SATHYABAMA
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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – I –Engineering Thermodynamics– SMEA1302

I. Basic Concepts and First Law of Thermodynamics

THERMODYNAMICS

Thermodynamics is a branch of Science that deals with the relationship among heat, work and properties of system which are in equilibrium with one another.

MACROSCOPIC AND MICROSCOPIC VIEW POINT

Macroscopic thermodynamics deals with the effects of action of many molecules concerned.

Eg. Pressure.

Pressure is the average rate of change of momentum due to all the molecular collisions made on a unit area.

Microscopic thermodynamics deals with the study of the behavior of the system by summing up the behavior of each molecule.

Eg. Air in a cylinder contains number of identical particles but moving with independent velocities.

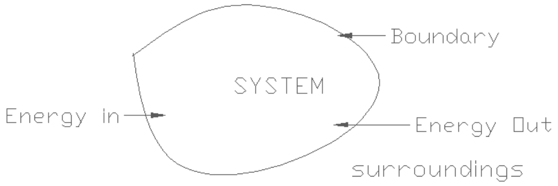
THERMODYNAMIC SYSTEMS

i) Closed system.
ii) Open system.
iii) Isolated system.

(i) Closed system.

A system in which only energy transfer takes place but there is no mass transfer across it, is called as closed system.

Eg.piston, and cylinder without valves



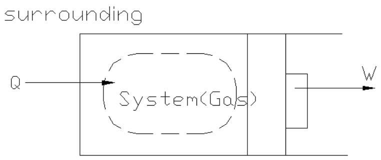


Figure 1.1

(ii) Open system.

A system in which both mass transfer and energy transfer takes place is called as open system.

Eg. Steam turbines.

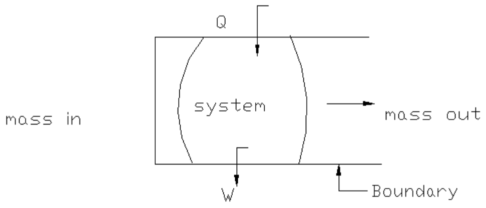


Figure 1.2

(iii) Isolated system.

A system in which neither mass transfer nor energy transfer takes place is called as Isolated system .

ie. The system is isolated from its surroundings

Eg. Thermo flask

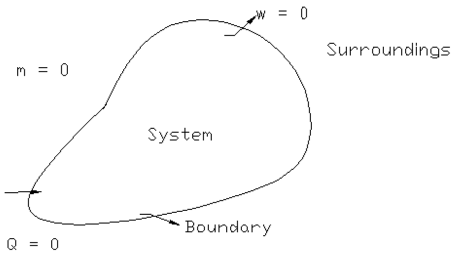


Figure 1.3

Homogeneous and Heterogeneous systems

A system, which contains only a single phase, is called as Homogeneous system.

Eg. Mixture of air and water vapour.

A system, which consists of more than one phase, is called as Heterogeneous system.

Eg. Mixture of water and steam.

Pure substance

A Substance with homogeneous and invariable chemical composition even though change of phase takes place is called as pure substance.

Eg. Water.

Thermodynamic Equilibrium

If there is no Spontaneous change in the properties of a system after small disturbance, then the system is said to be in Thermodynamic equilibrium.

Eg. Temperature and pressure at all points of a system are same means that the system exist in thermodynamic equilibrium.

Properties of Steam.

Certain characteristics which describe the physical condition of a system are called properties of a system.

Eg. Volume, Pressure.

Intensive properties

Properties which are independent of mass are called Intensive properties.

Extensive properties

Properties which depend on mass are called Extensive properties.

Eg. Volume, energy, entropy.

State

State is one which describes the condition of a system at an instant of time.

Process

The succession of states passed through during a change of state is called path.

Process is nothing but the complete specification of path.

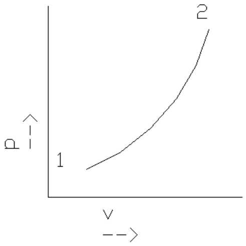


Figure 1.4

Cycle

It is defined as a series of state changes such that final state is identical with the initial state.

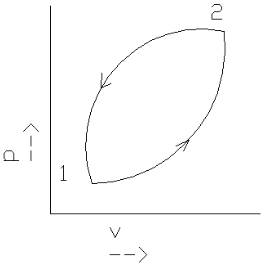


Figure 1.5

Quasi static process

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

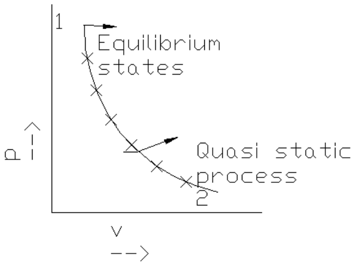


Figure 1.6

Cycle Efficiency

$$\eta_{CY} = \frac{\text{Work Output}}{\text{Heat supplied.}}$$

Point and path functions

When a point on the graph is located by means of two properties these are caused point functions.

Eg. Pressure, temperature, volume.

$$_1\int^2 dT = T_2 - T_1$$

Properties which cannot be located on a graph by a point are path functions.

Eg. Heat, work

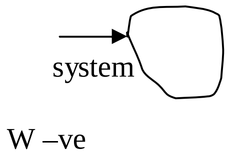
$$_1\int^2 dw \neq w_2 - w_1$$

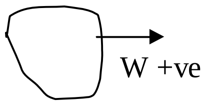
Energy work and heat

Energy is the capacity to do work. It may be stored energy or energy in transition.

Work

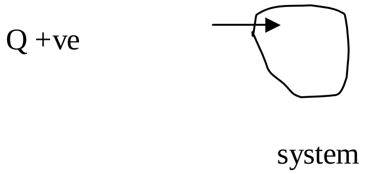
Form of energy in transit resulting from a force acting through a given distance.

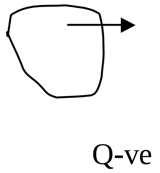




Heat

Heat is the internal energy transferred from one body to another due to temperature difference.





Temperature

It is defined as the degree of intensity of heat or measure of hotness or coldness of a body.

Zeroth law of Thermodynamics

When a body A is in thermal equilibrium with a body B and also separately with a body C then B and C will be thermal equilibrium with each other.

It is a basis of temperature measurement.

Thermometer is used for this purpose.

Methods to find the temperature

i) The thermometer is made to contact with a system whose temperature T (x) is to be measured, and also in contact with an arbitatriously chosen standard system in an easily reproducable state where the temperature is T(x1) .

then $[T (x1)] / [T (x)] = x_1 / x$

$[T (x2)] / [T (x)] = x_2 / x$

$$[T (X1) – T (X2)] / T(x) = (X_1 - X_2) / X$$

$$T(x)= \frac{(T(x_1)-T(X))X}{X_1 – X_2}$$

ii) Designating the triple point of water as T (t1) and with X_t be the value of thermodynamic property.

When the body whose temperature T is to be measured is placed in contact with water at its triple point,

$$\text{Then, } T = 273.16\ X / X_t$$

Pdv-work in various Quasi-static processes.

i) constant pressure process

this is also called as Isobaric process.

$$W_{1-2} = \int_{v1}^{v2} Pdv = P (V_2 – V_1)$$

Eg. 1. Diesel cycle works on constant pressure process.

2. Heating of Ideal gas in a piston cylinder assembly

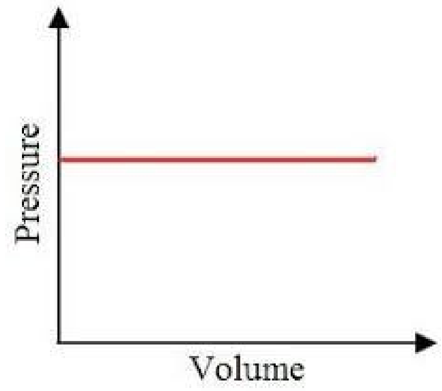


Figure 1.7

ii) Constant volume process

This is also called as Isochoric Process.

$W_{1-2} = \int_{v1}^{v2} pdv = 0$ here $v_1 = v_2$

Hence, there is no work transfer.

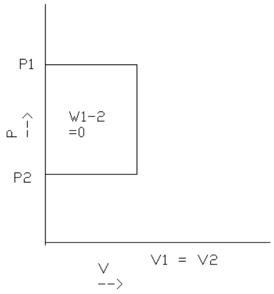


Figure 1.8

Eg. Otto cycle.

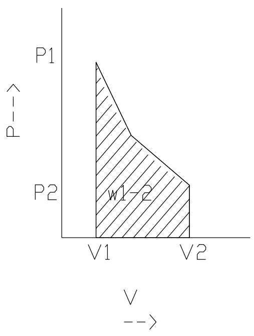
iii) Constant temperature process.

This is also called as Isothermal process.

$pv = p_1v_1 = p_2v_2 = c$

$$p = \frac{p_1v_1}{v}$$

$w_{1-2} = \int_{v1}^{v2} pdv = \int_{v1}^{v2} \underline{p_1v_1}\ dv$



$$= p_1v_1 \int_{v1}^{v2} dv / v = p_1v_1 \ln (v_2 / v_1) = p_1 v_1 \ln (p_1 / p_2)$$

Eg. Condensation of steam takes place at constant temperature.

Isothermal compression of perfect gas in a cylinder.

iv) process in which $pv^n = c$

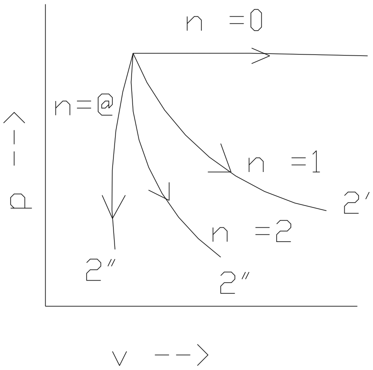
(Polytropic, isentropic, adiabatic)

for adiabatic process $pv^v = c$

Where,

$C_p = 1.005$ kj / KgK $\qquad C_v = 0.718$ kj / kgK

$C_p / C_v = 1.4$ for air.



$$Pv^n = p_1v_1^n = p_2v_2 = c$$

$$P = \frac{p_1v_1^n}{v^n}$$

$$w_{1-2} = \int_{v1}^{v2} pdv = \int_{v1}^{v2} \frac{p_1v_1^n \times dv}{v^n}$$

$$= p_1v_1^n \int_{v1}^{v2} dv / v^n$$

$$= p_1v_1^n \left[v^{1-n} / 1-n \right]_{v1}^{v2}$$

$$= p_1v_1^n \left[(V_2^{1-n} - V_1^{1-n}) / 1-n \right]$$

$$= (P_2V_2 - P_1V_1) / 1-n$$

$$= (P_1V_1 – P_2V_2) / n-1$$

$$= P_1V_1 \left[1 – (P_2 / P_1)^{n-1 / n} \right]$$

Eg. Compression, expansion processes of gas.

Specific heat and Latent heat

Specific heat of a substance is defined as the quantity of heat required to raise a unit mass of the substance through a unit raise in temperature.

For solids and liquids specific heat is independent of the process.

For gases if depends on the process C_p- specific heat at constant pressure C_v – specific heat at constant Volume.

Latent heat

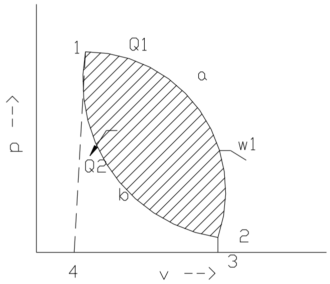
It is the quantity of heat required to cause a phase change in unit mass of a substance.

First law of Thermodynamics

When a system executes a cyclic process the algebraic sum of heat transfer equals to the algebraic sum of work transfer.

Consider the condition of the system

as represented by point 1 on pv diagram.



Q_1 --> heat added to the system.

Q_2 --> heat rejected from the system.

The system executes a cycle by following the path

1-a-2 and returning back by the path 2-b-1.

W_1 → work done by the system (1-a-2-3-4-1)

$W_2 \rightarrow$ work done on the system (2-3-4-2-b-2)

$$\ldots\int dQ = \int dw$$

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

If " w" is in work unit, then $\int dv/J = \int dq$

$J \rightarrow$ Mechanical equivalent of heat

When the system executes a process, $Q-W =$ E. △

Corollary of I law of Thermodynamics

The energy of the system remains constant if the system is isolated from its surroundings as regards heat and work interactions.

Perpectual Motion Machine of Kind I (PMMKI)

The device which working in a cycle delivers work continuously without the addition of any heat. The only interaction with the surroundings is the delivering of work.

It violates the First law of Thermodynamics and hence it is impossible.

Steady Flow Energy Equation

Steady flow means that rate of flow of mass and energy across the control surface are constant with respect to time

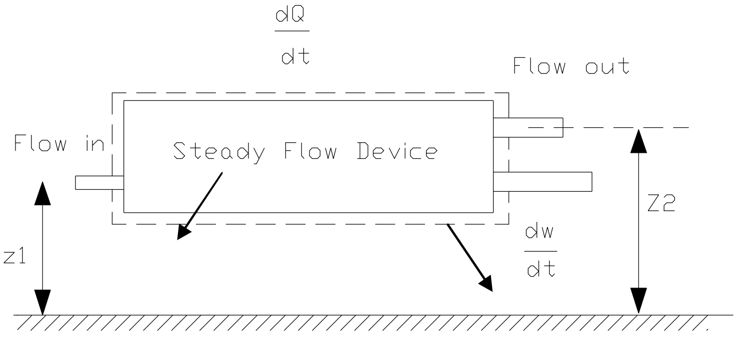


Figure 1.9

According the law of conservation of mass, the mass flow rate entering must equal to the mass flow rate leaving. ie. $m_{1=} m_{2.}$

ie. $A_1V_1 / v_1 = A_2V_2 / v_2$ (Continuity equation)

According to the law of conservation of energy the total rate of flow of all energy streams entering the control volume must equal to the total rate of flow all energy streams leaving the control volume.

ie. $m_1e_1 + dQ/dt = m_2e_2 + dw/dt$

where,

$dw/dt = dw/dt - p_1v_1 \ dm_1/dt + p_1v_1 \ dm_2/dt$,

where,

dwx/dt -→ Shaft work

$p_1v_1dm_1$ → displacement workdone by the fluid of mass dm, at inlet.

(-ve indicates workdone on the system.)

$p_2v_2dm_2$ → displacement workdone by the fluid of mass dm_2 at outlet.

(+ve indicates work is done by the system)

e → Specific energy

e → $v^2/2 + zg + u$

$$:. \ m_1 (v_1^2/2 + z_1g + u_1) + m_1 p_1v_1 + dQ/dt$$

$$= :. \ m_2 (v_2^2/2 + z_2g + u_2) + m_2 p_2v_2 + dwx/dt$$

$$m_1 (h_1 + v_1^2/2 + z_1g) + dQ/dt = m_2 (h_2 + v_2^2/2 + z_2g) + dwx/dt$$

where,

enthalpy $h = u + pv$

since, $m_1 = m_2 = m = dm/dt$.

$$h_1 + v_1^2/2 + z_1g + dQ/dm = h_2 + v_2^2/2 + z_2g + dwx/dm$$

This is known as **S.F.E.E.**

Problems.

1. Air at 5bar and 30°C is expanded till its volume is doubled adiabatically. Calculate the work done during the process.

Given : $p_1 = 5\text{bar}=5*10^5 \text{ N/m}^2$

$T_1 = 30°C = 303K$.

For air R = 287 J/Kg K.

$$\text{Specific Volume} \quad v_1 = RT_1 / p_1 = 287x303 / 5x10^5 = 0.174 \text{ m}^3/\text{kg}.$$

Pressure ratio.

$$p_2/p_1 = (v_1/v_2)^\gamma = (½)^\gamma \Rightarrow p_2 = (½)^\gamma \text{ x } 5 = 1.89\text{bar}.$$

work done

$$w = \gamma/\gamma\text{-}1 \; p_1v_1 \; [1\text{-} (p_2/p_2)^{\gamma\text{-}1/ \gamma}]$$

$$= 1.4/0.4 \text{ x } 5 \text{ x } 100 \text{ x } 0.174 [1\text{-} (1.89/5)^{0.4/1.4}]$$

$$= 73.89 \text{ kJ/kg}.$$

2. A perfect gas for which ratio of specific heat is 1.4 occupies a volume of 0.3 m^3 at 100 Kpa and 27°C. The gas undergoes compression to $0.06m^3$. Find the heat transfer during compression for the following methods of compression.

(a) PV=C (b) isentropic. Compare the compression work. Molecular weight of gas is 28.

Given : $p_1 = 100$ kpa, $v_1 = 0.3m^3$, $T_1 = 27°C = 300K$

$$v_2 = 0.06\ m^3, \quad \gamma = c_p/c_v = 1.4$$

$pv=c$ isothermal compression

$w_1=p_1v_1 \ln(v_2/v_1)$

$=100*0.3 \ln(0.06/0.3)$

$=-48.28kJ$

$pv^{\gamma}=c$ isentropic compression

$$w_2 = \gamma/\gamma\text{-}1 \ \ p_1v_1 \ [1- (p_2/p_1)^{\gamma-1/\gamma}$$

$p_2/p_1 = (v_1/v_2)^{\gamma} = \ \ p_2 = p_1 (v_1/v_2)^{\gamma} = 100 (0.3/0.06)^{1.4} = 951.8kPa$

$$w_2 = 1.4/0/4 \times 100 \times 0.3 \ [1- (951.8/100)^{0.4/1.4}]$$

$$= -67.77\ kJ$$

comparison of work

$$= w_1/w_2 = 48.28/67.77 = 0.712$$

3. An ideal gas initially in a piston cylinder assembly at 1.5bar and $0.2m^3$. The gas is first heated at constant pressure until the volume is doubled. It is then allowed to expand isothermally until the volume is again doubled. Determine the work done by the gas during the process and plot the process on a p-v diagram. The initial temperature is 300K for the gas.

Given :

$$p_1 = 1.5bar; \ v_1 = 0.2m^3 ; \ T_1 = 300k$$

work done by the gas during constant pressure process

$w = {}^{v2}\!\int_{v1} pdv \ = p (v_2 – v_1)$

$$= 1.5 \times 100 (2 \times 0.2 – 0.2)$$

$= 30kJ.$

Work done by the gas during isothermal process.

$w = p_1v_1 \int_{v1}^{v2} dv/v = p_1v_1 \ln v_2/v_1$

$= 1.5 \times 100 \times 2\ 0.2 \times \ln(2)$

$= 41.59kJ.$

4. An ideal gas is compressed through a pressure ratio of 10 and the temperature is increased from 30°C to 240°C.

Find (1) Polytropic index

(2) work of compression/unit mass.

Given : $p_2/p_1 = 10$, $T_1 = 30°C = 303K$, $T_2=240°C = 573K$

(i) Polytropic index of compression

$T_2/T_1 = (p_2/p_1)^{n-1/n}$

$\ln (T_2/T_1) = n-1/n \ \ln(p_2/p_1)$

$n-1/n = \ln (T_2/T_1) / \ln(p_2/p_1)$

$= \ln(573/303) / \ln(10) = 0.229$

$n = 1.3$

(ii) work of compression /unit mass

$w = RT_1 \times n / n-1 \ [1 – (p_2/p_1)^{n-1/n}]$

$= 0.287 \times 303 \times 1.3 / 0.3 \ [1- (10)^{0.3/1.3}]$

$= -264.25$ kJ/kg.

5. 1kg of ideal gas is heated from 18°C to 93°C. Assuming R=267J/kg K. Ratio of specific heats 1.18. Heat transfer of 160kJ. Find

(a) the specific heats

(b) change in internal energy

(c) change in enthalpy

(d) work transfer.

Given : $T_1 = 18°C = 291k$ $T_2 = 93°C = 366k$ m= 1 kg R= 264J/kgK

$C_p/C_v = 1.18$ $Q_{1\text{-}2} = 160kJ$.

(a) Specific heats C_p and C_v

$R = C_p - C_v = 264$

$C_p/C_v = 1.18$

$C_p = 1.18C_v$.

$1.18C_v - C_v = 264$

:. $C_v = 1466.67$ J/kgK.

$C_p = 1.18C_v = 1730$ J/kgK.

(b) change in internal energy

$\Delta u = mC_v (T_2 - T_1)$

$= 1 \times 1.46 (366-291)$

$= 109.5$ kJ/kg.

(c) Change in enthalpy (Δh)

$\Delta h = m C_p (T_2 - T_1)$

$= 1 \times 1.73 (93-18)$

$= 129.75$ kJ/kg

(d) work transfer ($w_{1\text{-}2}$)

$w_{1\text{-}2} = Q_{1\text{-}2} - (u_2 - u_1)$

$= 160 - 109.5 = 50.5$ kJ/kg.

6. Calculate the change in internal energy, heat transfer and change in enthalpy for 0.5kg of air expanding according to the law $pv^{1\text{-}2}=C$ from 1Mpa and 300°c to 100Mpa. What will be the workdone by air R=287 J/kgK.

Given : m=0.5kg p_1 = 1Mpa T_1= 300°C= 573K p_2 = 100Mpa

n=1.2= C_p/C_v R= 287 J/kgK.

$R = C_p - C_v = 287$

$C_p/C_v = 1.2 \Rightarrow C_p = 1.25C_v$

$1.25C_v - C_v = 287$

$C_v = 1435$ J/kgK

$C_p = 1722$ J/kgK

$T_2/T_1 = (p_2/p_1)^{n-1/n} \Rightarrow T_2 = 300\ (100/1)^{0.2/1.2} = 646.3°C$

Change in internal Energy : $\Delta u = mC_v\ \Delta T$

$= 0.5 \text{ X } 1.435\ (646.3 - 300)$

= 248.47 KJ.

Change in enthalpy.

$\Delta h = mC_p\Delta T$

$= 0.5 \text{ X } 1.722\ (646.3 - 300)$

= 298.16 kJ.

Work done by air

$w = n/n\text{-}1\ \ mRT_1 [\ 1\text{-}\ (p_2/p_1)^{n-1/n}\ ]$

$= 1.2/0.2 \text{ x } 0.5 \text{ x } 2.87 \text{ x } 573\ [\ 1\text{-}\ (100/1)^{0.2/1.2}\ ]$

= -569.5kJ.

Heat transferred

$$Q = \Delta u + w$$

$$= 248.47 - 569.5 = -321.03 \text{ kJ.}$$

7. Calculate the power required by a compressor if air flowing at the rate of 0.9kg/s enters at 1.01bar, 25°C with a velocity of 70m/s and leaves at 2.02 bar, 75°C with a velocity of 140m/s. heat transferred from the air to the cooling water circulating around the compressor casing amounts to 16kJ/kg of air.

Given : $p_1 = 1.01\text{bar}$ $p_2 = 2.02$ bar $T_1 = 25°C$ $T_2 = 75°C$

$m = 0.9\text{kg/s}$ $v_1 = 70\text{m/s}$ $v_2 = 140\text{m/s}$

by S.F.E.E.

$$m_1 (h_1 + v_1^2/2 + z_1 g) + dQ/dt = m_2 (h_2 + v_2^2/2 + z_2 g) + dw/dt$$

$$dw/dt = -m \left[(h_2 - h_1) + \frac{v_2^2 - v_1^2}{2} + (z_2 - z_1)g \right] + dQ/dt$$

$$= -0.9 \left[1.005(75-25) + \frac{(140^2 - 70^2)}{2} \times 10^3 \right) - 16$$

$$= -63.89\text{kW.}$$

8. In a Steam power station, steam flows steadily through a 0.2m diameters pipeline from the boiler to the turbine, at the boiler end, the steam conditions are found to be p=4Mpa;

t = 400°C; h =3213.6 kJ/kg and v =0.073m^3/kg. At the turbine and, the conditions are found to be p =35Mpa; t =392°C, h =3202.6 kJ/kg. And v =0.084m^3. There is a heat loss of 8.5 kJ/kg from the pipeline. Calculate steam flow state.

Given : $d_1 = 0.2\text{m}$, $p_1 = 4\text{Mpa}$, $t_1 = 400°C$, $h_1 = 3213.6\text{kJ/kg}$

$v_1 = 0.073 m^3/kg$ $p_2 = 3.5 Mpa$, $t_2 = 392°C$, $h_2 = 3202.6 kJ/kg$, $v_2 = 0.084 m^3/kg$

$dQ/dt = - 8.5$ kJ/kg (Heat loss)

by S.F.E.E.

$$h_1 + v_1^2/2 + z_1 g + dQ/dt = h_2 + v_2^2/2 + z_2 g + dw/dt$$

Applying Continuity equation

$$A1V_1/v_1 = A_2 V_2 / v_2$$

$$V_2 = \frac{\cancel{A_1}}{\cancel{A_2}} \times \frac{v_2}{v_1} \times V_1 = \frac{0.084}{0.073} = 1.15V_1.$$

Here $A_1 = A_2$ since cross-section of pipeline is same from boiler to turbine

And $dw/dm = 0$ $h_1 + V_1^2/2 + dQ/dm = h_2 + V_2^2/2 + dw/dm$

$$\frac{V_2^2 - V_1^2}{2} 10^{-3} = (h_1 - h_2) + dQ/dm$$

$$= (3213.6 – 3202.6) – 8.5$$

$$= 2.5 kJ/kg.$$

$$1.15V_1^2 – V_1^2 = 5 \times 10^{-3}$$

$$V_1^2 = 15650 m^2/s^2$$

$$V_1 = 125.1 m/s$$

Mass flow rate

$$m = \frac{A_1 V_1}{v_1} = \frac{\Pi/4 (0.2)^2 \times 125.1}{0.073}$$

$$m = 53.8 kg/s.$$

9. In many real processes, it is found that gases at low pressures fulfill the relationship $pv^n = C$, where n and c are constants. If n is taken as 1.3. determine the work done by the air in

a piston cylinder arrangement when it expands from $0.05m^3$ and 4bar to a final pressure of 1bar, in kNm. Also prove the formula you have used.

Given : $pv^n = C$, $v_1 = 0.05m^3$, $p_1 = 4bar$, $p_2 = 1bar$,

$n = 1.3$

$p_1v_1^{1.3} = p_2v_2^{1.3}$

$v_2 = (p_1/p_2)^{1.3} \text{ x } v_1$

$= 0.05(4/1)^{1.3} = 0.14m^3$

Work done by the gas and derivation of formula

$w = {}^{v2}\int_{v1} pdv$

$pv^n = p_1v_1^n = p_2v_2^n$

$p = p_1v_1 / v^n$

$w = {}^{v2}\int_{v1} p_1v_1 / v^n$

$= p_1v_1^n \; {}^{v2}\int_{v1} 1/v^n dv$

$= p_1v_1^n \; [v^{-n+1} / -n+1]^{v2}_{v1}$

$= p_1v_1^n / 1\text{-}n \; [v_2^{1-n} - v_1^{1-n}]$

$$= \frac{p_2v_2 - p_1v_1}{1-n} = \frac{p_1v_1 - p_2v_2}{n-1}$$

$$= \frac{(4 \text{ x } 0.005 - 1 \text{ x } 0.145)\ 100}{1.3-1}$$

= 18.3 kNm.

10. Determine the ratio of work done during a quasi-static adiabatic process to that done during an isothermal process when the pressure ratio is 6. The system contains an ideal gas which behaves as a simple substance, and the specific heat ratio is 1.67. Also prove the formula you have used.

Given : $p_1/p_2 = 6$; $n = C_p/C_v = 1.67$

Work done

Adiabatic process

$$w = \int_{v1}^{v2} p_1v_1^n / v^n \ dv.$$

$$= p_1v_1 \ [\ v^{-n+1}/ n+1 \ ]_{v1}^{v2}$$

$$= \frac{p_1v_1^n \ [\ v_2^{1-n} - v_1^{1-n}\ ]}{1-n}$$

$$w_1 = \frac{p_1v_1 - p_2v_2}{n-1}$$

$$= \frac{p_1v_1}{1.67-1} \left[1- (1/6)^{0.67/\ 1.6} \right]$$

$$w_1 = 0.765\ p_1v_1$$

Isothermal process

$$w = p_1v_1^n \int_{v1}^{v2} dv/v.$$

$$= p_1v_1 \ln(\ v_2/v_1\ )$$

$$= p_1v_1 \ln(\ p_1/p_2\ )$$

$$= p_1v_1 \ln 6$$

$$= 1.79\ p_1v_1$$

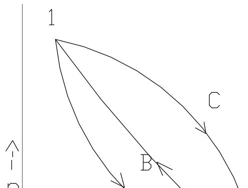
$$\frac{w_1}{w_2} = \frac{0.765\cancel{p_1v_1}}{1.79\cancel{p_1v_1}} = 0.427$$

Internal Energy as Property

Internal energy is the energy stored within the body itself.

Consider a system executes a cycle by following the path a from state 1 to state 2 and the path b from state 2 to 1.

$$Qa = \Delta Ea + Wa$$



For path B $Q_b = \Delta E_b + W_b$

As per the first law of thermodynamics

$$(\sum w)_{cy} = (\sum Q)_{cy}$$

$$W_a + W_b = Q_a + Q_b$$

$$Q_a - Q_b = W_b - Q_b$$

$$\Delta E_a + W_a - W_a = W_b - \Delta W_b - W_b$$

$$\Delta E_a = -\Delta E_b$$

Similarly considering the path b & c

$$\Delta E_b = \Delta E_c.$$

Hence it is proved that the change in energy between two states of a is same irrespective of the path of the system it follows.

Energy has a definite value at each state of the system. Hence it is a property of the system.

Internal Energy is a function of temperature only.

Enthalpy

It is the sum of internal energy and the flow work.

$$h = u+pv$$

It is heat transfer during constant pressure process

$$dQ = dE+W$$

$= du+pdv$

At constant pressure

$pdv = d(pv)$

$(dQ)p = du+ d(pu)$

$= d(u+ pu)$

$(dQ) p = dh.$

For ideal gas $dh = Cp(T_2-T_2)$

It is a property of a system.

For ideal gas it is a function of temperature only.

Specific heat at constant pressure.

It is defined as the rate of change of enthalpy with respect to temperature when pressure is constant.

$Cp = (dh/dT)_p$

For ideal gas

$(dh)_p = {}^{T2}\int_{T2} Cp\, dT.$

From the I law of thermodynamics

$dQ = du + pdv$

$h = u +pv$

$dh = du + pdv + vdp$

$$dh = dQ + vdp$$

so, $$dQ = dh - vdp$$

$$(dQ)_p = dh$$

$$(Q_p) = B\ (\Delta h)_p$$

$$Qp = {}^{T2}\int_{T1} Cp\ dT.$$

Cp is the property of the systm.

Specific Heat at constant Volume

It is defined as the rate of change of specific internal energy with respect to temperature when the volume is constant.

$$Cv = (du/dT)_v$$

For ideal gas

$$du = {}^{T2}\int_{T1} CvdT.$$

From the I Law of thermodynamics

$$dQ = du + pdv$$

$$(dQ)_v = du$$

$$(dQ)_v = {}^{T2}\int_{T1} CvdT$$

Cv is the property of the system.

Problems

1. Air at 0.8bat and 20°C, enters a compressor of a jet plane with a velocity of 200m/s and leaves the compressor at a pressure of 3.2bar, a temperature of 200°C and velocity of 250m/s. The cross-sectional area of the inlet to the compressor is 0.18m^2. Determine the power required to derive the compressor if the process adiabatic.

Given : $p_1 = 0.8$bar, $T_1 = 20°C = 293K$, $V_1 = 200m/s$

$p_2 = 3.2$bar, $T_2 = 200°C= 473K$, $V_2 = 250m/s$

$A_1 = 0.08m^2$. Power =?

$p_1v_1 = RT_1$

$$v_1 = \frac{RT_1}{p_1} = \frac{287x293}{0.85x10^5} = 1.05m^3kg.$$

Mass flow rate

$$m = \frac{A1V_1}{v_1} = \frac{0.08x200}{1.05} = 15.238 \text{ kg/s.}$$

$p_2v_2 = RT_2$

$$v_2 = \frac{RT_2}{p_2} = \frac{287x473}{3.25x10^5} = 0.424m^3/kg.$$

Applying S.F.E.E to find power.

$$m\,(h_1 + v_1^2/2 + z_1g) + dQ/dt = m\,(h_2 + v_2^2/2 + z_2g) + dw/dt$$

$$m\,(u_1 + p_1v_1 + V_1^2/2 + z_1g) = m\,(u_2 + p_2v_2 + V_2^2/2 + z_2g) + dw/dt$$

$$\frac{dw}{dt} = m\,[\,u_1 + p_1v_1 – u_2 - p_2v_2 + \frac{(V_1^2 – V_2^2)}{2}\,x10^{-3}\,]$$

$$= 15.238\,[\,0.718(293-473)+(0.8x100x1.05) – (3.2x100x0.424) + (200^2-50^2)/2\ x10^{-3}\,]$$

Power $dw/dt = -192.17kW$.

2. A closed system undergoes an application adiabatic process during which 90kJ are transferred from the surroundings to the system and the internal energy change by 200J/kg. Find the mass of fluid in the system.

Given : $dQ = 0$, $dw = -90kJ$. $du = 20\ kJ/kg$.

By I law of Thermodynamics

$dQ = du + w$

$du = -w/m°$

$m = 90/20 = 4.5\ kg$.

3. Steam flows through a turbine the rate of 4000kJ/kg. With inlet and outlet enthalpy values of 2800 and 2100kJ/kg respectively. Inlet and outlet velocities are 20 and 300m/s, respectively. Heat loss to the surroundings amounts to 300000 kJ/hr. Calculate the power outlet.

Given : $Q/m = 4000kJ/kg$, $h_1 = 2800kJ/kg$ $h_2 = 2100kJ/kg$

$V_1 = 20m/s$, $V_2 = 300m/s$, $Q/s = 300000kJ/hr.=83.33kj/s$

Mass $m = 83.33 / 4000 = 0.021kg/s$.

Applying Continuity equation

$$m\ (h_1 + V_1^2/2 + z_1g) + dQ/dt = m\ (h_2 + V_2^2/2 + z_2g) + dw/dt$$

$$dw/dt = m[\ (h_1-h_2) + (V_1^2-V_2^2)/2\ x10^{-3}\ ] + dQ/dt$$

$$= 0.21\ [\ (2800-2100) + (20^2-300^2)x10^{-3}\ ] – 83.33$$

$$= -69.6kW.$$

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – II– Engineering Thermodynamics – SMEA1302

II. Second Law of Thermodynamics and Entropy

Distinction between Heat and Work

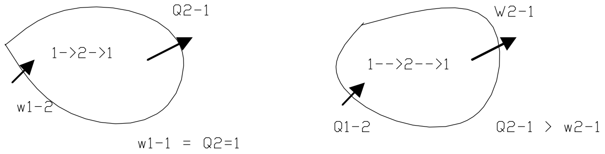


Figure 2.1

The complete conversion of heat into work is impossible.

Heat Engine Cycle

A heat engine cycle is a thermodynamic cycle in which there is a net heat transfer to the system and a net work transfer from the system. Here the heat engine is the system.

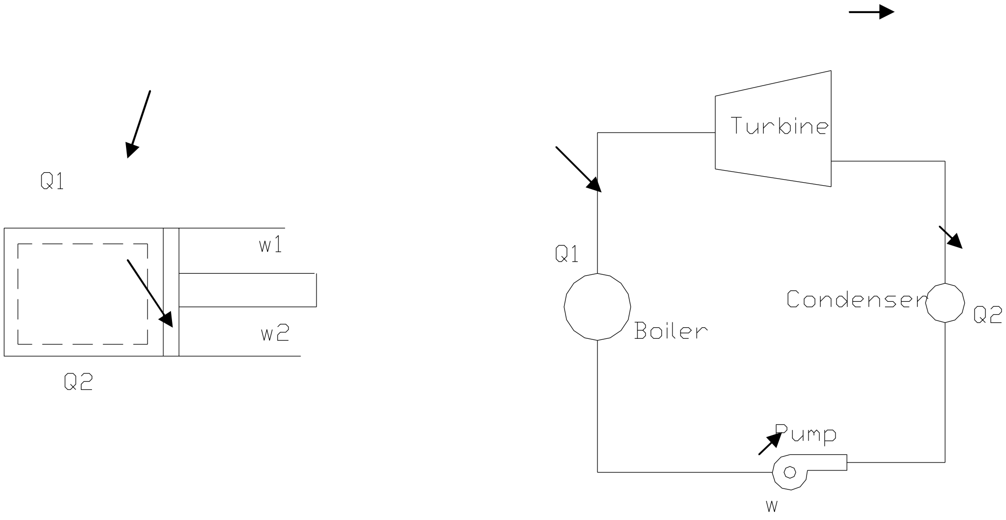


Figure 2.2

Consider,

$Q_1 \rightarrow$ heat transfer to the engine

$w_1 \rightarrow$ work done by the system

$Q_2 \rightarrow$ heat transfer from the system

$W_2 \rightarrow$ work done on the system.

Net heat transfer

$$Q_{net} = Q_1 - Q_2$$

Net work transfer

$$W_{net} = w_1 - w_2$$

As per I law of Thermodynamics

$$\int dQ = \int dw$$

$$Q_{net} = w_{net}$$

$$Q_1 - Q_2 = w_1 - w_2$$

Efficiency of engine

$$\eta = \frac{\text{Net workdone of the engine}}{\text{Total heat input to the cylce}}$$

$$= w_{net}/Q_1$$

$$= \frac{w_1 - w_2}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

Kelvin-Planck Statement of Second Law

It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

Efficiency $\eta = w_{net}/Q_1$

η is always less than unity because heat transfer to the system cannot be completely converted into work transfer.

So, η ≠ 100%. There is always heat rejection.

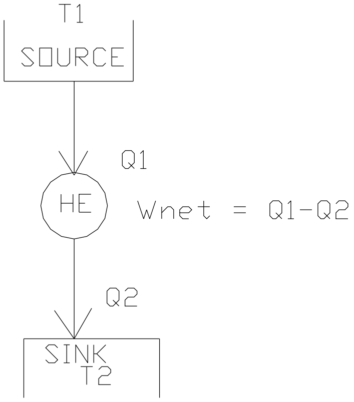


Figure 2.3

The thermal energy reservoir from which heat is transferred to the system is called source.

The thermal energy reservoir to which heat is rejected from the system is called sink.

To produce net work, heat engine has to exchange heat with two reservoir.

Perpetual Motion Machine of second kind

Heat engine which will produce net work in a complete cycle by exchanging heat with only one reservoir is called PMMK. It violates Kelvin-Plank statement.

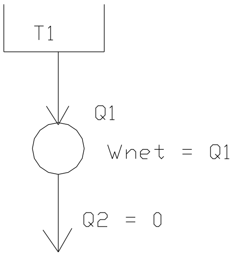


Figure 2.4

Clasius Statement

It is impossible to construct a device which, operating in a cycle, will produce no effect other than the transfer of heat from a cooler to a hotter body.

Refrigerator

Refrigeration is the process of maintaining the temperature of a body below that of its surroundings.

The working fluid used for this purpose is called Refrigerant the equipment used is called Refrigerator.

The refrigerant is compressed to high pressure and high temperature in the compressor and it gets cooled in the condenser at constant pressure.

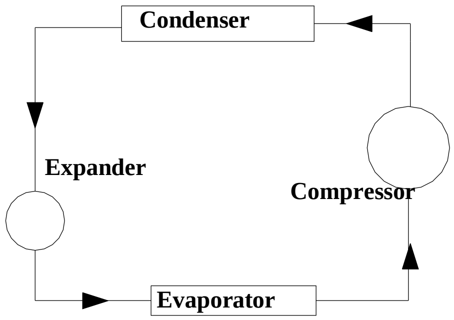


Figure 2.5

The high pressure refrigerant vapour is expanded in the expander and the required quantity of refrigerant evaporates in the evaporator by absorbing heat from the space to be cooled and the cycle is repeated.

Co-efficient of Performance (C.O.P)

Co-efficient of performance

$$= \frac{\text{Refrigeration Effect}}{\textbf{Workdone}} = \frac{Q_2}{\mathbf{w}}$$

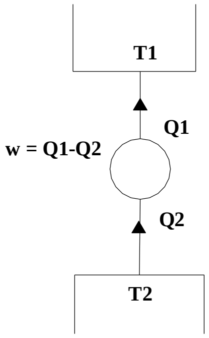


Figure 2.6

$$\text{COP} = \frac{Q_2}{Q_1 - Q_2}$$

COP is always greater than Unity.

Heat Pump

Heat pump is a device which maintains temperature of a body greater that of its surroundings.

$$\text{COP} = \frac{Q_1}{W}$$

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

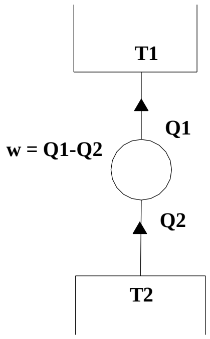


Figure 2.7

$$(\text{COP})_{H.P} = (\text{COP})_{ref} + 1$$

Thermal Energy Reservoir (TER)

It is a large body of infinite heat capacity capable of absorbing or rejecting an unlimited quantity of heat without suffering appreciable changes in its thermodynamics coordinates.

Mechanical Energy Reservoir (MER)

It is a large body enclosed by an adiabatic impermeable wall capable storing work as potential energy or kinetic energy.

Reversibility

A reversible process is one which performed in a manner that at the conclusion of the process, the system and surroundings are return to their initial states without producing any change in the rest of the universe.

It is an ideal process.

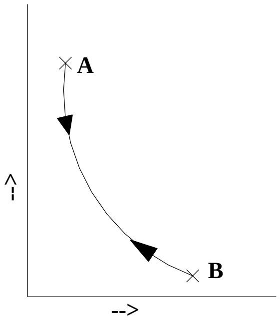


Figure 2.8

Irreversibility

A irreversible process is one which is preformed in a manner that at the conclusion of the process, the system and surroundings are not return back to their initial states.

Causes. 1) lack of equilibrium

2) Dissipative effects.

Carnot Cycle

It Is a reversible cycle. Hence it is ideal only. It consists of two isentropic process and two isothermal p

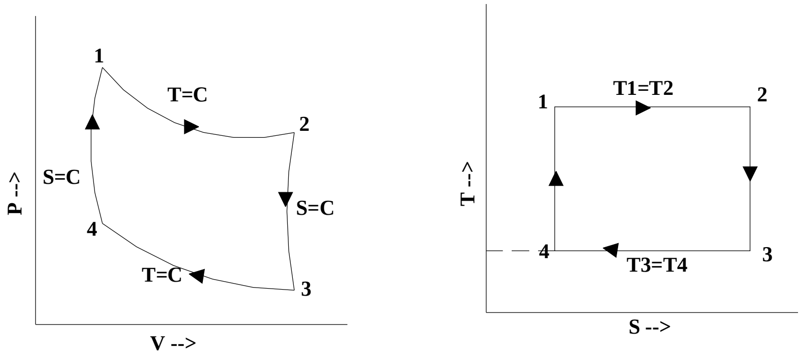


Figure 2.9

1-2→ Reversible isothermal process

consider a cylinder is made to contact with a diathermic cover. Hence Q_1 enters the system at $T_{1.}$

$$Q = u_2-u_1 + w_{1-2}$$

2-3 → Isentropic process.

Diathermic cover is replaced by an adiabatic cover,

Hence $Q_1 = 0$

$$0 = u_3-u_2 + w_{2-3}$$

3-4 → Reversible isothermal process

Diathermic cover is placed in place of adiabatic cover. Hence Q_2 is rejected from the system.

$$-Q = u_4-u_3 - w_{3-4}$$

4-1 → Isentropic process

Adiabatic cover is placed in place of diathermic cover.

$$0 = u_1-u_4- w_{4-1}$$

By adding all the equations, we get

$$Q_1-Q_2 = u_2-u_1 + w_{1-2} + u_3-u_2 + w_{2-3} + u_4-u_3 - w_{3-4} + u_1-u_4- w_{4-1}.$$

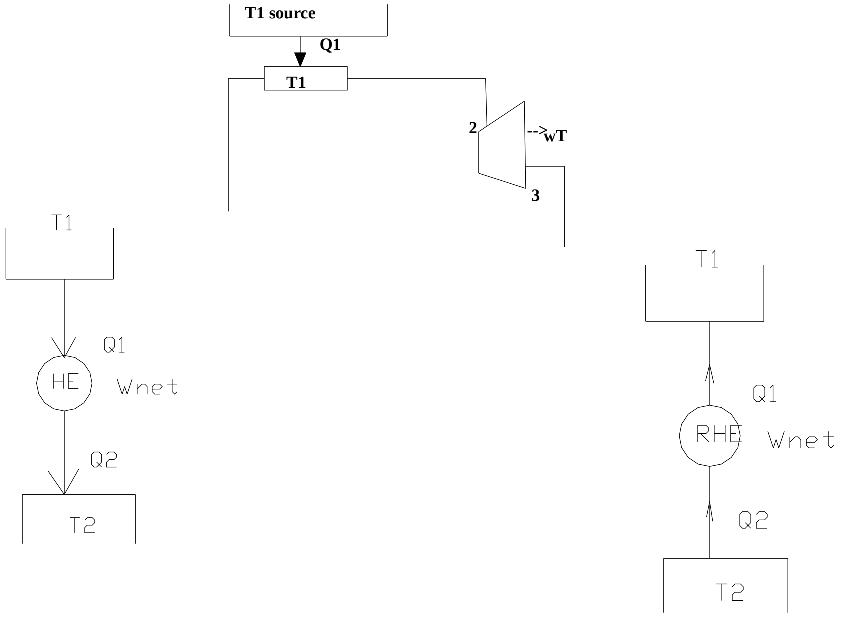
$$Q_1-Q_2 = (w_{1-2}+ w_{2-3}) - (w_{3-4} - w_{4-1})$$

$$\text{ie.} \qquad \sum_{cy} Q_n = \sum_{cy} w_n$$

Carnot Heat Engine

A cycle heat engine operating on Carnot cycle is called Carnot heat engine.

Flow diagram of Carnot cycle



Carnot heat engine Reversed Carnot heat engine.

Figure 2.10

Carnot's Theorem

All heat engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.

Proof:-

Consider $(H.E)_A$ and $(H.E)_B$ are the heat engines operating between T_1 and T_2.

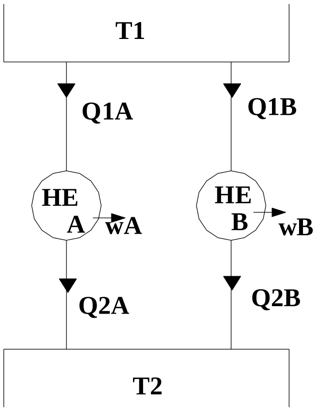


Figure 2.11

Consider $(HE)_A$ as any heat engine and $(HE)_B$ as reversible heat engine. For a reversible the efficiency should be high ie.$\eta_A > \eta_B$. For proof assume $\eta_A < \eta_B$ forsame heat absorption

ie. $Q_{1A} = Q_{1B}$.

$$\eta_A > \eta_B$$

$$\frac{w_A}{Q_{1A}} > \frac{w_B}{Q_{1B}}$$

$$w_B < w_A$$

Now assume $(HE)_B$ be reversed. Hence through the magnitudes remain same, the directions are changed.

$w_A > w_B$: Remaining part of w_n is used to drive the reversed $(HE)_B$

Where, $Q_{1A} = Q_{2B}$

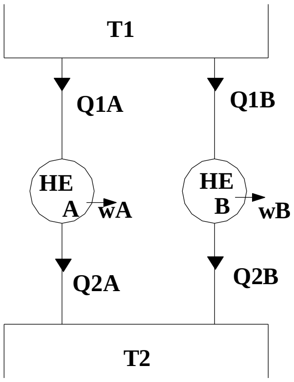


Figure 2.12

Since $Q_{1A} = Q_{2B}$, the source maybe be eliminated

It violates the Kelvin-planck

statement. Hence it is impossible.

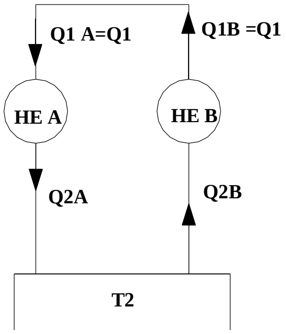


Figure 2.13

$\eta_B > \eta_A$

Hence the proof.

$$_{Rev} = \eta_{max} = \frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1} = \frac{w}{Q_1}$$

For a reversible refrigerator

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$

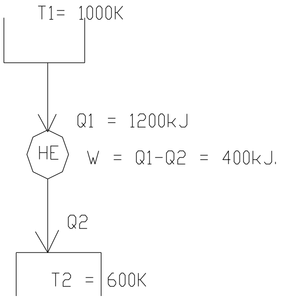
$$(COP)_{ref} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2} \qquad (COP)_{HP} = \frac{Q_1}{Q_1 - Q_2} = \frac{T_1}{T_1 - T_2}$$

Problems.

1. An inventor claims that an engine opening between 1000k and 600K develops 400kJ work while 1200kJ are transferred during heat addition. Prove that the engine is irreversible.

Given : $T_1 = 1000K$, $T_2 = 600K$, $w = 400kJ$, $Q_1 = 1200kJ$.

For a reversible heat engine



$$\frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1}$$

$$\frac{400}{1200} = 0.33 \;,. \quad \frac{T_1 - T_2}{T_1} = \frac{1000-600}{1000} = 0.4$$

Here,

$$\eta = \frac{Q_1 - Q_2}{} \neq \frac{T_1 - T_2}{}$$

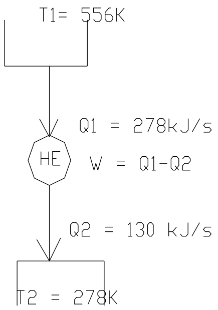
Q_1 T_1

Hence the engine is irreversible.

2. A heat engine is supplied with 278kJ/s of heat constant fixed temperature of 283°C. 130kJ/s of heat is rejected to a sink at temperature of 5°C. Identify whether the cycle is reversible or irreversible or impossible one.

Given : $Q_1 = 278kJ/s$, $Q_2 = 130kJ/s$, $T_1 = 283°c$,

$T_2 = 5°C$.

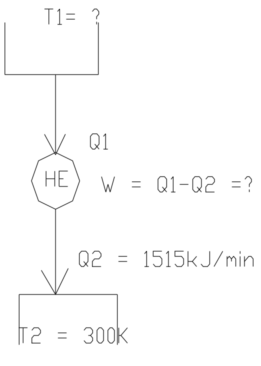


$$\eta_A = \frac{Q_1-Q_2}{Q_1} = \frac{278-130}{278} = 53.24\%$$

$$\eta_B = \frac{T_1-T_2}{T_1} = \frac{556-278}{556} = 50\%$$

Hence it is a irreversible engine.

3. The efficiency of a carnot engine discharging to a cooling pond at 27°C is 40%. If the cooling pond receives 1515kJ/min. What is the temperature of source and power rating of the engine.



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

$$0.4 = T_1\text{-}300 \Rightarrow T_1 = 500K.$$

$$\eta = \frac{Q_1-Q_2}{Q_1} = \frac{w}{Q_1}$$

$$0.4 = \frac{Q_1-1515}{Q_1} \Rightarrow Q_1 = 2625kJ/min.$$

Temperature of Source T_1 = 500K.

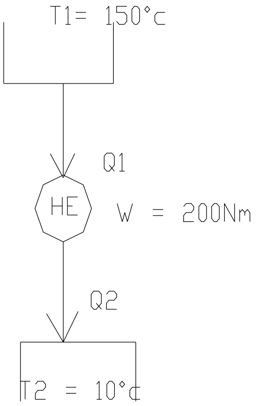
Power rating of the engine $w = Q_1 - Q_2$

$$= \frac{2625-1515}{60} = 18.5\text{kw.}$$

4. (i) A reversible heat engine operates between systems at constant temperature of 150°C and 10°C. Evaluate the efficiency of the engine. (ii) The work output from the engine is 2000Nm. Evaluate the heat transfer from the system at 150°C and the heat rejected to the system at 10°C. (iii) The above engine is reversed and operates as a heat pump between the same system. Evaluate the power input required when the heat transfer rate from the system at 10°C is 40kJ.

(i) For a reversible heat engine.

$$\eta_{H.E} = 1 - \frac{T_2}{T_1} = 1- \frac{283}{423} = 33\%.$$



(ii) $$\eta_{H.E} = \frac{w}{Q_1} = 0.33 \Rightarrow Q_1 = \frac{2000}{0.33} = 6060.6\text{Nm.}$$

Heat transfer from the system at 150°C

Q_1 = 6060.6Nm.

Heat rejected to the system at 10°C

$$Q_2 = Q_1 - w = 6060.6-2000 = 4060.6\text{Nm.}$$

(iii) operates as a heat pump.

$$(COP)_{H.P} = \frac{T_1}{T_1-T_2} = \frac{423}{423-203} = 3.02.$$

$$(COP)_{H.P} = \frac{Q_1}{}$$

Q_1-Q_2

$3.02 = \frac{Q_1}{Q_1-40}$ => $Q_1 = 59.8$kw.

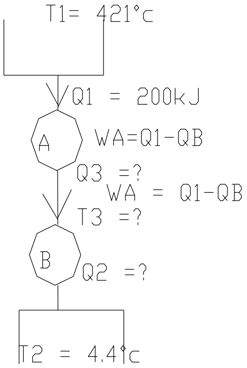
Power i/p to the system $w = Q_1-Q_2$

$= 59.8-40 = 19.8$kW.

5. Two reversible heat engine A and B are arranged in series. A rejecting heat directly to B. Engine A receives 200kJ at temperature of 421°C. From a hot source while engine B is in communication, with a cold sink at temperature of 4.4 °C. If the work output of A is twice that of B. Find(i) the intermediate temperature between A and B (ii) the η of each engine and (iii) heat rejected to cold sink.

Given : $T_1 = 421°C$, $Q_1 = 200kJ$. $T_2 = 4.4°C$. $w_a = 2W_b$

Work done of engine A



$W_A = Q_1-Q_3 = 2(Q_3-Q_2)$

ie. $3Q_3-2Q_2 = Q_1 = 200$

For reversible engine

$T_1-T_3 = 2(T_3-T_2)$

$3T_3-2T_2 = T_1$

$3T_3-2(4.4) = 421$

(i) $\Rightarrow T_3 = 143.26°C$

(ii) Efficiency of engine 'A'

$$\eta_a = \frac{T_1-T_3}{T_1} = \frac{694-426.26}{694} = 0.4 = \frac{Q_1-Q_3}{Q_1}$$

=> $Q_1-0.4Q_1 = Q_3$ => $0.6x200 = 120kJ$.

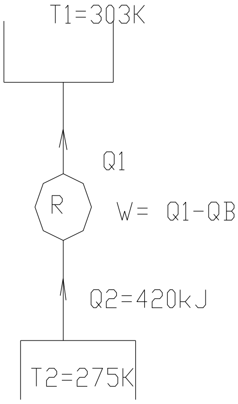
Efficiency of engine “B”

$$\eta_B = \frac{T_3-T_2}{T_3} = \frac{416.26-277.4}{416.26} = 0.335 = \frac{Q_3-Q_2}{Q_3}$$

$$\frac{120-Q_2}{120} = 0.335$$

(iii) $Q_2 = 79.8$kJ.

6. A house hold refrigerator is maintained at a temperature of 2°c. Every time the door is opened, warm material is placed inside, introducing an average of 420kJ. But making only a small change in the temperature of the refrigerator. The door is opened 20 times a day, and the refrigerator operates at 15%of ideal COP. The cost of work is 32 paise per kWhr. What is the monthly bill for this refrigerator? The atmosphere is at 30°C.



Given : T_1 =303K. T_2 = 275K. Q_2 = 420kJ.

$$(\text{COP})_{id} = \frac{T_2}{T_1-T_2} = \frac{275}{303-275} = 9.82$$

$(\text{COP})_{AC}$ = 0.15 x (COP)id

= 1.47.

$$(\text{COP})_{AC} = \frac{Q_2}{Q_1-Q_2}$$

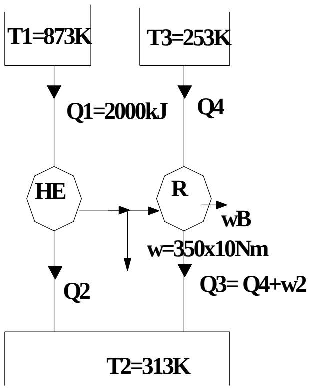
$$1.47 = \frac{420}{Q_1-Q_2} \Rightarrow Q_1-Q_2 = 285.7\text{kJ}.$$

Cost of work is 32 paise per kWhr.

The monthly bill for the refrigerator

$$= \frac{285.7x0.32x20x30}{3600} = \text{Rs. } 15.23/-$$

7. A reversible heat engine operates between two systems at constant temperatures of 600°C and 40° c. The engine drives a reversible refrigerator which operates between systems of constant temperatures of 40°C and -20°C. The heat transfer to the heat engine is 2000kJ and the net work output of the combined engine –refrigerator plant is 350x10^{3}Nm. Evaluate the heat transfer to the refrigerant and the net heat transfer to the system at 40°C. If the efficiency of the engine and the co-efficient of performance of the refrigerator are each 40% of their maximum possible values. What would be the heat transfer to the refrigerant and the net heat transfer to the system at 40°C?



The maximum efficiency of the reversible heat engine cycle is given by

$$\eta_{max} = 1-\frac{T_2}{T_1} = 1-\frac{313}{873} = 0.642$$

Also $\eta_{max} = w_1 / Q_1 \Rightarrow w_1 = Q_1 x \, \eta_{max} = 2000 \times 0.642 = 1284$

The maximum Cop of the refrigerator is given by

$$(Cop)_{max\ ref} = \frac{T_3}{T_2 - T_3} = \frac{253}{313-253} = 4.22$$

For a reversible refrigerator,

$$(Cop)_{max} = \frac{Q_4}{w_1} = 4.22.$$

work output of combined cycle $w = w_1 - w_2 = 350kJ.$

$w_2 = 1284-350 = 934kJ.$

$Q_4 = W_2 \, x \, (Cop)_{max} = 934 \times 4.22 = 3941.48kJ.$

$Q_3 = Q_4 + w_2 = 3941.48 + 934 = 4875.48kJ.$

$Q_2 = Q_{1\text{-}}w_1 = 2000 - 1284 = 716kJ.$

Heat rejection to the sink at 40°C.

$= Q_{2\,+\,Q}3 = 716 + 4875.48 = 5591.48kJ.$

Now, the η_{AC} of heat engine cycle,

$\eta = 40\% \, \eta_{max} = 0.2568.$

$w_1 = \eta Q_1 = 0.256 \times 2000 = 573.6Kj.$

power i/p to the refrigerator

$w_2 = w_1 - w = 513.6 – 350 = 163.6$kJ.

Actual COP of refrigerator

$(COP)_{AC} = Q_4 / W_2 = 40\% \ (COP)_{max}$

$= 0.4 \times 4.22 = 1.69$

$Q_4 = w_2 \times (COP)_{AC} = 1.69 \times 163.6 = 276.48$kJ.

$Q_3 = Q_4 + w_2 = 276.48 + 163.6 = 440.08$kJ.

Now, $Q_2 = Q_1 - w_1 = 2000 – 573.6 = 1486.4$kJ.

Heat rejected to the sink at 40°C.

$= Q_2 + Q_3 = 1486.4 + 440.08$

$= 1926.48$kJ.

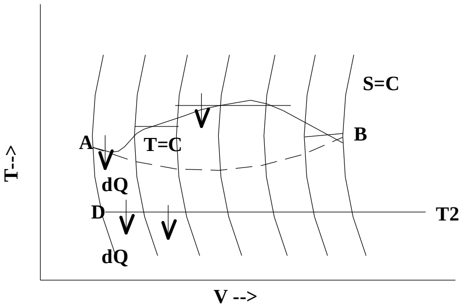
ENTROPY

Tropee means “Transformation” it is a Greek word

Entropy is an extensive property of a system.

It is unit is J/K.

The inequality of clauius



Consider AB a reversible (or) irreversible process.

Let BC, CD & DA are reversible process.

Divide the cycle into infinitesimal elementary cycles.

$$\eta = 1 - \frac{dQ_2}{dQ}$$

where, dQ→ heat supplied at T

dQ_2→ heat rejected at T_2.

The efficiency of a cycle will be less than or equal to the efficiency of reversible process.

I (ie) $\left(1 - \frac{dQ_2}{dQ}\right) \leq \left(1 - \frac{dQ_2}{dQ}\right)_{rev}$

$$\frac{dQ_2}{dQ} \geq \frac{(dQ_2)_{rev}}{dQ}$$

$$\frac{dQ_2}{dQ_2} \leq \frac{(dQ)_{rev}}{dQ_2}$$

W.K.T

$$\frac{(dQ)_{rev}}{dQ_2} = \frac{T}{T_2}$$

$$\frac{(dQ)_{rev}}{dQ_2} \leq \frac{T}{T_2}$$

(or) $\frac{dQ}{T} \leq \frac{dQ_2}{T_2}$

For reversible process

$$Ds = \frac{dQ\ rev}{T} > \frac{dQ_2}{T_2}$$

For any process AB

$$\frac{dQ}{T} \leq ds$$

For any cycle $\int dQ/T \leq \int ds$.

Since Entropy is a property and cyclic integral of any property is zero.

$\int dQ/T \leq 0$.

This Equation is called inequality of Clausius.

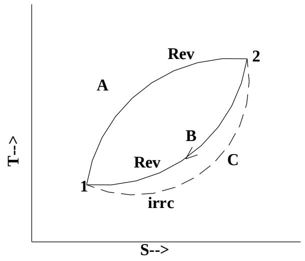
Case(i)

$\int dQ/T = 0$ (Reversible)

$\int dQ/T < 0$ (Irreversible)

$\int Dq/T > 0$ (In possible)

Principle of Increase of Entropy.



Consider A,B are reversible and C as irreversible process.

For a reversible cycle A & B

$$\int_R dQ/T = {}^{2}\int_{A1} dQ/T + {}^{1}\int_{B1} dQ/T = 0$$

$${}^{2}\int_{A1} dQ/T = - {}^{1}\int_{B1} dQ/T$$

For irreversible process A & C

$$\int dQ/T = {}^{2}\int_{A1} dQ/T + {}^{1}\int_{C2} dQ/T < 0$$

$$- {}^{1}\int_{B2} dQ/T + {}^{1}\int_{C2} dQ/T < 0$$

$${}^{1}\int_{B2} dQ/T > {}^{1}\int_{C2} dQ/T$$

Where,

Path B is reversible

$${}^{1}\int_{B2} dQ/T = {}^{1}\int_{C2} ds.$$

Since, entropy is a property, the change in entropy for paths B&C is same.

$${}^{1}\int_{B2} ds = {}^{1}\int_{C2} ds.$$

$${}^{1}\int_{B2} ds > {}^{1}\int_{C2} dQ/T$$

For any irreversible process

$ds > dQ/T$

For reversible process

$ds = dQ_{rev} / T$

In general,

$ds \geq dQ/T$

ie. $S_2 - S_1 \geq {}^2\int_1 dQ/T$

When the system is isolated from its surroundings $dQ = 0$

ie. $ds_{iso} \geq 0$

For a reversible process $dS_{ir} = 0$. ie. $S = C$

For an irreversible process $dS_{iso} > 0$

From this it is known than entropy of an isolated system can never decreases, S= constant, when the process is reversible and increases when the process is irreversible.

This known as principle of increase of entropy.

$dS_{univ} \geq 0$

$dS_{sys} + dS_{surr} \geq 0$

Entropy of an isolated system may decrease at same region but there is a increase if entropy at the remaining part of the system .

The entropy of universe increases by the thermodynamic process namely irreversible adiabatic.

Problem.

1. A Fluid undergoes a reversible adiabatic compression from 0.5Mpa, $0.2m^3$ according to the law, $PV^{n3} = C$. Determine the change in Enthalpy, internal energy and entropy and the heat transfer and work transfer during the process.

Given : $P_1 = 0.5$Mpa, $V_1 = 0.2m^3$, $V_2 = 0.05m^3$, $P_1V_1^n = P_2V_2^n$ $n = 1.3$

$P_2 = P_1 (V_1 / V_2)^n$

$= 0.5 (0.2/0.05)^{1.3}$

$= 3.0305$ MPa,

Change in Enthalpy,

$$H_2 - H_1 = \frac{n}{n-1}\left[P_1V_1 \quad - P_2V_2\right]$$

$$= \frac{1.3}{0.3}\left[\ 3.0305 \times 0.05 - 500 \times 0.2\right]$$

$$= 2233\text{kJ.}$$

Change in internal energy

$$u_2 - u_1 = (H_2 - H_1) - (P_2V_2 - P_1V_1)$$

$$= 223.3 \quad - \quad (57-53)$$

$$= 171.77\text{kJ.}$$

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – III– Engineering Thermodynamics – SMEA1302

III. Properties of Pure Substances

FORMATION OF STEAM:-

Consider water of 1 kg mass at 25’c is heated in a piston cylinder assembly at atmospheric pressure.

Water is heated till its temperature reaches 100’c. Volume of water increases due to expansion. At this stage, water is converted into vapour.

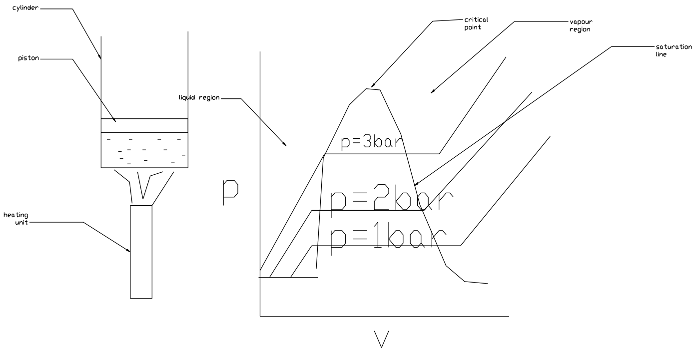

Figure 3.1

Saturation temperature:

The temperature at which vaporization takes place at a given pressure is called the saturation temperature. The given pressure is called the saturation pressure.

Sub cooled (or) compressed liquid.

A liquid is said to be sub cooled when the temperature of liquid on cooling becomes lower than the saturation temperature for the given pressure.

Superheated vapour:-

Vapour is called super heated when the temperature increases above the saturation temperature.

The temperature at this state is called super heated temperature.

Degree of super heat.

The difference between super heated temperature and saturation temperature at given pressure is called degree of super heat.

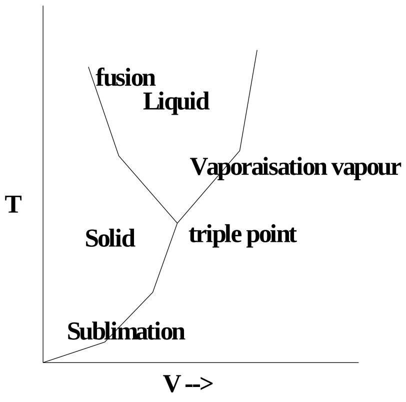

Figure 3.2

Triple point:

The state at which solid, liquid and vapour phases co-exist in equilibrium.

Critical point:-

The point at which latent heat is zero is called critical point.

Steam:

It is the water in vapour form . It is used as a working substance in steam engines and steam turbines.

Wet steam:-

Steam containing moisture is called wet steam.

Dry saturated steam:

Steam does not containing any water particles in suspension is called Dry saturated steam.

Super heated steam:

The steam produced by increasing the temperature of dry steam at constant pressure is called superheated steam.

Dryness fraction or quality.

It is the ratio of mass of dry steam to the mass of wet steam.

It is denoted by 'x'

$$x = m_g / (m_f + m_g)$$

where

m_g = mass of dry steam

m_f = mass of water in suspension.

Steam tables:-

The table which shows the properties of the steam at various conditions is called stem table.

Various thermodynamics processes:

1. Isochoric or reversible constant volume process

from the law of thermodynamics.

$dq = du + pdv$

$v = c,$

$dv = 0$

$dq = du$

Heat transfer $q_{1-2} = (u_2 - u_1)$ kj/kg

work done $w_{1-2} = \int pdv = 0$ (since volume is constant)

for perfect gas $q_{1-2} = c_V (T_2 - T_1)$ kj/kg

$s_2 - s_1 = \int dQ/t$

$= C_V l_n (T_2/T_1)$ kJ/kgK.

2.Isobaric or reversible constant pressure process

Heat transfer

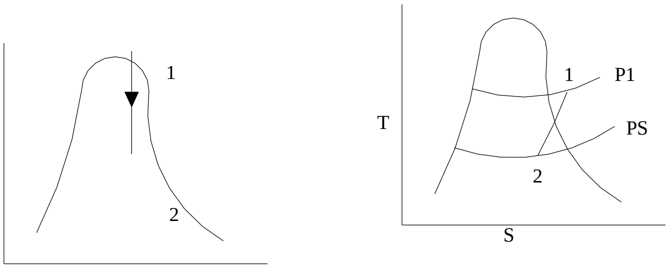

Figure 3.3

$q_{1-2} = (h_2 - h_1)$ kj/kg

Work transfer

$W_{1-2} = P(V_2 - V_1)$ kj/kg

Change in entropy $\Delta s = (S_2 - S_1)$ Kj/kgk

For a perfect gas,

$q_{1-2} = C_p(T_2 - T_1)$ kj/kg

$W_{1-2} = R(T_2 - T_1)$ kj/kg

$\Delta s = C_p l_n (T_2 / T_1)$ kj/kgK

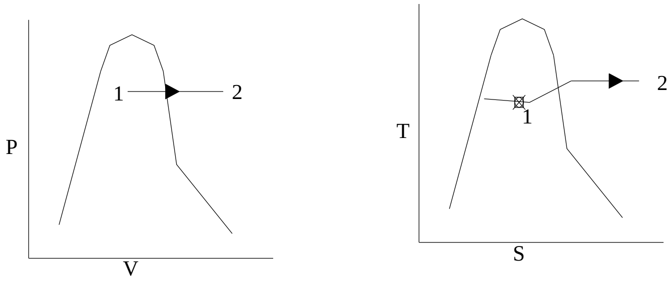

Figure 3.4

When heat is added to the System, to keep the temperature constant there should be some amount of work done by the system. When work is done on the system, to keep the temperature constant, there should be some amount of heat rejected by the system. $q_{1-2} = (u_2-u_1) + W_{1-2}$

$$= (u_2-u_1) + P_1V_1 l_n P_1/P_2$$

For the perfect gas,

$$q_{1-2} = W_{1-2}$$

$$= P_1V_1 l_n P_1/P_2 \text{ kJ/kg (since du=0)}$$

change in Entropy $S_2 - S_1 = R\ln P_1/P_2$ kJ/kgK

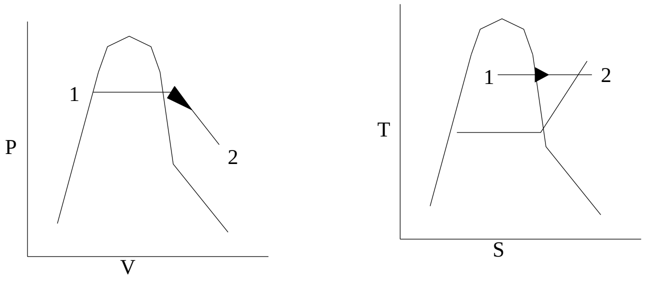

Figure 3.5

3. Reversible hyperbolic process

In this, the pressure multiplied by the volume is constant.

$$q_{1-2} = (u_2-u_1) + P_1V_1 l_n P_1/P_2 \text{kj/kg}$$

$$\Delta s = (S_2 - S_1) \text{ kj/kg k}$$

For the perfect gas, Reversible hyperbolic process is also called as isothermal process.

$q_{1-2} = W_{1-2}$

$= R \ln P_1/ P_2$ KJ/Kg

$S_2-S_1 = R \ln P_1/ P_2$ KJ/KgK

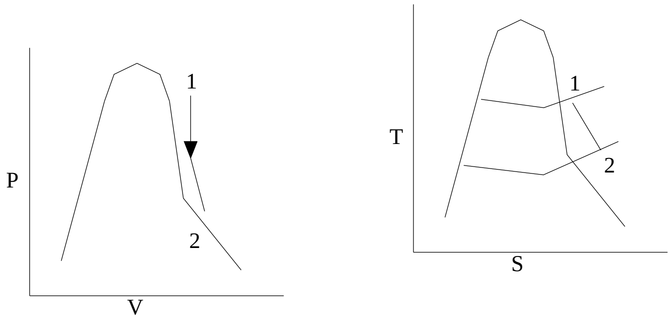

Figure 3.6

4. Reversible poly tropic process

The process which follows the law $pv^n=c$

n = Poly tropic index

Work Transfer $W_{1-2}=p_1v_1- p_2v_2/n-1$ kj/kg

Heat transfer $Q_{1-2} =(u_2-u_1) + p_1v_1- p_2v_2/n-1$ kj/kg

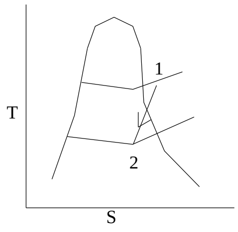

Figure 3.7

Change the entropy $\Delta s = (S_2-S_1)$ kj/kgk

Throttling process

Enthalpy at inlet and outlet are constant

$h_1=h_2$

If steam is the working substance the properties are taken from the steam tables and mollier diagram. If the air is used standared values of c_p, c_v, and R are taken for the solving problems.

1. Steam at 7 bar and 250°C has a volume of 0.5046 m^3 in the frictionless constant volume process the pressure changes to 3.5 bar. Find the final temperature and heat transferred. Also, determine the change in entropy,

Solution :-

p_1 =7 bar

T_1 =250 °C

V_1 =0.5046 m^3

P_2 =3.5 bar

From superheated steam tables at p_1 =7 bar, T_1 =250 °C V_1=0.3364 m^3/kg, u_1=2720 kJ/kg.

At p_2=3.5 bar, from the steam tables,

T_s=138.9 °C

Vg_2=0.5241 m^3/kg

Sf_2=1.727kJ/kg

Sfg_2=5.214kJ/kg

Here $v_2<vg_2$

So the Steam is in wet region.

Dryness fraction at the end.

$x_2 = v_2 / vg_2$ = 0.3364/0.5241 = 0.642.

Internal energy $u_2 = u_{f2} + x_2 u_{fg2}$

= 584 + 0.642 x 2148

= 1963kJ/kg

Heat transfer

$q_{1-2} = (u_2 - u_1)$ kJ/kKg

= 1963 – 2720

= -757kJ/kg

But mass flow rate of steam

m= v_1/vg_1 = 0.5046 / 0.3364 =1.5 Kg

Total heat transfer

Q_{1-2} = m x q_{1-2}

= 1.5 x (-757) = -1135.5kKJ

S_2 = $S_{f2} + x_2 S_{fg2}$

= 1.727 + 0.642 x 5.214

= 5.0744 kJ/kgK

Change in entropy

$\Delta S = S_2 - S_1$ = 5.0744 – 7.106

= - 2.0316 kJ/kgK

2. Steam at pressure of 10 bar and 250^oC in a closed vessle of volume 0.14m^3 is cooled so that pressure falls to 3.5bar. Determine the final temperature and change in entropy. Assume the volume as constant.

Given: P_1 = 10bar T_1 = 250^oC V = 0.14m^3

P_2 = 3.5bar $v_1 = v_2$ = 0.2328 m^3/kg

from superheated steam table at P_1 = 10bar & T_1 = 250^oC

s_1 = 6.926 KJ/kgk

from saturated steam table, At P_2 = 3.5bar

vg_2 = 0.52397 m^3/kg sf_2 = 1.727 Kj/kgk sfg_2 = 5.21 Kj/kgk

T2 = 138.9^oC

Since $v_2 < vg_2$. The steam is in wet region.

Dryness fraction at the end

$x_2 = v_2 / vg_2$ = 0.2328 / 0.52397 = 0.44

$S_2 = sf_2 + x_2\, sfg_2$ = 1.727 + (0.44 x 5.212)

= 4.02 Kj/kgk

Final temperature T_2 = 138.9^oC

Change in entropy $\Delta s = s_2 - s_1$ = 4.02 - 6.926 =-2.906 kJ/kgK

3. 2kg of a gas at a temperature of 17^oC is heated at constant volume to a temperature of 89^oC. The specific heat at constant volume is 0.5150 kJ/kg. Find heat supplied, Change in entropy.

Given T_1 = 17^oC, T_2 = 89^oC, C_v = 0.515 kJ/kgK

Heat transfer Q_{1-2} $= mC_v (T_2 – T_1)$

= 2 X 0.5150 (89-17)

= 79.3 kJ/kg

Change in entropy $\Delta s = mc_v \ln (T_2 / T_1)$

= 2 x 0.575 ln (362/290)

= 0.2284 kJ/K

4. 0.5kg of steam at a pressure of 6.5bar and a quality of 60% is heated at constant pressure until a quality of 100% achieved. Find change in enthalpy, change in internal energy, heat transferred, work transferred and change in entropy.

Given: $m=0.5kg$ $P_1 = 6.5bar$ $x_1=0.6$ $x_2 = 1$

$P_1=p_2$

From saturated steam tables at $P_1=6.5bar = P_2$

$h_{f1} = 683.5$ kJ/kg $h_{fg1} = 2077$ kJ/kg

$u_{f1} = 682.5$ kJ/kg $u_{fg1} = 1888$ kJ/kg

Change in enthalpy

= $h_2 - h_1$

= $hg_2 - (hf_1 + x1\ hf_{g1})$

= 2760.5 - (683.5 + 0.6 x 2077)

= 2760.5 - (683.5 + 0.6 x 2077)

= 830.8 kJ/kg

$H_2 - H_1 = m*\Delta h = 0.5 \text{ x } 830.8 = 415.4$ kJ/K

Change in internal energy

Δu = $m (u_2 - u_1) = m[ug_2 - (uf_1 + x_1\ ufg_1)]$

= 0.5 [2570.5 - (6825 (0.6 x 1888)]

= 377.6 kJ.

Heat transferred = ΔH = 415.4kJ

Work transferred $U_1 - 2$ = $mp(v_2 - v_1)$

= 0.5 x 6.5 x 100 [0.2942 x 0.6 x 0.2942]

= 38.25 kJ

Change in entropy Δs = $m(s_2 - S_1) = m[sg_2 - (sf_1 + x_1\ sfg_1)]$

= 0.5 [6.735 - (1.962 + 0.6 x 4.773)]

= 0.9545 kJ/kgK

5. 0.5kg of steam at 7bar and 200°C is compressed during a reversible non-flow constant pressure process until its volume is halved. Find (i) Work transfer

(ii) Heat transfer (iii) Final condition of steam (iv) Change in internal energy

Given: - m=0.5kg $P_1 = P_2 = 7bar, T_1 = 200^oC$

$v_2 = v_1 / 2$

From superheated steam table, at P_1=7bar, T_1 =200°c $v_1 = 0.2999\ m^3/kg$ h_1=2844 KJ/kgk

$s_1 = 6.886$ kJ/kgK

From saturated steam table at P_2 = 7bar

vg2 = 0.27268 m^3/kg hf_2 = 697.1 kJ/kg

hfg_2 = 2064.9 kJ/kg

sf_2 = 1.992 kJ/kgK

sfg_2 = 4.713 kJ/kgK

Since volume is halved

$v_2 = v_1 / 2 = 0.2999 / 2 = 0.14995\ m^3/kg$

$v_2 < vg_2$ steam is in wet region.

$x_2 = v_g / v_{g2} = 0.14995 / 0.27268 = 0.55$

(i) Work transfer

$w_1 - 2 = m\ P(u_2 - u_1)$

= 0.5 x 700 (0.14995 - 0.2999)

= -52.48 kJ

Heat transfer

Qt2 = $m\ (h_2 – h_1)$

$= \quad m\,(h_{f2} \text{ x } X_2 h_{fg2} – h_1)$

$= \quad 0.5\,[\,697.1 + (0.55 \text{ x } 2064.9) - 2844.2]$

$= \quad -505.7$ kJ

(ii) Final condition of steam $x_2 = 0.55$

(iii) Change in internal energy

$\Delta u = \quad m(u_2 - u_1)$

$= \quad m\,[(h_2 - h_1) - w_{1\text{-}2})]$

$= \quad Q_{1\text{-}2} - w_{1\,-\,2}$

$= \quad -505.7 + 52.48$

$= \quad -453.22$ kJ/K

6. 2kg of gas at a temperature of 20°C undergoes a reversible constant pressure process until the temperature is 100°C.Find the heat transferred during the process. C_p for the gas is 0.6448kj/kgK. C_v =0.515kj/kgk. Find γ& R. Also find work transfer and change in entropy

Given: m=2kg $\quad T_1=20^{O}C \quad T_2=100^{\circ}C \quad C_p=0.6448$ kJ/kgK

Cv = 0.575 kJ/kgK

Heat transfer $Q_{1\text{-}2} = mc_p(T_2 - T_1)$

$= 2 \text{ x } 0.6448\,(100\text{-}20)$

$= 103.2$ kJ

$\gamma = C_p / C_v = 0.6448 / 0.5150 = 0.1298$ kJ/kg

Work transfer $w_{1\text{-}2} \quad = mR(T_2 - T_1)$

$= 2 \text{ x } 0.1298\,(100\text{-}20)$

$= 20.77$ kJ

Change in entropy

$\Delta s = s_2 - s_1 = mc_p \ln (T_2 / T_1)$

$= 2 \text{ x } 0.6448 \ln (373 / 293)$

$\Delta s = 0.3113$ kJ/K

7. 3 kg of steam initially saturated at 6 MPa expands reversibly and isothermally to 1 MPa in a cylinder. Find the heat transferred and the work done. Find also the change of entropy.

Given

$m = 3$ kg $\quad P_1 = 6$ MPa $\quad X_1 = 1 \quad P_2 = 1$ MPa

from steam tables, at $P_1 = 6$ bar

$t_{sat1} = 275.6^0C = T_1 = T_2$

$v_1 = v_g = 0.032433\ m^3/kg$

$h_1 = hg = 2785$ kJ/kg

$S_1 = S_g = 5.891$ kJ/kgK $\quad$ Since x=1

from steam tables

At $P_2 = 1$ MPa $\quad T_{sat2} = 179.9^0C$

But $T_1 = T_2 \quad$ Hence $T_2 = 275.6^0C > T_{sat2}$

Hence steam is in superheated region

from superheated steam table at $P_2 = 1$ MPa & $T_2 = 275.6^0C$

specific volume $v_2 = 0.2328+(0.258-0.2328)\ (275.6-250)/(50)$

$= 299.8\ 86\ m^3/kg$

entropy $S_2 = 6.926+(7.125-6.926)\ 25.6/50$

$= 7.0279$ kJ/kgK.

Work transferred $w_{1-2} = p_1 v_1 l_n\ p_1/p_2$

$= 6 \times 10^3 \times 0.032433 \ln(6/1)$

$= 348.67$ kJ/kg.

Heat transferred $= T(s_2-s_1)$

$= 548.6\ (7.0279 - 5.891)$

$= 624.31$ kJ/kg

Change in entropy $= S_2 - S_1$

$= 7.0279-5.891$

$= 1.1369$ KJ/Kg.

(8) Stream expands hyperbolically from 30bar and 300 ^{0} C to 5 bar. Find the final condition of steam. Also determine the work of expansion, heat transferred and change of entropy.

Given

$P_1=30$ bar

$P_2=5$ bar

$T_1=300\ ^0$ C

From super Heated stream tables, at $P_1=30$ bar and $T_1=300\ ^0$ C

$v_1=0.0813\ m^3/kg$

$U_1=2757$kJ/kg

$S_1=6.541$ kJ/kg K

W.K.T

$P_1 V_1 = P_2 V_2$

$V_2 = P_1 V_1 / P_2$

$=30 \times 0.0812/5$

$=0.4872\ m^3/kg.$

From super heated steam table, at $P_2 = 5$ bar, $V_2 = 0.4872 m^3/kg$.

$$T_2 = 250 + 50\frac{(0.4872 - 0.4745)}{(0.5226 - 0.4745)} = 263.2^{\circ}C.$$

for $P_2=5$ bar,

$T_2=263.2^0C$

u_2= 2745.9 kJ/kg,

S_2=7.321 kJ/kgK,

Work of expansion

W_{1-2} = $P_1 V_1 \ln (V_2/v_1)$

= $30 \times 10^2 \times 0.0812 \ln(0.4872/0.0813)$

= 436.5 kJ/kg

From the I. law of thermodynamics,

Heat transfer q_{1-2} = $(u_2-u_1) + W_{1-2}$

= (2745.1 –2751) + 436.5

= 431.4 kJ/kg

Change in entropy ,s_2-s_1 = 7.321-6.541

= 0.780 kJ/kgK

9) Steam at 5bar and 0.95 dry is expanded to 2 bar by a hyperbolic process. Find out the workdone and change in entropy during the process using steam tables only.

Given:

P_1= 5bar

X_1= 0.95

P_2 = 2bar

From steam tabels, at P_1 = 5bar

T_1 = 151.9^{0}C

v_g = 0.37466 m^3/kg,

s_f = 1.86 kJ/kgK ,

s_{fg} = 4.959 kJ/kgK

at P_2 = 2bar

$v_g =$ 0.88540 m^3/kg,

$s_f =$ 1.53 kJ/kgK,

$s_{fg} =$ 5.597 kJ/kgK

for a hyperbolic process,

$p_1v_1 = P_2v_2$

$v_1 = xv_{g1}$

$= 0.95 \times 0.37466$

$= 0.355927\ m^3/kg$

$v_2 = P_1v_1/ p_2$

$= 5 \times 0.355927 / 2$

$= 0.8398\ m^3/kg$

Here $v_2 > v_{g2}$, the steam is in wet condition.

$v_2 = x_2v_{g2}$

$0.839818 = x_2 \times 0.88540$

$x_2 = 0.948$

$s_1 = sf_1 + x_1sfg_1 = 1.86 + (0.95 \times 4 \times 4.959) = 6.571$ kJ/kgK

$s_2 = sf_2 + x_2\ sfg_2 = 1.53 + (0.948 \times 5.597) = 6.836$ kJ/kgK

workdone $= p1v_1 \ln (v_2/v_1)$

$= 500 \times 0.355927 \ln (0.8398 / 0.355927)$

$= 152.77$ kJ/kg

change in entropy $= s_2 – s_1 = 6.836 – 6.571 = 0.265$ kJ/kgK

10. 1kg of superheated steam at 30bar and 400°C, contained in a cylinder – piston assembly is allowed to expand reversibly and adiabatically (isentropic) to a pressure of 1 bar. Determine the final condition of steam and the workdone.

Given: $P_1 = 3$ bar

$T_1 = 400^oC$

$P_2 = 1bar$

$s_1 = s_2$(isentropic)

soln: From superheated steam tables at $P_1 = 30bar$, $T_1 = 400^oC$

$V_1 = 0.09931\ m^3/kg$,

$s_1 = 6.925$ kJ/kgK

From the saturated steam taller, at $P_2 = 1$ bar

$V_g = 1.6937\ m^3/kg$,

$s_f = 1.203$ kJ/kgK

$s_{fg} = 6.057$ kJ/kgK

$s_1 = s_2$

$6.925 = 1.303 + (22 \times 6.057)$

$x_2 = 0.93$ (Steam is in wet region)

Specific Volume

$V_2 = x_2 V_{g2}$

$= 0.93 \times 1.6937$

$= 1.575\ m^3/kg$

Work done $= P_1 V_1 – P_2 V_2$/ﻷ-1

$= 30 \times 100 \times 0.09931 – 100 \times 1.575 / 1.4 –1$

$= 357 .08$ kg

PVT surface

The 3D surface which gives the relations among pressure, volume and temperature is called PVT surface.

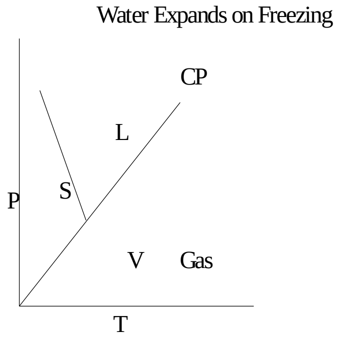

Figure 3.8

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – IV – Engineering Thermodynamics – SMEA1302

Iv. Ideal and Real gases, Gas mixtures and Thermodynamic relations

Equation of state of a gas

The equation which relates the properties, pressure, specific volume and Temperature is known as equation of state.

$Pv = RT$

where p – Pressure

v – specific volume

R – universal gas constant

T – Temperature

Ideal gas

The gas which obeys the law PV=mRT at all temperatures and pressures is called as an ideal gas.

Real gas

The gas which does not satisfy this equation of state is known as Real gas.

Vander walls equation

When pressure is is low and temperature is high, the intermolecular attraction and the volume of molecules compared to the total volume of gas are very small, the real gas obeys as ideal gas.

But when pressure increases, the real gases deviate from the ideal gas equation.

Vander walls introduced two correction terms in the equation of state, as

$(p+a/v^2)$ (v-b) =RT

a – account for existence of mutual attraction between the molecules.

a/v^2= force of cohesion

b- account for volumes of molecules

Berthelot equation

$P = RT/v\text{-}b \, . \, a/TV^2$

Dietrici equation

$P = RT/v\text{-}b \, . \, e^{-a/RTV}$

Redlich – kwong equation

$P= RT/v\text{-}b - a/T^{1/2} \, v(v+b)$

Redlick-kwong equation gives accurate results at high pressures and temperature

VIRIAL EXPANSIONS

Kammerlingh onnes a Dutch physicist introduced some coefficients to express the equation of state in power series known as virial coefficients.

The expression is given as

$Pv = A \, (1+ B \, P^1 + C \, P^2 + D \, P^3 + \ldots\ldots)$

$\lim pv = A = R \, T$

$P \rightarrow 0$

$Pv/ R \, T = 1 + Bp + C'P^2 + D'P^3 + \ldots\ldots$ (or)

$Pv/ RT = 1 + B'P + C'P^2 + D'P^3 + \ldots..$

These are known as Virial equations of state.

B’, C’, B,C are known as virial coefficients.

Where, PV/ RT is called compressibility factor and is denoted as “Z”

$$Z = 1 + B/v + C/ v^2 + D/ v^3 + \ldots\ldots$$

B/ v, C/ v^2 etc are the virial expression arise on account of molecular interactions.

If there is no interactions (ie. At low pressure B=0, C=0, Z=1 and

Pv = RT (ideal gas equation)

Compressibility Factor Chart

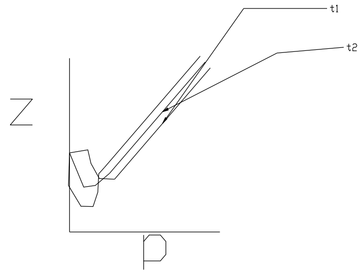

Figure 4.1

It is used to find the values of Z at any value of P and T

Then the volume by using the relation pv = ZRT can be find out.

Reduced properties

The general shape of this remains same for all substances but the scales may be different. This similarity is exploited by the dimensionless properties called reduced properties.

Reduced temperature is the ratio of existing temperature to the critical temperature of the substance

ie, Tr = T/T_c ,Pr=P/P_c & u/V_c

critical compressibility factor

ZC= P_cV_C/RT_c

Generalized compressibility chart

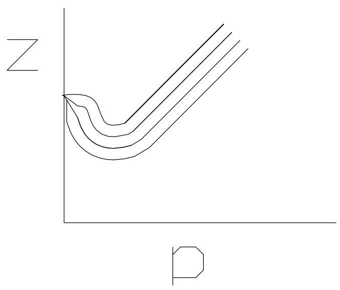

Figure 4.2

It is that in which T_r is plotted as a function of reduced pressure and compressibility factor.

Law of corresponding states

It is the relation among the reduced properties P_r,T_r and U_r

It is expressed as

$$(Pr+3/Ur^2)(3Ur - 1) = 8\ Tr$$

If any two gases have equal values of reduced pressure and reduced termperature, then have same values of reduced volume.

Dalton’s law of partial pressures

It states that the total pressure of a mixture of ideal gases is equal to the sum of the partial pressures.

consider a mixture of ideal gases at a temperature T,

pressure p and volume v

Assume

n_1 -> moles of gas A_1

n_2 -> moles of gas A_2

n_i = moles of gas Ac

Pv= $Cn_1+n_2+.........+nc)$ RT

where R = 8.314 KJ/kg molk

p= $n_1AT_/vn2RT/v+...ncRT/v$

The expression n_*RT/v represents the pressure that the k^{th} gas would exist if it occupied the volume at temperature T.

p= $P_1+P_2+.........+P_c$

where $P_1 = n_1RT_1/v$, $P_2 = n_2RT_/v$ .... P_C = nc RT/V

volume

$$V=(n_1+n_2+......n_c)\ RT/P$$

$$= \sum nk\ RT*p$$

where $\sum n_k = n_1+n_2+ ....+n_k$

= Total number of moles of gas.

mole fraction of a gas

it is denoted as nk/ $\sum$nk for k_{th} gas

ie, $x_1=n_1/\sum nk$, $x_2=n_2/\sum n_k$

ie, $x_1+x_2+............xc =1$

In terms of masses

pv = $(m_1R_1+m_2R_{2+}m_cR_c)T$

where $p=P_1+P_2+..........+P_c$

For the gas mixture

pv=$(m_{1+}m_2+................+m_c)R_m$ T

where R_m is the gas constant for the mixture

$R_m = (m_1R_1+m_2R_2+\ldots\ldots\ldots m_cR_c) /m_1+m_2+\ldots\ldots\ldots\ldots+m_c$

Equivalent molar weight

$\mu_m = \sum x_k \mu_k$

Partial volume of a component is the volume that the component alone would occupy at the same pressure and temperature of the mixture.

specific volume of the mixture

$V=v/m = v/m_1+m_2+m_c$

(or) $1/v= 1/v_1+1/v_2+ \ldots\ldots\ldots\ldots 1/v_c$

Density of the mixture

$\rho= \rho_1+\rho_2+\ldots\ldots\ldots+\rho_c$

Internal energy of mixture

$u_m=m_1u_1+m_2u_2+\ldots\ldots\ldots\ldots m_cu_c/m_1+m_2+\ldots\ldots\ldots m_c$

Enthapy of gas mixture

$h_m= m_1h_1+m_2+h_2+m_chc/m_1+m_2+\ldots\ldots\ldots m_c$

specific heats of mixture

$C_{vm=} m_1cv_1+m_2Cv_2+\ldots\ldots\ldots m_ccv_c/m_1+m_2+\ldots\ldots\ldots mc$

$C_{pm} = m_1c_{v1} +m_2c_{v2} +\ldots\ldots\ldots m_cc_{vc} /m_1+m_2+\ldots\ldots\ldots+m_c$

Entropy of Gas mixtures

Gibbs theorem

It states that the total entropy of a mixture of gases is the sum of the partial entropies.

$s_f-s_i = -(m_1R_1\ln P_1/p+m_2R_2\ln P_2/P+\ldots\ldots\ldots\ldots m_cR_c\ln P_c/P)$

Relation between Cp, Cv and R

The specific heat capacity at constant volume of any substance is given by C_v=(du/dt)v

Joule's law states u =f(T)

Hence C_v = du/dt

similarly h=f(T)

specific heat at constant pressure

C_p =dh/dT

We know that h=u+pv (or) h=u+RT

dh/dT =du/dT+R

substituting the values of c_p and C_v

C_p =C_v+R

(N) C_p _ C_V=R

1. 1 kg co_2 has a volume of $1m^3$ at 100'c compute the pressure by vander waal's equation Take a=362850Nm^4/kg-m0le)^2 perfect gas equation, b = 0.0423m^3/kg-mole

Given

molar specific volume = 1*44 =44m^3/kg-mole

T = 373 K

(i) vander waal's quation

$(p+a/v^2)$ (v-b) =R_oT

p = (RoT/v-b –a/v^2)

p =(8314*373/44-0.0423 –362850/44^2)

P =70361 N/m^2

= 0.7036 bar

(ii) perfect gas equation

pv=RoT

$P=RoT/v=8314*373/44 = 70480\ N/m^2$

$= 0.7048$ bar

2. It is necessary to strore one kmole of methane at a temperature of 300k and pressure of 60 Mpa. Determine the volume of the cylinder that is required for storage by each of the following laws.
   a. ideal gas equation
   b. vander waal's equation

   The vander waal's constants for methane are

   $a = 228.5\ kpa(m^3/kmole\ )^2$ 1b= $0.0427\ m^3/kgmol$

   Given

   T=300 K

   p =60 Mpa

   (i) ideal gas equation

   PV=RoT v

   $V= R_oT/p =8314*300/60*10^6$

   $= 0.04157\ m^3/kg.mole$

   (ii) vander waal's equation

   $(P + a/v^2)\ (v-b) = R_oT$

   $p+a/v^2 =R_oT/v-b$

   $(v-b)(pv^2+a) =v^2ROT$

   $pv^3-v^2(pb+ROT) +av = ab$

   $60*10^6v^3-u^{-2}(60*10^6*0.0427+8314*300)+228500*v$

   $= 228500*0.0427$

$v=0.069m^3/kgmole$

3. For a substance described by the equation of state

$p(v-b) = RT$

and whose internal energy is given by

$du = C_v\, dt$

Where C_V is the constant determine an expression for the entropy difference between the states defined by T_1, V_1 and T_2, V_2 in terms of these quantities.

$P(v-b) = RT$

$P/T = R/v-b \Rightarrow (\partial p/\partial T)_v = R/v-b$

$Tds = du + T(\partial p/\partial T)_v\, dv$

$= C_v dT + RT/v-b\, dv$

$ds = C_v\, dt/T + R/v-b\, dv$

$S_2 - S_1 = C_v \ln T + R \ln v_2-b/v_1-b$

4. Compute the specific volume of steam at 10 bar, 450C, by means of (i) The ideal- gas equation of state. (ii) a compressibility factor. Compare These results to the steam –table value and give the % error for each method.

Given

P= 10 bar, T= 450'C (superheated steam ie,air)

(i) Heat gas equation

$PV = RT$

Where $R = T/m = 8314/28.97 = 287$ J/kgk

$V = RT/P = 287*723/10*10^5 = 0.207\ m^3$

(ii) Compressibility factor

$PV = zRT$

Where $z = 0.284$

Hence $V = 0.284*287*723/10*10^5 = 0.059\ m^3$

From Superheated steam table,

At P= 10 bar, T = 450C

Volume = 0.325 m^3

% error in ideal gas equation of state

= 0.325 – 0.207/0.207 = 57%

% error in compressibility fractor method

= 0.325 – 0.059/0.059 =

1. A vessel of 0.35 m^3 capacity contains 0.4 kg of Co (μ =28) and 1 kg of air at 20’C calculate

(i) The partial pressure of each constituent

(ii) The total pressure in the vessel and

(iii) The gravimetric analysis of air is to be taken as 23.3% o_2(μ=32) & 76.7 % N_2(μ=28)

(iv) Given volume v=0.35m^3

Mass of Co =0.4 kg

Mass of air =1 kg

T = 293 k.

Mass of O_2 pressed in 1 kg of air =23.3/100*1 =0.233 kg

Mass of N_2 Present in kg of air = 76.7/100*1 =0.767

PV = mRT

(i) Partial Pressure

P_{02} = m_{02} RT/M_{02}*V_0

= o.233*8314*293/32*0.35*10^5

= 1.9065 bar

(ii) Total pressure in the vessel

$P \quad = P_{02} + P_{N2} + P_{CO}$

$= 0.5068+1.9065+0.9443$

$P \quad = 3.4076$ bar

MAXWELL'S EQUATIONS

Equations used to express any one property of a pure substance as a function of any two others are called Maxwell’s equations

$du = Tds - pdv$

Consider $S = f(T,v)$

$ds=(ds/dt)_v\, dT +(ds/dV)_T\, dV$

$Tds = T(ds/dt)_v\, dt+T(ds/dv)_T dv$

we know that $T(ds/dt)_v = C_v$ & $(ds/dv)_T = (dp/dt)_v$

Hence $Tds = C_v dT + T(dp/dt)_v\, dv$

This is known as first Tds equation.

2. $S = f(T,p)$

$ds = (ds/dt\,)_p\, dt+(ds/dp)_T\, dp$

we know that $T(ds/dt)_p =c_p$ &$(ds/dp)\, _{T\, =\, -}(dv/dt)_p$

Hence $Tds =C_p dT - T(dv/dt)_p\, dp$

This is known as Second Tds equation

Show that C_p is always greater Than C_v

From I& II Tds equations

$Tds = C_p dT -T(dv/dT)p\ dp = C_V\, dT+ (dP /dT)\, _v dv$

$(C_{p-}C_v)dt = T(dp/dT)_v dv+T(dv/dt)_p dp$

$dT = T(dp/dT)_v dv/(cp-cv) + T(dv/dT)_p\, dp/c_p - C_v$

but $dT=(dT/dv)_P\, dv+(dT/dp)v\, dp$

$T(dp/dt)_v\, dv =(dT/d\, v)_p dv$

& $T(dv/dt)_p\, dp = (dT/dp)_v\, d.P$

Hence $C_p-C_v = T(dp/d/T)_v\, (dv/dT)_p$

But $(dp/dT)_v\, (dT/dV)_p\, (dv/dp)_T = -1$

Hence $Cp-C_4 = -T(dv/dT)^2_p\, (dp/dv)_T$

$(dv/dT)^2_p$ is always +ve & $(dp/dp)_T$ is -ve

Hence $_{Cp} > C_v$

Joule-Thomson Coefficient

The numerical value of the slope of an isenthalpe on a T-P diagram at any point is called the Joule- kelvin coefficient (or) Joule Thomson Coefficient

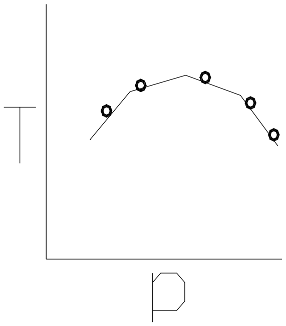

Figure 4.3

It as denoted by ---- μ_J

$\mu_J =(\mid dT/\mid dp)_h$

The Joudle Thomson coefficient of an ideal gas zero

Clausius - clapeyron equation

Whenever there is a change of phase, there is a change in entropy and volume

$dp/dT = S^{(f)}-S^{(i)}/V^{(f)} -V^{(i)}$

1.A certain gas follows the equation of state $p(v-b) =RT$. Show that for a reversible adiabatic process of this gas $T(v-b)^{R/Cv}$ =Constant

$P(v-b) =RT$ -1

from the first Tds equations

$Tds = C_v dT+T(dp/dT)_v\, dv$

$ds = C_v\, dT/T+(dp/dT)_v\, dv$ -2

from equation 1

$P/T = R/v-b$

$(dp/dT)_v =R/v-b$ - 3

substituting the value of $(dp/dT)_v$ in equation 2

$ds = Cv\, dT/T + R/v-b\, dv$

In a reversible adiabatic process $ds=0$

$C_v\, dT/T +R/v-b =0$

$Cv \ln T+R\ln(v-b) =\ln c$

$\ln T+\ln (v-b)^{R/cv} = \ln c$

$T(v-b)^{R/cv} = C$

Hence the proof.

2. Find the increase in entropy when 2 kg of oxygen at 60'C mixed with 6 kg of nitrogen at the same temperature. The initial pressure of each constituent is 103 kpa and is the same as that of the mixture?

$X_{O2} = P_{O2}/p = (2/32) / (2/32 + 6/28) = 0.225$

$X_{N2} = 1 - 0.225 = 0.775$

Increase in entropy

ds $= -mo_2 R_{02} \ln x_{02} - m_{N2} R_{N2} \ln x_{N2}$

$= -2 (8.3143 / 32) \ln (0.225) - 6 (8.3143 / 28) \ln (0.775)$

= 1.2314 KJ/kgk

3. Following shows gravimetric analysis of air 23.14% o_2, 75.53% N_2, 1.28% Ar & 0.05% Co_2. Calculate the analysis by volume and partial pressure of each constituent when the total pressure is 1bar.

constituent	mi	Mi	ni = mi / Mi	n1/n x 100%
02	0.2314	32	0.00723	20.94%
N2	0.7553	28	0.02697	78.10%
Ar	0.0128	40	0.00032	0.93%
Co2	0.0005	44	0.00001	0.03%

$n = \sum ni = 0.03453$

$Po_2 = ni/n \times P = 0.2094 \times 1 = 0.2094$ bar

$P_{N2} = 0.7810$ bar

$P_{Ar} = 0.0093$bar

$Pco_2 = 0.003$bar

GIBBS FUNCTION:

From the I law of Thermodynamics,

$dQ = du + pdv$ -------- 1

From the II law of thermodynamics

$ds \geq dQ/T$ ------- 2

from 1 & 2

$du + pdv - dQ = 0$

$du + pdv - Tds \leq 0$

since P & T are constants,

$d\,(u+pv-Ts)_{T,P} \leq 0$

$(dG)_{T.P} \leq 0$

(or) $G= u + pv - Ts = H - Ts$

G is called Gibbs function. Its significance is to knowing the concept of vapour phase equilibrium and chemical reactions.

Helmholtz function

From the I law of Thermodynamics,

$du = dQ - dw$

Consider the closed system at constant temperature and volume

$du = dQ$ ------ 1

From the II law of Thermodynamics,

$ds = d\,(Q/T) + dI$ ------ 2

Where dI is the irreversibility term to define the direction of change.

from 1 & 2

$ds = du / T + dI$

$Tds - du = dI \times T$

$TdI = -d(u-Ts)$

for stable equilibrium

$dI > 0$

$d(u - Ts)_{T,u} \geq 0$

$(d A)T,v \geq 0$

where $A = u - Ts$.

A is called Helmholtz function. Its significance is to analyse the chemical processes at constant T and V

Amagat Ludac law

It states that the volume of a mixture of ideal gases is equal to the sum of the partial volumes which the constituent gases would occupy if each existed alone at the pressure and temperature of the Mixture.

Gibb's law

It states that the internal energy, enthalpy and entropy of a mixture of perfect gases are respectively equal to sum of internal energies, enthalpies and entropies that each constituent would have if it alone occupied the volume of the mixture at the temperature of the mixture.

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – V – Engineering Thermodynamics – SMEA1302

V. Psychrometry

PSYCHROMETRY

The science which deals about the behaviour of mixtures of dry air and water vapour is called psychrometry.

Mixtures of air:-

(i) Unsaturated air mixture

It is a mixture of dry air and superheated water vapour, the partial pressure of water vapour, being less then its saturation pressure corresponding to the temperature of the mixture.

(ii) Saturated air mixture

It is the mixture of dry air and water vapour in which the partial pressure of water vapour is equal to its saturation pressure corresponding to the temperature of the mixture.

(iii) Super heated air mixture

It is a mixture of dry air and water vapour in which the partial pressure of of water vapour grater is than its saturation pressure corresponding to the temperature of the mixture.

Specific humidity (or) humidity ratio

It is the ratio of mass of water vapour to the mass of dry air in a specified volume of the mixture at the mixture temperature.

$W = M_v / M_a$ or $W = 0.622\ P_v / p - P_v$

Where

P_v = Partial pressure of water vapour.

P_a = Partial pressure of dry air.

Saturation Ratio

It is the ratio of absolute humidity of the moist air to the absolute humidity of saturated air at the same temperature and total pressure.

$\Psi = W/W_s$

Relative humidity

It is the ratio of the partial pressure of water vapour in the mixture at a given temperature to the saturation temperature of the vapour at the same temperature.

$\varphi = P_v/P_g$

Casi (i)

$\phi = 0$ (for dry air)

Casi (ii)

$\phi = 100\%$ (for saturated air)

Dew point temperature :

It is the temperature at which unsaturated air becomes saturated , that is vapur begins to condensate at constant pressure and specific humidity

Dry bulb temperature :

It is the temperature recorded by a thermometer with a dry bulb.

Wet bulb temperature.

It is the temperature recorded by a thermometer when the bulb is enveloped by a cotton wick saturated with water.

Adiabatic saturation temperature

When unsaturated air flows over a long sheet of water in an insulated chamber , the water evaporates , and the specific humidity of air increases.

Both the air and water are cooled, as evaporation takes place . The process continues until the energy transferred from the air to the water is equal to the energy required to vapourize the water.

At this point , thermal equilibrium exits between water- air and water -vapour. This equilibrium temperature is called adiabatic saturation temperature.

It is called as thermodynamic wet bulb temperature.

Psychometric chart

Chart which shows the specific humidity and partial pressure of water as ordinates and DBT as abscissa is called as Psychrometric chart.

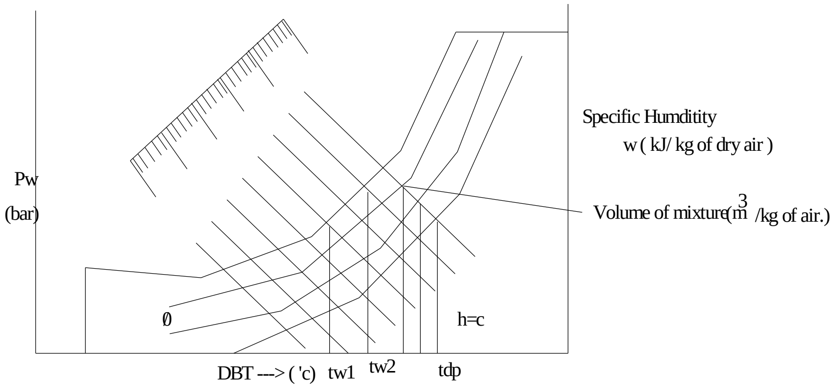


Figure 5.1

Psychometric processes:-

1. sensible heating (or) cooling

Heating (or) cooling of air at constant specific humidity is called sensible heating or sensible cooling.

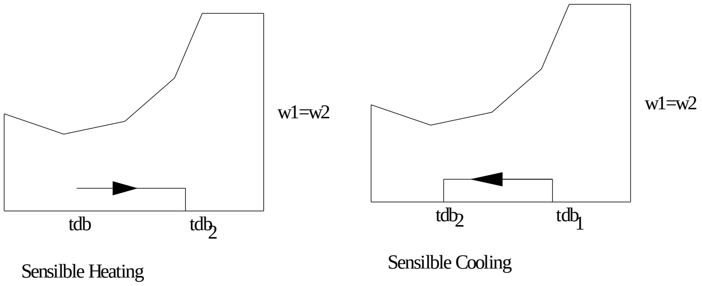


Figure 5.2

1. Cooling and Dehumidification

The process of removing water vapour from air is called dehumidification , cooling of air is the removal of heat from air. It is the used in summer air conditioning.

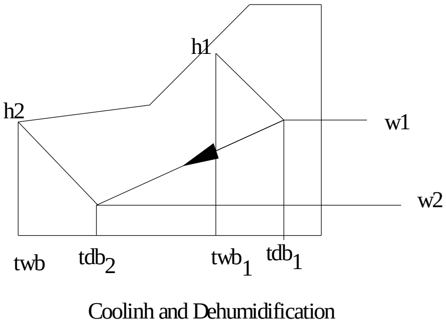


Figure 5.3

4.Adiabatic mixing of air streams

In air conditioning systems, the room air and ventilation air are mixed to the desired state and supplied to the conditioned space.

1. Chemical Dehumidification:

The process of removing water vapour from the air by passing the air through a bed of silica gel is called chemical dehumidification . The DBT of air increases by releasing the latent heat of condensation.

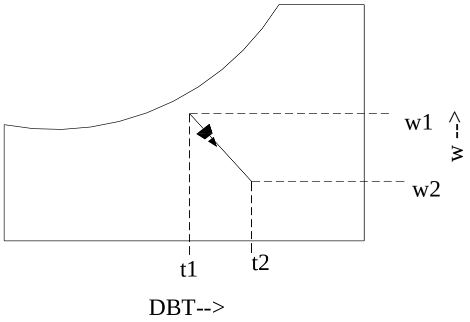


Figure 5.4

1. The readings from a sling psychomotor are as follows DBT =30° c WBT = 20° C, Barometer reading = 740mm of Hg,

Using steam tables, determine 1. DPT, 2. Relative humidity 3. specific humidity , 4. Degree of saturation , 5. vapour density and 6. Enthalpy of mixture / kg of air.

given:-

T_1 =30°C

T_w =20°C

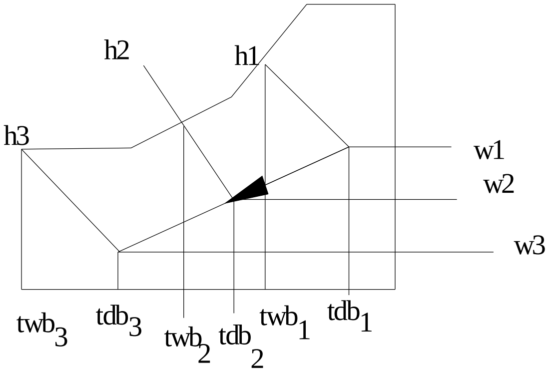
P_b=740 mm of Hg

From steam tables for T_w=20°c, p_w=0.02337 bar

P_b = 740 x 133.3

= 98642 N/m^2

= 0.98642 bar



Adiabatic mixing of air streams

Figure 5.5

Partial pressure of water vapor

P_v $=P_w-((P_b- P_w)(T_d-T_w) / 1547 – 1.44 T_w)$

$=0.02337 –((0.98462 – 0.02337)(30-20)/1547 – (1.44 x20))$

=0.01703 bar

DPT from steam tables at p_v=0.01703 bar

T_{DP}=15°C

2.Relative humidity

from steam tables at

T_b = $30^\circ c$

p_s = 0.04242 bar

$\Phi = p_v / p_s = 0.01703/0.4242 = 40.15\ \%$

3.Specific humidity

$w = 0.622\ p_v / p_b - p_v$

$= 0.622 \times 0.01703/0.98642 - 0.01703$

= 10.924 g/kg of dryer.

4. Degree of saturation

Sp. humity of saturation

$W_s = 0.622 ps/P_b - P_s$

$= 0.622 \times 0.04242\ /0.98642 - 0.04242$

= 0.027945 kg/ kg of dry again.

$\mu = w/w_s = 0.016924/0.027945 = 39.1\%$

5. Vapour density

$\rho_v = w(P_b - P_v)/Ra\ T_d$

$= 0.010924\ (0.98642 - 0.01703)/\ 287 \times 303$

$= 0.01218$ kg / m^3 of dry air.

6.Enthalpy of mixture / kg of dry air.

$h = 1.022\ T_d + W\ (h_{fg}\ dp + 2.3\ T_{dp}]$

where h_{fg} = latent heat of vapour saturation

h_{fg} = 2466.1 kg/kg

$h = 1.002 \times 30 + 0.01924\ (2466.1 + 2.3 \times 15)$

= 57.98 kj/kg of dry air.

(i) Atmospheric air has a DBT of 32 °c and WBT of 29 °c . Determine Specific humidity

(ii) Dew point

(iii) Enthalpy

(iv) specific volume

(v) relative humidity

3. Specific humidity

4. $W = 0.622\ P_v/P_b - P_v$

5. $P_b = 760$ mm of Hg

$H_g = 760 \times 133.32$

$= 101325\ N/m^2$

$= 1.01325$ bar.

P_w from steam tables , at $T_w = 19^0C$

$P_w = 0.04004$ bar.

Partial pressure of vapour

$P_v = P_w – (P_b - P_w)(T_d - T_w)/1547 – 1.44\ T_w$

$= 0.04004 – ((1.01325 – 0.04404)(32 – 29)/1547 – 1.44 \times 29)$

$= 0.0381$ bar.

Specific humidity

$W = 0.622\ P_v / P_b - P_V$

$= 0.622 \times 0.0381/1.01325 – 0.0381$

$= 0.0243$ kg /kg of dry air.

(ii) Dew point temperature:-

Dpt at P_v=0.0381 bar,

T_{dp} =28°C

(iii) Enthalpy

h = 1.022 T_d +w[h_{fg}+2.3T_{dp}]

h_{fg} at T_{dp} = 28° C

h_{fg} = 2435.4 kJ/kg

h = 1.022 x 32 + 0.0243 [2435.4 +2.3 x28]

= 93.45kJj/kg of dry air

(iii) Specific volume

V_r = R_aT_d / w (p_b- p_v)

= 287 x 305/0.0243 (1.01325 – 0.0381) x 10^5

= 36.9 m^3/kg of dry air.

6. The air enters a duct at 10° C and 80% RH at the rate of 150 m^3/min and is heated at 30°C without adding or removing any moisture. The pressure remains constant at 1.013bar. Determine the relative humidity of air at exit from the duct and the rate of heat transfer.

Solution:

T_{d1} = 10° C

ϕ_1 = 80%

V_1 = 150 m^3/min

T_{d1} = 30° C

p =p_b= 1.013 bar.

From the psychometric chart,

ϕ_2 = 23.5%

To find rate of heat transfer

Rate of heat transfer

$Q=m_a(h_2-h_1)$

Amount of air supplied m_a = V_1/V_{s1}

= 150 /0.81

= 185.2 m^3/min

From psychometric chart, v_{s1} = 0.81 m^3/kg of dry air

h_1 = 26 kJ/kg

h_2 = 46kJ/kg

Q = 185.2 (46 –26)

= 3704 kJ/min.

4. Atmospheric air at a pressure of 1.013 bar and 32.2° C has a specific humidity of 0.0096 kg/kg of dry air. Using psychrometric chart, calculate the relative humidity, vapour pressure, total enthalpy, the specific volume and DPT.

Given:-

P_b=1.013bar, T_d= 32.2° C W_b=0.0096kg/kg of dryair

From psychrometric chart

Retative humidity Φ=33%

WBT=20° C

From steam tables, at T_w=20° C p_w=0.02337 bar

Vapour pressure $p_v = p_w - (p_b-p_w)(T_d-T_w) / 1547-1.44T_w$

= 0.02337-(1.013—0.02337)(32.2-20)/ 1547 – 1.44*20

=0.015417bar.

Total enthalpy = 57.5kJ/kg

Specific volume =0.87m^3/kg of dry air.

DPT at p_v =0.015417bar, from steam tables

DPT =13° C

5. In a heating application moist air enters a steam heating coil at 10° C, 50% RH and leaves at 30°c. Determine the heat flow, if the mass flow rate of air is 100kg /s

From Psychrometric chart

h_1=19.3kJ/kg of dry air

h_2=39.8 kJ/kg of dryair

$Q = m_a (h_2-h_1)$

$= 100(39.8-19.3)=2050$ kJ/s

6. 200m^3 of air/ min is passed through the adiabatic humidifier, the condition of air at inlet is 40°C DBT 15% R.H and the outlet condition is 25°C DBT & 20°C WBT. Find DPT and amount of water vapour added to the air/minute.

Given :-

V_1=200m^3/ min T_{d1}=40°C Φ_1=15% T_{d2}=25°C T_{w2}=20°C

From the psychrometric chart,

T_{dp2} = 17.6°C

Amount of water vapour added to air

$= m_a(w_2-w_1)$

Mass of air supplied

$m_a=v_1/v_{s1}$ = 200/0.896 =223.2 kg /min

W_1=0.007 kg/kg of dry air

W_1=0.1026 kg/kg of dryair

Amount of water vapour added

= $m_a(w_2-w_1)$

= 223.3 (0.1026- 0.007)

= 1.25 kg/min

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