THERMAL ENGINEERING-1

FOR 3rd SEMESTER (MECHANICAL ENGG.)

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ACCORDING TO SCTE&VT SYLLABUS

PROCESSES

CHAPTER-3 PROPERTIES OF PERFECT GASES

Law of perfect gas:-

The physical properties of gas are controlled by the three variables.

1. Pressure exerted by the gas.
2. Volume occupied by the gas.
3. Temperature of the gas.

The behaviour of a perfect gas under going any change in the above mentioned variables is governed by the following laws which have been established from the experimental result.

i) Boyle's law
ii) Charle's law
iii) Gay-lussac's law
iv) Avogadro's law
v) Dalton's law of partial pressure

i) Boyle's law

It states "the absolute pressure of a given mass of a perfect gas varies inversely proportional as its volume when the temperature remains constant.

Mathematically,

$$P \propto \frac{1}{V} = PV = \text{constant}$$

$P = \frac{C}{V} \Rightarrow PV = C$

$P_1V_1 = P_2V_2 = P_3V_3 \dots$ constant

(ii) Charle's law

This law is formulated by a french scientist Jaques A.C charles. This may stated in two different forms

(i) "The volume of a given mass of a perfect gas varies directly as it's absolute temperature. when the absolute pressure remains constant".

Mathematically, $V \propto T$

$$\Rightarrow V = CT$$

$$\Rightarrow \frac{V}{T} = \text{constant 'or' } \frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V_3}{T_3} \dots \text{constant}$$

second statement is stated as follows.

(ii) All perfect gases change in volume by $\frac{1}{273}$th of its original volume at 0°C for every 1° change in temperature, when it's

Pressure remains constant.

Let V_0 = Volume of a given mass at 0°c.

V_t = Volume of a given mass at t°c.

According to the above statement

$$V_t = V_0 + \frac{1}{273} V_0 t = V_0 + \frac{V_0 t}{273} = V_0\left(1 + \frac{t}{273}\right)$$

$$= \left(\frac{273+t}{273}\right) V_0 = \frac{T V_0}{T_0} = V_0\left(\frac{T}{T_0}\right)$$

T_0 = absolute temp. corresponding to 0°c

T = absolute temp. corresponding to t°c

(iii) Gay-Lussac's law

This law states

"The absolute ~~temperature~~ Pressure of a given mass of a perfect gas varies directly as its absolute temperature when the volume remains constant.

Mathematically, $P \propto T$

$\Rightarrow P = CT$

$\Rightarrow \frac{P}{T} = C$ 'or' Constant $\frac{P_1}{T_1} = \frac{P_2}{T_2} = \frac{P_3}{T_3} \cdots$ constant

Imp General gas equation :-

→ We have discussed in Boyle's law and charle's law that two quantity varies when the third one remains constant.

→ But in actual practice all the three variables (Pressure, temperature & volume) change simultaneously.

→ In order to deal with the all practical cases, the boyle's law and the charle's law are combined together which gives a general gas equation.

→ According to Boyle's law,

$P \propto \frac{1}{V}$ or $V \propto \frac{1}{P}$ (Keeping temperature const.)

According to charle's law,

$V \propto T$ (keeping Pressure constant)

Combining the above two laws. It is obvious that

$V \propto \frac{1}{P}$ & $V \propto T$

$\Rightarrow V = \frac{C}{P} \cdot T$

$\Rightarrow \frac{PV}{T} = $ constant

Avogadro's law:-

It states, "Equal volumes of all gases, at the same temperature and pressure, contain equal number of molecules."

→ According to Avogadro's law, 1m³ of oxygen (O_2) will contain the same no. of molecules. as 1m³ of Hydrogen (H_2) when the temperature and pressure is same.

→ Since the molecular mass of Hydrogen is 2, and the oxygen is 16, therefore a molecule of oxygen has a mass which is $32/2 = 16$ times the mass of Hydrogen molecules.

→ As 1m³ of these two gases contain the same no. of molecules and a molecule of oxygen has a mass of 16 times than that of Hydrogen molecule.

→ Therefore it is evident that density of oxygen is 16 times the density of Hydrogen.

→ Hence Avogadro's law indicates that the density of any two gases is directly proportional to their molecular masses, if the gases are at the same temperature and pressure.

Note:- The density of oxygen at Normal Temperature and Pressure (briefly written as NTP), that is temperature 0°c and pressure 1.015 bar is 1.429 Kg/m³.

→ Hence specific volume of 1kg oxygen at NTP

$$V_s = \frac{1}{1.429} \, m^3/kg, \quad \left[\text{Specific value} = \frac{1}{\text{density}}\right]$$

Dalton's law of partial pressures:- or (Mixture of Air & steam)

It states "The pressure of the mixture of Air and steam is equal to the sum of the pressures, which each Constituent would exert, if it occupied the same space by itself."

Mathematically,

Pressure in the condenser containing mixture of Air and steam.

$P_c = P_a + P_s$ where P_c = Pressure in condenser

P_a = Partial pressure of air

P_s = Partial pressure of steam

Imp. Characteristic equation of a gas

→ It is a modified form of general gas equation.

→ If the volume (V) in the general gas equation is taken as that 1kg of gas then the constant c (in the general gas equation is represented by another constant) R (in the characteristic equation of gas).

→ The general gas equation may be written as

$PV_s = RT$ where R = characteristic gas constant
or Gas constant
V_s = Specific volume

* For any mass 'm' kg of a gas the characteristic gas equation becomes

$$mPV_s = mRT$$
$$PmV_s = mRT$$
$$\Rightarrow PV = mRT, \quad [\text{as } mV_s = V]$$

Note :-

(1) The units of gas constant

$$PV = mRT$$
$$\Rightarrow R = \frac{PV}{mT} = \frac{\frac{N}{\cancel{m^2}} \times m^{\cancel{3}}}{kg \times K} = \frac{N.m}{Kg.K} = \frac{J}{Kg.K} \quad (\text{as Joule} = N.m)$$

(2) The value of gas constant (R) is different for different gases.

→ In S.I units the value of gas constant R is 287 J/kgK.

(3) The equation PV = mRT may be written as

$$PV = mRT$$
$$\Rightarrow P = \frac{m}{V}RT \quad \Rightarrow P = \rho RT \quad (\rho = \text{Rho}) \left[\rho = \frac{m}{V}\right]$$

Universal gas constant :- (Molar constant)

The universal gas constant or molar constant of a gas is the product of the gas constant and the molar mass of the gas.

$R_u = MR$ where R_u = Universal gas constant
M = Molar mass of the gas
(unit = kg/mol)
R = Gas constant

Q) A vessel of capacity $3 m^3$ contains air at a pressure of 15 bar and a temperature of 25°c. Additional air is now pumped into the system until pressure rises to 30 bar and temperature rises to 60°c. Determine the mass of air pumped in and express the quantity as a volume at a pressure of 1.02 bar and a temperature of 20°c. If the vessel is allowed to cool until the temperature is again 25°c. calculate the pressure in the vessel.

<u>solution</u> :- Given data

$V_1 = 3m^3$ $\quad P_1 = 1.5 bar = 0.15 \times 10^6 N/m^2$, $T_1 = 25°C = 273+25 = 298K$

$P_2 = 30 bar = 3 \times 10^6 N/m^2$, $T_2 = 60°C = 273+60 = 333K$

$P_3 = 1.02 bar = 0.102 \times 10^6 N/m^2$, $T_3 = 20°C = 273+20 = 293K$

Mass of air pumped in

Let M_1 = mass of air initially filled in the vessel

M_2 = mass of air in the vessel after pumping

We know, $P_1 V_1 = m_1 R T_1$

$$\Rightarrow m_1 = \frac{P_1 V_1}{RT_1} = \frac{0.15 \times 10^6 N/m^2 \times 3m^3}{287 J/kgK \times 298K} = 5.26 kg$$

similarly, $P_2 V_2 = m_2 R T_2$ $\qquad (V_1 = V_2)$

$$\Rightarrow m_2 = \frac{P_2 V_2}{RT_2} = \frac{3 \times 10^6 N/m^2 \times 3m^3}{287 J/kg.K \times 33K} = 94.17 kg$$

Hence mass of air pumped in $(m) = m_2 - m_1 = 94.17 - 5.26$
$= 88.91 kg$

Volume of Air pumped in at pressure 1.02 bar and Temp. 20°c.

Let V_3 = Volume of Air pumped in

We know that $P_3 V_3 = m_3 R T_3$

$$\Rightarrow V_3 = \frac{mRT_3}{P_3} = \frac{88.91 \times 287 J/kgK \times 293K}{0.102 \times 10^6 N/m^2} = 73.29 m^3$$

Pressure in the vessel after cooling,

Let P_4 = Pressure in the vessel after cooling

Temperature after cooling = 25°C = 298K (given)

Since cooling is at constant volume

$$\frac{P_4}{P_2} = \frac{T_4}{T_2} \Rightarrow P_4 = \frac{T_4 \times P_2}{T_2} = \frac{298K \times 3 \times 10^6 N/m^2}{333K} =$$

1 bar $= 0.1 \times 10^6$ N/m^2
1mm of Hg $= 133.3$ N/m^2

Specific heat of a gas

→ The specific heat of a substance may be defined as the amount of heat required to raise the temperature of unit mass through one degree.

→ All the liquids and solids have one specific heat only.

→ But a gas can have any number of specific heat between zero to infinite. $(0-\infty)$

The following two types of specific heats of a gas are to be discussed.

1. Specific heat of constant volume
2. specific heat of constant pressure

1. Specific heat at constant volume (C_v)

→ It is the amount of heat required to raise the temperature of a unit mass of gas through one degree when it is heated at a constant volume.

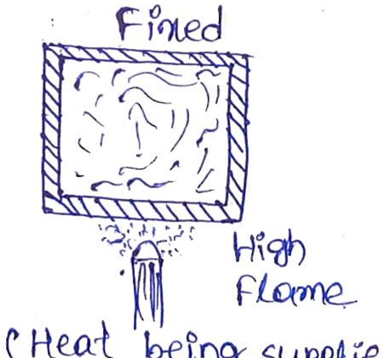
→ It is generally noted by C_v.

* Consider a gas contained in a container with a fixed lid

→ Now, if a gas is heated, it will increase the temperature and pressure of the gas in the container.

→ Since the lid of the container is fixed, therefore the volume of the gas remains unchanged.

Let M = mass of the gas
T_1 = initial temperature of the gas
T_2 = Final temperature of the gas



(Heat being supplied at constant volume)

Hence the total heat supplied to the gas at constant volume

Q_{1-2} = mass × specific heat at constant volume × rise in temperature
$= m \times C_v \times (T_2 - T_1)$

→ It may be noted that whenever a gas is heated at constant volume no work is done by the gas.

→ The whole heat is utilised in increasing the temperature and the pressure of the gas,

2. Specific heat at constant Pressure (C_P)

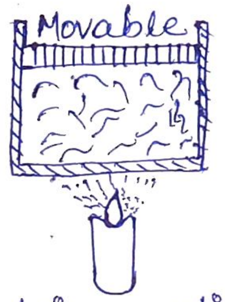
→ It is the amount of heat required to raise the temperature of a unit mass of gas ~~at~~ through one degree, when it is heated at constant pressure.

→ It is denoted by C_p.

* Consider a gas contained in a container with a movable lid

→ Now if the gas is heated it will increase the temperature and pressure of the gas, in the container.

→ Since the lid is movable, therefore it will move upwards, inorder to counter balance the tendency for the pressure to rise.



Heat being supplied at const. Pressure.

Let m = mass of the gas
T_1 = initial temperature of the gas
T_2 = final temperature of the gas
V_1 = initial volume of the gas
V_2 = Final volume of the gas

→ Total heat supplied to the gas at constant pressure

$$Q_{1-2} = \text{mass} \times \text{specific heat at const. pressure} \times \text{Rise in temperature}$$
$$= mc_p \times (T_2 - T_1)$$

→ Whenever a gas is heated at constant pressure, the heat supplied to the gas is utilised for the following two Purposes.

1) To raise the temperature of the gas. This heat remains within the body of the gas, and represents the increase in internal energy.

Mathematically,

$$du = mc_p(T_2 - T_1)$$

2) To do some external work during expansion.

Mathematically, Work done by the gas

$$W_{1-2} = P(V_2 - V_1)$$
$$= mR(T_2 - T_1)$$

→ It is obvious that the specific heat at constant pressure is higher than the specific heat at constant volume

$$\boxed{C_p \text{ greater than } C_v : C_p > C_v}$$

Relation between specific heat :-

→ Consider a gas enclosed in a container and being heated, at constant pressure, from the initial state 1 to final state 2.

Let m = mass of the gas
T_1 = initial temperature of the gas
T_2 = Final temperature of the gas
V_1 = initial volume of the gas
V_2 = Final volume of the gas
C_p = Specific heat at constant pressure
C_v = specific heat at constant volume
P = constant pressure

→ We know that, the heat supplied to the gas at constant pressure

$$Q_{1-2} = mC_p(T_2 - T_1)$$

→ After a part of this heat is utilised in doing the external work and the rest remains within the gas, and is used in increasing the internal energy of the gas.

Heat utilised for external work,

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

and increase in internal energy, $du = mC_v(T_2 - T_1)$.

We know that $Q_{1-2} = W_{1-2} + du$
$= P(V_2 - V_1) + mC_v(T_2 - T_1)$

Using characteristic gas equation i.e. $PV = mRT$

$PV_1 = mRT_1$ (for initial condition)
$PV_2 = mRT_2$ (for final condition)

So, $P(V_2 - V_1) = mR(T_2 - T_1)$

Now substituting the value of $P(V_2 - V_1)$ in

$$mC_p(T_2 - T_1) = mR(T_2 - T_1) + mC_v(T_2 - T_1)$$

$$\Rightarrow C_p m(T_2 - T_1) = Rm(T_2 - T_1) + C_v m(T_2 - T_1)$$

$$\Rightarrow C_p = R + C_v$$

$$\Rightarrow \boxed{C_p - C_v = R}$$

→ The above equation may be written as

$C_p - C_v = R$ or $C_v(\gamma - 1) = R$ where $\gamma = \frac{C_p}{C_v}$

$$\Rightarrow \boxed{C_v = \frac{R}{\gamma - 1}}$$

Enthalpy of a gas :

→ In thermodynamics, one of the basic quantities · most frequently recurring is the sum of the internal energy (U) and the product of pressure and volume (PV).

→ The sum of internal energy and the product of pressure and volume i.e. (U+PV) is termed as enthalpy.

so, Enthalpy(H) = U+PV

→ Since (U+PV) is made up entirely of properties, therefore enthalpy (H) is also a property.

→ For a unit mass, specific enthalpy,

$$h = u + PV_s$$

where u = specific internal energy
P = constant pressure
V_s = Specific volume

1. We know that total heat supplied is equal to the sum of internal energy and workdone during expansion.

   that is $Q_{1-2} = dU + W_{1-2}$

2. When gas is heated at constant pressure from initial condition. 1 to final condition 2, then the change in internal energy is $dU = U_2 - U_1$

3. Workdone by the gas $W_{1-2} = P(V_2 - V_1) = PV_2 - PV_1$

4. $Q_{1-2} = dU + W_{1-2}$

$$\begin{aligned} &= (U_2 - U_1) + P(V_2 - V_1) \\ &= (U_2 - U_1) + PV_2 - PV_1 \\ &= U_2 + PV_2 - U_1 - PV_1 \\ &= U_2 + PV_2 - (U_1 + PV_1) \\ &= H_2 - H_1 \end{aligned}$$

For unit mass $\boxed{Q_{1-2} = h_2 - h_1}$

Classification of thermodynamic Processes

1. Non-flow processes
2. Flow processes

1. Non-Flow Process

→ The process occuring in closed systems which don't permit the transfer of mass across their boundaries, are known as non-flow processes.

→ It may be noted that in a non-flow process, the energy crosses the system boundary, in the form of heat and work.

→ There is no mass flow into or out of the system.

2. Flow Process :-

→ The process occuring in open systems, which permits the transfer of mass to the system and from the system, are known as flow processes.

→ It may be noted that, in a flow process, the mass enters the system and leaves after increasing energy.

→ The flow process may be steady flow and non-steady flow.

→ Steady flow processes occured in nozzle, turbines and compressors.

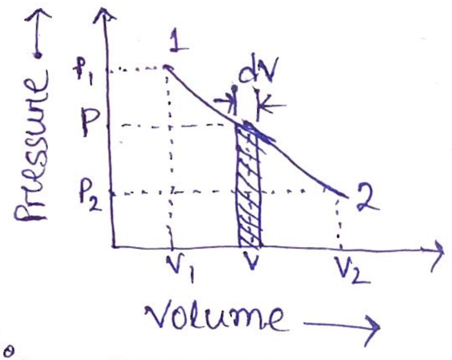
→ Non steady flow processes occured during filling and evacuation of vessels.

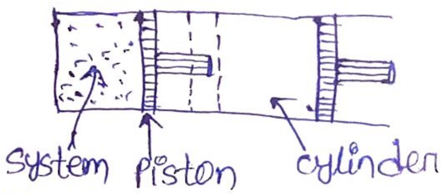
Work done during a non-flow Process :-

→ Consider a system contained in a frictionless piston and cylinder arrangement.

→ As the system expands from the original state 1, it overcomes the external resistance, which opposes the motion of the piston. by exerting force through a distance.

→ The variation of volume and pressure of the system is drawn in the figure in Pressure. Volume diagram. (P-V) diagram)





Let at any small section (shadden in the figure) the pressure of the system is constant.

→ If 'A' is the cross-sectional area of the piston, the force on the piston will be $F = P.A$, causes the piston to move through a distance dx.

So, workdone by the system

* δ = Delta, $\delta W = Fdx$

$= PAdx$

$= PdV$

Application of First law of thermodynamic to a non flow process :-

→ When a system undergoes a change of state or a thermodynamic process, then both the heat transfer and work transfer takes place.

→ The net energy transfered is stored within the system and is known as stored energy or total energy of the system.

Mathematically,

$$dE = Q_{1-2} - W_{1-2}$$
$$= E_2 - E_1$$

where Q_{1-2} = Heat transfered or heat supplied during process 1 to 2,

W_{1-2} = Workdone by the system on the sourrounding during the process

E_2 = Total energy of the system at the end of process

E_1 = Total energy of the system at the start of process

→ Various non-flow processes undergo the application of First law of thermodynamic are

(1) Isothermal Process (constant temperature process)
(2) Isobaric Process (constant pressure process)
(3) Isentropic Process
(4) Polytrophic Process

1. Isothermal Process or (constant temperature Process)

→ A process in which the temperature of the working substance remains constant during its expansion or compression, is called constant temperature process or isothermal process.

→ This will happen when the working substance remains in a perfect thermal contact with the surrounding. So that the heat sucked in or squeezed out is compansated exactly for the workdone by the gas.

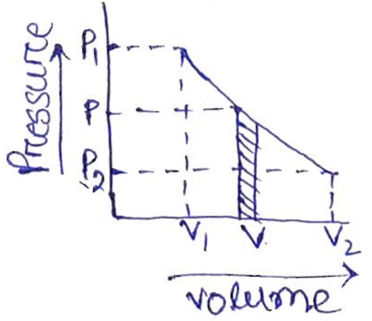
→ It is concluded for the isothermal process that,

i) There is no change in temperature.
ii) There is no change in internal energy.
iii) There is no change in Enthalpy.

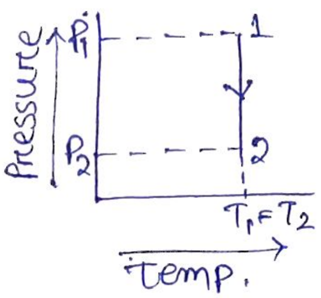
Now consider m kg of a certain gas being heated at constant temperature from initial state 1 to final state 2.

Let $P_1 V_1$ & T_1 = Pressure, Volume and temperature at initial state 1.

P_2, V_2 & T_2 = Pressure, volume and temperature at final state ;



P-V diagram



P-T diagram

1. Pressure - volume - Temp. Relationship (P-V-T)

We know the general gas equation

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

since gas is heated at constant temp. $T_1 = T_2$

so, $P_1V_1 = P_2V_2$

2. Work done by the gas

we know that $\delta W = PdV$

on integrating from state 1 to state 2

$$\int_1^2 \delta W = \int_1^2 PdV \quad \text{or} \quad W_{1-2} = \int_1^2 PdV$$

since the expansion of gas is isothermal i.e PV = constant

so, $PV = P_1V_1$ or $P = \frac{P_1V_1}{V}$

substituting the value of 'P' in equation ① we have

$$W_{1-2} = \int_1^2 PdV = \int_{V_1}^{V_2} \frac{P_1V_1}{V} dV$$

$$= P_1V_1 \int_{V_1}^{V_2} \frac{dV}{V} = P_1V_1 \int_{V_1}^{V_2} \frac{1}{V} dV = P_1V_1 [\log_e V]_{V_1}^{V_2}$$

$$= P_1V_1 \log_e \left(\frac{V_2}{V_1}\right)$$

$$W_{1-2} = P_1V_1 \log_e \left(\frac{V_2}{V_1}\right)$$

The above equation can be expressed in the terms of corresponding logarithm to the base 10 i.e.

$$W_{1-2} = 2.3 P_1V_1 \log\left(\frac{V_2}{V_1}\right)$$

$$= 2.3 P_1V_1 \log r \quad — ③ \quad \left(\because r = \frac{V_2}{V_1}\right)$$

The equation ③ may be written as follows.

We know that $P_1V_1 = P_2V_2 = mRT$

Work done $W_{1-2} = 2.3 \, mRT \log\left(\frac{V_2}{V_1}\right) = 2.3 \, mRT \log r$

since $P_1V_1 = P_2V_2$ therefore $\frac{V_2}{V_1} = \frac{P_1}{P_2}$

Workdone $W_{1-2} = 2.3 P_1V_1 \log\left(\frac{V_2}{V_1}\right)$

$$= 2.3 P_1V_1 \log\left(\frac{P_1}{P_2}\right)$$

$$\left(\because \frac{V_2}{V_1} = \frac{P_1}{P_2}\right)$$

Problem :- A quantity of air has a volume of $0.4 m^3$ at a pressure of 5 bar and a temperature of 80°C. It is expanded in a cylinder at a constant temperature on a pressure of 1 bar. Determine the amount of workdone by the air during expansion.

Solution :- Given data $V_2 = ?$ workdone = ?

$V_1 = 0.4 m^3$

$P_1 = 5 \text{ bar} = 0.5 \times 10^6 \text{ N/m}^2$

$P_2 = 1 \text{ bar} = 0.1 \times 10^6 \text{ N/m}^2$

$P_1 V_1 = P_2 V_2$

$\Rightarrow V_2 = \frac{P_1 V_1}{P_2} = \frac{0.5 \times 10^6 \text{ N/m}^2 \times 0.4 m^3}{0.1 \times 10^6 \text{ N/m}^2} = 2 m^3$

We know expansion ratio $r = \frac{V_2}{V_1} = \frac{2}{0.4} = 5$

Again we know

Workdone $W_{1-2} = 2.3 P_1 V_1 \log\left(\frac{V_2}{V_1}\right)$

$= 2.3 P_1 V_1 \log\left(\frac{2}{0.4}\right)$

$= 321526 J$

Problem :- $0.1 m^3$ of air at a pressure of 1.5 bar is expanded isothermally to $0.5 m^3$. Calculate the final of the gas and heat supplied during the process?

Solution :- Given data

$V_1 = 0.1 m^3$

$V_2 = 0.5 m^3$

$P_1 = 0.15 \times 10^6 \text{ N/m}^2$

$P_2 = ?$, $Q_{1-2} = ?$

We know that $P_1 V_1 = P_2 V_2$

$\Rightarrow P_2 = \frac{P_1 V_1}{V_2} = \frac{0.15 \times 10^6 \text{ N/m}^2 \times 0.1 m^3}{0.5 m^3}$

$= 0.03 \times 10^6 \text{ N/m}^2$

$= 0.3 \text{ bar}$

We know that expansion ratio $r = \frac{V_2}{V_1} = \frac{0.5}{0.1} = 5$

Workdone $W_{1-2} = 2.3 P_1 V_1 \log r$

$= 2.3 \times 0.15 \times 10^6 \times 0.1 \times \log 5$

$= 24114.46 J$

We know that during isothermal process Heat supplied is equal to workdone

So, $Q_{1-2} = W_{1-2} = 24114.46 J.$

Constant Pressure process or Isobaric Process

→ When the gas is heated at a constant pressure process, its temperature and volume will increase.

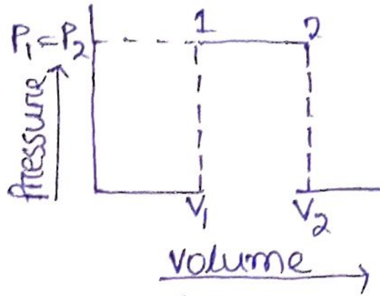
→ Since there is a change in its volume, therefore the heat supplied to the gas is utilised to increase the internal energy of the gas and for doing some external work.

→ It may be noted that this process occurs in charle's law.

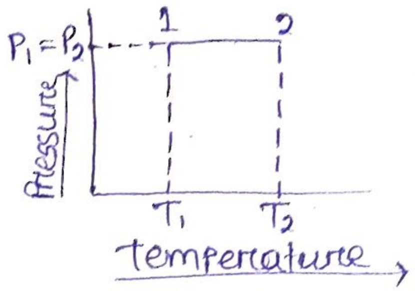
→ Now consider m kg of certain gas being heated at constant pressure from an initial state 1 to final state 2.

Let P_1, V_1 and T_1 = Pressure, volume & temp. at initial state 1

P_2, V_2 and T_2 = Pressure, volume & temp. at final state 2



(P-V diagram)



(P-T diagram)

1. Pressure - volume - Temperature (P-V-T Relationship)

We know general gas equation $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$ ——— ①

Since the gas is heated at constant pressure, so $P_1 = P_2$

so we can write $\frac{V_1}{T_1} = \frac{V_2}{T_2}$ From equation - ①

2. Workdone by the gas.

We know that $\delta W = PdV$

on integrating from state 1 to 2

$$\int_1^2 \delta W = \int_1^2 PdV = P\int_1^2 dV$$

$$\Rightarrow W_{1-2} = P(V_2 - V_1) = PV_2 - PV_1 = mRT_2 - mRT_1 = mR(T_2 - T_1)$$

3. Change in internal energy

Change in internal energy is same for all the process.

Therefore change in internal energy $dU = U_2 - U_1$

$= mC_v(T_2 - T_1)$

4. Heat supplied or Heat transfered

We know that $\delta Q = dU + \delta W$

on integrating from state 1 to 2

$$\int_1^2 \delta Q = \int_1^2 dU + \int_1^2 \delta W$$

$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

$$= mC_v(T_2 - T_1) + mR(T_2 - T_1)$$

$$= m(T_2 - T_1)\{(C_v + R)\}$$

Problem :- The value of specific heat at constant pressure and constant volume for an ideal gas are 0.984 KJ/kgK and 0.728 KJ/kgK. Find the value of characteristic gas constant (R) and ratio of specific heat (γ) for the gas. If 1kg of gas is heat at constant pressure from 25°C to 200°C. Estimate the heat added, ideal workdone, change in internal energy. Also calculate the pressure and final volume, if the initial volume was 2m³.

solution :- Given data

$m = 1\,kg$, $V_1 = 2\,m^3$

$V_2 = ?$

$C_p = 0.984\ KJ/kg.K$

$C_v = 0.728\ KJ/kg.K$

$T_1 = 25°C = 298\,K$

$T_2 = 200°C = 473\,K$

1. Value of characteristic gas constant (R)

We know $C_p - C_v = R$

$$\Rightarrow R = 0.984\ KJ/kgK - 0.728\ KJ/kg.K$$

$$= 0.256\ KJ/kg.K$$

2. Ratio of specific heat (γ)

We know $\gamma = \frac{C_p}{C_v} = \frac{0.984\ KJ/kg.K}{0.728\ KJ/kg.K} = 1.35$

3. Heat added (Q_{1-2})

We know that heat added during constant pressure

$$Q_{1-2} = mC_p(T_2 - T_1) = 1kg \times 0.984\ KJ/kg.K \times (473 - 298)K$$

$$= 172.2\ KJ$$

4. Ideal work done (W_{1-2})

We know $W_{1-2} = P(V_2 - V_1) = mR(T_2 - T_1)$

$$= 1kg \times 0.256\ KJ/kg.K \times (473 - 298)K$$

$$= 44.8\ KJ$$

5. Change in internal energy (dU)

We know $dU = U_2 - U_1 = mc_v(T_2 - T_1)$

$= 1kg \times 0.728\ KJ/kg.k \times (473 - 298)k$

$= 127.4\ KJ.$

6. Pressure and final volume if the initial volume was $2m^3$.

Let $P_1 = P_2$ = Pressure of the gas

V_2 = Final volume $2m^3$

We know general gas equation

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \Rightarrow \frac{V_1}{T_1} = \frac{V_2}{T_2} \quad (\because P_1 = P_2)$$

$$\Rightarrow \frac{2m^3}{298k} = \frac{V_2}{473k}$$

$$\Rightarrow V_2 = \frac{2m^3 \times 473k}{298k} = 3.17m^3$$

7. Pressure (P)

We know $P_1V_1 = mRT_1$

$$\Rightarrow P_1 = \frac{mRT_1}{V_1} = \frac{1kg \times 0.256\ KJ/kg.k \times 298.k}{2m^3}$$

$$= 38.14\ N/m^2$$

Isentropic Process or Adiabatic Process or

Isentropic Process

→ A process in which the working substance neither receives nor gives out heat to it's surrounding during it's expansion or compression is called an adiabatic process or isentropic process.

→ It may be noted that the reversible adiabatic process or frictionless adiabatic process is known as Isentropic process or Constant Entropy process.

→ During friction the adiabatic process is known as irreversible process.

→ During Isentropic process or adiabatic process, the working substance remains thermally insulated, so that no heat enters or leaves it.

Important points about Isentropic process.

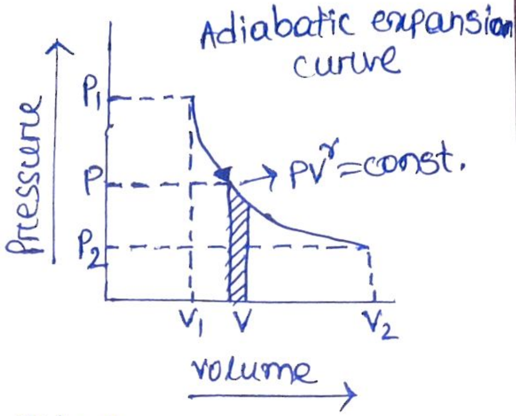
1. No heat leaves or enters the gas.
2. The temperature of the gas changes as the work is done at the cost of internal energy.

3. The change in internal energy equal to the work done.

Now consider m kg of certain gas being heated adiabatically from an initial state 1 to final state 2.

Let P_1, V_1 & T_1 = Pressure, volume and temp. at the initial state 1.

P_2, V_2 & T_2 = Pressure, volume and temp. at the final state 2.



1. Pressure - Volume - Temperature (P-V-T) Relationship

We know that $\delta Q = \delta W + dU$

first law of thermodynamic —— ①

Since in an adiabatic process no heat transfer takes place, therefore

$$\delta Q = 0$$

$$\delta W + dU = 0 \Rightarrow P(V_2 - V_1) + mc_v(T_2 - T_1) = 0$$

or $$Pdv + mc_v . dT = 0$$

$$\Rightarrow mc_v . dT = -Pdv$$

$$\Rightarrow dT = \frac{-Pdv}{mc_v}$$

We know $PV = mRT$ —— ②

Differentiating this expression we get

$$PdV + VdP = mRdT$$

$$dT = \frac{PdV + VdP}{mR} = \frac{PdV + VdP}{m(c_p - c_v)} \text{ —— ③} \quad (\because R = c_p - c_v)$$

Equating equation ② & ③

$$-\frac{PdV}{mc_v} = \frac{PdV + VdP}{m(c_p - c_v)} \Rightarrow \frac{c_p - c_v}{c_v} = \frac{\cancel{m}(PdV + VdP)}{\cancel{m}(-PdV)}$$

$$\Rightarrow \frac{c_p - c_v}{c_v} = \frac{PdV + VdP}{-PdV}$$

$$\Rightarrow \frac{c_p}{c_v} - \frac{c_v}{c_v} = -\frac{PdV}{PdV} - \frac{Vdp}{PdV}$$

$$\Rightarrow \gamma - 1 = -1 - \frac{VdP}{PdV}$$

$$\Rightarrow \gamma - 1 = -1 - \left(\frac{V}{dV} \times \frac{dP}{P}\right)$$

$$\Rightarrow \gamma = -\left(\frac{V}{dV} \times \frac{dP}{P}\right)$$

$$\Rightarrow \gamma \times \frac{dV}{V} = -\frac{dP}{P}$$

$$\Rightarrow \gamma \times \frac{dV}{V} + \frac{dP}{P} = 0$$

$$\Rightarrow \gamma \frac{dV}{V} + \frac{dP}{P} = 0$$

Integrating both sides

$$\gamma \int \frac{dv}{V} + \int \frac{dP}{P} = C$$

$$\Rightarrow \gamma \int \frac{1}{V}\,dv + \int \frac{1}{P}\,dP = C$$

$$\Rightarrow \gamma \log_e V + \log_e P = \log_e C$$

$$\Rightarrow \log_e V^{\gamma} + \log_e P = \log_e C$$

$$\Rightarrow \log_e (V^{\gamma} \cdot P) = \log_e C$$

$$\Rightarrow V^{\gamma} \cdot P = C$$

PV^{γ} = constant

or $P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$ = constant —— ④

The above equation may be expressed as

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{\gamma} \text{ —— ⑤}$$

From the general gas equation

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad \text{or} \quad \frac{P_1}{P_2} = \frac{T_1}{T_2} \times \left(\frac{V_2}{V_1}\right) \text{ —— ⑥}$$

$$\text{or} \quad \frac{P_1}{P_2} = \frac{T_1}{T_2} \times \left(\frac{V_1}{V_2}\right)^{-1}$$

$$\Rightarrow \left(\frac{V_2}{V_1}\right)^{\gamma} = \frac{T_1}{T_2} \times \left(\frac{V_2}{V_1}\right) \quad \Rightarrow \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma} \times \left(\frac{V_2}{V_1}\right)^{-1}$$

$$\Rightarrow \boxed{\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma - 1}}$$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{\gamma} \Rightarrow \left(\frac{P_1}{P_2}\right) = \left(\frac{V_1}{V_2}\right)^{1/\gamma} \Rightarrow \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} = \left(\frac{V_1}{V_2}\right) \text{ —— ⑧}$$

From general gas equation

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \Rightarrow \frac{V_1}{V_2} = \left(\frac{T_1}{T_2}\right) \times \left(\frac{P_2}{P_1}\right)$$

$$\Rightarrow \frac{V_1}{V_2} \times \frac{P_1}{P_2} = \frac{T_1}{T_2}$$

$$\Rightarrow \frac{T_1}{T_2} = \frac{V_1}{V_2} \times \frac{P_1}{P_2}$$

$$\Rightarrow \frac{T_1}{T_2} = \left(\frac{P_2}{P_1}\right)^{1/\gamma} \times \left(\frac{P_1}{P_2}\right)^{1} \quad (\because \text{from equation - ⑧})$$

$$\Rightarrow \frac{T_1}{T_2} = \left(\frac{P_2}{P_1}\right)^{1/\gamma} \times \left(\frac{P_2}{P_1}\right)^{-1}$$

$$\Rightarrow \frac{T_1}{T_2} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma} - 1}$$

$$\Rightarrow \frac{T_1}{T_2} = \left(\frac{P_2}{P_1}\right)^{\frac{1-\gamma}{\gamma}} \text{ —— ⑨}$$

2. Workdone during adiabatic expansion :-

We know that workdone $\delta W = PdV$

On integrating from state 1 to state 2

$$\int_1^2 \delta W = \int_1^2 PdV \quad \text{or} \quad W_{1-2} = \int_1^2 PdV . \text{———} \quad (3a)$$

Since adiabatic expansion of the gas follows the law

$$PV^\gamma = P_1V_1^\gamma \quad \text{or} \quad P = \frac{P_1V_1^\gamma}{V^\gamma}$$

substituting this value of 'P' in the equation (3a)

$$W_{1-2} = \int_1^2 PdV = \int_1^2 \frac{P_1V_1^\gamma}{V^\gamma} dV$$

$$\int_1^2 \frac{P_1V_1^\gamma}{V^\gamma} dV = \int_1^2 P_1V_1^\gamma \times \frac{1}{V^\gamma} dV = \int_1^2 P_1V_1^\gamma \times V^{-\gamma} dV$$

$$= P_1V_1^\gamma \int_1^2 V^{-\gamma} dV = P_1V_1^\gamma \left[\frac{V^{-\gamma+1}}{-\gamma+1}\right]_1^2 = P_1V_1^\gamma \left[\frac{V^{-\gamma+1}}{1-\gamma}\right]_1^2$$

$$= \frac{P_1V_1^\gamma}{1-\gamma}\left(V_2^{-\gamma+1} - V_1^{-\gamma+1}\right) = \frac{P_1V_1^\gamma}{1-\gamma}\left(V_2^{1-\gamma} - V_1^{1-\gamma}\right) = \frac{P_1V_1^\gamma V_2^{1-\gamma}}{1-\gamma} - \frac{P_1V_1^\gamma V_1^{1-\gamma}}{1-\gamma}$$

$$= \frac{P_1V_1^\gamma V_2^{1-\gamma} - P_1V_1^\gamma V_1^{1-\gamma}}{1-\gamma} = \frac{P_2V_2^\gamma V_2^{1-\gamma} - P_1V_1^\gamma V_1^{1-\gamma}}{1-\gamma} \quad (\because P_1V_1^\gamma = P_2V_2^\gamma)$$

$$= \frac{P_2V_2^{\gamma+1-\gamma} - P_1V_1^{\gamma+1-\gamma}}{1-\gamma}$$

$$= \boxed{\frac{P_2V_2 - P_1V_1}{1-\gamma}} \leftarrow \text{for compression} \qquad \boxed{\frac{P_1V_1 - P_2V_2}{1-\gamma}} \leftarrow \text{for expansion}$$

3. Change in Internal Energy (dU)

$$dU = U_2 - U_1 = mC_v(T_2 - T_1)$$

4. Heat Supplied or heat transferred

We know that heat supplied or heat transfered in case of adiabatic process is zero,

therefore $Q_{1-2} = 0$

5. Change in Enthalpy:

We know that change in Enthalpy $dH = H_2 - H_1 = mC_p(T_2 - T_1)$

Problem :

One litre of Hydrogen at 0°C is suddenly compressed to one half of it's volume. Find the change temperature of the gas if the ratio of two specific heats for hydrogen is 1.4.

Solution Given data

Initial Vol. $V_1 = 1$ ltr

Final Vol. $V_2 = \frac{V_1}{2} = \frac{1}{2}$ ltr $= 0.5$ ltr

$\gamma = 1.4$

Initial Temp. $T_1 = 0^\circ C = 273 K$

We have to find out the change in Temp. that is final Temp.

We know $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma - 1}$

$\Rightarrow \frac{273}{T_2} = \left(\frac{0.5}{1}\right)^{1.4-1} \Rightarrow \frac{273}{T_2} = (0.5)^{0.4} \Rightarrow T_2 = \frac{273}{(0.5)^{0.4}} = 360.22 K$ or $87.22^\circ C$

Isentropic Process Formulaes :

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

② $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma - 1}$

③ $\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma - 1}{\gamma}}$

④ Workdone during expansion & compression

(i) $\frac{P_1V_1 - P_2V_2}{\gamma - 1}$ for expansion

(ii) $\frac{P_2V_2 - P_1V_1}{\gamma - 1}$ for compression

⑤ change in internal Energy $dU = mC_v(T_2 - T_1)$

⑥ Heat supplied or heat transfered $Q_{1-2} = 0$

⑦ change in Enthalpy $\Rightarrow dH = H_2 - H_1 = mC_p(T_2 - T_1)$

Polytropic Process

→ A polytropic process is also known as the general law for the expansion and compression of gases.

→ It is given by the relation $PV^n =$ constant.

where n is polytropic index.

→ 'n' value may be any value from zero to infinite ($0 - \infty$) depending upon the manner, in which the expansion or compression has taken place.

Now consider 'm' kg of a certain gas being heated polytropically from an initial state 1 to final state 2.

Let P_1, V_1 & T_1 = Pressure, Volume & Temp. at initial state 1.

P_2, V_2 & T_2 = Pressure, Volume & Temp. at final state 2.

Pressure - Volume - Temperature (P-V-T) Relationship

(a) $P_1V_1^n = P_2V_2^n =$ constant

(b) $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{n-1}$

(c) $\frac{V_1}{V_2} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$

(d) $\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}}$

2. Workdone during polytropic expansion

The equation for the workdone during a polytropic process may also be expressed by changing the index 'n' for γ in the adiabatic process.

so, workdone during a polytropic process from state 1 to state 2.

$$W_{1-2} = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{mR(T_1 - T_2)}{n-1} \rightarrow \text{For expansion}$$

$$= \frac{P_2V_2 - P_1V_1}{n-1} = \frac{mR(T_2 - T_1)}{n-1} \rightarrow \text{For compression}$$

3. Change in Internal energy

We know that change in internal energy $dU = U_2 - U_1 = mC_v(T_2 - T_1)$

——— × ———

CHAPTER-6 FUELS AND COMBUSTION

→ Fuel may be defined as a substance (containing carbon and hydrogen.) which on burning with oxygen in the atmospheric air produces a large amount of heat.

Types of fuels

→ Fuels may be classified into the following three general forms.

(i) solid fuels
(ii) liquid fuels
(iii) Gaseous fuels

(i) Solid Fuels

→ The natural solid fuels are wood, peat, Lignite, bituminous coal, anthrasite coal.

1. Wood:→ It consists of carbon Hydrogen.

→ The wood is converted into coal when burnt in the absence of air.

→ The average calorific value of wood is 19700 KJ/kg.

2. Peat:→ It is the first stage in the formation of coal.

→ It has a large amount of water content (upto 30%), therefore, it has to be dried before use.

→ It's average calorific value is 23000 KJ/kg.

3. Lignite or brown coal:

→ It represents the next page of peat in the coal information.

→ It contains nearly 40% moisture and 60% of carbon.

→ It's average calorific value 25000 KJ/kg.

4. **Bituminous coal :-**

- → It represents the next stage of lignite in the coal formation
- → It contains 4.6 % moisture and 75 to 90 % carbon.
- → It is weather resistance and burns with a yellow flame.
- → It average calorific value is 33000 KJ/kg.
- → The bituminous coal is two types (a) caking bituminous coal
  (b) Non-caking bituminous coal

5. **Anthrasite coal :-**

- → It represents the final stage in the coal formation and contains 90 % carbon.
- → It is smokeless. and a very little flame.
- → It possesses a high calorific value i.e. 36000 KJ/kg.

6. **Wood charcoal :-**

- → It is made by heating wood with a limited supply of air.
- → It is used for various metallurgical process.

7. **Coke :-**

- → It is produced when coal is strongly heated continuously for 42 to 48 hours in the absence of air in a closed vesel.
- → this process is known as carbonisation of coal.
- → It has high carbon content. and high calorific value than coal.
- → If the carbonisation of coal is carried out at 500°-700°C, the resulting coke is called lower temperature or soft coke and used as domestic fuel.
- → If the carbonisation of coal is carried out at 900°-1100°C is known as hard coke and is used as blast furnace fuel.

8. **Briquetted coal :-**

- → It is produced by the finely ground coal by moulding under pressure with or without binding material,
- → The briquetted has advantage by high heating value.

9. **Pulverised coal :-**

- → The low grade coal with high ash content, is powdered to produce pulverised coal.
- → The coal is first dried, then crushed into fine powder.
- → Pulverised coal is widely used in cement industry and metallurgical process.

(ii) Liquid Fuels

Liquid fuels are basically 3 types such as

1. Petrol or gasoline
2. kerosine or Paraffin oil.
3. Heavy fuel oil

→ Almost all the commercial liquid fuels are derived from natural petroleum (crude oil).

→ The crude oil is obtained from above holes in the earth's crust in certain part of the world.

→ The natural petroleum may be separated into petrol or gasoline, paraffin oil or kerosine, fuel oil and lubricating oil.

→ For the separation of the various products from crude oil fractional distillation process is done.

1. Petrol or gasoline :-

→ It is the lightest and most volatile liquid fuel used for light petrol engines.

→ It is distilled at 65° to 220° C.

2. kerosine or Paraffin Oil :-

→ It is heavier and less volatile fuel than petrol and used as heating and lighting fuel.

→ It is distilled at 220° to 345° C.

3. Heavy Fuel Oil :-

→ The liquid fuels distilled after petrol and kerosine are known as heavy fuel oil

→ These oils are used in disel engines and in oil fired boilers.

→ These are distilled at 345° to 470°C.

Merits and demerits of liquid fuels over solid fuels.

* Merits :-

1. Higher calorific value.
2. Lower storage capacity required.
3. Better economy in handling.
4. Better control of consumption by using values.
5. Better cleanliness and freedom from dust.
6. Practically no ashes.
7. Non-corrosion of boiler plates.
8. Higher efficiency.

*** Demerits :**
- → High cost.
- → Greater risk of fire.
- → Costly container are required.

IMP Gaseous Fuels :
- → The natural gas is found in or near petroleum fields, under the earth's surface.
- → It consists of methane (CH_4), Ethane (C_2H_6), carbon dioxide (C and carbon monoxide (CO).
- → The gaseous fuels are (1) Coal gas
  (2) Producer gas
  (3) Water gas
  (4) Mond gas
  (5) Blast furnace gas
  (6) Coke oven gas

(1) Coal gas :-
- → It is also known as town gas.
- → It is obtained by carbonisation of coal.
- → It consists of Hydrogen, Carbon monoxide, Hydrocarbon.
- → It is very rich among combustible gases
- → It is used in town for street and domestic lighting ar heating.
- → It is calorific value is 21000 to 25000 KJ/m^3.

(2) Producer gas :
- → It is obtained by partial combustion of coal, coke, anthrasite coal, or charcoal in a mixed air, steam blas
- → It is used for furnaces for glass melting and power generation.
- → It's calorific value is 5000 to 6700 KJ/m^3.

(3) Water gas :
- → It is a mixture of Hydrogen and carbon monoxide and passing steam over incandescent coke.
- → As it burns with blue flame, it is also known as blue water gas.
- → Water gas is mixed with coal gas to form coal gas or Town gas.
- → Water gas is used in furnaces and welding.

(4) Mond gas :-

→ It is produced by passing air and a large amount of steam over waste coal about 650°c.
→ It is used for Power generation and heating.
→ It's calorific value is about 5850 kJ/m^3.

(5) Blast furnace gas :-

→ It is a by-Product in the production of pig iron in the blast furnace.
→ It is used in steel works, for power generation. in gas engine. For steam raising in boiler, and preheating the blast furnace.
→ It has low heating value or calorific value i.e. 3750 kJ/m^3.

(6) Coke oven gas :-

→ It is by product from coke oven.
→ It is obtained by carbonisation of bituminous coal.
→ It's calorific Value varies from 14,000 to 18,500 kJ/m^3.
→ It is used for industrial heating and power generation.

Merits and demerits of gaseous fuel.

Merits :-

1. The supply of fuel gas, the temperature of furnace is easily and accurately controlled.
2. The high temperature is obtained at a moderate cost by Pre-heating gas and air with heat of waste gases of combustion.
3. They are directly used in internal combustion engine.
4. They are free from solid and liquid impurities.
5. They donot produce ash or smoke.
6. they undergo complete combution with minimum air supply.

Demerits :-

1. They are readily inflamable.
2. They require large capacity.

Imp Requirement of good fuel :-

Following points are important for requirement of good fuel.

1. A good fuel should have low ignition point.
2. It should have high calorific value.
3. It should freely burn with high efficiency, once it is ignited.
4. It should not produce harmful gases.

5. It should produce least quantity of smoke and gases.
6. It should be economical, easy to store, convenient for transportation.

Important: Calorific value of fuels : (C.V) or heat value.

→ The calorific value (briefly written as C.V), or heat valu of a solid or liquid fuel may be defined as the amoun of heat given but by the complete combustion of 1kg of fuel.

→ It is expressed in the terms of KJ/kg of fuel and for gaseous fuel. It is expressed KJ/m3.

There are two types of calorific value of fuels:

1. Gross or higher calorific value
2. Net or lower calorific value

Rating of C.I (Compression Ignition) Engine fuels - Centane number:

→ The knocking tendency is also found in compression Ignition (C.I), engine with an effect similar to that of S.I (Spark Ignition) Engine.

→ The property of Ignition lag is generally measured in terms of centane number.

Imp → The centane number is defined as the percentage, by volum of centane in a mixture centane and alfa-methyle-napthalene that produces the same ignition lag as the fuel being tested, in the same engine under same operating condition.

→ The centane which is a straight chain paraffin with good ignition quality is assigned a centane number of 100 and alfa-methyle-napthalene which is a Hydro-carbon, with poor ignition quality is assigned 0 (zero) centane number.