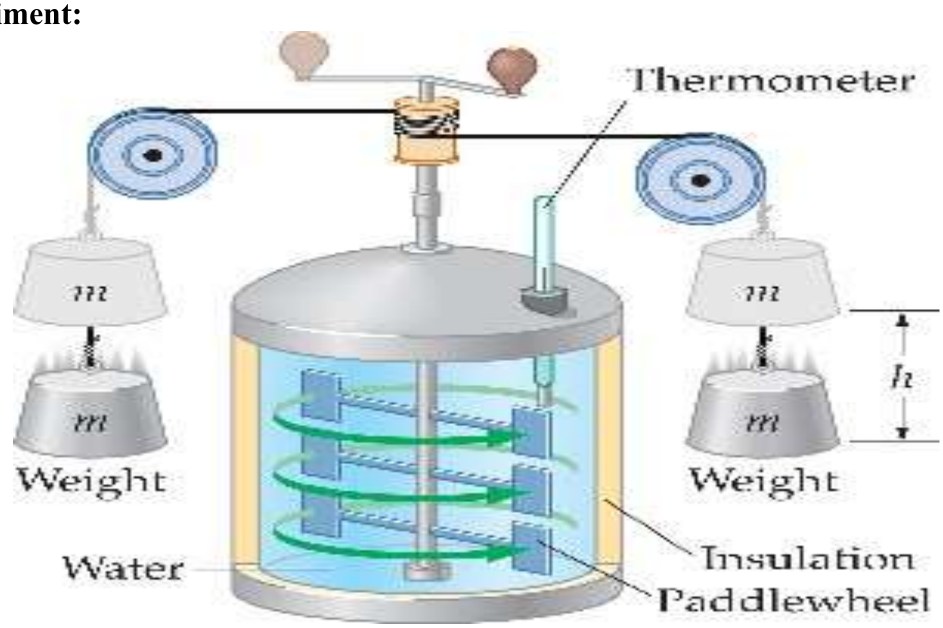
MODULE 2

OBJECTIVES: Study the basic laws of thermodynamics including, conservation of mass, conservation of energy or first law of Thermodynamics and second law of Thermodynamics.

STRUCTURE:

2.1 FIRST LAW OF THERMODYNAMICS

2.1.1 Joule's Experiment:



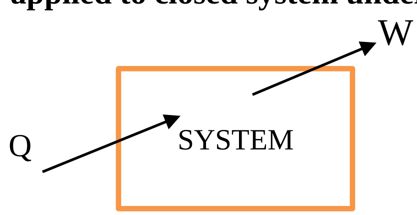
Joules Paddle wheel experiment setup

- Experimental apparatus consists of insulated cylindrical calorimeter, Spindle consisting of Paddles, Weights, Pulley, String, Thermometer and a Handle.
- A known mass of water M1 was taken inside the calorimeter

- By rotating the handle the weights where raised through a height ‘h’, again by rotating the handle in the reverse direction the weights where allowed to fall down through same height ‘h’.
- The falling weights rotated the spindle and thereby stirring the water contained in the calorimeter as a result mechanical energy was converted into heat & the temperature of the water increased.
- The process was repeated and noted the raise in temperature in each case and found that work transfer is directly proportional to Heat transfer. By conducting a series of experiments joule found that when the falling weights lost 4.186kJ of Mechanical Energy a temperature of 1kg of water raised by 1°C.
- Thus potential energy of the falling masses was converted into kintetic energy and finally into heat energy

$$W\ \alpha\ Q$$
$$W = J.Q$$
$$W = 4.186.Q$$

2.1.2 First law applied to closed system undergoing non-cyclic process:



“If a system undergoes a change of state during which both heat transfer and work transfer are involved, the net energy transfer will be stored or accumulated within the system.”

If Q is the amount of heat transferred to the system and W is the work transferred from the system during the process, then,

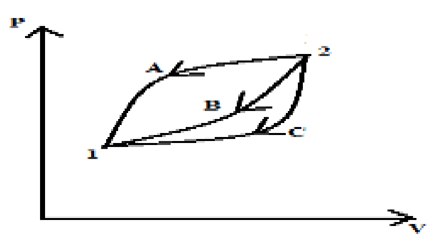
$Q - W = \Delta E$

The Energy in storage is neither heat nor work, but is given the name **internal energy.**

If more than one heat transaction and more than one work transaction are happening at the same time on a system then,

$(Q_1+Q_2+Q_3) = (W_1+W_2+W_3) + \Delta E$

2.1.3 Energy a Property of the System:



Existence of property

Consider a system undergoing a cycle, changing from state1 to state2 by process A and returning from state2 to state1 by process B.
Then, we have from First law of Thermodynamics,

$$\oint \partial Q = \oint \partial W$$

For the process 1-A-2-B-1

$$\oint_{1A}^{2B} \partial Q + \oint_{2B}^{1B} \partial Q = \oint_{1A}^{2B} \partial W + \oint_{2B}^{1B} \partial W \ldots\ldots\ldots\ldots (1)$$

Now, consider another cycle 1-A-2-C-1, for this process we can write,

$$\oint_{1A}^{2A} \partial Q + \oint_{2C}^{1C} \partial Q = \oint_{1A}^{2A} \partial W + \oint_{2C}^{1C} \partial W \ldots\ldots\ldots\ldots (2)$$

Now, eqn (1) – eqn (2) gives,

$$\oint_{2C}^{1C} \partial Q - \oint_{2B}^{1B} \partial Q = \oint_{2C}^{1C} \partial W - \oint_{2B}^{1B} \partial W$$

by rearranging, we get,

$$\oint_{2C}^{1C} (\partial Q - \partial W) = \oint_{2B}^{1B} (\partial Q - \partial W)$$

Hence, we can say that the quantity $(\boldsymbol{\partial Q - \partial W})$ is same for processes between state1 and state2. This value depends only on end states and not on the path it follows.
Therefore,
$(\boldsymbol{\partial Q - \partial W}) = \boldsymbol{\partial E}$ is a point function and hence, a **property of the system**.
If it is integrated between the state1 and state2, we get,

$$\mathbf{Q_{1\text{-}2} - W_{1\text{-}2} = E_2 - E_1}$$

2.1.4: Modes of Energy:

The property E (stored energy) in the first law of TD equation represents the sum of energy transfers across the boundary. This may present in any forms of energy namely, Kinetic energy, Potential energy, Chemical energy, Electrical energy etc.
However, in Thermodynamics it is a practice to consider Kinetic and Potential energies separately and group all other types under one category known as Internal energy (U). Thus,

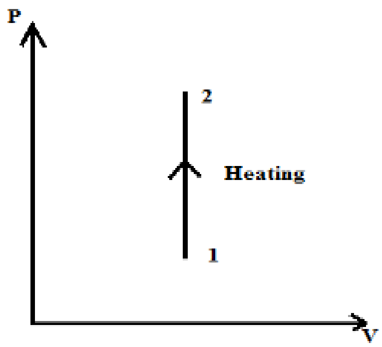
E= Internal energy + Kinetic energy + Potential energy

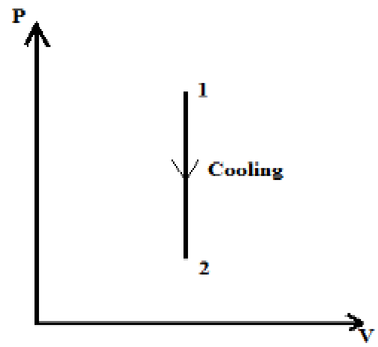
In the absence of motion and gravity effect further E reduces to Internal energy only in Thermodynamics. Hence the First law for a Non-flow process can be written as

$$(\boldsymbol{\partial Q - \partial W}) = \boldsymbol{\partial U}$$

2.1.5: First law applied to various TD processes.

2.1.5a: Constant Volume Process:





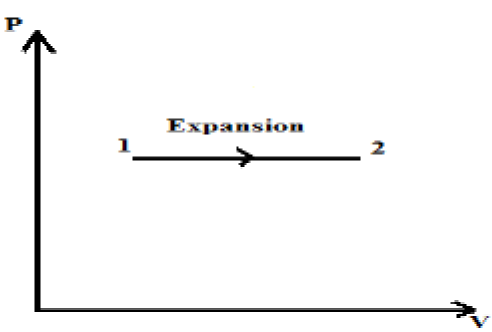
We Know that, Work done= Zero for a constant volume process from state1 to state2,
From First law, 2

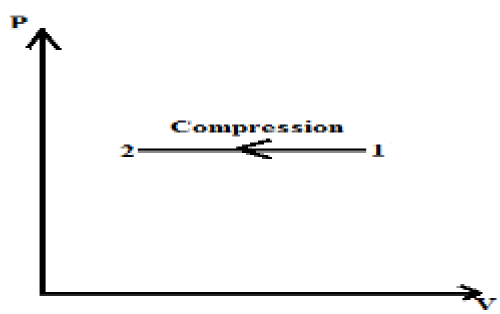
$$\int_1^2 \partial Q = \int_1^2 \partial W + \int_1^2 \partial U$$

or, $Q_{1-2} = W_{1-2} + U_2 - U_1$

$\mathbf{Q_{1-2} = U_2 - U_1}$ ……… **Change in Internal energy**

2.1.5b: Constant Pressure Process:





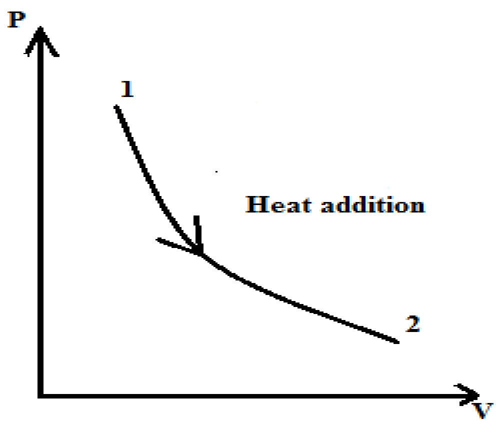
We know that for a Constant pressure process, Work done is $W_{1-2} = P(V_2-V_1)$
From First law,

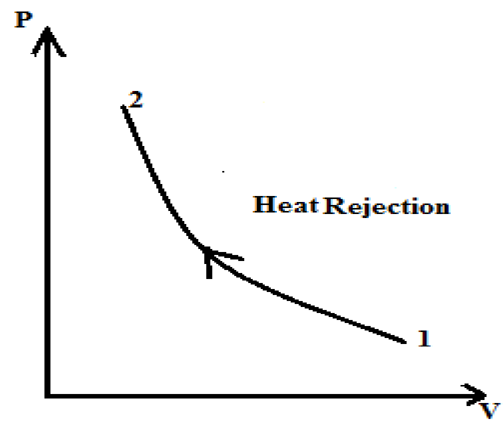
$$\int_1^2 \partial Q = \int_1^2 \partial W + \int_1^2 \partial U$$

$Q_{1-2} = P(V_2-V_1) + U_2-U_1$
$= (U_2+P_2V_2) - (U_1-P_1V_1)$

$$\mathbf{Q_{1\text{-}2} = H_2 - H_1} \qquad \text{……}\mathbf{Change\ in\ Enthalpy}$$

2.1.5c: Constant Temperature process (PV=Constant):





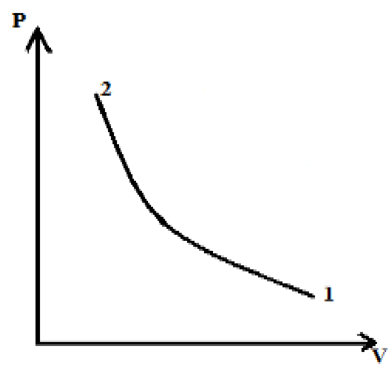
We know that work done $W_{1\text{-}2} = P_1V_1 \ln(V_2/V_1)$
From First law,

$$\int_1^2 \partial Q = \int_1^2 \partial W + \int_1^2 \partial U$$

$Q_{1\text{-}2} = P_1V_1 \ln(V_2/V_1) + mC_v(T_2 - T_1)$ but, $T_1 = T_2$

Therefore, $\mathbf{Q_{1\text{-}2} = P_1V_1 \ln(V_2/V_1)}$ **= Work done**

2.1.5d: Adiabatic Process. (PV^γ = Constant)

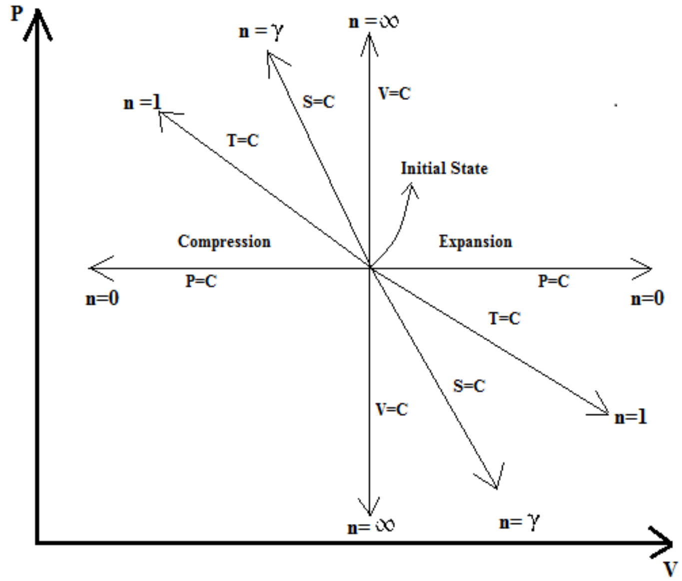


We know that, Work done = $\frac{P_1V_1 - P_2V_2}{\gamma - 1}$
From First law,

$$\int_1^2 \partial Q = \int_1^2 \partial W + \int_1^2 \partial U$$

But, $Q_{1-2} = 0$
Therefore, $0 = W_{1-2} + U_2 - U_1)$
or **Work done = Change in Internal energy**

2.1.5e: Polytropic process (PV^n = Constant):



Polytropic process

We Know that, Work done $=W_{1-2} = \frac{mR(T_1-T_2)}{n-1}$ and $\delta U = mC_v(T_2-T_1)$
From First law of TD,

$$\int_1^2 \partial Q = \int_1^2 \partial W + \int_1^2 \partial U$$

Substituting and simplifying we get,

$$Q_{1-2} = \frac{\gamma - n}{\gamma - 1} \times \frac{mR(T_1 - T_2}{n - 1}$$

or $\boldsymbol{Q_{1-2} = \frac{\gamma-n}{\gamma-1}}$ **× Polytropic Work done**

2.1.6: Extension of the First law to control volume:

Control Volume:

It is defined as any volume of fixed shape, position and orientation relative to the observer.

Comparison and differences between Control Volume and Closed system

Comparison:

Both Control Volume and Closed system are derived from the concept of boundary.

Differences:

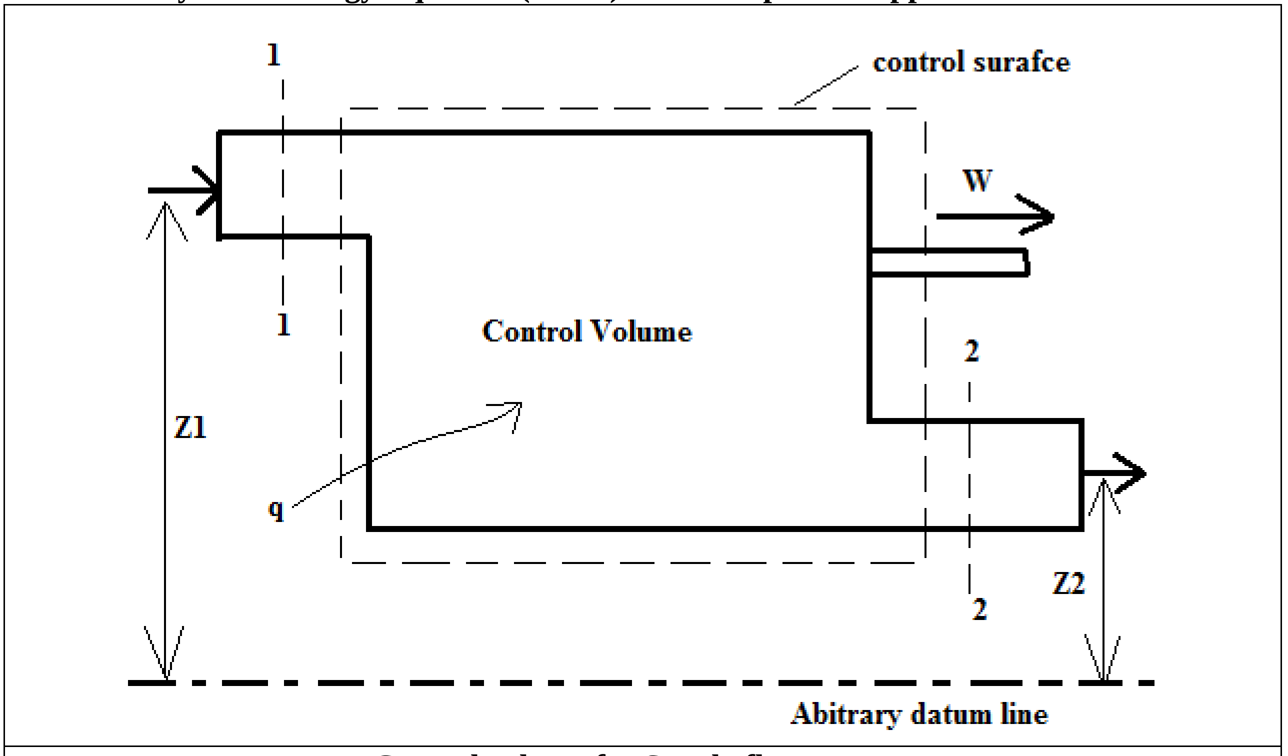
1) The Closed system boundary may(usually) change its shape relative to the observer, where as control volume does not change.
2) Mass usually crosses the control volume, where as it does not cross the boundary in a closed system.

Steady Flow process:

Steady Flow Process means that the rate of flow of **Mass** and **Energy** across the control volume are constant.

Mass/Energy entering the Control volume per unit time is equal to Mass/Energy leaving the system per unit time.

2.1.7: Steady Flow Energy Equation (SFEE) and its important applications:



Control volume for Steady flow process

Let,

P_1 = Pressure of the working substance entering the control volume in N/m^2.

v_1 = Specific volume of the working substance in m^3/kg.

V_1 = Velocity of the working substance entering the control volume in m/s.

u_1 = Specific internal energy of the working substance entering the control volume in kJ/kg.

Z_1 = Hight above the datum for inlet in m.

P_1, v_1, V_1, u_1, and Z_1 = corresponding values for the working substance leaving the control volume.

Q_{1-2} = heat supplied to the control volume in kJ/kg.
W_{1-2} = Work done by the system in kJ/kg.
Considering 1 kg of mass of the working substance. ie., m = 1 kg.

We know that total energy entering the control volume per kg of the working substance.
e_1 = Internal energy + Displacement work + Kinetic energy + Potential energy + Heat supplied.

$$e_1 = u_1 + P_1 v_1 + \frac{V_1^2}{2} + gZ_1 + q_{1-2} \quad \text{in kJ/kg}$$

Similarly, total energy leaving control volume per kg of the working substance is,

$$e_2 = u_2 + P_2 v_2 + \frac{V_2^2}{2} + gZ_2 + W_{1-2} \quad \text{in kJ/kg}$$

Assuming no loss of energy during flow (Steady Flow conditions), then according to First law of Thermodynamics,

$$e_1 = e_2$$

$$u_1 + P_1 v_1 + \frac{V_1^2}{2} + gZ_1 + q_{1-2} = u_2 + P_2 v_2 + \frac{V_2^2}{2} + gZ_2 + W_{1-2}$$

We know that,
$u_1 + P_1 v_1 = h_1$ = Enthalpy of the working substance entering the control volume in kJ/kg.
$u_2 + P_2 v_2 = h_2$ = Enthalpy of the working substance leaving the control volume in kJ/kg.

Therefore, $$\boldsymbol{h_1 + \frac{V_1^2}{2} + gZ_1 + q_{1-2} = h_2 + \frac{V_2^2}{2} + gZ_2 + W_{1-2}}$$

This is the Steady Flow Energy Equation for unit mass of the working substance.
When this equation is multiplied by mass 'm' , then we get total energy input and total energy output.

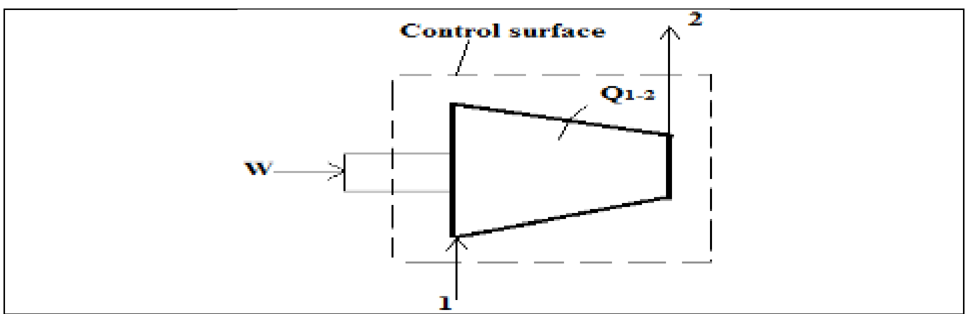
$$m_1\left(h_1 + \frac{V_1^2}{2} + gZ_1 + q_{1-2}\right) = m_2\left(h_2 + \frac{V_2^2}{2} + gZ_2 + W_{1-2}\right)$$

But in a steady flow process $m_1 = m_2$
Therefore,

$$\boldsymbol{m\left(h_1 + \frac{V_1^2}{2} + gZ_1 + q_{1-2}\right) = m\left(h_2 + \frac{V_2^2}{2} + gZ_2 + W_{1-2}\right)}$$

2.1.8 Important applications of SFEE:

1) Rotary Compressor:



Rotary Compressor

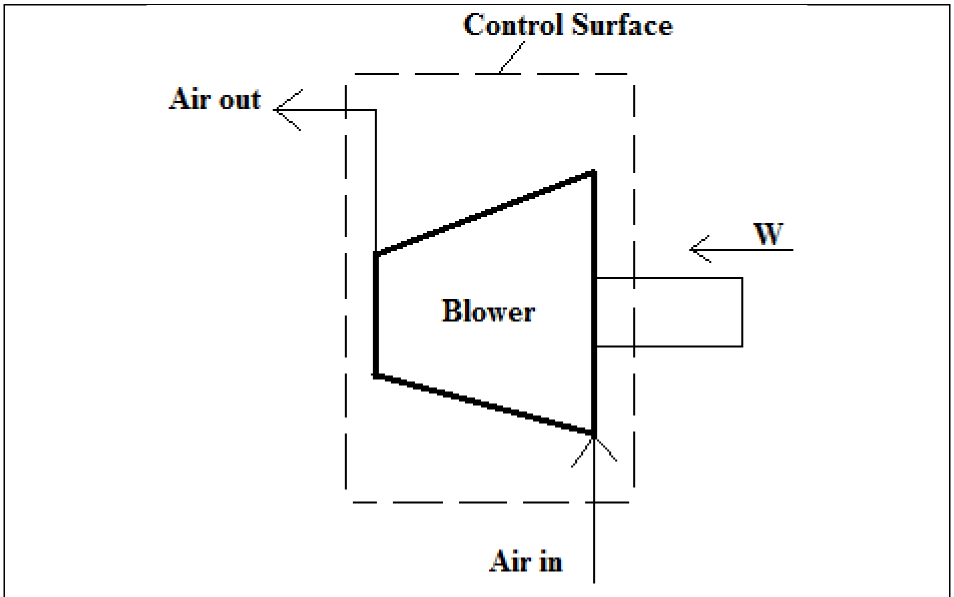
For a Rotary compressor,

a) Work is done on the system ie., W_{1-2} is Negative.
b) Heat rejected by the system, ie., Q_{1-2} is Negative and is negligible
c) Change in Potential Energy and Kinetic Energy is negligible.

Applying the above conditions to SFEE we get,

$$\mathbf{W_{1-2} = m\,(h_2 - h_1)}$$

2) Blower:



Blower

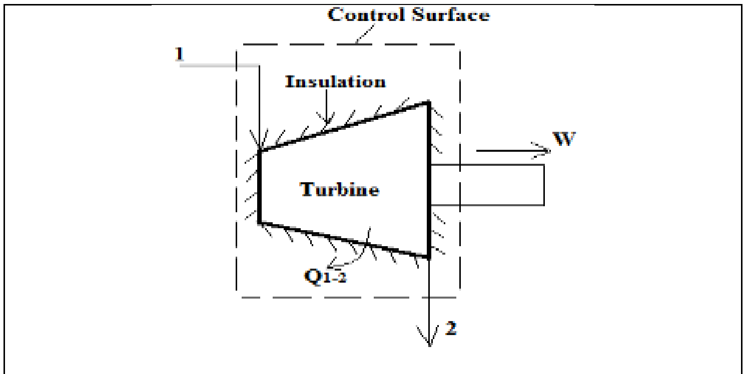
For a Blower,

a) Heat Transfer is Zero, ie., $Q_{1-2} = 0$,
b) Work done on the system is negative,
c) Change in Potential Energy and Internal Energy is negligible,
d) V_1 is very small when compared to V_2

Applying the above conditions to SFEE we get,

$$\boldsymbol{W_{1-2} = \frac{V_2^2}{2}}$$

3) Steam or Gas Turbine:



Turbine

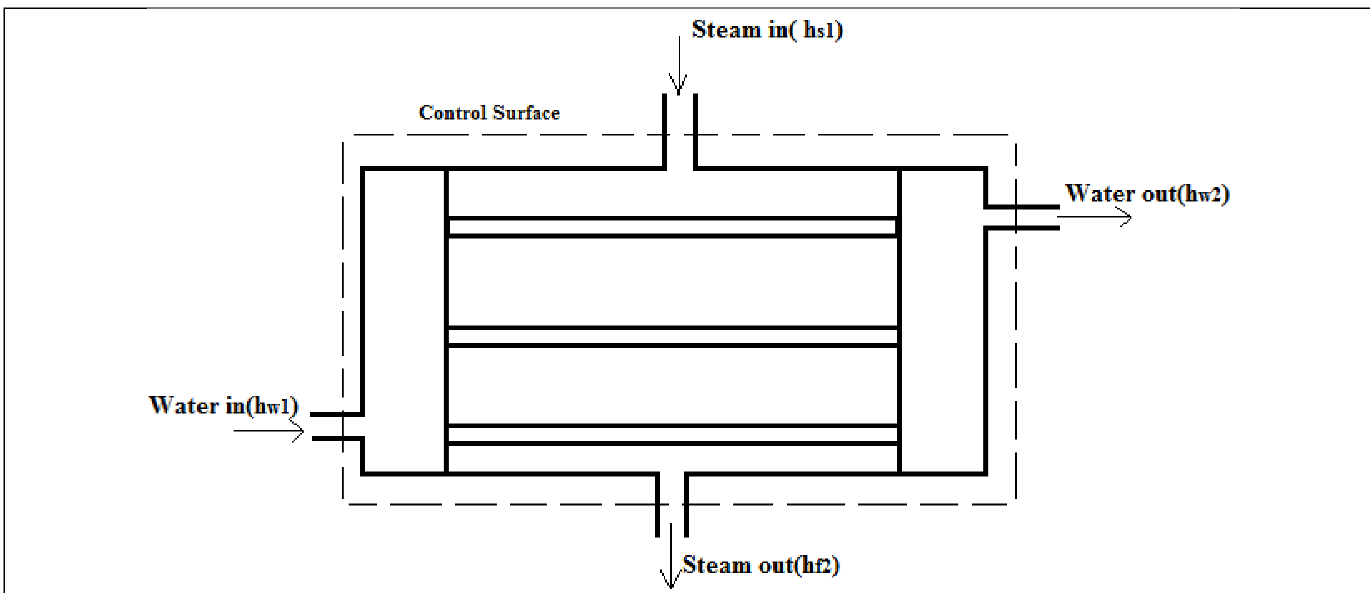
For a Turbine,

a) Work done is Positive,
b) Change in KE and PE is negligible.
c) Heat transfer is negligible

Applying the above conditions to SFEE we get,

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

4) Heat Exchanger(Condenser)



Heat Exchanger or Condenser

For a heat exchanger,

a) Change in KE and PE is negligible,

b) Work done is zero,

c) Heat transfer to the surroundings is also negligible,

Applying the above conditions to SFEE we get,

$$m_S h_{S1} - m_s h_{s2} = m_w h_{w2} - m_s h_{w1}$$

Heat lost by steam = Heat gained by water

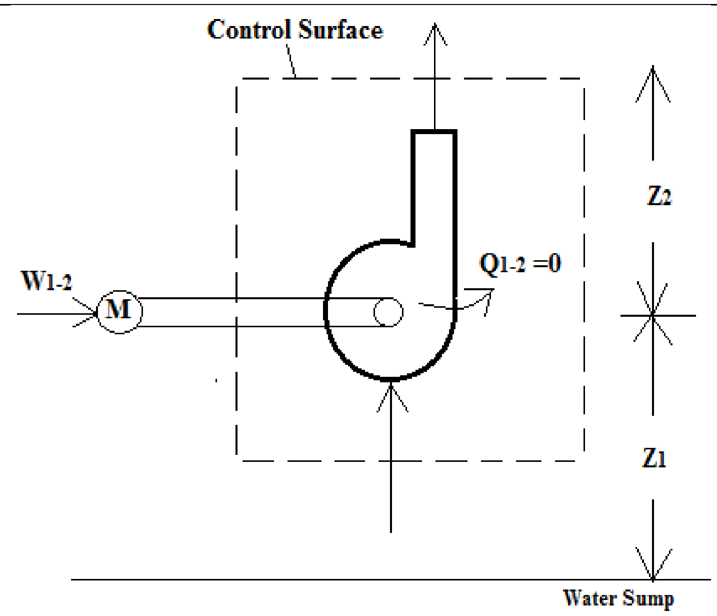
or $$\boldsymbol{m_s(h_{s1} - h_{f2}) = m_W(h_{w2} - h_{w1})}$$

Where m_W and m_s are mass flow rates of water and steam respectively,

and h_{W1}, h_{S1}, are the enthalpy of water and steam at inlet,

h_{W2}, h_{S2} are the enthalpy of water and steam at outlet.

5) Centrifugal Pump:



Centrifugal Pump

For centrifugal Pump

a) Work is done on the system which is considered as negative.

b) Heat transfer is Zero

c) Change in internal energy is Zero due to no change in temperature of water

Applying the above conditions to SFEE we get,

$$m(P_1 v_1 + \frac{V_1^2}{2} + gZ_1) = m(P_2 v_2 + \frac{V_2^2}{2} + gZ_2) - W_{1-2}$$

IMPORTANT THEORY QUESTIONS:

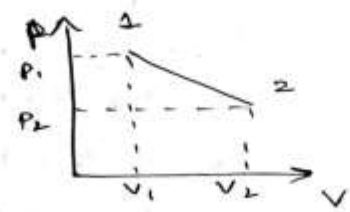
1. State second law of thermodynamics and Explain equivalence of Kelvin Planck and Clausius statements of second law of thermodynamics.
2. What is thermal energy reservoir? Explain source and sink
3. Represent schematically heat engine , heat pump, refrigerator. Give their performance.
4. Show that COP of the heat pump is greater than COP of a refrigerator by unity.
5. Explain Carnot cycle with P-V and T-s Diagram.
6. State and prove Carnot theorem.

PROBLEMS:

Problems :-

1) 1.5 kg of a gas undergoes a quasistatic process in which the pressure & specific volume are related by the equation $p = a + b\vartheta$, where a & b are constants. The initial & final pressures are 1000 kpa & 200 kpa respectively. The corresponding volumes are 0.2 m^3/kg & 1.2 m^3/kg. The specific internal energy of the gas is given by the relation $u = 1.5\,p\vartheta - 35$, where 'u' is in kJ/kg, ϑ is in m^3/kg. Find the magnitude & direction of the heat transfer & the maximum internal energy of the gas during the process.

$$\rightarrow {}_1W_2 = \int_1^2 p \cdot dV = \int_1^2 (a + b\cdot\vartheta)\,dV = m\int_1^2 (a + b\cdot V)\,dV$$



$${}_1W_2 = m\left[a(V_2 - V_1) + \frac{b}{2}(V_2^2 - V_1^2)\right]$$

$P = a + b\vartheta$

$P_1 = a + b\vartheta_1 \rightarrow (1)$

$P_2 = a + b\vartheta_2 \rightarrow (2)$

solving (1) & (2) we get

$a = 1160$ kpa , $b = -800$ kpa

$\therefore$ ${}_1W_2 = 900$ kJ

Given $u = 1.5\,pv - 35$

$u_1 = 1.5\,p_1 v_1 - 35 \qquad u_2 = 1.5\,p_2 v_2 - 35$

$U_2 - U_1 = m(u_2 - u_1) = m \times 1.5\,(p_2 v_2 - p_1 v_1)$

$U_2 - U_1 = 90\ KJ$

from first law for the process

$_1Q_2 = (U_2 - U_1) + {_1W_2}$

$_1Q_2 = 90 + 900 = 990\ KJ$ //

$_1Q_2$ is +ve therefore heat transferred to the system.

- $U_2 - U_1$ is +ve hence U_2 is maximum internal energy

$\therefore\ U_2 = U_{max} = m(1.5\,p_2 v_2 - 35)$

$= 1.5\,(1.5\,p_2 v_2 - 35)$

$$\boxed{U_{max} = 412.5\ KJ}$$

2) In a system, executing a non-flow process, the work & heat per degree change of temperature are given by $\frac{dW}{dT} = 200\ W\text{-}s/^\circ C$ & $\frac{dQ}{dT} = 160\ J/^\circ C$ what will be the change of internal energy of the system when its temperature changes from $T_1 = 55^\circ C$ to $T_2 = 95^\circ C$?

Solution :- initial Temp $= T_1 = 55^\circ C$

final temp $= T_2 = 95^\circ C$

$\frac{dW}{dT} = 200\ W\text{-}s/^\circ C\ ,\ \frac{dQ}{dT} = 160\ J/^\circ C$

change in internal energy :-

$\frac{dW}{dT} = 200\ W\text{-}s/^\circ C$

integrating the above equation we get

$dW = 200 \cdot \times dT$

$\int_{T_1}^{T_2} dW = 200 \int_{T_1}^{T_2} dT \Rightarrow {_1W_2} = 200(T_2 - T_1) = 200(95 - 35)$

I

$_1W_2 = 8000\ W\text{-}s = 8000\ J$ // $\{\because 1\,W\text{-}s = 1\,J\}$

Also $\frac{dQ}{dT} = 160\ J/°C$

Integrating

$${}_1Q_2 = 160 \int_{T_1}^{T_2} dT = 160(T_2 - T_1) = 160(95-55) = 6400\ J$$

Applying the first law of thermodynamics to the given non flow process

$${}_1Q_2 = \Delta U_{12} + {}_1W_2$$

$$6400 = \Delta U_{12} + 8000$$

$$\Delta U_{12} = -1600\ J = -1.6\ kJ$$

-ve sign indicates that there is decrease in internal energy

3) The properties of a system, during a reversible constant pressure non-flow process at p = 1.6 bar, changed from $v_1 = 0.3\ m^3/kg$, $T_1 = 20°C$ to $v_2 = 0.55\ m^3/kg$, $T_2 = 260°C$. The specific heat of the fluid is given by

$$C_p = \left(1.5 + \frac{75}{T+45}\right) kJ/kg\,°C \quad \text{where } T \text{ is in } °C$$

Determine i) heat added kJ/kg ii) work don kJ/kg iii) change in internal energy kJ/kg iv) change in enthalpy (kJ/kg)

Solution:- Initial Volume, $v_1 = 0.3\ m^3/kg$

Initial temperature, $T_1 = 20°C$

Final Volume, $v_2 = 0.55\ m^3/kg$

Final temperature, $T_2 = 260°C$

Constant pressure, $p = 1.6$ bar

Specific heat at constant pressure, $C_p = \left[1.5 + \frac{75}{T+45}\right] kJ/kg\,°C$

i) To find heat added per kg of fluid

$${}_1Q_2 = \int_1^2 c_p\, dT = \int_1^2 \left(1.5 + \frac{75}{T+45}\right) dT$$

$${}_1Q_2 = \left[1.5T + 75 \ln(T+45)\right]_1^2$$

$$= 1.5(T_2 - T_1) + 75\{\ln(T_2+45) - \ln(T_1+45)\}$$

$${}_1Q_2 = 1.5(260-20) + 75 \ln\left(\frac{260+45}{20+45}\right) = 475.94\ kJ$$

∴ Heat added $= {}_1Q_2 = 475.94\ kJ/kg$

ii) The work done per kg of fluid is given by

$$ {}_1W_2 = \int_1^2 p \cdot dv = p(v_2 - v_1) = 1.6 \times 10^2 (0.55 - 0.3) \text{ kN-m/kg} $$

$$ {}_1W_2 = 40 \text{ kJ/kg} = \text{work done} $$

iii) change in internal energy

$$ \Delta u_{12} = {}_1Q_2 - {}_1W_2 = 475.94 - 40 = 435.94 \text{ kJ/kg} $$

iv) Change in enthalpy (for non flow process)

for a constant pressure process

$$ {}_1Q_2 = m(h_2 - h_1) = m\,\Delta h_{12} $$

for 1 kg = m

$$ {}_1Q_2 = \Delta h_{12} $$

∴ change in enthalpy $\Delta h_{12} = 475.94$ kJ/kg

4) In a gas turbine unit, the gases flow through the turbine is 15 kg/s & the power developed by the turbine is 12000 kW. The enthalpies of gases at the inlet & outlet are 1260 kJ/kg & 400 kJ/kg respectively, & the velocity of gases at the inlet and outlet are 50 m/s & 110 m/s respectively. calculate

i) The rate at which heat is rejected to the turbine &

ii) The area of the inlet pipe given that the specific volume of the gases at the inlet is 0.45 m³/kg.

→ Rate of flow of gases, $\dot{m} = 15$ kg/s

Volume of gases at the inlet, $v = 0.45$ m³/kg

power developed by the inlet, P = 12000 kW

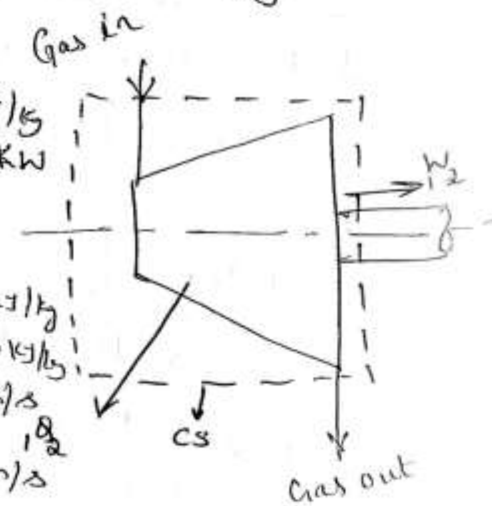
∴ work done $= \frac{12000}{15} = 800$ kJ/kg

Enthalpy of gases at the inlet, $h_1 = 1260$ kJ/kg

Enthalpy of gases at the outlet, $h_2 = 400$ kJ/kg

Velocity of gases at the inlet $V_1 = 50$ m/s

Velocity of gases at the outlet $= V_2 = 110$ m/s



i) Heat rejected ${}_1Q_2$:-

using the flow equation

$$h_1 + \frac{V_1^2}{2} + {}_1q_2 = h_2 + \frac{V_2^2}{2} + W \qquad \left\{ \text{Note } 1N = \frac{1\,kg\,m}{s^2} \right\}$$

$$1260\ (kJ/kg) + \frac{50^2}{2000} \frac{kg\,m^2}{s^2\,kg} = \frac{Nm}{kg}\ (kJ/kg) + {}_1q_2 = 400 + \frac{110^2}{2000} + 800$$

$$\boxed{{}_1q_2 = -55.2\ kJ/kg}$$

$${}_1Q_2 = -55.2 \times 15\ kJ/s$$

$${}_1Q_2 = -828\ kW$$ — ve sign indicates heat rejected

** Note:- Converting $\frac{V_0^2}{2}$ to kJ/kg

$$\left\{ \frac{m^2}{s^2} = \frac{kg\,m^2}{s^2\,kg} = \frac{Nm}{kg} = \frac{J}{kg} \quad \boxed{\frac{m^2}{s^2} = 10^{-3}\ kJ/kg} \right\}$$

$$\therefore \boxed{{}_1Q_2 = 828\ kW}$$

ii) inlet area, A :

using the relation

$$\dot{m}_1 = \rho_1 A_1 V_1$$

$$A_1 = \frac{\dot{m}_1}{\rho_1 V_1} = \frac{\dot{m}_1 v_1}{V_1} = \frac{15 \times 0.45}{50}$$

$$\boxed{A_1 = 0.135\ m^2}$$

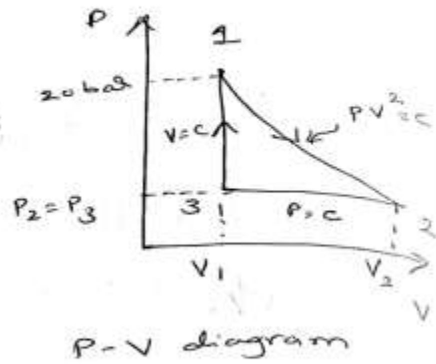
5) A cylinder contains 1 kg of a certain fluid at an initial pressure of 20 bar. The fluid is allowed to expand reversible behind a piston according to law pV^2 = constant until the volume is doubled. The fluid is then cooled reversibly at constant pressure until the piston regains its original piston. Heat is then supplied reversibly with the piston firmly locked in position until the pressure rise to the original value of 20 bar. calculate the net workdone by the fluid for an initial volume of $0.5\,m^3$

→ Given, $m = 1\,kg$, $P_1 = 20\,bar = 20 \times 100\,kPa$, $V_2 = 2V_1$,

$P_2 = P_3$, $V_1 = V_3$, $V_1 = 0.5\,m^3$, $\oint \delta W = ?$

Solution:

To find $\oint \delta W = W_{net} = {}_1W_2 + {}_2W_3 + {}_3W_1$



To find ${}_1W_2$

considering process 1-2 (polytropic ~~adiabatic~~ process)

$PV^2 = C$

$V_1 = 0.5\ m^3$, $P_1 = 2000\ kPa$

$V_2 = 2 \times V_1 = 1\ m^3$, $P_2 = ?$, $n = 2$

w.k.t

$${}_1W_2 = \frac{P_1V_1 - P_2V_2}{n-1} \quad \{\text{polytropic work done}\}$$

To find P_2 for process 1-2

$$P_1V_1^2 = P_2V_2^2$$

$$P_2 = P_1\left(\frac{V_1}{V_2}\right)^2 = 20000 \times 0.5^2$$

$$P_2 = 500\ Kpa$$

Hence ${}_1W_2 = 500\ KJ$

~~For~~ To find ${}_2W_3 : P(V_3 - V_2) = -250\ KJ$

$${}_3W_1 = 0 \quad (V=C)$$

$\therefore \quad W_{net} = 250\ KJ$

LIST OF FORMULAS:

1. $\partial Q = \partial U + \partial W$
2. $\oint \partial Q = \oint \partial W$
3. SFEE $\boldsymbol{m\left(h_1 + \frac{V_1^2}{2} + gZ_1 + q_{1-2}\right) = m\left(h_2 + \frac{V_2^2}{2} + gZ_2 + W_{1-2}\right)}$
4. h = u +pv
5. $C_P = du/dt$, $C_V = dh/dt$

OUTCOMES: Determine heat, work, internal energy, enthalpy for flow & non flow process using First Law of Thermodynamics.

FURTHER READING:

- Basic Engineering Thermodynamics, A.Venkatesh, Universities Press, 2008
- Basic and Applied Thermodynamics, P.K.Nag, 2nd Ed., Tata McGraw Hill Pub.
- http://www.nptel.ac.in/courses/112104113/4#

SECOND LAW OF THERMODYNAMICS

OBJECTIVE: Determine heat, work, internal energy, enthalpy for flow & non flow process using Second Law of Thermodynamics.

STRUCTURE:

2.2.1 Limitations of First Law of Thermodynamics
2.2.2 Device Converting Heat to Work
2.2.3 Device Converting Work to Heat
2.2.4 Statements of Second Law Of Thermodynamics:
2.2.5 Equivalence of Kelvin Planck And Clausius Statements
2.2.6 PMM-II
2.2.7 Carnot Cycle & Carnot Theorem

2.2.1 Limitations of first law of thermodynamics:

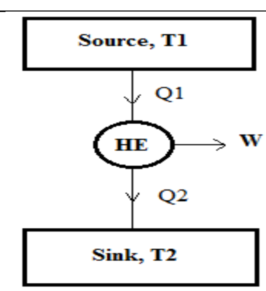
1. First law explains about the inter conversion of heat and work without placing any restriction on the direction.

2. All simultaneous processes proceed only in one particular direction and to reverse such processes, energy from external source is required.

3. First law provides all necessary conditions for a process to occur but in doesn't give sufficient conditions namely direction of the process.

2.2.2 Device converting Heat to Work:

A Heat Engine may be defined as a system operating in a cycle and producing useful work by abstracting heat from a suitable heat source.



Heat Engine

Consider a heat engine that receives Q_1 amount of heat from a high temperature source at T_1. Some of the Heat thus received is utilized to do mechanical work W. The engine rejects Q_2 amount of heat to a low temperature sink at T_2.
Applying the first law to the heat engine,

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

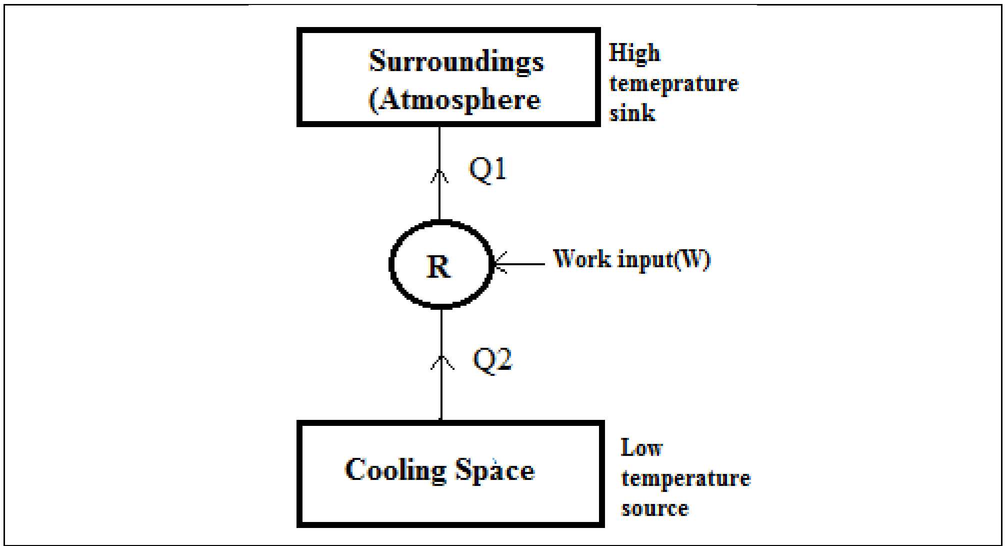
Net Heat Transfer = Net Work Transfer

Generally performance of the heat engine is expressed in efficiency of the engine . Thus thermal efficiency of heat engine,

$$\eta_{th} = \frac{\text{Net work output}}{\text{Gross heat input}} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

2.2.3 Devices converting work to heat (Reversed Heat Engine):

1. Refrigerator: A refrigerator is a device which working in a cycle delivers heat from low temperature to a high temperature region.
The performance of a refrigerator is expressed in terms of COP or coefficient of performance.

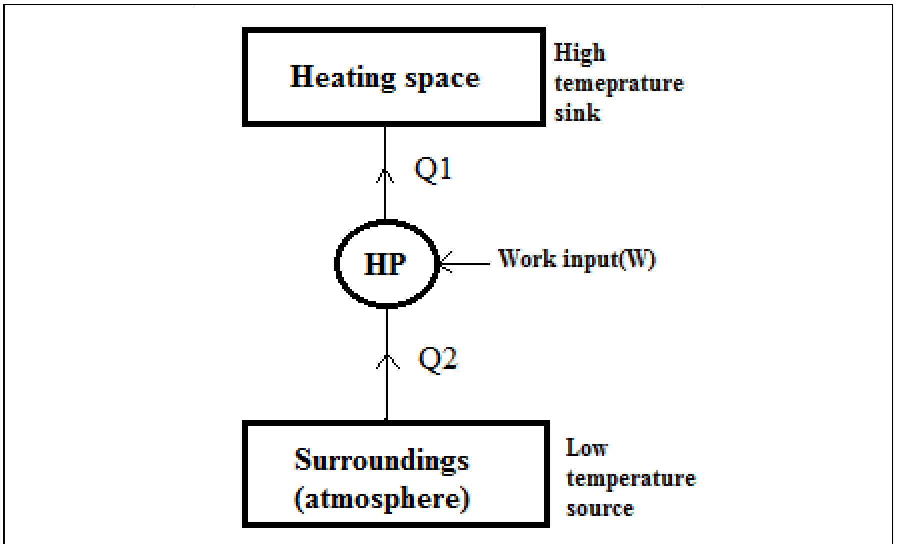


Refrigerator

$$COP_R = \frac{\text{Desired effect}}{\text{Work input}} = \frac{\text{Heat extracted at low temperature}}{\text{Work input}} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$$

2. Heat Pump:

A heat pump is a device which working in a cycle delivers heat from low temperature region to high temperature region.The efficiency of heat pump is expressed in terms of COP.Thus,



Heat Pump

$$COP_{HP} = \frac{\text{Desired effect}}{\text{Work input}} = \frac{\text{Heat to high temperature sink}}{\text{Work input}} = \frac{Q_1}{W}$$

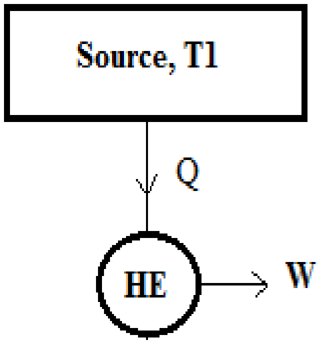
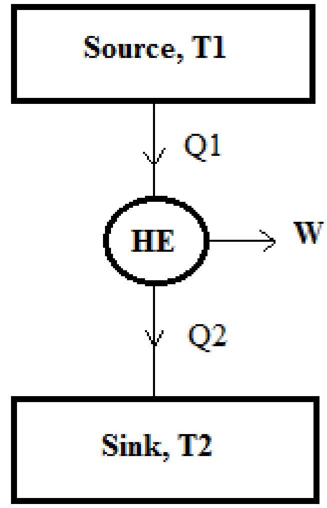
$$\mathbf{COP_{HP} = \frac{Q_1}{Q_1 - Q_2} = 1 + \frac{Q_2}{Q_1 - Q_2}}$$

COP_{HP} = 1 + COP of refrigerator

2.2.4 Statements of Second Law of Thermodynamics:

Kelvin – Planck statement:

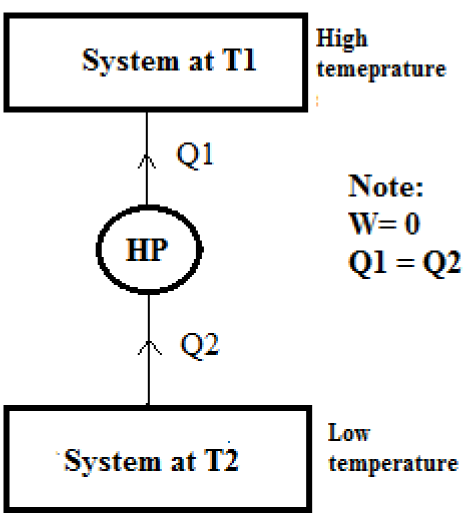
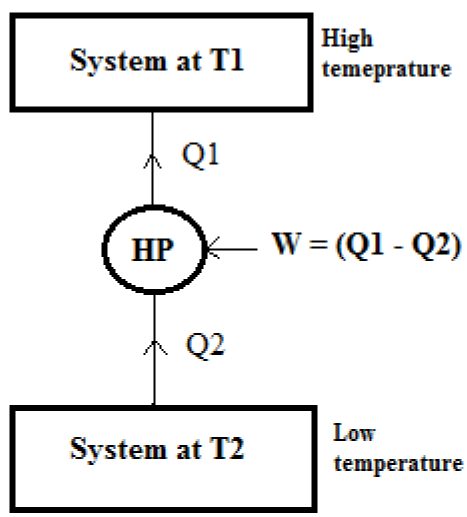
"It is impossible to construct an engine which operating in a cycle, will produce no other effect than the extraction of heat from a single heat reservoir and performs an equivalent amount of work"

	
impossible	**Possible**

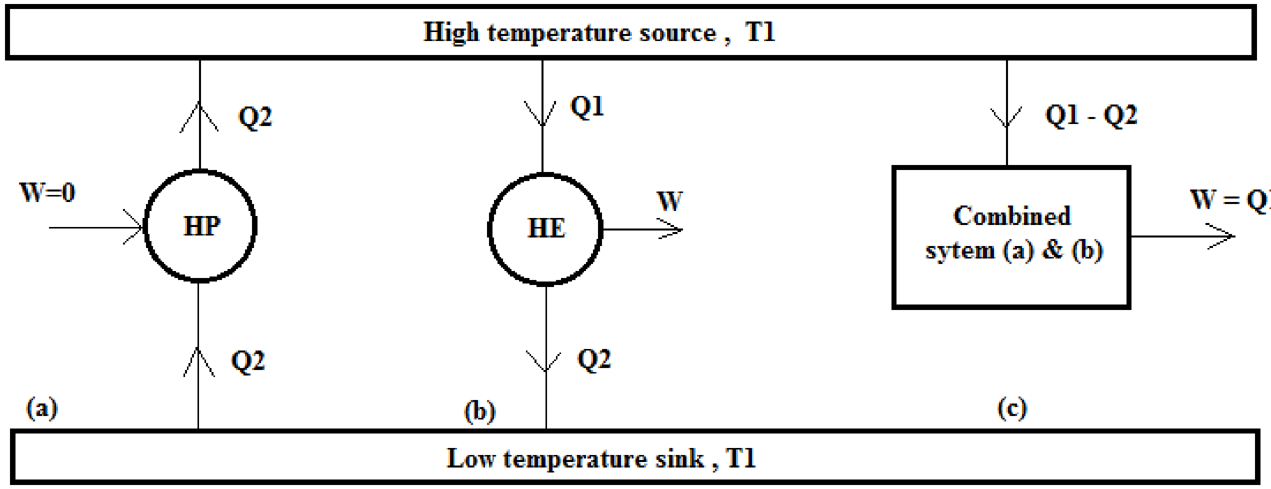
Heat engine can receive Q_1 amount of heat from a high temperature source, a part of it is utilized to do work W before Q_2 amount of heat is rejected to the low temperature sink as shown in the above figure.

Clausius statement:

"It is impossible to construct an engine which is operating in a cycle, transfers heat from a body at a lower temperature to a body at a higher temperature without the assistance of external work" or "It is impossible for heat energy to flow from a lower temperature body to a higher temperature body without the assistance of external work"

	
Impossible	**Possible**

2.2.5 Equivalence of Kelvin Planck and Clausius Statements:



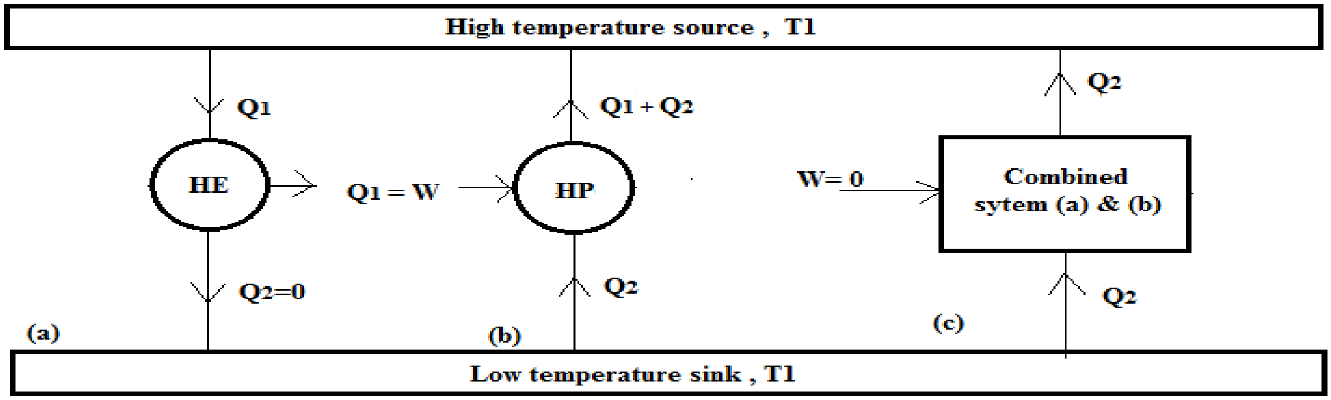
Violation of Clausius statement leads to violation of Kelvin Planck statement

Consider fig(a) in this case a heat pump HP operates in a cycle and transfers Q_2 amount of heat from a low temperature source without any work input. This system violates Clausius statement.

Consider fig(b) in this case , a heat engine HE operates in a cycle absorbing Q_1 amount of heat from a high temperature source. The engine does W amount of work and finally rejects Q_2 amount of heat to the low temperature sin. This system operates as per Kelvin Planck statement.

Consider fig(c) in this case both the heat pump and the heat engine are combined together to form a combined system. This system constitutes a device that receives $(Q_1 – Q_2)$ amount of heat from high temperature source and does an equivalent amount of work $W = (Q_1 – Q_2)$. Hence this system violates Kelvin Planck statement.

Thus, violation of Clausius statement leads to violation of Kelvin Planck statement.



Violation of Kelvin Planck statement leads to Violation of Clausius statement

Consider fig(a) in this case a heat engine extracts Q_1 amount of heat from a high temperature source and does an equivalent amount of work $W = Q_1$ without rejecting heat to the low temperature sink. This system violates Kelvin Planck statement

Consider fig(b) in this case , a heat pump working in a cycle extracts Q_2 amount of heat from a low temperature sink. The heat pump also receives $W = Q_1$ amount of work from an external source and supplies (Q_1+Q_2) amount of heat temperature source. This system works as per clausis statement.

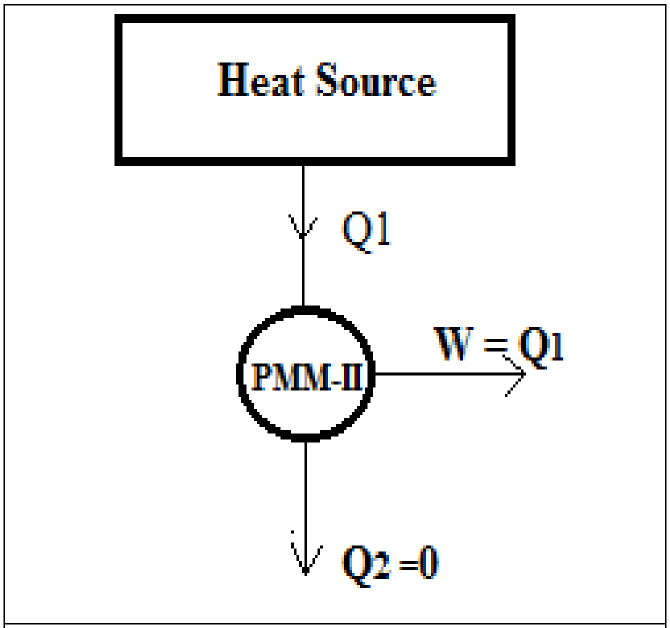
Consider fig(c) in this case, both the heat engine and the heat pump are clubbed together to form a combined system. Since the output of the engine W is used to drive the heat pump, input to the combined system is only from the Q_2 amount of heat extracted from the low temperature sink. The system rejects same amount of heat to the high temperature source without any external work input. This system violates Clausius statement.

Thus violation of Kelvin Planck statement leads to violation of Clausius statement.

Hence we can conclude that both Kelvin Planck and Calusius statements are equivalent in sense.

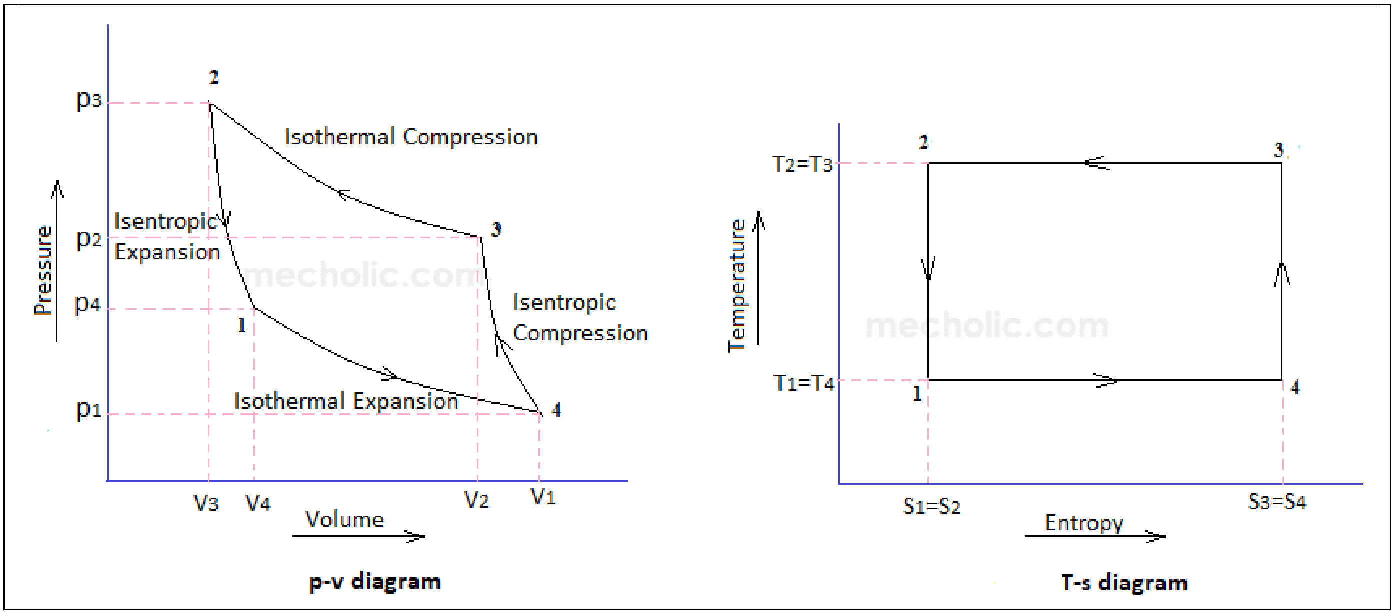
2.2.6 Perpetual Motion Machine of Second Kind (PMM-II):

It is an engine working in a cycle developing net work by exchanging heat from a single heat source. PMM-II Violates Kelvin Planck statement.



PMM-II

2.1.8 Carnot Cycle:



Carnot cycle consists of four reversible processes

1-2: Adiabatic compression

$$W_{1-2} = \frac{P_1V_1 - P_2V_2}{\gamma - 1} = \frac{-(P_2V_2 - P_1V_1)}{\gamma - 1} = -m.R.(T_1 - T_2)$$

$Q_{1-2} = 0$

2-3: Isothermal Expansion

$$W_{2-.3} = P_2V_2 \ln\frac{V_3}{V_2} = m.R.T_2 \ln\frac{V_3}{V_2}$$

$$Q_{2-3} = W_{2-3} = m.R.T_2 \ln\frac{V_3}{V_2}$$

3-4: Adiabatic Expansion

$$W_{3-4} = \frac{P_3V_3 - P_4V_4}{\gamma - 1} = m.R.(T_3 - T_4)$$

$Q_{3-4} = 0$

4-1: Isothermal Compression

$$W_{4-.1} = P_4V_4 \ln\frac{V_1}{V_4} = -P_4V_4 \ln\frac{V_4}{V_1} = -m.R.T_4 \ln\frac{V_4}{V_1}$$

$$Q_{4-1} = W_{4-1} = -m.R.T_4 \ln\frac{V_4}{V_1}$$

Net Work done /cycle = $\oint \mathbf{W} = -m.R.\ln\frac{V_3}{V_2}(\mathbf{T_2} - \mathbf{T_1})$

Thermal Efficiency of the cycle:

$$\eta = 1 - \frac{T_1}{T_2}$$

Carnot Theorem: "No engine, operating between two heat reservoirs each having fixed temperatures, can be more efficient than a reversible heat engine operating between the same temperatures"

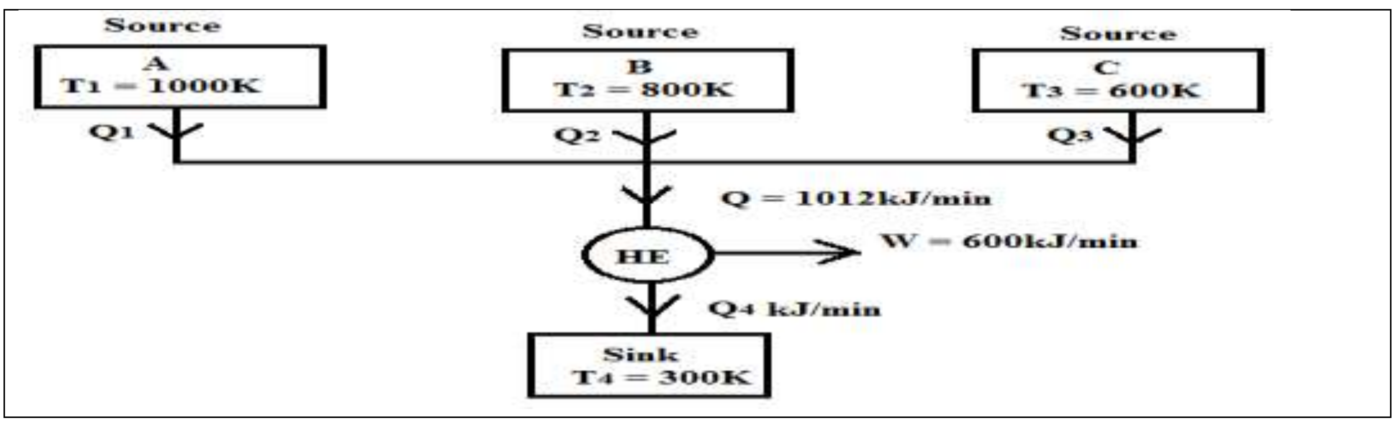
IMPORTANT THEORY QUESTIONS:

1. Write Kelvin Planck and Clausius statement of Second law of thermodynamics and prove that they are equivalent.
2. Define i) Heat Engine ii) Refrigerator and its COP iii) Heat Pump and its COP.
3. Sate Carnot theorem and derive an expression for work done by a system undergoing Carnot cycle.

Problems:

1. A reversible engine operates between 3 heat reservoirs 1000K , 800K and 600K and rejects heat to a reservoir at 300K, the engine develops 10kW and rejects 412kJ/min. If heat supplied by the reservoir at 1000K is 60% of heat supplied by the reservoir at 600K , find the quantity of heat supplied by each reservoir.

Solution:



Work output = 10kW = 10×60 = **600kJ/min**

From first law of thermodynamics

Total Heat supplied = W + Heat rejected

= 600 + 412

= 1012kJ/min

Let Q_1 be the heat absorbed by the engine from the source at 600K

Then , heat absorbed from the source at 1000K is **(0.6×Q_1)**

Therefore heat taken from the source at 800K is

Q_2 = 1012 - Q_1 – (0.6×Q_1)

As engine is reversible, Clausius theorem becomes,

$$\oint \frac{dQ}{T} = 0 = \frac{Q_1}{T_1} + \frac{Q_2}{T_2} + \frac{Q_3}{T_3} - \frac{Q_4}{T_4}$$

Substituting the values in the above equation we get

Q_1 = 405 kJ/min

Q_2 = 364 kJ/min

Q_3 =218.4 kJ/min

2. An inventor claims that his engine has the following specifications

Power developed = 76kW

Fuel burned per hour = 4kg

Heating value of fuel = 75000kJ/kg

Temperature limits = 727°C and 27°C

Solution:

For given Engine, Work done = 76kW = 76×3600 = 273600 kJ/hr

Heat supplied = Mass of fuel × Heating value of fuel

= 4×75000 = 3×10^5 kJ/hr

Thermal efficiency, $\eta_{th} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{273600}{3\times10^5}$

= 91.2%

Thermal efficiency of a reversible engine working between the same temperature limits

$$\eta_{th} = \frac{T_1 - T_2}{T_1} = \frac{1000 - 300}{1000} = 70\%$$

Since the thermal efficiency is greater than the efficiency of reversible engine the claim is false and engine needs to be redesigned

OUTCOMES: Determine efficiency and COP of refrigerator and equivalence of statement's of Second law of thermodynamics, efficiency of carnot cycle

FURTHER READING:

- Basic Engineering Thermodynamics, A.Venkatesh, Universities Press, 2008
- Basic and Applied Thermodynamics, P.K.Nag, 2nd Ed., Tata McGraw Hill Pub.
- http://www.nptel.ac.in/courses/112104113/4#