SSC-JE 2025

Staff Selection Commission

Junior Engineer Examination

Mechanical Engineering

Thermodynamics

Well Illustrated **Theory** *with*
Solved Examples and **Practice Questions**

MADE EASY PUBLICATIONS

Thermodynamics

Contents

CHAPTER 01

Introduction

1.1 Introduction

Thermodynamics is the science of energy transfer and its causes and effects.

- In **microscopic** thermodynamics, the behaviour of the gas is described by summing up the behaviour of each molecule.

  In **macroscopic** thermodynamics, the behaviour of the gas is described by the net effect of action of all the molecules, which can be perceived by human senses.
- A **system** is a matter or region on which analysis is done. System is separated from the surrounding by boundary. Everything external to the system is called ***surroundings***. System & surrounding together is called a *universe*.

Table 1.1:

	Mass Transfer	Energy Transfer	Example
Open	Yes	Yes	Compressor, Turbine etc.
Close	No	Yes	Piston cylinder arrangement, gas in a closed container.
Isolated	No	No	Universe

Control Mass: Analysis of system based on fixed amount of matter.

Control Volume: Volume surrounding an open system on which study is focussed.

1.1.1 Concept of Continuum

- Continuum hypothesis suggests that the matter is continuously distributed with no voids being present.
- In case of gases it is valid when mean free path (average distance travelled by a molecule between two successive collision) is much smaller than the system dimensions.
- In case of "Rarefied gases theory" the concept of continuum is not valid.

1.2 Properties

- Every system has certain characteristics by which its physical condition may be described.
  Example:- Volume, temperature, pressure. Such characteristics are called properties of the system.
- These are all macroscopic in nature.
- Properties are point function and are exact or perfect differentials.
  Ex. Internal energy, enthalpy, entropy

1.2.1 Categories of Properties

Catagories of Properties

Intensive Properties
Properties are independent of mass.
Ex. pressure, temp. density, specific vol.,
Specific heat (c_p, c_v) etc.

Extensive Properties
Properties are related to the mass.
Ex. volume, energy,
Heat capacity (c_v, c_p)

1.2.2 Specific Extensive Properties

- Extensive properties per unit mass is specific extensive properties.
- It is an intensive property.
  Example:- Specific volume, Specific energy.
- It is independent of mass.

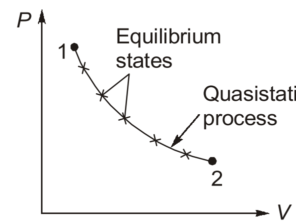


Figure 1.1: A quasi-static process

- State: It gives the complete description of the system.
- Phase: It is a quantity of mass that is homogeneous throughout in chemical composition and physical structure. Example:- solid, liquid, vapour, gas.
- Path and Process: The succession of states passed through during a change of state is called the path of the system. A system is said to go through a process if it goes through a series of changes in state.
- Quasistatic Process: Infinite slowness is the characteristic feature of quasistatic process. All states of the system passes through the equilibrium states.

1.3 Reversible Process or Ideal Process

- The process which can be reversed without leaving any effect on system and surrounding.
- All reversible processes can be shown on diagrams. Example:- P–V, T–S, P–T diagrams.
- A reversible process is carried out infinitely slowly with an infinitesimal gradient. Hence every state passed through by the system is an equilibrium state. So a reversible process coincides with a quasi-static process.
- A quasi-static process without friction is reversible process.
- All reversible processes are quasi-static process but all quasi-static process are not reversible.
- If the time allowed for a process to occur is infinitely large, even through the gradient is finite, the process becomes reversible.

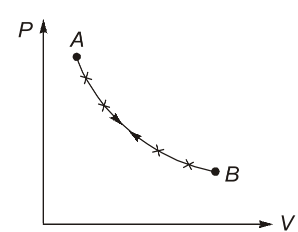


Figure 1.2: A reversible process

Example 1.1 A reversible process

(a) Must pass through a continuous series of equilibrium states.
(b) Leaves no history of the events in surroundings.
(c) Must pass through the same states on the reversed path as on the forward path.
(d) All options are correct

[SSC-JE (Forenoon) : 2017]

Solution: **(d)**

Example 1.2 Which of the following is/are reversible process(es)?

1. Isentropic expansion
2. Slow heating of water from a hot source.
3. Constant pressure heating of an ideal gas from a constant temperature source.
4. Evaporation of a liquid at constant temperature.

Select the correct answer using the code given below:

(a) 1 only (b) 1 and 2

(c) 2 and 3 (d) 1 and 4

[IES : 2005]

Solution: **(b)**

1.4 Irreversible Process or Natural Process

- All spontaneous processes are irreversible process.
- Irreversible process cannot be shown on diagrams. They are shown as dotted lines.
  Example:- Heat transfer through finite temperature difference, Free expansion, mixing of fluids, presence of friction.
- A system will be in a state of thermodynamic equilibrium if the conditions for the following three types of equilibrium are satisfied.
  (i) Mechanical equilibrium
  (ii) Chemical equilibrium
  (iii) Thermal equilibrium

1.5 A Pure Substance

- A substance homogeneous in chemical composition and homogeneous in chemical aggregation.
  Examples of Pure Substance: Atmospheric air, steam water mixture and combustion products of a fuel.
- Mixture of air and liquid air is not a pure substance since the relative proportion of oxygen and nitrogen differ in gas and liquid phases in eqn....

Example 1.3 Assertion (A): Water is not a pure substance.

Reason (R) : The term pure substance designates a substance which is homogeneous and has the same chemical composition in all phases.

(a) Both Assertion and Reason are true and Reason is the correct explanation of Assertion.

(b) Both Assertion and Reason are true but Reason is not a correct explanation of Assertion.

(c) Assertion is true but Reason is false.

(d) Assertion is false but Reason is true.

Solution: **(d)**

Assertion is false, Reason is true. Water for all practical purpose can be considered at pure substance because it is homogeneous and has same chemical composition under all phases.

1.5.1 Gibb's Phase Rule

$$P + F = C + 2$$

P = Number of phases

F = Degree of freedom

C = Number of component

Example 1.4 Determine the degree of freedom of the following systems and comment on the result:

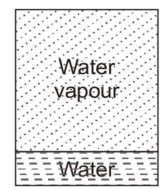
(1) Water and water vapour system

(2) A mixture of oxygen and nitrogen gas as system

(3) Water at its triple point

Solution :

(1)



In the given system,

Number of phases, $P = 2$ (liquid + vapour)

Number of components, $C = 1$ (only water)

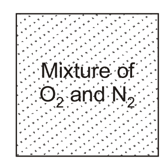
$\therefore$ From Gibbs phase rule,

$$P + F = C + 2$$

$$\Rightarrow \quad F = 1 + 2 - 2 = 1$$

Comment : Only one variable is enough to fix the state of the system.

(2) It the given system,



$P = 1$ (only gas)

$C = 2$ $(O_2 + N_2)$

$P + F = C + 2$

$F = 2 + 2 - 1 = 3$

Comment : We will require 3 independent intensive variables to fix the state of the system.

(3)

$P = 3$ (solid, liquid and gas)

$C = 1$ (only water)

$F = C - P + 2$

$F = 1 - 3 + 2 = 0$

Comment : Triple point of water is a fix point at particular pressure and temperature. $P_{TP} = 0.6112$ kPa

$T_{TP} = 0.01°C = 373.16$ k

1.6 Thermodynamic Cycle

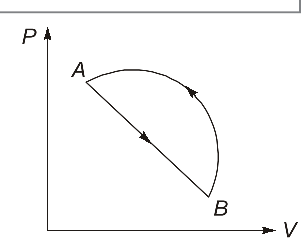


Figure 1.3:

- It is a series of processes when initial and final points are same.
- There is no change in property of system.
- Minimum number of processes required for a cycle are 2.

1.7 Temperature

1.7.1 Zeroth Law of Thermodynamics

- When a body A is in thermal equilibrium with a body B and also with a body C separately then body B & C will be in thermal equilibrium with each other.
- Zeroth law of thermodynamics is the basis of temperature measurement.

1.7.2 Thermometry

- It is based on finding the thermometric property.

Table 1.2:

Thermometer	Thermometric property
Constant volume gas thermometer	Pressure (P)
Constant pressure gas thermometer	Volume (V)
Electrical resistance thermometer	Resistance (R)
Thermo couple	EMF (E)
Mercury in glass thermometer	Length (L)

Table 1.3:

Thermometer	Temperature Range
Platinum resistance Thermometers	–200°C to 1200°C
Thermoelectric thermometers	–200°C to 1600°C
Radiation pyrometers	above 400°C
Segar cone	600°C to 2000°C
Optical pyrometers	above 650°C
Gas thermometers	–200°C to 1200°C

- Thermocouple uses copper-constantan, platinum-rhodium, chromel-alumel combinations.

1.7.2 Temperature Scales

$$\frac{t_C - 0}{100 - 0} = \frac{t_F - 32}{212 - 32}$$

$$T_k = t_C + 273.15$$

t_c = Temperature in °C

t_f = Temperature in °F

T_k = Temperature in Kelvin

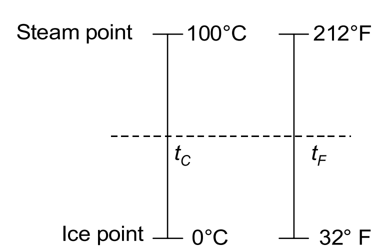


Figure 1.4

- Before 1954, temperature measurement was based on two reference point namely ice point and steam point.

  After 1954, the temperature measurement has been based upon single reference point is triple point of water.
- According to internationally accepted convention.

$$1\text{ K} = \left(\frac{1}{273.16}\right)^{\text{th}} \text{ of triple point of water}$$

Conversion of temperature unit:

$$\frac{°C}{5} = \frac{°F - 32}{9} = \frac{T - 273.15}{5}$$

°C → Temperature in degree Celsius

°F → Temperature in degree Fahrenheit

T → Temperature in Kelvin

Example 1.5 The boiling and freezing points of water are marked on a temperature scale *P* as 130°p and –20°p respectively. What will be the reading on this scale corresponding to 60°C on celcius scale?

(a) 60°p (b) 70°p

(c) 90°p (d) 110°p

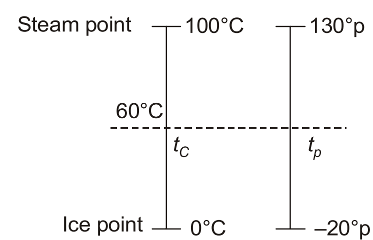
[SSC JE : 2014]

Solution: **(b)**

$$\frac{t_c - 0}{100 - 0} = \frac{t_p - (-20)}{130 - (-20)}$$

$$\Rightarrow \quad \frac{60}{100} = \frac{t_p + 20}{150}$$

$$\Rightarrow \quad t_p = 70°p$$



1.8 Ideal Gas Equation

A hypothetical gas which obeys $(p\bar{v} = \bar{R}T)$ at all pressures and temperatures is called an ideal gas

$$p\bar{v} = \bar{R}T \quad \Rightarrow \text{Ideal gas equation}$$

where molar volume, $\bar{v} = \frac{V}{n}$ m^3/kg mol

Absolute pressure, P (in Pa)

Absolute temperature, T (in k)

n = number of kg moles of the gas

$\bar{R}$ = universal gas constant = 8.3143 kJ/kgmol-K

→ As $p \to 0$ or $T \to \infty$, the real gas approaches the ideal gas behaviour.

$$pV = mRT$$

$$R = \text{characteristic gas constant}$$

$$= \frac{\bar{R}}{M} \text{ in kJ/kgK}$$

Here M = molecular mass of the gas.

1.9 The Gas Laws

All gases generally show similar behaviour when the conditions are normal. But with a slight change in physical conditions like pressure, temperature, or volume these show a deviation. Gas laws are an analysis of this behaviour of gases.

1.9.1 Boyle's law

It states that volume is inversely proportional to pressure when the temperature and the number of molecules are constant.

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

$$\Rightarrow \qquad P = (k_1) \times \frac{1}{V}$$

where, k_1 = Proportionally constant ; V = Volume ; P = Absolute value

1.9.2 Charle's Law

Jacques charles in 1787 analysed the effect of temperature on the volume of gaseous substance at constant pressure.

According to his findings, at constant pressure and for constant mass, the volume of a gas is directly proportional to the temperature.

In his experiment the calculated that the increase in volume with every degree equals $\frac{1}{273.15}$ times of the original volume.

∴ If $T = 0°C$, $V = V_0$, then $T = 7°C$, V_t is given by

$$V_t = V_0 + \frac{t}{273.15} V_0$$

$$\Rightarrow \qquad V_t = V_0\left(1 + \frac{t}{273.15}\right)$$

For the purpose of measuring the observations gaseous substance at temperature 273.15K, we use a special scale called the "Kelvin Temperature Scale".

The observation of temperature (T) on this scale is 273.15 greater than the temperature (t) of the normal scale.

$$T = 273.15 + t$$

So, according to charle's law,

$$v \propto T$$

$$\Rightarrow \qquad V = K_2 T$$

Example 1.6 According to the which law, all perfect gases change in the volume by $\frac{1}{273^{rd}}$ of their original volume at 0°C for every 1°C change in temperature when pressure remains constant?

(a) Joule's law (b) Boyle's law

(c) Gas-Lussac law (d) Charle's law

[SSC JE : 2007, 2017]

Solution: **(d)**

1.9.3 Gas Lussac's law

In 1802, a french scientist Joseph Louis Gas-Lussac discovered that at fixed volume and mass of gas, the absolute pressure of that gas is directly proportional to the absolute temperature.

$$P \propto T \qquad T \text{ in (k)}$$

$$\Rightarrow \qquad \frac{P}{T} = k_3 = \text{constant}$$

1.9.4 Avagadro's law

Avagadro's law states that the volume of a *g*-mol of all gases at the pressure of 760 mm of Hg and temperature of 0°C is the same, and is equal to 22.4 litres. Therefore, 1 kg mol of a gas has a volume of 22.4 m^3 at normal temperature and pressure (NTP).

NOTE

at NTP: $T = 0°C = 273.15$ k
$P = 760$ mm of Hg = 1 atm
at STP: $T = 25°C = 298$ k
$P = 1$ atm

In other words, this law implies that in unchanged conditions of temperature and pressure. The volume of any gas is directly proportional to the number of molecules of that gas,

$$V \propto n$$

$$\Rightarrow \quad V = k_4 n$$

Example 1.7 In case of Boyle's law, if pressure increases by 1% the percentage decreases in volume is

(a) $\frac{1}{101}\%$ (b) $\frac{100}{101}\%$
(c) $\frac{1}{100}\%$ (d) 0%

[SSC JE : 2012]

Solution: **(b)**

According to Boyle's law, $P_1V_1 = P_2V_2$

$\Rightarrow \quad P_1V_1 = 1.01 P_1V_2$

$\Rightarrow \quad V_1 = 1.01 V_2$

$\Rightarrow \quad V_2 = \frac{1}{1.01} V_1$

Percentage decrease in volume $= \frac{V_1 - V_2}{V_1} \times 100 = \frac{V_1 - \frac{V_1}{1.01}}{V_1} \times 100 = \frac{100}{101}\%$

1.10 Kinetic Theory of Gases

The kinetic theory of gases attempts to explain the microscopic properties of a gas in terms of the motion of its molecule.

Three Basic Assumptions:

1. The gas consists of identical particles (or atoms/molecules) of mass, m, in constant random (straight line) motion.
2. The size of the molecules are negligible, such that their diameters are much smaller than the average distance travelled between collisions.
3. The molecules interact only through brief, infrequent and elastic collisions.

NOTE : Gas particles move with constant speed between collisions gravity has no effect on molecular motion.