(EPR)_P / (COP) = \frac{T_H}{T_H - T_L}$	$(COP)_R = \frac{T_L}{T_H - T_L}$.
5.	$(COP)_P = 1 + (COP)_R$	$(COP)_R = (COP)_P - 1$

NUMERICALS

1. A cyclic heat engine operates between a source temperature of 800°C and sink temperature of 30°C. What is the least rate of heat rejection per KW net output of an engine.

⇒ Sol^n:-

Given Data:

Temperature of source $T_H = 800 + 273 = 1073\,K$.

Temperature of sink $T_L = 30 + 273 = 303\,K$.

Efficiency of heat engine is given by:

$$\eta_E = \frac{T_H - T_L}{T_H} = \frac{1073 - 303}{1073} = 0.7176.$$

but for heat engine

$$\eta_E = \frac{\text{Work output}}{\text{Heat input}}$$

$$0.7176 = \frac{1}{Q_A}$$

$$Q_A = \frac{1}{0.7176} = 1.3935.$$

and $W = Q_A - Q_R$

$1 = 1.3935 - Q_R$

$\therefore \boxed{Q_R = 0.3935 \text{ kW}}$

2. A refrigerator operates between -3°C and 27°C. The cooling load is 6.3 kJ/sec. Determine COP of the system and power required to operates the refrigerator.

⇒

Given data:

Temperature of sink $T_L = -3 + 273 = 270$ K.

Temperature of source $T_H = 27 + 273 = 300$ K.

Cooling load = 6.3 kW.

∴ Refrigerating effect = 6.3 kW.

Soln:

$$(COP)_R = \frac{T_L}{T_H - T_L}$$

$$= \frac{270}{300 - 270}$$

$$= 9.$$

COP of refrigerator is also given as:

$$(COP)_R = \frac{\text{Refrigerating Effect}}{\text{compressor power}}$$

$$9 = \frac{6.3}{\text{compressor power}}$$

$\therefore \boxed{\text{Compressor power} = 0.7 \text{ kW}}$

3. A domestic food freezer is to be maintained at temperature of −15°c. The ambient air temperature is 30°c. If the heat leaks into the freezer at the continuous rate of 1.75 kJ/s. Find the power required to pump this heat out continuously.

⇒

Given data:

Temperature to be maintained = −15°c

$T_L = 258\,K$.

Ambient temperature $T_H = 30+273 = 303\,K$.

RE = Heat transfer = Heat removed = 1.75 kW.

Soln:

$$(COP)_R = \frac{T_L}{T_H - T_L} = \frac{258}{303-258} = 5.73.$$

COP is also given as:

$$(COP)_R = \frac{RE}{\text{Power Required}}$$

Power Required = 0.3054 kW.

4. A stream of gases at 7.5 bar, 750°c and 140 m/s is passed through a turbine of jet engine. The stream comes out of the turbine at 20 bar, 550°c and 280 m/s. The process is assumed to be adiabatic. The enthalpy of gases at the entry and exit of the turbine are 950 kJ/kg and 650 kJ/kg of gas respectively. Find capacity of turbine.

⇒

Given data:

at inlet of turbine $p_1 = 7.5$ bar.

$T_1 = 750°C$

$C_1 = 140\ m/s$.

At exit of turbine

$P_2 = 20$ bar.

$T_2 = 550°C$.

$C_2 = 280\ m/s$.

$h_1 = 950$ KJ/kg $h_2 = 650$ KJ/kg.

steady flow energy equation for turbine canbe writen as.

$$h_1 + \frac{C_1^2}{2} + gz_1 + Q_{1-2} = h_2 + \frac{C_2^2}{2} + gz_2 + W_{1-2}$$

$Q_{1-2} = 0$ & $z_1 = z_2$

$$\therefore h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2} + W_{1-2}$$

$$950 \times 1000 + \frac{(140)^2}{2} = 650 \times 1000 + \frac{(280)^2}{2} + W_{1-2}$$

$W_{1-2} = 270600$ J/kg

Capacity of turbine = 270.6 KJ/kg.

5. A refrigerator works between the temperature limits of $-4°C$ and $35°C$. If refrigerator works on 'carnot cycle'. Find out its COP.

$$(COP)_R = \frac{T_L}{T_H - T_L} = 6.89.$$