# UNIT 5 UNITS OF MEASUREMENT, GAS LAWS AND FUELS

## Structure

## 5.1 INTRODUCTION

Engineering practices are dependent upon measurements or quantification of material characteristics, their behaviour and such other physical quantities as force, distance, current, light intensities etc. It is a common understanding that we cannot really understand which of the two metallic lumps is heavier unless we say in which system of units we are expressing the weights. We will not be able to visualize as to which place is farther unless we express the distance from a common point in the same system of units. It will not be possible for us to assess which of the two fluids is hotter unless we express their temperatures in a consistent system. Thus, the units of measurement are basic need of life and of engineering practice.

The scientists, based upon prevailing practices, evolved unit systems long ago. Scientific methods first converged upon their basic quantities, viz : length, mass and time. They assigned units to them as standard called meter, gramme and second. A sample of 1 meter length of rod made in a standard material (platinum)

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placed in certain laboratory in Paris (France) was regarded as the standard meter with which all measurements of length will be compared. Fractions will be measured in hundredth (centi) or thousandth (milli) of meter. Similarly, the gramme was defined. The unit of time, the second, is a fraction of time earth takes to revolve once round the sun. However, besides gramme and meter other two units became popular in scientific community of Britain and they were respectively foot (twelve inches) and pound. Two systems were thus developed. They were CGS (centimeter – gramme – second) and FPS (foot – pound – second) systems. CGS simultaneously had its associate in MKS (meter – kilogramme – second) systems which were preferred by engineers for many years until recently when most countries opted for SI unit system.

SI which stands for French "System International Units" meaning International System of Units has been proposed by "International Standard Organization" – ISO as their standard ISO 1000. This has become acceptable world over, at least among scientists and engineers yet its following in practice may not be claimed to be 100%. In particular the FPS system, under the name of "Conventional British system of Units" is still popular in USA for several reasons. The old machines and systems already working in USA were based on FPS and introduction of new system will require their replacement which could not become possible, hence they continue. As an example, think about a plant using several hundreds of bearings, all of them having standard characteristics in FPS. If one bearing fails, it cannot be replaced by another of SI system, hence the FPS system bearings have to be manufactured unless one changes all the bearings and other corresponding parts. By no means this explanation should be regarded as justification but only a reason for continuing with FPS system in USA.

SI comprises seven basic units from which a whole range of units can be derived in the form of products and quotients. Table 5.1 describes these seven basic units.

## Objectives

After studying this unit, you should be able to know

- units of force, pressure, work energy, power etc.,

- how a unit quantity is defined,

- what are basic thermodynamic processes,

- what is a cycle operation,

- how can a fuel help produce energy in usable form, and

- where are resources of fuel and in which form.

## 5.2 BASIC UNITS OF MEASUREMENT

Units represent the scale on which the relative magnitude of a quantity is judged. SI system of units has been accepted by scientific and technical world. This system is based on seven basic units described here.

**Meter or Metre (m)**

Meter is unit of length. It is defined as wavelength of a radiation. The radiation emitted when an electron transition occurs between 2 $p_{10}$ and 5 $d_5$ orbitals has a wavelength which is $6.0578 \times 10^{-7}$ of a meter. In other words, one meter is 1650763.73 time the wave length of this radiation.

**Kilogram (kg)**

Kilogram is the unit of mass. This mass is equal to mass of international prototype of kilogram.

**Second (s)**

This is unit of time and based upon transition time between two hyperfine levels of ground state of caesium – 133 atoms. This transition emits radiation whose time period is $1.0878 \times 10^{-10}$ of a second. In other words, one second is 9192631770 times the time period of this radiation.

**Ampere (A)**

This is unit of current. An ampere is that constant current which if maintained in two straight parallel conductors of infinite length, of negligible circular cross section and placed 1 m apart in vacuum would produce between these conductors a force equal to $2 \times 10^{-7}$ Newton per m length.

**Kelvin (K)**

It is the unit of thermodynamic temperature. The temperature of triple point of water is 273.16 K.

**Candela (cd)**

It is the unit of luminous intensity. It is luminous intensity in the perpendicular direction of a surface of $\dfrac{10^{-6}}{6}$ m$^2$ of a black body at the temperature of freezing platinum under a pressure of 101325 Newtons/m$^2$.

**Mole (mol)**

It is the unit of amount of substance. The standard for comparison in this definition is carbon – 12 element. The amount of substance is the number of elementary entities that constitute the substance. These entities could be electrons, atoms, molecules or any other particle. One mole of a substance contains as many elementary entities as there are atoms in 0.012 kg of carbon – 12.

**Table 5.1 : The Basic SI Units**

| Quantity | Name of Unit | Symbol |
|---|---|---|
| Length | Meter | m |
| Mass | Kilogram | kg |
| Time | Second | s |
| Electric current | Ampere | A |
| Thermodynamic temperature | Kelvin | K |
| Luminous intensity | Candela | cd |
| Amount of substance | Mole | mol |

Several units are derived from seven basic units. We are going to describe those related to thermodynamic measurements. But, for example, a few derived units are mentioned here.

Unit of velocity – m/s or m s$^{-1}$ (meter per second)

Unit of acceleration – m/s$^2$ or m s$^{-2}$ (meter per second per second or meter per second every second)

Electrical resistance – ohm ($\Omega$)

Frequency – Hertz, (Hz), 1/s or s$^{-1}$

Luminous Flux – lumen, (lm), cd sr$^3$

(sr is steradian, unit of solid angle, plane angle is measured in radians.)

It will be worthwhile here to mention that certain units are very large quantities while certain others are very small. So very large or very small numbers are required to describe these quantities. For example measuring distance between two cities, meter will be a small unit. For expressing mass of carbon dioxide in 1 kilogram of air, kilogram will be a large unit. For avoiding difficulties of expressing practical quantities decimal multiples and sub-multiples are used. Kilo in kilogram is $10^3$ factor which means 1000 times gramme. Kilo is similarly used in kilometer. Milli in milligram means $10^{-3}$ and expresses one thousandth of a gram. Such multiplying factors are prefixed to the basic unit or derived unit and its magnitude is properly taken care of in calculation. Table 5.2 describes such prefixes.

**Table 5.2 : Multiples and Sub-multiples of SI Units**

| Factors by which Unit is Multiplied | | Prefix | Symbol | Common Example |
|---|---|---|---|---|
| One million million, | $10^{12}$ | tera | T | – |
| One thousand million, | $10^9$ | giga | G | Gigahertz (GHz) |
| One million, | $10^6$ | mega | M | Megawatt (MW) |
| One thousand, | $10^3$ | kilo | k | kilometer (km) |
| One hundred, | $10^2$ | hecto* | h | |
| Ten, | 10 | deca* | da | decagram (dag) |
| Unity, | 1 | | | |
| One tenth, | $10^{-1}$ | deci* | d | decimeter (dm) |
| One hundredth, | $10^{-2}$ | centi* | c | centimeter (cm) |
| One thousandth, | $10^{-3}$ | milli | m | millimeter (mm) |
| One millionth, | $10^{-6}$ | micro | μ | microsecond (μs) |
| One thousandth million, | $10^{-9}$ | nano | n | nano second (ns) |
| One million millionth, | $10^{-12}$ | pico | p | pico farad (pf) |
| One thousand millionth, | $10^{-15}$ | femto | f | |
| One million million millionth, | $10^{-18}$ | atto | a | |

**\* Not preferred**

## 5.2.1 Force

Force appears to be fundamental in all engineering phenomena. It is very commonly used in its physical sense and in its numerical forms. The unit is derived from statement of second law of motion which states that "force is proportional to rate of change of momentum of a body". Hence force, *F*, acting upon a body of mass, *m*, and causing change in velocity from $v_1$ to $v_2$ over a time *t*, can be written as

$$F \; \alpha \; \frac{m \, (v_1 - v_2)}{t}$$

or
$$F \alpha \, m \, a$$

where $a$ = acceleration = $\dfrac{v_1 - v_2}{t}$

$\therefore \quad F = \text{constant} \times m \, . \, a$

Now the unit force is defined as one which when acts on unit mass body, produces in it a unit acceleration. So that

$$1 = \text{Constant} \times (1 \times 1)$$

$$\therefore \qquad \text{Constant} = 1$$

$$\therefore \qquad F = m.a \qquad\qquad \text{. . . (5.1)}$$

Eq. (5.1) serves as fundamental relationship between force on one hand and mass and acceleration on the other. The unit of force in SI is derived here.

If $\qquad m = 1 \text{ kg} \quad$ and $\quad a = 1 \text{ m/s}^2$

which can be stated that "a body of 1 kg mass is accelerated through 1 m/s$^2$" then the force acting upon the body is "one **Newton**". This is the unit of force and denoted by "N".

$$\therefore \qquad 1 \text{ N} = 1 \text{ kg} \times 1 \text{ m/s}^2 \qquad\qquad \text{. . . (5.2)}$$

The weight of a body like its mass has become its property. It must be realized that while mass is the quantity of matter in the body the weight is the force with which the earth pulls it toward its centre of gravity. The force of gravity on a body is its weight. Thus the weight of a body of mass 1 kg, i.e.

Weight of 1 kg mass = m (1 kg) × acceleration due to gravity (m/s$^2$)

$$= \text{m (1 kg)} \times g$$

$g$ is normally taken as a constant though it may vary slightly from one place to the other. Its constant value is taken as 9.81 m/s$^2$.

Weight of 1 kg mass = (1 kg × 1 m/s$^2$) × 9.81

$$= 9.81 \text{ N}$$

In MKS system, which was earlier used, "weight of 1 kg mass" was called "1 kg force" denoted as "1 kgf" and kgf was used as unit of force. Apparently
1 kgf = 9.81 N.

Interesting point to note is that in MKS system the magnitude of weight and mass would be same, i.e. mass of 1 kgf weight will be 1 kg, while mass of a body of weight 9.81 N will also be 1 kg.

Remember that the weight of a body of mass 1 kg in MKS system is 1 kgf but in SI it is 9.81 N, which means that mass of a body of 1 kgf weight is 1 kg or the mass in kg is equal to weight in kgf.

## 5.2.2 Pressure

Pressure is used in several engineering practices and therefore there are several units of pressure in common use. Pressure refers to a force distributed uniformly over an area. So naturally its unit should take form of force/area (like N/m$^2$, or N/mm$^2$ etc.). Incidentally yet another engineering quantity, stress is also defined as ratio "force/area" though for restricting stress to a point the area has to be very small. The units of pressure and stress have the same form. The pressure or stress unit, Newton per square meter (N/m$^2$), is largely used and is given name of **Pascal**, denoted by Pa. Pa, k Pa ($10^3$ Pa) and MPa ($10^6$ Pa) are common forms of this unit. Newton per square mm (N/mm$^2$) can also be used as an alternative to MPa.

It is advisable and is followed in practice that **stress** be expressed in units of MPa.

For pressure, however N/m$^2$ (with suitable multiples or submultiples can be used. A new term of **bar** is also coined where

$$1 \text{ bar} = 10^5 \text{ N/m}^2 = 10^{-1} \text{ MN/m}^2 = 10^{-1} \text{ N/mm}^2$$

Measurement of pressure and pressure difference by manometric tubes is a common practice, particularly in flowing fluids. The pressure in such situations is expressed in terms of height of the column of fluid which will necessarily depend upon fluid property (say density or specific gravity). It is necessary that such height of the column be converted into N/m$^2$ if the pressure is to be used in calculation. However, if measured pressure is only to be indicative or to be used for comparison it can be expressed in height of fluid along with the property of the fluid.

It may be remembered that atmospheric pressure is measured by the height of the mercury column which can be supported by atmospheric pressure. At sea level this height is 760 mm of Hg.

If pressure is measured from **zero** it is called **absolute**. If pressure is measured from **atmospheric pressure** it is called **gauge.** Absolute pressure or gauge pressures are expressed with these prefixes. For example "at a gauge pressure of 12.5 bar" or "at an absolute pressure of 2.34 MPa".

Atmospheric pressure often is taken as standard and used as unit. A pressure equal to 760 mm of Hg is called **"one atmosphere"** (1 atm), which is equal to 760 torr.

Pressure below atmospheric pressure is measured as vacuum, which is the difference between absolute pressure and atmospheric pressure. In this convention, atmospheric pressure is taken as zero. Atmospheric pressure in different units is expressed as

$$1 \text{ atm} = 760 \text{ mm of Hg} = 1.013 \text{ kN/m}^2 = 1013.25 \text{ mbar} = 760 \text{ torr}$$

Vacuum of 10 mm of Hg means an absolute pressure of 750 mm Hg.

Vacuum of 160 mm of Hg means an absolute pressure of 600 mm Hg.

or 600 torr or 0.8 kN/m$^2$.

For calculation it is the absolute pressure which is used. In FPS or conventional British system of units pressure is measured in lbf/in$^2$ (pounds per square inch).

Remember following conversions.

$$1 \text{ N/m}^2 = 1.45038 \times 10^{-4} \text{ lbf/in}^2$$

$$1 \text{ bar} = 14.5038 \text{ lbf/in}^2 = 0.987 \text{ atm}$$

$$= 401.463 \text{ in of water} = 29.53 \text{ in of Hg}$$

### 5.2.3  Work and Energy

Work is said to be done when point of application of force moves in the direction of force. Work is measured as product of force and displacement. If point of application of force moves a distance $d$ (displacement = $d$) under the action of force $F$, the work, $W$, is given by

$$W = F \times d \qquad \qquad \dots (5.3)$$

The unit work is done when unit force ($F = 1$) displaces point of application through unit distance ($d = 1$). If $F = 1$ N and $d = 1$m, SI unit of work is obtained.

$$\text{Unit work} = 1 \text{ N} \times 1 \text{ m} = 1 \text{ Nm}. \qquad \qquad \dots (5.4)$$

**Nm** is the unit of work. This unit has been given a name **Joule (J)**. 1 joule of work is done when 1 N of force displaces point of application through 1 m.

Since energy is capacity of doing work it is measured as work itself. Hence unit of energy is also same as that of work. Energy is measured in **Joules**.

Heat is common form of energy. Its unit is also Joule. According to first law of thermodynamics, heat and work are equivalent. Heat can be converted into work and vice-versa. Before advent of SI, heat has been commonly measured in three units, viz.., : **calorie** (cal), **CHU** (centigrade heat units) and **Btu** (British thermal units).

Btu is still commonly used in USA, particularly in Refrigeration and Air-conditioning practice. Following conversions can be used.

$$1 \text{ J} = 9.478 \times 10^{-4} \text{ Btu} = 0.239 \text{ cal} = 0.5266 \text{ CHU}$$

1 J is a small quantity, hence, kJ is used in practice.

## 5.2.4  Power

Power is defined as rate of doing work.

$$\text{Power, H} = \text{work/s}$$

Unit power is unit work done in a second. The unit of power is named as **Watt** (W). Hence

$$1 \text{ W} = 1 \text{Nm/s} = 1 \text{ J/s}$$

If a current of 1 A flows through a circuit across which a voltage of 1 V is applied the power consumed in the circuit is 1 W

$$1 \text{ W} = 1 \text{ V} \times 1 \text{ A} = 1 \text{ J/s}$$

Since *W* is unit of power then multiplying W by time we obtain unit of energy. This unit of energy can be called Watt second. This unit has been used and is still in use for charging consumers of electricity. Watt second (Ws) is very small quantity, hence much bigger unit called **kilo watt hour (kWh)** is used as unit of electrical energy.

$$1 \text{ kWh} = 1000 \; \frac{J}{s} \times 3600 \; s = 3.6 \times 10^6 \text{ J} = 3.6 \text{ MJ}$$

$$= 3412 \text{ Btu}$$

$$= 860 \text{ kcal}$$

**Horse power** (hp) is commonly used unit of power. Many engine and electric manufacturers mark their products in hp. Alternatively kW is used. hp as measure of power was introduced much earlier when FPS system was popular among engineers. Notwithstanding the dictionary meaning of horse power, it was defined as :

$$1 \text{ hp} = 550 \text{ ft lb of work/s}$$

$$= 75 \text{ kgf m of work/s}$$

$$= 736 \text{ W or } 0.736 \text{ kW}$$

$$= 736 \text{ J/s}$$

### 5.2.5  Enthalpy

Heat is the energy in transit from one mass to another due to a temperature difference between the two. Likewise work is also energy in transit. A body surrounded by its surroundings may receive energy in form of kinetic energy (energy of its motion), potential energy (energy of its position) and also energy of its molecules. The last one is due to motion of molecules which could be linear, spin or vibrational. This energy at internal particle level is called **internal energy** and appears as temperature of the body.

If we consider a gas at pressure $p$ with volume $v$ in a closed system (no matter leaves the boundary of the system) and the energy supplied to the system is heat, $Q$, then,

$Q$ = Change in energy (which includes $KE$ and $PE$) + Change in internal energy

The first term on right hand side is nothing but the work done upon the system or by the system. If work is done upon the system then it has same sign as heat added to the system. This work is denoted by $W$.

Then $\qquad Q = W + E$

where, $E$ = Change in internal energy

Between two states of system, identified as 1 and 2

$$Q_{12} = W_{12} + (E_2 - E_1) \qquad\qquad \ldots (5.5)$$

where $Q_{12}$ is heat absorbed by the system while system state changes from 1 to 2, and $W_{12}$ similarly is work done upon the system during state change from 1 to 2. $E_1$ and $E_2$ are internal energies respectively in state 1 and state 2.

It can be shown that $W = pv$ if $p$ = pressure and $v$ is the volume. The quantity on right hand side of the Eq. (5.5) is written as

$$h = pv + E \qquad\qquad \ldots (5.6)$$

and $h$ is called **Enthalpy**. The quantity $h$ is measured per unit mass, and its unit apparently is same as that of energy, i.e. $J$.

### 5.2.6  Entropy

Although we did not define state of a substance or a gas in specific terms, yet we have used the term. State of a gas is defined by two or three characteristics like pressure ($p$), volume ($v$) and temperature ($T$). The state may be determined uniquely by any two of the variables. If the state variables change then the system is said to undergo a **process.** What it means is that process occurs if the substance constituting a system changes its characteristics ($p$, $v$ and $T$). If changes occur from state 1 to 2, will it be possible to revert the changes and come back from 2 to 1. If it can happen without any external aid the process is called reversible. This is an ideal situation which does not exist in reality. The processes that systems actually undergo are **irreversible**. If the process is reversible, the system continuously changes its temperature while heat absorption takes place in one direction and heat rejection in the other (or vice-versa). If we concentrate on the ratio of heat absorbed or rejected to temperature then the ratio ($dQ/T$) does not change in a reversible process, i.e. $\int_1^2 \dfrac{dQ}{T}$ is zero. But in an irreversible process $\int_1^2 \dfrac{dQ}{T}$ is greater than zero.

This quantity $\int_1^2 \dfrac{dQ}{T} = S_{12} = S_2 - S_1$ is defined as change in entropy. Note that entropy has been defined as a change between state 1 and 2. The unit of entropy apparently is ratio of unit of $Q$ and $T$, i.e. J/K or J/$^o$C.

## 5.2.7  Heat Capacity, Specific Heat and Latent Heat

Heat capacity of any substance is the amount of heat required to raise unit mass of the substance 1 deg. in temperature. Heat capacities, thus, can be defined for all substances. The ratio of heat capacity of a substance to that of water is defined as **specific heat.** For engineering purposes specific heat is taken equal to heat capacity, or understood as heat required to raise unit mass of substance 1 deg. in temperature. The unit then becomes apparent as J/kg K or J/kg $^o$C.

The gases have two specific heats – constant volume specific heat and constant pressure specific heat. They are respectively denoted by $C_v$ and $C_p$. $C_v$ is that specific heat which is absorbed when volume of gas is constant and $C_p$ is that which is absorbed when pressure of the gas is constant. Apparently $C_p > C_v$ because when pressure is kept constant volume will increase and work will be done (work = $pv_1 - pv_2$). The heat will be required to do this work. The ratio $C_p/C_v$ is constant for a given gas. The ratio depends upon if gas is monoatomic or diatomic. Air being mixture of two diatomic gases ($N_2$ and $O_2$), the ratio $C_p/C_v = \gamma = 1.4$.

When a solid melts, it does so at constant temperature but not without absorbing heat. A solid will melt at constant temperature and keep absorbing heat until whole of it becomes liquid. Similarly, a liquid will evaporate into gas at constant temperature and will absorb heat during evaporation.

During the reverse process of condensation of gas into liquid and solidification of liquid into solid the heat will be given out and absorbed by the surrounding while temperature will remain constant.

The heat absorbed during change of state (from solid to liquid or from liquid to gas and vice-versa) without change of temperature is called **latent heat** which has unit of J/kg.

It may also be noted that in above definition the pressure also remains constant which means change of state is to occur at constant pressure and constant temperature.

Water is a very important substance as it is evaporated into steam and used to run engines and turbine. The process of evaporation occurs at constant pressure and temperature while **latent heat of evaporation** is absorbed. The gaseous state is conventionally called vapour. If water is heated from any temperature at constant pressure, the temperature first increases by absorbing **sensible** or **specific heat** till boiling beings. This corresponds to temperature called boiling point and liquid is said to be **saturated.** Further heat addition will cause evaporation or formation of **vapour** (also called steam). The specific volume of vapour is much larger than that of liquid from which this vapour is obtained.

Between the point (volume) where the evaporation begins and the point (volume) where it ends, the substance (water) is in a state of mixture, i.e. part liquid and part vapour. If we consider $m$ kg of mixture in which $x\,m$ kg is vapour then, $m(1 - x)$ kg will be liquid. The mass fraction $x$ is called dryness fraction or quality of steam or vapour. When $x = 1$, whole liquid is converted to steam, and if the steam is at the same temperature as the boiling point it is called saturated steam. Note that quality $x$ is just a fraction (a number) and has no units.

The above definition may also be expressed as :

$$x = \frac{m_s}{m}$$

where, $m_s$ = mass of vapour, and

$m$ = mass of mixture of liquid and vapour (both will be saturated).

## 5.2.8 Refrigeration Capacity

Refrigeration is understood as a process in which some medium or substance is cooled. In other words, in refrigeration heat is removed from a substance. A refrigerator is a machine which is used for removing heat. The refrigeration capacity is measured as heat removal rate.

For defining unit of refrigeration capacity we will write as below:

$$\text{Refrigeration capacity} = \frac{m \times (\text{Heat Removed})}{\text{Time}}$$

Take $m$ = 1 ton (or 9072 N) of water

Heat removed = Latent heat of fusion

i.e. water solidifies into ice, $0^o$C or $32^o$F.

Time = 24 hrs

The above definition translates into "refrigeration capacity called 1 ton of refrigeration (ITR) is the heat removed from 1 ton of water at zero degree Celsius or $32^o$F to convert into ice in 24 hours".

ITR = 303.85 MJ/24 hr

= 3.5168 kJ/s

= 3.5168 kW

So note that refrigeration capacity is actually the power. In US refrigeration capacity is expressed in Btu.

ITR = 288000 Btu/day

= 200 Btu/min

One quarter of standard ton of refrigeration has been used in Europe as unit of refrigeration capacity. This unit is called **Frigorie**. One frigorie equals 50 Btu/min.

The performance of refrigerator is measured in terms of coefficient of performance (COP),

$$\text{COP} = \frac{\text{Heat Removed}}{\text{Work Supplied}} = \frac{Q}{W}$$

Although, COP is appearing to be inverse of efficiency, it will be so only when same machine is used for producing work (or energy) by supplying heat. This hardly is the case, hence COP should not be regarded as inverse of efficiency. Actually the above definition is derived from very broad definition of efficiency stated as ratio of $\dfrac{\text{Desired effect}}{\text{Cause of effect}}$.

## SAQ 1

(a) Define mole. Is mole one of seven basic SI units? Mention the basic SI units from which other SI units are derived.

(b)     "Certain units are large quantities". What do you understand by this statement? Give examples of such large quantities and explain how do you express them in practice?

(c)     Distinguish between kgf and Newton. A body weighs 10 kgf, what is its mass? How much will this weight be in Newtons?

(d)     Atmospheric pressure is measured by height of mercury column. What do you understand by this? What is the height of mercury column that will represent atmospheric pressure? How much is this pressure in $kN/m^2$ and in torr?

(e)     Correlate work and power. A machine generates 0.95 Btu/s of energy. What is the power of this machine in kW, and hp?

(f)     Give units of enthalpy, entropy, specific heat and latent heat.

## 5.3  THERMODYNAMIC SYSTEMS

Before we proceed to study the gas laws let us look at the background. These laws form part of study of Thermodynamics. Thermodynamics is a science which deals with energy, matter and with interaction between them. Historically this science developed along with the machines that were used to produce energy or more correctly the machines that were used to convert heat energy into mechanical (mainly kinetic) energy. Steam turbines and internal combustion engines are the examples of such machines. They depended upon using some gaseous medium (matter in gaseous state) which would pass through the machine. These gases will either be obtained from burning of fuel or just air from atmosphere or vapour from water. These gases will expand, be compressed, heated, cooled or condensed during their passage through one or series of machines or several components of the same machine. The science of thermodynamics would consider the energy absorbed during heating or compression and energy released during expansion or condensation and correlate this energy with change in parameters of state or states of gas (which is matter). We avoid at this stage adopting the route of thermodynamics though it will not be possible and try to understand the processes only. Perhaps gas laws can help to some extent. Some basic definitions are, however, put forth first.
**Thermodynamics** is a science which deals with energy, matter and interactions between them. A **system** is a region of space containing matter which is confined within a boundary. The boundary separates the system from its **surrounding**. Anything which is outside the boundary constitutes the surrounding of the system. A system is analogous to a free body in the study of mechanics. The system can be **closed** or **open**. In a closed system, mass of matter remains constant. The boundary does not allow any matter to flow in or out. In an open system the matter can flow in and out. The boundary of an open system permits exchange of matter.

The energy can be exchanged across the boundary in both closed and open system. However, an **isolated** closed system exchanges neither matter nor energy with its surrounding.

The state of a system is described by its properties. Mass density, pressure, volume, temperature, energy and entropy are the properties of system used to

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describe its state. It is in the nature of the matter that out of the whole set of properties a few (two or three only) need be defined. The others can be uniquely determined from such specified properties.

The properties of the system can be **intensive** or **extensive.** The intensive properties are independent of mass contained in the system. Temperature, density and pressure are intensive properties. The extensive properties depend upon the matter content of the system. The total volume of the system is an extensive property, so is the mass of the matter contained in the system.

Gas is one of the three states of matter. At normal temperature and pressure some matter may exist in gaseous state only. Atmospheric gases (oxygen, nitrogen and many others) or air is the example of a gas. Water vapour in the atmosphere or that produced in well defined and fabricated devices is the example of a gas which would not stay at normal temperature and pressure as gas but change into liquid. Ideal gas has to follow certain rules specified in advance. Though no practical gas is ideal, yet many used in engineering practices can be regarded as ideal. The ideal gases follow several rules by way of which their properties (both intensive and extensive) will change and the mathematical relationships between the properties exist because of following of these rules. We will study such laws.

## 5.3.1 Processes

A system may be understood to be in thermodynamic equilibrium if its properties remain unchanged. The system exchanges neither mass nor energy with the surrounding. The system thus will continue to have same mass, volume, pressure and temperature if it is in thermodynamic equilibrium.

If the system changes from one equilibrium state to another it is said to have undergone a **process.** The processes are of different types depending upon the interaction that occurs or upon change (or no change) in a particular property. Normally "no change" becomes the basis of naming a process.

**Isothermal** process is one in which temperature does not change. **Adiabatic** process is one in which no heat exchange between system and surrounding occurs. In a **constant volume** process the volume at any state is same. A **constant pressure** process is the one in which pressure is always constant.

A process can be shown by a graph in which any state of matter is represented by two variables as coordinates of a point. Coordinate system of pressure and volume ($p$, $V$) is very common. Each point shows a state of equilibrium (or very close to equilibrium) and locus of such points shows the process or path of process.

Figure 5.1 represents one such process, in which 1 is the original state marked by $p_1$ and $V_1$ and 2 represents final state marked by $p_2$, $V_2$. *a, b* etc. represent intermediate states through which the medium passes. In a real process, the matter may not be in equilibrium but if process is very slow then each point may be close to equilibrium state.

**Figure 5.1**

Units of Measurement,
Gas Laws and Fuels
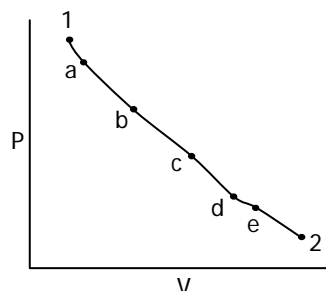
By definition of the process it is seen that the initial and final states are different. Can we go back to initial state such that both the system and surrounding will be restored to initial state of equilibrium? If process is reversible then it is possible that initial state is regained. However, such a process will be very slow. Practically all processes are irreversible. There are several reasons for the process to be irreversible. These reasons lie in the nature (properties) of the system. Internal friction and viscosity can be easily identified as reasons which will make a process irreversible.

A cycle which is a sequence of a few processes can bring the system to its original state. A cycle consisting of different processes will bring the system back to initial state but the state of the surrounding will have changed.

## 5.4  GAS LAWS

**Gas** is a state of any substance whose evaporation from liquid state is complete. Such substances as **air, oxygen, nitrogen, hydrogen** etc. are regarded as gases within the limits of temperature of practice.

A v**apour** consists of pure gaseous state and particles of liquid in suspension. Since the suspended liquid particles are liable to further evaporation and gaseous state to condensation, the behaviour of vaopurs and gases may not be quite the same. In engineering practice several vapours are used. These include steam (water), carbon dioxide, sulphur dioxide and ammonia.

The behaviour of the gases and vapours in engineering machines is of prime importance. The subject of thermodynamics deals with the behaviour and problems of their usage in such machines as boilers, steam engines, turbines, internal combustion engines and refrigerators. For the study of behaviour of gases we draw help from **gas laws** and **laws of thermodynamics**.

### 5.4.1  Joule's Law

We have already introduced the concept of internal energy earlier. Internal energy is the energy of vibrating particles or molecules which can increase in frequency and amplitude by adding heat to the body. Joule's law states that internal energy of a gas is a linear function of the temperature or change in internal energy is directly proportional to change in temperature.

i.e. $\qquad\qquad E \alpha\ (T_2 - T_1)$

if temperature rises from $T_1$ to $T_2$.

We have already seen that if the volume is kept constant, no external work is done and total heat exchange goes to change internal energy.

∴ $\qquad\qquad E = m\ C_v\ (T_2 - T_1)$ $\qquad\qquad$ . . . (5.7)

where $E$ is the change in internal energy of a gas of mass $m$ when heated from temperature $T_1$ to $T_2$ Kelvin.

### 5.4.2  Boyle's Law

The law states, "if a gas is so heated that its temperature remains constant then its pressure ($p$) is inversely proportional to volume ($V$)". It means that

$$p\ \alpha\ \frac{1}{V}\ \text{ or } pV = \text{Constant} \qquad\qquad \text{. . . (5.8)}$$

With large pressures as obtainable in modern engineering practices this law is true within 3%. The process to which Boyle's Law is applicable is indeed isothermal. The expansion with $pV$ = constant is also termed hyperbolic due to the nature of the plot on $p$-$V$ coordinates.

### 5.4.3  Charles' Law

This law states that if a gas is heated at constant pressure, its volume will change and change in its volume will be proportional to absolute temperature. It means that the volume varies as the absolute temperature, or

$$V \, \alpha \, T$$

i.e.
$$\frac{V}{T} = \text{Constant} \qquad \qquad \dots (5.9)$$

### 5.4.4  Avogadro's Law

This law sates that volume of a gas varies as its mass. If mass of the gas is $m$, then

$$V \, \alpha \, m$$

$$\frac{V}{m} = \text{Constant} \qquad \qquad \dots (5.10)$$

Another statement of Avogadro's Law is that the volume is inversely proportional to molecular weight. Keeping molecular weight as a constant and combining the statements of three laws

or
$$\frac{pV}{mT} = \text{Constant}$$

$$pV = mRT \qquad \qquad \dots (5.11)$$

Eq. (5.11) is called characteristic gas equation. $R$ is known as gas constant and it has a unique value for a given gas. The unit of $R$ can be found from following :

$$R = \frac{pV}{mT} = \frac{(\text{N/m}^2) \, (\text{m}^3)}{\text{kg. K}} = \text{Nm/kg.K or J/kg.K}$$

Universal gas constant, $R_u$, is defined as

$$R_u = MR \qquad \qquad \dots (5.12)$$

where $R_u$ is universal gas constant and $M$ is the molecular mass, which is evident from second statement of Avogadro's law.

The unit of $R_u$ is J/kg. mol.K and $R_u$ = 8318.9 J/kg.mol.k.

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**Example 5.1** ▬▬▬▬▬▬▬▬▬▬

A closed vessel contains 1 kg of $N_2$ at 20°C temperature and 98.1 kPa ($98.1 \times 10^3$ N/m$^2$) pressure (absolute). Heat is supplied to vessel till gas acquires a pressure of 196.2 kPa abs. Find

    (a)   final temperature of gas

    (b)   heat added

    (c)   changes in internal energy.

Take $C_v$ = 0.745 kJ/kg.K

**Solution**

Use initial conditions with suffix 1 and final with suffix 2.

Using gas equation, Eq. (5.11), for $m = 1$ kg

$$p_1 V_1 = RT_1 \qquad \ldots \text{(i)}$$

and
$$p_2 V_2 = RT_2 \qquad \ldots \text{(ii)}$$

But note that $V_1 = V_2$, since gas is in a closed container. Dividing Eq. (i) by Eq. (ii)

$$\frac{p_1}{p_2} = \frac{T_1}{T_2}$$

Use
$$\frac{p_1}{p_2} = \frac{1}{2}$$

$\therefore$
$$\frac{T_1}{T_2} = \frac{1}{2} \quad \text{or} \quad T_2 = 2T_1$$

But
$$T_1 = 20 + 273 = 293 \text{ K}$$

$\therefore$
$$T_2 = 2 \times 293 = 586 \text{ K}$$

or
$$586 - 273 = \mathbf{313^o C} \qquad \ldots \text{(iii)}$$

Heat is added at constant volume (closed vessel)

$\therefore$
$$Q_{12} = C_v\, m\, (T_2 - T_1)$$

$$= 0.745 \left( \frac{\text{kJ}}{\text{kg.K}} \right) \times 1 \text{ (kg)} \times (586 - 293) \text{ (K)}$$

$$= 0.745 \times 293 \text{ kJ}$$

or
$$\mathbf{Q_{12} = 218.285 \text{ kJ}}$$

From Eq. (5.7) or Joule's Law, change in internal energy

$$E = m\, C_v\, (T_2 - T_1)$$

which is same as $Q_{12}$

$\therefore$
$$\mathbf{E = 218.285 \text{ kJ}}$$

## 5.5 LAWS OF THERMODYNAMICS

Thermodynamics deals with mass, energy and entropy each as a variable of a system is to be accounted for. The most fundamental concept of the thermodynamics is that the mass remains constant which also means **conservation of mass** is a must for a thermodynamic system. If the system is closed then the matter is neither allowed to leave nor allowed to enter. If the system is open then mass entering the system is equal to the mass leaving the system.

Besides this law, two laws of thermodynamics became well understood and popular among scientists and engineers. These laws are based upon practical observations and are found to help greatly in the analysis of thermal systems. Much later it was felt that one more law was needed to be stated clearly, though it was being used inadvertently. Hence, quite contrary to traditions, this law has been named zeroth law.

### 5.5.1  Zeroth Law of Thermodynamics

When two systems *A* and *B* are in thermal equilibrium with a third system *C*, they are also in thermal equilibrium with each other.

Note that thermal equilibrium means that no heat exchange takes place between the systems when they are brought in thermal contact.

This law has been instrumental in introduction of the concept of temperature and that the heat will flow from a body of high temperature to the body of low temperature. Clausius also inspired by this concept and introduced the temperature scale with 100 divisions between melting point of ice and boiling point of water, at standard atmospheric pressure. This scale was earlier named centigrade but now called Celsius. Later, the Charle's Law gave the idea of absolute temperature by arriving at $-273^{\circ}$C as temperature where molecular activities will cease. $-273^{\circ}$C has been taken as $0^{\circ}$of absolute temperature scale called Kelvin. Thus $-273^{\circ}$C $= 0$ K.

### 5.5.2  First Law of Thermodynamics

The change in energy contents of the system is equal to the sum of heat transferred to the system and work done by the system on the surrounding.

The heat transferred to the system is energy addition while the work done by the system on the surrounding is the energy abstraction. Hence, while former is positive the latter is negative. If work is performed upon the system then it will be positive.

The energy contents of a system are kinetic energy, potential energy and internal energy, respectively denoted by *KE*, *PE* and *U*, and the sum of all three is denoted by *E*. Hence, the law states that

$$(KE + PE + U)_2 - (KE + PE + U)_1 = Q_{12} - W_{12}$$

Here the subscripts 1 and 2 respectively denote initial and final states. $Q_{12}$ is the heat transferred to system in bringing it from state 1 to state 2 and $W_{12}$ is the work done by the system on the surrounding when system moves from state 1 to 2.

The above algebraic expression can also be written as

$$E_2 - E_1 = Q_{12} - W_{12} \qquad \ldots (5.13)$$

Here, *E* represents total energy content of the system. In most thermodynamic system, the *KE* and *PE* are regarded as unchanged in which case

$$E_2 - E_1 = U_2 - U_1 = \Delta U$$

i.e. only internal energy will change.

**First Law Analysis of Some Thermodynamic Processes**

Some thermodynamic processes were described earlier.

**Constant Volume Heating**

If a substance is heated while volume is kept constant, the pressure increases but no work is done on the surrounding. The process is shown in Figure 5.2. All the heat goes to raise the internal energy of the system.

Thus, $\qquad \Delta U = U_2 - U_1 = Q_{12} \qquad \ldots (5.14)$

$p_2$ - - - - - - - ↑2
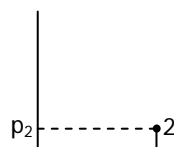
**Figure 5.2 : Constant Volume Process**

According to definition of the specific heat

$$Q_{12} = m \, C_v \, \Delta T$$

$\therefore$ $\qquad \Delta U = m \, C_v \, \Delta T$

It was the statement of Joule's Law.

## Constant Pressure Process

In this process the pressure remains constant while the heat exchange may result in change in volume. As an example see Figure 5.3 in which a piston in the cylinder confines certain volume of the gas (say $V_1$). The piston is pressed by a pressure $p$. When heat is added, the piston moves against pressure $p$ and volume increases to $V_2$.
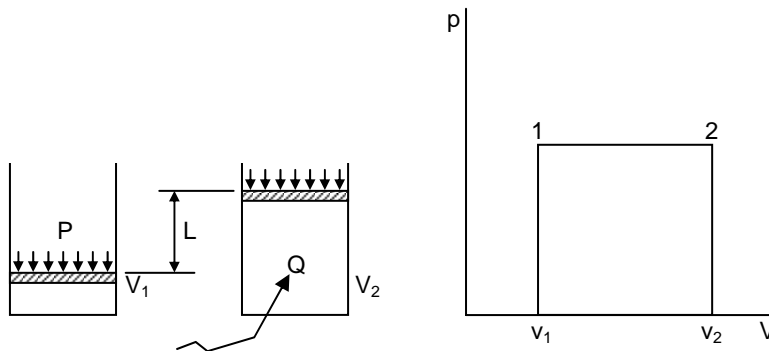


**Figure 5.3 : Constant Pressure Process**

The force on piston of area $A$ is $pA$ and if on application of heat the piston moves distance $L$, then work done by the system on the surrounding

$$W_{12} = pAL = p \, (V_2 - V_1)$$

Applying first law

$$U_2 - U_1 = Q_{12} - W_{12} = Q_{12} - p \, (V_2 - V_1)$$

$\therefore$ $\qquad Q_{12} = (U_2 - U_1) + p \, (V_2 - V_1)$

But $\qquad U_2 - U_1 = m \, C_v \, (T_2 - T_1)$

and $Q_{12} = m \, C_p \, (T_2 - T_1)$ since heat is supplied at constant pressure.

$\therefore$ $\qquad p \, (V_2 - V_1) = m \, (T_2 - T_1) \, (C_p - C_v)$

From Eq. (5.11)

$$m \, R \, (T_2 - T_1) = m \, (T_2 - T_1) \, (C_p - C_v)$$

$\therefore$ $\qquad C_p - C_v = R$ $\qquad\qquad\qquad$ . . . (5.15)

Remember $\dfrac{C_p}{C_v} = \gamma$

or $\qquad C_v = \dfrac{R}{(\gamma - 1)}$ $\qquad\qquad$ ... (5.16)

and $\qquad C_p = \dfrac{\gamma R}{(\gamma - 1)}$ $\qquad\qquad$ ... (5.17)

Eq. (5.15) is an important relation.

---

**Example 5.2** ▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬

A mass of 0.05 kg of a fluid is heated at constant pressure of $2.0 \times 10^5$ kPa until the volume increases to 0.0658 m³. Assume that the fluid is a perfect gas for which $C_p = 1.00$ kJ/kg.K and gas constant $R = 0.289$ kJ/kg.K. Calculate heat supplied and the work done if initial temperature was 130°C. What is the change in internal energy?

**Solution**

$p_1 = 2 \times 10^5$ Pa or N/m², $V_1 = ?$, $T_1 = 403$ K, $p_2 = p_1 = 2 \times 10^5$ Pa,

$V_2 = 0.0658$ m³, $T_2 = ?$, m = 0.05 kg, $R = 0.298$ kJ/kg.K

Use gas equation, $p_1 V_1 = m R T_1$

$$V_1 = \frac{0.05 \times 289 \times 403}{2 \times 10^5} = 2.91 \times 10^{-2} \text{ m}^3$$

$$W_{12} = p_1 (V_2 - V_1)$$
$$= 2 \times 10^5 (0.0658 - 2.91) \ 10^{-2}$$

or $\qquad \mathbf{W_{12} = 7.34 \ kJ}$

Again from gas equation

$\therefore \qquad T_2 = \dfrac{p_1 V_2}{m R}$

$$= \frac{2.0 \times 10^5 \times 0.0658}{0.05 \times 289}$$

or $\qquad T_2 = 910.7$ K

$\therefore \qquad Q_{12} = m \ C_p \ (T_2 - T_1)$
$$= 0.05 \times 10^3 \ (910.7 - 403)$$

or $\qquad \mathbf{Q_{12} = 25.385 \ kJ}$ $\qquad\qquad$ ... (ii)

$Q_{12}$ is heat supplied

From statement of first law of thermodynamics, change in internal energy

$$U_2 - U_1 = Q_{12} - W_{12}$$

In this case, $Q_{12}$ is the heat supplied to the system and $W_{12}$ is the work performed by the system.

$$U_2 - U_1 = 25.385 - 7.34$$

or $\qquad \mathbf{U_2 - U_1 = 18.045 \ kJ}$

## Isothermal Process (Constant Temperature Process)

This is the process envisaged in Boyle's law which means the process will be governed by the equation

$$pV = \text{Constant} \qquad \text{with } T = \text{Constant}$$

Since the change in internal energy is directly proportional to change of temperature, the change in internal energy is zero in this process.

$$U_2 - U_1 = 0$$

Let Figure 5.4 show the process.

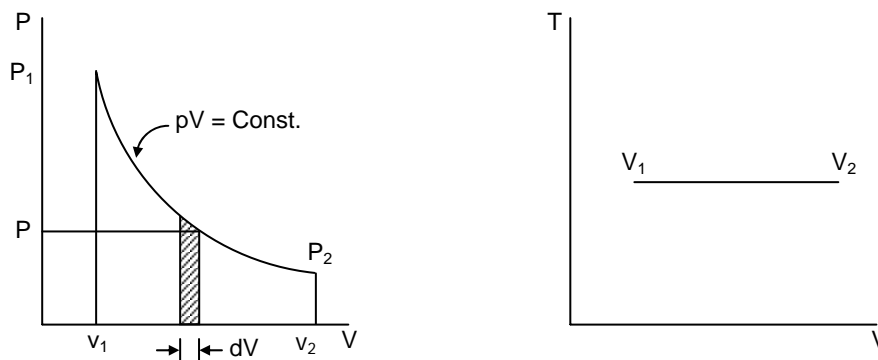Work done for a small volume change of $dV$

$$dW = p\, dV$$



**Figure 5.4**

From gas equation

$$p = \frac{mRT}{V}$$

$$dW = mRT\, \frac{dV}{V}$$

$$W_{12} = \int_{1}^{2} dW = mRT \int_{V_1}^{V_2} \frac{dV}{V}$$

Since $T$ is constant

$$W_{12} = mRT \ln \left( \frac{V_2}{V_1} \right)$$

Also note that from gas equation

$$p_1 V_1 = mRT$$

$$\therefore \qquad W_{12} = p_1 V_1 \ln \left( \frac{V_2}{V_1} \right) \qquad \qquad \ldots (5.18)$$

$$Q_{12} = p_1 V_1 \ln \frac{V_2}{V_1} \qquad \qquad \ldots (5.19)$$

## Adiabatic Process

This is the process in which no heat is exchanged.

Hence, $\qquad Q_{12} = 0$ and
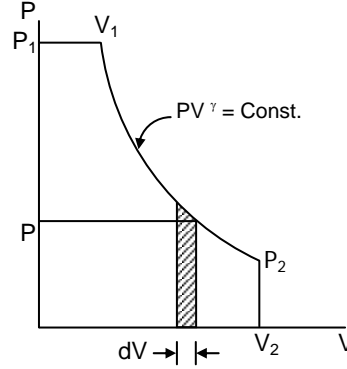
$$U_2 - U_1 = W_{12}$$

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But for a perfect gas

$$U_2 - U_1 = m\, C_v\, (T_2 - T_1) \text{ and note that } T_2 < T_1$$

or $\qquad dU = -\, m\, C_v\, dT = dW$

if we consider very small change in temperature

In Figure 5.5, an adiabatic process is shown.



**Figure 5.5**

An adiabatic process can be represented by

$$pV^{\gamma} = \text{Constant} \quad \text{(This is to be proved)}$$

where $\qquad \gamma = \dfrac{C_p}{C_v}$

Using gas equation $pV = mRT$ so that $p = \dfrac{mRT}{V}$

$\therefore \qquad dW = p\, dV = mRT\, \dfrac{dV}{V} = -\, m\, C_v\, dT$

But from Eq. (5.16)

$$C_v = \dfrac{R}{\gamma - 1}$$

$\therefore \qquad T\, \dfrac{dV}{V} = \dfrac{-1}{\gamma - 1}\, dT$

$$\dfrac{dV}{V} = \dfrac{-1}{\gamma - 1}\, \dfrac{dT}{T}$$

Integrating both sides

$$(\gamma - 1)\, \ln V = -\, \ln T + \text{Const}$$

or $\qquad \ln V^{\gamma - 1} = -\, \ln T + \text{Const}$

or $\qquad \ln (T\, V^{\gamma - 1}) = \text{Const}$

or $\qquad T\, V^{\gamma - 1} = \text{Const}$

put $\qquad T = \dfrac{pV}{mR}$

$\therefore \qquad pV\, V^{\gamma - 1} = \text{Const}$

or $\qquad pV^{\gamma} = \text{Const} = C \qquad\qquad \dots (5.20)$

Thus, we obtain the equation for an adiabatic process which has the characteristic that no heat is exchanged between the system and the

surrounding. If a gas is adiabatically expanded, its internal energy changes into work and gas is cooled. If a gas is adiabatically compressed the work is converted into internal energy and gas is heated.

For calculating work obtained during expansion

$$W_{12} = \int_{V_1}^{V_2} p\,dV = \int_{V_1}^{V_2} \frac{C\,dV}{V^\gamma}$$

$$= \frac{C}{\gamma - 1}[V^{-\gamma+1}]_{V_1}^{V_2}$$

$$= \frac{1}{\gamma - 1}[CV_2^{-\gamma+1} - CV_1^{-\gamma+1}]$$

But $\qquad C = p_1 V_1^\gamma = p_2 V_2^\gamma$

$\therefore \qquad W_{12} = \dfrac{p_1 V_1 - p_2 V_2}{\gamma - 1}$  $\qquad \cdots$

(5.21)

Using gas equation

$$W_{12} = \frac{mR\,(T_1 - T_2)}{\gamma - 1} \qquad \cdots (5.22)$$

**Polytropic Process**

A polytropic process is very general of the form of $pV^n = $ Const. Apparently when $n = 1$, it is isothermal process, when $n = \gamma$, it is adiabatic process and when $n = 0$, it is constant pressure process.

Work obtained from such an expansion is calculated in the same way as for adiabatic process – only $\gamma$ will be substituted by $n$.

$$W_{12} = \frac{p_1 V_1 - p_2 V_2}{n - 1} = \frac{mR\,(T_1 - T_2)}{n - 1} \qquad \cdots (5.23)$$

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**Example 5.3** ▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬

2 kg of air at pressure of 7 bar occupies a volume of 0.28 m³. This air is expanded to a volume of 1.4 m³ following a law $pV^{1.2} = $ Const. Find

    (a)   final temperature,

    (b)   the work done, and

    (c)   heat absorbed or rejected.

Take $R = 287$ J/kg.K, and $C_p = 1000$ J/kg.K

**Solution**

$m = 2$ kg, $p_1 = 7$ bar $= 7 \times 10^5$ N/m², $V_1 = 0.28$ m³

$p_2 = ?$ $V_2 = 1.4$ m³

$$p_1 V_1 = mRT_1$$

$$T_1 = \frac{7 \times 10^5 \times 0.28}{2 \times 287} = 341.46 \text{ K}$$

$$p_1 V_1^{1.2} = p_2 V_2^{1.2}$$

$$7 \times 10^5 \times (0.28)^{1.2} = p_2 \times (1.4)^{1.2}$$

$$p_2 = 7 \times 10^5 \times \frac{0.217}{1.5} = 1.014 \times 10^5 \text{ N/m}^2$$

$$T_2 = \frac{p_2\, V_2}{m\, R}$$

$$= \frac{1.014 \times 10^5 \times 1.4}{2 \times 287}$$

or $\qquad$ **$T_2$ = 247.3 K  final temp** $\qquad\qquad$ . . . (i)

From Eq. (5.23)

$$W_{12} = \frac{p_1 V_1 - p_2 V_2}{n-1} = \frac{m\,R\,(T_1 - T_2)}{n-1}$$

$$= \frac{2 \times 287\,(341.46 - 247.3)}{1.2 - 1}$$

or $\qquad$ **$W_{12}$ = 270239.2 J** $\qquad\qquad$ . . . (ii)

The work is done by the gas on the surrounding.

$$C_p - C_v = R$$
$$C_v = C_p - R = 1000 - 287 = 713 \text{ J/kg.K}$$
$$U_2 - U_1 = m\,C_v\,(T_2 - T_1)$$
$$= -2 \times 713\,(341.46 - 247.3)$$
$$= -134272.16 \text{ J}$$

Thus internal energy is reduced

$$U_2 - U_1 = Q_{12} - W_{12}$$
$$\therefore \qquad Q_{12} = W_{12} + (U_2 - U_1)$$
$$= (270.24 - 134.3) \text{ kJ}$$

or $\qquad$ **$Q_{12}$ = 136.00 kJ** $\qquad\qquad$ . . . (iii)

$Q_{12}$ is heat gained by the system.

## SAQ 2

(a)   A perfect gas with specific heat ratio of 1.4 occupies a volume of 0.3 m$^3$ at 105 kN/m$^2$ and 27°C. The gas undergoes a compression to 0.06 m$^3$. Find the heat absorbed or rejected by the gas for each of the following types of compression :

$\qquad$ (i)   Constant pressure

$\qquad$ (ii)   Isothermal

$\qquad$ (iii)   Adiabatic

$\qquad$ (iv)   Polytropic with $n = 1.1$

Take $R = 287$ J/kg.K

(b)   Air having a mass of 1.82 kg at pressure of 0.7MPa occupies a volume of 0.283m$^3$. Calculate final temperature, work done, heat absorbed or rejected by this air if expanded to volume = 1.415 m$^3$

$\qquad$ (i)   adiabatically, and

$\qquad$ (ii)   according to $pV^{1.2}$ = Const.

Assume $C_p = 1.0$ kJ/kg K, and $C_v = 0.704$ kJ/kg K.

## 5.5.3 Second Law of Thermodynamics

This law deals with the quality of energy. Quality in respect of energy may appear to be strange. We start from the basic concept that all the work we do or get done is through mechanical energy therefore mechanical energy is of interest. Where do we get mechanical energy from? It may be that heat is converted into mechanical energy and in the process some energy is lost. This loss is understood as degradation or loss of quality. This loss of quality may perhaps appear as change of some property of the system. To introduce the concept of degradation or loss of quality of energy, the second law of thermodynamics has been enunciated. It has been accumulated as experience that, "all processes on an isolated system always lead to degradation of energy such that the ability to do mechanical work always decreases."

The conclusion from above statement is that all the heat content of a system is not available for conversion into mechanical energy or work. In other words, certain fraction of energy content of the system is *available energy* while remaining portion is *unavailable*. Thus

$$\text{Energy of a system} = \text{Energy}_{\text{avail}} + \text{Energy}_{\text{unavail}}$$

or $\qquad\qquad E = E_{\text{av}} + E_{\text{ua}}$ . . . (5.24)

For making an estimate as to how much energy is convertible or available for conversion into work, we introduce a property called *entropy* which could become measure of degradation or loss of quality. Apparently the quantity of interest will be $(E - E_{\text{av}})$ or $(dE - dE_{\text{av}})$. The entropy is then defined as

$$dS \propto E - E_{\text{av}}$$

or $\qquad\qquad dS = C (dE - dE_{\text{av}})$ . . . (5.25)

where $C$ is a positive constant whose value will depend upon the type of energy reservoir with which energy is exchanged. Since $dE_{\text{av}}$ will always be less than $dE$ or at most it can be equal to $dE$, therefore

$$dS \geq 0$$

However, the change $dS$ will refer to both system and surrounding or

$$dS_{\text{system}} + dS_{\text{surrounding}} \geq 0$$

A reversible process in which system returns to original state is marked by

$$dS = 0$$

And an irreversible process is identified by

$$dS > 0$$

Since $dS$ is sum of $dS_{\text{system}}$ and $dS_{\text{surr}}$, it will mean that in the practical world where energy conversion is regularly taking place the entropy of the universe is increasing.

In this study, it is assumed that a heat reservoir is a system which interacts only through heat exchange. It works either as a source or a sink of heat, with infinite capacity that neither heat addition nor heat subtraction will change its temperature. At the same time a work reservoir is envisaged as a store of energy which is available to do work. This energy may be regarded to be stored in compressed spring or a mass raised on shaft. Whatever energy is stored; it can be

recovered fully by decompressing the spring or allowing the mass to fall. Hence, the entropy change of a work reservoir is zero.

A heat reservoir interacts only through energy exchange (no work), hence the first law of thermodynamics will result in

$$dE = dQ$$

Hence, from Eq. (5.25)

$$dS = C\,(dE - dE_{av}) = C\,(dQ - dE_{av}) = C_1\,dQ$$

where, $C_1$ is another constant. It can be shown that $C_1 = \dfrac{1}{T}$, where $T$ is the constant temperature of heat reservoir.

$$\therefore \qquad dS = \frac{dQ}{T} \qquad \qquad \ldots (5.26)$$

Eq. (5.26) serves as definition of entropy change. It must be understood here that we did not prove that $C_1 = \dfrac{1}{T}$ because it is beyond the scope of this text, though it is possible to prove this.

Suppose heat reservoirs $A$ and $B$ respectively at temperature $T_1$ and $T_2$ are brought in thermal contact so that heat $Q$ flows from $A$ to $B$. The change in entropies are

$$(\Delta S)_A = -\frac{Q}{T_1} \qquad \qquad \text{(Since heat is subtracted from } A\text{)}$$

and

$$(\Delta S)_B = \frac{Q}{T_2} \qquad \qquad \text{(Since heat is added to } B\text{)}$$

The net entropy change of the system (isolated) consisting of $A$ and $B$.

$$(\Delta S)_{\text{total}} = Q\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \qquad \qquad \ldots (5.27)$$

Since right hand side of Eq. (5.27) is required to be greater than zero, $\dfrac{1}{T_2} > \dfrac{1}{T_1}$ or $T_1 > T_2$. This establishes that heat will flow from higher temperature to lower temperature without requiring any external work. Imagine if heat is to transfer from $B$ to $A$ then $(\Delta S)_{\text{total}}$ will have to be negative and it is not possible. This could become possible if external work is provided. This fact was stated by Clausius in the form of a law which is popularly known as second law of thermodynamics.

**Second Law of Thermodynamics (Clausius Statement)**

"It is impossible to operate a cyclic device where sole effect is to transfer heat from a reservoir at lower temperature to another at higher temperature."
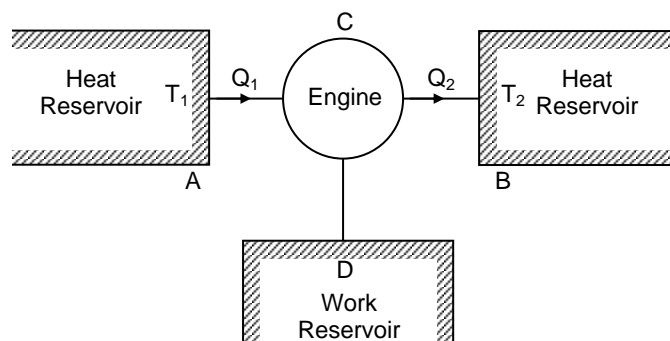
**Figure 5.6**

Figure 5.6 presents a situation wherein a device C has been placed between A and B. Imagine that C is a device that receives heat $Q_1$ from A and converts it into work. The heat loss of A results in change of entropy

$$(dS)_A = -\frac{Q_1}{T_1}$$

but no change of entropy due to work produced. If we assume A and C to constitute an isolated system then total entropy change is

$$(ds)_{ACD} = \frac{-Q_1}{T_1}$$

which being negative is not possible. This is another way of stating second law of thermodynamics.

**Kelvin-Planck Statement of Second Law of Thermodynamics**

"It is impossible to construct a device which operates in a cycle and produces no effect other than taking heat from a source of heat, and converting it into work."

If to the combine of A (heat source), C (work producing device) and D (work reservoir), B (heat reservoir at temperature $T_2$) is added and $Q_2$ heat is lost to the reservoir B in the process, the net entropy turns out to be greater than zero. It can be seen here.

$$(\Delta S)_{\text{isolated system}} = \frac{-Q_1}{T_1} + \frac{Q_2}{T_2}$$

and for $(\Delta S)$ to be positive, $\dfrac{Q_2}{T_2} \geq \dfrac{Q_1}{T_1}$

The energy balance (because $T_1$ and $T_2$ are constant) results in

$$W = Q_1 - Q_2$$

∴ $$Q_2 = Q_1 - W$$

∴ $$\frac{Q_1 - W}{T_2} \geq \frac{Q_1}{T_1}$$

or $$W \leq Q_1\left(1 - \frac{T_2}{T_1}\right) \qquad \ldots (5.28)$$

The device C, a work producing device, is called engine. Apparently, since $T_2 > 0$, $W < Q_1$ where $Q_1$ is the energy lost by heat source.

The equality sign in Eq. (5.28) places a limit on conversion of heat into work. The ratio of $W/Q_1$ can be regarded as the thermal efficiency of the engine. And when

$$\eta = \frac{W}{Q_1} = 1 - \frac{T_2}{T_1} \qquad \ldots (5.29)$$

it can be regarded as maximum achievable efficiency from an engine operating between heat reservoir and heat sink of temperatures $T_1$ and $T_2$ respectively. This will be possible only if the process is reversible and since

all processes in practice are irreversible the actual efficiency will be less than this efficiency.

The efficiency given by Eq (5.29) is called Carnot efficiency and denoted by $\eta_c$. Any other efficiency is denoted by $\eta$.

$$\eta \leq \eta_c$$

*If engines are operating between the same constant temperature heat reservoir, only that engine will be most efficient which is reversible.*

Above is the statement of Carnot principle. An important corollary of Carnot principle is, *all reversible engines operating between two constant temperature heat reservoirs will have same efficiency, irrespective of the working substance.*

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| **Example 5.4** | |

An inventor claims to have developed a heat engine which produces 5 kW and consumes 400 kJ of heat per min. The engine operates between 1000 K and 300 K. Examine the claim and say if it is true.

**Solution**

$T_1 = 1000$ K, $\quad T_2 = 300$ K

$$Q_1 = 400 \text{ kJ/min} = \frac{400 \times 10^3}{60} = 6666 \text{ J/s}$$

$$W = 5 \times 10^3 \text{ J/s}$$

$$\eta_c = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{1000} = 70\%$$

$$\eta = \frac{W}{Q_1} = \frac{5000}{6666} = 75\%$$

$\eta$, the efficiency, turns out to be greater than $\eta_c$, the Carnot efficiency, which is impossible.

Hence, claim is false.

---

## 5.6 FUELS

Through combustion chemical energy is converted into thermal energy and through devices like engine or turbines the thermal energy is converted into mechanical energy. This mechanical energy can be either used directly for doing useful work through machines or can be further converted into electrical energy for easy transmission.

Doing of useful work is the part of history of mankind. They first used muscular energy of their own for this purpose and then harnessed animals for the same. The man learnt to use wind energy in driving ships and windmills around 5500 years ago and followed his capturing of water power some 5000 years ago. The use of thermal energy for creating mechanical work is comparatively a modern phenomenon, as recent as 18$^{th}$ century. The man, however, has learnt to burn "fuel" for cooking food and keeping houses warm much earlier. The fuel of early days was only wood, although man has discovered coal and dug it out from the ground as early as the beginning of 13$^{th}$ century. The obnoxious gaseous emission from burning of coal did not encourage its general use and even at one point of

time a royal decree prohibited burning of coal. Until 1850 about 90% of fuel energy was obtained from wood. As for present time, the energy consumption is compartmentalized in commercial and non-commercial sources. All over the world around 65% of the energy is obtained from non-commercial sources which include wood, agricultural waste and dung cakes. India satisfies 50% of its energy needs through non-commercial sources.

The commercial energy sources are high energy density fuels which are found in all three states of solid, liquid and gas.

All these fuels, like wood, burn in the presence of oxygen which is derived from air. The products of combustion will depend upon the contents of fuel but will mainly consist of $CO_2$ and $H_2O$ since all fuels contain carbon and hydrogen. CO is also produced if combustion is not complete. $SO_2$ is produced if sulphur is present in the fuel. Many fuels contain nitrogen also. Otherwise nitrogen is provided by air. The temperature of combustion is sufficiently high to cause oxidation of nitrogen. The increasing concentration of these products of combustion in atmospheric air is a great source of worry to scientists and engineers since they are dangerous to the health of people. $CO_2$ has become the main source of worry as it causes green house effect raising atmospheric temperature.

## 5.6.1  Chemical Reaction

A chemically correct mixture of fuel and air is the one in which neither fuel nor the oxygen is deficient. The volumetric ratio of nitrogen to oxygen is 3.76. The volumetric ratio is also called *molar ratio*. We may remind ourselves that one mole is the quantity having mass, in grams, equal to the molecular weight. This quantity is also called molar mass. One mole of gas occupies a volume of 0.0224 $m^3$ at one atmospheric pressure and $0^oC$. Thus, the masses of each of one mole of $N_2$ and $O_2$ are respectively 28 g and 32 g.

We can assume that a fuel is made up of $x$ atoms of carbon and $y$ atoms of hydrogen so that its formula is $C_xH_y$. Let $m_s$ be the chemically correct moles of oxygen required for reaction. Then

$$C_x H_y + m_s (O_2 + 3.76 N_2) = x CO_2 + \frac{y}{2} H_2O + 3.76 m_s N_2$$
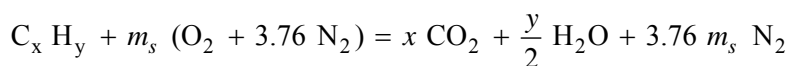
For molar balance of $O_2$ on two sides of equation

$$2m_s = 2x + \frac{y}{2}$$

$$m_s = x + \frac{y}{4} \qquad \qquad \dots (5.30)$$

For 1 mole of fuel, air used is $1 + 3.76 m_s = 4.76 m_s$ moles.

$$\therefore \qquad \text{Air/fuel ratio } = \frac{4.76 m_s}{1}$$

$$(A/F)_s = 4.76\left(x + \frac{y}{4}\right) \qquad \qquad \dots (5.31)$$

The above air/fuel ratio $(A/F)_s$ is known as *stoichiometric* air/fuel ratio. The chemically correct mixture and air and fuel is called *stoichiometric* mixture.

For air/fuel mass ratio, denoted by $(A/F)_m$

$$(A/F)_m = (A/F_s) \frac{\text{Molar mass of air}}{\text{Molar mass of fuel}}$$

$$\therefore \qquad (A/F)_m = \frac{4.76\left(x + \dfrac{y}{4}\right)}{12x + y} \times 28.96 \qquad \qquad \dots (5.40)$$

Air being mixture of oxygen and nitrogen, the molar mass of 28.96 is calculated depending upon their proportion.

Most fuels practically burn at temperature of 2200 K whereas the calculated value of the temperature varies from 2300 K to 2500 K.

*Flammability* is defined as the travel of the flame through any medium. The flame will travel to a point where both fuel particles and oxygen molecules are present. In a rich mixture (more fuel), fuel particles may be present but oxygen may not be. In a lean or weak (less fuel) mixture, oxygen molecules may be present but fuel particles may not be. Thus, in both cases flammability is restricted to stoichiometric A/F ratio.

### 5.6.2 Properties of Fuels

Most conventional and commercial fuels are extracted from underground. They have fossil origin. Some fuels are industrially produced, mostly as byproduct. There are still some derived from municipal wastes.

The fossil fuels are mostly complex compounds of carbon and hydrogen and are known as hydrocarbons. Solid fuels contain some nitrogen and water while liquid and gaseous fuels are free from such impurities. The manufactured fuels (as byproducts) which are mostly gas contain small amount of hydrogen, carbon monoxide, carbon dioxide, nitrogen and hydrogen sulphide. In natural solid fuels traces of sulphur, lead, vanadium etc. are mostly present. Material impurities are required to be removed from fuel before they are burnt else they will enter the atmospheric air. The solid fuels are mainly carbon. The liquid and gaseous fuels are complex compounds of carbon and hydrogen. The simplest of all hydrocarbons is methane, $CH_4$. Several other hydrocarbons are much more complex with varying chemical and physical properties. The molecules that are made of one to four carbon atoms have weak binding force and hence are gaseous. Larger molecules have stronger force fields hence are in liquid state. A few are solids also. These molecules in which all carbon bonds (there are four bonds in carbon atom) are made are saturated compounds and are stable. One out of four normally joins with another carbon and remaining three with three hydrogen atoms. In case of methane, all four bonds of carbon are saturated with hydrogen.

**Density** among physical properties and **calorific value** among chemical properties of fuel are important. There are standard methods of determining the density and calorific value. Such methods are recommended by ASTM (American Society for Testing and Materials) and other professional societies.

For gaseous fuels the density is measured at 15$^o$C and at atmospheric pressure and expressed as kg/m$^3$. The density of liquid fuel is measured at 15$^o$C. In case of solid fuel density of a lump of fuel is measured and it is called lump density. For finding bulk densities the voids between lumps are determined and their volumes are added to volume of lumps to determine the bulk volume. The density of solid or liquid is often expressed as kg/litre. Liquid fuels having several constituents are characterized by blend (mixture) density which is calculated from individual densities.

**Calorific Value** is perhaps the most important property of any fuel. Calorific value is the measure of heating value of the fuel.

It must be realized that water may be present in some fuels and water is formed during chemical reaction also. Both types of water will evaporate absorbing heat in the form of latent and superheat. In practical situations like furnaces, boilers or IC engines this steam in combustion product is not permitted to condense but let out as part of exhaust. Thus, the available heating value of the fuel is reduced by an amount equal to latent heat and superheat of water formed in combustion or of water which is present as impurity in fuel. This heat available for heating is called *Lower Calorific Value* (LCV).

In experimental determination the steam in combustion product is allowed to condense and in doing so it transfers its heat to the instrument and recorded as heat given by fuel. This heating value is gross and higher than actual heating value obtained in practice. This is called *Higher Calorific Value* (HCV.)

HCV and LCV are related as under

$$HCV - LCV = 2400 \, (M + 9H_2) \text{ kJ/kg}$$

where,     $M$ = moisture content of fuel, and

   $H_2$ = hydrogen mass fraction of fuel.

The CV of gaseous fuels is expressed as MJ/m$^3$ and hence it is also understood as *energy density*. The CV expressed as MJ/kg is also understood as *specific energy*. As an example consider $H_2$ as fuel. Its energy density is 17.70 MJ/m$^3$ while its specific energy is 37.66 MJ/kg.

The CV expressed as MJ/kg (specific energy) for gases decreases as fuel density increases. Thus, specific energy of $H_2$ is highest and $CH_4$ is next, followed by $C_2H_2$, $C_3H_8$ and $C_4H_{10}$.

The CV expressed as MJ/m$^3$ (energy density) for gaseous fuels increases as the density increases. This trend places $H_2$ at the lowest place in the group of $H_2$, $CH_4$, $C_2H_2$, $C_3H_8$ and $C_4H_{10}$.

The CV expressed as MJ/kg for solid fuel increases for wood, peat and coal in this order and remains almost constant for coal, coke and carbon. The CV expressed as MJ/litre for wood, lignite, anthracite, coke and carbon increases in this order with increasing densities.

For liquid fuel specific energy reduces while energy density increases with increasing fuel density.

## 5.6.3  Types of Fuel

The fuels are firstly classified as

   (a)   Natural

   (b)   Manufactured

      (i)    Modified Natural Fuels

      (ii)   Byproducts of Processes

The **naturally occurring fuels** are fossils found below the ground surface. They were produced from fossilization of carbohydraulic compounds. Having general chemical formula of $C_n (H_2O)_m$, the carbohydrates were produced through photosynthesis by living plants. The process is actually conversion of solar energy into chemical energy. After the plant died, they were buried, came under pressure of earth and also in the absence of oxygen the carbohydrates converted

into hydrocarbons of general chemical formula as $C_xH_y$. The process of conversion, of course, continued for a long period, estimated to be 325 million years.

The fossil fuels are found in three states.

**Gaseous Fuels**

Three gaseous fuels are in use. They are naturally occurring, chemically manufactured and those obtained as byproduct.

*Natural Gas*

It is the mixture of methane and smaller fractions of other gases. It is found trapped under limestone casing above petroleum reserves. Naturally occurring gaseous fuel may belong to one of two types. One was produced from decay of organic matter and other was trapped deep in earth's crust since the time when earth was formed. The latter gas sources are called *primordial* natural gas sources. The gas is normally trapped in its reservoir under a pressure of 35 to 70 MPa. The smaller fractions of other gases may be condensable. When extracted from the reservoir, the pressure of natural gas reduces where by water and heavier hydrocarbons freeze and can be separated. The natural gas associated with petroleum contains such condensable matter. This gas is often referred to as wet gas. Methane is a major part of gases collected from coal mines, landfills of garbage and sewage farms.

The condensate gases extracted from wet natural gas mainly consist of propane ($C_3H_8$) and butane ($C_4H_{10}$) together with higher and heavier hydrocarbons. The commercial grades of propane and butane each is 95% pure. The petroleum gases, available commercially, are the mixtures of butane and propane. These gases are compressed and liquified for convenient handling and storage. They are known as liquified petroleum gas (LPG) and used for domestic cooking.

Natural gas is also used for domestic and industrial heating, hot water supplies and cooking. This gas is also used in kilns, furnaces, boilers, engines and turbines. The natural gas for the purposes as mentioned above is transported and distributed through pipelines. Since the gas contains no sulphur and ash it is found preferable for automobile. For powering automobile the natural gas has to be compressed and carried in cylinders. Compressed natural gas is less polluting in comparison with coal (containing no sulphur and ash) and petroleum fuel (containing sulphur and particulate matter) and therefore is likely to be the fuel of the future. The natural gas is also used as raw material for producing plastics.

There are several other gaseous fuels and one of them, LPG was mentioned. However, it must be mentioned here that the butane and propane are obtained as light distillate form petroleum refining and for that they are also often called refinery gas. Both these gases have higher calorific value in MJ/m$^3$ than methane. Since these gases are heavier than air they are more difficult to handle. They can be liquified at pressure varying between 0.4 to 2.0 MPa.

*Water Gas*

Water gas is a mixture of CO and $H_2$ which is produced by alternately passing steam and air over bed of incandescent coke. This gas has low

volumetric calorific value. Oil vapours are sometimes added to water gas to improve its calorific value with resulting gas being named as carbureted water gas.

*Coke Oven Gas*

Coke ovens of steel industry are source of so called *coke oven gas* containing volatile matter of coal. Yet another gas comes as byproduct from blast furnace of steel industry. *The blast furnace gas* besides $CO_2$ and $N_2$ contains only combustible gas as CO. This gas is often used as a cover for molten iron to ward off oxidation and also in running IC Engines.

*Biogas*

Biogas is obtained from wastes from animals and farms. This gas mainly consists of $CH_4$, hence high in heating value. Biogas plants are erected for specific purpose and can run IC engines.

## Liquid Fuels

All liquified gases may be regarded as liquid fuels. When gases are liquified their water is completely removed by refrigeration or by passing over solid desiccants like silica gel, alumina or through molecular sieves. The liquified gases are stored in double walled cryogenic metallic tanks or in pre-stressed concrete tanks or underground caverns. The heat leakage to liquified gas has to be prevented which may require increasing pressure or reducing temperature of compressed gas. The petroleum gases, butane and propane, liquify at moderately high pressure of 0.4 to 2.0 MPa.

Liquid fuels are very commonly used in automobiles. The liquid fuels are mostly derived from fossil petroleum. These fuels are also conveniently used to power aeroplanes, ships and trains. They are very convenient for burning in furnaces whether in industry or homes. The liquid fuels offer convenience of storage, transport and stability at ambient conditions. It is understood that the liquid fuels are the result of fossilization of partially decomposed marine life under heavy pressure over millions of years.

Petroleum is obtained from underground as free flowing yellowish brown to black liquid of density varying between 0.78 to 1.0 $kg/m^3$. The constituents are saturated hydrocarbons. The actual composition and properties depend upon geographical location and age of deposit.

Petroleum extracted from ground is called crude which is refined by process of distillation which results in a number of fractions. The lightest fraction is petrol (or gasoline) and heaviest is residual fuel oil. Each fraction contains several hundred hydrocarbons. Each distillate fraction can be treated to have desired properties by breaking or joining the bonds.

The petroleum that leaves asphalt as residue is classified as *asphalt based*. The other is called *paraffin based* because it leave residue of paraffin. There are still some petroleum which leave combined wax and asphalt residues. They are called *mixed based*.

All the crudes are found to contain 84 to 81% C and 16 to 21% $H_2$ by mass. The oxygen and nitrogen fractions together vary between 0 and 1%, whereas sulphur may vary from 0 to 4%.

The commercially classified fuel fractions based upon boiling point range (mentioned in brackets) are in following order :

Petrol (40-185$^o$C), Kerosene (140-260$^o$C), Diesel fuel (> 180$^o$C).

Light fuel oil (> 200$^{\circ}$C), Heavy fuel oil (> 250$^{\circ}$C), Coal tar fuel (> 200$^{\circ}$C).

The density of fuel increases in the same order.

The higher calorific values of above fuels respectively (in kJ/kg) are 47.4, 45.9, 44.5, 46.07, 43.17 and 42.3.

All liquid fuels offer advantage of store, handling and transport, absence of ash. In some cases, very small amount of ash is produced and it sticks to the surface. This may alter dimensions. There are some fuel that contain sulphur which can be removed only through costly process.

**Solid Fuels**

The solid fuels are fossilized vegetable matter. These sources are continuously and regularly replenished during lifetime of man while other fossil materials are derived during periods of formation that extended over millions of years.

Coal is found in continuous layers underground, near surface or even on the surface. It is most abundantly found fuel on earth. Coal is classified into four groups.

 (a) Anthracite coal (Class I)

 (b) Bituminous coal (Class II)

 (c) Sub-bituminous coal (Class III)

 (d) Lignite coal (Class IV)

Coal contains sulphur in varying proportions. Sulphur is combustible and adds to heating value. $SO_2$ and $SO_3$ which are produced by sulphur cause acid rains and are bad pollutants hence sulphur is being removed. The coal can burn in lumps but its combustion efficiency is very high if it is in pulverized form. The grindability index is the measure of pulverization. Some coals do not burn completely to ashes but melt and form cake like lumps. They are used for making coke used in steel industry.

There are two ways in which coal is analysed.

*Proximate Analysis* gives mass fractions of fixed carbon (FC) volatile matter (VM), ash (A) and moisture (M).

*Ultimate Analysis* gives fractions of carbon (C), hydrogen ($H_2$), nitrogen ($N_2$) and sulphur (S) along with HCV.

Fuel wood and straw have been used as solid fuel since ages. The great advantage they offered in past was that they were reproducible. Unfortunately the higher rate at which they were consumed exceeded the rate at which they grow and hence their use is being curbed. Firewood and straw burn rapidly and leave very little residue (0.6%).

The human activities in the domestic and economic areas and industries together produce large amounts of solid wastes. These wastes consist of vegetables, wood, plastic paper etc. Most of these are combustible and are being used as fuel. Their use as fuel may also solve the problem of disposal. Yet effects on environment have to be taken care of.

**SAQ 3**

Define a fuel. What are different types of fuel?

# 5.7 SUMMARY

Terms which are commonly used in study of mechanics and thermodynamics have been defined and their units discussed. The behaviour of air and gases in engines is governed by several gas laws like $pV = RT$ and laws of thermodynamics. The heat and work are equivalent and interconvertible is the statement of first law of thermodynamics. The heat cannot be transferred from lower to higher temperature unaided is the second law.

The gases can expand and perform work on walls, atmosphere or piston. The expansion which is a process could be constant pressure, constant volume, constant temperature (isothermal) or adiabatic. It can also be governed by a general law $pV^n$ = constant. In each case work done has been calculated.

A sequence of processes at the end of which original state of gas is regained is defined as cycle. Otto cycle, Carnot cycle and Diesel cycle are standard gas (air) cycles which are used in engines. They will be discussed later. The ratio of work done to heat supplied in a cycle is defined as efficiency.

The heat is obtained from fuels which may be solid, liquid or gas. Most fuels are extracted from ground but fuel wood is obtained from trees. Domestic waste and industrial waste can also act as fuel. Fuel gases are also obtained from agricultural and animal wastes.

# 5.8 ANSWERS TO SAQs

**SAQ 1**

(c)  1 kgf is that force with which earth pulls a body, i.e. the acceleration of the body is 9.81 m/s$^2$

i.e. $\quad\quad$ 1 kgf = 1kg × 9.81 m/s$^2$

∴ $\quad\quad$ 10 kgf = 10 kg × 9.81

or $\quad\quad\quad m = 10$ kg

∴ $\quad\quad$ 10 kgf = $m$ (kg) × 9.81 m/s$^2$

∴ $\quad\quad\quad m = \dfrac{10}{9.81} = 1.02$ kg.

1 Newton is that force which will create an acceleration of 1 m/s$^2$ in body of 1 kg mass.

∴ $\quad$ Force required to create an acceleration of 9.81 m/s$^2$ (i.e. acceleration due to gravity)

$\quad\quad\quad$ = 1 (kg) × 9.81 (m/s$^2$)

$\quad\quad\quad$ = 9.81 Newton

∴ $\quad\quad$ 1 kgf = 9.81 N.

(d)  Atmospheric pressure creates a force over a section A which is equal to the cross sectional area of mercury column. On this area also acts a force which is the weight of mercury column which is equal to $\gamma_{Hg} AL$ where $\gamma_{Hg}$ is the specific weight (weight per cubic meter) of mercury. $A$ is cross sectional area of the tube in which column stands vertically and $L$ is the length of the column. The length of this column is used to express the atmospheric pressure and this length is 760 mm. If water

column is used in place of mercury then its length will be $\gamma_{Hg}/\gamma_{water}$ times $L$. That means the water column will be 13.5 times longer.

$$1 \text{ atm} = 760 \text{ mm } H_g = 1.013 \text{ kN/m}^2 = 760 \text{ torr.}$$

(e)  Power is the rate of doing work

$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

$$1 \text{ kWh} = 3412 \text{ Btu (unit of energy)}$$

$$1 \text{ kW} = 3412 \text{ Btu/hr}$$

$$= \frac{3412}{60 \times 60} = 0.95 \text{ Btu/s}$$

Hence, power of machine is 1 kW

$$0.736 \text{ kW} = 1 \text{ hp}$$

$$\therefore \qquad 1 \text{ kW} = 1.36 \text{ hp}$$

**SAQ 2**

(a)  (i)  Work done on the gas, $W = -24.78$ kJ

Decrease in internal energy $= 62$ kJ

Heat rejected by the gas $= 86.77$ kJ

(ii)  Work done on the gas, $W = -50$ kJ

Change in internal energy $= 0$

Heat rejected by the gas $= -50$ kJ

(iii)  Work done on the gas $= -70.14$ kJ

Increase in internal energy $= 70.14$ kJ

Heat exchange $= 0$

(iv)  Work done on the gas $= -54.18$ kJ

Increase in internal energy $= 13.6$ kJ

Heat rejected by the gas $= 40.6$ kJ

[**Note :**  Remember Heat absorbed by the system is positive,

Work done by the system is positive, and

Increase in internal energy is positive.]

(b)  (i)  $R = 1.0 - 0.704 = 0.296$ kJ/kg.K, $\gamma = \dfrac{C_p}{C_v} = \dfrac{1.0}{0.704} = 1.42$

$$T_1 = \frac{p_1 V_1}{mR} = \frac{0.7 \times 10^6 \times 0.283}{1.82 \times 0.296} = 367 \text{ K}$$

$$p_2 = \frac{p_1 V_1^{\gamma}}{V_2^{\gamma}} = \frac{0.7 \times (0.283)^{1.42}}{(1.415)^{1.42}} = 0.0724 \text{ MPa}$$

$$T_2 = \frac{p_2 V_2}{mR} = \frac{0.0724 \times 10^6 \times 1.415}{1.82 \times 296} = 190.16 \text{ K}$$

$$W = \frac{pV_1 - p_2V_2}{\gamma - 1} = \frac{0.7 \times 10^6 \times 0.283 - 0.0724 \times 10^6 \times 1.5}{1.42 - 1} = 228 \text{ kJ}$$

$$E = mC_v \ (T_2 - T_1) = 1.82 \times 0.704 \ (190.16 - 367) = -227.6 \text{ kJ}$$

$$Q = 0$$

(ii)   For $pV^{1.2} = $ const.

$W = 283$ kJ, $E = 138.4$ kJ, $Q = 144.6$ kJ.