12 Thermodynamics

Lesson at a Glance

• The branch of physics which deals with the study of transformation of heat into other forms of energy and vice-versa is called thermodynamics.

• Thermal Equilibrium

A thermodynamic system is in an equilibrium state if the macroscopic variables such as pressure, volume, temperature, mass composition etc. that characterise the system do not change in time. In thermal equilibrium, the temperature of the two systems are equal.

• Zeroth Law of Thermodynamics

This law identifies thermal equilibrium and introduces temperature as a tool for identifying equilibrium. According to this law "If two systems are in thermal equilibrium with a third system then those two systems themselves are in equilibrium."

• First Law of Thermodynamics

The first law of thermodynamics is simply the general law of conservation of energy applied to any system. According to this law, "the total heat energy change in any system is the sum of the internal energy change and the work done."

When a certain quantity of heat dQ is subjected to a system, a part of it is used in increasing the internal energy by dU and a part is used in performing external work dW, hence

$$dQ = dU + dW$$

• From First Law of Thermodynamics we find a relation between two principal specific heats of an ideal gas. According to the relation

$$C_p - C_v = R$$

Here C_p and C_v are molar specific heats under constant pressure and constant volume condition respectively.

• Isothermal Process

A change in pressure and volume of a gas without any change in its temperature, is called an isothermal change. In such a change, there is a free exchange of heat between the gas and its surroundings.

• Adiabatic Process

A process in which no exchange of heat energy takes place between the gas and the surroundings, is called an adiabatic process.

• The work done dW under adiabatic change is given by

$$dW = \frac{R(T_2 - T_1)}{(\gamma - 1)} = \frac{P_2V_2 - P_1V_1}{(\gamma - 1)}$$

where T_1 and T_2 are initial and final temperatures.

• Equation of state of an adiabatic process may be written in three different forms:

(*i*) PV^γ = a constant or $P_1V_1^\gamma = P_2V_2^\gamma$

(*ii*) $T.V^{\gamma-1}$ = a constant or $T_1V_1^{\gamma-1} = T_2V_1^{\gamma-1}$ and

(*iii*) $P^{\gamma-1}.\ T^\gamma$ = a constant or $\left(\frac{P_1}{P_2}\right)^{1-\gamma} = \left(\frac{P_2}{P_1}\right)^{\gamma-1} = \left(\frac{T_2}{T_1}\right)^\gamma$

Here γ is the ratio of two principal specific heats of gases *i.e.*,

$$\gamma = \frac{C_p}{C_v} = \frac{c_p}{c_v}.$$

• P-V Diagram

A graph representing the variation of pressure with the variation of volume is called P–V diagram.

• Reversible Process

A process which can retrace so that the system passes through the same states is called a reversible process, otherwise it is irreversible.

• Second Law of Thermodynamics

This principle which disallows certain phenomena consistent with the First law of thermodynamics is known as the second law of thermodynamics.

Following are the two statements of second law of thermodynamics.

Kelvin-Planck Statement: It is impossible to construct an engine, operating in a cycle, to extract heat from hot body and convert it completely into work without leaving any change anywhere *i.e.*, 100% conversion of heat into work is impossible.

Clausius Statement: It is impossible for a self acting machine, operating in a cycle, unaided by any external energy to transfer heat from a cold body to a hot body. In other words heat can not flow itself from a colder body to a hotter body.

• A heat engine is a device by which a system is made to undergo a cyclic process that results in conversion of heat to work. Basically, a heat engine consists of: (*i*) a heat source, (*ii*) a heat sink, and (*iii*) a working substance.

• **Carnot's Engine.** He proposed a hypothetical engine working on a cyclic/reversible process operating between two temperatures. Its efficiency is independent of the working substance and is given by,

$\eta = 1 - \frac{T_2}{T_1}$, where T_1 is the temperature of source and T_2 is the temperature of sink.

• Refrigerator

The process of removing heat from bodies colder than their surroundings is called refrigeration and the device doing so is called refrigerator.

In the refrigerator, heat is absorbed at low temperature and rejected at higher temperature with the help of external mechanical work. Thus, a refrigerator is a heat engine working backward and hence it is also called heat pump.

Refrigerator works on the reverse process of Carnot engine. By the work done on the system, heat is extracted from low temperature sink T_2 and passed on to high temperature source T_1. The coefficient of performance is given by

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

TEXTBOOK QUESTIONS SOLVED

12.1 *A geyser heats water flowing at the rate of 3.0 litres per minute from 27°C to 77°C. If the geyser operates on a gas burner, what is the rate of consumption of the fuel if its heat of combustion is 4.0 × 10⁴ J/g?*

Ans. Volume of water heated = 3.0 litre per minute

Mass of water heated, m = 3000 g per minute

Increase in temperature,

$$\Delta T = 77°C - 27°C = 50°C$$

Specific heat of water, $c = 4.2\ Jg^{-1}\ °C^{-1}$

amount of heat used, $Q = mc\,\Delta T$

or $Q = 3000\ g\ min^{-1} \times 4.2\ Jg^{-1}\ °C^{-1} \times 50°C$

$= 63 \times 10^4\ J\ min^{-1}$

Rate of combustion of fuel $= \dfrac{63 \times 10^4 \text{ J min}^{-1}}{4.0 \times 10^4 \text{ J g}^{-1}} = 15.75 \text{ g min}^{-1}$.

12.2 *What amount of heat must be supplied to 2.0×10^{-2} kg of nitrogen (at room temperature) to raise its temperature by 45 °C at constant pressure? (Molecular mass of N_2 = 28; R = 8.3 J mol^{-1} K^{-1}.)*

Ans. Here, mass of gas, $m = 2 \times 10^{-2}$ kg = 20 g

rise in temperature, ΔT = 45°C

Heat required, ΔQ = ?; Molecular mass, M = 28

Number of moles, $n = \dfrac{m}{M} = \dfrac{20}{28} = 0.714$

As nitrogen is a diatomic gas, molar specific heat at constant pressure is

$$C_P = \frac{7}{2}R = \frac{7}{2} \times 8.3 \text{ J mol}^{-1} \text{ K}^{-1}$$

As $$\Delta Q = nC_P\, \Delta T$$

$\therefore$ $$\Delta Q = 0.714 \times \frac{7}{2} \times 8.3 \times 45 \text{ J} = 933.4 \text{ J}.$$

12.3 *Explain why*

(a) Two bodies at different temperatures T_1 and T_2, if brought in thermal contact do not necessarily settle to the mean temperature $(T_1 + T_2)/2$?

(b) The coolant in a chemical or nuclear plant (i.e., the liquid used to prevent different parts of a plant from getting too hot) should have high specific heat. Comment.

(c) Air pressure in a car tyre increases during driving. Why?

(d) The climate of a harbour town is more temperate (i.e., without extremes of heat and cold) than that of a town in a desert at the same latitude. Why?

Ans. (*a*) In thermal contact, heat flows from the body at higher temperature to the body at lower temperature till temperatures become equal. The final temperature can be the mean temperature $(T_1 + T_2)/2$ only when thermal capacities of the two bodies are equal.

(*b*) This is because heat absorbed by a substance is directly proportional to the specific heat of the substance.

(*c*) When car is driven, some work is being done on tyres in order to overcome dissipative forces of friction and air resistance etc. This work done is transformed into heat, due to which temperature of the car tyres increases.

(*d*) The climate of a harbour town is more temperate (neither too hot nor too cool) due to formation of sea breeze at day time and land breeze at night time as already explained in Chapter 11.

12.4 *A cylinder with a movable piston contains 3 moles of hydrogen at standard temperature and pressure. The walls of the cylinder are made of a heat insulator, and the piston is insulated by having a pile of sand on it. By what factor does the pressure of the gas increase if the gas is compressed to half its original volume?*

Ans. Here the process is adiabatic compression and $V_2 = \frac{V_1}{2}$,

$P_2 = 1$ atm and for hydrogen (a diatomic gas) $\gamma = 1.4$.

$\because \quad P_1V_1^\gamma = P_2V_2^\gamma,$

Hence $\quad P_2 = P_1\left(\frac{V_1}{V_2}\right)^\gamma = 1 \text{ atm}\left(\frac{V_1}{\frac{V_1}{2}}\right)^{1.4}$

$\Rightarrow \quad P_2 = (2)^{1.4}$ atm

$= 2.64$ atm.

12.5 *In changing the state of a gas adiabatically from an equilibrium state A to another equilibrium state B, an amount of work equal to 22.3 J is done on the system. If the gas is taken from state A to B via a process in which the net heat absorbed by the system is 9.35 cal, how much is the net work done by the system in the latter case?*

(Take 1 cal = 4.19 J)

Ans. Here, when the change is adiabatic, $\Delta Q = 0$, $\Delta W = -22.3$ J

If ΔU is change in internal energy of the system, then

as $\quad \Delta Q = \Delta U + \Delta W$

$0 = \Delta U - 22.3 \quad$ or $\quad \Delta U = 22.3$ J

In the second case,

$\Delta Q = 9.35 \text{ cal} = 9.35 \times 4.2\text{J} = 39.3$ J

$\Delta W = ?$

As $\quad \Delta U + \Delta W = \Delta Q$

$\therefore \quad \Delta W = \Delta Q - \Delta U = 39.3 - 22.3 = 17.0$ J.

12.6 *Two cylinders A and B of equal capacity are connected to each other via a stopcock. A contains a gas at standard temperature and pressure. B is completey evacuated. The entire system is thermally insulated. The stopcock is suddenly opened. Answer the following:*

(a) What is the final pressure of the gas in A and B?

(b) What is the change in internal energy of the gas?

(c) What is the change in the temperature of the gas?

(d) Do the intermediate states of the system (before settling to the final equilibrium state) lie of its P-V-T Surface?

Ans. (*a*) Since the final temperature and initial temperature remain the same,

$\therefore \quad P_2V_2 = P_1V_1$

But $\quad P_1 = 1$ atm, $V_1 = V$, $V_2 = 2V$ and $P_2 = ?$

$$\therefore \quad P_2 = \frac{P_1V_1}{V_2} = \frac{1 \times V}{2V} = 0.5 \text{ atm}$$

(*b*) Since the temperature of the system remains unchanged, change in internal energy is zero.

(*c*) The system being thermally insulated, there is no change in temperature (because of free expansion)

(*d*) The expansion is a free expansion. Therefore, the intermediate states are non-equilibrium states and the gas equation is not satisfied in these states. As a result, the gas can not return to an equilibrium state which lie on the P-V-T surface.

12.7 *A steam engine delivers 5.4×10^8 J of work per minute and services 3.6×10^9 J of heat per minute from its boiler. What is the efficiency of the engine? How much heat is wasted per minute?*

Ans. Work done per minute, output = 5.4×10^8 J

Heat absorbed per minute, input = 3.6×10^9 J

$$\text{Efficiency,} \quad \eta = \frac{\text{output}}{\text{input}} = \frac{5.4 \times 10^8}{3.6 \times 10^9} = 0.15$$

$$\%\eta = 0.15 \times 100 = 15$$

Heat energy wasted/minute

= Heat energy absorbed/minute − Useful work done/minute

$= 3.6 \times 10^9 - 5.4 \times 10^8$

$= (3.6 - 0.54) \times 10^9 = 3.06 \times 10^9$ J.

12.8 *An electric heater supplies heat to a system at a rate of 100W. If system performs work at a rate of 75 Joules per second. At what rate is the internal energy increasing?*

Ans. Here $\Delta Q = 100 \text{ W} = 100 \text{ J/s}$

$\Delta W = 75 \text{ J/s}$

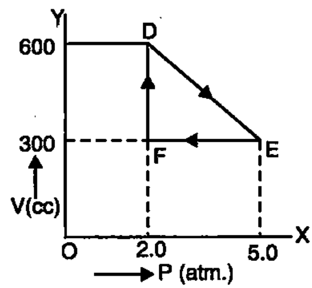
Since $\Delta Q = \Delta U + \Delta W$

$\therefore$ Change in internal energy,

$$\Delta U = \Delta Q - \Delta W = 100 - 75 = 25 \text{ J/s.}$$

12.9 *A thermodynamic system is taken from an original state to an intermediate state by the linear process shown in Fig.*

Its volume is then reduced to the original value from E to F by an isobaric process. Calculate the total work done by the gas from D to E to F.



Ans. As is clear from Fig.

Change in pressure,

$$\Delta P = EF = 5.0 - 2.0 = 3.0 \text{ atm} = 3.0 \times 10^5 \text{ Nm}^{-2}$$

Change in volume,

$$\Delta V = DF = 600 - 300 = 300 \text{ cc} = 300 \times 10^{-6} \text{ m}^3$$

Work done by the gas from D to E to F = area of ΔDEF

$$W = \frac{1}{2} \times DF \times EF$$

$$= \frac{1}{2} \times (300 \times 10^{-6}) \times (3.0 \times 10^5) = 45 \text{ J}$$

12.10 *A refrigerator is to maintain eatables kept inside at 9 °C, if room temperature is 36 °C. Calculate the coefficient of performance.*

Ans. Here, $T_1 = 36\ °C = (36 + 273)\ K = 309\ K$

$T_2 = 9\ °C = (9 + 273)\ K = 282\ K$

Coefficient of performance,

$$E = \frac{T_2}{T_1 - T_2} = \frac{282}{309 - 282} = \frac{282}{27} = 10.4.$$

❑❑❑