

Grade XI Physics – Notes on Thermodynamics

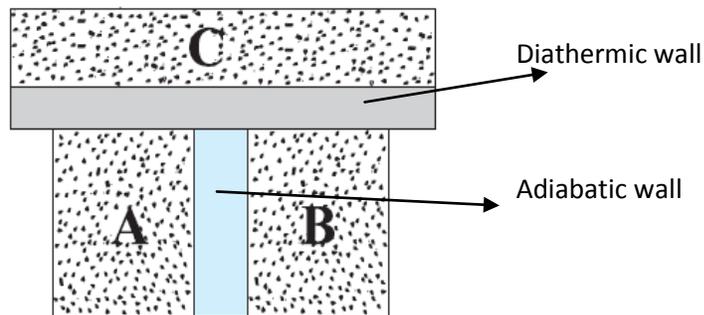
It is the study of the relation between heat energy and mechanical energy.

Some definitions:

- **Thermodynamic system:-** It is a collection of large number of molecules having some value of pressure volume and temperature.
- **Thermodynamic variables:-** the variables which determine the behavior of a system. E.g. Pressure, Volume, temperature.
- **Internal energy (U)** – the sum of kinetic and potential energies possessed by the molecules of a substance.
- **Dia-thermic wall:-** A wall that allows exchange of heat between system and the surroundings.
- **Adiabatic wall:-** A wall that does not allow exchange of heat between system and the surroundings.
- **Extensive variables:-** The variables that depend on the size of the system. E.g. Volume, mass etc.
- **Intensive variables:-** The variables that do not depend on the size of the system. E.g. density, temp.
- **Equation of state:-** The equation that relates thermodynamic variables. E.g. $PV = nRT$
- **Thermal equilibrium:** If two systems are at the same temperature, they are said to be in thermal equilibrium. Thus temperature is that property which determines whether two systems are in thermal equilibrium or not.
- **Thermodynamic process:-** When the thermodynamic variables of a system change with time, it is referred to as a thermodynamic process.

ZEROTH LAW OF THERMODYNAMICS

If two systems A and B are separately in thermal equilibrium with a third system C, then those two systems are in thermal equilibrium with each other.



Work done during a thermodynamic process.

Consider an ideal gas under pressure P , taken in a container fitted with a piston of area of cross-section A . Let it be moved through a distance dx . Then the work done for the process is given by,

$$dW = F \cdot dx. \quad \text{i.e., } dW = P \cdot A \cdot dx.$$

So $dW = PdV$, where $dV = A \cdot dx$, the change in volume.

Hence the total work can be found using, $W = \int P \cdot dV$

Note: Further, the total work done can also be determined by calculating the area enclosed by the P-V diagram called 'indicator diagram' of a thermodynamic process.

Different types of thermodynamic processes

1. **Isothermal process:-** It is the process during which the temperature of the system remains a constant throughout. So there is no change in internal energy of the system during the process. Thus the first law of thermodynamics gives, $\Delta Q = \Delta W$

The equation for the process is $PV = \text{a constant}$.

Work done during isothermal process

We know, $W = \int P.dV$ But $PV = nRT$ (Ideal Gas Equation)

$$\text{Thus } W = \int \frac{nRT}{V}.dV = nRT \int_{V_1}^{V_2} \frac{1}{V} dV = nRT [\log_e V]$$

this gives Work done, $W = nRT (\log_e V_2 - \log_e V_1)$ or

$$W = 2.303 nRT (\log \frac{V_2}{V_1})$$

2. **Adiabatic process:-** It is the process during which there is no exchange of heat between the system and the surroundings. So, during the process there is always a change in internal energy. In adiabatic expansion, the work done is completely by making use of the internal energy of the gas. Hence at the conclusion of the process, the internal energy decreases. i.e. temperature decreases. This shows that adiabatic expansion leads to *cooling*. (e.g. sudden bursting of a tyre). Similarly adiabatic compression causes heating.

The equation for the process is $PV^\gamma = \text{a constant}$. Where $\gamma = C_p/C_v$, the ratio of specific heats.

Work done during adiabatic process

We have, work done during a thermodynamic process,

$W = \int P.dV$ But for adiabatic process, $PV^\gamma = C$, a constant.

$$\text{Hence } W = \int_{V_1}^{V_2} \frac{C}{V^\gamma} dV = C \int_{V_1}^{V_2} V^{-\gamma} dV$$

$$\text{It gives } W = C \left[\frac{V^{-\gamma+1}}{-\gamma+1} \right] = \frac{C}{1-\gamma} [V_2^{1-\gamma} - V_1^{1-\gamma}]$$

$$W = \frac{C}{\gamma-1} [V_1^{1-\gamma} - V_2^{1-\gamma}] = \frac{C}{\gamma-1} \left[\frac{1}{V_1^{\gamma-1}} - \frac{1}{V_2^{\gamma-1}} \right]$$

However, $P_1 V_1^\gamma = P_2 V_2^\gamma = C$.

$$\text{So, } W = \frac{1}{\gamma-1} \left[\frac{P_1 V_1^\gamma}{V_1^{\gamma-1}} - \frac{P_2 V_2^\gamma}{V_2^{\gamma-1}} \right]$$

Thus the work done during adiabatic process can be expressed as

$$W = \frac{1}{\gamma - 1} [P_1 V_1 - P_2 V_2]$$

It can also be written as $W = \frac{nR}{\gamma - 1} (T_1 - T_2)$ using $PV = nRT$

3. *Isobaric process*:- It is the process during which the pressure of the system remains constant throughout.

Work done is given by $W = P (V_2 - V_1)$

4. *Isochoric process*:- It is the process during which the volume of the system remains constant throughout.

Hence **no** work is done on or by the system.

5. *Reversible process*:- A thermodynamic process, at the conclusion of which, the system and the surroundings are brought back to the same initial states, without any change in the rest of the universe. The following conditions are required for this process:

- It should be extremely slow.
- There should not be any dissipative forces such as friction.
- There should be no loss of heat in the form of convection, conduction or radiation.

Hence a reversible process is an ideal situation.

6. *Quasi-static process*: A process, at every stage of which system remains in thermal and mechanical equilibrium (i.e. pressure, temperature and volume do not differ much) with the surroundings throughout. The process should be extremely slow.

7. *Irreversible process*:- A thermodynamic process, at the conclusion of which, the system and the surroundings cannot be brought back to the same initial states.

FIRST LAW OF THERMODYNAMICS

It states that the heat supplied to a thermodynamic system is the sum of the change in internal energy and the external work done.

$$\Delta Q = \Delta U + \Delta W \quad (\text{this law is another form of 'the law of conservation of energy'})$$

Applications of the first law

- (a) **Cyclic process**: In a cyclic process, the final temperature of the system will become the same as the initial temperature. i.e., there will be no overall change in the internal energy. ($\Delta U = 0$).

So, $\Delta Q = \Delta W$

It shows that the heat supplied is completely used to do work during a cyclic process.

- (b) **Boiling**: The change in internal energy of a liquid during boiling can be found as below:

Heat supplied (ΔQ) = mL.

If the volume changes from V_1 to V_2 during boiling, the work done $(\Delta W) = P (V_2 - V_1)$.
Hence using the above law we can calculate the change in internal energy using,

$$\Delta U = mL - P (V_2 - V_1)$$

(c) **Mayer's relation:** It is the equation relating the two specific heats of gases.

Consider 'n' moles of a gas taken in a container. Let it be heated to raise its temperature through ΔT , such that the internal energy increases by ΔU . It can be done in two different ways:

At constant volume, $\Delta W = 0$. $\Delta Q = nC_v\Delta T$

Hence from the first law, we get, $\Delta U = nC_v\Delta T$ -----(1)

At constant pressure, $\Delta Q = nC_p\Delta T$ and $\Delta W = P\Delta V$

Hence $nC_p\Delta T = \Delta U + P\Delta V$ -----(2)

From $PV = nRT$, we can deduce $P\Delta V = nR\Delta T$

So, eqn (2) becomes $nC_p\Delta T = nC_v\Delta T + nR\Delta T$.

Thus $C_p - C_v = R$. This is **Mayer's relation**

Note: The ratio of the two specific heats is represented by γ . i.e., $\gamma = C_p/C_v$.

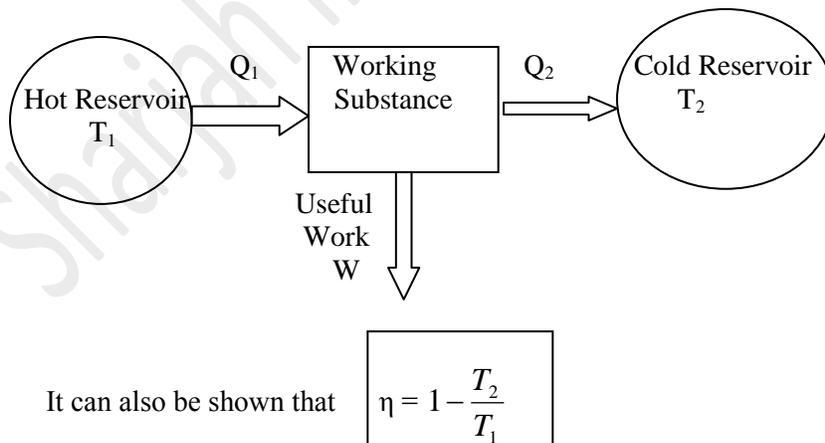
HEAT ENGINES

It is a device used to convert heat energy into mechanical energy.

A heat engine mainly consists of three essential components:

- (1) A source at a very high temperature, T_1 .
- (2) A working substance on which the operations are carried out.
- (3) A sink at a very low temperature, T_2 .

The working substance absorbs heat Q_1 from the source and performing useful work W . The excess heat Q_2 is rejected to the sink.



Thermal efficiency

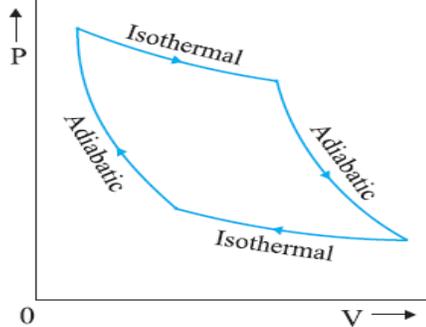
$(\eta) = (\text{Useful work done}) / (\text{heat supplied})$

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

$$\eta = 1 - \frac{Q_2}{Q_1}$$

It further shows that it is impossible to construct a heat engine with 100% efficiency because of the impossibility of keeping sink at absolute zero (i.e. 0 Kelvin).

The Indicator diagram of the operations performed in an ideal heat engine (called 'Carnot engine') is given below:



Here, more work is done by the system than that is done on the system. Hence the net work done is given by the area enclosed by the loop in the graph beside.

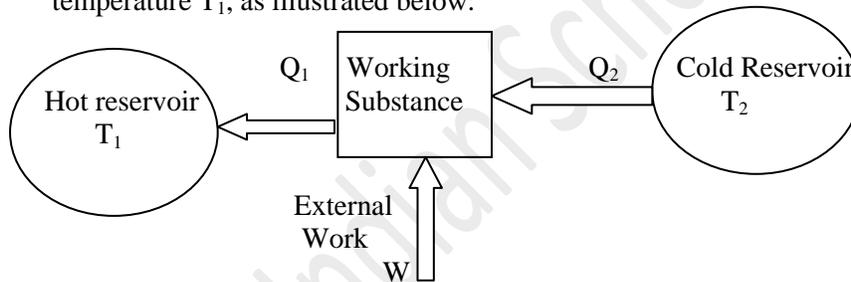
SECOND LAW OF THERMODYNAMICS

Kelvin's statement:- No process is possible whose sole result is the absorption of heat from a reservoir and the complete conversion of the heat into work..

Clausius statement:- No process is possible whose sole result is the transfer of heat from a colder object to a hotter object.

REFRIGERATOR OR HEAT PUMP

It is the reverse of Heat engine. Heat is absorbed (Q_2) from the cold reservoir at a lower temperature T_2 with the help of external work W and is rejected to the hot reservoir at a higher temperature T_1 , as illustrated below:



The coefficient of performance of a refrigerator is defined as the ratio of the heat absorbed from the source to the external work done.

$$\text{i.e. } \beta = Q_2 / W$$

But $Q_1 = Q_2 + W$

$$\text{So, } \beta = \frac{Q_2}{Q_1 - Q_2}$$

OR

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